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Breakup and early seafloor spreading between India and Antarctica

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SUMMARY

We present a tectonic interpretation of the breakup and early seafloor spreading between India and Antarctica based on improved coverage of potential field and seismic data off the east Antarctic margin between the Gunnerus Ridge and the Bruce Rise. We have identified a series of ENE trending Mesozoic magnetic anomalies from chron M9o (∼130.2 Ma) to M2o (∼124.1 Ma) in the Enderby Basin, and M9o to M4o (∼126.7 Ma) in the Princess Elizabeth Trough and Davis Sea Basin, indicating that India–Antarctica and India–Australia breakups were roughly contemporaneous. We present evidence for an abandoned spreading centre south of the Elan Bank microcontinent; the estimated timing of its extinction corresponds to the early surface expression of the Kerguelen Plume at the Southern Kerguelen Plateau around 120 Ma. We observe an increase in spreading rate from west to east, between chron M9 and M4 (38–54 mm yr^{-1}), along the Antarctic margin and suggest the tectono-magmatic segmentation of oceanic crust has been influenced by inherited crustal structure, the kinematics of Gondwanaland breakup and the proximity to the Kerguelen hotspot. A high-amplitude, E–W oriented magnetic lineation named the Mac Robertson Coast Anomaly (MCA), coinciding with a landwards step-down in basement observed in seismic reflection data, is tentatively interpreted as the boundary between continental/transitional zone and oceanic crust. The exposure of lower crustal rocks along the coast suggests that this margin formed in a metamorphic core complex extension mode with a high strength ratio between upper and lower crust, which typically occurs above anomalously hot mantle. Together with the existence of the MCA zone this observation suggests that a mantle temperature anomaly predated the early surface outpouring/steady state magmatic production of the Kerguelen LIP. An alternative model suggests that the northward ridge jump was limited to the Elan Bank region, whereas seafloor spreading continued in the West Enderby Basin and its Sri Lankan conjugate margin. In this case, the MCA magnetic anomaly could be interpreted as the southern arm of a ridge propagator that stopped around 120 Ma.

Key words: Antarctica, Enderby Basin, plate tectonics, sea floor spreading, Kerguelen.

1 INTRODUCTION

The Enderby Basin, Princess Elizabeth Trough and Davis Sea Basin (Fig. 1) are remote regions off the east Antarctic continental margin where the history of breakup and earliest seafloor spreading has been poorly constrained due to limited data coverage. They constitute a key area to understanding the timing and orientation of breakup and seafloor spreading between Antarctica and India.

The role of India in the dispersal of Gondwanaland has remained one of the largest uncertainties in the Mesozoic global plate circuit due to a lack of palaeomagnetic and marine geophysical data, as well as a complex breakup history (e.g. Powell *et al.* 1988; Coffin 1992; Grunow 1999). Early African–Antarctic spreading to the west of the Gunnerus Ridge (∼30°E) has been dated from Early Cretaceous with a reasonably well-defined sequence from M24 (∼153 Ma) (Roeser *et al.* 1996; Jokat *et al.* 2003). West and north of Conrad Rise, magnetic anomalies from chron 34 to 28 (∼83.5 to ∼64 Ma) have been identified (Goslin & Schlich 1976; Royer & Coffin 1992). Early Australian–Antarctic spreading to the east of the Bruce Rise and Vincennes Fracture Zone (∼105°E) has been identified with a Late Cretaceous spreading system between chron 34 (∼83.5 Ma) and 31 (∼71 Ma) (Tikku & Cande 1999).

For the early Indian–Antarctic spreading history different scenarios have been proposed. Previous work on the conjugate Indian and Antarctic margins (Ramana *et al.* 2001a) is based on scarce data with wide spacing and random orientations of ship tracks, Magnetic

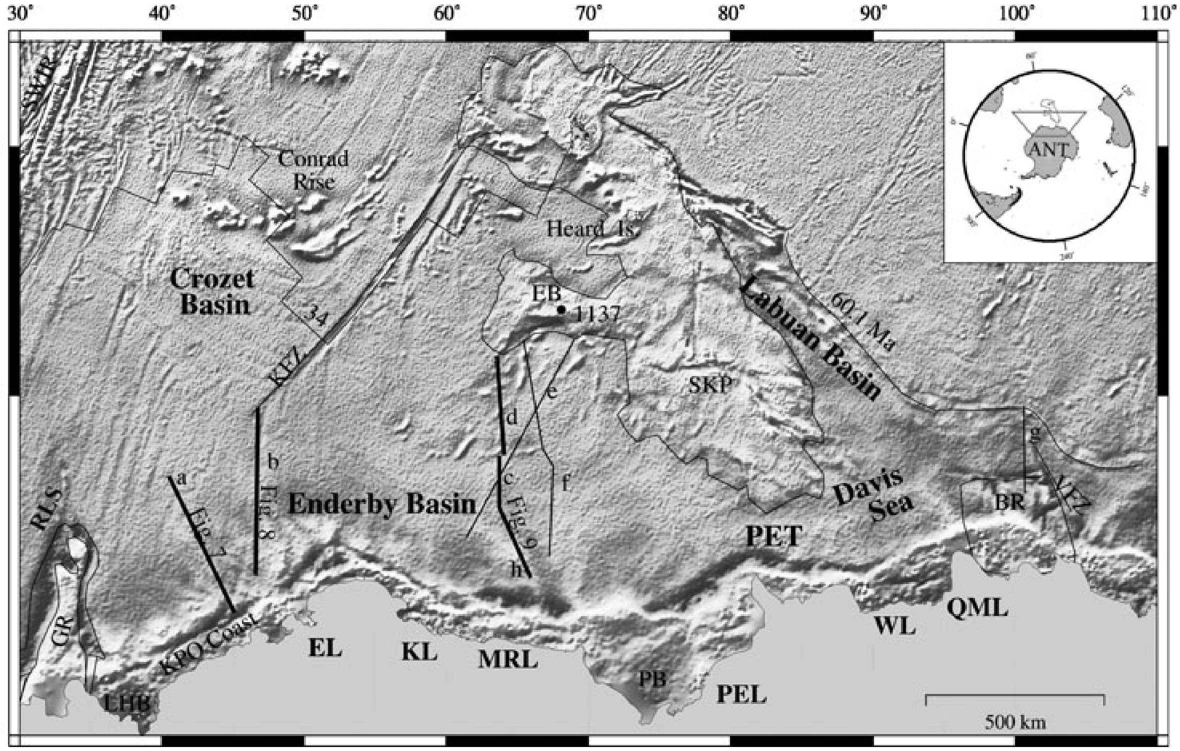

Figure 1. The satellite derived marine free-air gravity field along the East Antarctic margin, between Gunnerus Ridge and the Bruce Rise (outlined), illuminated with an azimuth of 330°S (Sandwell & Smith 2005). Inset figure shows the location of our study area. Lines annotated (a–g) correspond to magnetic anomaly profiles in Fig. 4a. Isochron C34 (∼83.5 Ma) from Müller *et al.* (1997) indicates the northern boundary of Cretaceous Quiet Zone crust along the SWIR, and lineament labelled 60.1 Ma indicates approximate timing and zone of breakup between Broken Ridge and Kerguelen Plateau (outlined). Abbreviations are as follows: 1137, ODP Leg 183-site 1137; BR, Bruce Rise; EB, Elan Bank; EL, Enderby Land; GR, Gunnerus Ridge; KFZ, Kerguelen Fracture Zone; KL, Kemp Land; KPO Coast, Kron Prinz Olav Kyst; MRL, Mac.Robertson Land; PB, Prydz Bay; PEL, Princess Elizabeth Land; PET, Princess Elizabeth Trough; LHB, Lutzow-Holm Bay; QML, Queen Mary Land, RLS, Riiser-Larsen Land, SKP, Southern Kerguelen Plateau; SWIR, Southwest Indian Ridge; VFZ, Vincennes Fracture Zone and WL, Willem II Land.

anomaly identification off the conjugate Indian margin (e.g. Ramana *et al.* 1994a,b; Banergee *et al.* 1995) has been inhibited by masking and interference from thick Bengal Fan sediments (>5 km) and igneous structures such as the 85°E and 90°E ridges (Curray 1991). This has resulted in two, equivocal models with the identification of magnetic anomalies M11 (∼133 Ma) to M0 (∼120 Ma) by Ramana *et al.* (1994a,b) and a model by Banergee *et al.* (1995) that proposes that the seafloor created in the Bay of Bengal is younger than 116 Ma within a portion of a long normal polarity interval, the Cretaceous Normal Superchron (CNS) (∼118–83.5 Ma). More recently, Desa *et al*. (2006) have identified magnetic anomalies M11 (134 Ma) to M0 (120 Ma) south of Sri Lanka as a conjugate to the West Enderby oceanic floor basin (Ramana *et al.* 2001b).

There have been some experimental three-component magnetometer surveys conducted in the Enderby Basin region by Japanese Antarctic Research Expeditions (JARE) during survey work on the icebreaker Shirase (e.g. Nogi *et al.* 1996). These data are thought to be helpful in detecting trends and lineations in areas with little data coverage. Nogi *et al.* (1991, 1996) have presented a model for a Mesozoic vector sequence from M9 (∼130 Ma) with a general NE–SW trend in the central Enderby Basin.

The uncertainty in magnetic anomaly identification in the Bay of Bengal and sparse data coverage off the Enderby Basin, Princess Elizabeth Trough, and in the Davis Sea has led to two alternative models for Cretaceous plate reconstructions for the Indian Ocean. One hypothesis is that the age of early ocean crust formed during breakup is largely Cretaceous Normal Superchron (CNS) (∼118–83.5 Ma) crust with little or no Mesozoic sequence (e.g. Royer & Coffin 1992; Müller *et al.* 2000). An alternative hypothesis suggests that older Mesozoic crust (∼120+ Ma) does exist and that spreading was roughly contemporaneous with the well-documented M-sequence (M10–M0) off the Perth Abyssal Plain (Müller *et al.* 1993; Powell *et al.* 1988).

During the mid-Cretaceous period there was also increasing magmatic activity in the region, related to the development of the Kergulen Large Igneous Province (LIP) from about 120 to 110 Ma (Frey *et al.* 2000; Nicolaysen *et al.* 2001). It is likely that the history of early seafloor spreading is complicated by ridge–hotspot interaction during the growth of the Kerguelen Plume. The Elan Bank microcontinent was most probably isolated from the Indian continent by one or several ridge jumps associated with the Kerguelen Plume (Müller *et al.* 2001; Gaina *et al.* 2003).

Our recent compilation of shiptrack potential field data in the Enderby Basin, Princess Elizabeth Trough and Davis Sea offers an opportunity to address questions about the early breakup and spreading history between India and Antarctica. We show the improved survey coverage of potential field and seismic data from both new and existing sources and present an interpretation of a Mesozoic seafloor spreading sequence based on marine magnetic anomaly data. We examine the tectono-magmatic variation along-axis of the zone of breakup, and spreading segmentation off the Antarctic margin, using potential field data and seismic refraction and reflection data. We also show supporting evidence for an abandoned ‘fossil’ spreading centre, in the Enderby Basin, west of Kerguelen Plateau and discuss the development of the early spreading system in the context of mantle–lithosphere interaction with the growth and influence of the Kerguelen Plume.

2 PHYSIOGRAPHIC SETTING

The region off the East Antarctic margin once conjugate to Southern Greater India (e.g., Powell *et al.* 1988; Harley & Henson 1990; Ramana *et al.* 1994a) extends over a large part of the Enderby Basin, the Princess Elizabeth Trough and the Davis Sea Basin (Fig. 1). The Enderby Basin is a wide area located between the Kerguelen Plateau and the Antarctic margin, bounded to the northwest by the Kerguelen Fracture Zone and by the Crozet Basin. It includes the area conjugate to the eastern Indian continental margin, and extends across Enderby Land, Kemp Land, Mac Robertson Land and Princess Elizabeth Land. The Princess Elizabeth Trough, to the east of the Enderby Basin, is a narrow zone that separates the southern extension of the Kerguelen Plateau from the Antarctic margin. The Davis Sea, further to the east, is the area where Southern Greater India and Australia were once joined to Antarctica, in the region offshore Wilhelm II Land and Queen Mary Land. The Russian and Japanese Antarctic programs named the western Enderby Basin the Cosmonaut Sea and the eastern Enderby Basin the Co-operation Sea (e.g. Joshima *et al.* 2001).

Our study area extends from approximately 30°E to 105°E between the Gunnerus Ridge and Bruce Rise (Fig. 1). Gunnerus Ridge is a narrow, submarine ridge that lies perpendicular to the Antarctic margin; it consists mostly of continental crust with an igneous structure at its northern tip (Bergh 1987; Roeser *et al.* 1996). To the east of Gunnerus Ridge, Sri Lanka has been correlated with the onshore Pre-Cambrian terranes at Lutzow-Holm Bay (e.g. Fedorov *et al.* 1982; Yoshida *et al.* 1992; Buchel 1994, Shiraishi *et al.* 1994; Kriegsman 1995; Yoshida *et al.* 1996; Lawver *et al.* 1998). In between Gunnerus Ridge and Bruce Rise lies the Prydz Bay-Lambert Graben structure; geophysical and geological correlation suggests that it is part of a pre-existing N–S Palaeozoic intracontinental rift, conjugate with the Mahanadi Graben in eastern India (Fedorov *et al.* 1982; Stagg 1985; Lisker *et al.* 2003). The graben has undergone an active tectonic history with repeated intrusive and extrusive igneous activity, and inferred uplift around Miocene to Recent times (Wellman & Tingey 1982). The Bruce Rise is a crystalline continental basement plateau that has been correlated to the Naturaliste Plateau off the southwest Australian margin (Murakami *et al.* 2000; Stagg *et al.* 2004). The eastern flank of the Bruce Rise is adjacent to the Vincennes Fracture Zone, which is conjugate to the Perth Fracture Zone and related to Australian–Antarctic spreading along the Southeast Indian Ridge (Tikku & Cande 1999).

The physiographic setting of the region is dominated by igneous structures related to the Kerguelen Large Igneous Province (LIP), as well as large areas of relatively thick sediment. It is possible that a large area of seafloor and potentially a number of continental fragments are now overprinted by voluminous igneous activity associated with the Kerguelen Plume, which began forming at the Southern Kerguelen Plateau at about 118 ± 2 Ma (Frey *et al.* 2000; Nicolaysen *et al.* 2001). ODP Legs 119 (sites 738–746), 120 (sites 747–751) and 183 (sites 1135–1142) were drilled with the object of investigating the Kerguelen LIP. In particular, the recovery of core material including garnet-biotite gneiss on Elan Bank at ODP 183 (site 1137) indicated a continental origin (Nicolaysen *et al.* 2001). Several wide-angle and reflection seismic profiles acquired by French and Australian surveys describe the crustal properties and structure of the microcontinent (Charvis & Operto 1999; Gladczenko & Coffin 2001; Borissova *et al.* 2003) and the basins directly off the Kerguelen Plateau, including the Labuan Basin (Borissova *et al.* 2002).

The marine free-air gravity field anomalies derived from satellite altimetry (Smith & Sandwell 1997) do not resolve many shorter wavelength free-air gravity features off the Antarctic margin due to areas of thick ice and/or sediment cover (e.g. McAdoo & Laxon 1997; Rotstein *et al.* 2001). Sediment thickness is commonly 1–2 km in the abyssal plain and increases up to 6–8 km in areas toward the continental margin (Mizukoshi *et al.* 1986; Murakami *et al.* 2000; Stagg *et al.* 2004). As a consequence, the identification of basement fabric, such as the gravimetric expressions of fracture zones (e.g. Goslin & Schlich 1982) is difficult. Further to the north of the study area a series of relatively short NNE-trending fracture zone lineations can be observed and the might indicate the development of oceanic crust between East Antarctica and India/Sri Lanka younger than 120 Myr. The parallel series of NNE fracture zones located north of Gunnerus Ridge also extend into the Riiser-Larsen Sea; they are more likely to belong to the Africa–Antarctica (AFR–ANT) spreading system described by Nogi *et al.* (1996) and Jokat *et al.* (2003). To the north they are truncated by NNW fracture zones in the Crozet Basin (Fig. 1), which includes CNS crust, south of the C34 isochron (∼83.5 Ma).

3 DATA

In addition to existing open-file geophysical data from the National Geophysical Data Center (NGDC 1998) and older French surveys (R/V *Marion Dufresne* surveys 1, 5, 11, 38 and 47) (e.g. Goslin & Schlich 1982), there are several more recent offshore survey programs that have vastly improved shiptrack data coverage in the Enderby Basin region. These surveys include: Japan National Oil Company (JNOC) TH83, TH84, TH85, TH98 and TH99 (e.g. Mizukoshi *et al.* 1986; Murakami *et al.* 2000; Joshima *et al.* 2001), Soviet Antarctic Expeditions/Russian Antarctic Expeditions surveys 31–47 (e.g. Gandyukin *et al.* 2002; Golynsky *et al.* 2002) and Geoscience Australia surveys 228 and 229 (e.g. Stagg & Colwell 2003). There has been a unique opportunity through various data agreements to compile virtually all the available shiptrack magnetic anomaly, free-air gravity and bathymetry data in the Enderby Basin, Princess Elizabeth Trough and Davis Sea, between approximately 30°E and 110°E. This has provided the most complete magnetic anomaly data set for the region to date; Fig. 2 provides a summary of the coverage of both the older and new data sets. The marine free-air gravity field derived from satellite altimetry (Sandwell & Smith 2005) and GEBCO bathymetry (GEBCO 2004) were used in this study, in conjunction with magnetic anomaly data to identify the age of seafloor spreading and tectonic structure of the Enderby Basin. Additional access to some seismic reflection profiles (Australian and Japanese survey data) and sonobuoy velocity–depth data (Japanese, Russian and Australian surveys) has allowed us to build upon our interpretation of potential field data. A detailed description of this integrated seismic data set is included in Stagg *et al.* (2004).

3.1 Magnetic anomalies

The newly collated magnetic anomaly data (Fig. 2) were reformatted and assembled into one database. Magnetic data collected at these latitudes are often more affected by electromagnetic disturbances

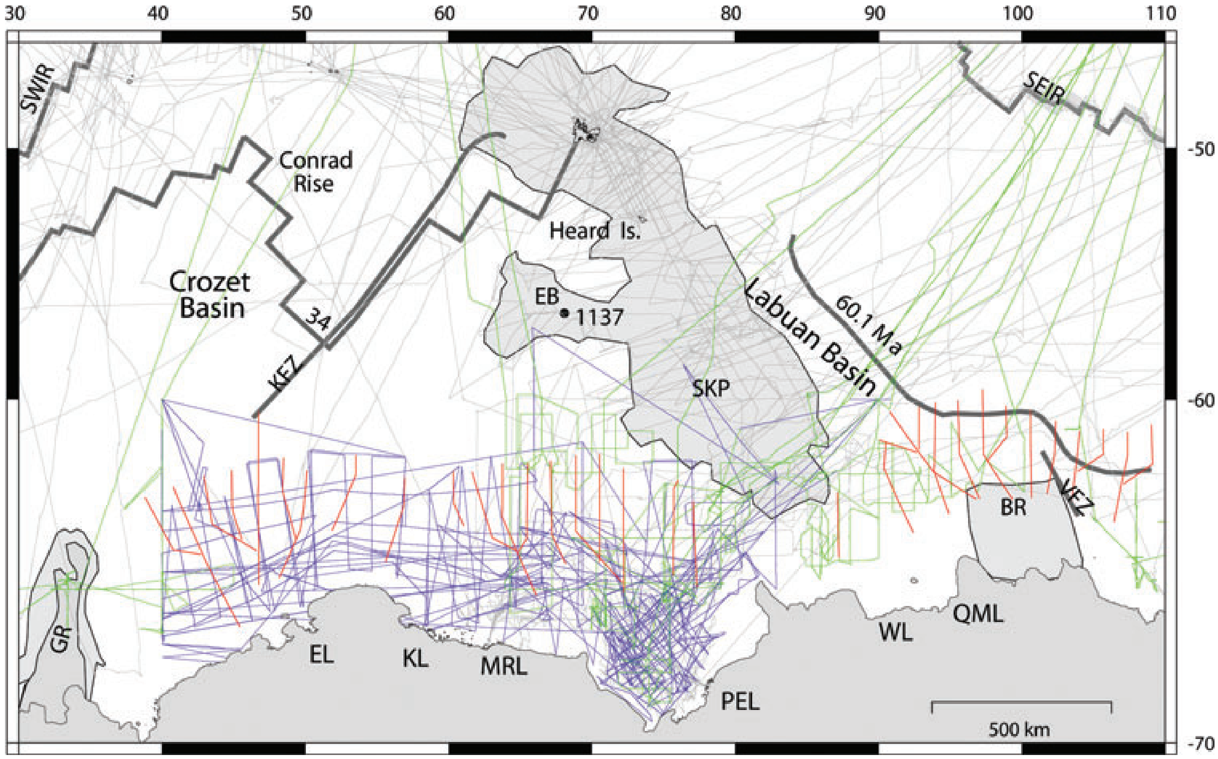

Figure 2. Trackline coverage of magnetic anomaly data in the Enderby Basin region. Tracklines in pale grey represent older data sets from NGDC (1998) and R/V *Marion Dufresne*. The colored tracklines represent recent data compilation from: Russian data (blue); Japanese data (green); and new Australian data (red). Annotations and abbreviations as in Fig. 1, SEIR, Southeast Indian Ridge; the Kerguelen Plateau is outlined and shaded grey.

(e.g. Kleimenova *et al.* 2003), in addition to wind and instrument noise. The magnetic anomaly data were filtered with a high-pass filter of 300 km and smoothed with a low-pass filter of 10 km. The filtering process cleaned up the magnetic anomaly data sufficiently to apply a gridding technique, following the method of the North American Magnetic Anomaly Group (NAMAG 2002). The filtered data were gridded with the GMT (Wessel & Smith 1991) spline gridding tool ‘surface’ and a near neighbour weighting algorithm based on an elliptical allocated search area, with its long axis oriented along the strike of the magnetic lineations, and an 0.5° grid interval. The gridding method is dependent on line spacing, sample density and interpolation errors, so data gaps greater than a 0.25 degrees cell radius were excluded in order to reduce sampling function bias, using the GMT ‘near-neighbour’ routine. The improved coverage of magnetic anomaly data has allowed gridding techniques to augment the identification of lineations, trends and sequences. The colour-shaded magnetic anomaly grid highlights trends that are not seen as easily with a conventional along-track anomaly plot, and allows interpretation of seafloor fabric character (Fig. 3).

From along-track and gridded magnetic anomaly data, a series of ENE trending magnetic anomalies can be observed off the Antarctic margin, between the Gunnerus Ridge and Bruce Rise, in particular east of 55° longitude. In the Enderby Basin to the west of the Kerguelen Plateau and to the south of Elan Bank (central Enderby basin), a symmetric magnetic anomaly sequence from M9o (∼130.2 Ma) to M2o (∼124.1 Ma) has been observed on either side of a central axis, as suggested by Gaina *et al.* (2003). The character and distance of the magnetic anomaly profiles between both M2 lineations suggests the existence of a palaeospreading axis, which trends ENE. Spreading is likely to have slowed prior to extinction and the width of the central axis anomaly indicates it ceased after M2, possibly around M0 time (∼120 Ma). A new active ridge north of Elan Bank replaced the extinct ridge due to the proximity of the Kerguelen Plume (Gaina *et al.* 2003), the timing of this jump roughly coincides with the first recorded surface expression of the plume at the Southern Kerguelen Plateau dated at about 118 ± 2 Ma (e.g. Coffin *et al.* 2002). North of Elan Bank the magnetic anomaly pattern is very chaotic resembling CNS crust (∼118–83.5 Ma). This also implies most of the crust subsequently accreted to the Indian Plate is younger than M2, and is largely Cretaceous Quiet Zone crust. This would explain the difficulty in discerning a magnetic anomaly sequence in the Bay of Bengal (Curray 1991; Ramana *et al.* 1994a,b; *cf.* Banergee *et al.* 1995)

Fig. 4 presents a series of north–south oriented magnetic anomaly stacked-profiles from the central, western and eastern Enderby basin and the correlation with the interpreted seafloor spreading sequence. The Mesozoic global geomagnetic reversal timescale of Gradstein *et al.* (1994) was used to create a synthetic seafloor spreading model and assign ages to oceanic crust. Model 1 (Fig. 4a) suggests that the seafloor spreading in the entire Enderby basin became extinct some time between M2o and M0 as a result of a northward ridge jump due to the Kerguelan plume. A prominent positive magnetic anomaly can be well distinguished on each side of the extinct ridge and we have interpreted it as chron M4. The youngest magnetic anomaly in this model is interpreted to be chron M2, is characterized by lower amplitude magnetic anomaly peaks separated by a trough and is visible on most of the profiles. The oldest magnetic anomaly (chron M9) is characterised by a high amplitude, narrow peak northward of the MCA anomaly (well defined on profiles b, e and g, southern flank), but it is more difficult to be interpreted on the northern flank due to the proximity of the Kergulen plateau and later volcanic intrusions [see profiles and e and c (northern flank)]. Half-spreading

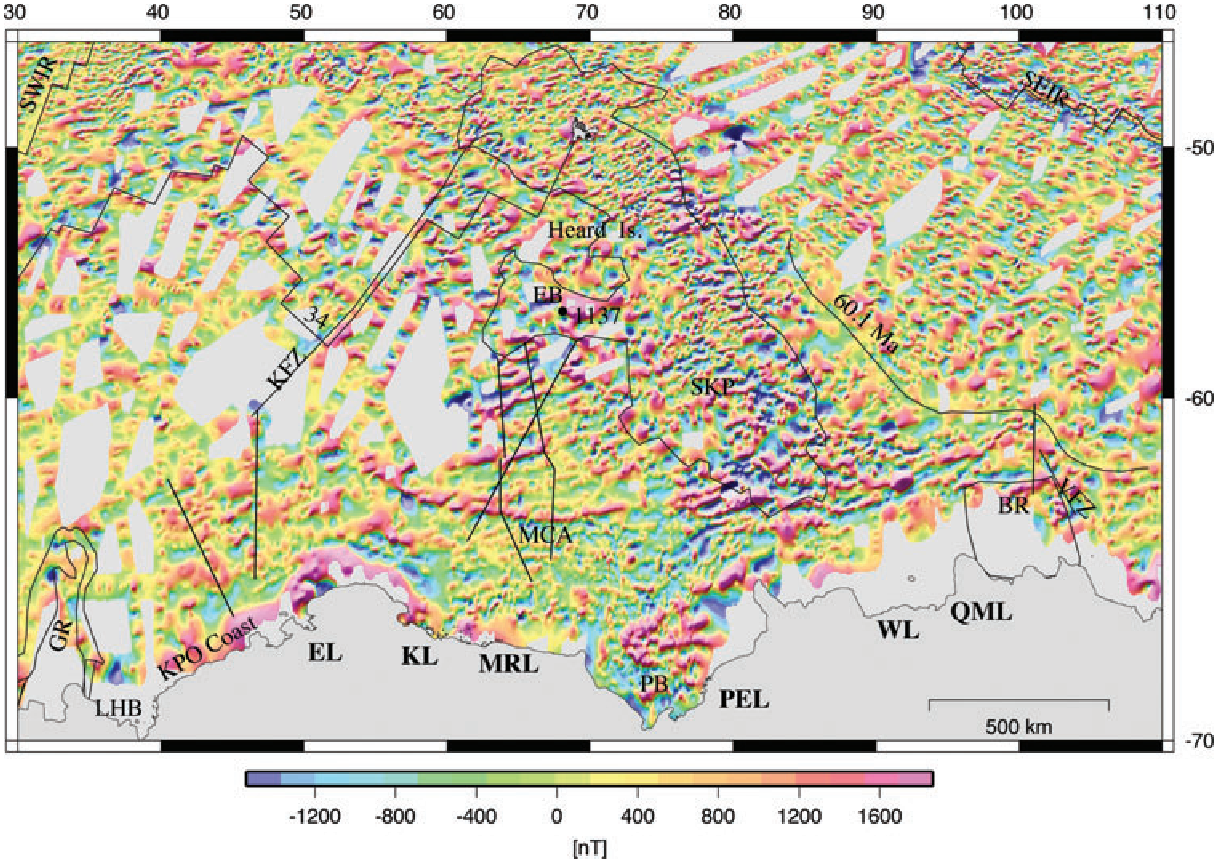

Figure 3. Gridded magnetic anomaly data after the new data compilation. Grey areas indicate gaps in data coverage greater than 0.25° spacing. Annotations and abbreviations as in Fig. 1; MCA, Mac.Robertson Coast Anomaly Lineation.

rates are calculated from the central Enderby Basin, based on a complete, symmetric M-sequence. These rates also show the slowing of spreading prior to extinction of the early active ridge from 39 mm yr^{-1} (M9y–M4o) to 22 mm yr^{-1} (M4o-M2o) and they compare well to the half-rates for the Perth Basin 36 mm yr^{-1} (M10-M5) to 32 mm yr^{-1} (M5-M2), and 24 mm yr^{-1} (M2-M0) (Mihut 1997; Mihut & Müller 1998). Model 2 (Fig. 4b) analyses the magnetic data in the western Enderby basin in concert with the conjugate south of Sri Lanka magnetic anomalies. Half seafloor spreading rates from 39 to 30 mm yr^{-1} have been modelled for the western Enderby Basin and from 36 to 22 mm yr^{-1} for south of Sri Lanka region.

In this interpretation chrons M0, M2 and M4 are well defined on two profiles south of Sri Lanka (Fig 4b, profiles jr116 and c2706), but less visible on profiles SE of Sri Lanka. The magnetic anomaly profiles from the conjugate Enderby basin show two high amplitude, narrow peaks (identified as M2 and M0, profiles agso229(1) and c1704(4) on Fig. 4b) south of a zone of chaotic and more subdued magnetic anomalies (identified as CNS), but chron M4 is less well defined [profiles agso229(1) and c1704(3) on Fig. 4b].

The filtered and projected along track magnetic anomaly data were plotted at a scale to show a more detailed sequence interpretation for the spreading segments in the western and eastern Enderby Basin (Fig. 5). The extent of the identified Mesozoic magnetic anomaly sequence and extinct ridge axis varies across the margin due to data coverage. The magnetic anomaly data coverage in the western Enderby Basin (~30°E–65°E) remains limited north of 62°S. In the Princess Elizabeth Trough and Davis Sea (between ~75°E and 105°E) there is a relatively narrow area of crust between the Antarctic continental margin and the Kerguelen Plateau. In this area data further to the north are obscured by the Kerguelen Plateau igneous structure and to the east there is a truncation of Mesozoic crust by the sharp transition to the E–W trending anomalies of the fast-spreading Southeast Indian Ridge between Australia and Antarctica (Fig. 3).

Since the magnetic anomalies in the western Enderby Basin have lower amplitude and are more difficult to correlate with the central and eastern Enderby Basin, we also evaluate an alternative model for the evolution of this area (Figs 4b and 5b). N–S oriented fracture zones identified from the free-air gravity anomaly appear to isolate a V-shaped zone of oceanic crust in the central Enderby Basin, also the MCA magnetic anomaly has a northern counterpart that outlines the southern end of the N–S fracture zones (Fig. 5b). This configuration resembles a ridge propagator very similar to the ones described NW of Australia by Robb *et al.* (2005) and Mihut & Müller (1998), suggesting that the northward ridge jump occurred only in the central and eastern Enderby basin (which were closer to the Kerguelan plume), whereas seafloor spreading in the western Enderby basin continued after 124 Ma. A sequence of magnetic anomalies and fracture zones identified south of Sri Lanka (Desa *et al.* 2006) may represent the conjugate of the seafloor spreading system NE of Gunerus Ridge. However, based on the overall geometry of seafloor spreading in the Enderby basin, the location of the boundary between continental and oceanic crust and regional plate kinematics, we interpret a M9o to M0 sequence in both western Enderby basin and S of Sri Lanka. This model requires an

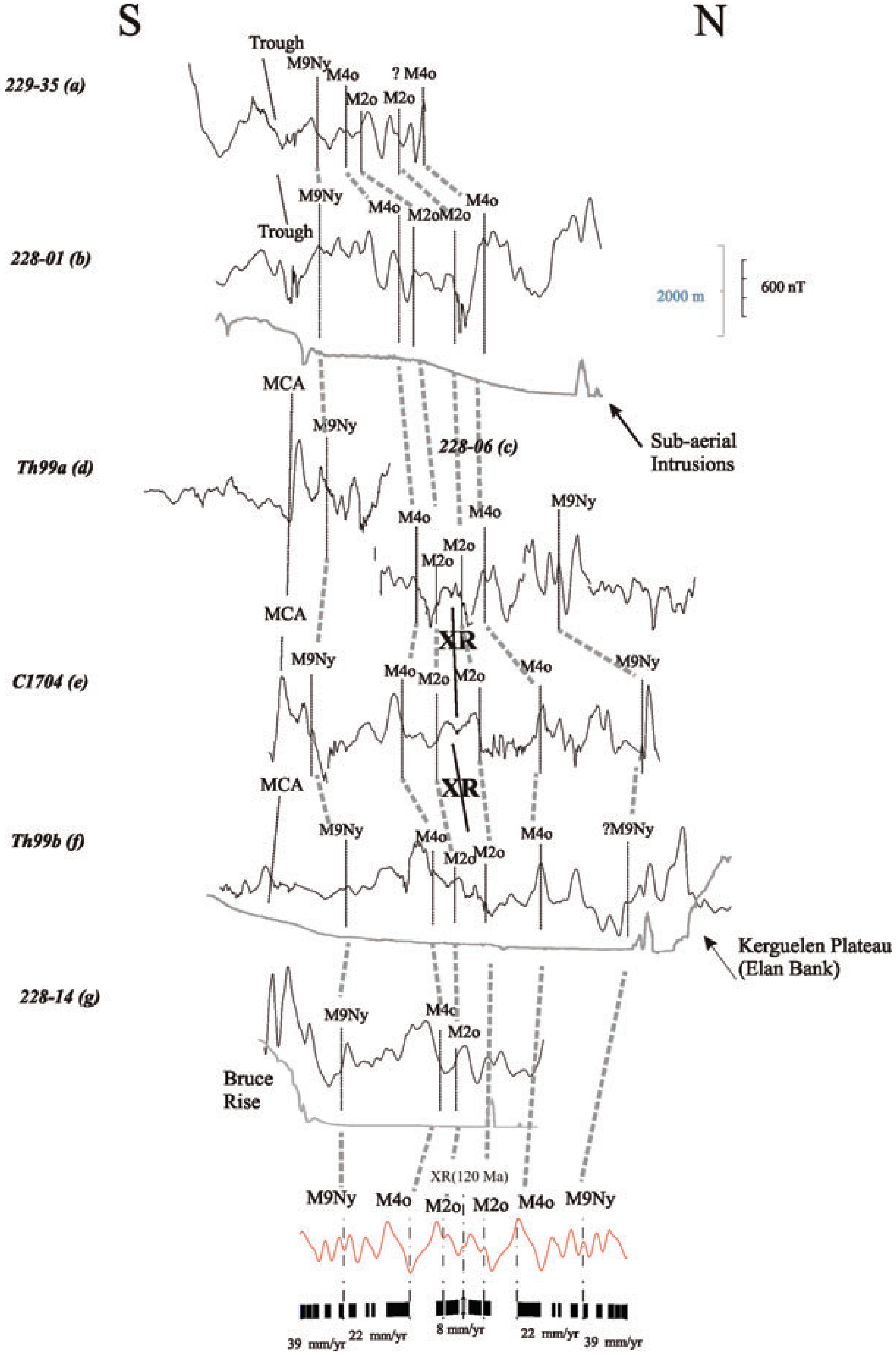

Figure 4. Selected, representative magnetic anomaly profiles along the East Antarctic margin, between the Gunnerus Ridge and the Bruce Rise. Location of profiles (a–g) indicated in Figs. 1 and 5. Corresponding shiptrack bathymetric profiles also displayed where there are bathymetric highs, including Bruce Rise and Elan Bank; also the bathymetric trough feature in the Kron Prinz Olav (KPO) coast segment. MCA, Mac.Robertson Coast Anomaly; XR, extinct ridge. A synthetic profile is included based on the geomagnetic timescale of Gradstein *et al.* (1994), using a depth to the top of the magnetized layer of 5.5 km and a seafloor deepening calculated by Parson & Sclater's (1977) half-space cooling formula. The thickness of magnetized layer is 0.3 km. The body is assumed to have been magnetized at 55 °S latitude.

asymmetric seafloor spreading and possibly a plate boundary between the western and central Enderby Basin. A drawback of this model is that although the magnetic anomalies south of Sri Lanka could represent Mesozoic crust older than CNS, the amplitude and shape of magnetic anomalies in the western Enderby basin north of interpreted M0 (Fig. 5b) do not have a clear CNS signature. Until additional information will better constrain the age of the crust in the western Enderby Basin, our preferred model is model 1 that

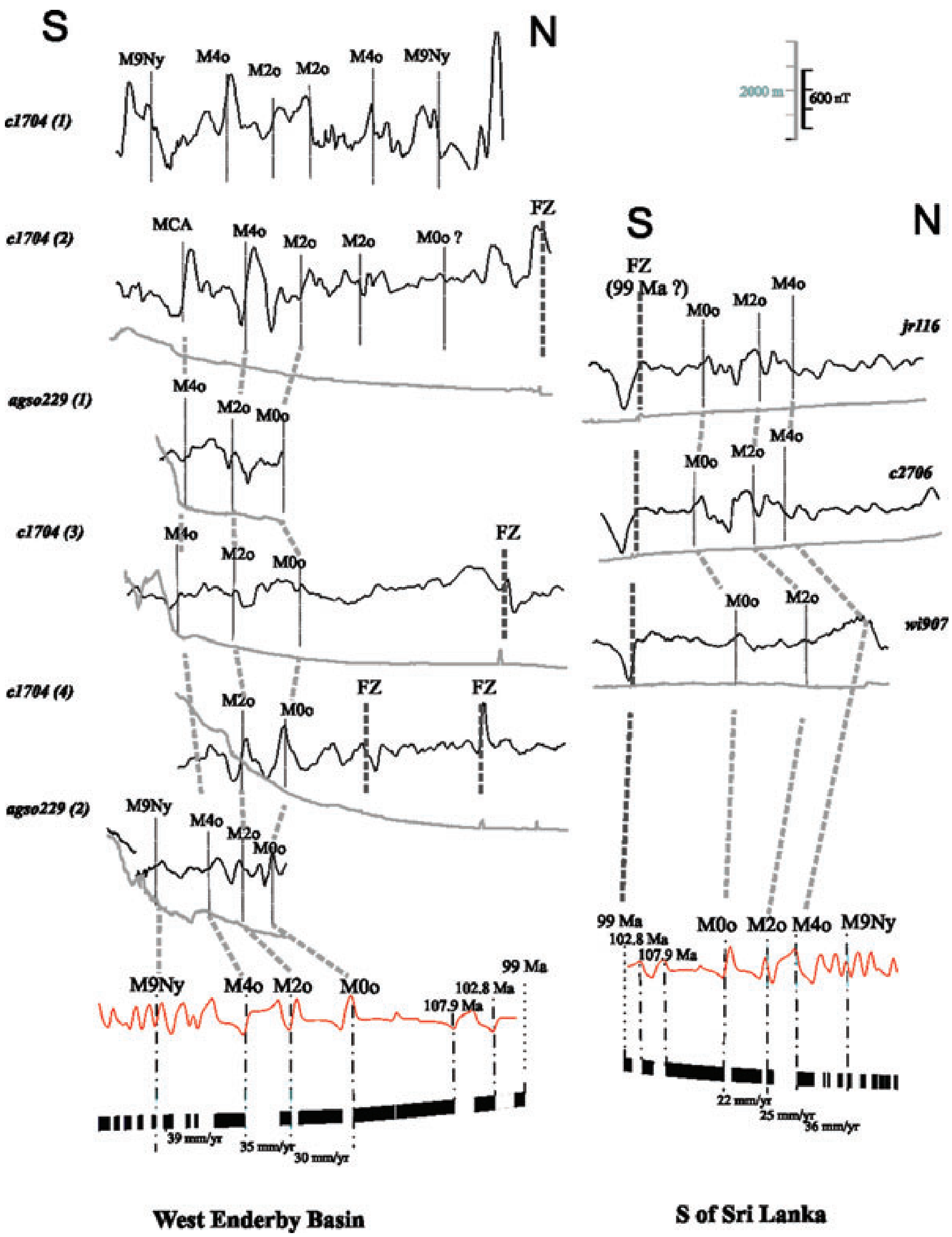

Figure 4. (*Continued.*)

postulates a northward propagation of seafloor spreading ridge around 120 Ma for the entire Enderby basin.

4 BREAKUP AND EARLY SPREADING SEGMENTATION

We have used other available geological and geophysical data in order to develop a more integrated tectonic model for breakup and early seafloor spreading. While we can identify a seafloor spreading sequence with a general ENE trend along the Antarctic margin (Figs 4 and 5), from west to east we can observe an increase in spreading rate and tectono-magmatic variations across the spreading segments from the potential field data (e.g. Figs 3 and 5), seismic refraction velocity–depth data (e.g. Fig. 6) and seismic reflection profiles (e.g. Figs 7–9). Tectono-magmatic variations are expected along a margin of this size, not just from the magmatic processes that create seafloor but also the conditions of breakup along different terranes and pre-existing structures, as well as the kinematics of opening, ridge propagation and plate separation. The variation in spreading segment character observed along the margin suggests that breakup segmentation is related to a combination of these factors as well as mantle–lithosphere interaction from the developing Kerguelen Plume.

Here, we present a description of observed large-scale variation for area over 3000 km long off the Antarctic margin between the Gunnerus Ridge and Bruce Rise. These differences are described below, broadly divided into areas of longitude for the segments from west to east between: (1) the Kron Prinz Olav Coast (KPO) and the Enderby Land Promontory (∼30°E–60°E), (2) the Mac.Robertson Coast and Prydz Bay (∼60°E–80°E) and (3) the Princess Elizabeth Trough (PET) and Davis Sea Basin (∼80°E–105°E).

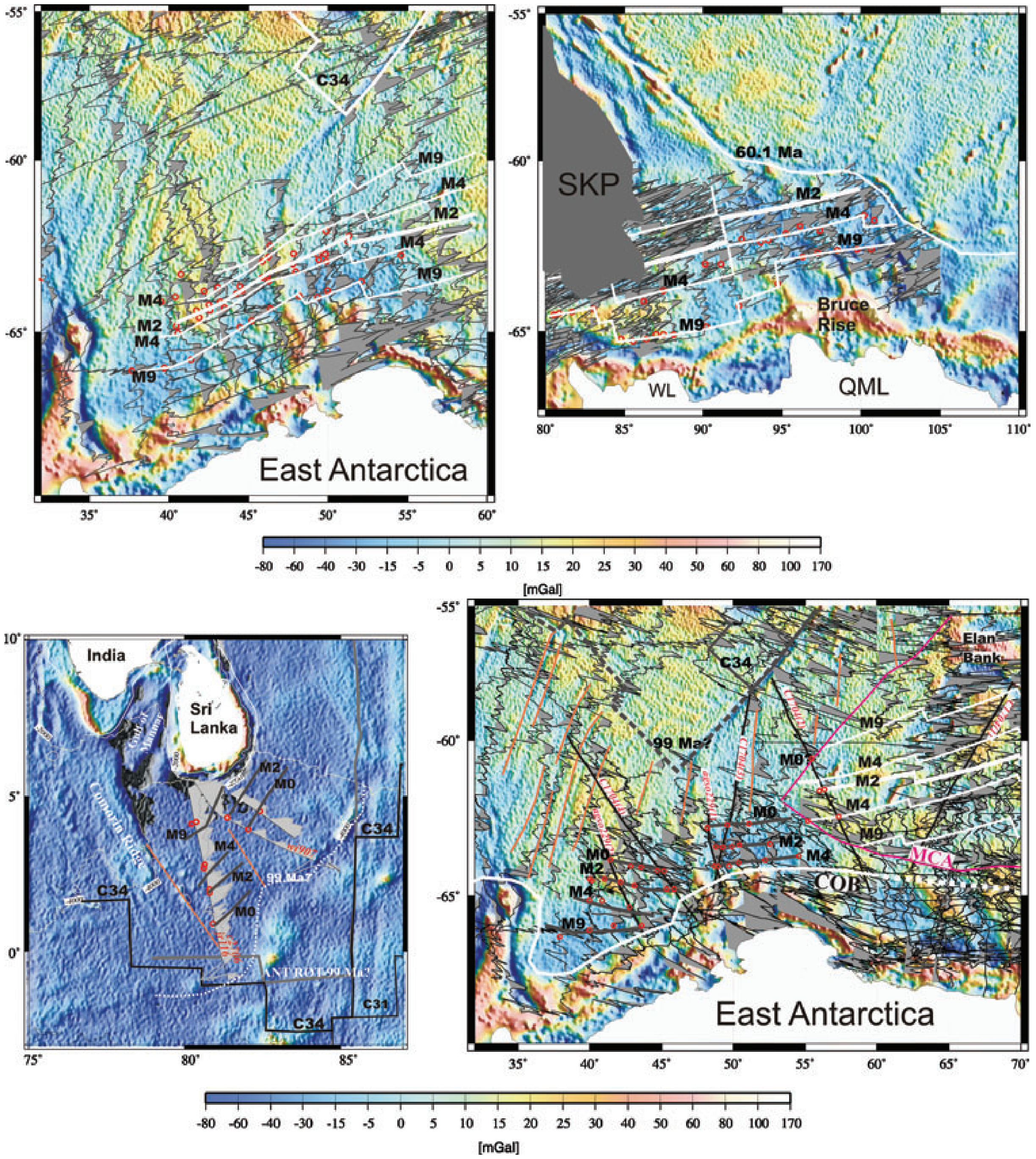

Figure 5. Free air gravity anomaly (Sandwell & Smith 2005) and magnetic anomaly data in the (a) western and eastern Enderby basin (model 1) and b) western Enderby basin and S of Sri Lanka (model 2). Magnetic anomaly identifications are shown as red circles and the interpreted isochrones as white and grey lines. Interpreted fracture zones are drawn in orange. A V-shaped lineation identified in the gravity anomaly is interpreted as a change in the spreading direction (probably at 99 Ma) both NW of the Enderby basin and south of Sri Lanka (b). The MCA anomaly (south of the central Enderby basin) and a northern counterpart identified in the gravity anomaly are shown in magenta and are interpreted as the trace of a propagator (b, model 2). Tracklines are in black with cruise names attached. For a more detailed interpretation of the central Enderby basin magnetic anomalies see Gaina *et al.* 2003. Annotations as in Fig. 1.

4.1 Zone of breakup variations

Along-axis margin segmentation is identified based on observations of the variable nature of the identified boundary between continental and oceanic crust. In the western Enderby basin, along the Kron Prinz Olav coast segment, the COB has no continuous boundary signal or distinct seismic character. Near the end of the continental slope a magnetic trough is observed inboard of the southern limit of identified seafloor spreading anomalies (Fig. 5). The magnetic trough roughly corresponds to a trough/low in shiptrack free-air gravity and bathymetry data. It also lies above a basement 'hollow' feature in the seismic reflection profiles, near the end of the

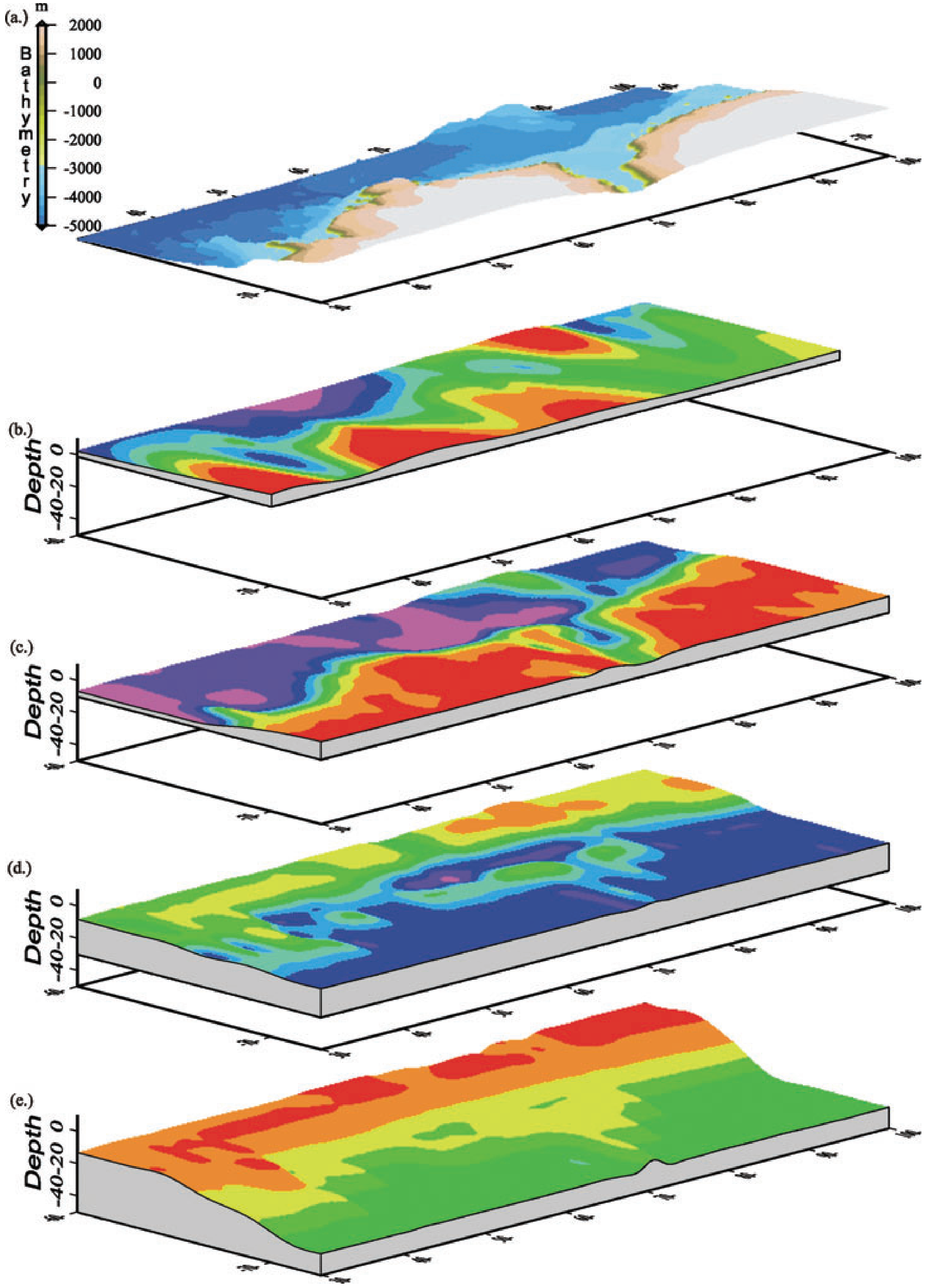

Figure 6. Selected grids for the Enderby Land margin viewed from 220° azimuth. (a) Bathymetry [Etopo5]; (b) Gridded sonobouy velocity data at the 6km/s isovel. Seismic crustal character and depth estimated from *Crust 2.0* (Masters *et al.* 2000), depth to (c) to top of basement; (d) to base of upper crust and (e) to base of lower crust (depth with respect to sea level). The grid cell is 2 minutes. Basement and upper and lower crust highs are in warm colours, basement and upper and lower crust lows are in colder colours. Note variations from west to east, including the Prydz Bay and Lambert Graben structure between approximately 70°E and 80°E.

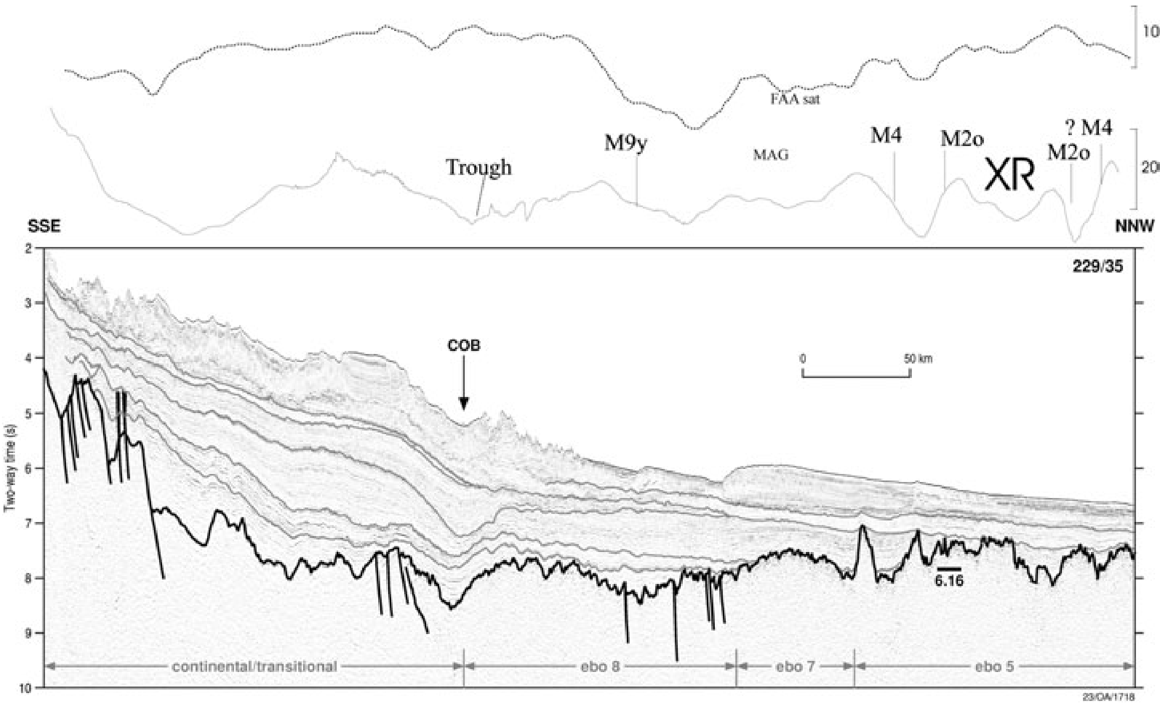

Figure 7. Seismic reflection profile 229/35 reproduced from Stagg *et al.* (2004) to show oceanic basement morphology. Location of profile (a) indicated on Fig. 1. Free-air satellite derived gravity anomaly and magnetic anomalies are juxtaposed here to show the correlation with the interpreted extinct ridge (XR) and seafloor spreading sequence.

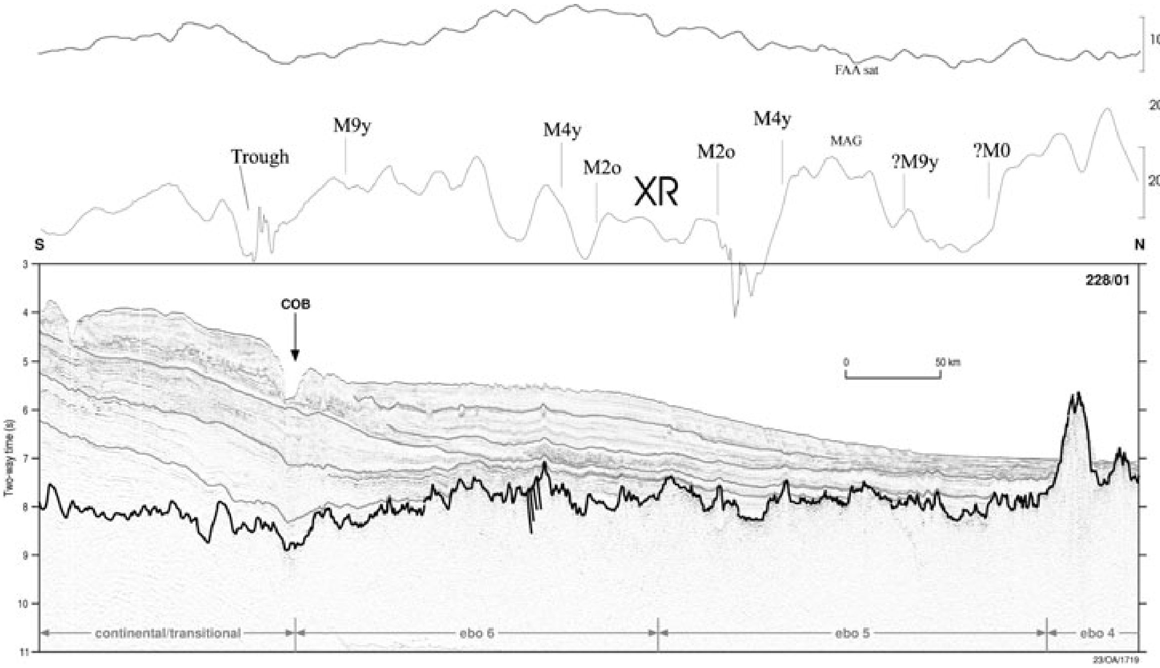

Figure 8. Seismic reflection profile 228/01 reproduced from Stagg *et al.* (2004) to show oceanic basement morphology. Location of profile (b) indicated on Fig. 1. Free-air satellite derived free-air gravity anomaly and magnetic anomalies are juxtaposed here to show the correlation with the interpreted extinct ridge (XR) and seafloor spreading sequence. As this profile extends across a maximum segment length, from the south (the continental rise) to the north (to the Kerguelen Fracture Zone), presumably it represents the full spreading segment sequence. Here we speculate on the location of M0 and CNS crust based on this assumption.

continental sediment wedge which is underlain by the seafloor multiple. This feature can be observed on several profiles and corresponds to the interpreted boundary between continental and oceanic crust from Stagg *et al.* (2004) (Figs 7 and 8).

In the central Enderby Basin between approximately 60°E–73°E, the southern limit of identified seafloor spreading anomalies is marked by a prominent series of high-amplitude magnetic anomalies (over 500 nT), which lie to the north of a magnetic subdued

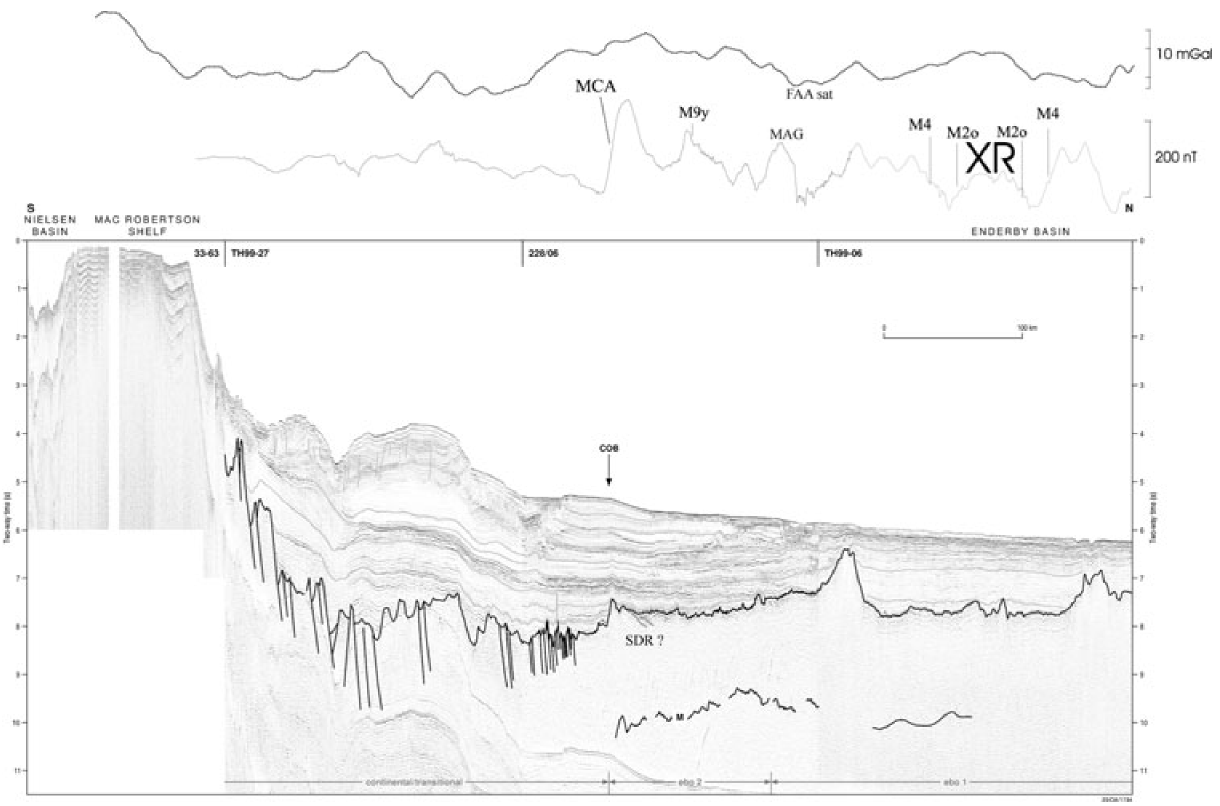

Figure 9. Composite seismic reflection profiles 33–63, TH99–27, 228/06 and TH99–06 re-produced from Stagg *et al.* (2004) to show oceanic basement morphology and internal crustal character. Location of profiles indicated on Fig. 1. Free-air satellite derived gravity anomaly and magnetic anomalies are juxtaposed here to show the correlation with the interpreted extinct ridge (XR) and seafloor spreading sequence. Note the northward step in basement corresponding to the Mac.Robertson Coast Anomaly (MCA).

zone (Fig. 3). The high amplitude anomalies form a large arcuate lineation that trends approximately E–W, oblique to the ENE orientation of the seafloor spreading lineations (Fig. 3). This anomaly, named the Mac Robertson Coast Anomaly (or MCA), coincides with a landwards step-down in basement that is observed in the regional Japanese and Australian seismic data (e.g. Fig. 8). It is interpreted to mark a major crustal boundary, probably the boundary between continental and oceanic crust (COB) or a propagator.

In the Princess Elizabeth Trough (PET) the boundary between continental and oceanic crust appears to be closer to the continental margin shelfbreak. Mizukoshi *et al.* (1986) speculate from their observations of seismic reflection data (e.g. their Line SMG7, ~79°E) that a steep rise in acoustic basement and corresponding negative free-air anomaly may indicate the COB, with the seaward boundary of crystalline continental basement marked by a large fault. Off the Bruce Rise there is the narrowest gap between the interpreted continent–ocean boundary off the crystalline basement plateau and the M9o chron, the southern limit of the interpreted seafloor spreading sequence (Fig. 5).

4.2 Spreading segment variation

Spreading segment variation that occurs within/along the same ridge system have been attributed to differences in mantle temperature (e.g. along the present day Southwest Indian Ridge (SWIR), Sauter *et al.* 2004). Variation between the spreading segment centres and ends is also to be expected, especially at slow spreading ridges (Patriat & Segoufin 1988).

Oceanic basement morphology is also reflected in variation of magnetic anomaly character. Here we present characteristics of spreading segments of the Enderby Basin that are most likely related to magma supply, spreading rate and proximity to the developing Kerguelen Plume thermal anomaly.

The magnetic anomalies in the KPO segment trend roughly ENE but have more variable shape than those to the east of 60°E (Fig. 3). In general, thick sediments and water depth contribute to the variation in magnetic anomaly character as do differences in basement topography (Srivastava & Roest 1995). There are relatively thick sediment sequences and drifts observed in the KPO segment, as well as the observed rough oceanic basement topography with quite varied relief (Figs 7 and 8). The variable character of magnetic anomalies is likely due to varying depth to source with a combination of the effects of sediment thickness and pronounced basement roughness and relief. However, this pattern might be also due to a dense distribution of offset fracture zones that cannot be clearly mapped due to the N–S oriented ship tracks and thick sediment cover.

In contrast, the region situated between the Enderby Land Promontory and the Princess Elizabeth Trough includes the widest area of extended continental crust off Prydz Bay and the widest zone of Mesozoic seafloor crust between the margin and the Elan Bank microcontinent (Fig. 1). This area exhibits relatively high-amplitude magnetic anomaly lineations. It has been suggested that the increase in amplitude of magnetic anomalies towards the Aegir Ridge in the Norwegian-Greenland Sea could reflect an increase in thickness of the magnetized layer as the ridge became closer to the Iceland hot spot (Jung & Vogt 1997). The Mac Robertson Coast and Prydz Bay segment of the margin was closer to the Kerguelen Plume at the time of formation and this is reflected in the type of oceanic crust observed. Charvis & Operto (1999) indicate areas of crustal thickness up to 10–13 km from OBS data transects near the southwest of Elan Bank.

In the central Enderby Basin, Princess Elizabeth Trough and Davis Sea area deep-crustal Australian seismic profiles image different types of oceanic basement morphology and crustal structure (e.g. Stagg *et al.* 2004; Figs 7–9). Seismic profiles in the western Enderby Basin off the Kron Prinz Olav (KPO) coast segment exhibit a pronounced oceanic basement roughness with a crustal structure characterized by chaotic internal reflectors. The seismic profiles intersect several fracture zones at an oblique angle, which might explain part of the basement roughness. In comparison, to the east of this segment, in the central Enderby Basin and Davis Sea, oceanic basement topography observed in Australian and Japanese seismic reflection profiles is generally low relief without any pronounced roughness. Profiles in the eastern segments often exhibit high amplitude reflectors characterizing internal crustal features and strong Moho. In particular, the seismic character of many profiles in the MCA sector and the Davis Sea, close to the Kerguelen Plateau area, exhibit an internal reflector pattern that looks similar to an irregular series of diagonal crosses; they are comparable to the type of crust observed in the Cuvier Abyssal Plain off Western Australia (Colwell *et al.* 1994).

The PET spreading segment lies off a narrower area of continental shelf. The area also comprises of a reasonably complex zone of oceanic crust as it was formerly adjacent to the Cretaceous triple junction between Antarctica, Greater India and Australia and an area of crust left over from the division of the Broken Ridge and Kerguelen Plateau by the SEIR at about 61 Ma. The Broken Ridge-Kerguelen Plateau experienced some shear motion prior to their separation, and some minor deformation that may be related to this event is imaged in seismic reflection lines as a deformation zone with more chaotic or disturbed sediments. Surprisingly, there is no evidence from seismic reflection profiles for the rough oceanic basement topography that is observed at the conjugate Diamantina Zone, which extends from Broken Ridge to the Great Australian Bight.

Stagg *et al.* (2004) suggest the division of at least two crustal provinces between the western and eastern Enderby Basin segments based on the observed variation of oceanic crustal morphology and seismic structure. This variation is reflected in differences of the velocity–depth structure of oceanic crust between the western and eastern spreading segments in the Enderby Basin (Fig. 6). The area between the eastern and western Enderby Basin provinces appears to be a highly segmented offset zone probably because it is the location of maximum curvature in the spreading system, north of the Enderby Land promontory. Margin segmentation is also likely influenced by major continental crustal discontinuities. Recent onshore/continental seismic lithospheric thickness studies (Morelli & Danesi 2004) indicate a discontinuity at about 60°E and at 90°E.

There is also a cluster of seamounts populating the region near Elan Bank (Fig. 1) as opposed to other segments where there are only a few scattered seamounts observed closer to the Antarctic continental margin. This seamount cluster appears to be at an oblique orientation to the early spreading direction, and follows rather a similar trend to the younger Kerguelen Fracture Zone. The proximity to the Kerguelen Plateau leads to the suggestion that the timing and nature of their emplacement are related to the Kerguelen plume. Volcanic elongated ridges are thought to be formed mainly by extrusive volcanism in a melt-channel. For instance, the Musician seamounts chain related to the Hawaiian Plume are oblique to the hotspot trace (Kopp *et al.* 2003), where hotspot–ridge interaction leads to asthenospheric channeling from the plume to the nearby spreading centre over a maximum distance of 400 km. Often the amount of excess hotspot volcanism is related to the spreading rate, where intermediate-slow ridges can focus the plume to the ridge but not be enough to entrain all the excess melt (Jellinek *et al.* 2003). The extra magmatic activity is not unexpected in this region where ridge–hotspot interaction isolated the Elan Bank microcontinent.

4.3 A 'Fossil' spreading centre

Several lines of evidence suggest the existence of an extinct 'fossil' spreading centre in the central Enderby Basin. From the magnetic data, we could not clearly identify chron M0, but the two conjugate M2o magnetic anomalies observed in the central Enderby basin are separated by a trough that signifies seafloor spreading continued until the next normal polarity (approximately 120 Ma). A synthetic model that matches the observed pattern and distances between conjugate M2o chrons indicates that seafloor spreading rate dropped to around 8 mm yr^{-1} (half spreading rate) before becoming extinct (Fig. 4a).

In addition to the observed magnetic anomaly pattern, there are corresponding changes in free-air gravity and oceanic basement morphology around the central axis of the abandoned spreading centre, which suggests that there is a remnant crustal feature in this zone. Sedimentary sequences are up to 2 km thick and therefore too thick to reveal a bathymetric expression of the extinct ridge feature. A basement feature that might be interpreted as an abandoned spreading centre is visible in the seismic data from the central Enderby basin (Fig. 9), but the rough basement structure of the western Enderby basin makes difficult to recognize any possible fossil ridge (Figs 7 and 8). The location of the extinct ridge identified by magnetic anomalies is characterized by a step in the satellite derived free air gravity anomaly in the western Enderby basin (Figs 7 and 8), and a peak in the gravity anomaly in the central Enderby basin (Fig. 9).

The differences in the gravity anomaly signature along the extinct ridge might indicate differences in the last stage of seafloor spreading within the Enderby basin. Many studies suggest that before active accretion ceases, there is a protracted period whereby the spreading rate slows (e.g. Osler & Louden 1995; Grevemeyer *et al.* 1996; Livermore *et al.* 2000). The change in crustal thickness or magma composition as spreading slows is often reflected by a change in the gravity anomaly at extinct ridges. Some observations and models suggest the spreading rate and crustal variation in this zone results in more anomalous features like a deeper ridge or thinner crust, and possibly even the remains of a palaeomagma chamber structure. Evidence from seismic refraction studies at the extinct spreading centre in the Labrador Sea indicates thinner crust and lower crustal velocities (e.g. Osler & Louden 1995). These features associated with the Labrador extinct ridge correspond to a gravity low. The gravity high observed at the inferred extinct spreading centre in the Enderby Basin is one of the few extinct ridges characterized by a positive gravity anomaly**.** This positive gravity anomaly may be related to a crustal structure generated by a relatively higher than normal spreading rate prior to extinction, as explained below.

The largest variation of oceanic crustal thickness as a function of spreading rate is observed when spreading rates are less than 15–10 mm yr^{-1} (e.g. Reid & Jackson 1981; White 1992; Bown & White 1995). Most half-spreading rates calculated at other extinct ridges indicate a slowing to quite low rates prior to extinction of the active ridge; for example, the Labrador system slowed from 10 to

3 mm yr^{-1} (Srivastava & Keen 1995) and the Aegir system slowed to between 8 and 5 mm yr^{-1} (Jung & Vogt 1997). In the Enderby Basin, the western and eastern segments slowed from 22 mm yr^{-1} (29 mm yr^{-1}, respectively) to $<$10 mm yr^{-1}. The rates may have been higher in the Enderby Basin prior to extinction as most of the early motion during early seafloor spreading was taken up by the Indian continent moving away from a relatively stationary Antarctica; and in the late Cretaceous there were plate boundary forces from the Tethys subduction system to the north. This may partly account for the relatively high spreading rates in the last stages of spreading before the ridge jump. Also to consider is the spatial relationship linked to melting depth and spreading rate with ridge morphology. Huang & Solomon (1998) use earthquake observations to suggest the maximum centroid depth at an active ridge crest increases from 2 to 3 km at faster spreading rates (20–23 mm yr^{-1} half-rate) up to 5–6 km at slower spreading rates (2.5–5 mm yr^{-1} half-rate). In the case of the extinct spreading centre in the Enderby Basin, the spreading rates would not be slow enough to result in lower than expected crustal thickness, the palaeoridge also would not be as deep as those formed at lower spreading rates, and hence not be linked to a gravity low as at many other extinct ridges.

If spreading in the Enderby Basin ceased between chron M2 and M0, then this would be consistent with the active ridge relocating northward, towards the Kerguelen Plume. There seems to be a general case for noticeable changes in spreading rate in other basins in the Indian Ocean around this time, which suggests a general re-organization before the onset of the CNS. There is an observed decrease in spreading rate between M4 and M0 in the Weddell Sea (Kovacs *et al.* 2002). Slowing spreading rates and subsequent ridge jumps have been observed around M2-M0 in Natal Valley and Somali Basin off Africa (Marks & Tikku 2001), and around 118 Ma in the Perth Basin off Western Australia (Mihut & Müller 1998). Also in the Enderby Basin the rotation poles change from SW from M9-M2 to ENE for M2-M1 and this is perhaps indicative of a tectonic event.

Extinct spreading centres have been identified in several areas affected by mantle plumes or by the re-organization of plate boundaries. The slowing of spreading and extinction of the palaeospreading ridge, prior to a ridge jump has been observed at the Aegir Ridge in the Norwegian Sea (Jung & Vogt 1997), the Labrador Sea extinct ridge (Srivastava & Roest 1999), and the Phoenix Ridge in the Drake Passage (Livermore *et al.* 2000). An example similar to the Enderby Basin scenario is that associated with the Iceland Plume, where ridge–hotspot interaction stranded the Jan Mayen microcontinent with a major ridge jump up to 400 km from the Aegir Ridge to the Kolbeinsey Ridge (Grevemeyer *et al.* 1996). However, the closest example to a propagating ridge of Enderby Basin length (almost 2500 km) is probably the Mascarene Basin ridge that jumped north of the Seychelles microcontinent. Schlich (1982) and Masson (1984) proposed that the Deccan-Reunion hotspot initiated seafloor spreading between India and the Seychelles along the northern Carlsberg Ridge at Chron 27 (61 Ma), after spreading in the Mascarene Basin became extinct. More recently, Bernard *et al.* (2005) proposed a gradual ridge jump from the Mascarene Basin toward the hotspot, separating the Seychelles microcontinent. Due to the timing of the interpreted ridge jump in the Enderby Basin that coincides with CNS (and therefore the lack of magnetic reversals), we could not identify the detailed expression of the new seafloor spreading ridge north of the Elan Bank. The proposed ridge jump and microcontinent formation model are more fully explained in Gaina *et al.* (2003). The plate kinematic model showing how ridge–hotpot interaction at the Kerguelen Plume caused at least one ridge jump, transferring most early ocean crust in this area to the Antarctic plate and isolating the Elan Bank microcontinent from the Indian continent is presented in Fig. 10.

5 DISCUSSION

The new data and observations presented here help to offer insights into the evolution of the East Antarctic margin and its relationship with the Kerguelan plume during breakup and early seafloor spreading. In the case of the spreading system between the Enderby Basin and Perth Basin, the incipient development of the Kerguelen Plume is a likely factor during breakup and early spreading with varying degrees of lithosphere–mantle and ridge–hotspot interaction. Here, we discuss the tectonic and magmatic along-axis margin segmentation in the context of the growth and development of the Kerguelen Plume.

5.1 Kerguelen Plume activity

There is evidence of a mantle thermal anomaly related to the Kerguelen Plume prior to its formation of the Southern Kerguelen Plateau (SKP) at about 118 ± 2 Ma. Coffin *et al.* (2002) provide a comprehensive overview and summary of isotopic data characterizing the timing, distribution and magma output from the Kerguelen Plume. The first identifiable surface expression related to a Kerguelen mantle source (Bunbury Basalts, Western Australia (WA) around 132 Ma, Coffin *et al.* 2002) coincides with the time just prior to the onset of seafloor spreading in the Perth and Enderby Basins (∼130 Ma). There has also been minor Neocomian (137–127 Ma) magmatic activity observed in the Perth Basin (Gorter & Deighton 2002). In general however, there is a lack of voluminous rift-related magmatism or seaward dipping reflectors (SDR's) in the Enderby Basin and Perth Basin. This seems to suggest that early breakup occurred with minor magmatic activity, about 15 Myr prior to the first surface expression at the SKP ∼118 Ma and the Rajmahal Traps, India (∼117 Ma).

Recent work on estimates of palaeolatitude for the Kerguelen Plume (Antretter *et al.* 2002; O'Neill *et al.* 2003) suggest a southward movement of the plume to its present day position, which is now thought to be active underneath the Heard Island volcano. The maximum diameter of a plume's near-surface influence is estimated to be 1500–2000 km (White & McKenzie 1989). By placing the early plume at around 35°S with a plume diameter up to 2000 km, then this could encompass part of the Enderby and Perth margins, and possibly part of the Cuvier margin. As White & McKenzie (1989) suggest, volcanism at least for the southern WA margin could be caused by a 'broad thermal anomaly' from a mantle plume present in the area shortly before breakup, particularly as the long period of rifting and basin subsidence prior to breakup had little associated volcanism. While presumably part of the WA and Antarctic margin was underlain by the Kerguelen Plume not all margin segments are truly volcanic. The initial output of the plume was not hot or voluminous enough despite the thinned passive margin lithosphere and decompression melting for wide-scale SDR's, but plume-related magmatism appears to manifest at the surface in several separate locations suggesting a series of aerial and subaerial alkaline basaltic events (Coffin *et al.* 2002).

Ideas about plume–lithosphere interaction include a variety of possibilities about plume conduit size and shape with their growth and development over a lifecycle. Coffin *et al.* (2002) suggests a plume may not behave with only a plume-head configuration but a

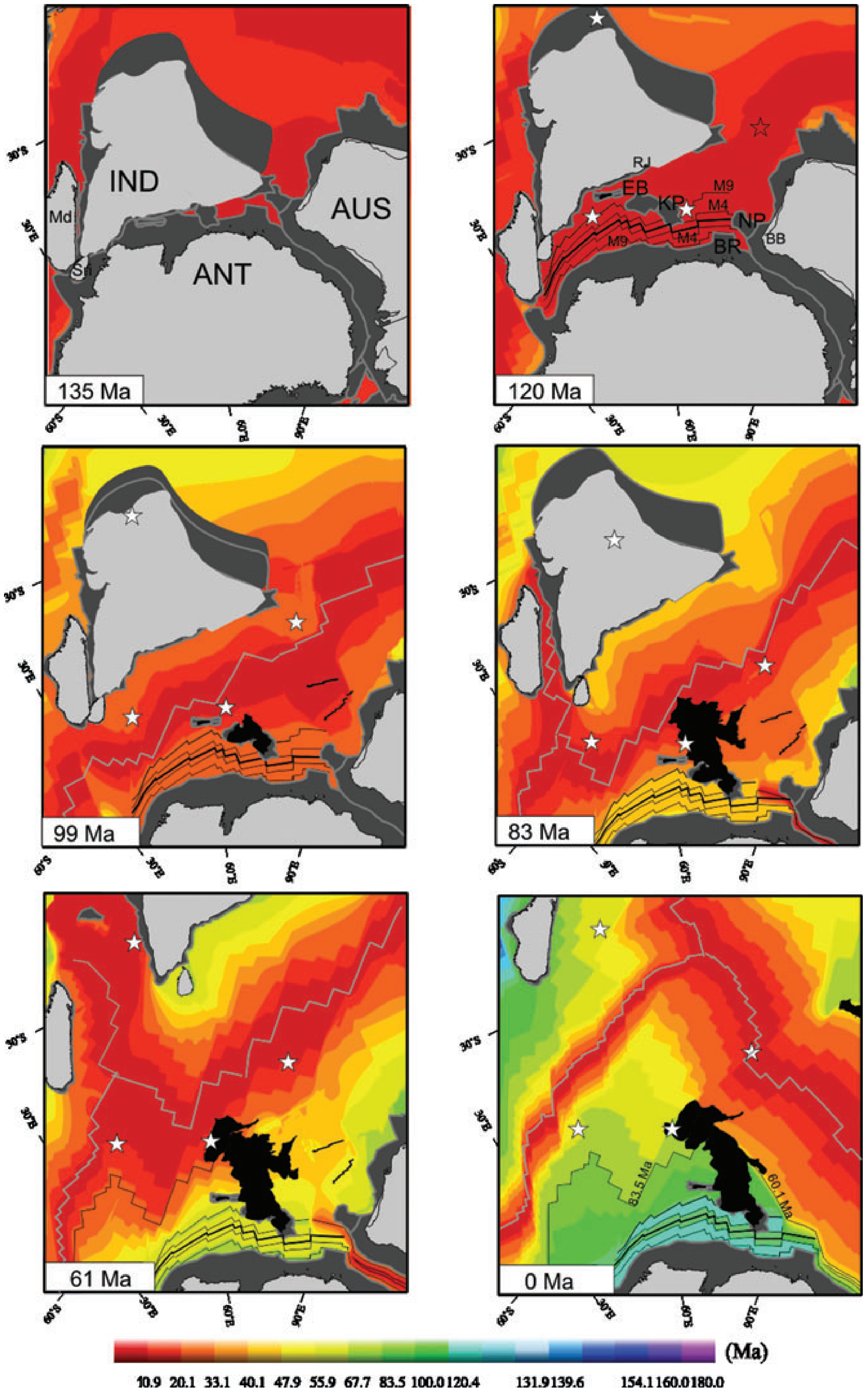

Figure 10. Plate reconstruction models for early breakup between India (IND) and Antarctica (ANT) based on new seafloor spreading isochrons between the Gunnerus Ridge and Bruce Rise, and the model in Gaina *et al.* (2003) including the subsequent ridge jump to north of Elan Bank (EB) and growth of the Kerguelen Plume (KP). Poles of rotation are from Gaina *et al.* (2003). Stars indicate hotspots (from left to right: Deccan-Seychelles, Marion, Kerguelen, St. Paul-Amsterdam) in Indian Ocean reference frame based on O'Neill *et al.*. (2003). BB, Bunbury Basalts; BR, Bruce Rise; NP, Naturaliste Plateau; Md, Madagascar; RJ, Rajmahal Traps and Sri, Sri Lanka.

series of smaller conduits may also originate from the core–mantle boundary so it can exist both at on-ridge or off-ridge locations. For example, the Ontong-Java LIP is interpreted as bi-modal (Berrovicci & Mahoney 1994). If the Bunbury Basalts are dated at about 132 Ma and Rajmahal Traps are about 117 Ma, and they are isotopically linked to a Kerguelen Plume mantle source, then this implies that igneous activity pre-dates Kerguelen LIP formation. In comparison, dating of Reunion hotspot magmatism indicates it was active before the voluminous production at the Deccan Traps, and appears far to the northwest of the flood basalt outcrops (Mahoney *et al.* 1995; O'Neill *et al.* 2003). In particular, Ar–Ar dating yields ages around 73–72 Ma, while the bulk of Deccan flood basalts are around 66–65 Ma. Indeed these models suggest that accumulation of the Reunion plume-head under the (slow moving) continental lithosphere did not just cause the huge surface expression of the Deccan traps, but had an earlier surface expression as intrusions 300–400 km north from the main Deccan body.

5.2 Plume driven breakup?

The segmentation observed along the east Antarctic margin between Gunnerus Ridge and Bruce Rise raises the question of the nature of its formation and the magmatic conditions in the zone of breakup and early seafloor spreading. It has been suggested that a primary cause of along-margin segmentation is due to the variation in the amount of underplated igneous crust and the strength of the lithosphere (e.g. Callot *et al.* 2002). Work in the present-day Afar rift (Ebinger & Casey 2001) suggests along axis magmatic segmentation, related to strain distribution (faulting and dyking) and a Palaeogene mantle plume (asthenosphere temperature). Callot *et al.* (2002) emphasize the important role of small-scale intrusions of mantle material in breakup from their observations and analogue models for the North Atlantic divergent margins. For example, across all spreading segments we observe M9o (130.2 Ma) as the southern limit of identifiable seafloor spreading lineations. The distance between the oldest magnetic anomaly, M9o (130.2 Ma) and the interpreted continent–ocean boundary is between 20 and 50 km in the western, eastern and parts of central Enderby basin (Fig. 5). However, the distance increases between the ENE-trending M9o lineation and the MCA anomaly (interpreted as COB) to around 100km at the eastern end of the MCA segment ∼70°E. Seismic reflection profiles image unequivocal oceanic crust in this zone (e.g. Joshima *et al.* 2001; Stagg *et al.* 2004) and there are no coherent magnetic anomalies or observable lineations past M9o before the COB. The crust between the shelf break and MCA anomaly could be a transitional type crust formed by stretched continental crust that was subsequently modified by magmatic intrusions and/or mantle exhumation/initial oceanic accretion as described by Shilington *et al.*. (2006) along the Newfoundland margin. In this case, the MCA anomaly might reflect a significant amount of melt emplacement, or as in our alternative model, a ridge propagator. The East Coast Magnetic Anomaly (ECMA) off the eastern U.S. continental margin, is characterized by a prominent magnetic anomaly that corresponds to an abrupt change in seismic and magnetic profiles at the edge of a continental transition zone about 70 km wide. The MCA and ECMA are both prominent anomalies whose formation is linked to specific magmatic conditions. At the ECMA Holbrook *et al.* (1994) infer the emplacement of highly mafic material in the continent–ocean transition zone during rifting using seismic constraints on crustal thickness and magnetic susceptibility models of the East Coast and Brunswick magnetic anomalies. The resulting model for the ECMA suggests the amount of igneous material produced would require either a mantle plume, for which there is no evidence, or increased small-scale convection causing increased melt production during rifting. Its origin in relation to a plume or non-plume setting is still debated despite numerous studies (*cf.* White & McKenzie 1989; Talwani & Abreu 2000).

There are some notable differences between the ECMA and MCA anomalies, the ECMA is twice as long and lies adjacent to a narrow passive margin segment, whereas the MCA lies against a wide zone of stretched continental crust off Prydz Bay. However different in their rift and magmatic settings, a significant amount of melt emplacement is implied to form both the ECMA and MCA. Initial melt production at the MCA segment would be reasonably voluminous as early half-spreading rates are estimated to be over 48 mm yr^{-1}. As opposed to the ECMA, seaward dipping reflectors (SDR) are scarce (we have tentatively interpreted SDR south of the central Enderby, Fig. 9). The Antarctic margin of the central Enderby Basin appears to be in a zone of previously thinned lithosphere or transitional crust. As an alternative, the interpreted MCA could be rather compared with the Blake Spur Magnetic Anomaly (BSMA) situated offshore of ECMA in presumably transitional oceanic crust. Many studies (e.g. White & McKenzie 1995; Marks *et al.* 1999) describe how large quantities of decompression melting can be generated during rifting and breakup in either areas of previously stretched lithosphere or zones thinner than the surrounding lithosphere. In the case of the Enderby Basin, both cases apply, where there is the thinned area of crust of the Lambert Graben-Prydz Bay adjacent to the east of an Archaean Craton (the Napier Complex, at the Enderby Land Promontory). There is also the likely factor of the incipient thermal anomaly related to the Kerguelen Plume preferentially developing near the boundary of this zone (e.g. Courtillot *et al.* 1999). In general, LIPs are thought to form preferentially at cratonic boundaries or at a contrast in lithospheric thickness as these act as a 'focusing' mechanism (e.g. Callot *et al.* 2002). One perspective is that the relief of the base of the lithosphere can act like an inverted drainage system that either traps plume material or channels it to zones of higher relief. Nielsen *et al.* (2002) use this idea as a basis to explain observations of nearby volcanic and non-volcanic margin segments, off the Greenland and Labrador margins, near the Icelandic mantle plume; whereby plume material can be channeled into lithospheric thin spots while cratons may act as barriers as melting, cooling and dehydration impedes lateral flow due to increased viscosity and decreased buoyancy. The initial surface expression of Kerguelen Plume at SKP is where presumably there was the weakest area of crust for early breakup magmatism and seafloor spreading to nucleate. The combined effects of thinner than normal crust (more decompression melting) and a developing mantle plume (increasing thermal anomaly) could explain the crustal features observed in this sector.

An additional observation is important for linking our observations to the mode of rifting along the Enderby margin, and that is related to the Precambrian lower crustal rocks (e.g. high grade granulites and igneous charnockites) exposed along the coastline of Enderby Land, Kemp Land and Mac.Robertson Land (Young *et al.* 1997), which constitute the most well exposed area of the East Antarctic Precambrian Shield. The lower crust is exposed in rifts where the strength ratio between the upper and lower crust is large, resulting in 'metamorphic core complex' mode of extension (Wijns *et al.* 2005). This ratio is large when the lower crust is relatively weak compared to the upper crust, as is the case when rifting occurs above anomalously hot mantle. Our observations suggest that it might be possible that this margin formed in a metamorphic core complex (MCC) mode. MCC-mode rifting was likely triggered by the thermal mantle anomaly associated with the formation of the margin-parallel MCA magnetic anomaly, preceding the arrival of the Kerguelen Plume head. Rifting in this mode resulted in exposure of lower crustal rocks at the coastline and a relatively narrow rift, as expressed in the small total width of the conjugate eastern Indian-Enderby margin pair (Fig. 10). The Antarctic continental margin is the wider area of the conjugate rift zone, and this may be a result of more resistant 'lock zones' at the ends of the rift located at the Gunnerus Ridge and Bruce Rise, following the model of Dunbar & Sawyer (1996).

Although a thermal anomaly seems to have influenced this margin after breakup (leading to northward relocation of plate boundary and microcontinent formation), the break-up central Gondwanaland was probably triggered by passive rifting driven by changes in plate driving forces, not active rifting driven by mantle upwelling. Evidence for a major thermal mantle anomaly, such as that associated with the Iceland Plume during breakup of the Norwegian-Greenland Sea, is missing along the Enderby and Perth Basin margins. The most likely driving force for the separation of India from Antarctica and Australia was the gradual subduction of the Neotethys spreading ridge north of India (e.g. Stampfli 2000; Stampfli and Borel 2004), leading to the reduction of ridge push forces and increasing northward-directed slab pull forces to the north of India.

6 CONCLUSIONS

The timing and direction of early seafloor spreading in the area off the Antarctic margin, once conjugate to part of the Southern Greater Indian margin, along the largely unknown region of the Enderby Basin and Davis Sea, has been analysed using a new data compilation. These data provide a basis to examine along-axis breakup and early seafloor spreading across the margin. A considerable amount of tectono-magmatic variation is observed both along and across-axis, related to spreading rate, magma production and distance from the developing Kerguelen Plume. For example, the prominent magnetic anomaly boundary signal and sharp basement step correlated with the Mac.Robertson Coast Anomaly (MCA) is not observed elsewhere in the Enderby Basin, Princess Elizabeth Trough or Davis Sea. In the central Enderby Basin we show evidence for an abandoned 'fossil' spreading centre that might continue to the west of the Kerguelen Plateau, east of Gunnerus Ridge. The estimated timing of its extinction corresponding to the early surface expression of the Kerguelen Plume at the Southern Kergulen Plateau around 120 Ma and the subsequent formation of the Elan Bank microcontinent. Alternatively, the ridge jump occurred only in the central Enderby basin, due to the proximity of the Kerguelan plateau, whereas seafloor spreading continued in the western Enderby basin and conjugate south of Sri Lanka basin.

It is likely a mantle temperature anomaly predated the early surface outpouring/steady state magmatic production of the Kerguelen LIP. However the scarcity of seaward dipping reflectors in the Enderby Basin and Perth Basin suggests that no major mantle plume existed during breakup (∼130 Ma). Our observations suggest that it is possible that the Antarctic-Enderby margin formed in a metamorphic core complex (MCC) mode that was likely triggered by a thermal mantle anomaly in this area, preceding the arrival of the Kerguelen Plume head.

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