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Constraining the Jurassic extent of Greater India: Tectonic evolution of the West Australian margin

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[1] Alternative reconstructions of the Jurassic northern extent of Greater India differ by up to several thousand kilometers. We present a new model that is constrained by revised seafloor spreading anomalies, fracture zones and crustal ages based on drillsites/dredges from all the abyssal plains along the West Australian margin and the Wharton Basin, where an unexpected sliver of Jurassic seafloor (153 Ma) has been found embedded in Cretaceous (95 My old) seafloor. Based on fracture zone trajectories, this NeoTethyan sliver must have originally formed along a western extension of the spreading center that formed the Argo Abyssal Plain, separating a western extension of West Argoland/West Burma from Greater India as a ribbon terrane. The NeoTethyan sliver, Zenith and Wallaby plateaus moved as part of Greater India until westward ridge jumps isolated them. Following another spreading reorganization, the Jurassic crust resumed migrating with Greater India until it was re-attached to the Australian plate ~95 Ma. The new Wharton Basin data and kinematic model place strong constraints on the disputed northern Jurassic extent of Greater India. Late Jurassic seafloor spreading must have reached south to the Cuvier Abyssal Plain on the West Australian margin, connected to a spreading ridge wrapping around northern Greater India, but this Jurassic crust is no longer preserved there, having been entirely transferred to the conjugate plate by ridge propagations. This discovery constrains the major portion of Greater India to have been located south of the large-offset Wallaby-Zenith Fracture Zone, excluding much larger previously proposed shapes of Greater India.

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Theme: Plate Reconstructions, Mantle Convection, and Tomography Models: A Complementary Vision of Earth's Interior

1. Introduction

[2] The original, pre-collision extent of India's northern margin, known as Greater India, continues to be poorly constrained despite the many papers written on this topic. Greater India was part of East Gondwana until the Early Cretaceous. East Gondwana, comprising India, Africa, Madagascar, Sri Lanka, Australia, Antarctica and other microcontinents, had a northern margin that was molded by several major rifting events that led to the formation of a succession of ancient ocean basins. The PaleoTethys bounded this margin from the Middle/Late Devonian until the rifting and northward motion of the Cimmerian Continent in the Early Permian [*Metcalfe*, 1996]. The eventual collision of Cimmeria led to the subduction of the entire PaleoTethys by the Late Permian. The cycle was repeated with the MesoTethys following rifting and subsequent collision of the Lhasa Block in the Late Triassic and Late Jurassic, respectively [*Metcalfe*, 1996]. Greater India's northern margin stretching from Africa to East Timor, was finally formed by Late Jurassic rifting of Argoland (also referred to as the West Burma Block), shortly before India's westward migration commenced [*Metcalfe*, 1996].

[3] Most tectonic models reconstructing East Gondwana breakup feature Greater India, as a single block, rifting from the West Australian margin (Figure 1a). Yet, the estimated extents for Greater India vary greatly with many different techniques used to constrain its extent. A thorough summary of the alternative published models is provided by *Ali and Aitchison* [2005]. We include a short overview here to highlight these discrepancies.

[4] Seismic data show that the Himalayas are composed of stacked continental crust [*Searle et al.*, 1987] approximately 65–80 km thick [*Hirn*, 1988; *Li et al.*, 2009; *Teng*, 1987], while the Indian crust south of the Himalayas is only about 35 km thick [*Zhang et al.*, 2007]. Models that derive crustal shortening estimates from balancing lithological cross-sections from the India-Eurasian collision zone, between Himalaya and Tibet, often result in the smallest estimates for the minimal extent of Greater India, such as 536 km [*Ratschbacher et al.*, 1994]. More crustal shortening is accommodated laterally, into China [*Wang et al.*, 2001]. A pre-collision Greater India extent of only 536 km matches poorly with the West Australian margin bathymetry as Greater India would not have reached beyond the Naturaliste Plateau on the southwest edge of Australia (NP, Figure 1a), implying that there was no continental crust conjugate to the majority of the West Australian margin.

[5] Another approach to constrain Greater India's extent is to look at the timing of collision between Greater India and Eurasia, but a lack of consensus on this timing has led to a diverse range of estimated extents. Estimates for the onset of India-Eurasia collision range from 35 Ma [e.g., *Aitchison et al.*, 2007; *Aitchison and Davis*, 2004] to 70 Ma [e.g., *Ding et al.*, 2005; *Shi et al.*, 1996; *Willems et al.*, 1996; *Yin and Harrison*, 2000]. The proposed 35 Ma collision is based on two distinct collision events: the collision of an intraoceanic island arc with the Eurasian margin around 60–55 Ma and the collision of Greater India and Eurasia around 40–35 Ma. Some proponents of the 70 Ma collision also acknowledge this intraoceanic arc may have contributed as the earlier collision [*Ding et al.*, 2005].

[6] Changes in convergence rates between India and Eurasia can also help constrain the timing of their collision [e.g., *McKenzie and Sclater*, 1971; *Norton and Sclater*, 1979; *Schlich*, 1982; *Sclater and Fisher*, 1974]. Many studies agree this decrease in convergence took place at 50–55 Ma [e.g., *Besse and Courtillot*, 2002; *Patriat and Achache*, 1984], though ∼38 Ma (near the Eocene-Oligocene boundary) has also been suggested [*Molnar and Tapponnier*, 1975]. A more recent study using seafloor spreading and plate circuits identified an initial slowdown in India-Eurasia convergence from around 52 Ma, with a sharper drop at 42 Ma [*Cande and Stegman*, 2011]. A 35 Ma collision requires a Greater Indian extent of ∼1200 km, reaching the Wallaby-Zenith Fracture Zone (WZFZ, Figure 1a), while a 55 Ma collision requires a ∼2000 km Greater Indian extent, reaching the northern tip of the Exmouth Plateau (EP, Figure 1a). An extent of

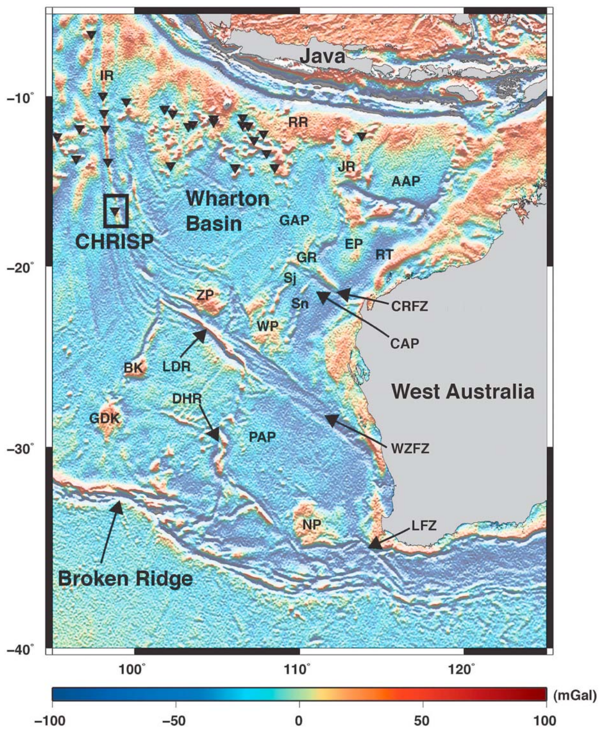


Figure 1a. The *Sandwell and Smith* [2009] 1-degree free-air satellite derived gravity along the West Australian margin showing the location of the Argo Abyssal Plain (AAP), Gascoyne Abyssal Plain (GAP), Cuvier Abyssal Plain (CAP), Perth Abyssal Plain (PAP), Exmouth Plateau (EP), Rankin Trend (RT), Naturaliste Plateau (NP), Wallaby Plateau (WP), Zenith Plateau (ZP), Batavia Knoll (BK), Gulden Draak Knoll (GDK), Wallaby-Zenith Fracture Zone (WZFZ), Cape Range Fracture Zone (CRFZ), Dirk Hartog Ridge (DHR), Galah Rise (GR), Investigator Ridge (IR), Lost Dutchmen Ridge (LDR), Leeuwin Fracture Zone (LFZ), Joey Rise (JR), Roo Rise (RR), Sonne Ridge (Sn), Sonja Ridge (Sj), Investigator Ridge (IR), Broken Ridge and the Wharton Basin. Inverted black triangles show positions of the CHRISP 2008 seamount dredge samples. Area shown in the black box is the location of the CHRISP 2008 Jurassic oceanic crust, zoomed in for Figure 1b.

∼4000 km would be required for the 70 Ma collision, reaching well beyond East Gondwana in a Mesozoic reconstruction. The 70 Ma collision therefore could not have been Greater India but might have been another Gondwana-derived tectonic block, such as the western extent of Argoland, which rifted from Gondwana in the Late Jurassic [*Heine and Müller*, 2005].

[7] Paleomagnetic studies combined with apparent polar wonder paths can show when and by how much terranes migrated following tectonic events, but the results pertinent to our study encompass a broad range. For instance, paleomagnetic data from the Linzilong volcanics (from the Lhasa Block in Southern Tibet) suggest that the India-Eurasia collision occurred between 64 and 44 Ma [*Chen et al.*, 2010], but that the onset of collision was at 53–49 ± 6 Ma [*Liebke et al.*, 2010] or 46 ± 8 Ma, the latter producing a total convergence of 2900 km ± 1200 km [*Dupont-Nivet et al.*, 2010]. *Sun et al.* [2010] argue for a 55 Ma onset of collision resulting in an India-Eurasia combined shortening of 3400 ± 1150 km, while *Tan et al.* [2010] date the onset of collision to 43 Ma, implying a total of ∼2000 km of convergence. A Greater Indian extent of 3400 km would reach well over 500 km beyond the Exmouth Plateau in a Mesozoic Gondwana reconstruction while 2000 km would reach just into the Exmouth Plateau. *Klootwijk et al.* [1992] suggested a distinct reduction in India's northward motion before 55 Ma based on paleomagnetic data in the Ninetyeast Ridge. Combining this with a comparison between north Indian margin paleolatitudes and collision-induced secondary magnetizations, they defined a minimal Greater India extent reaching 1120 km from the Indian-Himalayan main boundary thrust, which includes at

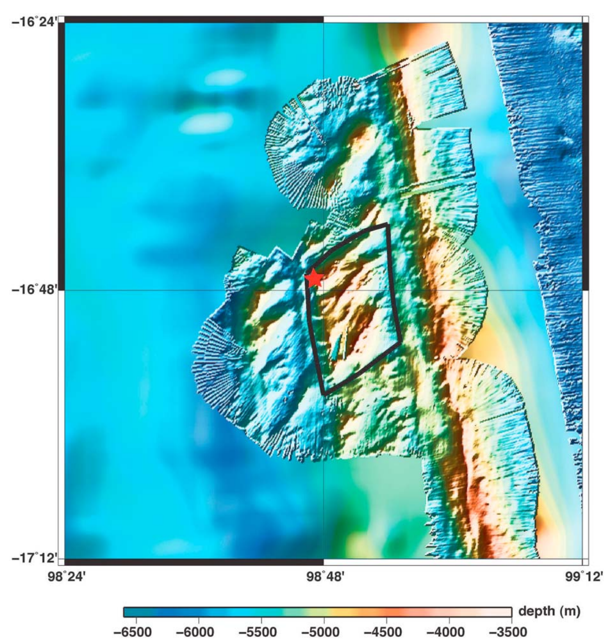


Figure 1b. CHRISP EM120 Bathymetry profile along the Investigator Ridge running north–south along the Wharton Basin. Red star shows the location of the CHRISP 2008 Jurassic sample SO199-DR30, taken from 5060 m below sea level. Thick black line shows boundary outlining the limits for the Jurassic sliver interpreted from the bathymetry profile.

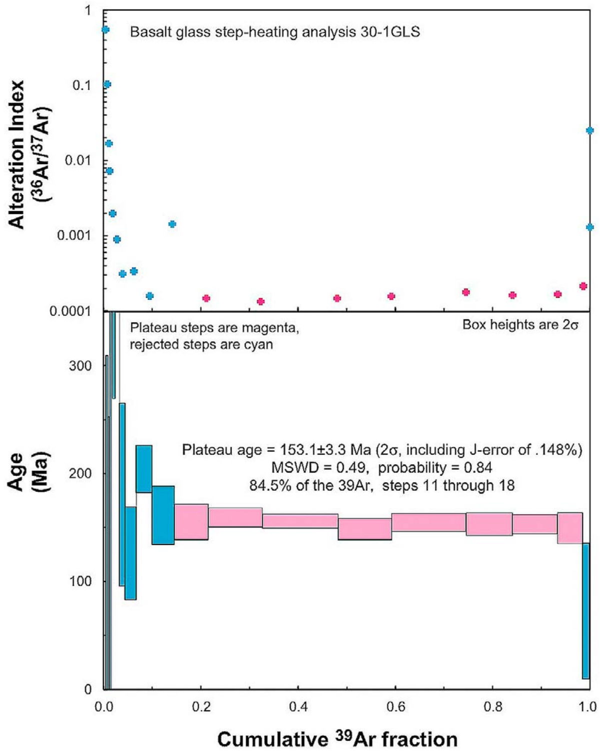


Figure 1c. Step-heating age spectrum for the CHRISP sample where the plateau age, representing the inverse-variance weighted mean of the plateau step ages and errors, is 153.1 ± 3.3 Ma. Alteration indices of the plateau heating steps are low (0.0003–0.0006) and close to the cut-off values for fresh sample material suggested by *Baksi* [2007]. Low-temperature heating steps yield significantly higher alteration indices (up to ~0.5) and are excluded from the plateau.

least 470 km of cumulative crustal shortening across the Himalayas. This minimal extent of Greater India would have reached the Wallaby-Zenith Fracture Zone. By comparison, *van Hinsbergen et al.* [2011] suggest a vast Greater Indian extent based on continental collision at 50 Ma. This implies 650–1050 km of intraAsian shortening (north of the Himalayas), necessitating subduction of extensively thinned continental crust for a prolonged period of time. An even greater extent for Greater India has been proposed by *Johnson* [2002], who summarized existing magnetic anomaly, paleomagnetic and volumetric balancing studies, finding that the total convergence between India and Eurasia was 1800–2100 km in the west, 2475 km in the center and 2750–2800 km in the east. This outlines a wedge-shaped Greater India that reached over 500 km beyond the northern tip of the Exmouth Plateau.

[8] Another way to constrain the extent of Greater India is to use the morphology of the Western Australian margin. The relatively undeformed morphology of the ocean basins along the West Australian margin offers an abundance of constraints to apply to the problem of Greater India, such as the Cape Range and Wallaby-Zenith Fracture Zones or continental fragments such as the Wallaby and Naturaliste plateaus (Figure 1a). In the context of a reconstructed Mesozoic East Gondwana reconstruction, *Ali and Aitchison* [2005] proposed that Greater India must have reached to the Wallaby-Zenith Fracture Zone (WZFZ, Figure 1a), the equivalent of at least 950 km north of where the Himalayas currently meet India. *Lee and Lawver* [1995] also used West Australian bathymetry to propose that Greater India originally reached the northern tip of the Exmouth Plateau. Even using a combined approach can result in different estimates for Greater India. For instance, *Powell et al.* [1988], using bathymetric and palaeomagnetic data, as well as Tibetan underplating, proposed a Greater India extent of 1500 km, extending roughly to the Cape Range Fracture Zone (CRFZ, Figure 1a). Yet, no studies have attempted to combine the morphological evidence offshore West Australia with a regionally constrained plate tectonic model.

[9] The West Australian margin formed through two distinct phases, yet studies have predominantly focused on subsets of the margin and no model for the formation of the entire West Australian margin has been attempted. Existing tectonic interpretations of subsets of the margin have resulted in conflicting tectonic models both within and between the West Australian abyssal plains (Figure 1a). Conflicts include the presence or absence of ridge jumps in the Argo Abyssal Plain and alternative Jurassic versus Early Cretaceous magnetic anomalies in the Gascoyne Abyssal Plain [*Heine and Müller*, 2005; *Robb et al.*, 2005; *Sager et al.*, 1992]. A further complication is that most of these abyssal plains formed adjacent to volcanic margins, resulting in the masking of seafloor spreading magnetic anomalies by widespread excess volcanism. The West Australian margin is also characterized by many complex structural features, which form narrow, linear gravity anomalies and discontinuities within the magnetic lineations, and many are due to numerous ridge propagation events, adding to the complexity of the margin, though these features can also give clues as to the margin's formation.

[10] Understanding the temporal and spatial evolution of all the West Australian abyssal plains is

crucial for accurately constraining the extent and kinematic history of Greater India and other blocks that rifted from the West Australian margin. Considering both local and regional constraints, we build a tectonic reconstruction for the separation of Australia and India that satisfies all the available constraints along this margin and fully links the Jurassic and Cretaceous spreading episodes. We develop a dynamic, continuous plate tectonic model for the formation of the West Australian abyssal plains by integrating (i) recently collected magnetic ship track data with existing magnetic data sets, (ii) our interpretations of fracture zones, pseudofaults (age discontinuities from ridge jumps), extinct ridges and microcontinental rafts, and (iii) regional plate tectonic constraints from the neighboring Gondwana-derived continental blocks and local microblocks.

2. Geological Setting and Previous Work

[11] The West Australian margin and its adjacent abyssal plains make up the physiogeography of the eastern Indian Ocean [*Heezen and Tharp*, 1965]. This passive margin runs from the Java-Sunda subduction zone in the north to Broken Ridge in the south and includes the Argo, Gascoyne, Cuvier and Perth abyssal plains (Figure 1a). Much of the conjugate seafloor located offshore Greater India has now been consumed by subduction/collision beneath Eurasia and Southeast Asia. The remaining seafloor offshore West Australia is riddled with tectonic anomalies such as seamounts, volcanic plateaus and continental rafts.

[12] The Argo Abyssal Plain, at roughly 600 km across and 5.7 km deep, is situated at the northern tip of the West Australian margin. It is an almost featureless expanse of old ocean floor bordered by submerged continental horsts, grabens and half-grabens from the Exmouth Plateau (west) to the Scott Plateau (east), and bounded to the north by the Java-Sunda subduction zone [*Falvey and Veevers*, 1974]. Formation of Argo seafloor was initially compartmentalized between several northwest-trending fracture zones, accommodating the curved margin (Figures 2a and 2b). Most studies agree on the presence of several fracture zones with dextral offsets in the west and greater sinistral offsets in the east [*Fullerton et al.*, 1989; *Heine and Müller*, 2005; *Heirtzler et al.*, 1978; *Powell and Luyendyk*, 1982]. The exact locations of fracture zones vary between studies and have been inferred mainly on the basis of magnetic anomaly offsets. Cenozoic magnetic anomalies C32-C24 (71–52 Ma), were initially identified in the Argo Abyssal Plain trending at 60° [*Falvey*, 1972]. They were revised to the Mesozoic after ODP Site 261 revealed a basement age of 152 Ma [*Heirtzler et al.*, 1978; *Veevers et al.*, 1974]. The first study to link the Argo spreading system to those to the southwest proposed a southward ridge jump in only the western Argo at 136 Ma (essentially over the Joey Rise), forming a triple junction, though this resulted in a large offset between the Argo and Gascoyne anomalies [*Powell and Luyendyk*, 1982]. Following the acquisition of new aeromagnetic data, *Fullerton et al.* [1989] identified chrons M25-M15 (155–138 Ma, Figure 2a) as a continuous sequence throughout the Argo Abyssal Plain. *Heine and Müller* [2005] proposed a southward ridge jump at 136 Ma (chron M14) over the north Argo Abyssal Plain, identifying a pseudofault following a high-amplitude (∼−500 nT) magnetic anomaly and prominent positive gravity anomaly near the Sunda Rise. They also linked the Argo to the Gascoyne Abyssal Plain by extending the Argo Jurassic anomalies M25-M22A around the Exmouth Plateau, juxtaposing them with anomalies M6-M0 along a pseudofault that is not visible in the marine gravity grid (Figure 2b).

[13] Marking the western limit of the Argo Abyssal Plain is the Joey Rise, a set of almost equally spaced volcanic ridges splaying north from the northwest tip of the Exmouth Plateau, a platform of stretched and intruded continental crust composed of northeast-oriented, subsided segments [*Falvey and Veevers*, 1974]. The Exmouth Plateau marks the eastern boundary of the Gascoyne Abyssal Plain, another smooth expanse of old ocean floor with some seamounts in the north and a volcanic complex underlying the Galah Rise further east [*Rey et al.*, 2008]. *Fullerton et al.* [1989] identified conjugate anomalies M10-M4 (130–127 Ma) reflected about an extinct ridge, with curving fracture zones to account for the converging younger anomalies M4-M0 (126–120.4 Ma) further west (Figure 2a). This convergence is better explained by *Robb et al.* [2005], who proposed a dominant southward propagating ridge, originating west of the Joey Rise, that trapped conjugate anomalies M4-M2 (126–124 Ma), as the spreading center propagated south (Figure 2c). This interpretation abandoned the conjugate series in the eastern Gascoyne Abyssal Plain and did not attempt to link it with the Argo spreading system, having not extended their study to that area.

[14] The Cape Range Fracture Zone (CRFZ), at the southern end of the Exmouth Plateau, marks the north of the Cuvier Abyssal Plain, which contains two north-striking linear features: the Sonne

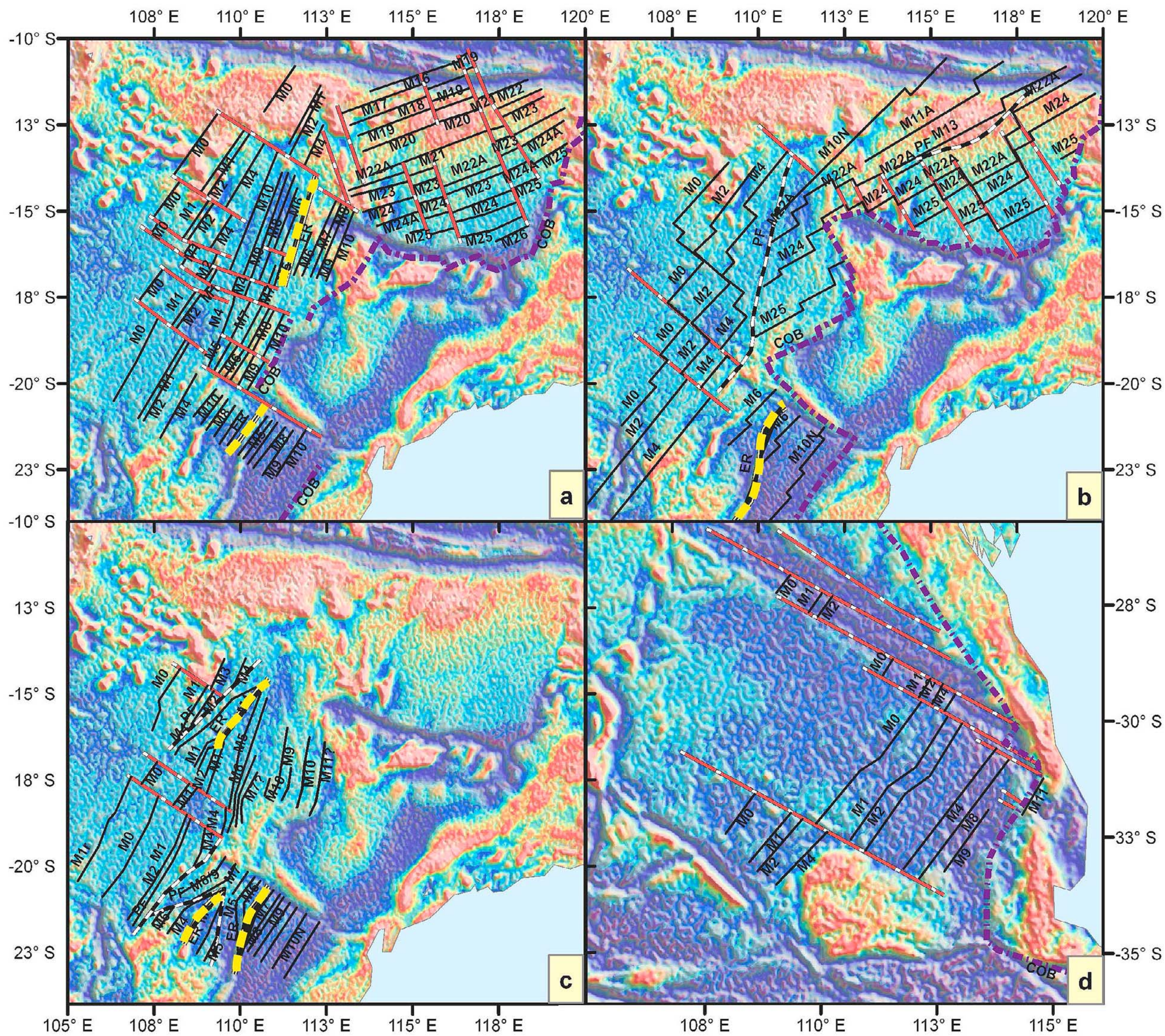


Figure 2. Comparison of previous magnetic anomaly, fracture zone and continent-ocean boundary (COB) interpretations of the Abyssal Plains offshore Western Australia, overlain on 1-degree free-air satellite-derived gravity [*Sandwell and Smith*, 2009] (a) *Fullerton et al.* [1989]; (b), *Heine and Müller* [2005]; (c), *Robb et al.* [2005]; (d) *Markl* [1974]. Red dashed lines indicate fracture zones, black lines indicate isochrons, purple dashed lines indicate COB, black and white lines indicate pseudofaults (PF), thick dashed yellow lines indicate extinct ridges (ER). Isochrons are identified in black lettering.

and Sonja Ridges (Figure 1a). The Sonne Ridge is interpreted as an extinct spreading center reflecting anomalies M11-M5 (132–127 Ma) about its axis, while the Sonja Ridge is a pseudofault resulting from the westward ridge jump [*Mihut and Müller*, 1998]. Other magnetic anomaly studies had similar results identifying conjugate anomalies M10-M5 (130–127 Ma) about the Sonne Ridge. Chron M4 was the oldest anomaly in the southern Gascoyne Abyssal Plain, following a westward ridge jump [*Fullerton et al.*, 1989; *Robb et al.*, 2005; *Sager et al.*, 1992]. Only *Robb et al.* [2005] identified both the Sonja and Sonne as extinct ridges, resulting from a duelling ridge scenario with anomalies M4-M6 and M10-M5 about their respective axes.

[15] Further south, the Zenith and Wallaby plateaus comprise the southern portions of the Gascoyne and Cuvier abyssal plains, respectively. Dredging between the Wallaby Plateau and the margin yielded tholeiitic basalts [*von Stackelberg et al.*, 1980], a product of oceanic ridges. Only one study identified magnetic anomalies M14-M11 (136–132 Ma), east of the Wallaby Plateau [*Mihut and Müller*, 1998]. Seismic studies of the Wallaby Plateau suggest a

non-volcanic basement core modified by magma from seafloor spreading [*Symonds et al.*, 1998]. *Planke et al.* [2002], reviewing seismic and dredge data, proposed that both the Wallaby and Zenith plateaus have continental cores that were intruded by magmatic rocks emplaced by rift propagation events during the breakup. More evidence of continental material was presented by *Nelson et al.* [2009], who reported that dredge samples, south of the Wallaby Plateau, included volcanic rocks showing variability in their silica content, as well as several terrigenous clastic, fossil-rich rocks, which were likely deposited when a portion of the plateau was near or above sea level. A continental origin is also suggested by the pre-breakup sedimentary section recently identified beneath parts of the Southern Wallaby Plateau [*Stilwell et al.*, 2012].

[16] The Gascoyne and Cuvier abyssal plains, and their plateaus, are terminated to the south by the 2000 km-long Wallaby-Zenith Fracture Zone (WZFZ), which has an unusually large width (∼200 km) and is composed of several smaller offset ridges oriented at acute angles to its southern edge [*Nelson et al.*, 2009]. The WZFZ marks the northern limit of the Perth Abyssal Plain, within which there are several major tectonic features, including the Naturaliste Plateau, Lost Dutchmen Ridge, Dirk Hartog Ridge, and the Batavia and Gulden Draak knolls (Figure 1a). Continental rocks were recently dredged from both knolls [*Williams*, 2011]. The Naturaliste Plateau, next to the southernmost portion of the West Australian margin, has been identified as stretched continental crust with intrusions from seafloor spreading [*Borissova*, 2002]. Samples from the Naturaliste Plateau contain reworked Mesoproterozoic crust with affinities to the Albany-Fraser-Wilkes orogenic rocks of Australia and Antarctica [*Halpin et al.*, 2008]. The crustal nature of the other anomalous features still remains unclear due to a lack of investigation. The magnetic anomalies in the Perth Abyssal Plain have been interpreted as M11-M0 (132–120.4 Ma, Figure 2d), with M4-M0 (126–120.4 Ma) offset dextrally southwest of the Naturaliste Plateau [*Johnson et al.*, 1980; *Markl*, 1974, 1978; *Veevers et al.*, 1991]. The remainder of the Perth Abyssal Plain was created during the Cretaceous Normal Superchron (CNS).

[17] The Wharton Basin, west of the Zenith Plateau and Batavia and Gulden Draak knolls, contains a remarkable set of curved fracture zones (Figure 1a), which have been linked to the 100 Ma spreading reorganization when the Indian Ocean's seafloor spreading ridges were realigned from trending 20 degrees to 90 degrees, so that Greater India could migrate north [*Müller et al.*, 2000; *Veevers*, 2000]. These curved fracture zones have yet to be replicated in a tectonic model.

3. Methodology and Data

[18] We formulate a new plate tectonic model for the breakup and early spreading history between India and Australia using the oceanic crust offshore West Australia. This area provides numerous constraints, such as seafloor spreading magnetic anomalies, fracture zones, extinct spreading ridges, pseudofaults, oceanic plateaus and seamounts, with which we can define our tectonic blocks and their migration. We use the satellite-derived free-air gravity anomaly grid of *Sandwell and Smith* [2009] to interpret fracture zones and features formed as a result of spreading reconfigurations, such as extinct ridges and pseudofaults (a raised 'step' in the seafloor where a new ridge began forming in older oceanic crust). Pseudofaults are visible as subtle differences in gravity anomaly strength between areas of the ocean floor. Extinct ridges can appear as linear negative gravity anomaly features and/or give an axis of symmetry in the magnetic anomalies. Fracture zones are perceptible as negative linear features. We also identify areas of anomalous oceanic crust, which may be volcanic features or continental rafts.

3.1. Tectonic Outlines and Micro-blocks

[19] If reconstructed as Indian continental slivers, Gulden Draak and Batavia knolls appear to fit well with the NW Naturaliste Plateau, while the Zenith Plateau appears to fit with the SW Wallaby Plateau (Figure 1a). These may have been micro-continental blocks transferred to the Australian plate during separate ridge jumps. We test their fit in a Mesozoic reconstruction. We define their boundaries using features identified in the marine gravity grid. We take the WZFZ as the southern limit of the Zenith and Wallaby plateaus, and the CRFZ and Sonne ridge for the northern and eastern limits of the Wallaby Plateau, respectively. The Wallaby Plateau's western limit is constrained by the location of the oldest magnetic anomalies we identify in the southern Gascoyne Abyssal Plain. Batavia and Gulden Draak knolls, if continental rafts, would have originally abutted the Naturaliste Plateau, given the fracture zone constraints. Greater India's eastern margin would have remained juxtaposed to the west side of the knolls, until their transferral to the Australian plate several million years later. We identify the linear feature running west of the knolls as a pseudofault resulting from this transferral. Where

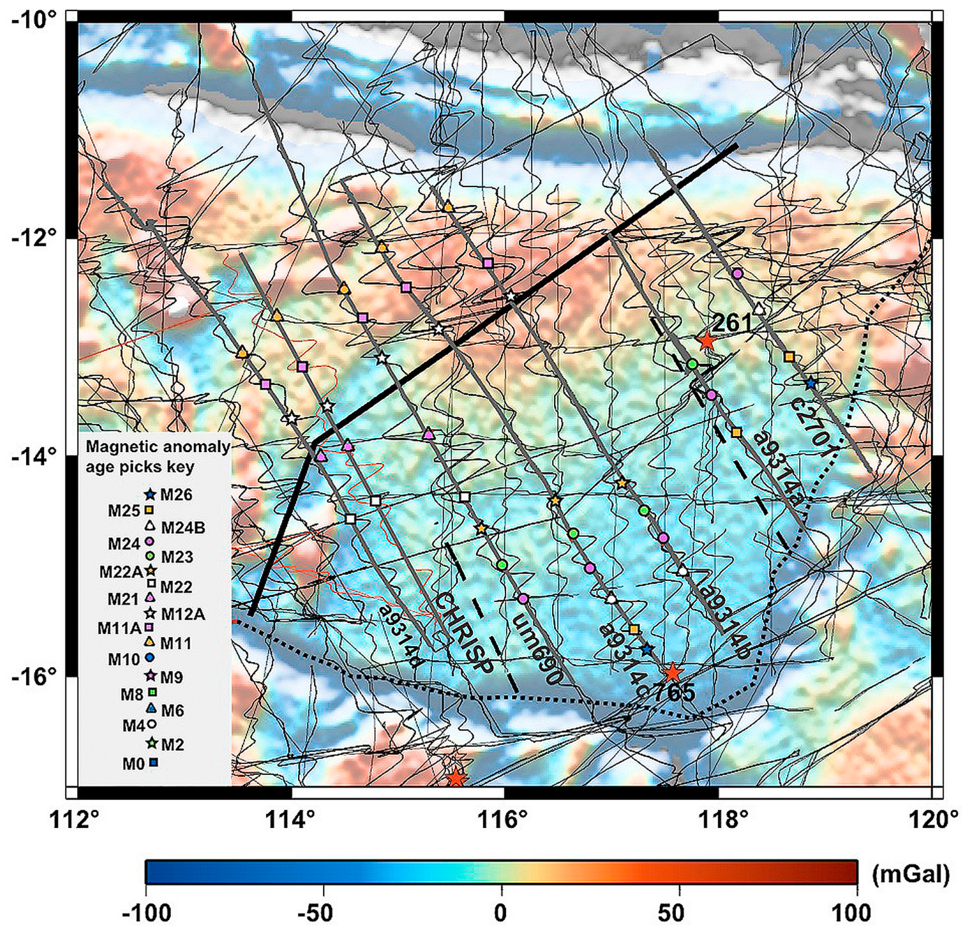


Figure 3a. Marine magnetic anomalies projected at 70 degrees from North for the Argo Abyssal Plain, overlain on 1-min satellite-derived free-air gravity field. Thin black lines show marine magnetic anomalies with ship tracks, thick gray lines show the selected, representative magnetic anomaly profiles shown for Figure 4a, thick dashed black lines show fracture zones, thick solid black lines show pseudofaults and thick dotted back line shows the COB. Identification of marine magnetic anomalies, picked at the young end of normal polarity, is shown in the map key.

there are no other constraints available, we pick the continent-ocean boundary (COB) using anomaly contrasts in the marine gravity grid (e.g., Naturaliste, Zenith, East Batavia and Gulden Draak). We outline Australia's northwest COB according to published interpretations north [*Müller et al.*, 2005] and south [*Brown et al.*, 2003] of the WZFZ.

3.2. Seafloor Spreading Magnetic Anomalies

[20] We analyze GEODAS (Geophysical Data System) data from of the National Geophysical Data Centre (NGDC), and incorporate new magnetic profiles acquired during the August–September 2008 IFM-Geomar CHRISP research cruise. All magnetic ship track data were smoothed by high-pass (300 km) and lowpass (10 km) filters to remove electromagnetic disturbances and noise. We make magnetic anomaly identifications for the Argo, Gascoyne, Cuvier and Perth abyssal plains by comparing magnetic anomalies from selected ship track profiles (Figures 3a–3c) against a synthetic model of seafloor spreading created using Modmag [*Mendel et al.*, 2005]. Table 1 outlines the parameters used for the synthetic models. We use the combined timescale of *Cande and Kent* [1995] and *Gradstein et al.* [1994]. We pick the young end of the normal polarity for Mesozoic magnetic anomalies: 26 (155 Ma), 25 (154.1 Ma), 24B (153.5 Ma), 24 (152.1 Ma), 23 (150.7 Ma), 22A (150.4 Ma), 22 (148.1 Ma), 21 (146.7 Ma), 12A (135 Ma), 11A (133.3 Ma), 11 (132.1 Ma), 10N (130.9 Ma), 10 (130.2 Ma), 9 (129.5 Ma), 8 (128.9 Ma), 6 (128.2 Ma), 4 (126.7 Ma), 2 (124.1 Ma), 0 (120.4 Ma). See Figures 4a–4d for the stacked plots of our interpretation of selected tracks compared to our synthetic model for each abyssal plain (see key for gravity and bathymetry).

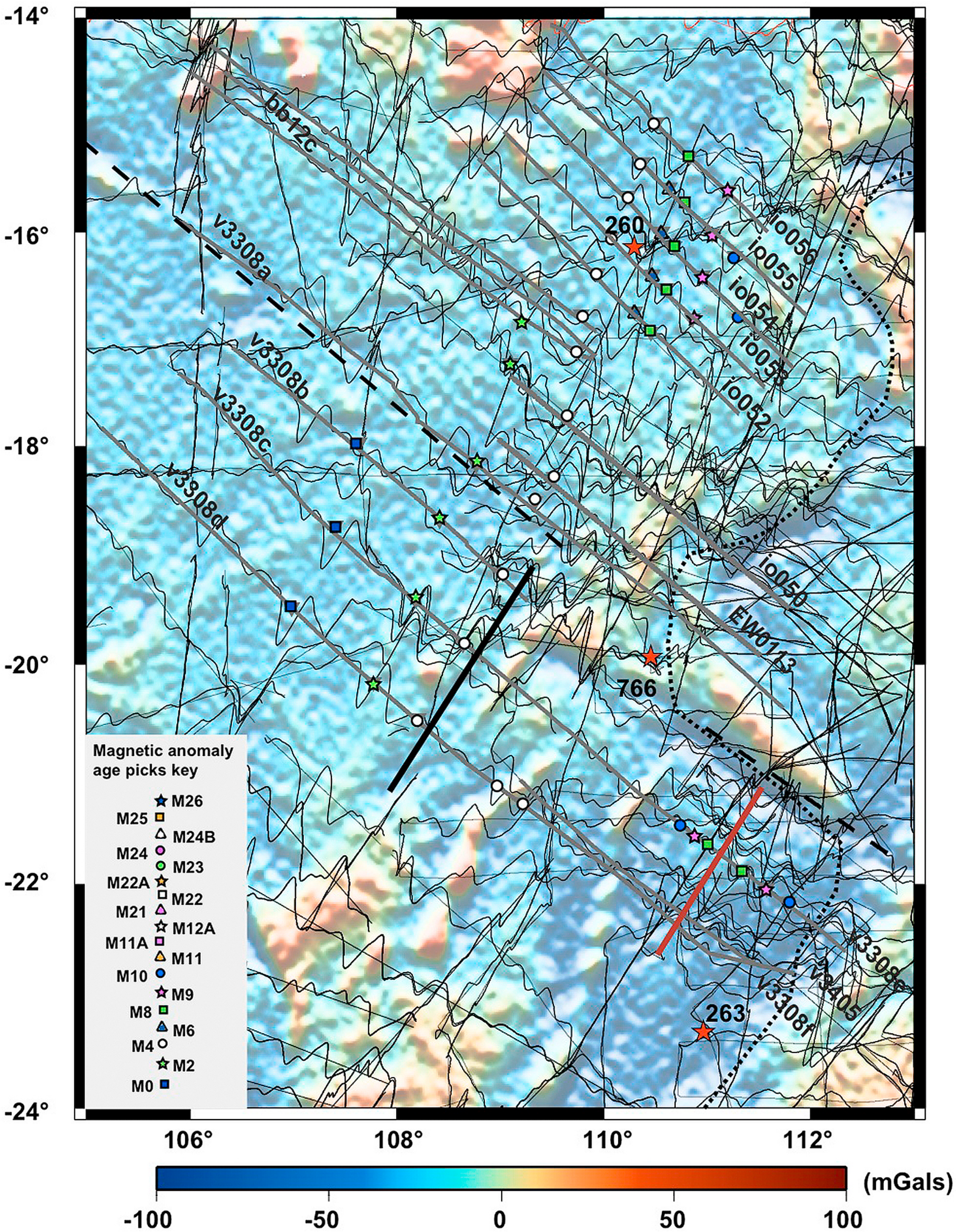


Figure 3b. Marine magnetic anomalies projected at 20 degrees from North for the Gascoyne and Cuvier abyssal plains, overlain on 1-min satellite-derived free-air gravity field. Thin black lines show marine magnetic anomalies with ship tracks, thick gray lines show the selected, representative magnetic anomaly profiles shown for Figures 4b and 4c, thick dashed black lines show fracture zones, thick brown line shows location of extinct ridge, thick solid black lines show pseudofaults and thick dotted back line shows the COB. Identification of marine magnetic anomalies, picked at the young end of normal polarity, is shown in the map key.

3.3. $^{40}Ar/^{39}Ar$ Dating of CHRISP Samples

[21] Dredging during the August–September 2008 IFM-Geomar CHRISP research cruise in the Wharton Basin recovered many samples for dating [*Hoernle et al.*, 2011]. One sample of volcanic glass, dredged from the flank of the Investigator Ridge (Figures 1a and 1b), was found to have a Jurassic age given the following procedure.

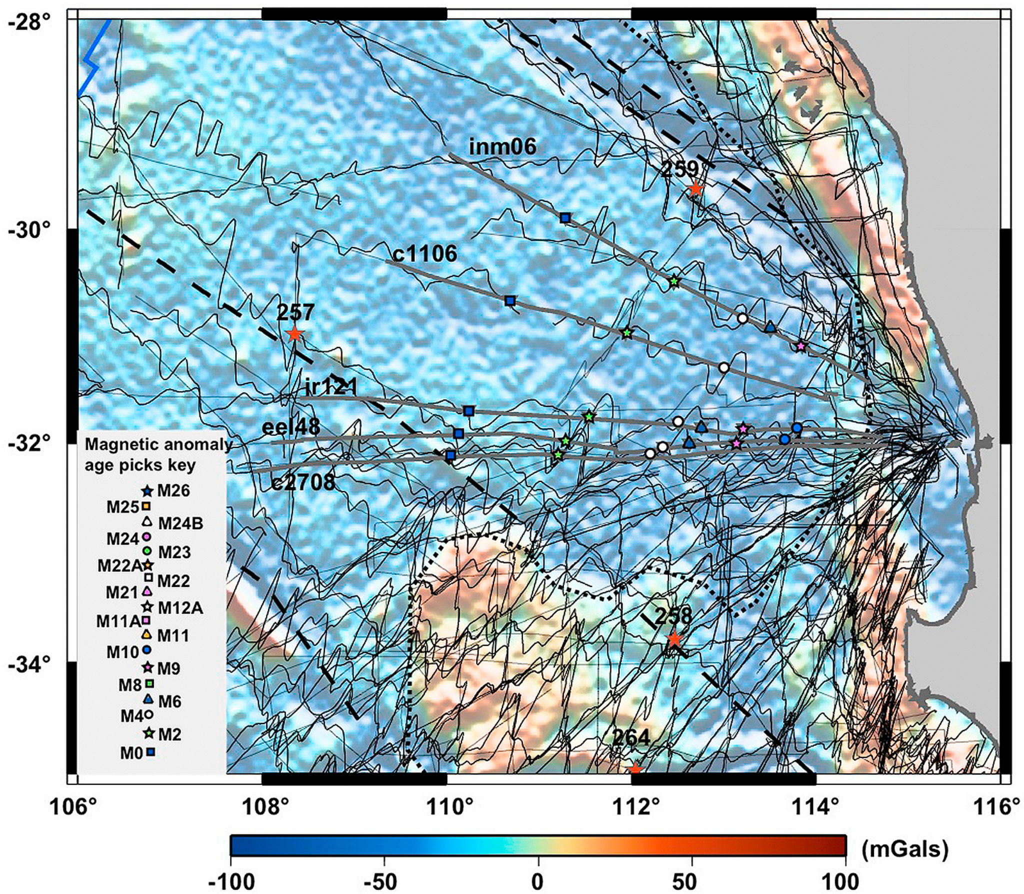


Figure 3c. Marine magnetic anomalies projected at 20 degrees from North for the Perth Abyssal Plain, overlain on 1-min satellite-derived free-air gravity field. Thin black lines show marine magnetic anomalies with ship tracks, thick gray lines show the selected, representative magnetic anomaly profiles shown for Figure 4d, thick dashed black lines show fracture zones, thick solid black lines show pseudofaults and thick dotted back line shows the COB. Identification of marine magnetic anomalies, picked at the young end of normal polarity, is shown in the map key.

[22] Fresh basalt glass fragments from dredged rock sample SO199-DR-30-1 were handpicked, crushed, sieved split (250–500 μm), washed, and cleaned using an ultrasonic disintegrator. The glass separate was lined by cadmium foil and irradiated at the 5-MW reactor of the GKSS Research Centre (Helmholtz-Zentrum Geesthacht, Germany). The neutron flux was monitored using Taylor Creek Rhyolite Sanidine (TCR-2: 27.87 $\pm$ 0.04 Ma) [*Lanphere and Dalrymple*, 2000]. $^{40}Ar/^{39}Ar$ laser step-heating analyses were carried out using a 20W SpectraPhysics Argon-Ion laser and an MAP 216

Table 1. Parameters Used for the Modmag Synthetic Block Models [*Mendel et al.*, 2005]

Parameters	Argo Abyssal Plain	Gascoyne/Cuvier/Perth
Spreading direction/profile azimuth:	155 degrees	130 degrees
Spreading full-rate:	100 mm/yr after 136 Ma 70 mm/yr before 136 Ma	70 mm/yr
Axis (ridge) jump:	390 km south at 136 Ma	n/a
Depth of the magnetized layer:	6 km	6 km
Thickness of the magnetized layer:	0.5 km	0.5 km
Magnetization on (and off)-axis:	10 A/m	10 A/m
Magnetic field declination:	1 degrees	−1 degrees
Magnetic field inclination:	−46 degrees	−55 degrees

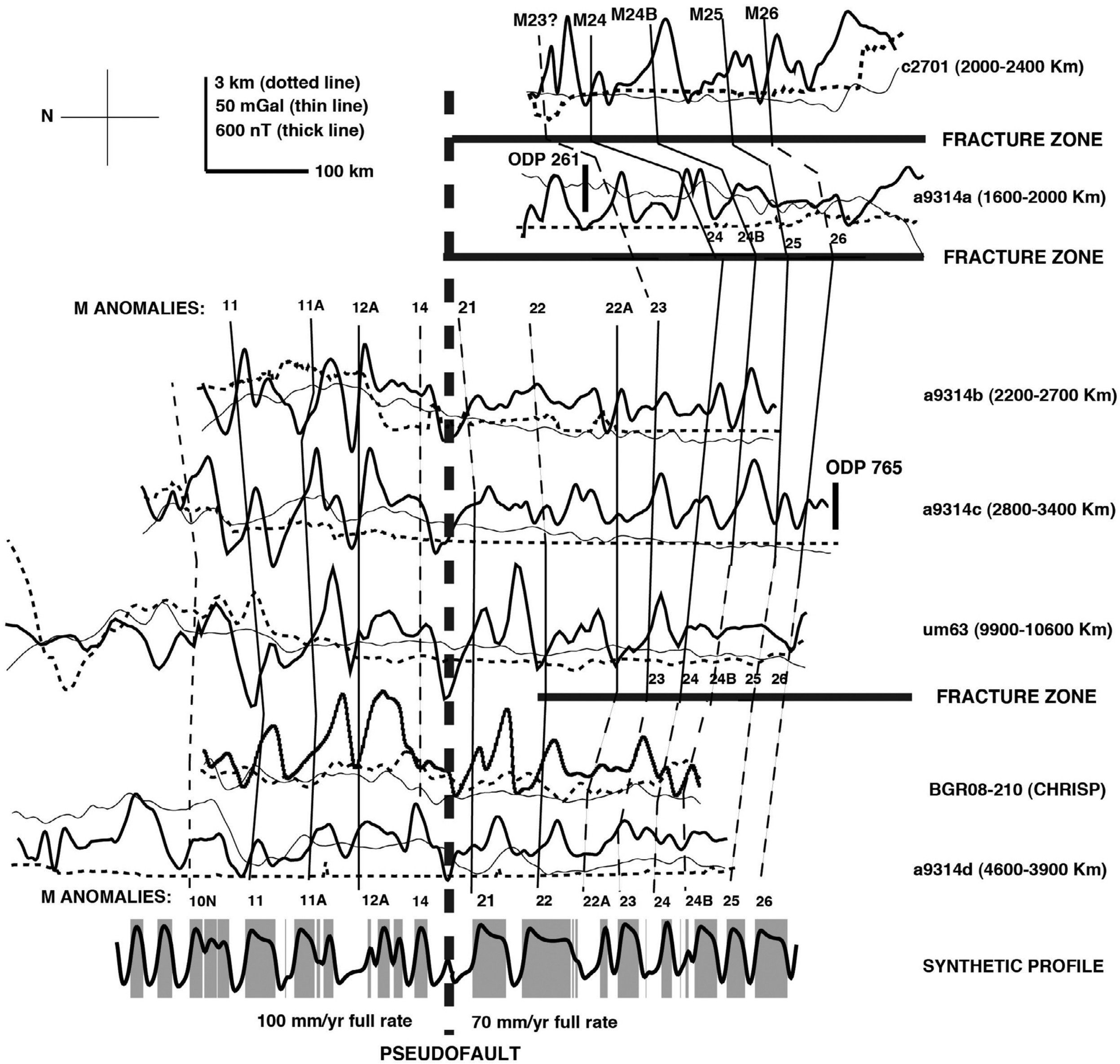


Figure 4a. Selected, representative magnetic anomaly profiles for the Argo Abyssal Plain. The location of the profiles is shown in Figure 3a. The synthetic profile is based on the geomagnetic timescale of *Cande and Kent* [1995], for Cenozoic anomalies, and *Gradstein et al.* [1994], for Mesozoic anomalies, using a depth to the top of the magnetized layer of 6 km and a thickness of the magnetized layer of 0.5 km. The oceanic crust was assumed to have been magnetized at 42 °S. Bathymetry profiles were taken from ship track data where available (BGR08–210 was extracted from the etopo2 topography grid).

series noble gas mass spectrometer. Argon isotope ratios from mass spectrometry were corrected for mass discrimination, background and blank values, J-value gradients, and interfering neutron reactions on Ca and K.

[23] The step-heating age spectrum (apparent age and error versus cumulative ^{39}Ar) yields a statistically valid plateau (8 consecutive steps comprising 84% of the ^{39}Ar released, with ages overlapping within 2Sigma errors), and robust statistics (MSWD = 0.49, Probability = 0.84). The plateau age, representing the inverse-variance weighted mean of the plateau step ages and errors, is 153.1 ± 3.3 Ma (2Sigma, including a 0.15% error in J). Alteration is monitored by calculating the alteration indices (AI), based on the measured ^{36}Ar/^{37}Ar ratios [*Baksi*, 2007]. Alteration indices of the plateau heating steps are low (0.0003–0.0006) and close to the cut-off values for fresh sample material suggested by

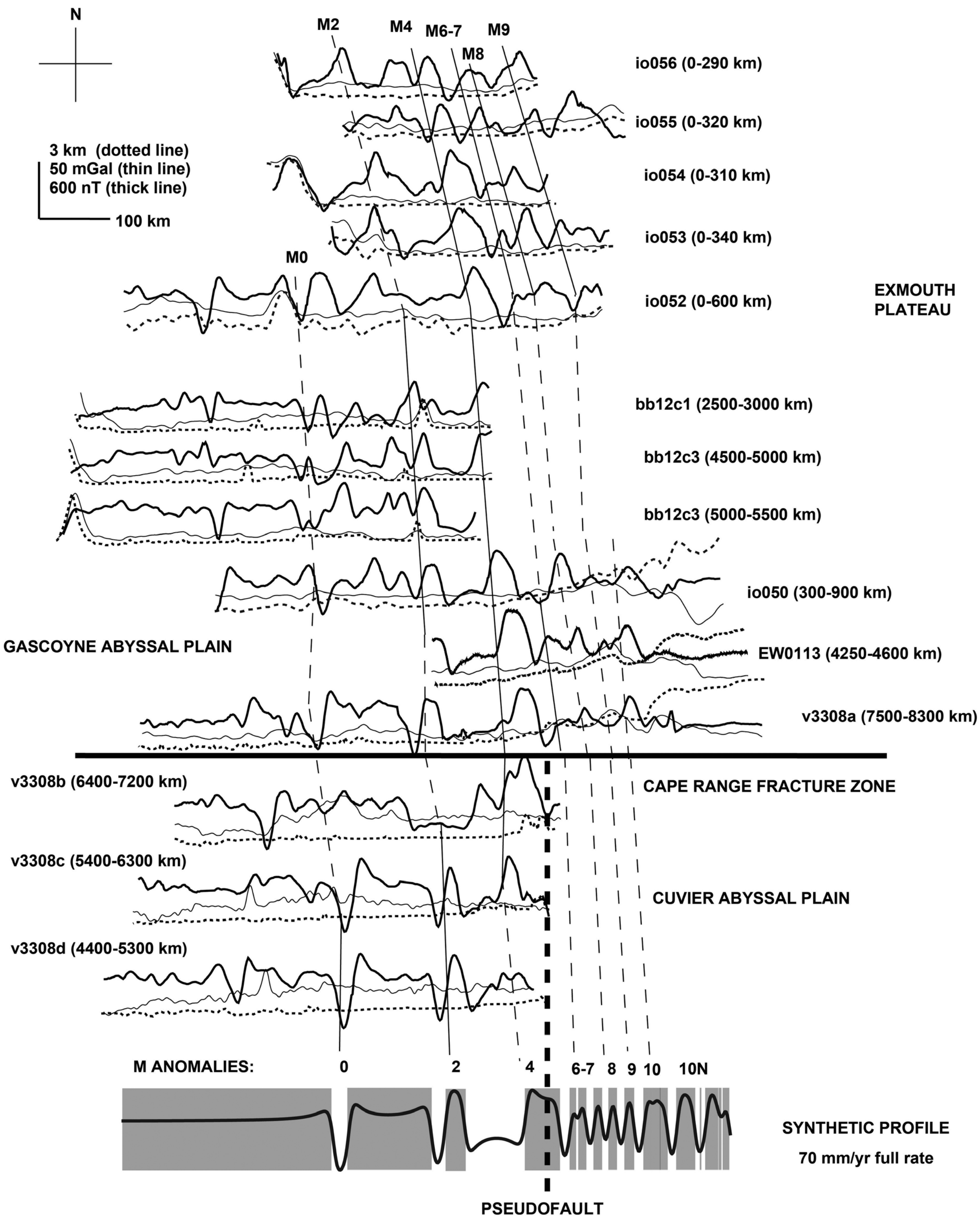


Figure 4b. Selected, representative magnetic anomaly profiles for the Gascoyne Abyssal Plain. The location of the profiles is shown in Figure 3b. The synthetic profile is based on the geomagnetic timescale of *Cande and Kent* [1995], for Cenozoic anomalies, and *Gradstein et al.* [1994], for Mesozoic anomalies, using a depth to the top of the magnetized layer of 6 km and a thickness of the magnetized layer of 0.5 km. The oceanic crust was assumed to have been magnetized at 42°S. Bathymetry profiles were taken from ship track data where available (io50–io56 were extracted from the etopo2 topography grid).

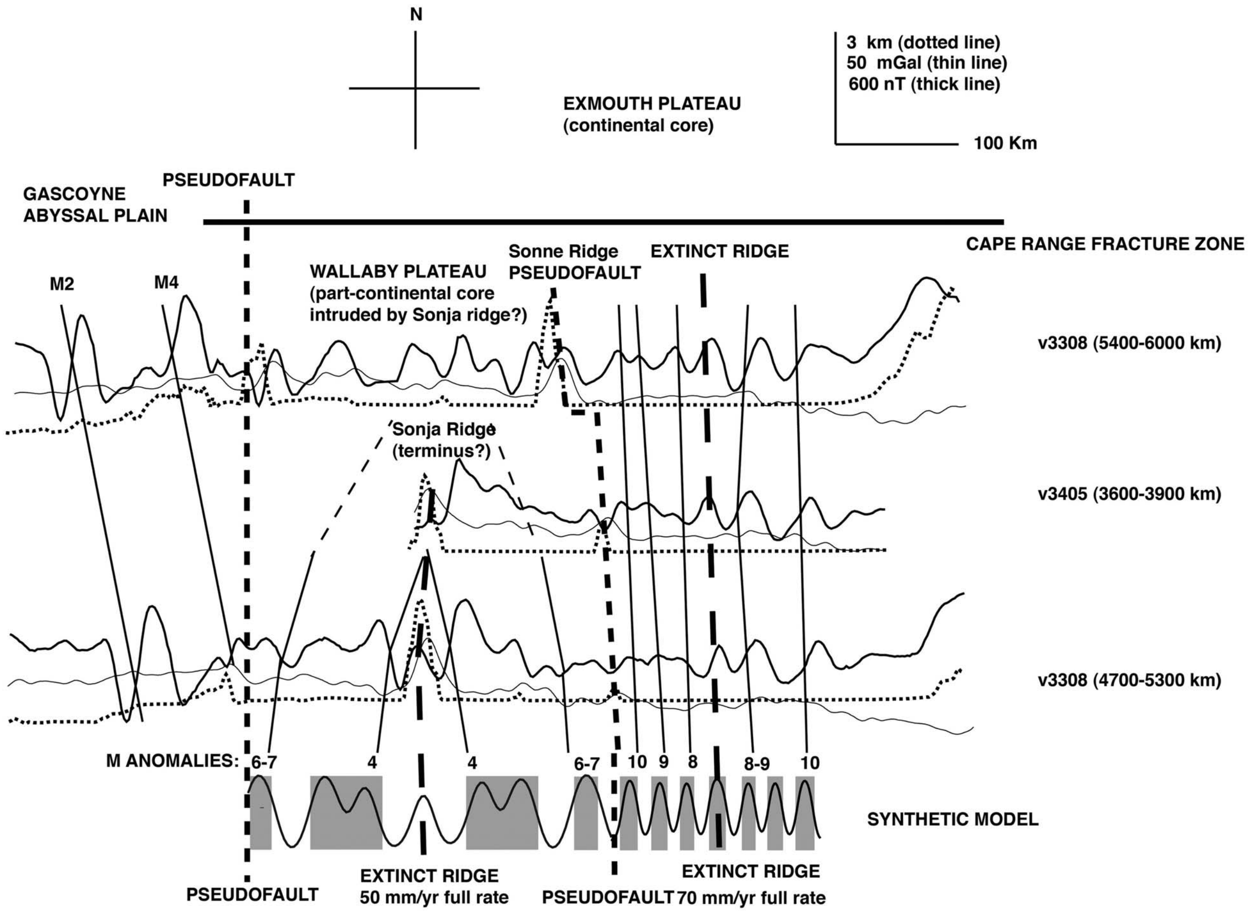


Figure 4c. Selected, representative magnetic anomaly profiles for the Cuvier Abyssal Plain. The location of the profiles is shown in Figure 3b. The synthetic profile is based on the geomagnetic timescale of *Cande and Kent* [1995], for Cenozoic anomalies, and *Gradstein et al.* [1994], for Mesozoic anomalies, using a depth to the top of the magnetized layer of 6 km and a thickness of the magnetized layer of 0.5 km. The oceanic crust was assumed to have been magnetized at 46°S. Bathymetry profiles were taken from ship track data.

Baksi [2007]. Low-temperature heating steps yield significantly higher alteration indices (up to ~0.5) and are excluded from the plateau. Step-heating results are shown in combined Age and AI spectra (Figure 1c), and full analytical data are given in Table S2 in the auxiliary material.[1]

4. Magnetic Anomaly Interpretation

[24] We identify two sequences of isochrons in the Argo Abyssal Plain: M26-M21 (155–147 Ma) and M14-M10N (136–131 Ma), becoming younger to the north (Figures 3a, 4a and 5), and two fracture zones from offsets in the magnetic anomalies. Only the older anomalies are bounded by the fracture zones, in the west and east, the latter having a much greater offset (about 100 km), mimicking the margin. Our interpretation for the older anomalies in the Argo Abyssal Plain is in good agreement with previous studies [*Fullerton et al.*, 1989; *Heine and Müller*, 2005; *Sager et al.*, 1992]. The younger anomalies (M14-M10) we interpret in the northern Argo Abyssal Plain, are a good match to a more recent model [*Heine and Müller*, 2005, Figure 2b]. The M14-M10 anomalies are a better fit to our synthetic model than the M20-M16 anomalies arising from a continuous sequence [*Fullerton et al.*, 1989; *Sager et al.*, 1992] (Figure 2a). The northern Argo anomalies have higher magnetic intensities, possibly indicating a separate event. Anomalies M21 and M22, located just south of the M14 (136 Ma) pseudofault appear attenuated, which could be due to remelting, following the ridge emplacement near them at 136 Ma. Over the Joey Rise, an area masked by volcanism, we tentatively identified

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GC003919.

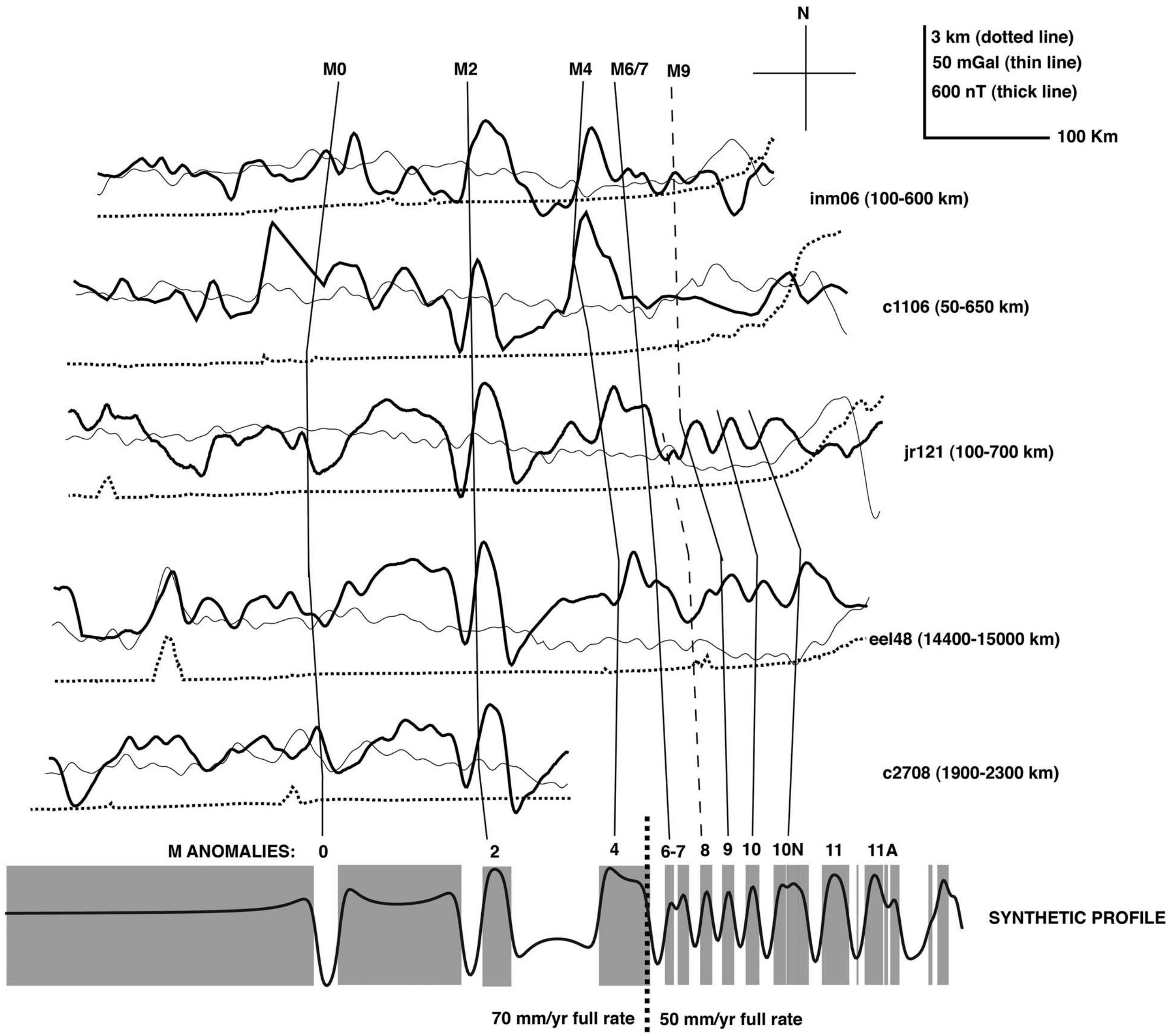


Figure 4d. Selected, representative magnetic anomaly profiles for the Perth Abyssal Plain. The location of the profiles is shown in Figure 3c. The synthetic profile is based on the geomagnetic timescale of *Cande and Kent* [1995], for Cenozoic anomalies, and *Gradstein et al.* [1994], for Mesozoic anomalies, using a depth to the top of the magnetized layer of 6 km and a thickness of the magnetized layer of 0.5 km. The oceanic crust was assumed to have been magnetized at 55°S. Bathymetry profiles were taken from ship track data.

chrons M12A-10N (135–131 Ma) trending at 20 degrees, which links the Argo with the remaining abyssal plains located southwest.

[25] In the Gascoyne Abyssal Plain, we interpret anomalies M10-M0 (130–120.4 Ma) as a continuous sequence trending 20 degrees east from the Exmouth Margin (Figures 3b, 4b and 5). The anomalies are bisected by a fracture zone, which is just discernable in the marine gravity grid as a faint lineation oriented at roughly 110 degrees, and may be a westward extension of the CRFZ that is offset slightly to the north. We follow the magnetic anomaly interpretations featuring Cretaceous seafloor in the Gascoyne Abyssal Plain [*Fullerton et al.*, 1989; *Sager et al.*, 1992], as opposed to the Jurassic seafloor of *Heine and Müller* [2005], Figure 2b, though we cannot identify the conjugate series M10-M4 (130–126 Ma) by the Exmouth margin [*Fullerton et al.*, 1989; *Sager et al.*, 1992], Figure 1a. Our interpretation differs from that of *Robb et al.* [2005] because the geometry and juxtaposition of their interpreted conjugate magnetic anomalies M2 and M4 cannot be accounted for by any reasonable plate motion/ridge propagation model.

[26] In the Cuvier Abyssal Plain, we identify two sets of conjugate anomalies divided by the Sonne

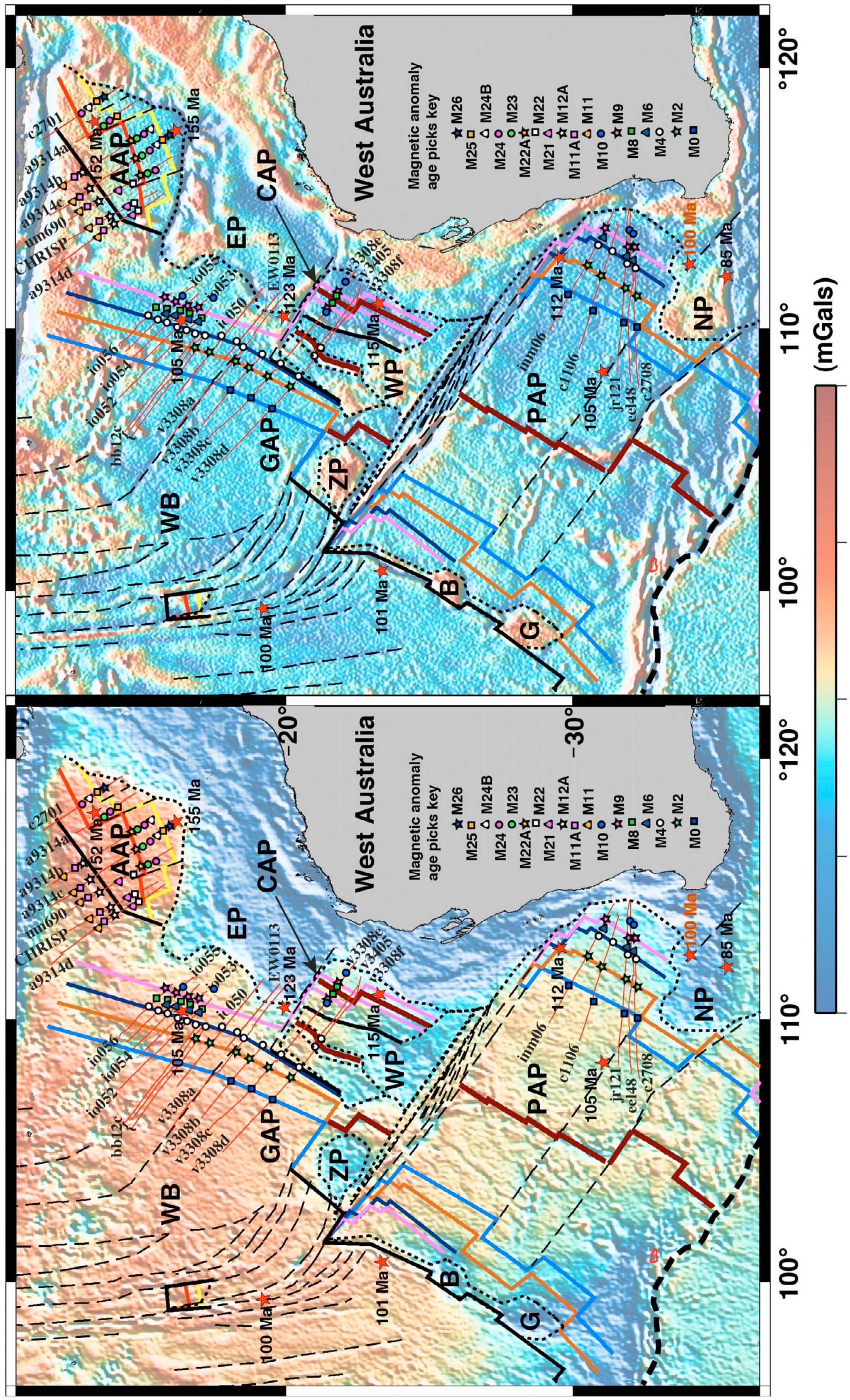


Figure 5. Location of isochrons (age-coded: M25, orange; M24, blue; M22A, magenta; M13, light blue; M11A, gray; M10N, lilac; M6, apricot; M4, yellow; M2, green; M0, black), pseudofaults (black lines), tectonic boundary (thick dashed blue line), extinct ridges (thick dark brown lines), continental rafts as outlined by the COB (purple dashed line), interpreted in this study along the Western Australian margin, overlain on 1-min satellite-derived (left) Bouguer and (right) free-air gravity field. Red stars are the locations of ODP/DPSP drillsites relevant to this study with minimum ages shown in black (only site 258 on the NE Naturaliste Plateau did not reach basement, age is shown in brown). Abbreviations are same as in Figure 1.

Ridge, here interpreted as a pseudofault (Figures 3b, 4c and 5). East of the Sonne Ridge, we identify anomalies M10-M8 (130.5–128.2 Ma) about an extinct spreading axis. West of the Sonne Ridge, we identify M6-M4 (127.2–126.7 Ma) reflected about the Sonja Ridge, a failed propagating ridge, as the anomalies appeared to converge to the north. Our results differ from previous studies, which identify the Sonne as an extinct spreading center surrounded by the conjugate series M10/11-M5 (130/131–126 Ma) [*Fullerton et al.*, 1989; *Mihut and Müller*, 1998], though they are similar to *Robb et al.* [2005] in having two conjugate sequences. Our results are supported by the different intensity in the marine gravity grid on either side of the Sonne Ridge, and the character of the CRFZ, which appears to be bisected directly north of the Sonne Ridge.

[27] In the Perth Abyssal Plain, our model (Figures 3c, 4d and 5) is in agreement with previous interpretations where chrons M10N (131 Ma) to M0 (124 Ma) are present in the eastern portion of the basin [*Johnson et al.*, 1980; *Markl*, 1974, 1978], Figure 2d. Though our model shows that the SW Australian margin formed ~136 Ma, no older anomalies were discernible due to the initially slow full spreading rate of ~32 mm/yr.

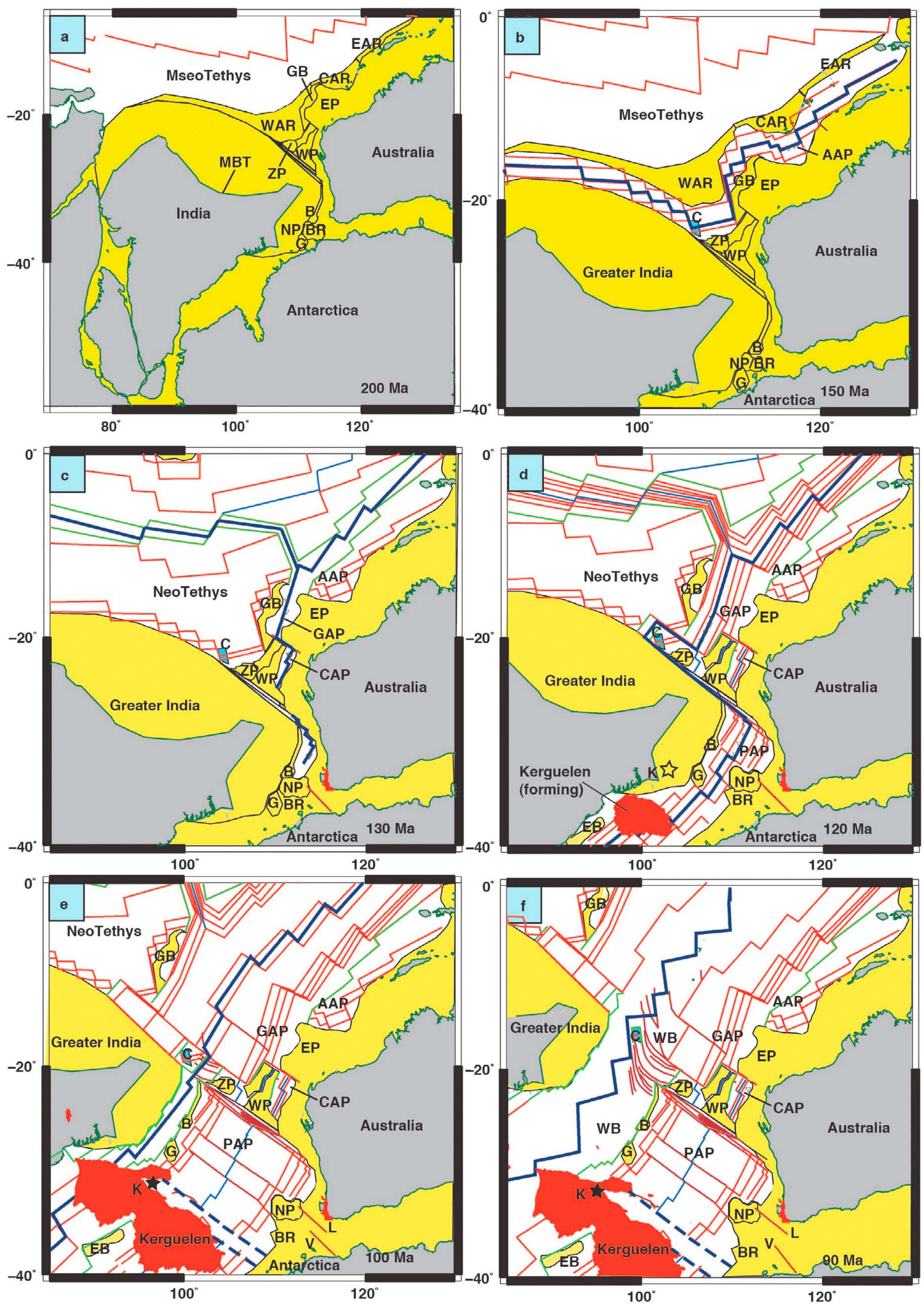
[28] Our results are in good agreement with all ODP drillsite age constraints (Figure 5). The two drillsites in the Argo Abyssal Plain report Late Jurassic ages. Site 261, in the northeast Argo, reported an age of 152 Ma having Kimmeridgian-Tithonian clay on a tholeiitic basalt sill overlying basement. To the south, site 765 was dated to 155 Ma having Tithonian-Berriasian siltstone on pillow basalt [*Gradstein*, 1992; *Veevers et al.*, 1974]. These are in good agreement with the ages of the magnetic anomalies we interpreted. Results from site 261 support a large sinistral offset in the eastern portion of the Argo Abyssal Plain. The next oldest drillsite, 766, is located near the southwest edge of the Exmouth Plateau and revealed an oldest date of 130 Ma from Valanginian sandstone/siltstone overlaying a tholeiitic basalt sill [*Gradstein*, 1992]. This site is just on the oceanic side of our COB and matches well with our modeled onset of spreading at 136 Ma. At drillsite 263, located in the southern portion of the Cuvier Abyssal Plain, inboard of the Wallaby Plateau, near-basement Albian clay containing dinoflagellates and nannofossils was dated at 115 Ma [*Veevers et al.*, 1974]. While this is younger than our interpreted age of ~132 Ma, it is allowable given that the sample did not reach the basement. In the Perth Abyssal Plain, drillsite 259, just southeast of the start of the WZFZ, Neocomian-Aptian claystone overlying a tholeiitic basalt flow was dated to 112 Ma [*Veevers et al.*, 1974]. This is younger than our modeled age of ~124 Ma but is still reasonable given that the sample was not taken from the basement. Drillsites 260 and 257, in the Gascoyne and Perth abyssal plains, respectively, reached mid-Albian clay near tholeiitic basement and both resulted in minimal seafloor ages of 105 Ma [*Davies et al.*, 1974; *Veevers et al.*, 1974] again, a reasonable match to our modeled ages of ~126 Ma for site 260 and ~115 Ma for site 257. Site 260 shows the largest age discrepancy between our interpretation and the drillsite ages but we are in agreement the majority of previous interpretations in that area [e.g., *Fullerton et al.*, 1989; *Robb et al.*, 2005, *Sager et al.*, 1992]. Just west of Batavia and Gulden Draak knolls, and the CHRISP Jurassic crust, drillsite 256 reached Late Albian brown clay [*Davies et al.*, 1974] and drillsite 212 reached basalt basement overlain by brown clay [*von der Borch et al.*, 1974]. Both reported minimal ages of around 100 Ma, which is a reasonable match to our interpreted seafloor ages of 108 and 100 Ma, respectively.

5. Discussion of Tectonic Model and Constraints

[29] Mesozoic reconstructions of East Gondwana remain poorly constrained and too tightly fit, particularly around Madagascar [*Lawver et al.*, 1998; *Marks and Tikku*, 2001]. We test a new fit-reconstruction for East Gondwana, which shifts the position of Australia, relative to Antarctica, several hundred kilometers further east than previously modeled at 83 million years [*Whittaker et al.*, 2007; *Williams et al.*, 2011], creating more accommodation space for the tectonic blocks. As a result, our blocks have a reasonable fit within Mesozoic East Gondwana and avoid excessive gaps or overlap. The two main tectonic blocks we migrate are Argoland and Greater India (including its micro-continental rafts). We have used all available constraints to define their outlines and motion, as follows. The tectonic element outlines and rotation poles relating to this study can be found in the auxiliary material provided and viewed in GPlates (http://www.gplates.org/index.html).

5.1. Argoland Extent and Motion

[30] New age data from seamounts sampled in the Wharton Basin (Figure 1) during the 2008 CHRISP research cruise add a pivotal constraint to the extents of Argoland and Greater India. Volcanic glass, dredged from the flanks of the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EB
90 Ma
-20°
-40°
100°
120°

Figure 6

Investigator Ridge (IR, Figure 1), was Ar-Ar dated at 153 ± 3.3 Ma, indicating the presence of a portion of Jurassic oceanic crust. This finding is striking since Cretaceous seafloor is prevalent in the abyssal plains inboard of the sample and we would expect this area to have been created after the inboard abyssal plains. The CHRISP Jurassic seafloor formed coevally to the seafloor in the Argo Abyssal Plain (from 155 Ma), as an extension of the spreading ridge between Argoland and Greater India. This new data is therefore instrumental in defining the southern extent of Argoland and the northern margin of Greater India. We infer that the Jurassic CHRISP crust originally formed just west of the Zenith Plateau and was transferred to its present-day position along the prominent curved fracture zones. The CHRISP Jurassic sliver could not have formed east of the Zenith Plateau, as it would have permanently joined the Australian plate when the Zenith Plateau was transferred via a ridge jump, see next section.

[31] We divide Argoland into West, Central and East portions to allow a multistaged accretion. The northern margins of all three Argoland blocks are minimum extents and the width of the slivers varies along strike from 100 km in the east to 500 km in the west (Figure 6). Due to the margin geometry, the widest portions occur in West and Central Argoland. West Argoland originally stretched from Africa to the Exmouth Plateau, it was the longest of the Argoland slivers. From at least the Mid Cretaceous, a transform fault must have existed off Africa to allow India to move north relative to Africa. Extending West Argoland to this transform fault is the simplest way to avoid creating a separate transform fault across the Eastern MesoTethys Ocean, stretching ~8000 km between Gondwana and Eurasia. New transform faults are unlikely to be able penetrate such a span of old oceanic crust because of its density and strength.

[32] The Tethyan Himalayas are considered to have formed from a large area of highly extended crust forming the northernmost extension of Greater India [e.g., *van Hinsbergen et al.*, 2011]. However, greatly extended continental crust is prone to breakup and subsequent seafloor spreading. The most straightforward way to explain the provenance of the Tethyan Himalayas is that it actually separated from Greater India and collided with Eurasia before Greater India. We propose that the Tethyan Himalayas correspond to West Argoland. Central Argoland, also referred to as the West Burma Block, is wider in the middle because of the curving geometry of its conjugate, the Argo Abyssal Plain. East Argoland, which stretched from northeast of the Argo Abyssal Plain to Seram/Birdhead/Papua New Guinea in the east, was conjugate to Australia's linear northern margin. We have outlined it as a narrow continental sliver.

[33] To reconstruct Argoland's motion, we compute half stage Euler poles and convert them into full-stage Euler poles given constraints from magnetic anomaly picks and fracture zones from the Argo Abyssal Plain, including chrons M25-M11 (155–132 Ma). For time periods where the oceanic crust of the Argo Abyssal Plain has been subducted, including chrons M20-M15 (146–136 Ma), we maintain a similar rate and direction of motion for Argoland to that of pre-146 Ma.

[34] Active mid-ocean ridges terminate at strike-slip faults or triple junctions. The spreading center forming the Argo Abyssal Plain in the Late Jurassic was likely connected to the spreading center in the West Somali Basin as these spreading systems operated during the same timeframe with compatible spreading configurations. When the Somali ridge became extinct is contentious with models interpreting extinction at M10 (130 Ma) [*Eagles and König*, 2008; *Rabinowitz et al.*, 1983] or M0 (120.4 Ma) [*Ségoufin and Patriat*, 1980]. We prefer the latter model (extinct at 120 Ma) as this links better to the extinction of the triple junction that temporarily divided Argoland, India and Australia from 136 to 120 Ma. During this time, a triple junction would have existed offshore northeast Africa, separating Africa from India and Argoland. The northern arm of this triple junction would have been a strike-slip fault between the

Figure 6. Mercator-projected tectonic reconstructions of the West Australian margin at (a) 200 Ma, (b) 150 Ma, (c) 130 Ma and (d) 120 Ma (e) 100 Ma, (f) 90 Ma, constructed using GPlates exported geometries with Australia fixed in present-day coordinates. Showing pseudofaults (green dashed lines), tectonic boundary (thick dashed blue line), extinct ridges (blue dashed lines), COB (thin black line, continental material shown in yellow), isochrons (red lines), spreading centers (brown dashed lines). Coastlines are outlined in gray and large igneous provinces are filled in red. Abbreviations are Batavia Knoll (B), Bruce Rise (BR), CHRISP Jurassic sliver (C, not to scale), Central Argoland (CAR), East Argoland (EAR), Elan Bank (EB), Gulden Draak Knoll (G), Kerguelen Plateau (K), Leeuwin Fracture Zone (L), Main Boundary Thrust (MBT), Vincennes Fracture Zone (V), West Argoland (WAR). Other abbreviations are same as in Figure 1.

Western and Central MesoTethys, so that it could accommodate the separate motions of Argoland relative to the MesoTethys. This seafloor has since been subducted beneath the Farah Block (North Afghanistan). The extinction of the active ridge linking the triple junctions north of Greater India around 120 Ma could also explain India's northward acceleration [*Müller*, 2007], reaching ~20 cm/yr [*Acton*, 1999; *Klootwijk et al.*, 1992; *Patriat and Achache*, 1984].

5.2. Greater India Extent and Motion

[35] Based on the CHRISP Jurassic age and potential field data offshore West Australia, we divide Greater India into three distinct portions: (1) the Gascoyne Block, a narrow indenter located between West Argoland and the Exmouth Plateau, which created the Gascoyne Abyssal Plain as it migrated from the Exmouth margin, (2) the Wallaby and Zenith Plateaus, comprising all the Greater Indian continental material between CRFZ and WZFZ, these became attached to the Australian plate following two westward ridge jumps, and (3) the main portion of Greater India, located south of the WZFZ reaching roughly 3500 km to the west to meet the margins of Africa and Madagascar in a Mesozoic full-fit plate reconstruction.

[36] We bring the northern extent of Greater India (the Gascoyne Block) inline with the northern tip of the Exmouth Plateau, a highly extended passive margin, which requires a conjugate continental flank during rifting. The presence of continental crust west of the Exmouth Plateau before breakup is supported by seismic stratigraphy in the Rankin Trend (RT, Figure 1a) that reveals a northwest Precambrian sediment source was present along the northwest shelf during most of the Palaeozoic and Mesozoic [*Martison et al.*, 1973]. We limit the Gascoyne Block to a narrow indenter in order to be able to link the CHRISP Jurassic seafloor, southwest of the pre-stretched Exmouth Plateau, to the Argo Abyssal Plain via a ridge oriented at ~70°N. The Gascoyne Block's northeast margin, which was conjugate to the Exmouth Plateau, is outlined to match the Australian COB and allows seafloor of compatible age to the magnetic anomaly picks, identified in our study, to form halfway between the blocks as they separate. The Gascoyne Block's southern edge was conjugate to the Wallaby Plateau, to allow complete continental overlap between itself, West Argoland and Greater India (including the plateaus), in a full-fit Mesozoic reconstruction (Figure 6a).

[37] For Euler rotations describing the motion of Greater India, including its Gascoyne Block indenter, we visually fit conjugate magnetic anomaly and fracture zone interpretations in the Gascoyne, Cuvier and Perth abyssal plains and compute full-stage rotation poles using GPlates [*Boyden et al.*, 2011]. The relative motions between Madagascar and Africa and Antarctica provide additional constraints for the relative position and motion of Greater India through time. There are several models available that describe the initial motion for Africa-Antarctica and Africa-Madagascar. Here we adopt *König and Jokat* [2010] and *Müller et al.* [2008], respectively. To build robust plate tectonic models it is important to consider regional constraints provided by neighboring plates to avoid excessive overlap or unlikely motion in regions further afield from the main area of study. This is particularly significant for the commonly tight fit between southwest India and Madagascar, which is difficult to resolve without causing overlap between north India and the WZFZ, which was formed by India's migration. We avoid this overlap by fitting Greater India to Madagascar in such a way that it results in less than 150 km of dextral strike-slip motion between the two plates.

[38] We extend the 136 Ma spreading reorganization, which formed the northern portion of the Argo Abyssal Plain and Joey Rise ridges, into a triple junction operating until ~120 Ma. The western arm of the triple junction is linked to the African triple junction, where India's anticlockwise motion prior to ~120 Ma causes minor compression along East Africa. This is supported by the presence of the Masirah ophiolite of eastern Oman. Based on the age of potassic granites, the Masirah ophiolite was obducted around 125–145 Ma [*Smewing et al.*, 1991], inline with a Tithonian age obtained by the analysis of radiolaria in cherts in the ophiolite [*Moseley*, 1990], which corresponds to Greater India's anticlockwise rotation, from 136 to 120 Ma. The nucleus of the West Australian triple junction originated just east of the Joey Rise (Figure 6), though subduction has ensured there is little evidence remaining for the proposed triple junction, except possibly for the volcanic Joey and Roo Rises. Its northeast spreading branch was initiated after a relocation of the NeoTethyan spreading center to the north Argo Abyssal Plain, leaving the pseudofault near the Java subduction trench. The southeast arm began rifting India from Australia, thereby linking the Jurassic and Cretaceous spreading systems of West Australia.

[39] The micro-continental blocks, including Zenith, Wallaby and Naturaliste plateaus, Batavia and

Gulden Draak knolls, share the same Euler rotations as Greater India until they are transferred to the Australian plate by localized ridge jumps. We date these ridge jumps using our magnetic anomaly interpretations and/or interpolation of India-Australia spreading rates to: Wallaby Plateau ~128 Ma, Naturaliste and West Wallaby Plateau ~127 Ma, Zenith Plateau ~124 Ma (along with the CHRISP Jurassic seafloor), Batavia and Gulden Draak knolls ~108 Ma (transferring the CHRISP Jurassic seafloor back to the Indian plate). Throughout the CNS, we maintain a steady spreading rate for Greater India that compares with spreading rates before and after that time. Greater India's motion slows down slightly from 98 Ma due to the onset of relative motion between India from Madagascar. The 98 Ma onset of relative motion is required to satisfy the change in transform fault azimuths in the Wharton Basin, as India began to migrate north instead of northwest, ultimately resulting in the curved fracture zones visible today. The onset of this major spreading reorganization also transferred the CHRISP Jurassic seafloor to its present-day location on the Australian plate ~99 Ma. Seafloor spreading between India and Madagascar then propagated from south to north from 94 to 83.5 Ma. We calculate the full spreading rate from 99 to 84 Ma to be about 47 mm/yr along the Wharton Basin fracture zones, with the bend maxima occurring ~94 Ma. This model is a good match to the onset of separation between India and Madagascar, commonly dated at around 87 Ma [*Storey et al.*, 1995; *Yatheesh et al.*, 2006]. The timing of this event also fits well with a major spreading reorganization identified in the Indian Ocean ~100 Ma [*Müller et al.*, 2000; *Veevers*, 2000], as well as the emplacement of the Androy and Morondava basalts on Madagascar's east and west margins from 103 and 94 Ma, respectively [*Bardintzeff et al.*, 2010] and the St Mary islands basalts, emplaced off West India ~84–92 Ma [*Torsvik et al.*, 2000].

5.3. Tectonic Model

[40] The West Australian margin began forming at ~155 Ma, with the onset of seafloor spreading along the Argo Ridge. The ridge likely linked from East Timor to a triple junction offshore Somalia (west). Spreading about this ridge caused the northward migration of Argoland, creating the Argo Abyssal Plain and CHRISP Jurassic crust (Figure 6b). Argoland continued migrating north but its spreading system underwent a reorganization at 136 Ma, forming a new, steeper arm along the north Argo Abyssal Plain pseudofault, roughly 800 km further south of the old Argo spreading ridge at this time (Figures 4a and 6c). This new portion of the ridge reached around the entire West Australian margin, forming the triple junction whose nucleus was located between the Joey and Roo Rises (Figure 6c). Separation between India and Australia followed, with the formation of the Australian western margin abyssal plains.

[41] Greater India and its northern indenter, the Gascoyne Block, began migrating from the West Australian margin in an anticlockwise motion as the new spreading center propagated south from the Exmouth Plateau after the 136 Ma spreading reorganization. This is close to the onset of seafloor spreading between India and East Antarctica at 130 Ma (chron M9) [*Gaina et al.*, 2007]. The ~6 million year discrepancy is reasonable given the initial anticlockwise motion for Greater India about its southern pivot. India's anticlockwise motion is a vital component in our model to avoid overlap between India's southwest margin and Madagascar, and India's northeast margin and the WZFZ. As a result, spreading rates were higher in the northern part of the West Australian abyssal plains, with the maximum rates presumably near the Joey Rise volcanic province, where the triple junction nexus was located. From 136 Ma, the Exmouth margin underwent crustal stretching while the Joey Rise ridges formed at its north. These volcanic ridges have been attributed to magma concentrated in crustal drainage channels beneath the underplated Exmouth plateau [*Frey et al.*, 1998] or as failed rifts [*Direen et al.*, 2008]. The presence of sills connecting the Joey Rise to the Exmouth Plateau [*Heirtzler et al.*, 1978] support our interpretation that both formed concurrently. The West Australian margin was formed in the following sequence: Perth margin from ~136 Ma, the Gascoyne margin from ~135 Ma and the Cuvier margin from ~133 Ma. This unusual age progression is due to our allocated boundaries for the blocks, as discussed earlier.

[42] From 136 Ma to 100 Ma, Greater India continued its westward migration, leaving several microcontinental blocks behind via ridge jumps. The first ridge jump occurred in the Cuvier Abyssal Plain ~128 Ma, transferring the Wallaby Plateau to the Australian Plate, trapping the older conjugate anomalies inboard of the Sonne Ridge and introducing an offset in the middle of the CRFZ at the northern tip of the Sonne Ridge (Figure 5). The Naturaliste Plateau and Bruce Rise (NP and BR, Figure 6), as conjugate Indian and Gondwanan continental crust, were stretched until ~127 Ma. Initial

motion between the Naturaliste Plateau and Bruce Rise formed the conjugate Leeuwin and Vincennes fracture zones, located off SW Australia and East Antarctica, respectively (L and V, Figure 6). These are known to be conjugate tectonic features but they did not form as fracture zones during Australia-Antarctica breakup [*Williams et al.*, 2011]. We propose that they formed during India's initial rifting from Gondwana. The second westward ridge jump, at roughly 127 Ma, transferred the West Wallaby Plateau to the Australian plate. Between the West and East Wallaby Plateau, the Sonja Ridge is the extinct ridge, or failed rift system, which corresponds to this second westward ridge jump. The third westward ridge jump, at around 124 Ma, transferred the Zenith Plateau and CHRISP Jurassic sliver to the Australian plate.

[43] The CHRISP Jurassic sliver (C, Figure 6d) remained west of the Zenith Plateau from 124 Ma until a fourth ridge jump, at 108 Ma, attached Batavia and Gulden Draak knolls to the Australian plate (B and G, Figure 6e) and the CHRISP Jurassic sliver to the Indian plate (C, Figure 6e). Two ridge jumps in opposing directions in adjacent spreading corridors are modeled to satisfy key observations: south of the WZFZ a westward ridge jump is required to attach Batavia and Gulden Draak knolls to the Australian plate, while north of the WZFZ an eastward ridge jump is required to attach the CHRISP Jurassic sliver back to the Indian plate so that it can be transferred to its present-day location on the Investigator Ridge. This ridge jump also left an extinct spreading center in the middle of the Perth Abyssal Plain and presumably a conjugate sequence of Mesozoic anomalies in the western portion, though the area is heavily influenced by volcanism and a lack of magnetic anomaly tracks. We interpret Dirk Hartog Ridge as this extinct spreading center. This interpretation matches a continuous spreading rate of roughly 70 mm/yr from 126.7 to 108 Ma with about 10% faster spreading rates on the Australian flank, given the amount of seafloor produced in that time. This >700 km westward relocation for the spreading center at 108 Ma was likely a ridge-hot spot induced ridge jump [*Mittelstaedt et al.*, 2008] toward the Kerguelen Plume, which was located about 300 km directly south of Gulden Draak Knoll at the time (Figure 6e).

[44] The Dirk Hartog Ridge is a linear feature mimicking the margin orientation and it is linked along its northern limit to the Gulden Draak and Batavia knolls via the Lost Dutchmen Ridge. Since they were recently dredged, the crustal nature of the knolls is now known to be at least part-continental [*Williams*, 2011]. We incorporate Batavia and Gulden Draak knolls into our model as tectonic blocks with continental cores. The 108 Ma ridge jump in the Perth Abyssal Plain conserves a reasonable COB overlap (50–300 km) in a Mesozoic full-fit reconstruction (Figures 6a and 6b), where the knolls fit well about the western edge of the Naturaliste Plateau.

5.4. The Anomalous Wallaby-Zenith and Wharton Basin Fracture Zones

[45] Our model accurately reconstructs the unusual width and morphology of the WZFZ, which was originally composed of three major east–west trending fracture zones. We also identify the en-echelon offset ridges in the marine gravity grid, oriented southwest from the base of the Wallaby, and agree with *Nelson et al.* [2009] that they were formed gradually under a transtensional regime. We model the en-echelon fracture zones as forming from ~110 Ma, bifurcating the original Wallaby-Zenith fracture zones as Greater India underwent a slight southward motion just prior to the 108 Ma ridge jump, which can be seen in the curved fracture zones directly west of the southern Zenith Plateau. This transtensional motion could also be responsible for creating Lost Dutchmen Ridge via a leaky transform, west of the WZFZ, where the en-echelon fracture zones are not observed. This leaky transform (Lost Dutchmen Ridge) may have extended to the Perth spreading center (Dirk Hartog Ridge), which was to become extinct at 108 Ma. This process may have contributed to its volcanic appearance as seen in the marine gravity grid.

[46] This is the first study to reproduce the trace of the Wharton Basin curved fracture zones in a tectonic reconstruction model. The curved fracture zones are only found west of the Zenith Plateau so their prominence may be related to the presence of the older/colder CHRISP Jurassic oceanic crust, when the ridge initiated spreading between the CHRISP Jurassic seafloor and the Zenith Plateau at 108 Ma. The seafloor south of the curving fracture zones formed closer to the Kerguelen hot spot, where warmer mantle may have resulted in ocean floor with a smoother morphology. The seafloor northwest of the Zenith Plateau is also smooth but this area did not experience a ridge jump at 108 Ma. We propose that the curved fracture zones were a manifestation of the eastward ridge jump that transferred the Jurassic CHRISP crust back to the

Indian plate at 108 Ma, as well as a continuation of the WZFZ.

6. Conclusions

[47] We derive a comprehensive regional tectonic model that can account for all major tectonic features visible in the marine gravity grid off the West Australian margin. These include volcanic ridges, submerged plateaus/continental rafts, the CHRISP Jurassic sliver, and fracture zones including the complex morphology of the WZFZ and those curving in the Wharton Basin, coinciding with the 100 Ma spreading reorganization. Our plate tectonic model satisfies the potential field and ODP/CHRISP age data, yet remains relatively simple and provides a complete scenario for the early formation of the eastern Indian Ocean. The CHRISP Jurassic seafloor provides essential new insights into the original extents of Argoland and Greater India so that the major extent of Greater India lay south of the WZFZ in a Mesozoic West Australian margin reconstruction. To form the CHRISP Jurassic seafloor so that it could be emplaced where it is today, the spreading center migrating Argoland from Greater India veered around the margin that later became the Exmouth Plateau. This ridge configuration reduced the portion of northern Greater India north of the WZFZ, also conjugate to the Exmouth and Wallaby Plateaus, to an indenter roughly 750 km long by 100 km wide, which we call the Gascoyne Block.

[48] Our model links the Jurassic and Cretaceous spreading episodes from the rifting of Argoland and Greater India, respectively, via a spreading reorganization at ~136 Ma. From this time, a triple junction operated between Argoland, India and Australia, in order to avoid applying India's initial anticlockwise rotation to Argoland. The northwest Australian triple junction linked to an East African triple junction but both triple junctions became extinct around 120 Ma when Argoland and India were attached to the same pole of rotation. The Early Cretaceous migration of Greater India formed West Australia's abyssal plains, including the Gascoyne Abyssal Plain, which was formed by the migration of India's northern indenter, the Gascoyne Block. The Cuvier and Perth abyssal plains became bounded by continental crust following ridge jumps isolating the Zenith and Wallaby plateaus, and Batavia and Gulden Draak knolls, respectively, though this occurred several million years earlier for the northern abyssal plain.

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