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Tectonic drivers and the influence of the Kerguelen plume on seafloor spreading during formation of the early Indian Ocean

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ABSTRACT

The Perth Abyssal Plain (PAP), located offshore southwest Australia, formed at the centre of Mesozoic East Gondwana breakup and Kerguelen plume activity. Despite its importance as a direct and relatively undisturbed recorder of this early spreading history, sparse geophysical data sets and lack of geological sampling hamper our understanding of the evolution of the PAP. This study combines new bathymetric profiles across the PAP with petrographic and geochemical data from the first samples ever to be dredged from the flanks of the Dirck Hartog Ridge (DHR), a prominent linear bathymetric feature in the central PAP, to better constrain the formation of the early Indian Ocean floor and the influence of the Kerguelen plume. Seafloor spreading in the PAP initiated at ~136 Ma with spreading observed to occur at (half) rates of ~35 mm/yr. Changes in spreading rate are difficult to discern after the onset of the Cretaceous Quiet Zone at ~120 Ma, but an increase in seafloor roughness towards the centre of the PAP likely resulted from a half-spreading rate decrease from 35 mm/yr (based on magnetic reversals) to ~24 mm/yr at ~114 Ma. Exhumed gabbro dredged from the southernmost dredge site of the DHR supports a further slowdown of spreading immediately prior to full cessation at ~102 Ma. The DHR exhibits a high relief ridge axis and distinctive asymmetry that is unusual compared to most active or extinct spreading centres. The composition of mafic volcanic samples varies along the DHR, from sub-alkaline dolerites with incompatible element concentrations most similar to depleted-to-normal mid-ocean ridge basalts in the south, to alkali basalts similar to ocean island basalts in the north. Therefore, magma sources and degrees of partial melting varied in space and time. It is likely that the alkali basalts are a manifestation of later excess volcanism, subsequent to or during the cessation of spreading. In this case, enriched signatures may be attributed tectonic drivers and melting of a heterogeneous mantle, or to an episodic influence of the Kerguelen plume over distances greater than 1000 km. We also investigate possible scenarios to explain how lower crustal rocks were emplaced at the crest of the southern DHR. Our results demonstrate the significance of regional tectonic plate motions on the formation and deformation of young ocean crust, and provide insight into the unique DHR morphology.

1. Introduction

The Perth Abyssal Plain (PAP), offshore Western Australia (Fig. 1), was at the nexus of Mesozoic East Gondwana breakup between Australia, Antarctic, and India. The PAP and the Enderby Basin (Fig. 1) formed a continuous spreading system following continental rifting and breakup between India and Australia (from ~136 Ma) and continued during the formation of the nearby Southern (110–118 Ma) and Central (105–95 Ma) Kerguelen Plateaux (Gibbons et al., 2012). Despite its importance as a direct and relatively undisturbed recorder of this early spreading history, sparse geophysical data sets and lack of geological sampling hamper our understanding of the evolution of the PAP. Obtaining good geophysical and geological data in the PAP is critical to understanding the early evolution of the eastern Indian Ocean as primary seafloor morphology is masked by widespread Kerguelen-related volcanism in the Enderby Basin (Fig. 1; Gaina et al., 2007), the conjugate ocean floor (offshore Greater India) is obscured through the process of subduction beneath Southeast Asia and thick sediment cover in the Bay of Bengal (Divins, 2003; Krishna et al., 2009; Williams et al., 2013). Further difficulties are caused by much of the PAP ocean floor having formed within the Cretaceous Quiet Zone (CQZ; Williams et al., 2013), during which there is an absence of magnetic anomaly reversals with which to constrain seafloor spreading.

A scientific voyage on the *R/V Southern Surveyor* in 2011 (SS2011_V06) acquired magnetic and bathymetric data across the

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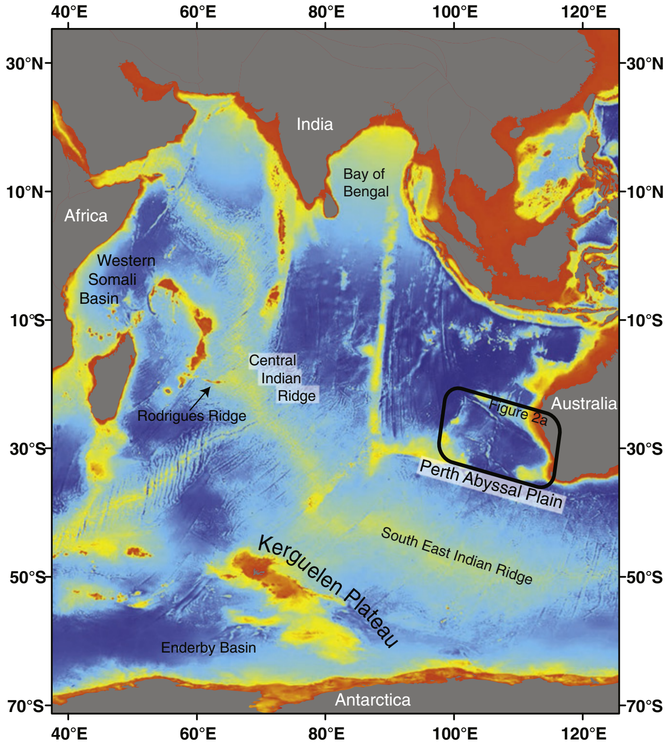

Fig. 1. Present day regional bathymetric map of the Indian Ocean (*Etopo 2v2*; NOAA, 2006), continents are in gray. The Perth Abyssal Plain study area is outlined in the black rectangle (also representing the location of Fig. 2a), and features referred to in the text are labelled.

PAP. During this voyage, geological material was dredged from the previously unsampled Batavia and Gulden Draak knolls, now newly identified as microcontinents (Gardner et al., 2015), and the Dirck Hartog Ridge (DHR), an enigmatic linear bathymetric feature, oriented approximately north–south, located in the centre of the PAP (Fig. 2a; Williams, 2011). Williams et al. (2013) interpreted the new magnetic anomaly data to constrain the Mesozoic seafloor spreading in the PAP and suggested that multiple ridge jumps were likely caused by the proximal Kerguelen plume (Fig. 2a).

In this study, we use the new bathymetric data and geochemical results to reveal a complex tectonic history for the PAP and formation of the DHR. We present the first results from mafic igneous samples dredged from the flanks of the DHR (Sites 5, 6, and 7; Fig. 2b). We investigate the tectonic evolution of the DHR, detailing the timing and complex geological processes involved during the cessation of spreading, and explain the unusual morphology of the DHR. The bathymetric data and geochemical results presented here enable us to revise the evolution of the latter stages of spreading and cessation of the PAP. We evaluate the influence of contemporaneous Kerguelen plume-related magmatic upwelling and tectonic plate reorganisation on the morphology and volcanism on the DHR. Our results provide new insights into the geodynamic processes associated with seafloor spreading in the PAP and contribute to a greater understanding of the complex history of Mesozoic seafloor spreading between India and Australia during East Gondwanan dispersion.

2. Tectonic setting

2.1. Breakup of East Gondwana and the formation of the Perth Abyssal Plain

Breakup of East Gondwana initiated as Argoland rifted from the northwest Australian margin forming the Argo Abyssal Plain from ~155 Ma (Gibbons et al., 2012). In the Early Cretaceous, rifting propagated southward separating India from Australia-Antarctica, progressively forming the western margin of Australia, and the Cuvier and Gascoyne Abyssal Plains (Fig. 2a; Müller et al., 2000; Gibbons et al., 2012, 2013). Spreading initiated in the PAP by at least M10 (~130 Ma) with extension of spreading rates to the continent–ocean boundary (Gibbons et al., 2012; Whittaker et al., 2013) and an interpreted Valanginian breakup unconformity (Crostella and Backhouse, 2000; Jones et al., 2012) supporting breakup at ~136–7 Ma. At this time, the PAP and the Enderby Basin (now located on the Antarctic plate; Fig. 1) formed one diverging plate boundary between India and Australia-Antarctica (Gaina et al., 2007). A number of microcontinental fragments (Wallaby and Zenith plateaux, and the Gulden Draak and Batavia knolls) on the West Australian margin, as well as the Elan Bank (the western salient of the Kerguelen Plateau) in the Enderby Basin, were isolated by a series of westward ridge jumps between 130 Ma and 100 Ma (Fig. 2a; Mihut and Müller, 1998; Müller et al., 2000; Gibbons et al., 2013).

In the PAP, magnetic anomalies interpreted prior to the onset of the CQZ (M0; ~121 Ma) are used to determine a minimum constraint for the onset of seafloor spreading (M10; 130 Ma; Williams et al., 2013). Based on these interpreted magnetic anomalies, early spreading progressed at an intermediate rate (~35 mm/yr half spreading rate; Gibbons et al., 2012; Williams et al., 2013). Magnetic anomalies decrease in age towards the centre of the PAP and conjugate anomalies in the East and West PAP suggest the presence of at least two extinct spreading centres in the PAP (Fig. 2a) (Williams et al., 2013).

The Mesozoic magnetic anomalies in the East PAP show the repetition of M0 (~121 Ma; Fig. 2a), indicating a ridge jump occurred at ~M0 after formation of ~600 km of oceanic crust, relocating the ridge axis ~200 km to the west (Williams et al., 2013). Another westward ridge jump from the PAP to the Wharton Basin at 101–104 Ma (Whittaker et al., in review) marked the cessation of spreading in the PAP and effectively isolated microcontinental fragments Batavia and Gulden Draak Knolls (Müller et al., 1998; Kobler, 2012; Whittaker et al., 2013; Gardner et al., 2015).

Coeval with and proximal to PAP formation (130–101/104 Ma), the Kerguelen plume extruded over 1.3×10^7 km^3 of volcanic rock (Coffin et al., 2002). Kerguelen plume volcanism prior to the formation of the South Kerguelen Plateau (110–119 Ma) was widespread. For example, the onshore Tibetan Comei Large Igneous Province and the Western Australian Bunbury Basalts are both attributed to the early Kerguelen plume (Frey et al., 1996; Zhu et al., 2009). The profuse influence of the Kerguelen plume suggests a long-term incubation of the plume beneath East Gondwana, commencing with relatively low-supply interspersed continental volcanism and increasing dramatically during the formation of the South Kerguelen Plateau (Coffin et al., 2002). At the peak of its production (119–100 Ma), the Kerguelen plume extruded vast voluminous volcanic sequences forming the Southern and Central Kerguelen Plateaux (including the Elan Bank; Frey et al., 2000; Coffin et al., 2002).

2.2. The Dirck Hartog Ridge

The DHR located in the centre of the PAP comprises a series of ridges of high bathymetric relief (in some locations >2000 m above surrounding ocean floor; Fig. 2a and b). Based on satellite gravity data and inferences from plate tectonic modelling, the DHR has previously been interpreted as an extinct mid-ocean ridge (Powell et al., 1988; Gibbons et al., 2012; Williams et al., 2013), or a pseudofault (Mihut, 1997; Mihut and Müller, 1998; Fig. 2c) but could possibly be a seamount chain associated with the Kerguelen plume. Interpretations of the DHR as a pseudofault were based on available magnetic anomalies (M0–M9) in the East PAP and an absence of conjugate anomalies in the west (Mihut, 1997; Fig. 2c). The type of pseudofault in this scenario develops as a result of a ridge jump forming an extinct ridge sub-parallel to