JOURNAL OF GEOPHYSICAL RESEARCH: SOLID EARTH, VOL. 118, 1–10, doi:10.1002/jgrb.50239, 2013

Early India-Australia spreading history revealed by newly detected Mesozoic magnetic anomalies in the Perth Abyssal Plain

Simon E. Williams,[1] Joanne M. Whittaker,[1,2] Roi Granot,[3] and Dietmar R. Müller[1]

Received 22 February 2013; revised 31 May 2013; accepted 6 June 2013.

[1] The seafloor within the Perth Abyssal Plain (PAP), offshore Western Australia, is the only section of crust that directly records the early spreading history between India and Australia during the Mesozoic breakup of Gondwana. However, this early spreading has been poorly constrained due to an absence of data, including marine magnetic anomalies and data constraining the crustal nature of key tectonic features. Here, we present new magnetic anomaly data from the PAP that shows that the crust in the western part of the basin was part of the Indian Plate—the conjugate flank to the oceanic crust immediately offshore the Perth margin, Australia. We identify a sequence of M2 and older anomalies in the west PAP within crust that initially moved with the Indian Plate, formed at intermediate half-spreading rates (35 mm/yr) consistent with the conjugate sequence on the Australian Plate. More speculatively, we reinterpret the youngest anomalies in the east PAP, finding that the M0-age crust initially formed on the Indian Plate was transferred to the Australian Plate by a westward jump or propagation of the spreading ridge shortly after M0 time. Samples dredged from the Gulden Draak and Batavia Knolls (at the western edge of the PAP) reveal that these bathymetric features are continental fragments rather than igneous plateaus related to Broken Ridge. These microcontinents rifted away from Australia with Greater India during initial breakup at ~130 Ma, then rifted from India following the cessation of spreading in the PAP (~101–103 Ma).

Citation: Williams, S. E., J. M. Whittaker, R. Granot, and D. R. Müller (2013), Early India-Australia spreading history revealed by newly detected Mesozoic magnetic anomalies in the Perth Abyssal Plain, *J. Geophys. Res. Solid Earth*, *118*, doi:10.1002/jgrb.50239.

1. Introduction

[2] Reconstructing the early spreading history of the Eastern Indian Ocean is difficult, since much of the oceanic crust formed between India and Australia has been subsequently subducted beneath Southeast Asia. Remaining oceanic crust recording the earliest motions between India, Antarctica, and Australia is found in the Enderby Basin offshore Wilkes Land, Antarctica, the Bay of Bengal, offshore eastern India, and the Perth Abyssal Plain (PAP). Interpretation of the spreading history in the PAP has been hampered by a lack of ship track data in the western part of the basin, while compatible interpretations of the Enderby Basin [*Gaina et al.*, 2007; *Gibbons et al.*, 2012] and the Bay of Bengal [*Krishna et al.*, 2009] have proved elusive due to the difficulties in interpreting magnetic and gravity data that have been severely overprinted by plume-related magmatism and buried beneath a thick sedimentary package, respectively.

[3] The PAP (Figure 1) formed at the nexus of rifting and breakup between three major Gondwanan continents—India, Australia, and Antarctica. Oceanic crust within the PAP is the only region of preserved seafloor that directly records the history of Early Cretaceous seafloor spreading between India and Australia. However, despite the clear importance of the seafloor spreading history of the PAP, little attention has been paid to this basin, particularly the west PAP, since the early interpretations of *Markl* [1974, 1978], largely due to a lack of magnetic data in this region.

[4] Up until now, insufficient evidence has existed in the western part of the PAP to validate tectonic models of the PAP. 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 (Figure 2) [*Markl*, 1974; *Johnson et al.*, 1976; *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.

[5] In this paper, we present new evidence for the early seafloor spreading history between India and Australia within the PAP. This work is based on new total-field surface

[1]Earthbyte Group, School of Geosciences, University of Sydney, Sydney, New South Wales, Australia.
[2]Now at: The Institute of Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia.
[3]Department of Geological and Environmental Sciences, Ben Gurion University of the Negev, Beer Sheva, Israel.

Corresponding author: S. E. Williams, Earthbyte Group, School of Geosciences, University of Sydney, Madsen Building F09, Sydney, NSW 2006, Australia. (simon.williams@sydney.edu.au)

2169-9313/13/10.1002/jgrb.50239

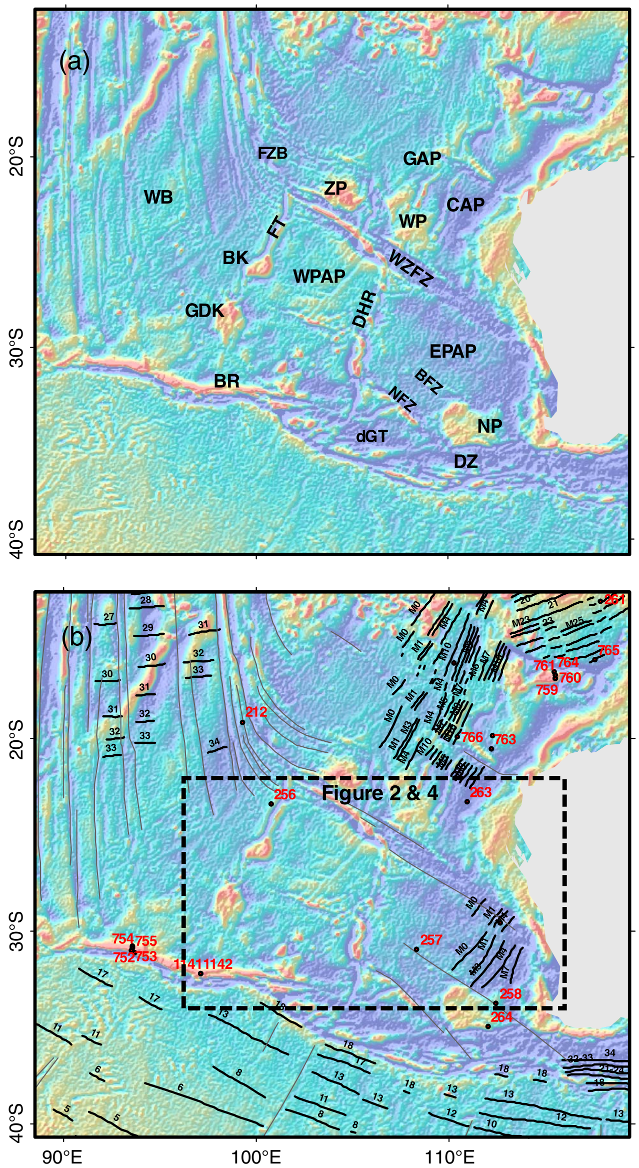

Figure 1. (a) Tectonic features in and around the Perth Abyssal Plain. (b) Magnetic isochron interpretations from the compilation of *Cande et al*. [1989]. Three alternative interpretations for the area shown in the dashed box are presented in Figure 2. The underlying image in all three panels is free-air gravity derived from satellite altimetry [*Sandwell and Smith*, 2009]. Dots with red labels are ocean drilling sites. Abbreviations: EPAP, East Perth Abyssal Plain; WPAP, West Perth Abyssal Plain; CAP, Cuvier Abyssal Plain; GAP, Gascoyne Abyssal Plain; WB, Wharton Basin; BK, Batavia Knoll; GDK, Gulden Draak Knoll; DHR, Dirck Hartog Ridge; BR, Broken Ridge; NP, Naturaliste Plateau; WP, Wallaby Plateau; ZP, Zenith Plateau; FT, Folau Trough; dGT, de Gonneville Triangle; NFZ, Naturalite Fracture Zone; BFZ, Batavia Fracture Zone; WZFZ, Wallaby-Zenith Fracture Zone; FZB, Fracture Zone Bends; DZ, Diamantina Zone.

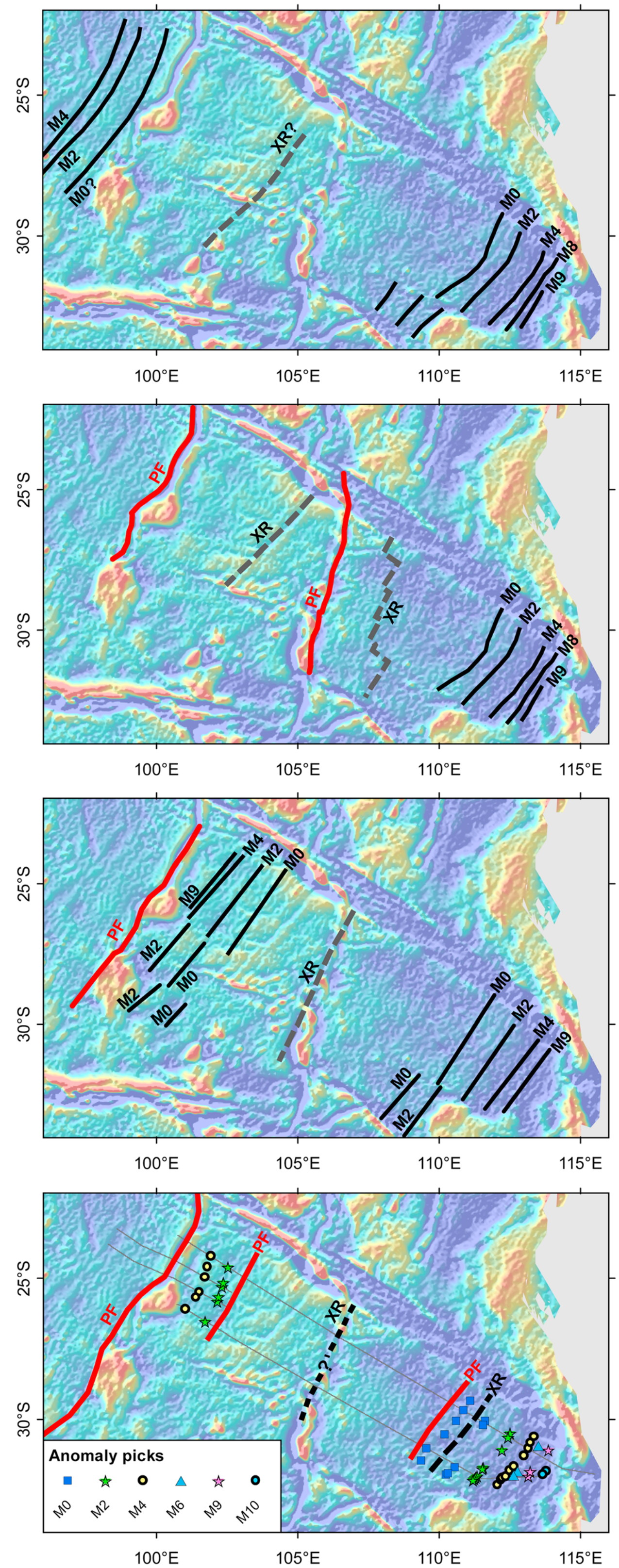

Figure 2. Alternative interpretations for the distribution of seafloor ages in the west Perth Abyssal Plain and adjacent part of the Wharton Basin. (a) *Markl* [1974], (b) *Mihut* [1997], (c) *Gibbons et al*. [2012], and (d) anomaly picks from this study. Gray lines show tracks of new magnetic profiles. XR, Extinct ridges; PF, pseudofault.

marine magnetic anomaly data collected across the PAP in October–November 2011 onboard the *R/V Southern Surveyor*. These new magnetic profiles reveal previously unrecognized M-series anomalies in the western PAP,

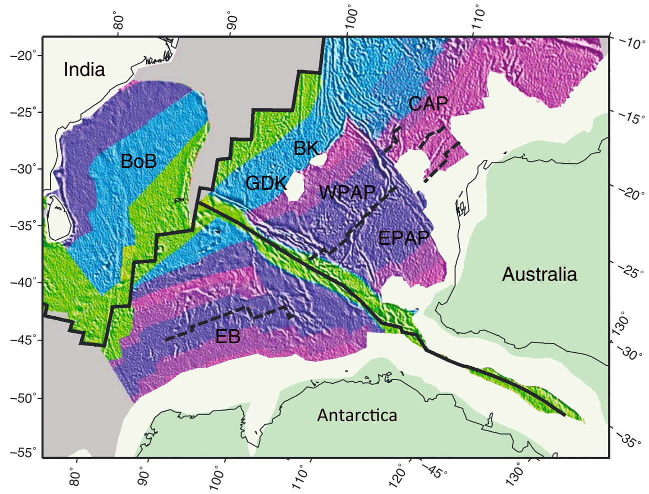

Figure 3. Reconstruction of Australia, India, and Antarctica at 83 Ma [after *Gibbons et al*., 2012; *Whittaker et al*., 2013]. EB, Enderby Basin; GDK, Gulden Draak Knoll; BK, Batavia Knoll; PAP, Perth Abyssal Plain; CAP, Cuvier Abyssal Plain; BoB, Bay of Bengal. Solid black lines show active plate boundaries; dashed black lines within the EB, PAP, and CAP represent extinct spreading ridges. Color of ocean areas represent age of the ocean floor; light purple > 120.4 Ma, dark purple 108–120.4 Ma, blue 100–108 Ma, and green 83–100 Ma.

conjugate to the sequence in the eastern PAP, and lead us to reinterpret the youngest anomalies in the eastern PAP. Further evidence for the spreading history comes from dredge samples collected from a series of bathymetric knolls and ridges in the PAP. We conclude with a discussion of the implications of our results for the spreading history oceanic crust within the PAP.

2. Tectonic Setting of the Perth Abyssal Plain

[6] The PAP spans the area between the western continental margin of Australia and the southern section of the Wharton Basin (Figure 1). Free-air gravity anomalies derived from satellite altimetry [*Sandwell and Smith*, 2009] help to define structural elements of the PAP.

[7] During the Late Jurassic to Early Cretaceous, Australia and Antarctica formed one continuous continent (Figure 3), albeit with some slow continental rifting occurring throughout this period [*Totterdell et al*., 2000]. Both the Enderby Basin and the PAP formed during Early Cretaceous motion of India away from Australia-Antarctica. To the north of the PAP, submerged continental fragments (the Zenith and Wallaby Plateaus [*Symonds et al*., 1998]) (Figure 1) provide evidence for a transform margin between northern greater India and Australia during Gondwana breakup [*Ali and Aitchison*, 2005]. East of these continental fragments, the Cuvier Abyssal Plain records early Cretaceous seafloor spreading (anomalies M0–M10) (Figure 1b). The original extent of Greater India is much argued over, and uncertainty surrounds whether the crust in the Cuvier Abyssal Plain formed following breakup between the northernmost part of greater India [e.g., *Hall*, 2012] or a separate continental fragment [e.g., *Gibbons et al*., 2012]. If the Wallaby-Zenith Fracture Zone (WZFZ) does represent the northernmost limit of Greater India adjacent to Australia within Gondwana, then the PAP is the only region of seafloor that directly records Early Cretaceous Australia-India plate motions.

[8] The orientation of the WZFZ, together with the Naturaliste and Batavia Fracture Zones (Figure 1), suggests that the spreading direction in the PAP is broadly WNW-ESE. This is also consistent with the orientation of interpreted magnetic lineations adjacent to the west Australian margin [*Markl*, 1974; *Veevers and Li*, 1991]. Within the PAP, the Naturaliste and Batavia Fracture Zones follow trends broadly parallel to the WZFZ. Aside from these structures, the gravity data provide little clear evidence for the locations of fracture zones within the PAP itself—in common with other ocean basins of a similar age, such as the Enderby Basin and West Somali Basin. Where the PAP meets the Wharton Basin, bends in the fracture zone trends observed in free-air gravity data record a major change in relative plate motion estimated at 99 Ma [*Veevers*, 2000] or 100–105 Ma [*Matthews et al*., 2012].

[9] The western margin of the PAP is defined by two prominent bathymetric knolls, the Batavia and Gulden Draak Knolls, where the shallowest seafloor lies more than 3000 m above the surrounding seafloor (Figure 1). The Folau Trough, a prominent linear bathymetric low, links the Batavia Knoll with the WZFZ. In the southeastern part of the PAP, the Naturaliste Plateau is another bathymetric feature which also lies several kilometers shallower than the adjacent ocean crust. The crustal nature of this plateau has been debated as oceanic or continental by many previous works, but recent dredge samples have demonstrated that the basement within much of the plateau is of continental origin [*Beslier et al*., 2004; *Halpin et al*., 2008].

[10] Within the PAP, a series of bathymetric highs following a NNE-SSW trend between the WZFZ and the de Gonneville Triangle, collectively referred to as the Dirk Hartog Ridge (DHR, Figure 1). This ridge has been previously interpreted as an extinct spreading center, with estimates of cessation of spreading from 96 Ma [*Powell et al*. 1988] to 108 Ma [*Gibbons et al*., 2012]. Alternatively, *Mihut* [1997] interpreted the DHR as a pseudofault formed

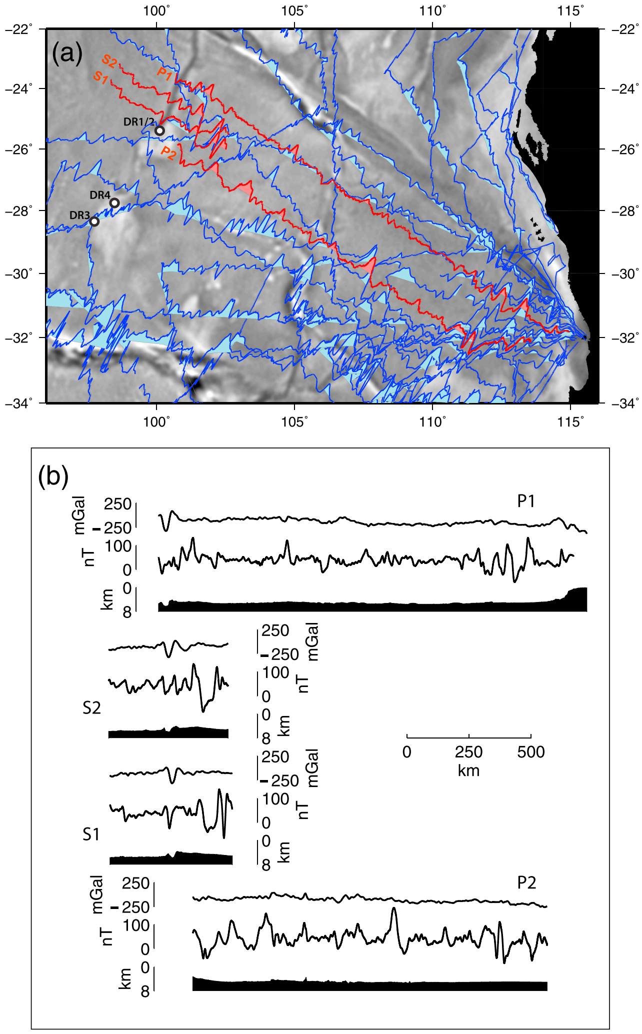

Figure 4. (a) Ship track magnetic anomaly profile data for the Perth Abyssal Plain, displayed as wiggle plots projected using an azimuth of N30°E. Data from ss2011/v06 are plotted in red, data from the NGDC database are plotted in blue. Circles denote dredge sites on the Batavia and Gulden Draak Knolls. (b) Ship tracks plotted with bathymetry profiles derived from ss2011/v06 swath data, and free-air gravity extracted from gravity grid derived from satellite altimetry [*Sandwell and Smith*, 2009].

during an eastward jump in the spreading axis between Australia and India. However, the morphology of the DHR is not typical of either an extinct midocean ridge or pseudofault, and it is likely that the original feature has been modified by subsequent tectonic and/or magmatic activity.

[11] The southern limit of the PAP is marked by Broken Ridge and the Diamantina Zone (Figure 1). The morphology of this southern boundary largely reflects the location of the Australia-Antarctica plate boundary in the Late Cretaceous, after the PAP had formed and around the time seafloor spreading initiated between Australia and Antarctica. A reconstruction of India-Australia-Antarctica at 83 Ma (Figure 3) [*Whittaker et al.*, 2013] illustrates the juxtaposition of these plates at the end of the Cretaceous Normal Superchron (CNS).

2.1. Existing Constraints on Seafloor Age of the PAP

[12] Magnetic anomaly profiles crossing the PAP available within the National Geophysical Data Center (NGDC) database are shown in Figure 4. The east PAP is well-covered by magnetic profiles, on the basis of which several authors have produced broadly consistent interpretations of anomalies M9 to M0 [*Markl*, 1974; *Veevers and Li*, 1991; *Gibbons et al.*, 2012]. Southwest of the Batavia Fracture Zone, *Markl* [1978]

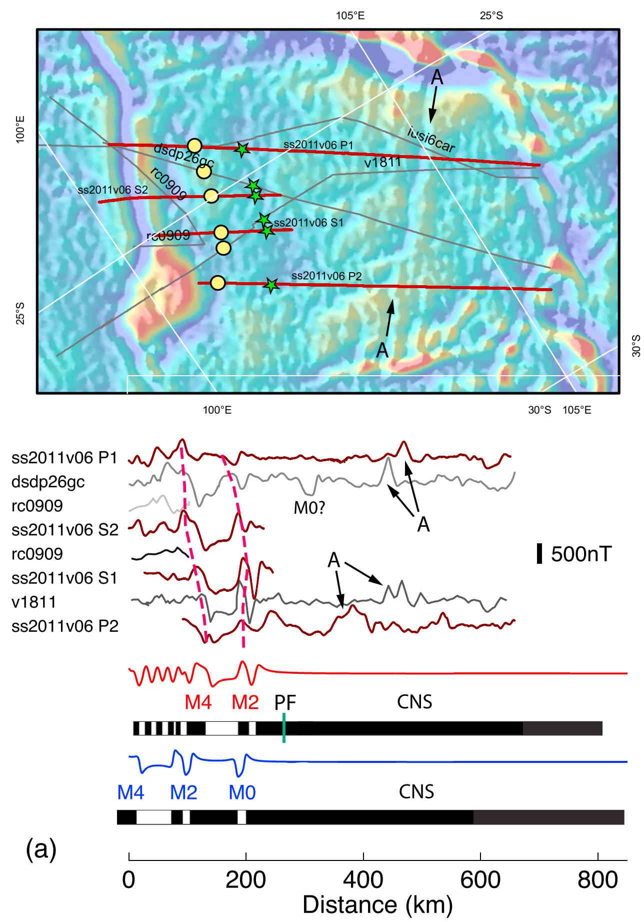

Figure 5. Stacked plots of ship track magnetic anomalies for (a) the west PAP and (b) the east PAP. The top panel shows the locations of the plotted profiles in an oblique Mercator projection. Anomaly picks are symbolized according to the legend shown in Figures 2 and 6. The anomaly profiles are projected such that the distance along profile is measured in a direction S120°E (for the west PAP) and N300°W (for the east PAP) and are plotted in order from north to south based on their location at the eastern ends of the profiles. The red and blue profiles show synthetic magnetic anomaly sequences generated assuming a half-spreading rate of 35 mm/yr. Synthetic profiles were created using modmag [*Mendel et al.*, 2005] and generated assuming a magnetic source layer at a depth of 4 km, with a thickness of 0.5 km, magnetization of 10 A/m, and a contamination coefficient of 0.5. The anomaly profiles are plotted such that profiles parallel to the inferred spreading direction are plotted as black lines, while profiles more oblique to the spreading direction are plotted in increasingly lighter shades of gray. See text for discussion of features labeled A and B. XR denotes extinct ridge; PF denotes pseudofault.

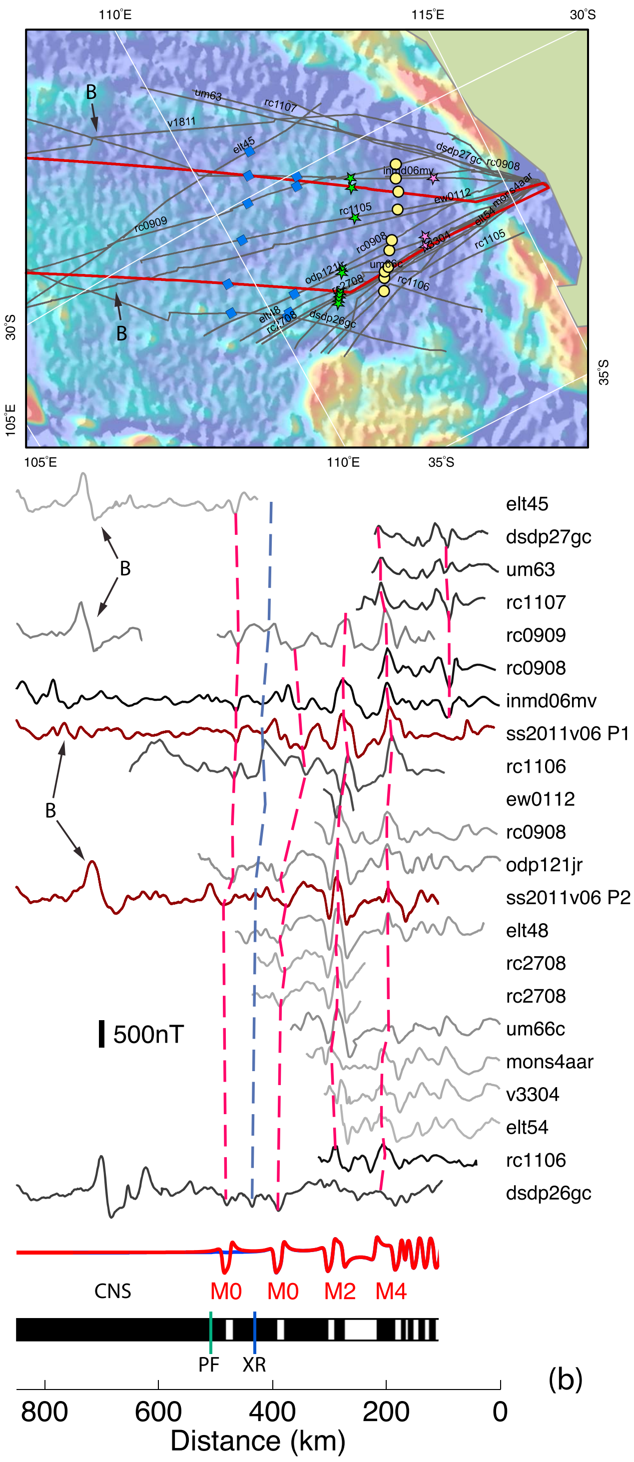

Figure 5. (continued)

identified anomalies M0 to M5, offset by ~90 km from the equivalent isochrons on the other side of the BFZ.

[13] The location of the conjugate, Indian Plate anomalies, is thus-far unresolved as magnetic data are sparse over the western section of the PAP. *Markl* [1974] proposed that the conjugate crust lies to the west of the Batavia and Gulden Draak Knolls based on widely spaced magnetic profiles (Figure 2a). Subsequent plate reconstructions have shown that the Perth margin was adjacent to greater India—these models predict that much of the crust accreted to the Indian Plate conjugate to the Perth M-series would have since been subducted beneath southeast Asia (Figure 2b) [e.g., *Johnson et al.*, 1980; *Mihut*, 1997]. *Powell et al.* [1988] predicted that some of M-series anomalies should be observed east of the Batavia and Gulden Draak Knolls, truncated by younger spreading systems. Recent plate reconstructions of *Gibbons et al.* [2012] predict that a full sequence of anomalies conjugate to the Perth sequence should be observed east of these knolls. These authors produced a set of synthetic isochrons for the west PAP based on this hypothesis (Figure 2c).

[14] Additional constraints on the age of the crust in the PAP come from sediments sampled at sites on Deep Sea Drilling Project (DSDP) legs 26 and 27 [*Heirtzler et al.*, 1973; *Luyendyk and Davies*, 1974; *Veevers and Heirtzler*, 1974]. The minimum basement age at Site 256, on the western flank of the Folau Trough (Figure 1), is estimated to be late Albian (~101 Ma) based on nanofossils in the sediments overlying the basement. At site 257, located in the eastern PAP, the oldest sediment is middle Albian (~106 Ma).

2.2. New Data

[15] New magnetic anomaly profiles were obtained along flow line-parallel profiles traversing the PAP (Figure 4). Data were acquired using a total-field Seaspy magnetometer towed 200 m behind the survey vessel. The contribution from the geomagnetic field was removed from the data using the 11th generation of the International Geomagnetic Reference Field [*Finlay et al.*, 2010].

[16] Dredge samples were collected from seven sites—two sites on the northwest flank of the Batavia Knoll, two sites on the north and west flanks of the Gulden Draak Knoll, and three sites on the DHR (Figures 1 and 4). Samples recovered from dredge sites 1 and 2 on 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 (dredge site 3), and highly altered basalts (dredge site 4). Basement rocks recovered from the Dirck Hartog Ridge are igneous in nature—gabbros and basalts. A full listing of the samples can be found in *Williams* [2011].

3. Interpretation of Magnetic Anomalies

[17] A general issue for interpreting ship track magnetic anomaly data for the PAP is that only a few ship tracks are available, and many of those are oblique to the likely spreading direction. We include all available data, but with the caveat that some profiles from the NGDC database may cross fracture zones and so should be treated with caution.

3.1. Western PAP—Batavia Knoll

[18] Our new magnetic data provide constraints on the crustal age of the western PAP. The crust east of the BK exhibits a series of large (>500 nT) amplitude magnetic anomalies which can be traced confidently between profiles. Further east (>300 km, Figure 5a), the anomaly profiles are generally subdued, and major anomalies show no obvious correlations with adjacent profiles. Subdued anomalies in Cretaceous crust characterize the edges of the quiet zones

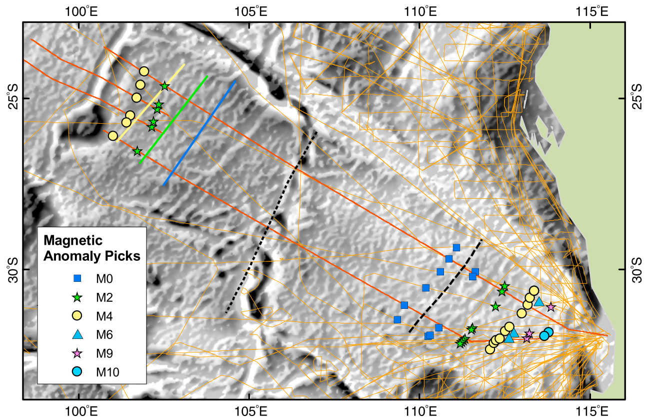

Figure 6. Magnetic anomaly picks for the PAP. Red lines show southern surveyor ship tracks, orange lines show ship tracks from the NGDC database for which magnetic anomalies are available. Also plotted are synthetic isochrons predicted by the reconstruction model of *Gibbons et al.* [2012]. The coloring of the isochron lines for the young ends of M0, M2, and M4 is consistent with the pick symbols. Black dashed line shows approximate path of ~119 Ma extinct spreading center proposed in this study. Black dotted line shows extinct spreading center along DHR proposed by *Gibbons et al.* [2012].

(CNS-aged crust [*Granot et al.*, 2012]). Therefore, a simple explanation for these first-order observations is that the edge of the quiet zone lies about 300 km east of the BK. Dredge samples reveal that the BK and GDK are continental fragments [*Williams*, 2011], with the implication that these fragments originally rifted from Australia as part of the Indian Plate. The sequence observed in the west PAP adjacent to the BK must therefore be conjugate to the anomalies in the east PAP. Our profiles therefore young toward the east and cross into the quiet zone.

[19] In Figure 5a, we plot two alternative magnetic forward models for the spreading sequence east of the BK, using the timescale of *Gee and Kent* [2007]. The blue line shows a model containing a continuous sequence of M4 to M0 anomalies leading into quiet zone crust. This model implies a relatively simple spreading history, with a sequence that is the mirror image of the sequence previously interpreted in the west PAP [*Markl*, 1974; *Veevers and Li*, 1991] with comparable spreading rates. However, the shapes of the observed anomalies do not show a clear correspondence with the model, and the M4 anomalies on profiles S1, P1, and v1811 would lie within the continental crust of the Batavia Knoll (assuming a constant half-spreading rate of ~35 mm/yr).

[20] An alternative interpretation is constructed where the first large anomaly is assigned to M2 (half-spreading rate of 35 mm/yr, red curve in Figure 5a). This model matches well the distinctive shapes of the M2 and M4 anomalies in profiles P1, S1, and S2 as well as profiles v1811 and dsdp26gc, in each case with anomaly amplitudes of several hundred nanoteslas. Assuming a continuous spreading rate after M2, we would expect to observe M0 ~90 km further east along these profiles. Of the four profiles that cross the expected location of M0 profile dsdp26gc contains an anomaly (Figure 5a where shown) that could be interpreted as M0. A phase-shifted M0 may be seen in ss2011v06 profile 2, adjacent to a major positive anomaly (labeled A in Figure 5a). Similar high amplitude positive anomalies (each labeled A) are observed east of our preferred M2 interpretation on all four profiles that span region between here and the Dirck Hartog Ridge. These anomalies, labeled A in Figure 5a, follow a linear trend whose orientation differs by >20° the M2 and M4 lineations in the WPAP. Further, they follow the trend of a linear feature observed in free-air gravity and features in bathymetry profiles (Figure 5a, also Figure 4).

[21] The lack of any clear M0 identifications raises the possibility that the crust of M0 age is missing from the west PAP. If this model is correct, then we ought to observe anomaly M0 doubled in the east PAP.

3.2. East PAP Revisited

[22] Magnetic anomaly profile data for the east PAP are shown in Figure 5b. The synthetic anomaly curve shows the sequence of anomalies reinterpreted from other authors' M9 to the CNS [*Markl*, 1974; *Veevers and Li*, 1991; *Gibbons et al.*, 2012]. The observed anomalies can be reasonably modeled using a uniform half-spreading rate of 35 mm/yr. *Veevers and Li* [1991] inferred a decrease in spreading rate around the time of M4o using the same anomaly identifications but an older timescale [*Berggren et al.*, 1985; *Kent and Gradstein*, 1985]. The interpreted M2–M4 anomalies show a clear linear continuity within the available profiles. The anomalies interpreted as M0 have a less distinctive shape but are still apparent, and they are located where we would expect them to be based on spreading rates implied by the M2 and M4 anomalies.

[23] The previously interpreted anomaly sequence implies that the crust in the east PAP youngs continuously to the west and that all crust to the west of the M0 anomaly formed during the CNS. Based on our observations from the WPAP, we propose that both our new and archival data reveal seafloor spreading magnetic anomalies to the west of and parallel to the previously identified magnetic lineations. The synthetic profile in Figure 5b shows one possible interpretation, in which a series of anomalies observed in all profiles can be modeled as an isolated, reversely magnetized block with the same width as the M0 block modeled to the east. It is important to stress that this interpretation is considerably more speculative than the new M2 and M4 identifications in the WPAP. The amplitude of both the eastern and western M0 anomalies is small compared to the older anomalies. Alternative interpretations are possible—for example, the eastern M0 identified on line rc0909 in Figure 5b could alternatively be interpreted as a single wide M0, separating conjugate M1 anomalies that progressively disappear to the south. This scenario would be consistent with a gradual ridge propagation event rather than a discrete ridge jump, as interpreted for example across the Carlsberg Ridge [*Dyment*, 1998] and in the Cuvier Abyssal Plain [*Mihut and Müller*, 1998].

[24] While the delineation of M0 anomalies in the EPAP remains uncertain, it is likely that some of the crust formed at M0 time on the Indian Plate, conjugate to the crust of the Australian Plate M0 anomaly already identified <100 km to the east. Such an anomaly sequence can be explained by a model in which an extinct ridge lies between the conjugate

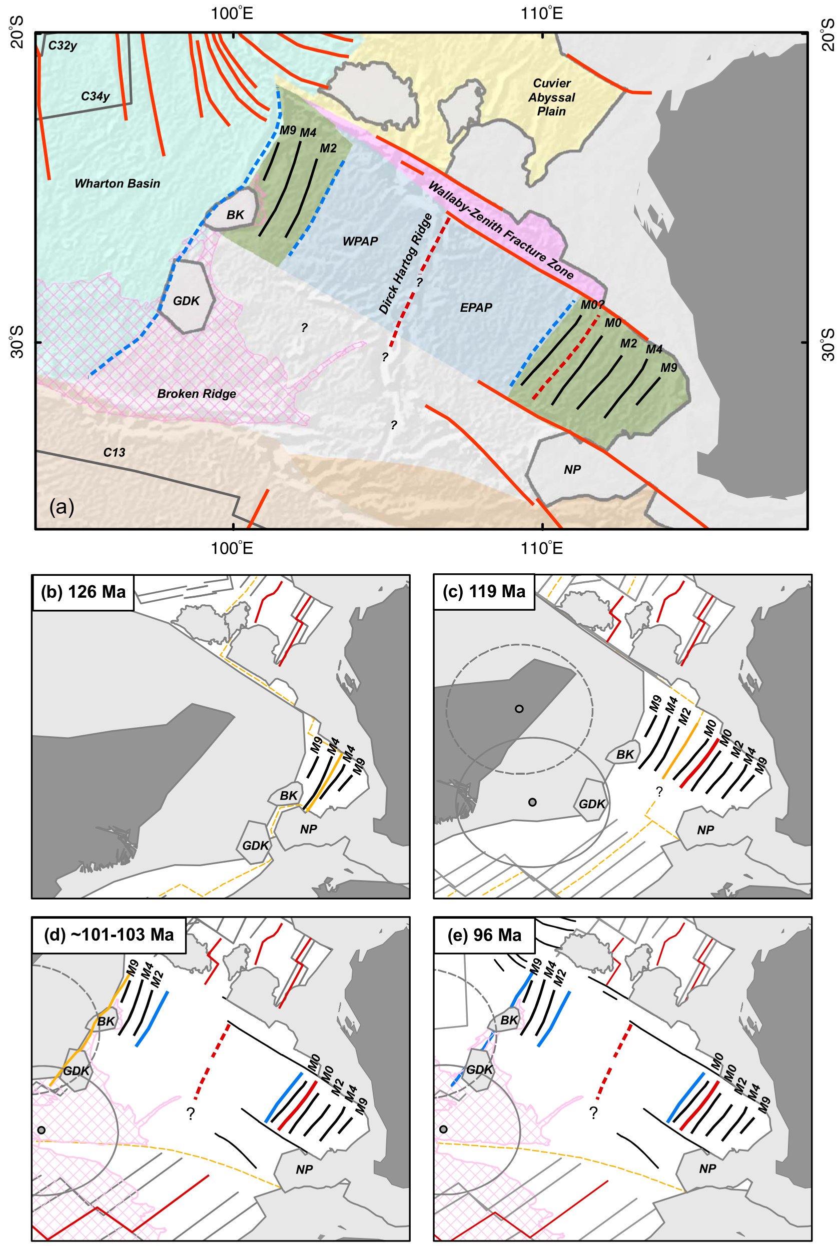

Figure 7

M0 anomalies. We note, however, that no clear gravity signature is observed that would indicate the existence of a single buried fossil spreading center beneath the sediments. Spreading ceased, possibly progressively, at this ridge shortly after the beginning of the CNS (~119 Ma, taking 35 mm/yr half-spreading rate). The India-Australia plate boundary jumped westward, into the M1-aged crust of the Indian Plate. In addition to accounting for possible double M0 anomalies in the east PAP, this scenario also provides an explanation for the lack of M0 anomalies in the west PAP.

[25] In common with the WPAP, the Quiet zone within the EPAP contains several magnetic anomalies with amplitudes greater than 500 nT (labeled B in Figure 5b). Also, as in the WPAP, these anomalies are not aligned parallel to the EPAP M-series anomalies, although in this case, there is no associated feature within the satellite-derived gravity data. Magnetic anomalies with amplitudes of several hundred nanoteslas are observed within similar parts of quiet zones in other ocean basins [*Granot et al.*, 2012] and therefore probably reflect an increase in the fluctuation of the dipolar geomagnetic field strength. Alternatively, these anomalies may reflect local variations in the thickness and/or iron content of the magnetic source layer, which in turn could be due to variations in magma supply during additional ridge jump/propagation events within the CNS.

4. Discussion

4.1. Implications for Reconstructing Gondwana Breakup

[26] Our new data allow us to interpret an entire sequence of M-series magnetic anomalies formed on the Indian Plate

conjugate to the Australian plate sequence identified in the Perth Basin (Figure 6). We identify Indian Plate anomalies M2–M4 in the west PAP, east of the Batavia Knoll. Our preferred interpretation places the Indian Plate M0 anomaly <100 km west of the Australian Plate M0 anomaly, within crust left on the Australian Plate following a westward ridge jump shortly afterward, although this aspect of the interpretation is less well constrained. Together with continental basement rocks dredged from both the Batavia and Gulden Draak Knolls, the new magnetic data have important implications for the early spreading history between India, Australia, and Antarctica.

[27] Our interpretation for the location of M-series anomalies is plotted in Figure 6. The anomaly locations are incompatible with earlier interpretations, which identified the crust in the west PAP as having formed within the CNS (Figure 2) [*Markl*, 1974; *Mihut*, 1997]. The locations of our picks for M2 and M4 differ by 20–90 km from the synthetic isochrons of *Gibbons et al*. [2012]. This model differs from our interpretation of a westward ridge jump shortly after M0 time, instead predicting the existence of M0 anomalies in the west PAP that are not observed. Interestingly, there is a systematic orientation difference between our magnetic anomaly interpretations and the synthetic isochrons of *Gibbons et al*. [2012]. The offset, which is not observed in the east PAP implies a counterclockwise rotation of the west PAP. This may help explain the unusual morphology of the DHR and western WZFZ. A relatively small counterclockwise change in spreading direction between India and Australia is also inferred from seafloor fabric in the Wharton Basin, initiating around 108.4–105.8 Ma, prior to the major clockwise change that resulted in N-S spreading [*Matthews et al*., 2012]. The morphology of the DHR is not typical of an undisturbed fossil spreading center, such as those observed in the Wharton Basin, Coral Sea, Labrador Sea, or Tasman Sea [*Jonas et al*., 1991; *Gaina et al*., 1998]. If the DHR does represent an extinct spreading center, then its morphology may be the result of similar process to what we see in other fossil spreading centers where postspreading deformation took place [*Müller et al*., 2005; *Granot et al*., 2010; *Livermore et al*., 2000].

[28] Our new data confirm that the Batavia and Gulden Draak Knolls are continental fragments, thus requiring a major westward jump in the India-Australia plate boundary to rift these fragments from India as hypothesized by *Gibbons et al*. [2012].

4.2. Westward Plate Boundary Jumps—Influence of the Kerguelen Plume?

[29] Our data provide evidence for two westward jumps of the India-Australia plate boundary during the evolution of the PAP. These jumps are summarized in Figure 7, where we illustrate our revised spreading history within the regional plate configuration from *Gibbons et al*. [2012]—as discussed above, of the available published models for the region, this model is the most consistent with our observations for the west PAP with mismatches <100 km in magnitude. For simplicity, the ridge jumps are illustrated as discrete events rather than gradual propagations. The first ridge jump is shown by the sequence of magnetic anomalies and occurred entirely within oceanic crust shortly after M0 time (~119 Ma). Ridge jumps and asymmetry in crustal

Figure 7. (a) Regions of ocean crust within and adjacent to the Perth Abyssal Plain classified by the spreading ridge at which they formed. Within the PAP, green regions contain crust formed prior to a ridge jump shortly after M0 time, while regions in blue formed between this ridge jump and cessation of spreading in the PAP around 101–103 Ma. The gray region between the Gulden Draak Knoll and the Naturaliste Plateau formed during the same period, but the details of the spreading history are less clear. The yellow crust in the Cuvier and Gascoyne Abyssal plains formed during the Early Cretaceous as a result of rifting between Australia and West Argoland [*Gibbons et al*., 2012]. The Wharton Basin formed as part of India-Australia spreading after cessation of spreading in the PAP during the CNS, while the light brown region south of Broken Ridge shows crust formed during Australia-Antarctica spreading following chron 34. Dashed red lines are extinct ridges, dashed blue lines are pseudofaults, solid red lines are fracture zones [*Matthews et al*., 2011], and solid black lines are isochrons (not shown for the PAP and selected chrons in adjacent basins). The pink hatched area shows the extent of the Broken Ridge Large Igneous Province from *Coffin and Eldholm* [1994]. The underlying texture is derived from the gradient of Smith and Sandwell bathymetry [*Smith and Sandwell*, 1997]. (b–e) Plate tectonic reconstruction illustrating our revised spreading history for the Perth Abyssal Plain. Relative positions of Australia, Antarctica, and India and isochrons for the Enderby Basin and Cuvier Abyssal Plain are adapted from *Gibbons et al*. [2012]. Reconstructions are presented with Australia fixed to its present-day position. Red lines represent extinct ridges, blue lines are pseudofaults, black lines are isochrons from this study, and gray lines outside the PAP are isochrons from *Gibbons et al*. [2012]. Filled gray regions show the extent of continental crust. The Kerguelen hot spot locations based on a fixed hot spot reference frame (solid circle) [*Müller et al*., 1993] and the most recent moving hot spot reference frame (dashed circle) [*Doubrovine et al*., 2012]. The hot spot reference frames are linked to the reconstruction that uses Africa-Antarctica rotations from *Marks and Tikku* [2001] and *Müller et al*. [2008], and Australia-Antarctica rotations from *Whittaker et al*. [2013]. Circles with radius 400 km are plotted around the hot spot center after *Montelli et al*. [2004]. The pink hatched area shows the extent of the Broken Ridge Large Igneous Province from *Coffin and Eldholm* [1994]. In Figure 7a, at 126 Ma, a >250 km-wide ocean basin has formed in the PAP. Around this time, the Batavia Knoll (labeled BK) and Gulden Draak Knoll (labeled GDK) rift away from the Naturaliste Plateau (labeled NP). In Figure 7b, shortly after M0 time, the India-Australia plate boundary in the PAP jumps toward India, transferring M0-age crust formed on the Indian plate to the Australian plate. In Figure 7c, at around 101–103 Ma, spreading ceases in the PAP, and the India-Australia plate boundary jumps to the passive margin of greater India, resulting in the rifting the BK and GDK. In Figure 7d, after 100 Ma, the BK and GDK are isolated continental fragments within the Australian plate. Divergence between the Indian and Australian plates is accommodated at a spreading ridge in the Wharton Basin.

accretion are common features of oceanic crust, and ridge jumps are often associated with hot spots [*Small*, 1995; *Müller et al*., 1998; *Mittelstaedt et al*., 2011]. In Figure 7, we illustrate the spatial relationship between the crust in the PAP around the time of the ridge jump and the location of the Kerguelen Plume, the closest plume to the PAP during this period. Hot spot locations are plotted using a fixed Kerguelen plume with a fixed hot spot reference frame [*Müller et al*., 1993] and a moving Kerguelen plume and matching moving hot spot reference frame [*Doubrovine et al*., 2012].

[30] The interpreted ridge jump is consistent with the notion that ridges typically jump toward hot spots and into relatively young (<4 Ma old) ocean crust [*Small*, 1995; *Müller et al*., 1998; *Mittelstaedt et al*., 2011]. The reconstruction implies the plume center is located between 700 and 900 km from the newly initiating ridge. Plume-ridge interaction over similar length scales has been inferred between Reunion hot spot and the Central Indian Ridge [*Morgan*, 1978; *Dyment et al*., 2007].

[31] The second and major ridge jump in the India-Australia plate boundary occurred when seafloor spreading ceased in the PAP and a new plate boundary initiated along the continental margin of greater India. As this new plate boundary developed, fragments of the continental margin were rifted from greater India and became isolated microcontinents on the Australian Plate, now observed as the Batavia and Gulden Draak Knolls. A link between microcontinent formation and plumes has been proposed [*Müller et al*., 2001; *Gaina et al*., 2003], although the details of the mechanisms by which microcontinents form are still debated [*Péron-Pinvidic and Manatschal*, 2010]. The timing of the jump in spreading from the PAP to the Wharton Basin is uncertain since it occurred during the CNS. Half-spreading rates in the PAP prior to M0 are roughly 35 mm/yr—if we assume a similar spreading rate for the CNS crust, then the entire PAP would have formed by ~107 Ma. However, based on the ages of the oldest sediments that were drilled in DSDP site 256 (~101 Ma), drilled on top of the oldest crust in the Wharton Basin, we speculate that spreading rates decreased toward the middle part of the PAP quiet zone, and spreading has ceased sometime between 103 and 101 Ma. A slowdown toward cessation of spreading was observed near other fossil spreading systems [e.g., *Cande et al*., 2000; *Livermore et al*., 2000]. A detailed analysis of spreading history during the quiet zone of the PAP will be presented elsewhere. Figure 7b shows that the two newly discovered microcontinents lie between 300 and 600 km from the Kerguelen plume center around the time a new plate boundary initiated within this part of the greater Indian margin. Although the plate tectonic model suggests that both knolls formed within the region of influence of a major plume, in common with other microcontinents such as Jan Mayen, the Seychelles, and Elan Bank [*Müller et al*., 2001], basaltic rocks were recovered from only one of the four dredge sites on the Batavia and Gulden Draak Knolls, suggesting that the formation of these microcontinents may not have been accompanied by plume-related voluminous magmatism.

[32] The time period between the two plate boundary jumps illustrated in Figure 7 are separated by 16–18 Ma, and we speculate that interaction between material from the Kerguelen plume and the spreading system in the PAP may have continued throughout this period. Indeed, satellite gravity data (Figure 1) and bathymetry data show that the quiet zone crust contains several anomalous features, notably the DHR and a subparallel structure to the west, which may represent extinct ridges or pseudofaults as proposed by previous authors (Figure 2) [*Markl*, 1974; *Mihut*, 1997; *Gibbons et al*., 2012; *Matthews et al*., 2012]. The west PAP contains several other significant free-air gravity and bathymetric highs whose origins remain enigmatic. We hypothesize that some or all of these features formed as part of ongoing ridge-plume interaction during seafloor spreading in the PAP.

[33] **Acknowledgments.** This work was only possible with the support of the crew and scientific party aboard voyage ss2011/v06 of the CSIRO R/V *Southern Surveyor*. We also thank Statoil for providing additional financial support to for this voyage. Our coprincipal investigators for this project were Nathan Daczko and Jacqui Halpin. We thank Geoscience Australia for allowing us to use their marine magnetometer. Figures in this paper were created using Wessel and Smith's GMT software, and ArcGIS. S.W. and R.D. M. were supported by ARC grant FL0992245. J.W. would like to gratefully acknowledge support received from Statoil. R.G. was supported by the European Union Seventh Framework Program (FP7/2007–2013) under grant agreement 320496 (GEOPLATE). The FAST project (23212VF) allowed RG to meet RDM, JW, and SW and become involved in the cruise. We thank editor André Revil, Jerome Dyment and an anonymous reviewer for their helpful suggestions.

References

Ali, J. R., and J. C. Aitchison (2005), Greater India, *Earth Sci. Rev.*, *72*, 169–188.

Berggren, W. A., D. V. Kent, J. J. Flynn, and J. A. Van Couvering (1985), Cenozoic geochronology, *Geol. Soc. Am. Bull.*, *96*, 1407–1418.

Beslier, M. O., J. Y. Royer, J. Girardeau, P. J. Hill, E. Boeuf, C. Buchanan, F. Chatin, G. Jacovetti, A. Moreau, and M. Munschy (2004), A wide ocean-continent transition along the south-west Australian margin: First results of the MARGAU/MD110 cruise, *Bull. Soc. Geol. Fr.*, *175*, 629–641.

Cande, S. C., J. L. LaBrecque, R. L. Larson, W. C. Pittman, X. Golovchenko, and W. F. Haxby (1989), *Magnetic Lineations of the World's Ocean Basins*, Am. Assoc. of Pet. Geol., Tulsa, Okla.

Cande, S. C., J. M. Stock, R. D. Müller, and T. Ishihara (2000), Cenozoic motion between east and west Antarctica, *Nature*, *404*, 145–150.

Coffin, M. F., and O. Eldholm (1994), Large igneous provinces: Crustal structure, dimensions, and external consequences, *Rev. Geophys.*, *32*, 1–36.

Doubrovine, P. V., B. Steinberger, and T. H. Torsvik (2012), Absolute plate motions in a reference frame defined by moving hot spots in the Pacific, Atlantic, and Indian oceans, *J. Geophys. Res.*, *117*, B09101, doi:10.1029/2011JB009072.

Dyment, J. (1998), Evolution of the Carlsberg Ridge between 60 and 45 Ma: Ridge propagation, spreading asymmetry, and the Deccan-Reunion hotspot, *J. Geophys. Res.*, *103*, 24,067–24,084.

Dyment, J., J. Lin, and E. T. Baker (2007), Ridge-hotspot interactions: What mid-ocean ridges tell us about deep Earth processes, *Oceanography*, *20*, 102–115.

Finlay, C., S. Maus, C. Beggan, T. Bondar, A. Chambodut, T. Chernova, A. Chulliat, V. Golovkov, B. Hamilton, and M. Hamoudi (2010), International geomagnetic reference field: The eleventh generation, *Geophys. J. Int.*, *183*, 1216–1230.

Gaina, C., D. R. Müller, J.-Y. Royer, J. Stock, J. Hardebeck, and P. Symonds (1998), The tectonic history of the Tasman Sea: A puzzle with 13 pieces, *J. Geophys. Res.*, *103*, 12,413–12,433.

Gaina, C., R. Müller, B. Brown, and T. Ishihara (2003), Microcontinent formation around Australia, *Spec. Pap. Geol. Soc. Am.*, *372*, 405–416.

Gaina, C., R. D. Müller, B. Brown, T. Ishihara, and S. Ivanov (2007), Breakup and early seafloor spreading between India and Antarctica, *Geophys. J. Int.*, *170*, 151–169.

Gee, J. S., and D. V. Kent (2007), Source of oceanic magnetic anomalies and the geomagnetic polarity time scale, in, *Treatise on Geophysics*, vol. 5, *Geomagnetism*, pp. 455–507, Elsevier, Amsterdam.

Gibbons, A. D., U. Barckhausen, P. van den Bogaard, K. Hoernle, R. Werner, J. M. Whittaker, and R. D. Müller (2012), Constraining the Jurassic extent of Greater India: Tectonic evolution of the West Australian margin, *Geochem. Geophys. Geosyst.*, *13*, Q05W13, doi:10.1029/2011GC003919.

Granot, R., S. Cande, J. Stock, F. Davey, and R. Clayton (2010), Postspreading rifting in the Adare Basin, Antarctica: Regional tectonic consequences, *Geochem. Geophys. Geosyst.*, *11*, Q08005, doi:10.1029/2010GC003105.

Granot, R., J. Dyment, and Y. Gallet (2012), Geomagnetic field variability during the Cretaceous Normal Superchron, *Nat. Geosci.*, *5*, 220–223.

Hall, R. (2012), Late Jurassic and Cenozoic reconstructions of the Indonesian region and the Indian Ocean, *Tectonophysics*, *570-571*, 1–41.

Halpin, J. A., A. J. Crawford, N. G. Direen, M. F. Coffin, C. J. Forbes, and I. Borissova (2008), Naturaliste Plateau, offshore Western Australia: A submarine window into Gondwana assembly and breakup, *Geology*, *36*, 807–810.

Heirtzler, J. R., J. V. Veevers, H. M. Bolli, A. N. Carter, P. J. Cook, V. A. Krasheninnikov, B. K. McKnight, F. Proto-Decima, G. Renz, and P. T. Robinson (1973), Age of the floor of the eastern Indian Ocean, *Science*, *180*, 952.

Johnson, B., C. M. A. Powell, and J. Veevers (1976), Spreading history of the eastern Indian Ocean and Greater India's northward flight from Antarctica and Australia, *Geol. Soc. Am. Bull.*, *87*, 1560–1566.

Johnson, B., C. M. A. Powell, and J. Veevers (1980), Early spreading history of the Indian Ocean between India and Australia, *Earth Planet. Sci. Lett.*, *47*, 131–143.

Jonas, J., S. Hall, and J. F. Casey (1991), Gravity anomalies over extinct spreading centers: A test of gravity models of active centers, *J. Geophys. Res.*, *96*, 11,759–11,777.

Kent, D. V., and F. M. Gradstein (1985), A Cretaceous and Jurassic geochronology, *Geol. Soc. Am. Bull.*, *96*, 1419–1427.

Krishna, K., L. Michael, R. Bhattacharyya, and T. Majumdar (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, *J. Geophys. Res.*, *114*, B03102, doi:10.1029/2008JB005808.

Livermore, R., J. C. Balanyá, A. Maldonado, J. M. Martínez, J. Rodríguez-Fernández, C. S. de Galdeano, J. G. Zaldívar, A. Jabaloy, A. Barnolas, and L. Somoza (2000), Autopsy on a dead spreading center: The Phoenix Ridge, Drake Passage, Antarctica, *Geology*, *28*, 607–610.

Luyendyk, B., and T. Davies (1974), Results of DSDP Leg 26 and the geologic history of the southern Indian Ocean, *Initial Rep. Deep Sea Drill. Proj.*, *26*, 909–943.

Markl, R. G. (1974), Evidence for the breakup of eastern Gondwanaland by the Early Cretaceous, *Nature*, *251*, 196–200.

Markl, R. G. (1978), Further evidence for the Early Cretaceous breakup of Gondwanaland off Southwestern Australia, *Mar. Geol.*, *26*, 41–48.

Marks, K., and A. Tikku (2001), Cretaceous reconstructions of East Antarctica, Africa and Madagascar, *Earth Planet. Sci. Lett.*, *186*, 479–495.

Matthews, K. J., Müller, R. D., Wessel, P., and Whittaker, J. M. (2011), The tectonic fabric of the ocean basins, *J. Geophys. Res.*, *116*, B12109, doi:10.1029/2011JB008413.

Matthews, K. J., M. Seton, and R. D. Müller (2012), A global-scale plate reorganization event at 105–100 Ma, *Earth Planet. Sci. Lett.*, *355*, 283–298.

Mendel, V., M. Munschy, and D. Sauter (2005), MODMAG, a MATLAB program to model marine magnetic anomalies, *Comput. Geosci.*, *31*, 589–597.

Mihut, D. (1997), Breakup and Mesozoic seafloor spreading between the Australian and Indian plates, PhD thesis, Univ. of Sydney, Sydney, N. S. W., Australia.

Mihut, D., and R. D. Müller (1998), Volcanic margin formation and Mesozoic rift propagators in the Cuvier Abyssal Plain off Western Australia, *J. Geophys. Res.*, *103*, 27,135–27,149.

Mittelstaedt, E., G. Ito, and J. van Hunen (2011), Repeat ridge jumps associated with plume-ridge interaction, melt transport, and ridge migration, *J. Geophys. Res.*, *116*, B01102, doi:10.1029/2010JB007504.

Montelli, R., G. Nolet, F. Dahlen, G. Masters, E. R. Engdahl, and S.-H. Hung (2004), Finite-frequency tomography reveals a variety of plumes in the mantle, *Science*, *303*, 338–343.

Morgan, W. J. (1978), Rodriguez, Darwin, Amsterdam, a second type of hotspot island, *J. Geophys. Res.*, *83*, 5355–5360.

Müller, R. D., J. Y. Royer, and L. A. Lawver (1993), Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks, *Geology*, *21*, 275–278.

Müller, R. D., W. R. Roest, and J. Y. Royer (1998), Asymmetric sea-floor spreading caused by ridge-plume interactions, *Nature*, *396*, 455–459.

Müller, R. D., C. Gaina, W. R. Roest, and D. L. Hansen (2001), A recipe for microcontinent formation, *Geology*, *29*, 203–206.

Müller, R. D., S. C. Cande, J. M. Stock, and W. R. Keller (2005), Crustal structure and rift flank uplift of the Adare Trough, Antarctica, *Geochem. Geophys. Geosyst.*, *6*, Q11010.

Müller, R., M. Sdrolias, C. Gaina, and W. R. Roest (2008), Age, spreading rates, and spreading asymmetry of the world's ocean crust, *Geochem. Geophys. Geosyst.*, *9*, Q04006, doi:10.1029/2007GC001743.

Péron-Pinvidic, G., and G. Manatschal (2010), From microcontinents to extensional allochthons: Witnesses of how continents rift and break apart?, *Pet. Geosci.*, *16*, 189–197.

Powell, C. M. A., S. Roots, and J. Veevers (1988), Pre-breakup continental extension in East Gondwanaland and the early opening of the eastern Indian Ocean, *Tectonophysics*, *155*, 261–283.

Sandwell, D. T., and W. H. F. Smith (2009), Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge segmentation versus spreading rate, *J. Geophys. Res.*, *114*, B01411, doi:10.1029/2008JB006008.

Small, C. (1995), Observations of ridge-hotspot interactions in the Southern Ocean, *J. Geophys. Res.*, *100*, 17,931–17,946.

Smith, W. H. F., and D. T. Sandwell (1997), Global sea floor topography from satellite altimetry and ship depth soundings, *Science*, *277*, 1956–1962.

Symonds, P. A., S. Planke, O. Frey, and J. Skogseid (1998), Volcanic evolution of the Western Australian continental margin and its implications for basin development, in *The Sedimentary Basins of Western Australia 2: Proceedings of the PESA Symposium*, edited by P. G. R. R. Purcell, p. 33–54, Pet. Explor. Soc., Perth, West. Aust., Australia.

Totterdell, J., J. Blevin, H. Struckmeyer, B. Bradshaw, J. Colwell, and J. Kennard (2000), Petroleum frontiers, systems and plays—A new sequence framework for the Great Australian Bight: Starting with a clean slate, *APPEA J.*, *40*, 95–120.

Veevers, J. (2000), Change of tectono-stratigraphic regime in the Australian plate during the 99 Ma (mid-Cretaceous) and 43 Ma (mid-Eocene) swerves of the Pacific, *Geology*, *28*, 47–50.

Veevers, J. J., and J. R. Heirtzler (1974), Tectonic and paleogeographic synthesis of leg 27, *Initial Rep. Deep Sea Drill. Proj.*, *27*, 1049–1054.

Veevers, J., and Z. Li (1991), Review of seafloor spreading around Australia. II. Marine magnetic anomaly modelling, *Aust. J. Earth Sci.*, *38*, 391–408.

Whittaker, J. M., S. E. Williams, and R. D. Müller (2013), Timing of Kerguelen Plateau formation: Constraints from plate kinematics and triple junction migration, *Geochem. Geophys. Geosyst.*, in press.

Williams, S. E. (2011), *RV Southern Surveyor ss2011/06 Voyage Summary*, CSIRO Mar. Natl. Facil., Hobart, Tasmania, Australia.