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Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potential field data

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SUMMARY

A new plate tectonic model is presented which describes the emplacement of the Mozambique Ridge off southeast Africa as the result of long lasting volcanic activity (140–122 Ma) during the initial opening between Africa and Antarctica. Thus, an oceanic origin for the Mozambique Ridge is proposed. This model is based on a new and systematic high resolution magnetic anomaly data set acquired across the Mozambique Ridge and throughout the Mozambique Basin.

Data from the Mozambique Basin allow the identification of Mesozoic magnetic anomalies from M0r to M26 (124.61–155.3 Ma) with previously unmatched accuracy. Small-scale fracture zones are recognized by offsets of magnetic anomalies in the westernmost part of the basin. Additionally, a bend in the major fracture zones 'F' and 'E' between M17r and M18n (142.84–144.04 Ma) and a recognized sinusoidal change in spreading direction with an amplitude of about 15° indicate that the basin experienced several small scale changes in spreading direction through time. A maximum change in spreading direction to almost 0° at around M11n (135.69 Ma) is followed by a short lived increase in spreading half rate from 23.5 km Ma^{-1} to about 27.5 km Ma^{-1} in the time frame from M10r to M9n (134.30–132.83 Ma). We propose that this is related to the initial opening of the South Atlantic Ocean represented by the onset of seafloor spreading between the Falkland Plateau and Africa in the conjugate Georgia and Natal basins.

Across the Mozambique Ridge, high amplitude magnetic anomalies at major structural boundaries suggest that the different plateaus of the ridge were formed at different times. A simple 2-D gravity and magnetic model for the ridge supports the hypothesis of multiple volcanic episodes which formed the ridge though long lasting volcanic activity between about 140 and 122 Ma. Together with new and verified rotation parameters from the Mozambique Basin and its conjugate, the Riiser-Larsen Sea, Antarctica, a series of plate tectonic reconstructions are presented which demonstrate when and how the different parts of the ridge evolved through time.

Key words: Magnetic anomalies: modelling and interpretation; Marine magnetics and palaeomagnetics; Oceanic plateaus and microcontinents; Large igneous provinces; Africa; Antarctica.

1 INTRODUCTION

The Mozambique Basin and Mozambique Ridge are located between southeast Africa and Madagascar in the southwest Indian Ocean (Figs 1 and 2). The Mozambique Basin was formed as a result of the opening between Africa and Antarctica during the early stages of the Gondwana breakup starting in the Middle to Late Jurassic. At its southern end, it consists of a deep ocean basin with water depths of more than 5000 m. To the north, the basin is bordered by the Mozambique Channel, a narrow gateway between Mozambique and Madagascar. Water depths decline to about 2500 m in this channel. The Mozambique Ridge and the Madagascar Ridge terminate the basin to the west and east. The Mozambique Ridge is formed of several bathymetric plateaus rising up to 3500 m from the ocean floor. To the west, this prominent bathymetric feature is bordered by the southern Natal Valley that formed during the early opening of the South Atlantic Ocean between South America and Africa starting at about 130 Ma. Thus, the Mozambique Ridge separates two Mesozoic ocean basins that formed at two different spreading regimes. In contrast to its outstanding plate tectonic position, little

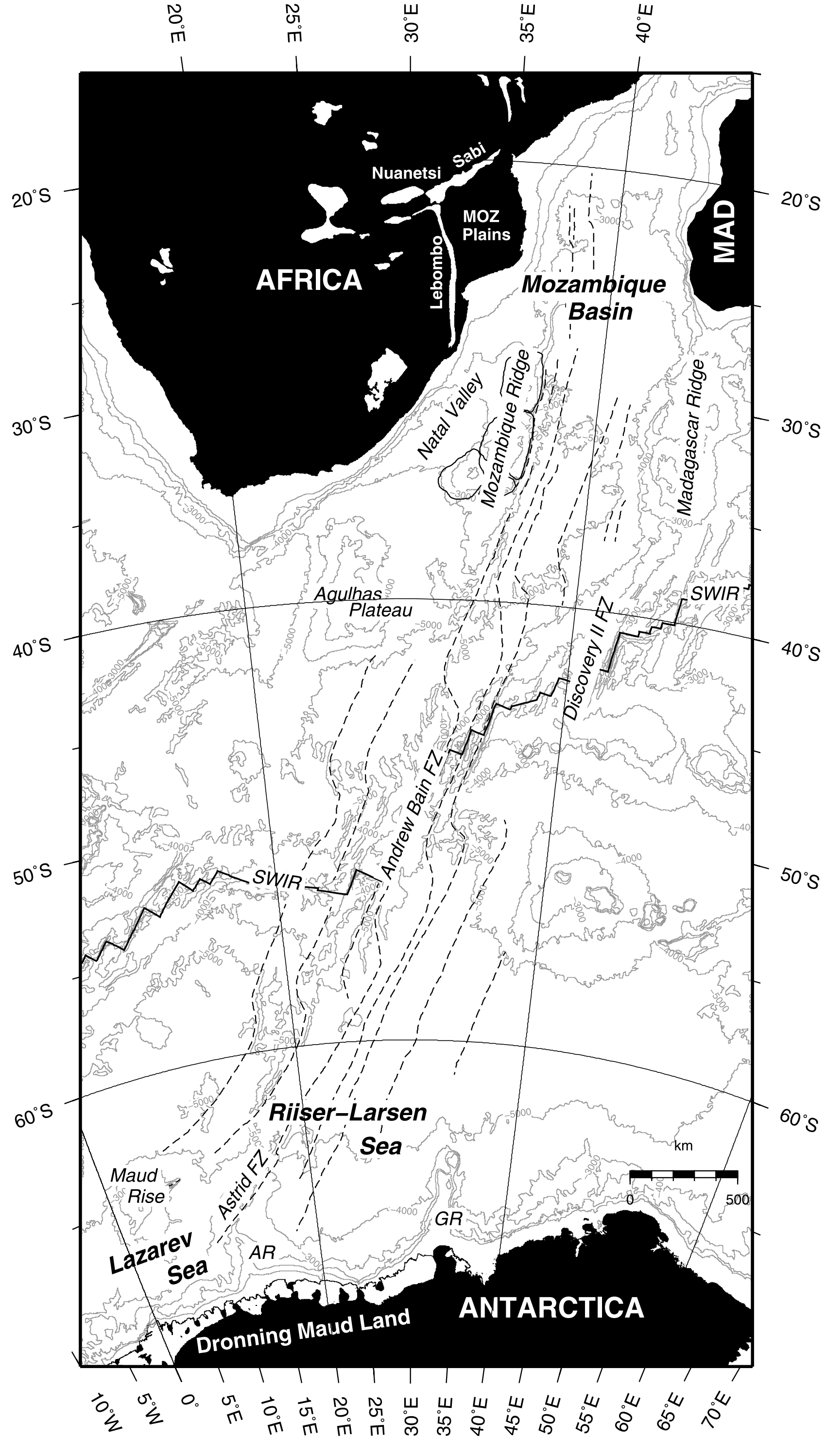

Figure 1. Overview map of the conjugate Mozambique Basin and Riiser-Larsen Sea. The global 2 min bathymetry data set of Smith & Sandwell (1997) is used in this and all other figures showing bathymetrical data. Also the major fracture zones correlating the individual parts of the basins to each other are shown. White patches across Africa indicate the presence of Karoo volcanic rocks. Abbreviations: AR: Astrid Ridge, GR: Gunerus Ridge, MAD: Madagascar, MOZ Plains: continental Mozambique Plains, SWIR: Southwest Indian Ridge.

is known about the deeper structure of the Mozambique Ridge, and much uncertainty still exists about the origin and composition of the ridge. Any model dealing with the development of the Mozambique Ridge is directly dependent on the parameters describing the opening between Africa and Antarctica in the Mozambique Basin, and its conjugate, the Riiser-Larsen Sea (Fig. 1). Recent models for the breakup of Gondwana describe the general movements of continents like Africa, Antarctica and South America in a closed plate circuit from a global point of view (Jokat *et al.* 2003; König & Jokat 2006; Eagles & König 2008). However, the chronology of these models is mainly based on high resolution magnetic anomaly data available only from the Antarctic side of the spreading system

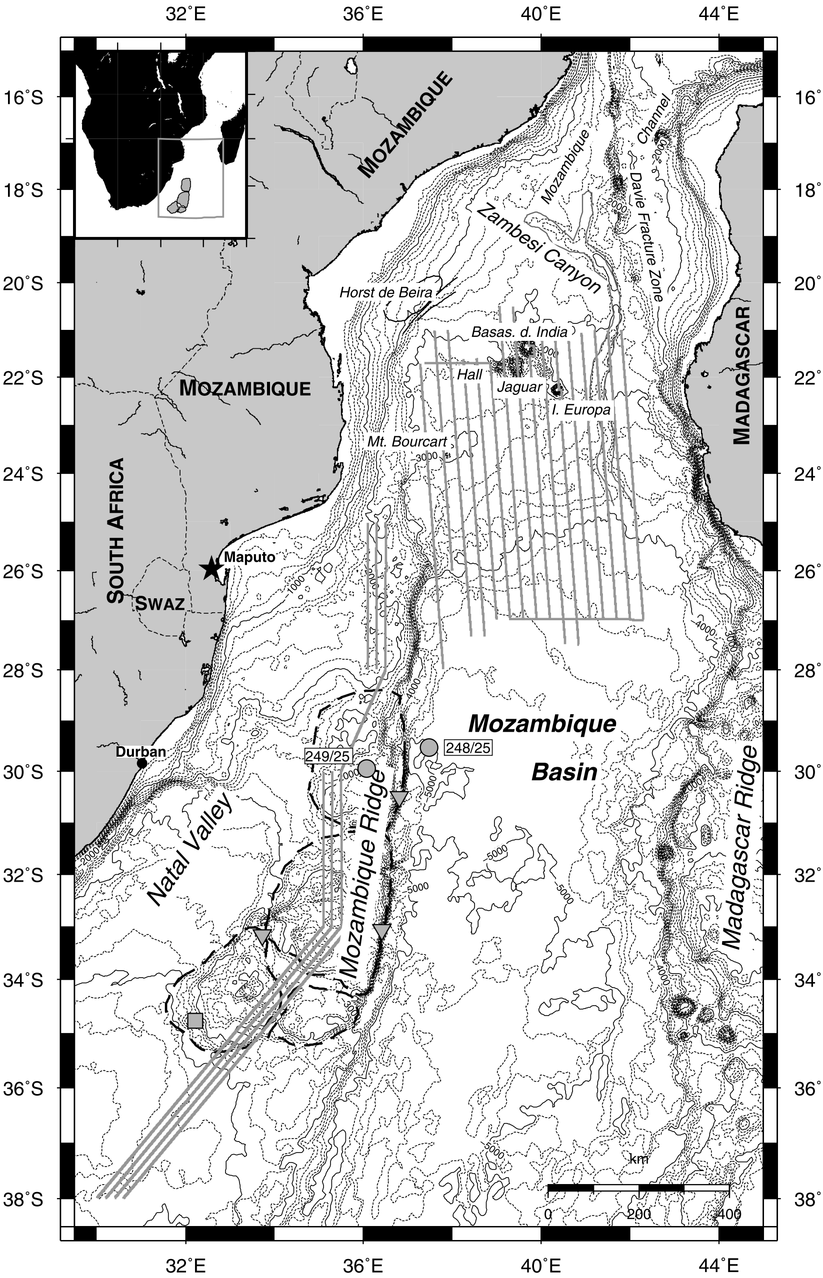

Figure 2. Bathymetric map for the Mozambique Ridge and Mozambique Basin with track lines along which magnetic anomaly data were acquired. The outline of the individual plateaus of the Mozambique Ridge as deduced from free-air gravity and bathymetry data is marked as heavy dashed line. DSDP drilling sites are marked as grey circles, dredge positions reported of by Mougenot *et al.* (1991) are marked by grey inverted triangles and a dredge position reported of by Hartnady *et al.* (1992) and Ben-Avraham (1995) is labelled with a grey square.

(Jokat *et al.* 2003). Age constraints from the African side of the spreading system are less well defined since the existing magnetic data bases suffer from a systematic approach, and are often only of poor resolution (e.g. National Geophysical Data Center, NGDC, Boulder; Sclater *et al.* 1997).

An expedition with the ‘R/V Sonne’ in 2005 to the Mozambique Ridge and the Mozambique Basin provided a systematic high resolution magnetic anomaly data set for the Mozambique Basin and parts of the Mozambique Ridge (Fig. 1). The compilation of this new data set with existing data from the Mozambique Basin and data from the conjugate Riiser-Larsen Sea, Antarctica, resulted in a well-defined model for the opening between Africa and Antarctica. The newly acquired magnetic anomaly data from the Mozambique Ridge allow the interpretation of the ridge as being of oceanic origin. Based on this assumption, a new model is presented which describes the evolution of the ridge as a process of long lasting excessive volcanism that occurred in the Lazarev Sea along the coast of Dronning Maud Land, between about 140 and 122 Ma.

2 BACKGROUND

2.1 The Mozambique Basin

Fundamental information about the Mozambique Basin was provided by magnetic and seismic studies by French expeditions in the

1970s (e.g. Segoufin 1978). Additionally, magnetic anomaly data from the Mozambique Basin from various expeditions conducted by the United States and the Republic of South Africa further helped to describe the evolution of this area. These data were introduced by Simpson *et al.* (1979). The interpretations presented in the studies of Segoufin (1978) and Simpson *et al.* (1979) are very similar, and show east–west striking magnetic anomalies from about 27°S to 22°S. These anomalies were assigned the magnetic chrons M0r to M22 with ages between 108–147 Ma according to the geomagnetic polarity timescale of Larson & Hilde (1975) that was used in these studies. Following this data the Mozambique Basin was recognised to have been created by almost north–south oriented spreading between Africa and Antarctica. Besides these two fundamental studies, no dedicated systematic magnetic surveys were carried out in the Mozambique Basin since that time. Magnetic data were acquired in the following years by many different ships mostly on transit through the basin. Some of these data are available through the National Geophysical Data Center, Boulder, Colorado (NGDC). However, these lines mostly pass the basin in a rather east–west direction, which is not favourable for the interpretation of east–west striking magnetic anomalies. A detailed interpretation of many of these magnetic anomaly data was done by Cande *et al.* (1989) for the compilation of the map of the 'Magnetic Lineations of the World's Ocean Basins'. The identifications of the magnetic anomalies of Segoufin (1979) were slightly changed by these authors excluding M0r from their interpretations. Another compilation of magnetic anomaly data was provided by Sclater *et al.* (1997) as a result of the 'International Indian Ocean Compilation Project' (IODCP). These authors incorporated previously unpublished data, and provided a sequence of magnetic anomaly picks with almost 5 Myr spacing. However, all these data sets were acquired rather unsystematic and failed to cover the complete basin in its full extent, leaving much uncertainty about the age of the oldest ocean floor in the Mozambique Basin, and the age of the ocean floor at its western and eastern termination to the northern Natal Valley and the coast of Madagascar, respectively.

2.2 The Mozambique Ridge

Since the early expeditions to the Indian Ocean, the structure and origin of the Mozambique Ridge has been a matter of various speculations. Central to all investigations was the question whether this submarine plateau is of continental or oceanic origin. Contradicting models have been published since the first investigations in the 1960s and 1970s. Laughton *et al.* (1970) proposed that the ridge is a continental fragment based on its bathymetric relation to the African continent, published sediment data of Upper Cretaceous to Upper Tertiary age (Saito & Fray 1964), and a reported sediment thickness of 300–500 m (Ewing *et al.* 1969). This interpretation is in conflict with the model presented by Green (1972), who suggested that the ridge is an extinct north–south trending spreading centre that was responsible for the east–west oriented separation of Madagascar from Africa from Late Triassic until Late Cretaceous/Early Tertiary times. These interpretations were based on aeromagnetic profiles conducted between Africa and Madagascar. Support for the model of an oceanic origin of the ridge came from seismic refraction studies carried out with free floating buoys across the southern and central part of the ridge. Hales & Nation (1973) reported that despite its depth to the Moho of about 22 km, the ridge is in isostatic equilibrium with the surrounding deep ocean basins, and thus proposed an oceanic origin for the Mozambique Ridge. Hints on a continental affinity of the ridge were provided by the interpretation of seismic refraction data as being representative for regional continental crust (Chetty & Green 1977). However, the data used in that study only have a maximum penetration depth of up to 5 km and Chetty & Green (1977) concluded that a basement of continental crust is not strongly supported from their point of view. First direct samples from the basement of the Mozambique Ridge were taken during DSDP Leg 25, Site 249, on the central part of the ridge (Simpson *et al.* 1974). 3.1 m of basalt were recovered at this site. Unfortunately, no radiometric dating was possible, but major and trace element analyses indicate that the basalt has compositional similarities with the low K Tholeiites recovered from mid-ocean ridges (Erlank & Reid 1974). However, this result has to be compared with basalts recovered from site 248 approximately 150 km east of site 249 in the westernmost part of the Mozambique Basin (Fig. 2). In that area, Tholeiites were identified with compositions that distinguish themselves from the average mid-ocean ridge abyssal Tholeiite and fall within the range of observed Karoo lavas on the African continent (Erlank & Reid 1974). These results simply suggest that magmatic processes of different kinds were active in the region of the Mozambique Ridge. However, no age control is available. Support for a continental origin of the Mozambique Ridge came from Tucholke *et al.* (1981), who compared the results from Hales & Nation (1973) and Chetty & Green (1977) with seismic refraction data from the Agulhas Plateau that was interpreted to be representative for continental basement of South Africa. However, Gohl & Uenzelmann-Neben (2001) interpreted new seismic refraction data across the Agulhas Plateau to indicate an area of excessive volcanism rather than a continental fragment. On the basis of the same seismic refraction data of Hales & Nation (1973) and Chetty & Green (1977), Recqu & Goslin (1981) concluded that the Mozambique Ridge is in isostatic equilibrium with the surrounding ocean basin (Transkei Basin) in the sense of an Airy type of isostatic compensation. However, the calculated density of 2.81 kg m^{-3} is higher than that of the bordering ocean basins (2.6–2.7 kg m^{-3}). This model is supported by the results of a gravity study presented by Maia *et al.* (1990). They conclude that the Mozambique Ridge formed as the result of the anomalous activity of an east–west trending spreading axis. This confirms the model of Recqu & Goslin (1981), and the calculated densities between 2.7 and 2.8 kg m^{-3} are close the ones presented in the former model. The model of Maia *et al.* (1990) again shows density values that are higher than that of the surrounding normal oceanic crust. Strong evidence in favour of a continental origin of the Mozambique Ridge came from dredged samples along the eastern and southern end of the Mozambique Ridge (Raillard 1990; Mougenot *et al.* 1991) during the French expedition MD-60/MACAMO-II. Fragments of Archean basement were dredged which are similar to the Rhodesian African craton, made of Anorthosites, Gneiss and Metagabbros. Additionally, Kinzigites bearing Garnet and Silimanites were recovered which are characteristic of the Precambrian Namaqualand orogeny. More dredge samples supporting the idea of a continental origin of the Mozambique Ridge were presented by Hartnady *et al.* (1992) and Ben-Avraham (1995). Their samples from the southern end of the Mozambique Ridge consisted of metamorphic rocks as well as fresh quenched glasses with no significant alteration. Unfortunately, as with all the other basement samples reported before, no radiometric dating was possible. The dredged metamorphic rocks show garnet-bearing metapelites and a number of fragments consisting of well-developed gneissic layering. These are interpreted to be similar to those found in the Natal Belt of the Namaqualand Province in southern Africa. The origin of the young volcanic rocks remains somewhat unclear, since parts of them are more like mid-ocean ridge basalts, while others clearly do not fall into the category of oceanic basalts. Ben-Avraham *et al.* (1995) conclude that neotectonic activity and magmatism must have been present beneath the Mozambique Ridge in the last few tens of 1000 yr. Although the dredge samples of Mougenot *et al.* (1991) and Hartnady *et al.* (1992) seem to manifest the hypothesis of a continental affinity of the Mozambique Ridge, there is still much uncertainty about the deeper crustal structure of the ridge. So far, the interpretation of gravity and seismic data favour an oceanic origin of the ridge, whereas dredged samples point more towards a continental affinity.

2.3 Plate tectonic models

Many different and varying plate tectonic models for the evolution of the Mozambique Basin and the Mozambique Ridge were discussed in the last 25 yr, based on all or selections of the above discussed magnetic data. One of the first models of this kind was presented by Norton & Sclater (1979). In their model, the Mozambique Ridge is treated as a pre-drift structure similar to the Falkland Plateau, and was placed between Africa and Antarctica in a loose continental fit. Based on different interpretations regarding the origin of the Mozambique Ridge, Martin & Hartnady (1986) discussed three possible scenarios for the development of the Mozambique Ridge from a plate tectonic perspective. The first two consider the ridge to be oceanic. Thereafter, the Mozambique Ridge may have formed either entirely on the African Plate or, with its southern end being formerly part of the oceanic Antarctic Plate, in close proximity to the Astrid Ridge. Both models imply that an east–west oriented spreading centre between the Mozambique Ridge and Africa once existed. The third scenario is based on the assumption of a continental origin of the Mozambique Ridge, and fits the ridge between Astrid Ridge, and the volcanic rocks of Lebombo, Nuanetsi and Sabi into the continental Mozambique Plains (Fig. 1). The ideas presented in that paper were frequently used in successive models for the breakup of Gondwana and the separation between Africa and Antarctica (e.g. Livermore & Hunter 1996; Roeser *et al.* 1996; Lawver *et al.* 1998; Marks & Tikku 2001). Although presenting no new data, the re-interpretation of existing data in the northern Natal Valley by Tikku *et al.* (2002) yielded important new constraints on the possible development of an active spreading centre between the Mozambique Ridge and the African continent. In Marks & Tikku (2001), these constraints are used to present a refined model for the opening between Africa, Madagascar and Antarctica with respect to the model of Martin & Hartnady (1986) of a continental Mozambique Ridge. Here, the Mozambique Ridge behaves like a microplate between about M11 and M2 (133–124 Ma, using the geomagnetic polarity timescale of Gradstein *et al.* 1994). Recent plate tectonic models of Jokat *et al.* (2003), König & Jokat (2006) and Eagles & König (2008) are based on new aeromagnetic data sets off the coast of Dronning Maud Land, Antarctica. The global model presented by König & Jokat (2006) includes the extinct spreading centre as proposed by Marks & Tikku (2001), and discusses the consequences of an independent Mozambique Ridge microplate as it may have existed prior to 120 Ma. Common in the models of Marks & Tikku (2001) and König & Jokat (2006) is the large overlap of the Mozambique Ridge onto Africa for some time before the initial breakup began. Although, continental extension in the Mozambique Plains are discussed by these authors to account for a considerable amount of space in that region, there is still the question whether the Mozambique Ridge even existed at this time or not. The model of Eagles & König (2008) is based on a re-interpretation of old magnetic anomaly data from the Riiser Larsen Sea, the Mozambique Basin and the Somali Basin. The main focus of this study is the plate kinematic three plate solution for the combined opening of the Somali and the Mozambique Basin with respect to Madagascar, Africa and Antarctica. No new constraints on the possible origin or structure of the Mozambique Ridge have been provided by any of these studies since no new data from the Mozambique Ridge or basin were available at that time. With the data presented in this study, the lack of high resolution magnetic anomaly data from the Mozambique Ridge and the Mozambique Basin is compensated and new constraints are derived which help to describe the structure and evolution of the Mozambique Ridge and the Mozambique Basin.

3 MAGNETIC DATA ACQUISITION AND PROCESSING

During the expedition SO-183 with the German research vessel ‘Sonne’ between 2005 May and July a total amount of 16 000 km of magnetic, gravity and bathymetric data were acquired along 4 parallel lines across the Mozambique Ridge, and 16 almost north–south oriented lines in the Mozambique Basin with a line spacing of about 30 km (Fig. 2). A Caesium magnetometer system was towed about 200 m behind the ship in order to record the variations of the total magnetic field. Additionally, to record the components of the earth magnetic field a three-component fluxgate magnetometer system was temporarily installed onboard the vessel (Jokat *et al.* 2006 and Kitada *et al.*, in preparation). The total field magnetic data were corrected for the ‘International Geomagnetic Reference Field’ using the IGRF-10 (International Association of Geomagnetism and Aeronomy, IAGA Division V-MOD). Daily corrections were not performed since no base station could be deployed in the vicinity of the survey area. The geomagnetic observatories next to the survey area, Hermanus (Rep. South Africa), Hartebeesthoeck (Rep. South Africa) and Antananarivo (Madagascar), were too far away to be used as reference stations (>500 km). However, a comparison of recordings from these three observatories and synchronous ship magnetic data show that the amplitudes of the daily variations of 10–20 nT are far below the amplitudes of seafloor spreading anomalies in the Mozambique Basin (50–200 nT, Fig. 3) and the anomalies across the Mozambique Ridge (200–800 nT, Fig. 4). Thus, disregarding the daily variations will not result in any substantial error regarding the modelling and identification of seafloor spreading anomalies in the Mozambique Basin. Additionally, all data were filtered with a 500 km high pass before modelling in order to remove long wavelength variations of the regional field and long period daily variations.

Although the new set of magnetic data covers almost the complete Mozambique Basin and many parts of the Mozambique Ridge, additional data from the National Geophysical Data Centre, Boulder, Colorado (NGDC) were used to enhance the coverage across the ridge and to densify the identifications of the magnetic anomalies in the basin. A list of the additional lines used in this study is shown in Table 1. Two lines (MDU02 and MDU07) that are not available through the NGDC could be added with the help of Marc Munschy from the ‘Institut de Physique du Globe de Strasbourg’. In the same way as for the data from the expedition SO-183, all these lines were filtered with a 500 km high pass filter to reduce long wavelength distortions. The track lines of the data added to our database are also shown in Figs 3 and 4.

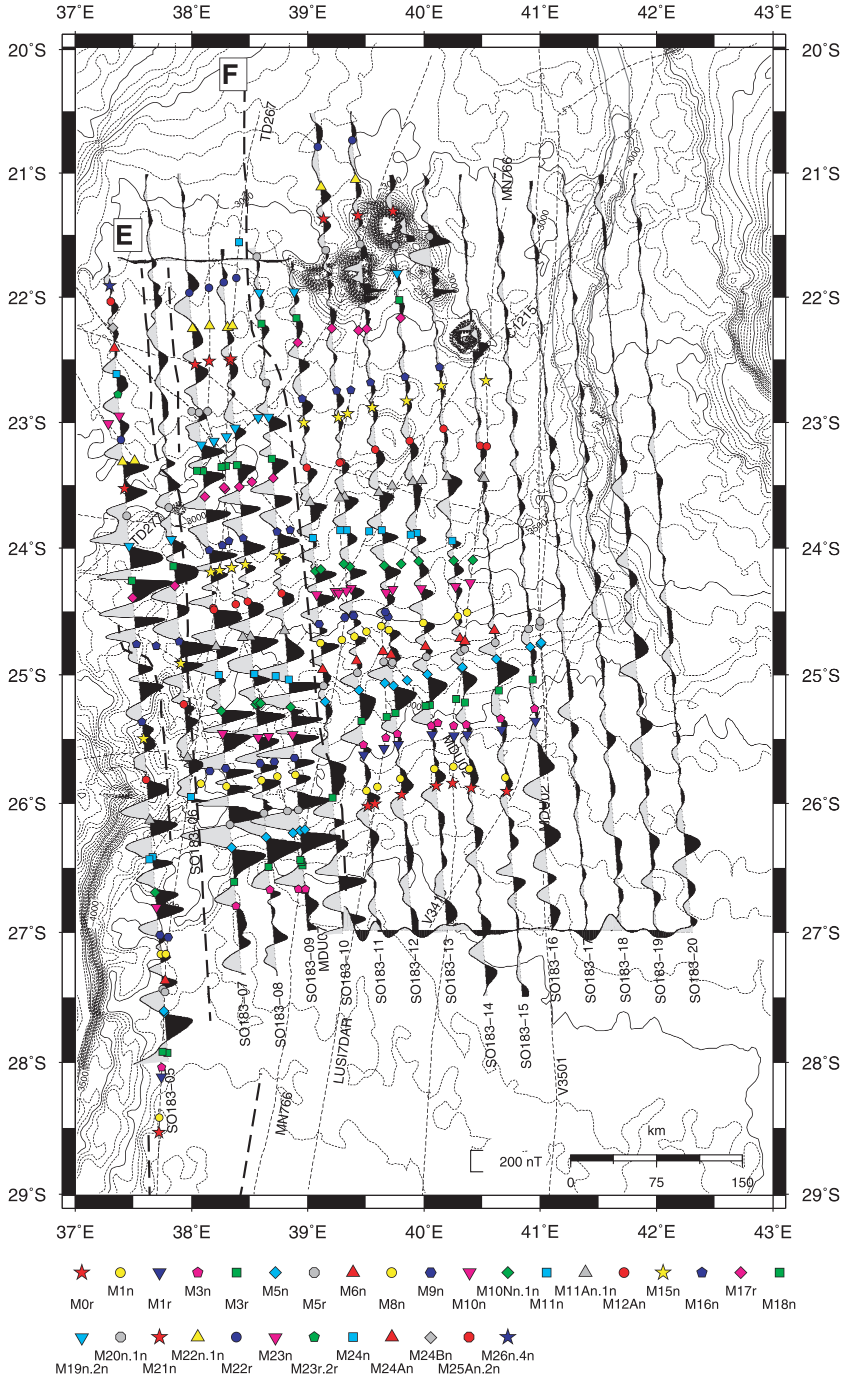

Figure 3. Magnetic anomaly data from the survey SO-183 with R/V Sonne plotted along their respective tracks. Additional ship track data used to densify the data set are plotted as stippled lines. Magnetic anomaly picks are shown in coloured symbols and fracture zones are shown as heavy dashed lines.

Data from the Riiser-Larsen Sea (Jokat *et al.* 2003; Fig. 5) were used to identify magnetic anomalies conjugate to those in the Mozambique Basin. Magnetic anomaly picks made along these data were later used for the calculation of rotation parameters that bring together picks of the same age from the conjugate ocean basins of the African and Antarctic continental block. Additionally, four lines from an aeromagnetic project (EPICA) carried out in 1996 on- and offshore Dronning Maud Land by the Alfred Wegener Institute, Bremerhaven are included which extend the helicopter borne survey to the east. These data sets were combined with ship magnetic data from the expedition ANT8–4 with 'RV Polarstern' (Roeser *et al.* 1996) and digitized ship magnetic data from Bergh (1977) and Bergh (1987). A plot of the profiles is shown in Fig. 5. Processing of the data is described by the corresponding authors. Since no base station data or gradiometer data were available for all these campaigns, the general processing steps are reduced to spike removal and correction for the IGRF. For our purposes, these data were subsequently high pass filtered to reduce long wavelength distortions as it was done for the data from the Mozambique Ridge and Mozambique Basin.

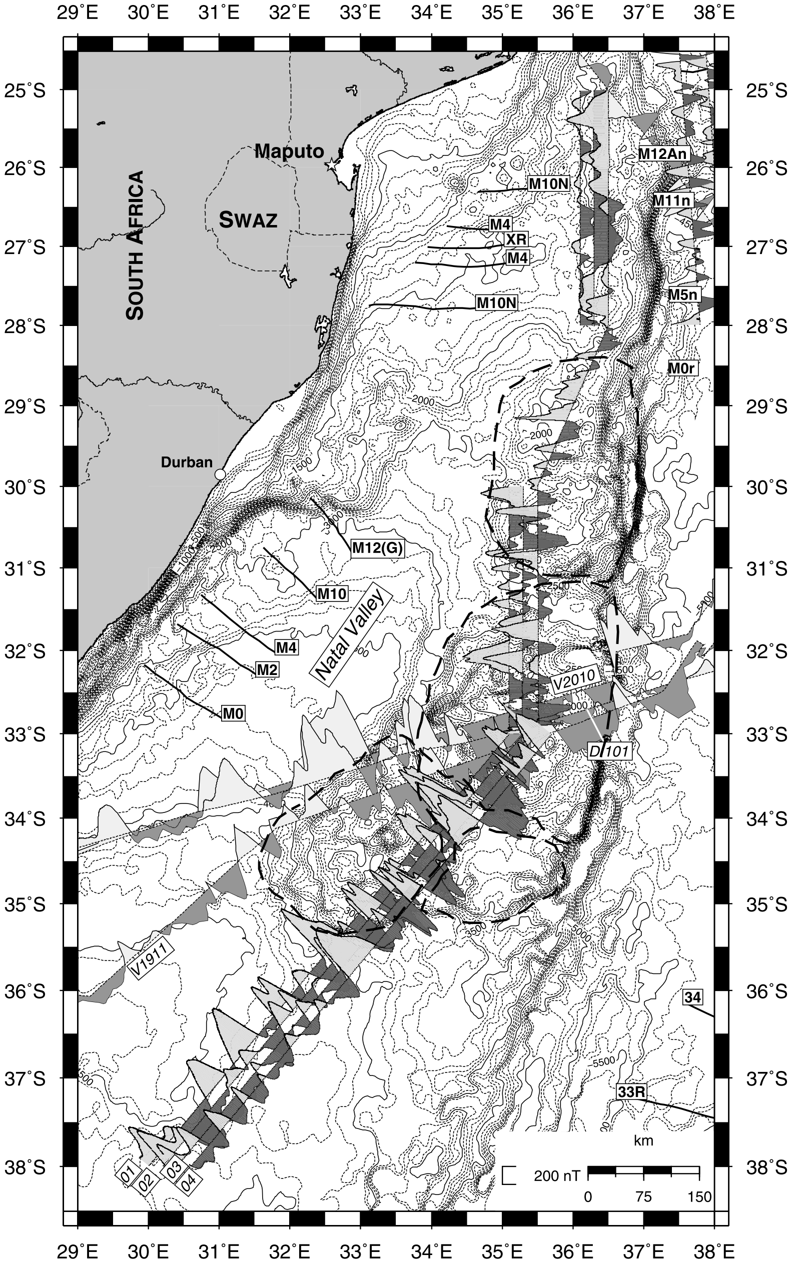

Figure 4. Magnetic anomaly data from the Mozambique Ridge plotted along their respective tracks. Additional ship track data are also plotted. The identified magnetic anomaly lineations in the Natal Valley after Goodlad *et al.* (1982) and Tikku *et al.* (2002) are labelled and shown as heavy black lines. The naming of the new magnetic track lines is shortened and should be used as SO183–01, SO183–02, etc.

4 MOZAMBIQUE BASIN: RESULTS AND INTERPRETATION

The processed magnetic anomaly data from the Mozambique Basin are shown in Fig. 3. From west to east, a significant decrease in the amplitude of the anomalies is easily recognized. While maximum amplitudes in the west (between 37°E and 39°E) reach values of about 400–500 nT (SO183–05 to 09), their maximum values decrease to about 200–300 nT in the central part of the basin (39°E-40.5°E, SO183–10 to 16) and to less than 100 nT in the easternmost part of the basin (east of 40.5°E, SO183–17 to 20). The change in amplitude is probably caused by a varying thickness of the magnetic source layer. The proximity to the Mozambique Ridge might have played a vital role during the emplacement of a bigger amount of magma in the west compared to the east. Another possible reason for the differing amplitudes might be the increased sediment thickness from west to east and south to north. Ludwig *et al.* (1968) reported 500 m of sediment for the western part of the Mozambique Basin from a seismic refraction profile. Ewing *et al.* (1969) showed that the sediments beneath the abyssal plain of the Mozambique Basin vary in thickness between 0.5 and 1.5 s two way traveltime (500–1500 m, $V_p = 2.0\ \mathrm{km\,s^{-1}}$), with the thickest sediments in the centre of the basin. Segoufin (1978) identified a step in the depth to the acoustic basement from west to east along three seismic profiles, indicating the position of a north–south trending fracture zone. Thus, magnetic anomalies (e.g. M0r-M5n, 124.61–129.76 Ma) in the southwest of the basin are covered by only 500 m of sediments while anomalies of the same age some 200 km further northeast

Table 1. List of additional track data used in this study.

Label	Ship	Expedition	Year	Institution
LUSI7DAR	R/V Argo	Lusiad leg 7D	1963	Sripps Inst. of Oceanography, USA
TD267	R/V Thomas B. Davie	Cruise 267, traverse 336	1971	University of Capetown, Geology, RSA
TD277	R/V Thomas B. Davie	Cruise 277, traverse 336	1972	University of Capetown, Geology, RSA
MN766	M/V Mering Naude	Cruise 76/6	1976	Nat. Research Institute of Oceanology, RSA
RC1215	R/V Robert D. Conrad	Cruise 12, leg 15	1969	Lamont-Doherty Geological Observatory, USA
V3501	R/V Vema	Cruise 35, leg 01	1978	Lamont-Doherty Geological Observatory, USA
V3410	R/V Vema	Cruise 34, leg 10	1977	Lamont-Doherty Geological Observatory, USA
V2010	R/V Vema	Cruise 20, leg 10	1964	Lamont-Doherty Geological Observatory, USA
V1911	R/V Vema	Cruise 19, leg 11	1963	Lamont-Doherty Geological Observatory, USA
V3410	R/V Vema	Cruise 34, leg 10	1977	Lamont-Doherty Geological Observatory, USA
V3619	R/V Vema	Cruise 36, leg 19	1980	Lamont-Doherty Geological Observatory, USA
CH099L04	R/V Chain	Cruise 99, leg 04	1970	Woods Hole Oceanographic Institute, USA
CH099L05	R/V Chain	Cruise 99, leg 05	1970	Woods Hole Oceanographic Institute, USA
CIRC07AR	R/V Argo	CIRCELEG07	1968	Scripps Institute of Oceanography, USA
DI101	Discovery	Cruise 101	1979	Inst. of Oceanographic Sciences, UK
MDU02	Marion Dufresne	–	1973	Comité des Études pétrolières Marines
MDU07	Marion Dufresne	–	1975	Comité des Études pétrolières Marines

Note: List of additional lines used within this study. Track data MDU02 and MDU07 were supplied by the Institut de Physique du Globe de Strasbourg, France, all other data are available through the National Geophysical Data Centre, Boulder, U.S.A.

are covered by up to 2000 m of sediments. At the same time, depth to the seafloor is only decreasing from about 4500 m in the south to 4200 m in the north of the basin. This difference of 1200 m in depth to the magnetic basement can cause considerable changes in the magnetic amplitudes (80–100 nT).

In order to roughly estimate the average depth to the magnetic basement in the different parts of the Mozambique Basin, power spectrum densities of the magnetic anomaly data were calculated for six profiles. The results are shown in Fig. 6. Depth values were estimated by fitting a straight line to the logarithmic power spectrum (Spector & Grant 1970; Treitel *et al.* 1971). Half the negative gradient of this line approximates the mean depth to the magnetic source layer. Errors were evaluated by calculating the standard deviation of the straight line from the respective parts of the power spectrum. Additionally, a magnetic anomaly grid was evaluated for the southwestern corner of the Mozambique Basin, and a radially averaged power spectrum was calculated. The estimated depth values for the different profiles are presented in Table 2.

The results are very consistent for the western part of the Mozambique Basin and cumulate at about 5.8 ± 0.2 km below sea level (Fig. 6). All depth values agree within their respective error ranges, including the one calculated from the grid. This depth estimate fits well with a reported sediment thickness of 1.5–2.0 s two way traveltime (1500–2000 m) by Segoufin (1978) and an average depth to the seafloor of 3500 m. Thus, the top of the magnetic basement, which coincides with the top of the acoustic basement, may be located at a depth of about 5.5 km below the sea level. For the easternmost profiles, slightly higher depth values are evaluated, averaging 6.8 ± 0.5 km (Fig. 6) (SO183–19, 20; Fig. 3). Amplitudes of the magnetic anomalies are considerably smaller in this area than further to the west. This might be caused by a higher sediment thickness originating from the close proximity to the coast of Madagascar or by a magnetic source layer, which is situated more deeply in the oceanic or any transitional crust. It should be noted that the different levels of the spectra in Fig. 5 are directly related to the different amplitudes in the respective sectors of the basin. Accordingly, the highest amplitudes in the spectrum can be found for lines SO183–07 and 09 in the middle sector and the smallest ones for lines SO183–19 and 20 in the easternmost part of the basin (Fig. 6).

A seafloor spreading block model was evaluated for the Mozambique Basin that almost perfectly fits the calculated to the observed magnetic anomaly sequences (Fig. 7). For the modelling procedure, the magnetic source body was assumed to be a horizontally flat lying layer at about 6 km depth. This is in agreement with the estimated depth to the magnetic basement as outlined above. The thickness of the magnetic source body varies between 800 m for the westernmost lines and 500 m for the lines in the central and eastern part of the basin, taking into account the decrease in magnetic amplitudes from west to east. The magnetization is assumed to be 5 $\mathrm{A\,m^{-1}}$, palaeostrike direction is about 90°E and palaeolattitude is set to 50°S. For the anomaly-age conversion, the geomagnetic polarity timescale (GPTS) of Gradstein *et al.* (2004) was used. It should be noted that significant differences exist between the GPTS of Gradstein *et al.* (2004) and the ones of Kent & Gradstein (1986), Gradstein *et al.* (1994) and Channell *et al.* (1994), which are still frequently in use. While Kent & Gradstein (1986) proposed an age of 118.00 Ma for the top of M0r (reversed polarity), Gradstein *et al.* (1994) used an age of 120.38 Ma for the beginning of the same chron and almost similarly, Channell *et al.* (1994) proposed an age of 120.00 Ma. This significantly changed with Gradstein *et al.* (2004) to 124.61 Ma. This shift of about 4.5 Ma gradually decreases for older chrons. However, significant changes in interval lengths of magnetic chrons are also present between M11 and M22 between the GPTS of Gradstein *et al.* (1994) and, for example, Kent & Gradstein (1986). This should be taken into account when comparing the results of the final spreading model with other models published before (e.g. Segoufin 1978; Marks & Tikku 2001; Jokat *et al.* 2003; König & Jokat 2006). The calculation of the spreading model was performed with the freely distributed program MODMAG (Mendel *et al.* 2005) that was developed at the Institut de Physique du Globe de Strasbourg, France. Picks of the magnetic anomalies were always made at the younger end of each polarity chron. The resulting magnetic anomaly pick data set is shown in Fig. 3 as coloured symbols. The same spreading model evaluated for the Mozambique Basin was applied to the magnetic anomaly data from the conjugate Riiser-Larsen Sea (Fig. 8). There, anomaly picks were made corresponding to the ones made in the Mozambique Basin (Fig. 5).

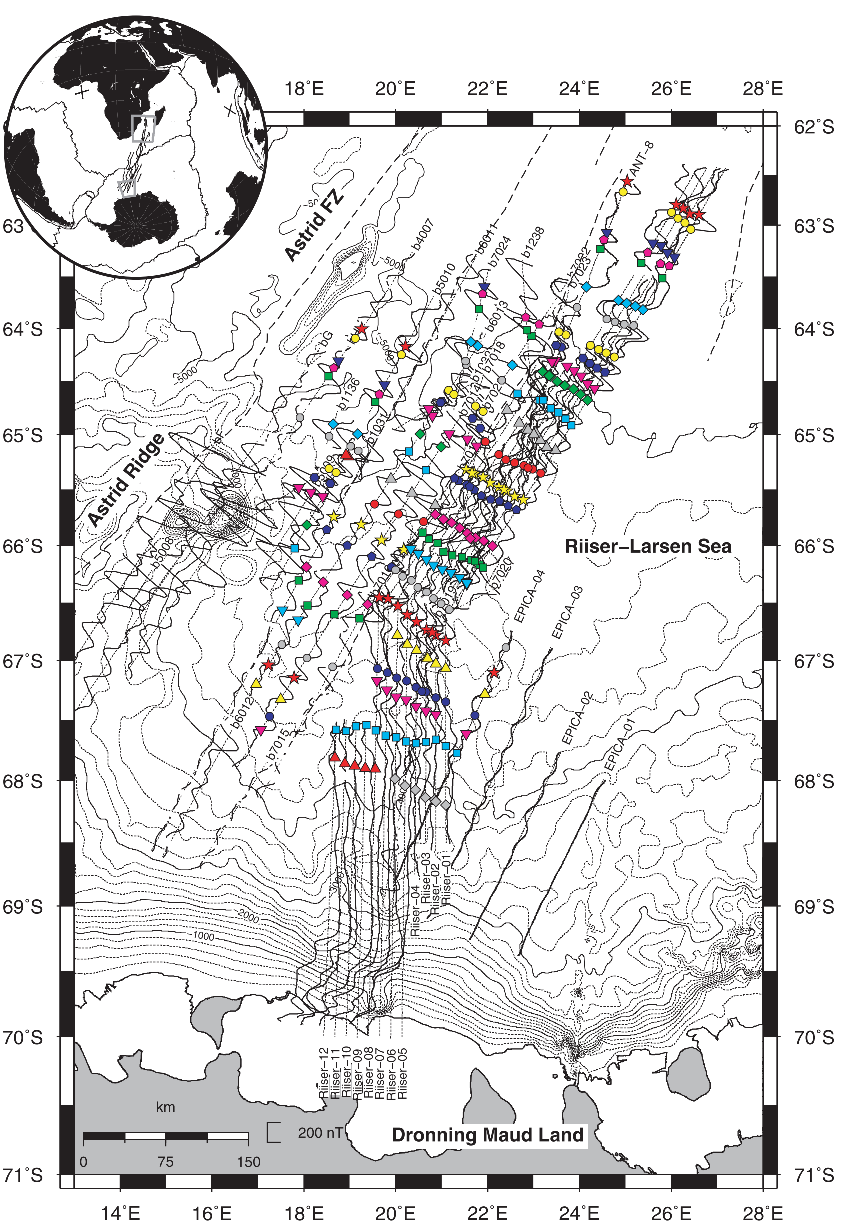

Figure 5. Magnetic anomaly data from the Riiser-Larsen Sea, Antarctica, compiled from different sources. See text for details of the different data sets. The symbols used to identify the magnetic anomaly picks are the same as shown in the legend of Fig. 2. The inset gives an overview of the relation between the conjugate Mozambique Basin in the north and the Riiser-Larsen Sea in the south.

The correlation between modelled and measured magnetic anomaly sequence in the Mozambique Basin is very good for the lines SO183–05 to SO183–15 (Figs 3 and 7). East of line SO183–16, correlations across the lines can be done only very tentatively due to the subdued magnetic signal. No consistent spreading model could be calculated for these lines. M0r (124.61 Ma) could be identified along line TD267 at the southward extension of line SO183–05 and along the lines SO183–11 to SO183–15. Lines SO183–06 and SO183–09 are situated too far in the north to be able to record M0r (124.61 Ma). However, on lines SO183–07 and SO183–08 a big positive anomaly of unknown origin is masking the end of C34, the cretaceous normal polarity super chron. To the north, M3n (127.61 Ma) could be identified on all lines representing a broad negative anomaly. This is followed by the onset of M5n (129.76 Ma) which is characterized as a strong positive anomaly across the lines SO183–05 and SO183–07 to SO183–09. Further to the east, M5n (129.76 Ma) is still easily recognized across the lines but is of significantly smaller amplitude. The continued spreading anomaly sequence can be identified along the lines SO183–05 to So183–12 at least until about M22r (150.21 Ma). Only the seamounts of Mount Bourcart, Hall Tablemount, Jaguar Seamount, Bassas da India and Europa Island cause a local distortion of the Mesozoic anomaly sequence (Figs 2, 3, and 7). Although a direct age information (e.g. from rock samples) is missing for any of the seamounts, from the interpretation of seismic data across Mount Bourcart and Bassas da India, Raillard (1990) proposed volcanic activity in this region since the early Eocene (∼55 Ma). Additionally, recent tectonic activity around Mount Bourcart was reported by Segoufin & Patriat (1980). Along the profiles crossing the seamounts, seafloor spreading anomaly lineations can be observed on either side of the

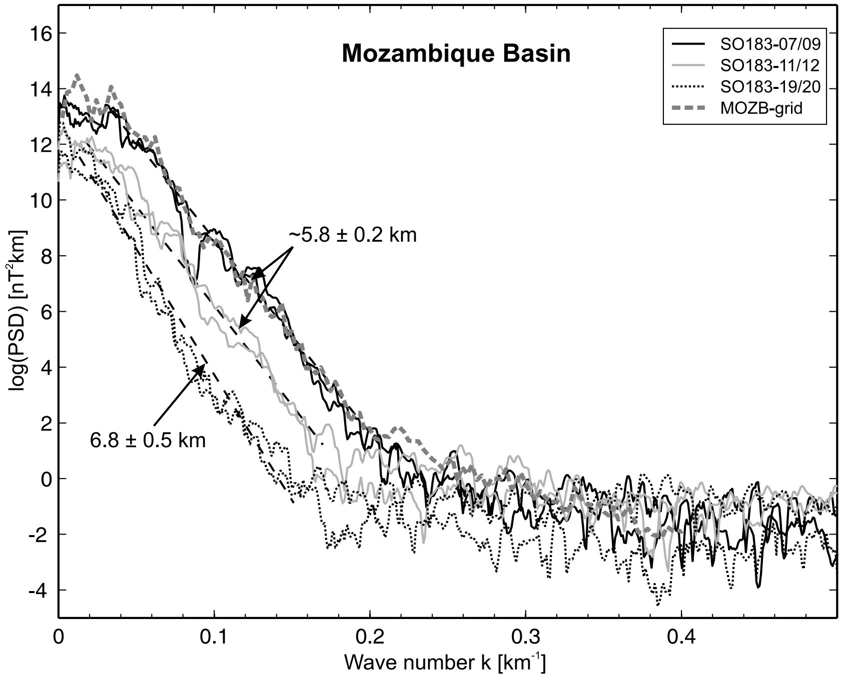

Figure 6. Power spectral densities calculated for six profiles in the Mozambique Basin and one magnetic anomaly grid from the southwestern corner of the Mozambique Basin. For a discussion on the calculation of the depth estimate see text.

Table 2. Estimated depth values and their respective errors for the Mozambique Basin.

Line	SO183–07	SO183–09	SO183–11	SO183–12	SO183–19	SO183–20	MOZB-grid
Depth (km)	5.7	5.6	5.6	6.1	7.1	6.5	5.8
SD (km)	0.6	0.4	0.5	0.5	0.8	0.6	0.4

Note: Estimated depths to the magnetic basement in the Mozambique Basin and their respective error values derived from power spectrum analysis.

respective seamounts. The magnetic effect of the seamounts shortly distorts the spreading sequence but has no long wavelength effect on the local magnetic field. This supports the interpretation of the seamounts to be of considerably younger age (∼55 Ma) than the surrounding ocean floor (>M15n, 140 Ma).

The oldest ocean floor in the Mozambique Basin is identified along line SO183–05 in the northwestern corner of the basin, having an age of approximately 155.3 Ma (M26) (Figs 3 and 7). This goes ahead with a gradual decrease in amplitude of the magnetic anomalies and is consistent with a reduced palaeointensity of the earth magnetic field during Jurassic times (Tivey *et al.* 2006 and references therein). It should be noted that this corresponds well with the oldest magnetic anomalies in the conjugate Riiser-Larsen Sea already tentatively dated to about M24 (153 Ma) by Jokat *et al.* (2003) and also included in our model (Figs 5 and 8).

There are two major north–south trending fracture zones present in the Mozambique Basin that are easily recognized through an offset of the magnetic anomalies. These fracture zones subdivide the basin into a western (lines SO183–05, 06), central (lines SO183–07 to 09) and eastern part (lines SO183–10 to 20). The fracture zones were first described by Segoufin (1978) and Simpson *et al.* (1979) through the interpretation of seismic and magnetic data. With respect to the naming convention of these authors, the fracture zones are called ‘E’ and ‘F’ throughout this study. According to our new magnetic data, these fracture zones bend to WNW between anomalies M17r–M18n (142.84–144.04 Ma) and cross the lines SO183–06 and SO183–09 at about 23.5°S and 22.5°S, respectively. In the south, fracture zone ‘F’ crosses line SO183–10 at about 25.7°S. The western sector comprising of lines SO183–05 and SO183–06 is subdivided by another fracture zone south of 25°S. This fracture zone was not known before. While north of 25°S magnetic anomalies can be correlated between the lines SO183–05 and SO183–06, this is not possible south of 25°S. There is a distortion in the magnetic anomaly sequence of line SO183–05 at about the position of anomaly M16n (141.05 Ma). A fracture zone is probably crossing line SO183–05 at this place (Figs 3 and 7). South of this fracture zone, crossing anomalies M3n (127.61 Ma) to M16n (141.05 Ma) can be identified. North of the fracture zone, the magnetic anomaly sequence can be continued starting with M16n (141.05 Ma) until M26 (155.3 Ma). The offset along this westernmost fracture zone between lines SO183–05 and SO183–06 is about 50 km. Further east, between lines SO183–06 and SO183–07, the offset along fracture zone ‘E’ is estimated to about 80 km. Along fracture zone ‘F’, anomalies of the same age are offset by about 115 km. North of 23.5°S, no correlation can be found between lines SO183–06 and SO183–07. Either another fracture zone exists between these two lines or line SO183–06 is influenced by the nearby fracture zone ‘E’ overprinting the expected seafloor spreading anomalies. In the easternmost part of the basin, east of line SO183–16, no direct hint for the existence of fracture zones can be derived from the interpretation of the total magnetic anomaly field. However, from the interpretation of the shipboard three-component

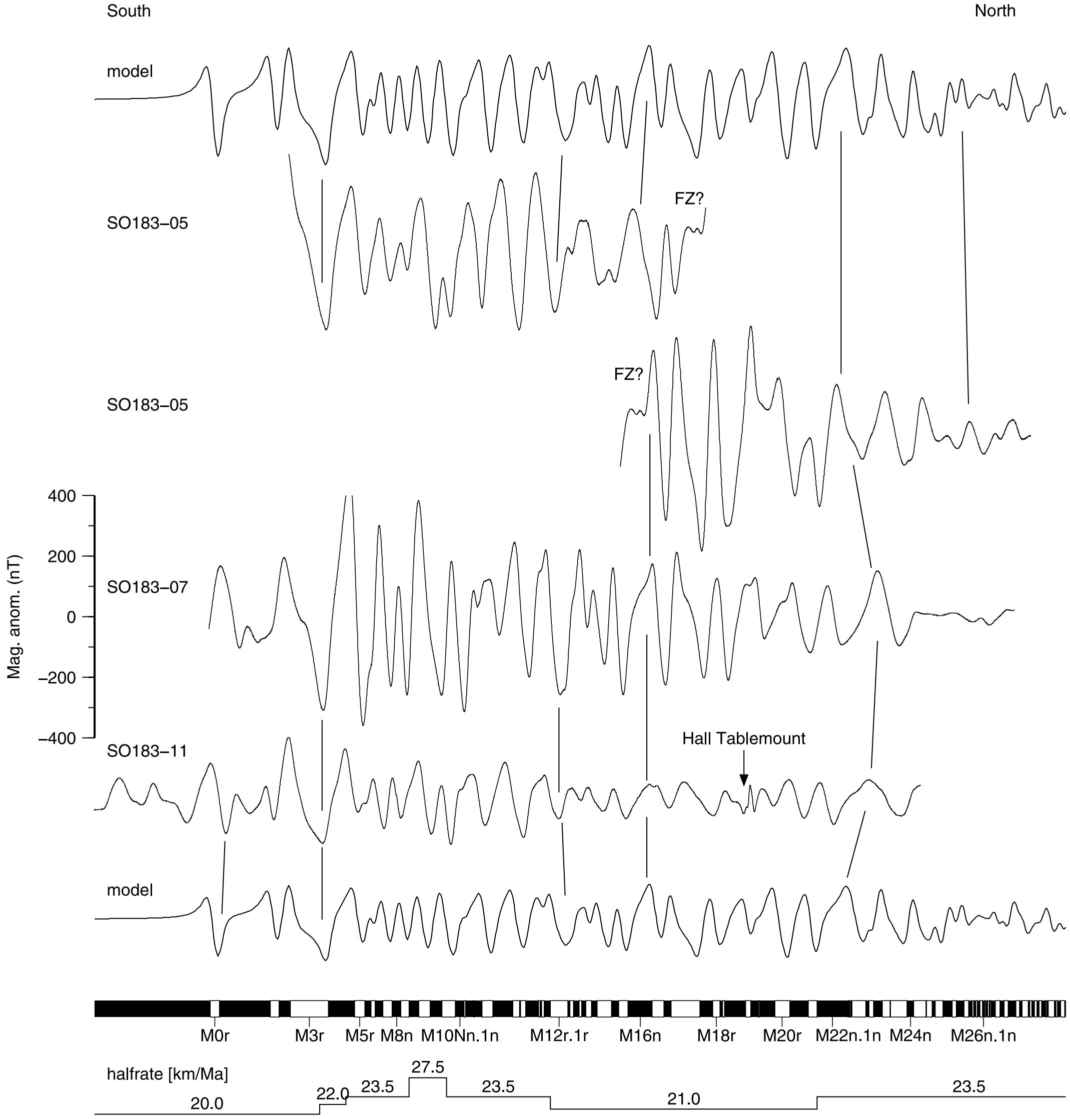

Figure 7. Spreading model for the Mozambique Basin compared to track lines in the western (SO183–05), central (SO183–07) and eastern (SO183–11) part of the basin. All magnetic anomaly sequences are scaled according to the scale bar shown on the left side of track SO183–07. The beginning of each track was shifted along the distance axis in order to match the first recognized anomaly with the model. The model on the lower end of the figure is calculated with a thickness of the magnetic source layer of 500 m and the model on the top of the figure is calculated with a thickness 800 m. The approximate position and influence on the magnetic data of Hall Tablemount along line SO183–11 is indicated by an arrow.

magnetometer data, Kitada *et al.* (in prep) propose a fracture zone to be present between lines SO183–16 and SO183–17. Similar to the Mozambique Basin, the Riiser-Larsen Sea is separated (at least) into three spreading corridors by two major fracture zones (black dashed lines in Fig. 5). One of these fracture zones exists at the western boundary of the helicopter borne magnetic anomaly data of Jokat *et al.* (2003). There anomalies are displaced by about 110 km with respect to the anomaly lineations defined by the data of Bergh (1977 and 1987). This fracture zone was first described by Roeser *et al.* (1996), based on the interpretation of a ship magnetic line labelled as ANT-8 on Fig. 5. The second major fracture zone further west in the Riiser-Larsen Sea was already discussed by Bergh (1977) and offsets the neighbouring spreading corridors by about 125 km. These offsets correspond to the ones reported from the Mozambique Basin along fracture zones 'E' (130 km between SO183–05 and SO183–07) and 'F' (115 km). However, a conjugate fracture zone to the one found between lines SO183–05 and SO183–06 in the Mozambique Basin cannot be identified in the western Riiser-Larsen Sea since data coverage and quality is not good enough in that area.

A significant change in the strike of the magnetic anomaly lineations occurs at around M11n (135.69 Ma). This change is clearly visible in the middle and eastern sector of the Mozambique Basin (Fig. 3). This happens shortly before a sudden step in spreading velocity occurs at around M10r (134.30 Ma), as shown in the spreading model in Fig. 7. The step from about 23.5 km Ma^{-1} to about 27.5 km Ma^{-1} half rate is confined to a time span of less than 2 Myr until M9n (132.83 Ma). A sudden change in spreading velocity around this time has already been recognized by Segoufin (1978). The change in spreading direction and the subsequent short acceleration in spreading rate are probably related to the initiation of seafloor spreading between the eastern Falkland Plateau and Africa in the southern Natal Valley. This marks the initial phase of the South Atlantic Ocean opening between Africa and South America,

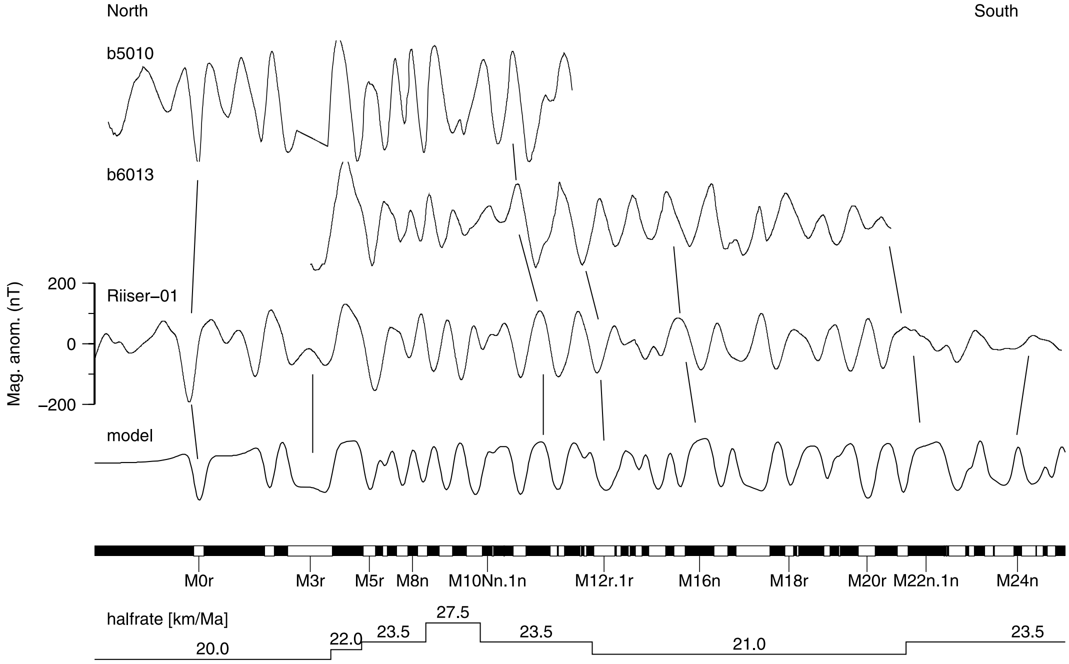

Figure 8. Spreading model for the Mozambique Basin compared to track lines in the western (b5010), central (b6013) and eastern (Riiser-01) part of the Riiser-Larsen Sea. The same scaling as for the magnetic anomaly sequences shown in Fig. 7 is applied. A shortened scale bar is shown on the left side of line Riiser-01.

and possibly had its effects not only on the conjugate ocean basins along the African and South American margins but also on the neighbouring ocean basins along the African coast. A similar change in spreading direction cannot be found in the data available from the Riiser-Larsen Sea. This might be due to the reduced data coverage in the western part of the basin.

5 MOZAMBIQUE RIDGE: RESULTS AND INTERPRETATION

The magnetic anomaly profiles across the Mozambique Ridge are shown in Fig. 9 along their distances from the beginning of each profile south of the ridge together with free-air gravity anomaly data acquired during the cruise and the new bathymetry. The ridge is divided into four distinct plateaus, each separated by a strong gradient in free-air anomaly and bathymetry (also see Fig. 2). The boundaries to the southeastern plateau are not covered by our data but can be recognized on satellite derived free-air gravity anomaly data of Sandwell & Smith (1997). According to this data set, the boundaries shown in Fig. 2 were defined. The transition between normal oceanic crust south of the ridge and the southern flank of the ridge is marked by a steep rise of the ocean floor from more than 4000 m to about 2300 m below sea level. This goes ahead with a long wavelength high amplitude magnetic anomaly of up to 600 nT. Similarly, the boundary between the southern and the central plateau is rimmed by a strong positive magnetic anomaly of up to 800 nT. This is accompanied by a steep rise of the ocean floor from about 2500 to 1500 m and a shift in free-air anomaly of up to 60 mGal. Using track line data from the expeditions V1911, V2010 and D101 (see Table 1 for reference), the positive long wavelength magnetic anomaly found in the SO183 data can be followed along a valley further northwest until the southern Natal Valley (Fig. 4). Between the central and the northern plateau, strong positive magnetic anomalies can be found at the position of the steepest gradient in gravity and bathymetry, at around kilometres 800–850 (Fig. 4). It seems that strong magnetic anomalies are directly related to the boundaries of the individual plateaus, possibly indicating the boundary between blocks of oppositely polarized remnant magnetized basalts. As a consequence, a change in polarization implies that the different parts of the ridge were formed at different ages.

The frequency content of the magnetic anomalies changes significantly between the ocean floor south of the ridge and the ridge itself. While south of the ridge the shape of the anomalies is comparable to normal seafloor spreading anomalies, in the shallowest part of the ridge short wavelength magnetic anomalies indicate a reduced distance to the magnetic source bodies. Power spectrum densities were calculated for the profiles across the Mozambique Ridge in order to estimate the depth to the magnetic basement (Spector & Grant 1970; Treitel *et al.* 1971). The results are shown in Fig. 10. The spectra of the profiles south of the Mozambique Ridge have similar characteristics to those from the Mozambique Basin. There, a steep decline in the spectrum to wavenumbers of about 0.18 km^{-1} (∼5.6 km) can be easily approximated by a straight line. This is followed by a more or less horizontal plateau-like spectrum which is due to noise of the sensor. The mean depth to the magnetic basement estimated from these four lines is about 6.8 ± 0.3 km below sea level. However, with a mean water depth of about 4100 m and a sediment thickness of 1500 m at maximum (Schlüter & Uenzelmann-Neben 2007), the estimated depth to the acoustic basement is about 5600 m. This is about 1000 m above the estimated mean depth to the magnetic basement. Depth to the (acoustic) basement is also interpreted to about 6000 m from a refraction seismic line that has been acquired during 'R/V Sonne' cruise SO182 across the southern Mozambique Ridge, starting south of the ridge (Gohl *et al.* submitted). Probably, the difference between the estimated mean depth to the magnetic basement and the depth to the top of the acoustic basement is the result of a thicker than usual oceanic crust resulting from the

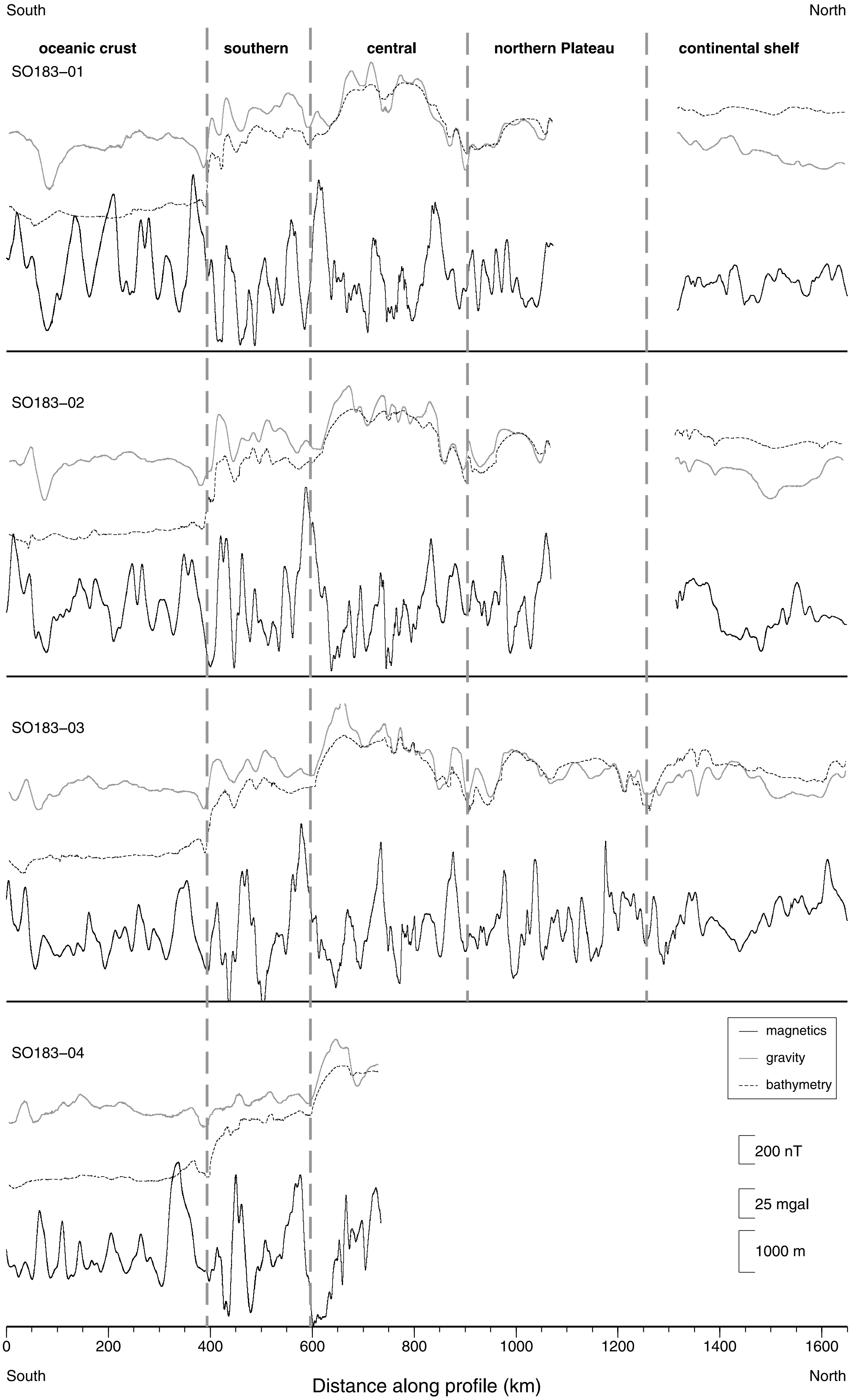

Figure 9. Magnetic and gravity anomaly data as well as bathymetry of the Mozambique Ridge plotted along profile distance. The heavy dashed grey lines mark the boundaries between the normal oceanic crust south of the ridge, the individual plateaus of the ridge and the continental shelf north of it.

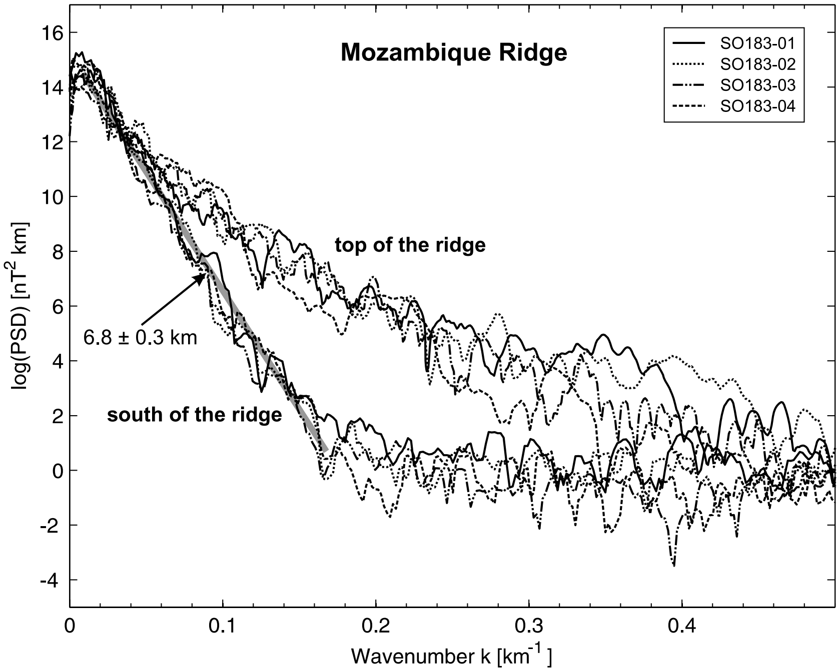

Figure 10. Power spectral densities calculated from magnetic anomaly data south of the Mozambique Ridge and on top of the ridge. A reliable estimate of the depth to the magnetic source body is only possible for the area south of the ridge. See the text for a more detailed discussion.

emplacement of an anomalous high amount of basaltic material. The spectra of the profiles from the top of the Mozambique Ridge differ significantly in shape from the ones south of the ridge and in the Mozambique Basin (Figs 6 and 10). Generally, the gradient in the spectra is not as steep as for the other profiles. It is difficult to approximate the trend of the spectra by a straight line. However, for lines SO183–01 to 03 the power spectra were roughly approximated by two straight line segments (omitted in Fig. 10 for clarity). The trends of the fitted straight lines were grouped into a lower source level with depth values between 4.3 and 5.0 km and a shallower level of 1.4–3.0 km. The wide range of depth values might be explained by the three-dimensionality of the source bodies and the idea that the source bodies are not strictly confined to distinct layers within the Mozambique Ridge but are rather distributed randomly at a certain depth range of about 1.4–5.0 km mean depth below sea level with varying lateral extend. This result was used to generate a 2-D-model roughly describing the magnetic- and gravity field over the Mozambique Ridge in a general way. The model is shown in Fig. 11. The bodies of normal and reversed magnetization were positioned as close to the top of the Mozambique Ridge as possible. Additionally, seismic data plots from the French expedition MACAMO-II (Mougenot *et al.* 1991; Raillard 1990) and from the newly acquired data during the German expedition SO-182 (Uenzelmann-Neben 2005; Gohl *et al.* submitted) were used to constrain the sediment thickness on top of the ridge and in the Transkei Basin. The crustal thickness of the ridge in the southern part is in agreement with free floating buoy data from Hales & Nation (1973), suggesting a thickness of 22–24 km, as well as with latest results from ocean bottom seismometer data acquired across the southern end of the ridge during expedition SO-182 with RV Sonne (Gohl *et al.* submitted) which propose a depth to the Moho of about 24 km beneath this part of the ridge. The magnetic anomalies were modeled using normal and reversed magnetized prismatic blocks bearing a remnant magnetization of ±2.6 A m^{-1}. This is comparable to remnant magnetizations measured on cores from ODP Leg 183 sites 1137 and 1140 on the Ellan Bank and Kerguelen plateau, where sub aerial and submarine lava flows were sampled (Delius *et al.* 2003). For the gravity model, standard densities for the oceanic crust were used (water 1.03×10^3 kg m^{-3}, sediment 2.10×10^3 kg m^{-3}, basalt 2.90×10^3 kg m^{-3} and upper mantle 3.25×10^3 kg m^{-3}). The simple model consists of a thick oceanic crust with a depth of up to 24 km. Within this crust there are blocks of different magnetization, variable width and depth. Large susceptibility contrasts had to be introduced in order to model the high-amplitude long-wavelength magnetic anomalies of these blocks. These large susceptibility contrasts only could be realized by introducing normally and reversed polarized blocks. This in turn implies that the different blocks were emplaced at different times represented by their different magnetic polarity, indicating a long lasting process of magmatic activity. Consequently, the Mozambique Ridge is interpreted as having been formed by massive basaltic extrusions or intrusions and dikes and conduits that were emplaced at different times of normal and reversed magnetic polarity. This clearly favours the model of an oceanic origin for the Mozambique Ridge. However, it cannot be excluded that small continental fragments may exist within the magmatic body of the ridge, which cannot be resolved.

6 DISCUSSION

6.1 Rotation parameters for the AFR-ANT spreading system

Based on the interpretation of the magnetic anomalies in the Mozambique Basin and its conjugate the Riiser-Larsen Sea, rotation parameters were calculated for the opening between Africa and Antarctica (Table 3).

The rotation poles and angles were calculated by fitting conjugate magnetic anomaly picks (Fig. 12). Additionally, digitized fracture zone data were compared with calculated flow lines to adjust the alignment of conjugate spreading compartments (Figs 13 and 14).

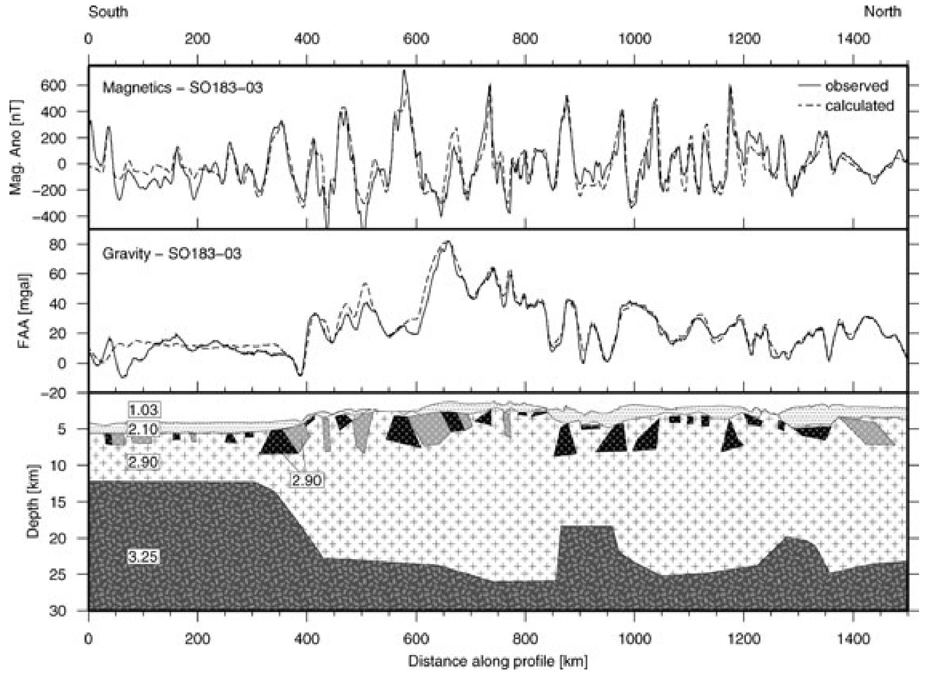

Figure 11. Simple 2-D magnetic and gravity model for the Mozambique Ridge along line SO-183 (see Fig. 4 for position of line). This is one of an infinite number of possible models to explain the gravity and magnetic data. Densities in the lower panel are given in 10^3 kg m^{-3}. Blocks with a magnetization of normal polarity are painted in black and blocks of inversed polarity are painted in grey.

Table 3. Rotation parameters for the opening between Africa and Antarctica.

Chron	Age	Lon	Lat	Angle
M0r	124.61	329.18	−6.05	40.52
M3n	127.61	330.50	−7.76	42.15
M5n	129.76	331.25	−8.87	43.54
M8n	132.20	331.03	−8.63	44.47
M10n	133.50	330.84	−8.50	45.07
M11n	135.69	330.58	−8.27	45.90
M12An	138.78	330.24	−7.97	47.04
M16n	141.05	329.98	−7.75	47.91
M17r	142.84	329.73	−7.81	48.74
M20n.1n	146.16	328.87	−7.29	49.80
M22n.1n	148.92	328.46	−6.90	50.72
M22r	150.21	328.22	−6.69	51.26
JQZ	163.00	326.34	−5.20	56.22

Notes: Rotation parameters for the opening between AFR and ANT. Besides for JQZ (163.00 Ma), all poles and angles were newly calculated within this study. The rotation parameters for 163.00 Ma were taken from König & Jokat (2006).

The relation of conjugate spreading corridors has been adopted from Bergh (1987). This means the westernmost spreading anomalies from the Riiser-Larsen Sea were fitted to the anomaly picks west of fracture zone 'E', and the Astrid Fracture Zone was aligned with the eastern scarp of the Mozambique Ridge. The other conjugate corridors were then defined correspondingly. This relation of corresponding spreading corridors has already been used by many others before like Livermore & Hunter (1996), Marks & Tikku (2001), König & Jokat (2006) and Eagles & König (2008). Since we have data from the African side of the westernmost spreading corridor for the first time, we were able to use three corridors to fit our magnetic anomalies. Although it should be mentioned that the subdivision of the westernmost corridor in the Mozambique Basin by an additional fracture zone makes the correlation with the conjugate anomaly picks from the Riiser-Larsen Sea more difficult and somehow tentative. Rotation parameters for the initial fit of the continents are derived by extrapolation of the spreading system until the closure of the basin. Here, we adopted the rotation pole and angle from König & Jokat (2006) since these perfectly extend our spreading model, and lead to a tight fitting reconstruction between Africa and Antarctica at about 163 Ma. A misfit that quantifies the spatial error of conjugate magnetic anomaly picks after the corresponding rotation was performed was calculated according to the method of Hellinger (1981). A detailed discussion on the calculation of this misfit and misfits in plate tectonic reconstructions in general can be found, for example, in Royer & Chang (1991) and Matias *et al.* (2005). In short, the misfit used here is the sum of the squared distance from each point in a segment to the best fitting great circle divided by the square of the uncertainty for each point. In our calculations we assumed the uncertainty in the magnetic anomaly picks to be less than 5 km, including the ones from the Riiser-Larsen Sea. An example for such a best fitting great circle is given in Fig. 12 for the rotation of M5n (129.76 Ma, according to Gradstein *et al.* (2004)). For each of the spreading corridors, an error analysis was made for all ages. The results are shown in Table 4.

The error values from the westernmost corridor are only based on the fit of three to four points and are not as reliable as those calculated for the other two corridors. The central sector shows significantly higher error levels than the eastern one. This is based on the reduced number of points available for the calculations in the central sector, and the inaccuracy of the data from the Riiser-Larsen Sea in this sector. The data from this sector are digitized from a published map of Bergh (1987) and, therefore, may be affected by systematic errors during a conversion to geographic coordinates. Since the final rotation parameters were optimized to reduce the errors in the easternmost sector, these are the smallest ones, resulting in values between 1.2 and 5.5 km. The azimuths of the best-fitting

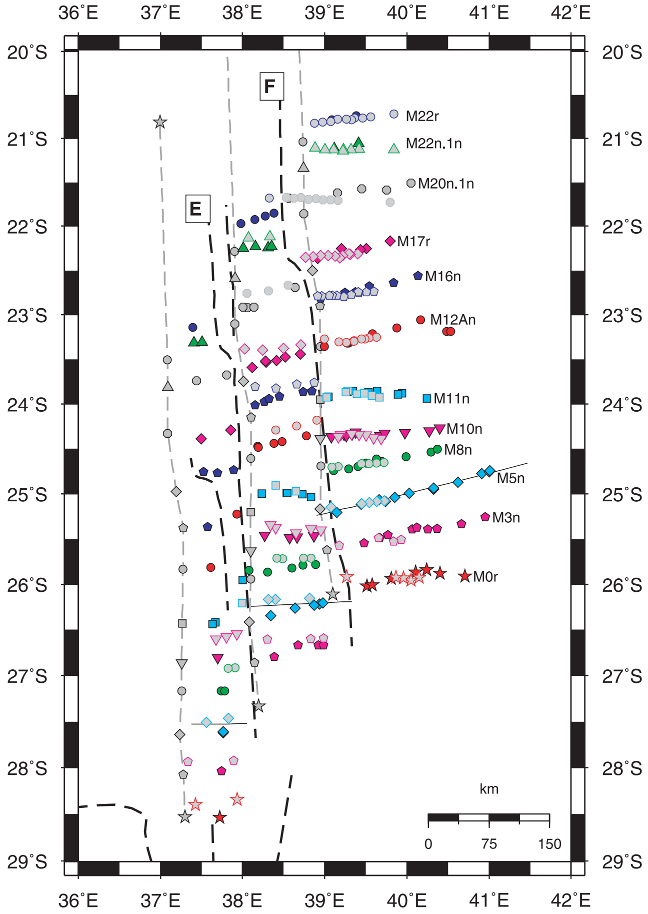

Figure 12. Magnetic anomaly picks for the Mozambique Basin (coloured filled symbols) and rotated picks from the Riiser-Larsen Sea (grey filled symbols). The symbols used are the same as explained in Fig. 2. Labels to the anomalies are also shown for the eastern sector. The rotation parameters from Table 3 were used to rotate the Riiser-Larsen Sea picks and to calculate the flowlines shown as grey dashed lines. Three points on the present day southwest Indian Ridge were rotated to generate the flowlines ([32.66°–46.94°]; [34.10°–45.90°]; [35.53°–44.83°]). As an example three best fit great circle segments are shown for the M5n rotation. Misfits as shown in Table 4 and discussed in the text are evaluated with respect to such great circle segments.

great circles for the central and eastern sector are also shown in Table 4, and are plotted in Fig. 15. A systematic change of the spreading azimuth for about 10°–15° through time can be observed, especially for the easternmost segment. The peak at about M11n (135.69 Ma) coincides with the changing strike of the magnetic anomaly lineations as was already discussed above, and is visible in Fig. 3. According to Fig. 15, this change in spreading direction is not only a single phenomenon but seems to be a continuous process with a frequency of about 10–15 Ma. The M11n (135.69 Ma) change in spreading direction was related to the opening of the South Atlantic between South America and Africa in the above paragraph. However, the reasons for a continuous change in spreading direction are not clear thus far. In a general plate circuit sense, the changes during older times (older than M11n, 135.69 Ma) are probably related to processes in the central and western Indian Ocean as described for example by Heine *et al.* (2004). The comparison of flow lines calculated within this study with those derived from models of König & Jokat (2006) and Eagles and König (2008) shows major differences in the positioning of M0r (Figs 13 and 14). While M0r is easily recognized on the new magnetic anomaly data, only rough estimates on the accurate position of this important anomaly were possible before. Thus, rotation parameters for this age are significantly different to that of former models. In general, our plate tectonic model based on the new high resolution magnetic anomaly data from the Mozambique Basin results in a better fit between rotated magnetic anomaly picks and aligns calculated flow lines and fracture zone data more accurately than the models before.

6.2 The Mozambique Ridge—product of long lasting volcanic activity

The rotation parameters for the opening between Africa and Antarctica and the constraints from the Mozambique Ridge model were used to develop a plate kinematic model for the opening of the Mozambique Basin and its conjugate, the Riiser-Larsen Sea, and the evolution of the Mozambique Ridge between 163 Ma (Jurassic Quiet Zone, JQZ) and 120 Ma (C34). A series of five reconstructions is presented in Figs 16(a)–(e), showing the general steps in the evolution of the ocean basins and the sequential emplacement of the Mozambique Ridge. The model demonstrates that the area between Africa and Antarctica, where the Mozambique Ridge evolved over a time span of about 20 Myr, was a region of high volcanic activity since the early beginning of Gondwana breakup. It emphasizes our finding that the ridge may be of oceanic origin. However, this does not exclude the possibility that small continental fragments may exist in the vicinity of the Mozambique Ridge.

The first volcanic activity related to the early breakup of Gondwana took place in southern Africa and parts of East Antarctica at about 184 Ma (Encarnacion *et al.* 1996; Duncan *et al.* 1997) (Fig. 16a). During only a few million years large volumes of magma were emplaced, forming the Karoo continental flood basalts. Latest studies published by Jourdan *et al.* (2007) propose a continued phase of volcanism, although not as excessive as before, that lasted until about 174 Ma. This later stage of volcanism is mainly sampled at dikes along the Lebombo and Sabi monocline. It is suggested by Jourdan *et al.* (2007) that the emplacement of the Rooi Rand dikes (174 Ma) along the Lebombo mountains represent the transition from rifting to oceanization and mark the end of the Karoo magmatism. Here, we propose that magmatism did not gradually decay with time but shifted rather further south to the coast of East Antarctica, leading to the emplacement of a sequence of volcanic layers that are known today as seaward dipping reflector sequences (SDRS) in the Lazarev Sea. Hinz *et al.* (2004) and Jokat *et al.* (2004) show that two wedges of SDRS exist in the Lazarev Sea which were emplaced at different times. The oldest of them might have been formed simultaneously with the Karoo volcanism on the African continent. Opposed to other models, where the SDRS along the coast of Dronning Maud Land are interpreted to be of the same age as the Karoo volcanism (e.g. Elliot & Fleming 2000), we confine this only to the oldest SDRS in the Lazarev Sea. This is in agreement with the model of König & Jokat (2006), who interpret the SDRS in the eastern Weddell Sea to be of much younger age (150–138 Ma, only one wedge of SDRS). After the initial phase of volcanism in the proto-Lazarev Sea, the north–south directed drift of Antarctica with respect to Africa started at about 163 Ma (Fig. 16a). This resulted in seafloor spreading in the Mozambique Basin and possibly stretching and extension in the Mozambique Plains, if this is interpreted as thinned continental crust (Cox 1992). When East Antarctica finally split off the coastal plains of Mozambique, the second phase of volcanism in the proto-Lazarev Sea may

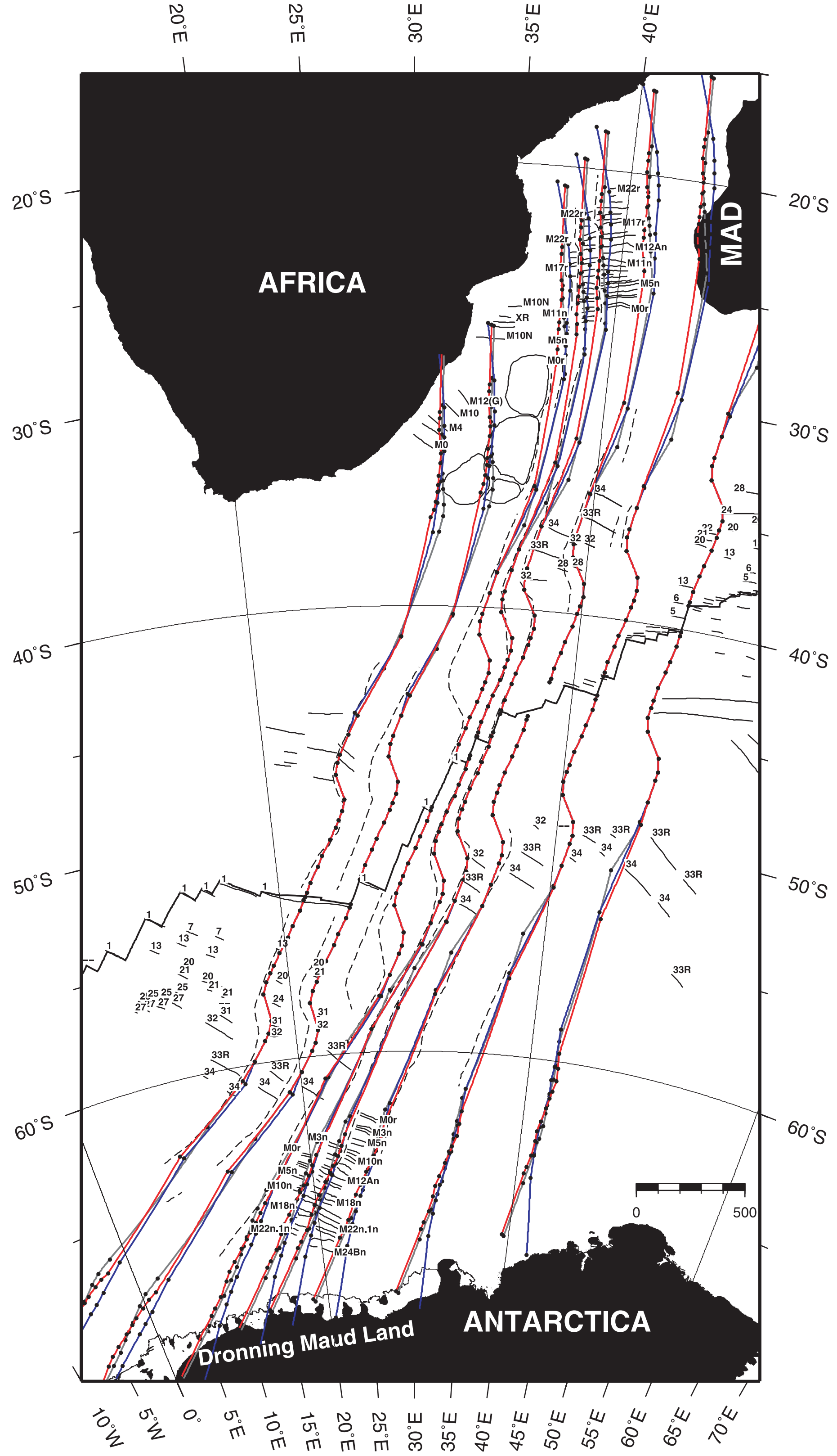

Figure 13. Calculated flow lines for the opening between Africa and Antarctica based on rotation parameters shown in Table 3 (red line) and taken from König & Jokat (2006) (grey line) and Eagles & König (2008) (blue line). Fracture zones are shown as black dashedlines and magnetic anomalies as black solid lines, some of them annotated with their corresponding age.

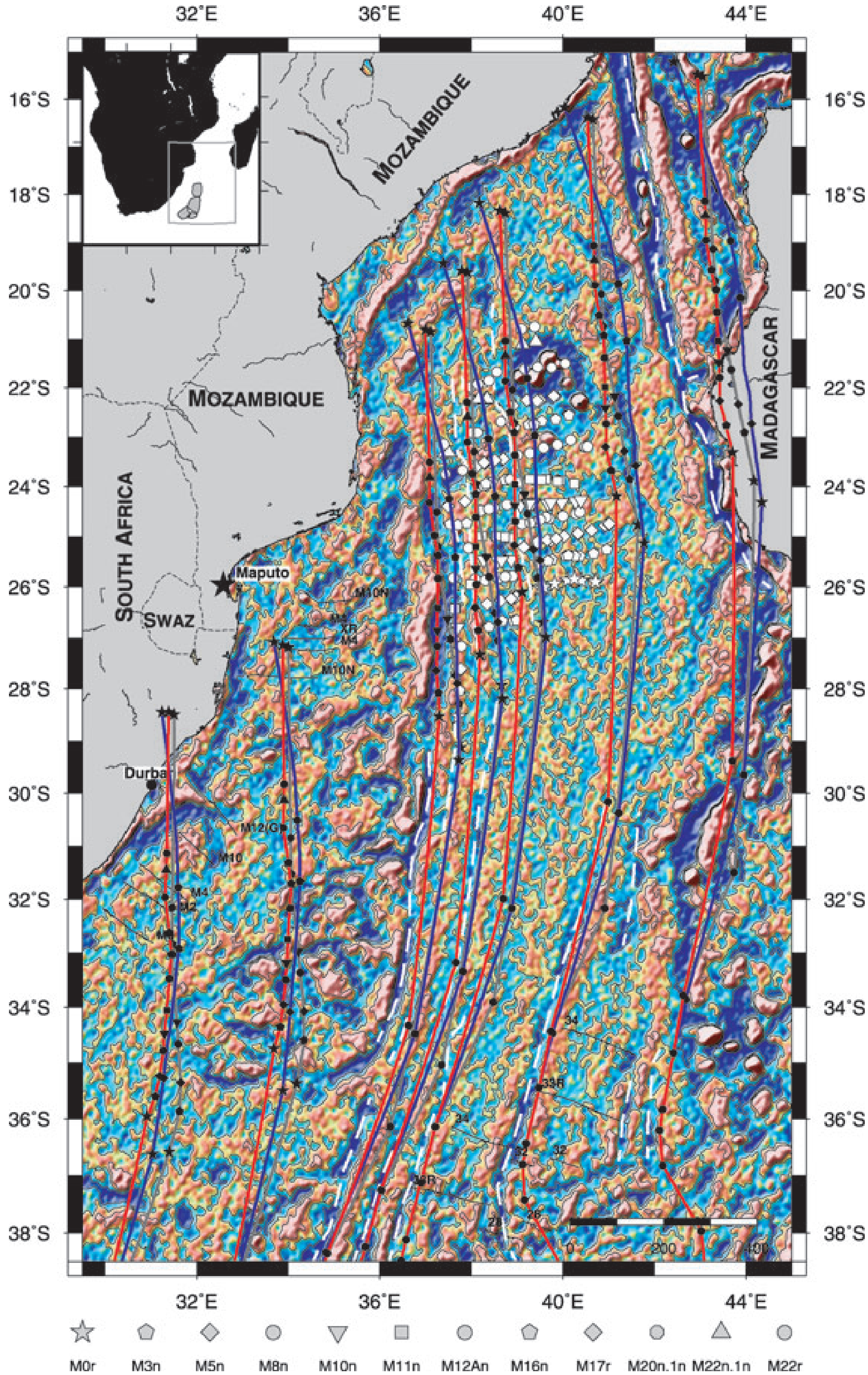

Figure 14. High pass filtered (cut-off at 250 km) free-air gravity anomaly map (after Sandwell & Smith 1997, 11.2) for the Mozambique Basin area showing the major fracture zones in the Mozambique Basin (white dashed line) and the segmentation of the Mozambique Ridge. Selected magnetic anomaly picks are plotted as white symbols and are compared to the flow lines calculated from different models: this study: red line; König & Jokat (2006): grey line; Eagles & König (2008): blue line. Note the difference in the position of M0r (white star) between the individual models.

have occurred (Fig. 16b). Possibly, at this time (150–145 Ma), the second wedge of SDRS in the Lazarev Sea was emplaced as well as parts of the Astrid Ridge at the junction between the active spreading centre in the Mozambique Basin and the extensional regime in the Lazarev Sea. An oceanic origin of the Astrid Ridge has already been proposed by Bergh (1987) and Roeser *et al.* (1996), and is further discussed by Hinz *et al.* (2004) and Jokat *et al.* (2004) based on the interpretation of seismic and magnetic data. The next phase of magmatism started only 5 Myr later with the emplacement of the northern plateau of the Mozambique Ridge at the prolongation of the Astrid Ridge at about 140 Ma. In this way, the Mozambique Ridge may have acted as an oceanic extension of

Table 4. Error estimates for the rotated magnetic anomaly picks.

Chron	Age	Misfit	*SD* (km)	AZ (°)	Misfit	*SD* (km)	AZ (°)	Misfit	SD (km)	AZ (°)
M0r	124.61	9.271	10.8	83.7				9.538	4.7	84.4
M3n	127.61	3.654	6.8	91.2	13.282	6.9	84.1	5.411	3.4	78.1
M5n	129.76	8.342	8.3	100.8	13.662	7.0	86.8	2.783	2.1	75.3
M8n	132.20	1.346	3.3	22.1	11.211	5.9	81.4	1.944	1.9	79.1
M10n	133.50	0.232	1.4	72.0	9.527	5.5	91.7	3.669	2.4	86.4
M11n	135.69				3.314	3.7	95.6	5.293	3.1	90.6
M12An	138.78				12.398	6.7	66.9	16.628	5.1	81.2
M16n	141.05				20.625	7.6	77.1	4.485	2.6	78.2
M17r	142.84				26.033	8.5	80.2	5.97	3.3	79.5
M20n.1n	146.16				10.728	6.7	66.7	15.884	5.5	84.8
M22n.1n	148.92				8.812	6.6	86.9	2.765	2.8	89.2
M22r	150.21							0.674	1.2	82.8
		Western segment			Central segment			Eastern segment		

Note: Misfit, standard deviation and azimuth of a great circle fitted to the rotated magnetic anomaly picks from the Riiser-Larsen Sea and the picks from the Mozambique Basin.

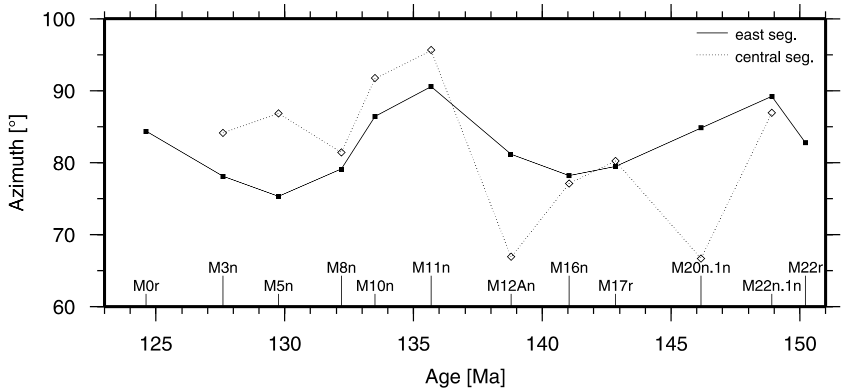

Figure 15. Azimuth of the best-fitting great circles calculated for each segment for all ages. Note the sinusoidal change in azimuth especially for the eastern segment through time.

the Antarctic continent as discussed by Martin & Hartnady (1986). The plate boundary between Africa and Antarctica thus extended from the Mozambique Basin–Riiser-Larsen Sea spreading system further west into the northern Natal Valley (Fig. 16c). Although no spreading anomalies north of the Mozambique Ridge could be identified, a continuation of the spreading system to the west cannot be excluded. Marks & Tikku (2001) propose a spreading ridge to be active in the northern Natal Valley for the time between M10N to M2 (134.30–127.61 Ma). They suggest that the Mozambique Ridge acted as an independent micorplate during that time. We included the rotation parameters from Marks & Tikku (2001) in our model, although they are not crucial. Another possible configuration of the plate boundaries suggests a precursor of the Astrid fracture zone being active along the eastern edge of the Mozambique Ridge, with the ridge being formed on the African Plate (question mark in Fig. 16c). Shortly before M11n (135.69 Ma), seafloor spreading started in the southern Natal Valley and the conjugate, the Georgia Basin, resulting in the separation of the Maurice Ewing Bank at the eastern end of the Falkland Plateau from the African continent (Fig. 16c). The opening of the Natal Valley and the Georgia Basin occurred in a northeast–southwest direction. Since the strike of the southwestern plateau of the Mozambique Ridge is almost perfectly parallel to this direction, we propose that this part of the ridge formed at an extension of the spreading system in the southern Natal Valley on the African Plate during the time frame between M11n (135.69 Ma) and M3n (127.61 Ma). The triple junction between Africa, South America and Antarctica was located just south of the ridge, and separated the ocean floor conjugate to the Mozambique Ridge into a South American and an Antarctic domain. There is no ocean floor left from the South American branch as it was later subducted beneath the Sandwich plate. However, east–west trending magnetic anomalies do exist in the magnetic anomaly data for the Lazarev Sea shown by Jokat *et al.* (2003) which match well with the trend of the inferred ridge axis between South America and Antarctica (thick black lines in Figs 16c and d). Additionally, further east in the Lazarev Sea we observe northwest–southeast trending lineations in the magnetic anomaly map of Jokat *et al.* (2003) which perfectly match with the southeastern boundary of the southwestern plateau of the Mozambique Ridge (Fig. 16d). The strike of these lineations is also parallel to the strike of the magnetic anomalies in the Riiser-Larsen Sea, indicating the same spreading direction for both spreading regimes. The middle plateau of the Mozambique Ridge probably started to develop at the same time as the southern part (M11n, 135.69 Ma) but volcanism there lasted longer and probably terminated at around M0r (124.61 Ma). Shortly after M0r (124.61 Ma), the Mozambique Ridge finally clears the coast of Dronning Maud Land and moves in a northeast direction along the Astrid fracture zone, as part of the African continent (Fig. 16e). During this final phase of separation, the southeastern part of the Mozambique Ridge may have formed while passing the Astrid Ridge. The triple junction between Africa, South America and Antarctica is still located south of the Mozambique Ridge, in today's area between the Agulhas

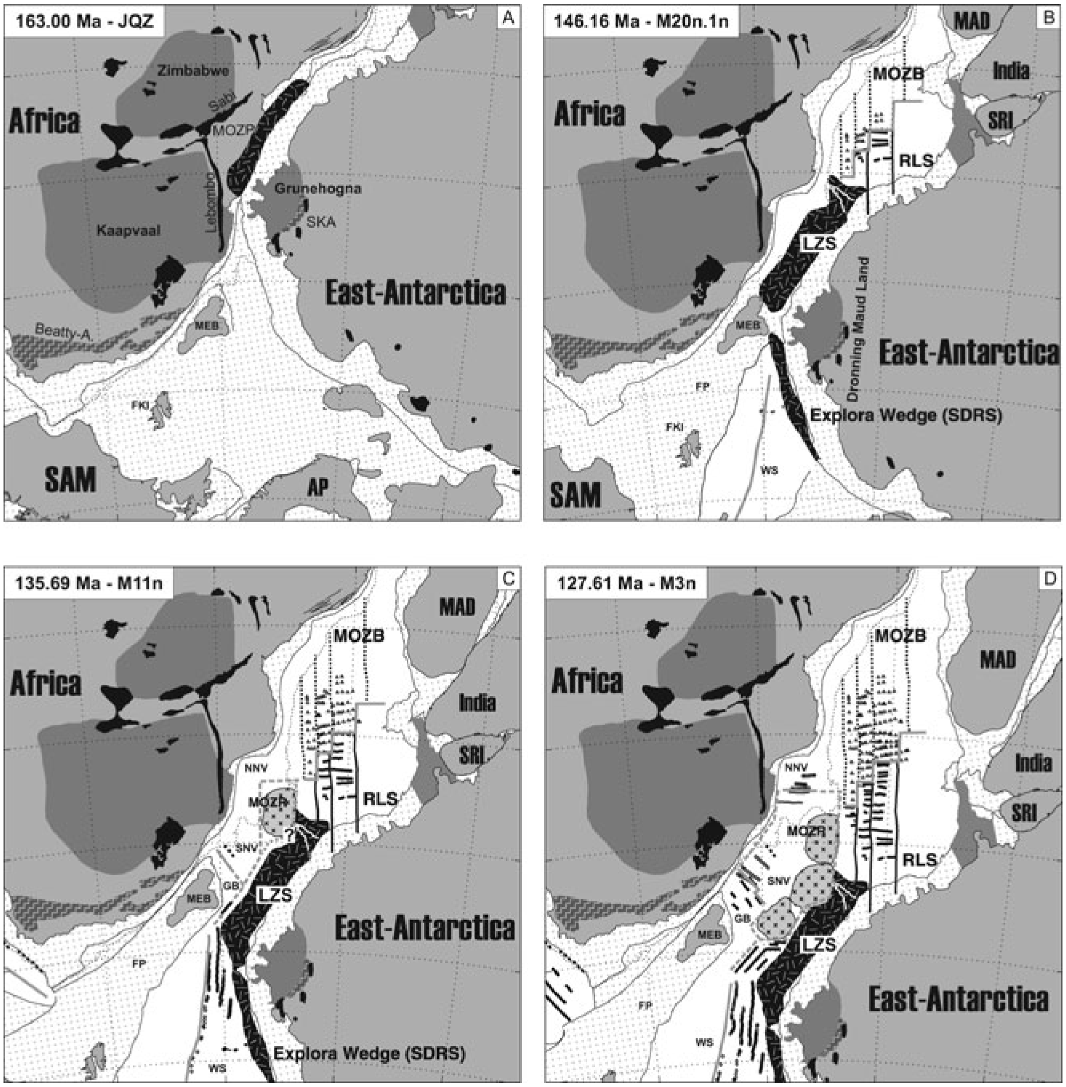

Figure 16. (a–e) Plate tectonic reconstructions showing significant steps in the evolution of the Mozambique Basin and its conjugate the Riiser-Larsen Sea and the successive development of the Mozambique Ridge and the Lazarev Sea. For a detailed discussion see the text. Black filled areas are Karoo basalts on the African and Antarctic continent (184 Ma). Black filled areas with white dashes are volcanic sequences offshore East Antarctica in the eastern Weddell Sea and the Lazarev Sea (184 Ma and *ca.* 150 Ma). Grey area with black crosses marks the Mozambique Ridge (*ca.* 140–120 Ma). Dark grey areas are representative for the Zimbabwe, Kaapvaal and Grunehogna Cratons. Dark grey areas with white lines are correlated deep seated magnetic anomalies in Africa and East Antarctica, the Beatty and Sverdrupfjella Kirwanveggen Anomalies. Ridge axes are highlighted as thick grey lines and magnetic anomalies are shown either as heavy black lines (RLS, GB, LZS) or open symbols like triangles (MOZB), squares (SNV) and diamonds (WS). Abbreviations: AP: Antarctic Peninsula, FKI: Falkland Islands, FP: Falkland Plateau, GB: Georgia Basin, LZS: Lazarev Sea, MAD: Madagascar, MEB: Maurice Ewing Bank, MOZB: Mozambique Basin, MOZP: Mozambique Plains, MOZR: Mozambique Ridge, NNV: Northern Natal Valley, RLS: Riiser-Larsen Sea, SAM: South America, SKA: Sverdrupfjella Kirwanveggen Anomaly, SNV: Southern Natal Valley, SRI: Sri Lanka, WS: Weddell Sea.

Plateau and the Mozambique Ridge. Seafloor spreading anomalies cannot be identified for this last phase of Africa–Antarctica separation since it occurred entirely during the Cretaceous Quiet Zone (84–124.6 Ma) between 124 and 120 Ma (Fig. 16e).

7 CONCLUSION

The new and high resolution magnetic anomaly data from the Mozambique Ridge and Mozambique Basin acquired during the expedition SO183 with R/V Sonne better constrains the spreading system between Africa and Antarctica and allows us to determine a well-defined model for the opening of the Mozambique Basin and its conjugate, the Riiser-Larsen Sea. While former models mostly suffered from a lack of significant data to identify M0r (124.61 Ma), we now have a good insight of the position of the first Mesozoic magnetic anomalies in the eastern and western sector of the Mozambique Basin. In the westernmost part of the basin, the identification of additional fracture zones shows that this region is more strongly segmented and disrupted than previously assumed. So far, corresponding features are not known from the westernmost Riiser-Larsen Sea. One problem is the magnetically overprinting character of the Astrid Ridge. The changing azimuth of the magnetic anomaly lineations in the Mozambique Basin and its correlation with a subsequent sudden increase in spreading rate at about M10r (133.87 Ma) suggests that this is related to the initial opening of the South Atlantic Ocean. The incipient opening of the neighbouring southern Natal Valley between the eastern scarp of the Falkland Plateau and

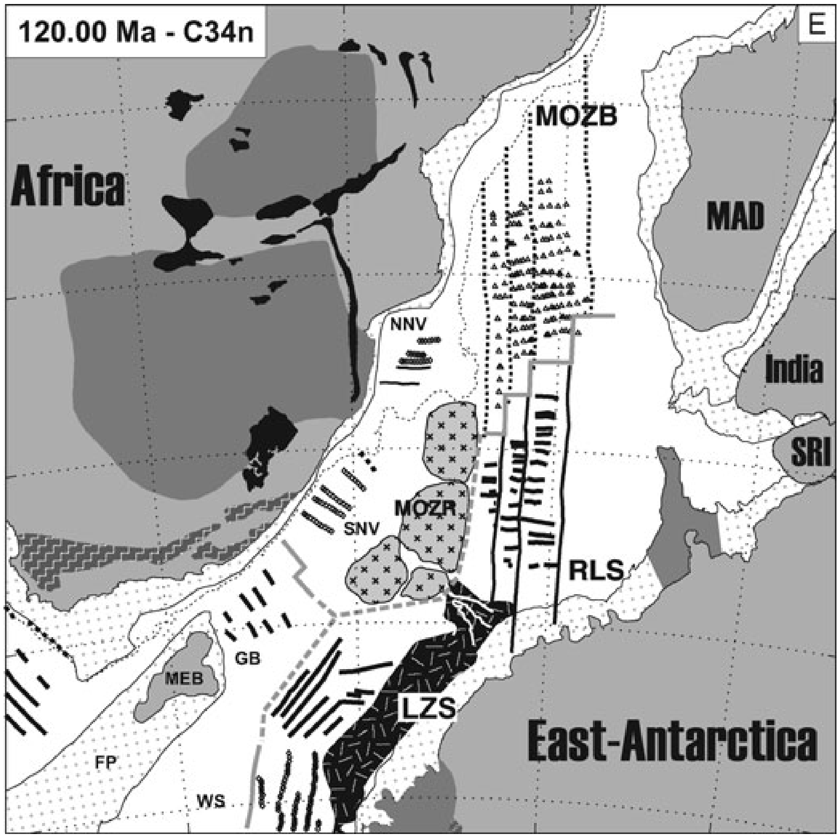

Figure 16. (*Continued.*)

the African continent may also have had its influence on the spreading regime in the Mozambique Basin between Africa and Antarctica. The magnetic anomaly data from the Mozambique Ridge allow the interpretation of the ridge as being of mostly volcanic origin, having evolved over a period of several million years. The modelling of the gravity and magnetic anomaly data of the ridge with blocks of normal and reversed remnant magnetization supports this hypothesis. Although continental affinity of the ridge cannot be excluded, we propose the ridge to be of purely oceanic origin. This assumption is used to build a plate tectonic model that clearly outlines the possible evolution of the Mozambique Ridge through time in an area of long lasting high volcanic productivity. Still unsolved in this context is the provenance of dredged rocks with continental affinity from the eastern scarp of the ridge (Mougenot *et al.* 1991) and from its southern boundary (Hartnady *et al.* 1992). These are probably remnants of smaller continental blocks that were displaced from the African continent during the phase of rifting between Africa and Antarctica in the continental Mozambique Plains. The timing for the beginning (140 Ma) and end (120 Ma) of the emplacement of the Mozambique Ridge is strongly dependent on the existence of a possible extinct spreading centre active in the northern Natal Valley as proposed by Marks & Tikku (2001). This spreading centre is not obligatory for our model, but it gives the ridge more time to evolve through time. The model presented here suggests that volcanic activity in the area of the Lazarev Sea and on- and offshore southeast Africa started already with the emplacement of the Karoo basalts at about 184 Ma (Encarnacion *et al.* 1996; Duncan *et al.* 1997), and continued with the emplacement of the two wedges of SDRS along the coast of Dronning Maud Land in the Lazarev Sea with ages of about 174 Ma or younger for the older wedge and 150–145 Ma for the younger wedge. Magmatism or even volcanism continued with the formation of the Mozambique Ridge between 140 and 122 Ma, and probably had its continuation with the development of the Agulhas Plateau, the Georgia Rise and Maud Rise during Early Cretaceous times (Parsiegla *et al.* 2008).

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REFERENCES

Ben-Avraham, Z., Hartnady, C.J.H. & le Roex, A.P., 1995. Neotectonic activity on continental fragments on the Southwest Indian Ocean: Agulhas Plateau and Mozambique Ridge, *J. geophys. Res.,* **100**(B4), 6199–6211.

Bergh, H.W., 1977. Mesozoic seafloor off Dronnig Maud Land, Antarctica, *Nature,* **269,** 686–687.

Bergh, H.W., 1987. Underlying fracture zone nature of Astrid Ridge off Antarctica‘s Queen Maud Land, *J. geophys. Res.,* **92**(B1), 475–484.

Cande, S.C., LaBrecque, J.L., Larson, R.L., Pittman, W.C., Golovchenko, X. & Haxby, W.F., 1989. *Magnetic Lineations of the World's Ocean Basins, Map,* American Association of Petroleum Geologists, Tulsa, Oklahoma.

Channell, J.E.T., Erba, E., Nakanishi, M. & Tamaki, K., 1994. Later Jurassic-Early Cretaceous time scales and oceanic magnetic anomaly block models, in *Geochronology, Time Scales and Global Stratigraphic Correlation,* Vol. 54, pp. 51–63, eds Berggren, W.A., Kent, D.V., Aubry, M.-P. & Hardenbol, J., SEPM, Society for Sedimentary Geology, Special Publication, Tulsa.

Chetty, P. & Green, R.W.E., 1977. Seismic refraction observations in the Transkei Basin and adjacent areas, *Mar. geophys. Res.,* **3,** 197–208.

Cox, K.G., 1992. Karoo igneous activity, and the early stages of the break-up of Gondwanaland, in *Magmatism and the Causes of Continental Break-up,* Vol. 68, pp. 137–148, eds Storey, B.C., Alabaster, T. & Pankhurst, R.J., Geological Society Special Publication, London.

Delius, H., Brewer, T.S. & Harvey, P.K., 2003. Evidence for textural and alteration changes in basaltic lava flows using variations in rock magnetic properties (ODP Leg 183), *Tectonophysics,* **371,** 111–140.

Duncan, R.A, Hooper, P.R., Rehacek, J.S., Marsh, J.S. & Duncan, A.R., 1997. The timing and duration of the Karoo igneous event, southern Gondwana, *J. geophys. Res.,* **102**(B8), 18127–18138.

Eagles, G. & König, M., 2008. A model of plate kinematics in Gondwana breakup, *Geophys. J. Int.,* **173**(2), 70–717.

Elliot, D.H. & Fleming, T.H., 2000. Weddell triple junction: The principal focus of Ferrar and Karoo magmatism during initial breakup of Gondwana, *Geology,* **28**(6), 539–542.

Encarnacion, J., Fleming, T.H., Elliot, D.H. & Eales, H.V., 1996. Synchronous emplacement of Ferrar and Karoo dolerites and the early breakup of Gondwana, *Geology,* **24**(6), 535–538.

Erlank, A.J. & Reid, D.L., 1974. Geochemistry, mineralogy, and petrology of basalts, LEG 25, Deep Sea Drilling Project, in *Initial Reports of the Deep Sea Drilling Project,* Vol. 25, pp. 543–551, eds Simpson, E.S.W. & Schlich, R., U.S. Government Printing Office, Washington.

Ewing, M., Ettreim, S., Truchah, M. & Ewing, J.I., 1969. Sediment distribution in the Indian Ocean, *Deep Sea Res.,* **16,** 231–248.

Gohl, K. & Uenzelmann-Neben, G., 2001. The crustal role of the Agulhas Plateau, southwest Indian Ocean: evidence from seismic profiling, *Geophys. J. Int.,* **144,** 632–646.

Gohl, K., Uenzelmann-Neben, G. & Parsiegla, N., submitted. Is the Mozambique Ridge related to the Agulhas Plateau Large Igneous Province? *Geology*, submitted.

Goodlad, S.W., Martin, A.K. & Hartnady, J.H., 1982. Mesozoic magnetic anomalies in the southern Natal Valley, *Nature,* **295,** 686–688.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., Van Veen, P., Thierry, J. & Huang, Z., 1994. A Triassic, Jurassic and Cretaceous Time Scale, in *Geochronology Time Scales and Global Stratigraphic Correlation,* Vol. 54, pp. 95–126, eds Berggren, W.A., Kent, D.V., Aubry, M.-P. & Hardenbol, J., SEPM, Society for Sedimentary Geology, Special Publication, Tulsa.

Gradstein, F.M., Ogg, J.G., Smith, A.G., Bleeker, W. & Lourens, L.J., 2004. A new Geologic Time Scale, with special reference to Precambrian and Neogene, *Episodes,* **27**(2), 83–100.

Green, A.G., 1972. Sea-floor spreading in the Mozambique Channel, *Nature,* **236,** 19–21.

Hales, A.L. & Nation, J.B., 1973. A seismic refraction study in the Southern Indian Ocean, *Bull. seism. Soc. Am.,* **63**(6), 1951–1966.

Hartnady, C.J.H., Ben-Avraham, Z. & Rogers, J., 1992. Deep-ocean basins and submarine rises off the continental margin of southeastern Africa, new geological research developemtens, *S. Afric. J. Sci,* **88,** 534–539.

Heine, C.R., Müller, D. & Gaina, C., 2004. Reconstruction of the Lost Eastern Thety Ocean Basin: Convergence History of the SE Asian Margin and Marine Gateways, in *Continent-Ocean interactions within East Asian Marginal Sea,* Vol. 149, pp. 37–54, eds Clift, P., Kuhnt, W., Wang, P. & Hayes, D., American Geophysical Union, Washington, DC.

Hellinger, S.J., 1981. The Uncertainties of Finite Rotations in Plate Tectonics, *J. geophys. Res.,* **86**(B10), 9312–9318.

Hinz, K., Neben, S., Gouseva, Y.B. & Kudryavtsev, G.A., 2004. A Compilation of Geophysical Data from the Lazarev Sea and the Riiser-Larsen Sea, Antarctica, *Mar. geophys. Res.,* **25,** 233–245.

Jokat, W., Boebel, T., König, M. & Meyer, U., 2003. Timing and geometry of early Gondwana breakup, *J. geophys. Res.,* **108**(B9), 2428, doi:10.1029/2002JB001802.

Jokat, W., Ritzmann, O., Reichert, C. & Hinz, K., 2004. Deep crustal structure of the continental margin off the Explora Escarpment and in the Lazarev Sea, East Antarctica, *Mar. geophys. Res.,* **25,** 283–304.

Jokat, W., and shipboard scientific party, 2006. Southeastern Atlantic and southwestern Indian Ocean: reconstruction of the sedimentary and tectonic development since the Cretaceous AISTEK-II: Mozambique Ridge and Mozambique Basin, *Rep. Polar . Mar. Res.,* **521,** 13–16.

Jourdan, F., Féraud, G. Bertrand, H. & Watkeys, M.K., 2007. From flood basalts to the inception of oceanization: Example fom 40Ar/39Ar high-resolution picture of ther Karoo large igneous province, *Geochem. Geophys. Geosyst.,* **8,** Q02002, doi:10.1029/2006GC001392.

Kent, D.V. & Gradstein, F.M., 1986. A Jurassic to recent chronology, in *The Geology of North America,* Vol. M, The Western North Atlantic Region, pp. 45–50, eds Vogt, P.R. & Tucholke, B.E., Geological Society of America, Boulder, Colorado.

König, M. & Jokat, W., 2006. The Mesozoic breakup of the Weddell Sea, *J. geophys. Res.,* **111**(B12), 102, doi:10.1029/2005JB004035.

Larson, R.L. & Hilde, T.W.C., 1975. A revised time scale of magnetic anomalies for the Early Cretaceous and Late Jurassic, *J. geophys. Res.,* **80,** 2586–2594.

Laughton, A.S., Matthews, D.H. & Fisher, R.L., 1970. The Structure of the Indian Ocean, in *The Sea,* Vol. 4, 2, pp. 543–586, ed. Maxwell, A.E., Wiley, New York.

Lawver, L.A., Gahagan, L.M. & Dalziel, I.W.D., 1998. A tight fit Early Mesozoic Gondwana, a plate reconstruction perspective, *Mem. Natl. Inst. Polar Res.,* **53,** 203–213.

Livermore, R.A. & Hunter, J., 1996. Mesozoic seafloor spreading in the southern Weddell Sea, in *Weddell Sea Tectonics and Gondwana Break-up,* Vol. 108, pp. 227–241, eds Storey, B.C., King, E.C. & Livermore, R.A., Geological Society Special Publication, London.

Ludwig, W.J., Nafe, J.E., Simpson, E.S.W. & Sacks, S., 1968. Seismic Refraction Measurements on the Southeast African Continental Margin, *J. geophys. Res.,* **73**(12), 3707–3719.

Maia, M., Diament, M. & Recqu, M., 1990. Isostatic response of the lithosphere beneath the Mozambique Ridge (SW Indian Ocean) and geodynamic implications, *Geophys. J. Int.,* **100,** 337–348.

Martin, A.K. & Hartnady, C.J.H., 1986. Plate tectonic development of the South West Indian Ocean: A revised reconstruction of East Antarctica and Africa, *J. geophys. Res.,* **91**(B5), 4767–4786.

Marks, K.M. & Tikku, A.A., 2001. Cretaceous reconstructions of East Antarctica, Africa and Madagascar, *Earth planet. Sci. Lett.,* **186,** 479–495.

Matias, L.M., Olivet, J.-L., Aslanian, D. & Fidalgo, L., 2005. PLACA: a white box for plate reconstruction and best-fit pole determination, *Comput. Geosci.,* **31,** 437–452.

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

Mougenot, D., Gennesseaux, M., Hernandez, J., Lepvrier, C., Malod, J.-A., Raillard, S., Vanney, J.-R. & Villeneuve, M., 1991. La ride du Mozambique (Océan Indien): un fragment continental individualisé lors du coulissement de lAmérique et de lAntarctique le long de lAfrique de lEst? *Comptes Rendus de l'Académie des Sciences, Series II,* **312,** 655–662.

Norton, I.O. & Sclater, J.G., 1979. A model for the evolution of the Indian Ocean and the breakup of Gondwanaland, *J. geophys. Res.,* **84**(B12), 6803–6830.

Parsiegla, N., Gohl, K. & Uenzelmann-Neben, G., 2008. The Agulhas Plateau: structure and evolution of a Large Igneous Province, *Geophys. J. Int.,* **174,** 336–350, doi:10.1111/j.1365–246X.2008.03808.x.

Raillard, 1990. Les Marges de l'Afrique de l'est et les Zones de Fracture associées: Chaine Davie et Ride du Mozambique, *PhD thesis*. Université Paris, Paris.

Recqu, M. & Goslin, J., 1981. Etude de l'Equilibre isostatique dans le sud-ouest de l'Ocean Indien a l'Aide des Resultates de Refraction sismique, *Mar. Geol.,* **41,** M1–M10.

Roeser, H.A., Fritsch, J. & Hinz, K., 1996. The development of the crust off Dronning Maud Land, east Antarctica, in *Weddell Sea Tectonics and Gondwana Break up,* Vol. 108, pp. 243–264, eds Storey, B.C., King, E.C. & Livermore, R.A., Geological Society Special Publication, London.

Royer, J.-Y. & Chang, T., 1991. Evidence for relative motions between the Indian and Australian Plates during the Llast 20 m.y. From Plate Tectonic Reconstructions: Implications for the Deformation of the Indo-Australian Plate, *J. geophys. Res.,* **96**(B7), 11779–11802.

Saito, T. & Fray, C., 1964. Cretaceous and tertiary sediments from the southwestern Indian Ocean, *Geol. Soc. Am. Special Paper,* **82,** 171–172.

Sandwell, D.T. & Smith, W.H.F., 1997. Marine gravity anomaly from Geosat and ERS 1 satellite altimetry, *J. geophys. Res.,* **102,** 10039–10054.

Schlüter, P. & Uenzelmann-Neben, G., 2007. Indications for bottom current activity since Eocene times: the climate and ocean gateway archive of the Transkei Basin, South Africa, *Global planet. Change,* **60**(3-4), 416–428, doi:10.1016/j.gloplacha.2007.07.002.

Sclater, J., G., Munschy, M., Fisher, R.L., Weatherall, P., Cande, S.C., Patriat, P., Bergh, H. & Schlich, R., 1997. *Geophysical synthesis of the Indian/Southern Oceans: Part I, The Southwest Indian Ocean,* Ref. Series 97–6, 68 pp., Scripps Institute of Oceanography, La Jolla, California, USA.

Segoufin, J., 1978. Anomalies magnétiques mésozoïques dans le bassin de Mozambique, *Comptes Rendus de l'Académie des Sciences,* **287,** 109–112.

Segoufin, J. & Patriat, P., 1980. Existence d'anomalies mésozoiques dans le bassin de Somalie. Implications pour les relations Afrique-Antarctique-Madagascar, *Comptes Rendus de l'Académie des Sciences,* **291,** 85–88.

Simpson, E.S.W., 1974. *Initial Reports of the Deep Sea Drilling Project,* Vol. 25, pp. 259–346, U.S. Government Printing Office, Washington, USA.

Simpson, E.S.W., Sclater, J.G., Parsons, B., Norton, I. & Meinke, L., 1979. Mesozoic magnetic lineations in the Mozambique Basin, *Earth planet. Sci. Lett.,* **43,** 260–264.

Smith, W.H.S. & Sandwell, D.T., 1997. Global Sea Floor topography from satellite altimetry and ship depth soundings, *Science,* **277,** 1956–1962.

Spector, A. & Grant, F.S., 1970. Statistical Models for Interpreting Aeromagnetic Data, *Geophysics,* **35**(2), 293–302.

Tikku, A.A., Marks, K. & Kovacs, L.C., 2002. An Early Cretaceous extinct spreading center in the northern Natal Valley, *Tectonophysics,* **347,** 87–108.

Tivey, M.A., Sager, W.W., Lee, S.-M. & Tominaga, M., 2006. Origin of the Pacific Jurassic quiet zone, *Geology,* **34**(9), 789–792.

Treitel, S., Clement, W.G. & Kaul, R.K., 1971. The spectral determination of depth to buried magnetic basement rocks, *Geophys. J. R. astr. Soc.,* **24,** 415–428.

Tucholke, B.E., Houtz, R.E. & Barrett, D.M., 1981. Continental crust beneath the Agulhas Plateau, Southwest Indian Ocean, *J. geophys. Res.,* **86**(B5), 3791–3806.

Uenzelmann-Neben, G., 2005. Southeastern Atlantic and southwestern Indian Ocean: reconstruction of the sedimentary and tectonic development since the Cretaceous AISTEK-I: Agulhas Transect, *Rep. Polar Mar. Res.,* **515,** 73 pp.