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The Mesozoic breakup of the Weddell Sea

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[1] A new set of rotations is presented that describes a refined model for the early opening of the Weddell Sea between South America and Antarctica and the Mesozoic breakup of Gondwana. Published high-resolution aeromagnetic data from the eastern Weddell Sea and additional track data farther west in the Weddell Sea were used to constrain the new model for the opening of the Weddell Sea. Rotation parameters derived for the South America–Antarctica spreading regime were combined with constraints on the South America–Africa and Africa-Antarctica spreading systems to calculate a refined model for the Mesozoic breakup of Gondwana. Thereafter, at the time when the north-south oriented separation between Africa and Antarctica is initiated by rifting in the Somali and Mozambique basins ($\sim$167 Ma), stretching and extension takes place in a basin comprising continental crust of the Filchner-Ronne Shelf, the Falkland Island block and the Maurice Ewing Bank. The first true ocean floor in the Weddell Sea is formed at about 147 Ma, after rifting between the Antarctic Peninsula and southernmost South America occurred. This is about 15–20 Myr later than previously estimated. Separation between South America and Antarctica takes place at slow spreading rates (14–12 mm/yr half rate) from 147 to 122 Ma and after 122 Ma (M2) at ultraslow spreading rates ($\sim$8 mm/yr half rate) with little change in the NNW spreading direction throughout this time. A revised age range is proposed for the formation of the Explora Wedge (150–138 Ma), which is more than 30 Myr later than previously published ($\sim$183 Ma).

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1. Introduction

[2] Detailed knowledge of plate motions during the early breakup of Gondwana in the region of the South Atlantic Ocean is essential to describe the Mesozoic changes in paleoceanography and terrestrial environment. While recent investigations have put strong constraints on the movements between Africa (AFR) and Antarctica (ANT) for the time between initial rifting and 118 Ma (M0) [*Jokat et al.*, 2003a] and for the time between 96 Ma till present [*Bernard et al.*, 2005], much uncertainty still exists about the geometrical fit and subsequent drift history between South America (SAM) and ANT. Geophysical and geological data which describe the tectonic history between these two continents, are sparsely distributed and often of poor quality [i.e., *Ghidella et al.*, 2002; *Jokat et al.*, 2003a]. This is mostly due to the remoteness of the region, with parts of it being covered by ice for almost the entire year. Additionally, seafloor spreading anomalies from the spreading system between SAM and ANT are strongly subdued in the southern Weddell Sea, where the oceanic basement is covered by several kilometers of sediments [*LaBrecque and Ghidella*, 1997; *Rogenhagen and Jokat*, 2000]. Thus valuable information on the age of the ocean floor is hard to interpret for the ANT side of the spreading system. The situation on the SAM side is even worse. There, the ocean floor containing geochronological information about the evolution of the plate pair has been destroyed by subduction beneath the overriding Sandwich plate.

[3] On the basis of these ambiguous data, a great number of different and differing models for the early opening of the Weddell Sea and the tectonic evolution of its neighboring continents have been developed in the last 25 years [*Barker and Jahn*, 1980; *LaBrecque and Barker*, 1981; *Martin et al.*, 1982; *Martin and Hartnady*, 1986; *Lawver et al.*, 1992; *Storey et al.*, 1996; *Ghidella and LaBrecque*, 1997; *LaBrecque and Ghidella*, 1997; *Ghidella et al.*, 2002; *Kovacs et al.*, 2002]. Some of these models describe the early breakup of Gondwana as a two-plate problem between rigid East (ANT, India, Madagascar) and West Gondwana (AFR and SAM) plates [*Lawver et al.*, 1992; *Livermore and Hunter*, 1996; *Reeves and de Wit*, 2000]. Common to these reconstructions is a large strike-slip movement (several 100 km) between southernmost SAM, represented by the Falkland Plateau, and ANT.

[4] From the interpretation of a new high-resolution aeromagnetic data set covering large areas in the eastern Weddell Sea, the Lazarev Sea, and Riiser-Larsen Sea, *Jokat et al.* [2003a] propose an alternative model for the early stages of Gondwana breakup. Although focussing on the AFR-ANT sector, they show that extensional forces were

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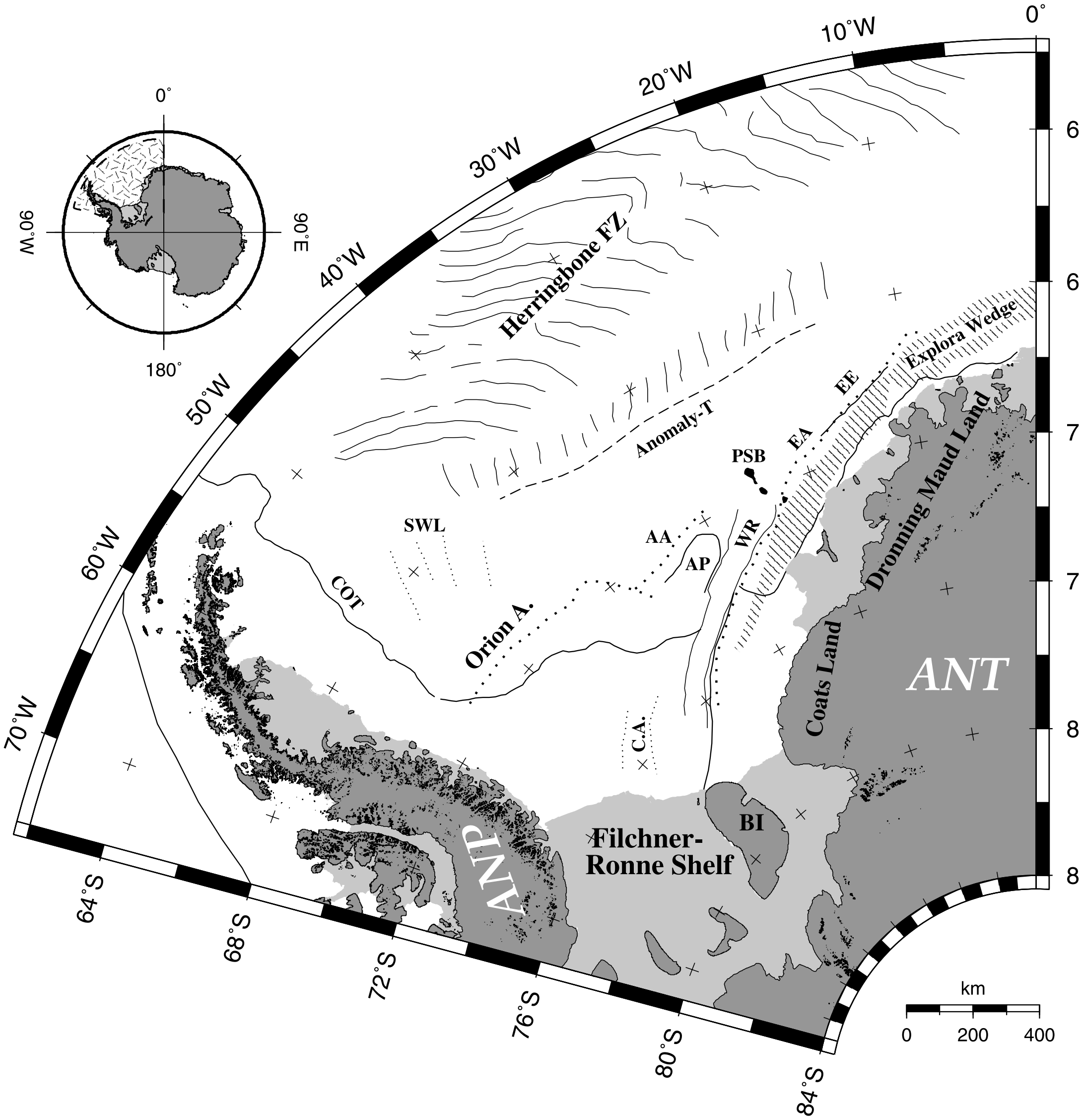

Figure 1. Tectonic overview of the Weddell Sea. The dominant features are the Orion Anomaly and the Explora Wedge (hatched area) in the southern and eastern Weddell Sea and the Herringbone fracture zone pattern in the northern Weddell Sea. Abbreviations are AA, Andenes Anomaly; ANP, Antarctic Peninsula; AP, Andenes Plateau; BI, Berkner Island; C.A., central anomalies [after *Ferris et al.*, 2000]; COT, continent-ocean transition; EA, Explora Anomaly; EE, Explora Escarpment; PSB, Polarstern Bank; SWL, southwest striking lineations [after *Ghidella et al.*, 2002]; WR, Weddell Rift.

active in the Weddell Sea and between SAM and AFR since the beginning of seafloor spreading in the Mozambique Basin and Riiser-Larsen Sea (160 Ma). Thus a three-plate system (SAM, AFR, ANT) was active since the beginning of the disintegration of Gonwana. In this study, we combined the extensive magnetic database, as presented by *Jokat et al.* [2003a], with other published aeromagnetic and shipborne track data farther west in the Weddell Sea to redate identified seafloor spreading anomalies in the central Weddell Sea and build a detailed model for the opening of this ocean basin. With the constraints from this spreading regime and an extensive database defining movements between SAM, AFR, and ANT, a more complete Gondwana breakup model is derived. This model, and the resulting implications for the tectonic evolution of ocean basins and continents, is presented and discussed in this paper.

2. Background

[5] The major tectonic features of the Weddell Sea (Figure 1) were investigated in the 1970s and 1980s by magnetic, bathymetric, gravimetric and seismic surveys of various nations (Germany, Great Britain, Japan, Norway, Russia, USA). Knowledge of the geodynamics of the southwestern Weddell Sea was significantly enhanced by the accomplishment of airborne surveys (magnetics and gravimetry) like the U.S.–Argentina-Chile (USAC) Project between 1985 and 1989 [*LaBrecque et al.*, 1986; *LaBrecque*, 1987; *LaBrecque et al.*, 1989] or the reconnaissance flights

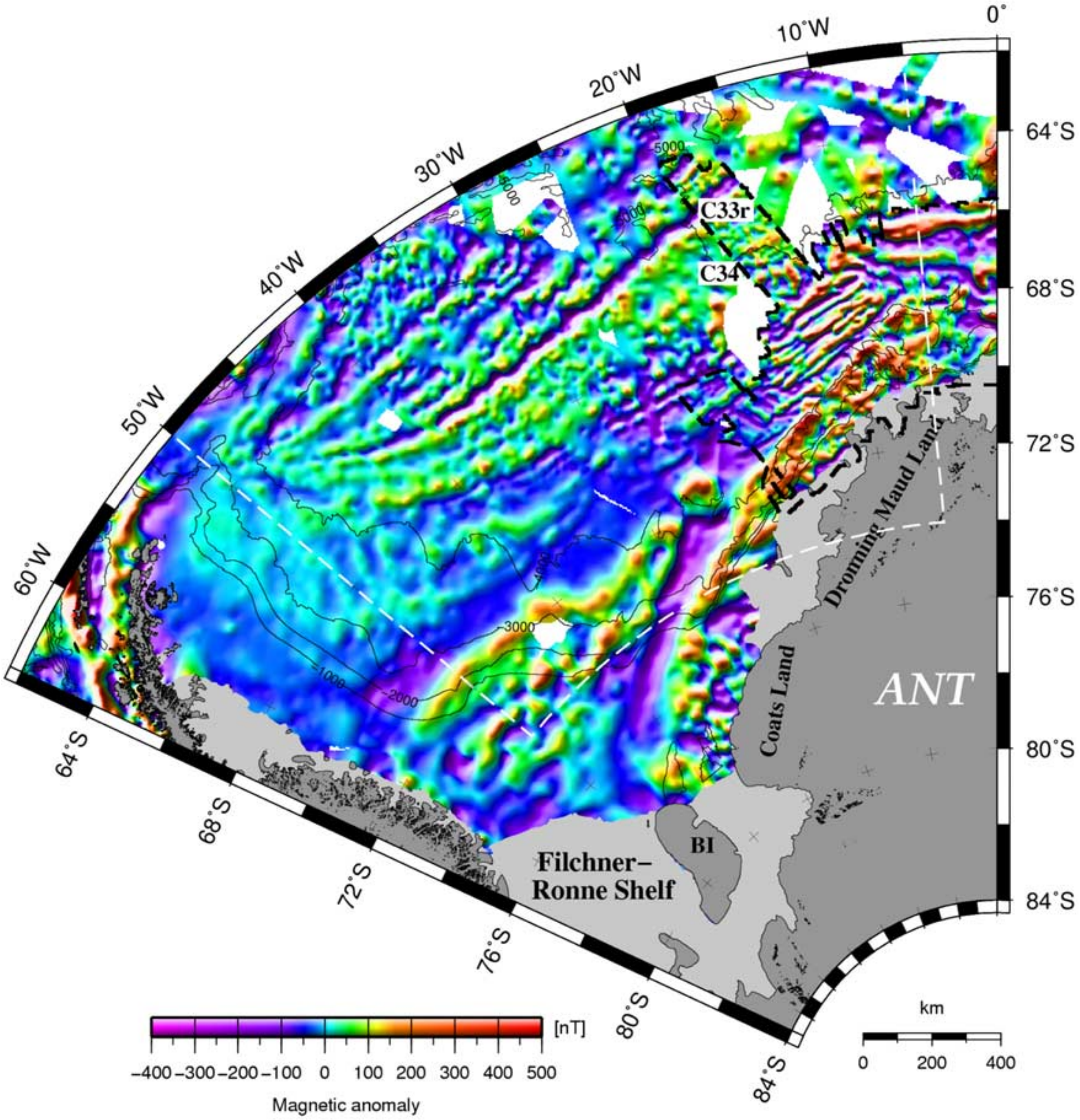

Figure 2. Combined magnetic anomaly map showing the ADMAP compilation [*Golynsky et al.*, 2001] for the Weddell Sea sector and the EMAGE compilation [*Jokat et al.*, 2003a] in the eastern Weddell Sea and the Lazarev Sea. The area covered by the EMAGE data set is outlined by a thick dashed line. Both grids were interpolated on 2 × 2 min grid cells. The most prominent magnetic anomalies are labeled as C33r and C34. The white dashed line marks the area of detailed investigation displayed in Figure 5.

by Russian Antarctic expeditions in the years 1979 to 1989 [*Masolov*, 1980; *Golynsky and Aleshkova*, 2000]. As part of the Antarctic Digital Magnetic Anomaly Project (ADMAP), these magnetic data were merged into a single data set together with a vast number of additional airborne and shipborne track data. From this extensive magnetic database, a regional magnetic anomaly grid was calculated, as presented by *Golynsky et al.* [2001] (Figure 2). This grid covers almost the complete western and central Weddell Sea but has significant gaps in the eastern Weddell Sea and the Lazarev Sea. The recently acquired (1996–2002) high-resolution aeromagnetic data set of the East Antarctic Margin Aeromagnetic and Gravity Experiment (EMAGE) [*Jokat et al.*, 2003a] closes one of the outstanding gaps not covered by previous expeditions (Figure 2). While the area between 20°W and 8°E was only sparsely covered by a loose network of ship tracks, a dense network of aeromagnetic flight lines was provided by the EMAGE project for this region. As shown by *Jokat et al.* [2003a], this data set yields significant information on the age of the ocean floor north of Dronning Maud Land.

[6] The *Kent and Gradstein* [1986] timescale will be used throughout this paper, in order to easily integrate our work with age models for Mesozoic breakup of Gondwana from earlier regional studies. Wherever possible, we cite magnetic chron identifications, in anticipation of revised ages using *Gradstein et al.* [2004] or future timescales. On the magnetic anomaly map (Figure 2), east-west oriented sea-

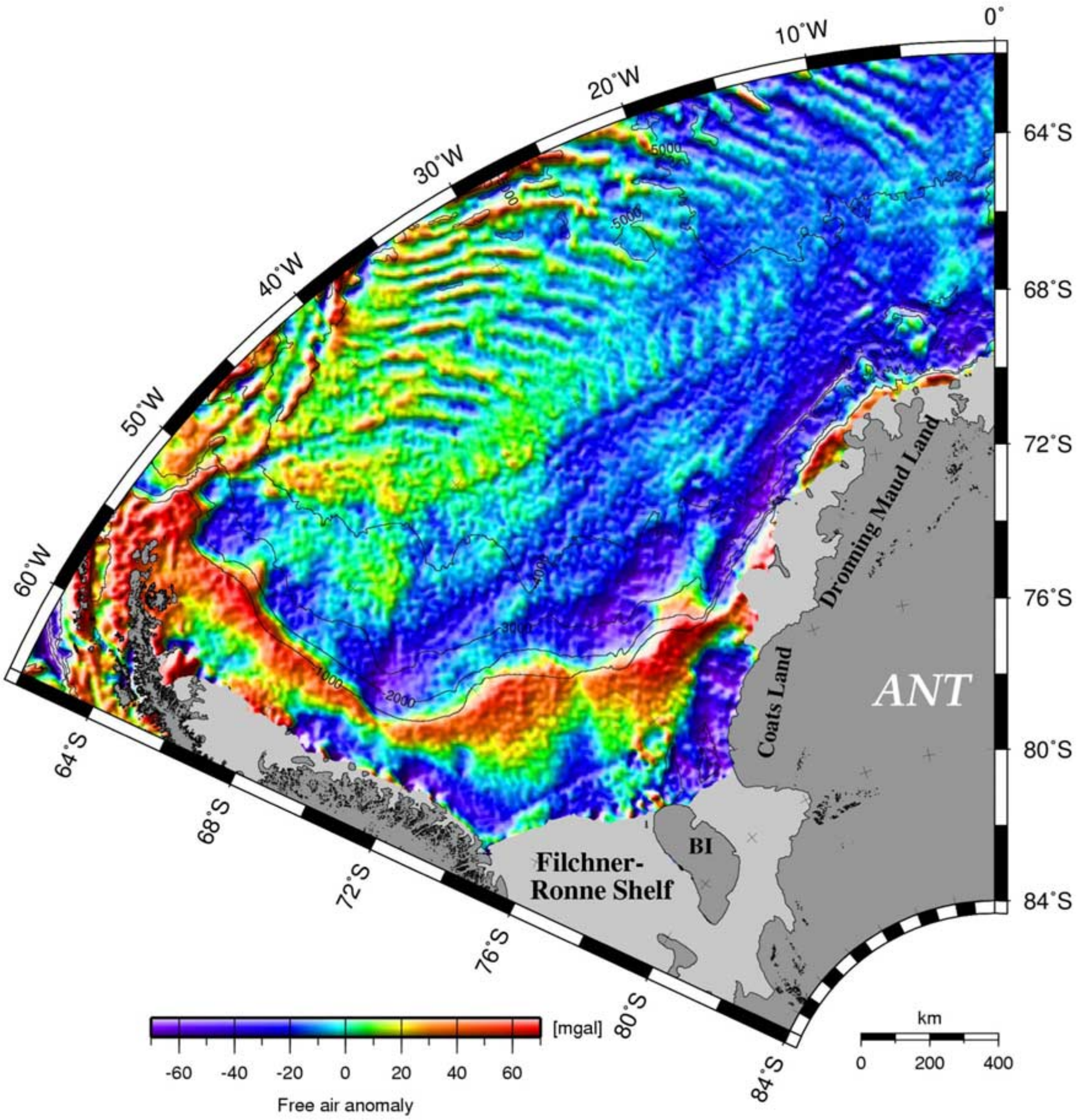

Figure 3. Free-air gravity anomaly map after *McAdoo and Laxon* [1997] calculated on 2 × 2 min cells. The Herringbone Fracture Zone pattern in the northern Weddell Sea is clearly identifiable.

floor spreading anomalies are clearly visible between 45°W and 15°W in the northern Weddell Sea. The most significant anomaly is the strong negative polarity anomaly C33r (79 Ma) at about 65°S. This is followed to the south by the onset of C34 (83–118 Ma), the Cretaceous normal polarity superchron. The amplitudes of the magnetic anomalies are strongly reduced south of C34, in the central Weddell Sea. Precise dating of this part of the ocean floor is difficult and rather tentative as reported, for example, by *Livermore and Hunter* [1996] and *Ghidella et al.* [2002]. At 70°S between 55°W and 40°W, an elongated magnetic anomaly high, named the Orion Anomaly by *LaBrecque et al.* [1986], is juxtaposed with an area of low magnetic amplitudes farther north. The dominant feature along the west coast of Dronning Maud Land is a continuous magnetic anomaly high of several hundred kilometers length and amplitudes of up to 500 nT. This is the Explora Anomaly [*Johnson et al.*, 1992; *Hunter et al.*, 1996]. Its tectonic origin and relevance will be discussed later in this paper.

[7] Another comprehensive data set is provided by the means of satellite altimetry [*Haxby*, 1988; *McAdoo and Marks*, 1992a, 1992b]. The latest and most detailed compilation for the Weddell Sea was released by *McAdoo and Laxon* [1997], who calculated a free-air gravity anomaly grid from retracked phase waveform data from the ERS-1 satellite (Figure 3). The most prominent feature revealed by this free-air gravity anomaly grid is a pattern of closely spaced curvilinear gravity highs and lows in the northern Weddell Sea [*Haxby*, 1988] (Figure 3). These anomalies are caused by fracture zones resulting from seafloor spreading between SAM and ANT [*Haxby*, 1988; *Livermore and Woollett*, 1993]. A combination of magnetic anomaly data with this herringbone pattern [*Livermore and Hunter*, 1996]

of flow lines indicates a WNW-ESE directed spreading regime being active from before magnetic anomaly C34 (83 Ma) until the present [*Livermore et al.*, 2006]. South of the well-defined onset of C34, the direction of the flow lines, and consequently the earlier spreading direction, changes to NNE-SSW. Precise dating of this event is difficult since it occurs entirely within the Cretaceous normal polarity superchron [*Livermore and Hunter*, 1996]. The southern part of the fracture zone pattern is bound to the south by a linear east-west oriented low amplitude gravity anomaly, termed Anomaly T by *Livermore and Hunter* [1996] (Figures 1 and 3). A continuation of the fracture-zone-related gravity anomalies across Anomaly T was mentioned by *Livermore and Hunter* [1996] and *McAdoo and Laxon* [1996], but the anomalies are rather vague and were not included in their interpretations. Anomaly T is interpreted as the gravity expression of an abrupt decline in spreading rate [*Livermore and Hunter*, 1996; *Rogenhagen and Jokat*, 2000]. Because of uncertainties in the identification of the magnetic anomalies older than C34 (83 Ma), Anomaly T could only be tentatively dated at between M0 (118 Ma) and M4 (126 Ma) in these publications. From the interpretation of marine geophysical data (seismic and gravity), *Rogenhagen and Jokat* [2000] confirm the interpretation of Anomaly T as being related to a decrease in spreading velocity during the opening between SAM and ANT. However, they are able to show that this gravity anomaly is not caused by a basement step as proposed by *Livermore and Hunter* [1996], or an inactive ridge as suggested by *Barker and Jahn* [1980].

[8] Despite the existence of regional potential field data sets and thousand of kilometers of seismic lines in the central Weddell Sea, the structure and age of the oceanic crust south of Anomaly T is still only sparsely known. One major problem that arises from uncertainties in the crustal structure is the definition of the boundary between continental and oceanic crust. This problem exist not only for the southern Weddell Sea and its boundary to the Filchner-Ronne Shelf as part of the East Antarctic continent, but also for many other continental margins. Often this is rather a broad area forming a zone of transition between purely continental and oceanic crust and is called COT (continent-ocean transition). However, for the purpose of plate reconstructions and their limited resolution, this transitional area was approximated by a straight line, in this study. It is believed that the prominent Orion magnetic anomaly (Figures 1 and 2) marks the northern limit of the COT in the southwestern Weddell Sea [*LaBrecque et al.*, 1986; *Ghidella et al.*, 1991; *Ghidella and LaBrecque*, 1997; *Ferris et al.*, 2000; *Hübscher et al.*, 1996]. The Orion anomaly is the southernmost pronounced magnetic anomaly and may be formed over extensive volcanic rocks that erupted at a volcanic rifted margin during the final breakup between SAM and ANT. The southern boundary of the COT may be located farther south below the Filchner-Ronne Shelf along the long wavelength gravity high between 72°S, 50°W and 74°S, 30°W (Figure 3) and the 500 m isobath [*Jokat et al.*, 1996]. If this assumption is true, a long phase of extension and rifting took place in the southern Weddell Sea before the onset of seafloor spreading. Since no wide angle seismic data exist across the Orion anomaly to give more information on the deeper structure of the source body, no definite solution to this problem can be proposed. Along the eastern margin of the Antarctic Peninsula (ANP), the COT is marked by a strong linear north-south striking gravity gradient between 54°W and 56°W [*Bell et al.*, 1990; *Brozena et al.*, 1990] (Figure 3). The low-amplitude magnetic anomalies along the entire margin, the thick sedimentary overburden, and the characteristic bathymetry, caused *Ghidella and LaBrecque* [1997] to suggest that the eastern margin of the ANP is a nonvolcanic rifted margin. *Ferris et al.* [2000], on the other hand, interpret the sharply defined, straight nature of the gravity signal as typical of a sheared margin. The eastern margin of the Weddell Sea, bound by the coast of western Dronning Maud Land, is a volcanic rifted margin [*Hinz and Krause*, 1982; *Kristoffersen and Haugland*, 1986]. A continuous pattern of seaward dipping reflectors, named the Explora Wedge [*Hinz*, 1981] (Figure 1), forms part of this volcanic margin between 25°W–0°W. Between 20°W and 10°W, the Explora Wedge coincides with the Explora Escarpment (Figure 1), a pronounced bathymetric feature [*Hinz and Krause*, 1982; *Kristoffersen and Haugland*, 1986; *Hinz and Kristoffersen*, 1987; *Miller et al.*, 1990; *Kaul*, 1991]. The Explora Anomaly represents the magnetic expression of this structural boundary. The anomaly was correlated with the seaward dipping reflectors of the Explora Wedge by *Kristoffersen and Hinz* [1991]. *Jokat et al.* [1996] propose the existence of a COT zone between the northern limit of the seaward dipping reflector sequences and a positive free-air gravity anomaly (50–100 mGal), which roughly coincides with the 500 m shelf break, on the continental side.

[9] Farther south in the eastern Weddell Sea, the Weddell Rift (Figure 1), a failed rift attributed to transtensional rifting between SAM and ANT during or before the opening of the Weddell Sea [*Kristoffersen and Haugland*, 1986; *Kristoffersen and Hinz*, 1991], marks a structural boundary between the East ANT craton and the Weddell Sea Basin. This rift structure was correlated with a magnetic anomaly low of 100 km width by *Johnson et al.* [1992]. *Hunter et al.* [1996] propose a southwestward continuation of the failed Weddell Rift along the prolongation of the magnetic low to the northwestern corner of Berkner Island. East of this magnetic low, a pronounced Bouguer anomaly low is interpreted as representing Precambrian continental crust almost 200 km off the west coast of Coats Land [*Studinger*, 1998]. Another hint on the existence of continental crust directly east of the inferred Weddell Rift comes from an interpretation of seismic lines off the coast of Coats Land by *Haugland et al.* [1985]. They report basement outcrops, which may represent the East ANT craton, up to 50–100 km west of the ice front between 78°S and 75°30s.

[10] As reported from seismic refraction experiments by *Grikurov et al.* [1991], *Miller et al.* [1984], *Hübscher et al.* [1996], and *Leitchenkov and Kudryavtzev* [2000], the southernmost part of the Weddell Sea in front of the Filchner-Ronne Ice Shelf apparently consists of highly stretched continental crust (about 20 km thick, after *Hübscher et al.* [1996]) overlain by a 10–15 km thick sedimentary unit. *Ferris et al.* [2000] present a gravity and magnetic model for the Weddell Sea embayment starting north of the Filchner-Ronne Ice Shelf and ending at about 68°S, north of the Orion Anomaly. They modelled a thinned

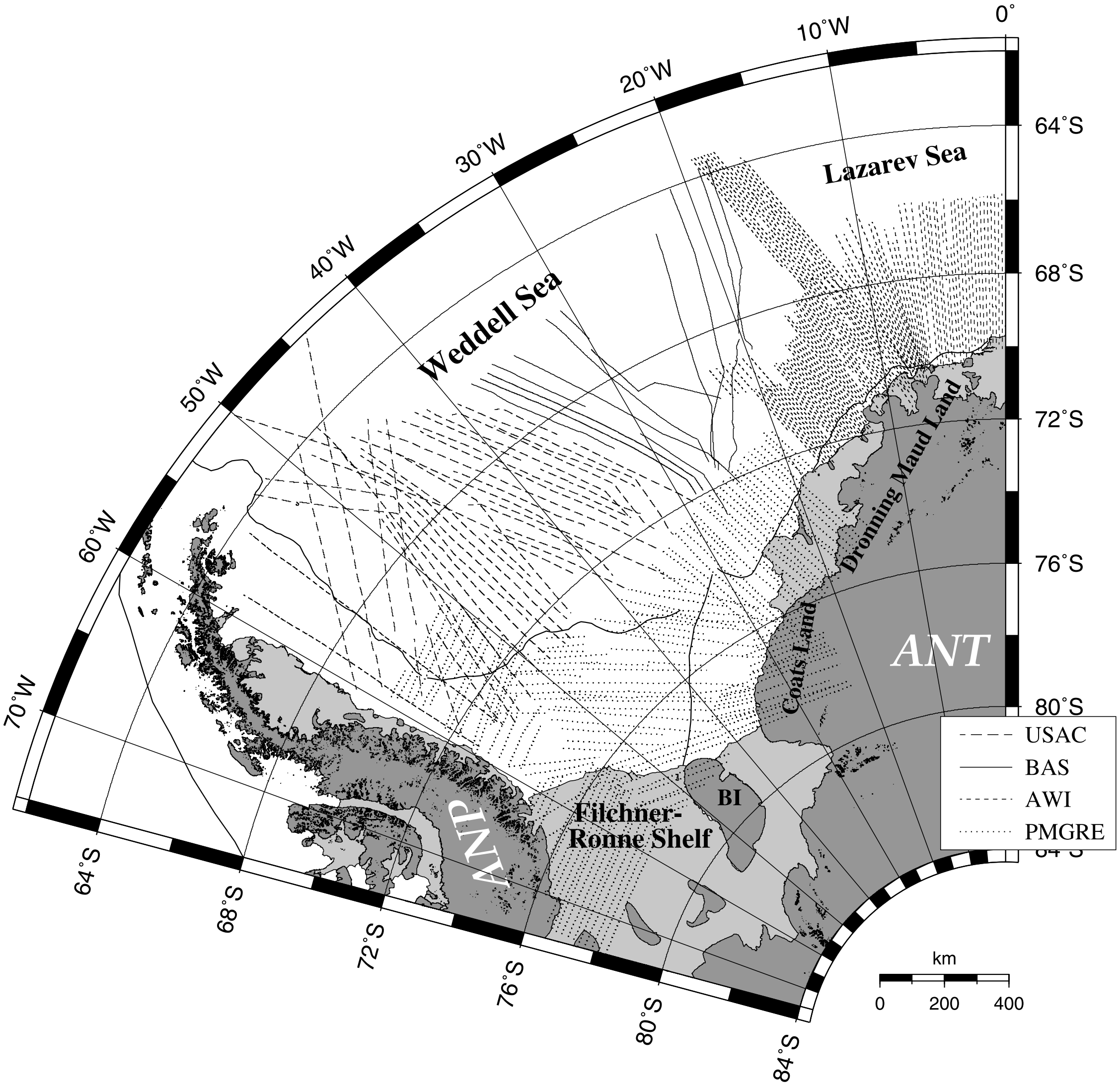

Figure 4. Overview map of the Weddell Sea showing magnetic track lines used to identify the magnetic anomalies. Abbreviations used in the legend: USAC, U.S.–Argentina-Chile project (1985–1989); BAS, British Antarctic Survey expeditions (1974–1980); AWI, Alfred Wegener Institute (1996–2002); PMGRE, Polar Marine Geological Research Expedition (1976–1989), former Soviet Antarctic Expedition.

continental crust with up to 10 km of sediment loading over a large area in the southern Weddell Sea. This model supports the interpretation that the southern Weddell Sea underwent significant extension during or prior to seafloor spreading in the Weddell Sea and the breakup of Gondwana.

[11] The structural units and continental boundaries that were described above are the data to be dealt with in any plate tectonic reconstruction for the Weddell Sea. These data put strong constraints on the fit of continental shore lines and the initial extend of continents and continental fragments.

3. Database

[12] The magnetic track data used to define the age of the ocean floor in the Weddell Sea and the orientation of the former spreading system are shown in Figure 4. The data in the easternmost part of the Weddell Sea already were presented by *Jokat et al.* [2003a] as part of the EMAGE data set. The processing and interpretation of these lines are discussed by *Jokat et al.* [2003a]. Farther west in the Weddell Sea ship track data were digitized from early expeditions carried out by the British Antarctic Survey (BAS) between 1974 and 1980 [*Barker and Jahn*, 1980]. An extensive aeromagnetic data set from the southernmost parts of the Weddell Sea and onshore Dronning Maud Land was provided by the Polar Marine Geological Research Expedition (PMGRE, Russia) carried out in the years 1979 to 1989 [*Masolov*, 1980; *Golynsky and Aleshkova*, 2000]. Another important data set for the Weddell Sea Basin and the Antarctic Peninsula comes from the U.S.–Argentina-Chile project [*LaBrecque et al.*, 1986; *LaBrecque*, 1987; *LaBrecque et al.*, 1989]. This was carried out in the years 1985 to 1989 using a long-range Orion P-3 based at Punta Arenas and Ushuaia.

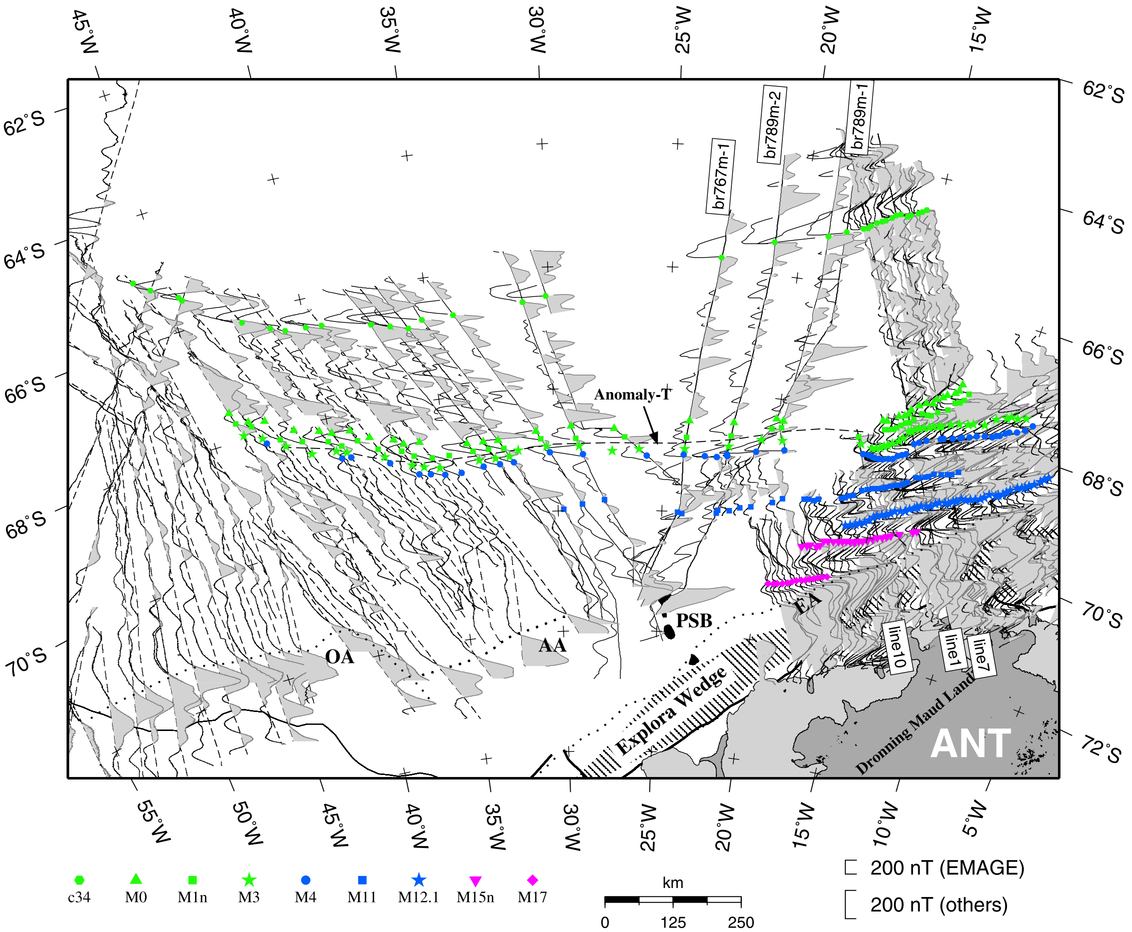

Figure 5. Wiggle plot of profiles used to identify the magnetic anomalies in the Weddell Sea. Note the different scale of the magnetic anomalies for the EMAGE and BAS, USAC profiles. Grey areas indicate positive anomalies. The anomaly picks shown are those used to define the rotations for the opening of the Weddell Sea. The profiles used for the correlation with synthetic anomaly sequences are labeled. Abbreviations are the same as explained in Figure 1.

[13] A wiggle plot of all the lines in the Weddell Sea Basin is shown in Figure 5. Note that the wiggles from the EMAGE data set are scaled to half the amplitude of the USAC and BAS track data. Amplitudes along the Explora Anomaly and within the magnetic seafloor spreading stripes in the eastern Weddell Sea are almost twice as high as those in the central and southern part of the Weddell Sea. To determine the magnetic anomaly picks for anomalies C34 (83 Ma), M0 (118 Ma), M1n (122 Ma), M3 (123 Ma), M4 (125 Ma), M11 (133 Ma), M12 (135 Ma) and M15n (138.3 Ma) correlations with synthetic anomaly sequences were made. Some selected profiles together with the applied spreading model are shown in Figure 6. In order to reduce the skewness of the anomalies along the selected profiles, the track data were projected onto lines parallel to the expected spreading direction. Thus the EMAGE lines were projected onto lines with an azimuth of 155° and the BAS profiles onto 170° (counterclockwise positive from north). The synthetic anomaly sequence was calculated using a magnetic block model confined to a magnetic layer at 6 km depth and a thickness of 1 km. The spreading rates used to calculate the model are shown in Figure 6.

[14] The onset of magnetic anomaly C34 (83 Ma) can easily be identified on all lines in Figure 6. The long period of the Cretaceous normal polarity superchron consists of several isolated anomaly highs on line1, br789m-1, and br767m-1, however these cannot be correlated over longer distances. The beginning of M sequence anomalies, starting with M0 (118 Ma), can be identified on all lines. Although the westernmost line, br767m-1, shows no distinctive negative anomaly for M0, the position of the picked anomaly correlates with the anomalies identified farther east (Figure 5). M1n (122 Ma) and M3 (123 Ma) are also picked on all profiles and are shown in Figure 5. These two anomalies almost perfectly bracket the indicated position of the gravimetric Anomaly T (thick dashed line). Magnetic anomaly M4 (125 Ma) can be identified as a dominant positive anomaly on all profiles. While M11 (133 Ma) can be revealed as a strong negative anomaly on all the EMAGE lines, its correlation on the ship track data is more difficult. However, the small helicopter magnetics pattern between 69°S–70°S and 20°W–23°W clearly indicates the continuation of the pronounced M11 (133 Ma) anomaly in the east and can be used to constrain M11 (133 Ma) on the ship track data farther west. M12 (135 Ma) can also be

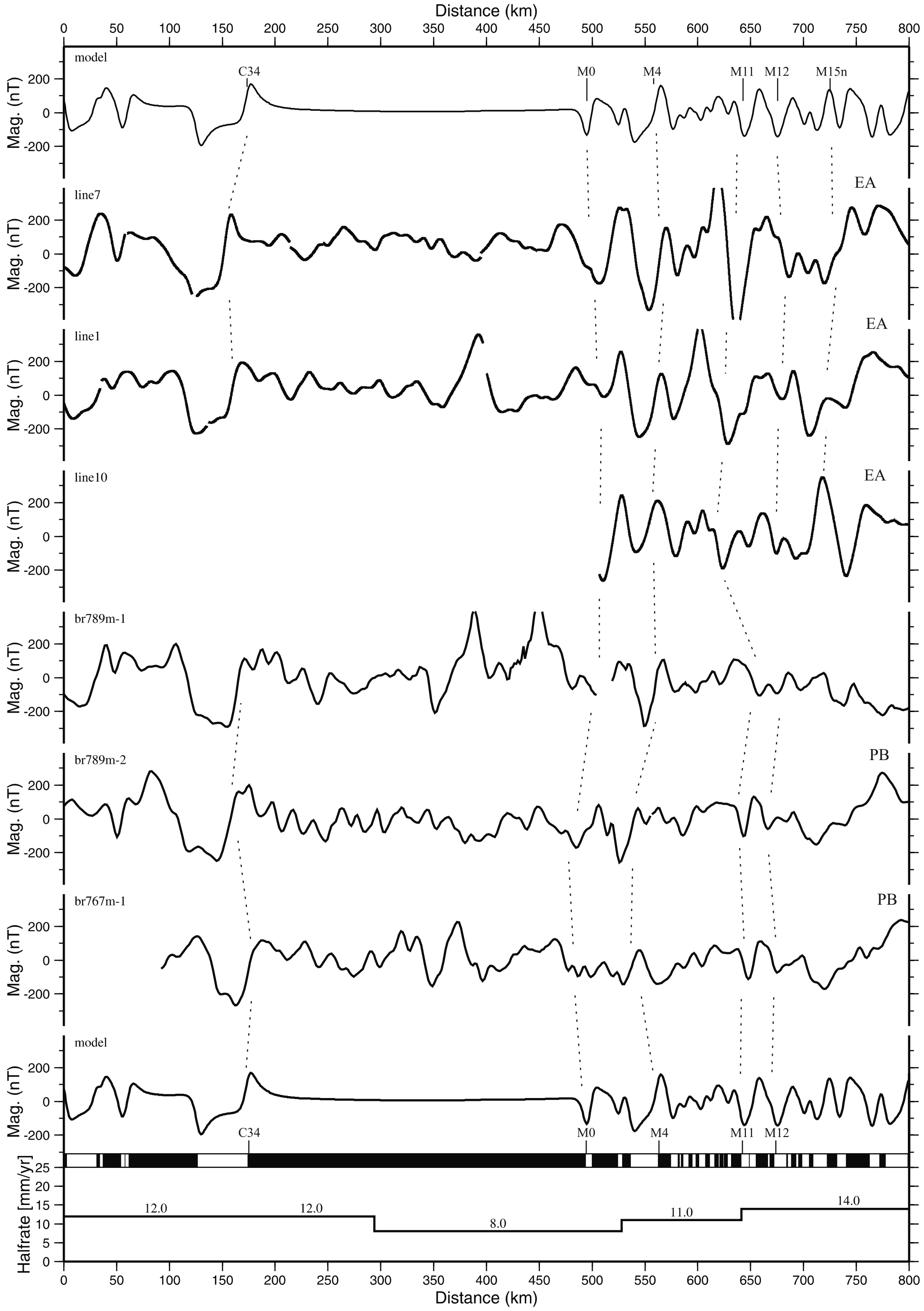

Figure 6. Selected magnetic anomaly profiles correlated with a spreading model for the Weddell Sea. The anomaly profiles shown here are indicated in Figure 5. The spreading model is calculated using a 1 km thick source layer at 6 km depth. The bottom graph shows the corresponding spreading half rates. Correlated anomalies are connected with dashed lines. For abbreviations see Figure 1.

identified on the BAS ship track data, except for line br789m-1. Farther south, no unique correlations can be made between the ship profiles and anomalies picked from the EMAGE data set. Consequently, anomalies M15n (138.3 Ma) and M17 (142 Ma) can only be identified on the EMAGE profiles. This set of magnetic anomaly picks and the spreading rates shown in the lower part of Figure 6 were used to constrain the rotations for the opening of the Weddell Sea.

[15] Most of the lines from the USAC project end just to the south of the Orion Anomaly. Thus seafloor spreading anomalies along the aeromagnetic profiles can only be identified north of this long wavelength anomaly. Unfortunately, amplitudes are rather low in this area, due to the 5–7.5 km of nonmagnetic sedimentary cover [*Rogenhagen and Jokat*, 2000]. Correlations of magnetic anomalies across several lines are only possible north of 69°S. The BAS ship track data are overprinted in the south by the

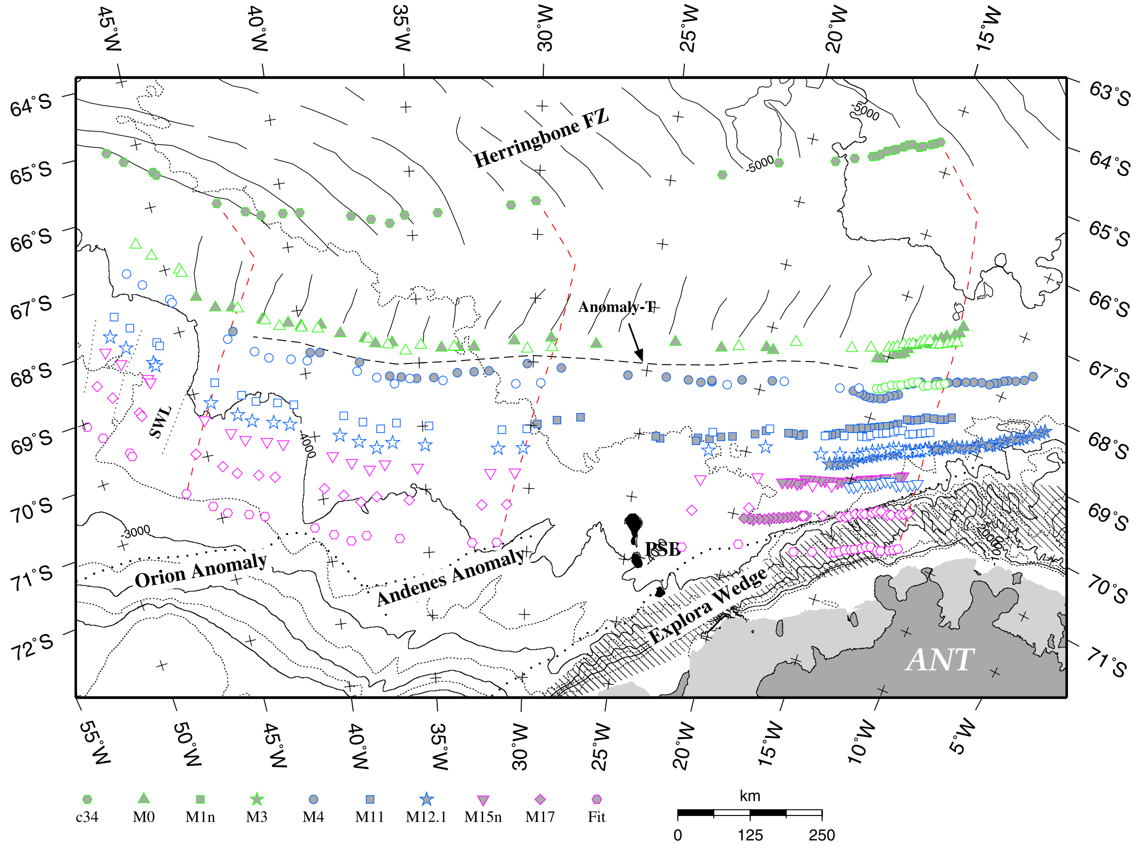

Figure 7. Synthetic isochrons calculated from the successive rotations of C34 (83 Ma) magnetic anomaly picks to fit the older identified anomalies. Calculated flow lines are compared to fracture zone lineations north of Anomaly T. The southernmost synthetic isochron (labeled Fit) is determined from an extrapolation of the spreading system to the south assuming constant spreading rate and azimuth.

magnetic expression of the Polarstern Bank, a chain of seamounts off the northwestern coast of Dronning Maud Land [*Jokat et al.*, 1996]. The strong magnetic signature of the seamounts interferes with any possible seafloor spreading anomaly signal and makes their identification almost impossible in this region. From Figure 5, a westward continuation of M17 (142 Ma) would be expected to be present in the vicinity of the Polarstern Bank, but cannot be identified in the data due to the strong magnetic overprint induced by the seamounts. In the northern part of the Weddell Sea, the distinctive onset of magnetic anomaly C34 (83 Ma) can clearly be correlated between all profiles. This and the younger C31 (~68 Ma) magnetic anomaly were used as anchors for the calculation of synthetic anomaly sequences.

4. Defining the New Model

4.1. SAM-ANT Rotations

[16] The SAM-ANT spreading regime is only constrained by magnetic anomaly and fracture zone data from the Weddell Sea Basin on the ANT side of the spreading system. While fracture zones can be identified in free-air gravity data north of Anomaly T, they are either absent or their signal is too weak for being detected south of this east-west trending gravity anomaly (Figure 3). Thus the only available information constraining the SAM-ANT spreading history for times older than M3 comes from the interpretation of magnetic anomaly data. This sparse database makes the use of inversion techniques like those presented by *Livermore et al.* [2006] for the northern Weddell Sea difficult and the results rather speculative. Therefore a method like the one presented by *Ghidella et al.* [2002] was used in this study. In this method, rotation parameters are estimated by rotating picks of a well-constrained magnetic anomaly of one flank of the spreading system to fit the picks of older or younger anomalies of the same flank of the spreading system. Assuming symmetric spreading, these stage rotations can be used to calculate total reconstructions for the SAM-ANT two-plate

Table 1. Stage Rotations for SAM With Respect to AFR[a]

Age, Ma	Longitude, deg	Latitude, deg	Angle, deg
0.00–83.00	−77.92	246.51	−30.08
83.00–118.00	−71.90	296.21	−7.83
118.00–125.36	−80.08	312.78	−1.08
125.36–132.53	−94.90	336.15	−0.88
132.53–134.75	−120.50	27.27	−0.34
134.75–138.30	−66.38	299.14	−1.38
138.30–142.27	−117.83	30.64	−0.59
142.27–147.00	−117.77	30.74	−0.71

[a] The finite rotation for 83.00 Ma is used to calculate the total reconstruction rotations.

Table 2. Finite Rotations for the Gondwana Breakup Model

		Pole of Rotation			
Age, Ma	Chron	Latitude, deg	Longitude, deg	Angle, deg	Source
		Falkland Plateau–Antarctica (Weddell Sea Opening)			
83.00	C34	−77.92	246.51	−30.08	after *Shaw and Cande* [1990] [SAM-AFR] and *Royer et al.* [1988] [AFR-ANT]
93.00	E	−75.90	241.00	−33.02	*Livermore and Hunter* [1996]
118.00	M0	−72.96	263.97	−45.17	this study
122.25	M2	−72.40	265.30	−46.80	this study
125.36	M4	−71.75	264.10	−47.10	this study
130.00	M10	−70.74	262.89	−47.87	this study
132.53	M11	−70.26	262.30	−48.30	this study
134.75	M12	−69.67	260.65	−48.20	this study
138.30	M15n	−69.08	262.53	−50.85	this study
142.27	M17	−68.07	260.04	−50.64	this study
147.00	M20	−66.81	257.33	−50.42	this study
		Antarctica-Africa			
83.00	C34	−2.00	320.80	17.98	after *Royer et al.* [1988]
93.00	E	2.90	321.70	22.60	*Livermore and Hunter* [1996]
118.00	M0	−6.00	330.50	39.60	this study
122.25	M2	−8.07	331.89	42.20	this study
125.36	M4	−8.49	331.89	43.50	this study
130.00	M10	−8.31	331.21	44.86	modified after *Jokat et al.* [2003a]
132.53	M11	−8.21	330.86	45.60	this study
134.75	M12	−8.16	330.57	46.25	modified after *Jokat et al.* [2003a]
138.30	M15n	−8.13	330.14	47.30	this study
142.27	M17	−7.80	329.62	48.33	this study
147.00	M20	−7.33	329.02	49.53	this study
155.00	M24	−6.52	328.00	51.93	modified after *Jokat et al.* [2003a]
167.20	JQZ	−5.20	326.34	56.22	this study
		South America (Northern Part)–Africa (Central South Atlantic Opening)			
83.00	C34	61.59	325.85	33.50	*Shaw and Cande* [1990]
93.00	E	58.96	325.91	40.02	*Livermore and Hunter* [1996]
118.00	M0	51.78	325.26	52.51	*Martin et al.* [1982]
122.25	M2	50.07	326.00	53.66	this study
125.36	M4	48.99	326.36	54.37	*Martin et al.* [1982]
130.00	M10	50.12	327.21	55.20	after *Nürnberg and Müller* [1991]
		Madagascar-Africa			
118.00	M0	90.00	0.00	0.00	*Reeves and de Wit* [2000]; MAD fixed to AFR
136.00	M12	2.00	115.00	−6.80	after *Reeves and de Wit* [2000]
148.00	M20	2.00	115.00	−10.30	after *Reeves and de Wit* [2000]
155.00	M24	2.00	115.00	−12.50	intperpolated after *Reeves and de Wit* [2000]
167.20	JQZ	5.16	109.24	−16.12	intperpolated after *Reeves and de Wit* [2000]
		Mozambique Ridge–Africa			
125.31	M3	90.00	0.00	0.00	*Tikku et al.* [2002], MOZR fixed to AFR
131.36	M10	−6.00	−50.00	1.45	*Tikku et al.* [2002]
134.75	M12	−8.01	310.24	2.48	this study
138.30	M15n	−8.87	310.35	3.56	this study
142.27	M17	−8.03	309.42	4.72	this study
147.00	M20	−6.49	−51.91	6.07	this study
167.20	JQZ	7.00	−77.00	10.50	extrapolated from *Marks and Tikku* [2001]
		Antarctic Peninsula–Antarctica			
147.00	M20	90.00	0.00	0.00	Antarctic Peninsula fixed to Antarctica
167.20	JQZ	−73.74	310.51	23.13	this study

system. In this way, *Ghidella et al.* [2002] calculated a set of finite rotations for the SAM-ANT spreading regime for the time between 160 Ma and 33 Ma.

[17] In this study, picks of the well-defined northern limit of magnetic anomaly C34 (83 Ma) are rotated to fit picks of older anomalies in the southern Weddell Sea. A comparison between the picks made on the anomaly data and the rotated and adjusted C34 anomaly picks is shown in Figure 7. The rotation parameters used to calculate the position of the rotated C34 anomaly picks are listed in Table 1. The poles are stage poles for the rotation of SAM with respect to ANT. The angles are half the angles of the stage rotations (the angle for the 83.00 Ma total reconstruction is a full angle). To calculate the total reconstruction rotation for SAM with respect to ANT from these stage rotations, all stage rotations starting from the present-day have to be summed up. In this way, total reconstruction rotations for M0 (118 Ma), M4 (125 Ma), M11 (133 Ma), M12.1 (135 Ma), M15n (138 Ma) and M17 (142 Ma) were obtained. These are listed in Table 2.

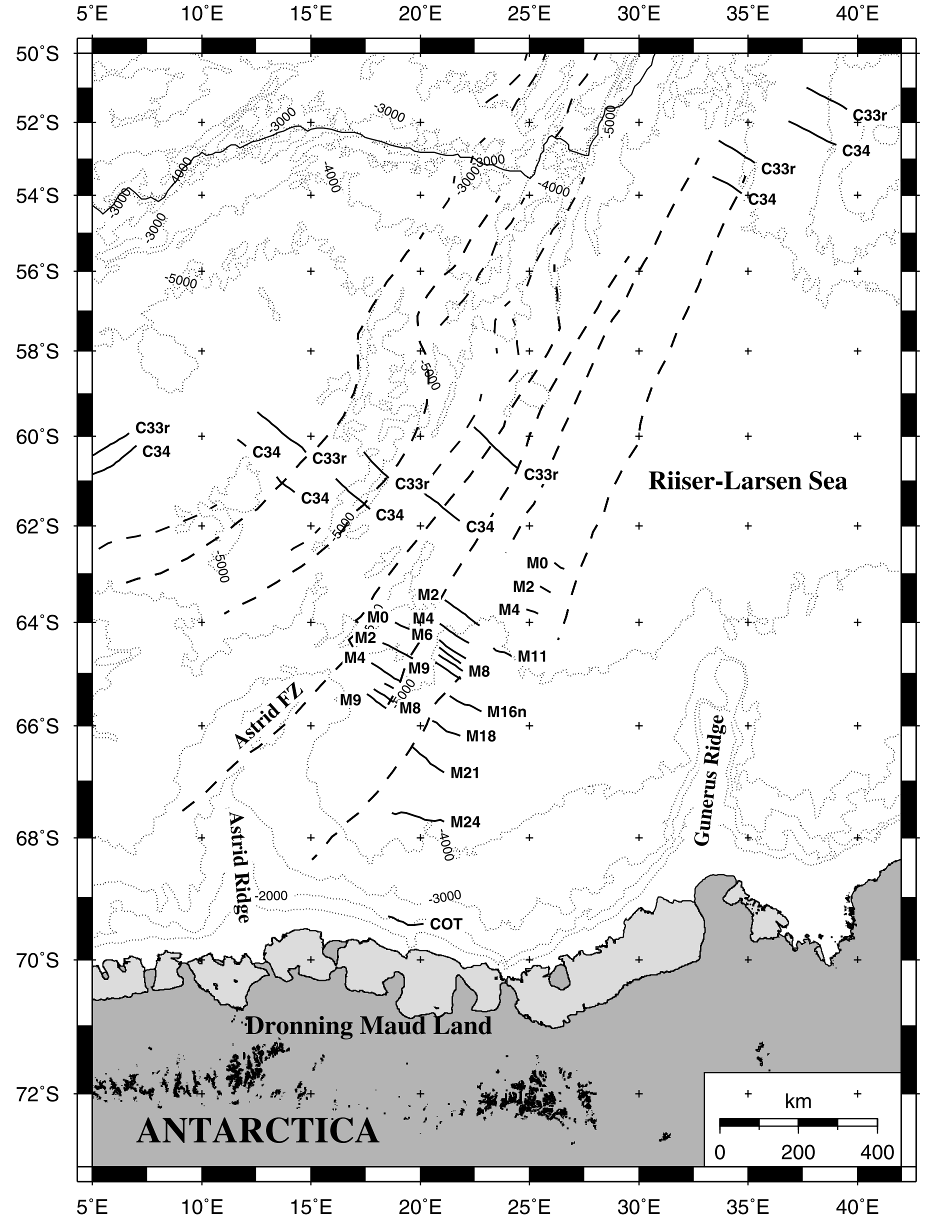

Figure 8. Magnetic anomaly lineations and fracture zone data in the Riiser-Larsen Sea used to constrain the position of AFR with respect to AFR. Magnetic anomaly lineations are plotted as black solid lines, and fracture zones are plotted as heavy dashed lines. See text for references.

[18] Assuming a constant spreading rate and direction for times older than magnetic anomaly M17 (142 Ma), the spreading system is extrapolated to the south until the rotated C34 (83 Ma) anomaly picks occupy a position just north of the Orion magnetic anomaly (Figure 7). Since purely oceanic crust is very unlikely to exist farther south in the Weddell Sea, this may be the position of the initial rift after initiation of the SAM-ANT separation. This extrapolation results in a maximum age for the oldest ocean floor in the Weddell Sea of about 147 Ma.

[19] Synthetic flow lines were calculated using the rotation parameters presented above (Figure 7). These are used to visualize the spreading direction and to make a comparison with fracture zone lineations digitized from gravity data [*McAdoo and Laxon*, 1997].

4.2. Constraints for AFR-ANT Rotations

[20] Mesozoic seafloor spreading between AFR and ANT was confined to the conjugate Riiser-Larsen Sea and Mozambique Basin. Magnetic anomaly and fracture zone data used to constrain the relative position of these two continents are shown in Figures 8 and 9. Magnetic anomaly identifications in the Riiser-Larsen Sea were digitized from *Bergh* [1977] and picked on line data from the high-resolution aeromagnetic data set presented by *Jokat et al.* [2003a]. For the conjugate part, the Mozambique Basin, data from *Cande et al.* [1989] and the "digital seafloor spreading lineations for the world's oceans" database (NGDC, Boulder) were used (Figure 9). Outlines of the major fracture zones in these two ocean basins were

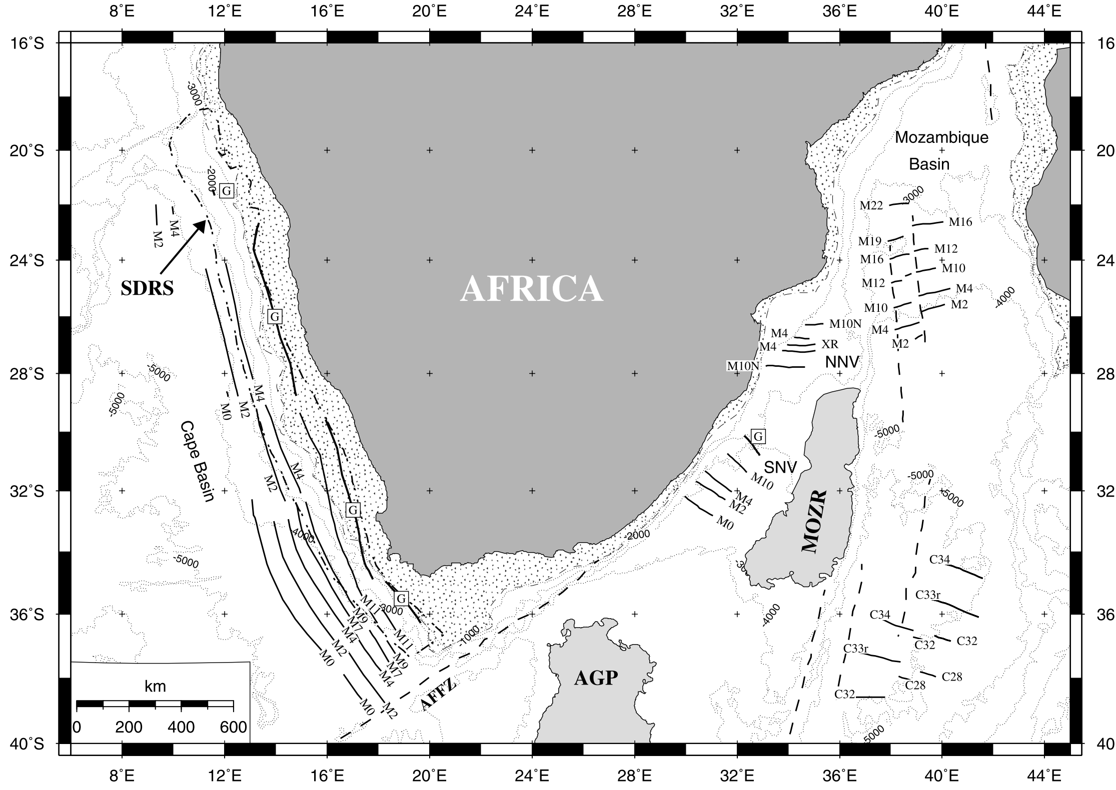

Figure 9. Map of the ocean basins bordering the AFR continent and the magnetic anomalies used to constrain the AFR-ANT and SAM-AFR reconstructions. Magnetic anomaly G is interpreted as an edge effect anomaly separating oceanic from continental basement, after *Rabinowitz and LaBrecque* [1979]. The maximum extend of truly continental material is indicated by the stippled area bordered by thin dashed lines. See text for references. Abbreviations are AFFZ, Agulhas Falkland Fracture Zone; AGP, Agulhas Plateau; MOZR, Mozambique Ridge; NNV, northern Natal Valley; SDRS, seaward dipping reflector sequences; SNV, southern Natal Valley.

digitized from the satellite altimetry-derived free-air gravity data of *Sandwell and Smith* [1997].

[21] *Tikku et al.* [2002] proposed that an extinct Cretaceous spreading center was active between AFR and the Mozambique Ridge in the northern Natal Valley between about 132 Ma and 122 Ma. This implies an independent Mozambique Ridge block at least for this time period. To define the boundaries of this block its positive signal in the free-air gravity field was used as proposed by *Tikku et al.* [2002]. The magnetic anomaly identifications in the northern Natal Valley were digitized from *Tikku et al.* [2002] and are shown in Figure 9.

4.3. Constraints for SAM-AFR Rotations

[22] Constraints on the early seafloor spreading history between SAM and AFR are obtained from magnetic anomaly and fracture zone data in the conjugate Argentine and Cape basins and the Georgia and southern Natal basins. Figures 9 and 10 give an overview of the data used to describe this spreading regime. Magnetic anomaly lineations in the Argentine Basin were digitized from data presented by *Rabinowitz and LaBrecque* [1979] and *Max et al.* [1999]. For the Cape Basin, anomaly data presented by *Rabinowitz and LaBrecque* [1979] and *Schreckenberger and Neben* [2003] were used. The outline of magnetic anomaly C34 (83 Ma) in both ocean basins was taken from *Cande et al.* [1989]. Anomalies in the Georgia Basin (east of Maurice Ewing Bank), representing the SAM side of a spreading system between the Falkland Plateau and AFR, were picked from the original track line data as distributed by the NGDC on the GEODAS CD-ROM and from digitized maps for the 1976 cruise of RRS Shackleton [*Barker*, 1979; *Martin et al.*, 1982]. The identification of the anomalies was taken from *LaBrecque and Hayes* [1979]. For the conjugate to the Georgia Basin, the southern Natal Valley, magnetic anomaly lineations were digitized from the original work of *Goodlad et al.* [1982]. Fracture zone lineations in the above mentioned ocean basins were digitized from the gravity data presented by *Sandwell and Smith* [1997].

[23] To define the fit of the continents, detailed knowledge of the COT is of crucial importance. *Lawver et al.* [1998] used the coastal free-air gravity anomaly high as a proxy for the mean position of the COT along the margins of SAM and AFR. Thus the zone of transitional crust is approximated by a line, defining the boundary between continental and oceanic crust. For the purpose of plate reconstructions that are not taking into account any stretch-

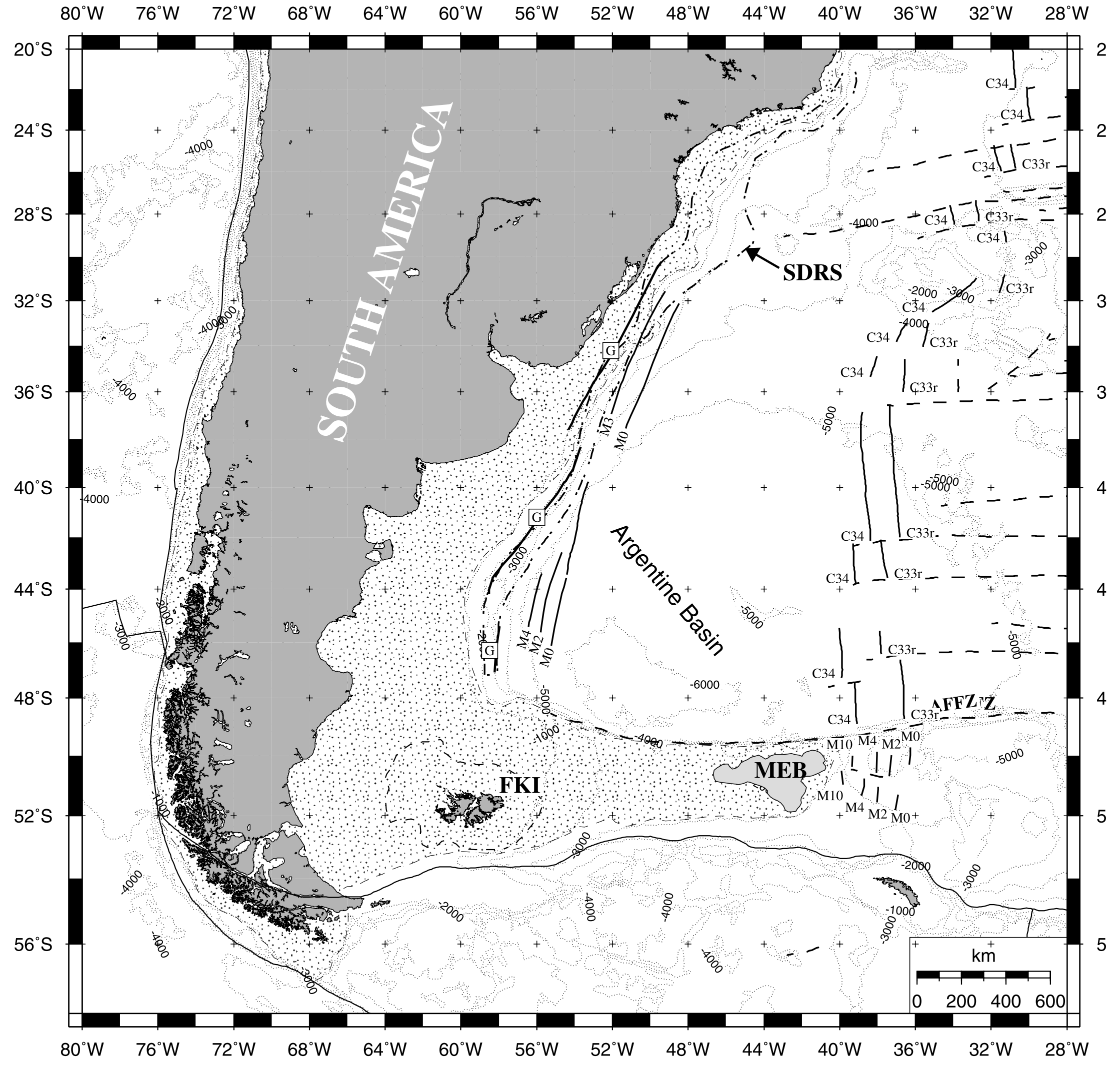

Figure 10. Magnetic anomaly lineations and fracture zone data off the coast of SAM and the Falkland Plateau used to constrain the reconstruction of SAM with respect to AFR. See text for references. Abbreviations are FKI, Falkland Islands; MEB, Maurice Ewing Bank; SDRS, seaward dipping reflector sequences.

ing during the continental breakup, this is a reasonable simplification. This interpretation was adopted here and the outline of the anomaly was digitized from the satellite-derived free-air gravity data set of *Sandwell and Smith* [1997]. The approximated outlines of the COTs off the coast of SAM and AFR are shown in Figures 9 and 10 as dashed lines, and the areas residing over continental crust are lightly stippled.

[24] Additionally, where present the occurrence of seaward dipping reflector sequences (SDRS) was used to further constrain the position of the outer and inner parts of the COT. Recent results from the cruises of the German Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) across the continental margins of SAM and AFR show that the landward edge of the SDRS (feather edge) is underlain by stretched continental crust, as indicated by seismic velocities of 7.2–7.6 km/s (S. Neben, personal communication, 2004). The oceanward side, on the other hand, occurs over pure oceanic crust. This implies that the outline of the SDRS contains the COT. Along the coast of SAM, the outline of the province of SDRS was digitized from *Hinz et al.* [1999] (Figure 10). On the AFR side of the spreading system, outlines of SDRS provinces were digitized from data presented by *Bauer et al.* [2000], *Hinz et al.* [1999], and *Gladczenko et al.* [1997] (Figure 9).

4.4. Closing the Plate Circuit

[25] Total reconstructions for the breakup of Gondwana were determined by visually searching for the best fitting set of rotations that bring together magnetic anomalies from conjugate ocean basins and maintain the spreading directions indicated by fracture zone data. Additionally, constraints from onshore geology were taken into account, where available. In a first step, a trial and error analysis was used to define the finite rotations for each ocean basin, separately. The fit of conjugate magnetic anomalies was visually inspected and adjusted. The basic theory for

Table 3. Finite Rotations for the Intracontinental Deformations in South America and Movements of the Falkland Plateau and the Falkland Islands Block

		Pole of Rotation			
Age, Ma	Chron	Latitude, deg	Longitude, deg	Angle, deg	Source
		Paraná–South America (North)			
125.36	M4	90.00	0.00	0.00	Paraná fixed to South America
130.00	M10	−10.22	288.54	1.70	this study
132.53	M11	−10.22	288.54	1.96	this study
134.75	M12	−6.82	289.69	2.19	this study
138.30	M15n	−2.69	291.07	2.58	this study
142.27	M17	−8.20	291.01	3.00	this study
		Salado-Paraná			
125.36	M4	90.00	0.00	0.00	Salado fixed to Paraná
130.00	M10	20.92	321.51	0.30	this study
132.53	M11	20.92	321.51	1.00	this study
134.75	M12	19.64	315.41	1.10	this study
138.30	M15n	33.77	310.52	1.40	this study
142.27	M17	5.02	301.02	1.92	this study
147.00	M20	5.02	301.02	1.92	this study
167.20	JQZ	−16.22	294.79	4.17	this study
		Colorado-Salado			
132.53	M11	90.00	0.00	0.00	Colorado fixed to Salado
134.75	M12	−10.12	310.15	0.83	this study
138.30	M15n	74.48	62.85	1.77	this study
142.27	M17	16.97	307.36	1.45	this study
147.00	M20	16.97	307.36	1.45	this study
167.20	JQZ	−20.26	294.89	3.98	this study
		Patagonia-Colorado			
138.30	M15n	90.00	0.00	0.00	Patagonia fixed to Colorado
142.27	M17	50.62	87.37	2.89	this study
147.00	M20	56.87	34.01	2.85	this study
167.20	JQZ	25.16	347.96	3.08	this study
		Falkland Plateau–Patagonia			
125.36	M4	90.00	0.00	0.00	Falkland Plateau fixed to Patagonia
130.00	M10	−4.29	153.20	0.71	this study
132.53	M11	11.63	147.21	1.09	this study
134.75	M12	8.76	133.31	1.39	this study
		Falkland Islands–Patagonia			
125.36	M4	90.00	0.00	0.00	Falkland Islands fixed to Patagonia
130.00	M10	39.20	−30.00	−1.00	this study
167.20	JQZ	39.20	−45.00	−2.00	this study

calculating finite rotations has been adopted from *Cox and Hart* [1986] and *Greiner* [1999, and references therein]. Next, all rotations were put together into a common reconstruction with a reference frame where AFR is fixed in its present-day position. The rotations of ANT with respect to AFR, SAM including the Falkland Plateau (FKP) with respect to ANT and AFR with respect to SAM were visually adjusted to define a closed plate circuit. The resulting finite rotations are listed in Tables 2 and 3.

[26] The new model for the breakup of Gondwana involves not only motions of rigid SAM, AFR and ANT plates but also incorporates intracontinental deformations in SAM and the motion of microcontinents or continental fragments like the Antarctic Peninsula and the Mozambique Ridge (see Tables 2 and 3 for rotation parameters). Where necessary, motions of these smaller elements were adjusted in accordance with the constraints resulting from the motions of the major continents and surrounding ocean basins. If not otherwise mentioned, rotation parameters from other authors are used.

[27] Special attention should be drawn to the rotation parameters for 93 Ma. This time lies within the Cretaceous magnetically quiet zone (C34, 83.0–118.0 Ma) and cannot be calculated from a fit of seafloor spreading anomalies. However, within this 35 Myr of normal polarity, a significant change in spreading direction between SAM and ANT occurs, as can be inferred from fracture zones seen in satellite gravity data [*McAdoo and Laxon*, 1997] (Figure 3). The pole of rotation used in our model has been adopted from *Livermore and Hunter* [1996]. They extrapolated older stage pole parameters to fit the change in direction of flow lines in the Weddell Sea and to infer the age of this significant change in spreading direction. They gave their rotation the name "E" (extrapolated).

5. New Gondwana Breakup Model

[28] Paleogeographic reconstructions calculated with rotation parameters listed in Tables 2 and 3 are presented in Figures 11 to 15. The reconstructions show the configuration of the continents and ocean basins at 167.2 Ma, 147.0 Ma, 140.0 Ma, 130.0 Ma, and 118 Ma in a reference

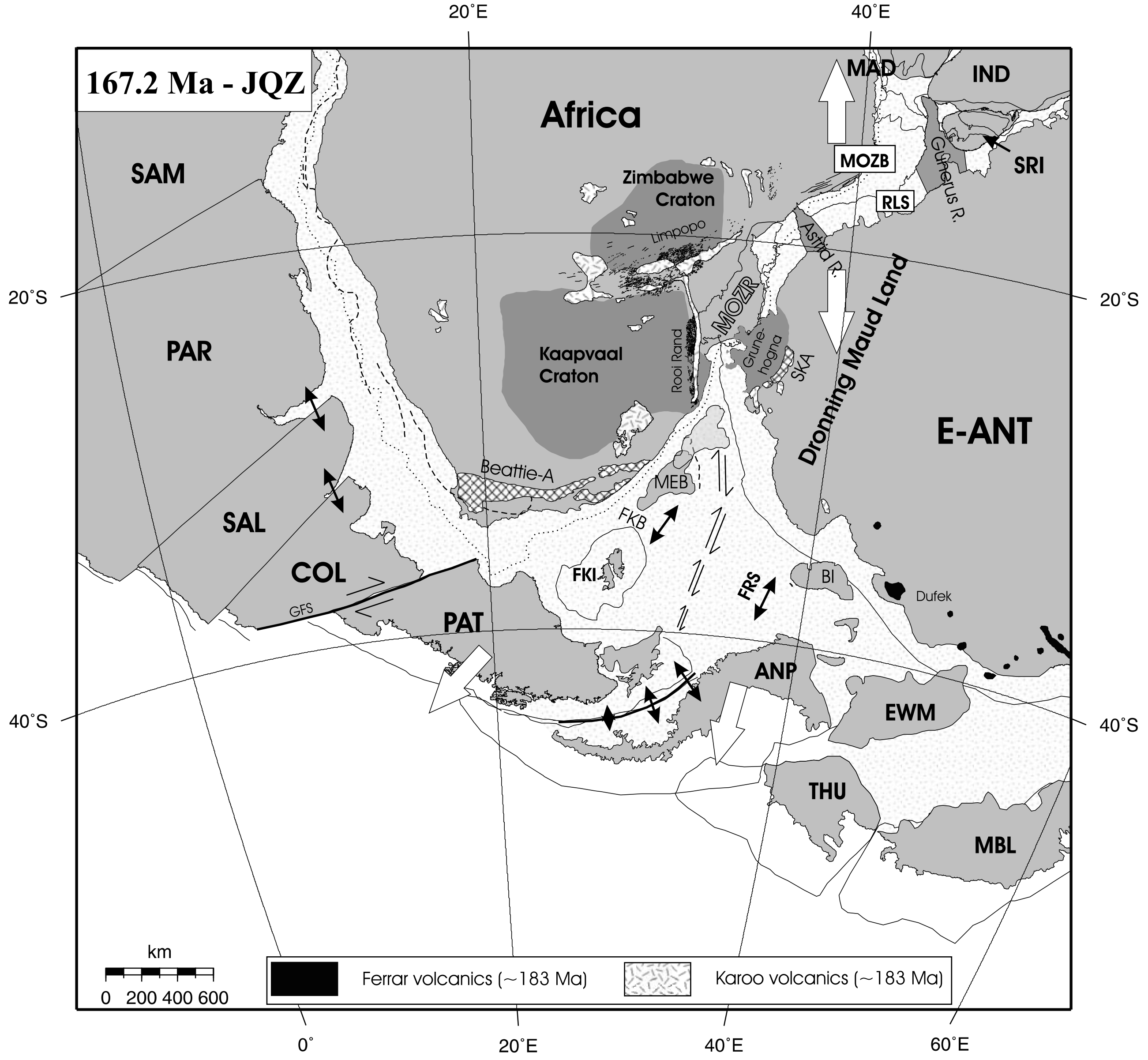

Figure 11. The 167.2 Ma (JQZ) reconstruction for the breakup of Gondwana, showing the situation after initial east-west oriented rifting between AFR and ANT and before first north-south directed rifting in the Mozambique Basin–Riiser-Larsen Sea and Somali Basin began (not shown). In this, and all consecutive reconstructions, AFR is fixed in its present-day position. A Lambert azimuthal equal-area projection centered on 25°E and 35°S with a scale of 1:37,000,000 is used. Abbreviations used in this and Figures 12–15 are AFFZ, Agulhas Falkland Fracture Zone; AFR, Africa; ANP, Antarctic Peninsula; AP, Agulhas Plateau; Beattie-A, Beattie Anomaly; C.A., central anomalies [*Ferris et al.*, 2000]; COL, Colorado; E-ANT, East Antarctica; EWM, Ellsworth Whitmore mountains; FKB, Falkland Plateau Basin; FKI, Falkland Islands; FRS, Filchner-Ronne Shelf; GFS, Gastre Fault System; IND, India; LZS, Lazarev Sea; MAD, Madagascar; MBL, Marie Byrd Land; MEB, Maurice Ewing Bank; MOZB, Mozambique Basin; MOZR, Mozambique Ridge; MR, Maud Rise; O-A, Orion Anomaly; PAR, Paraná; PAT, Patagonia; RLS, Riiser-Larsen Sea; RV, Rocas Verdes; SAL, Salado; SAM, South America (northern part); SKA, Sverdrupfjella Kirwanveggen Anomaly; SRI, Sri Lanka; THU, Thurston Island.

frame with AFR fixed in its present-day position. These stages cover a sequence of events during the breakup of Gondwana, which begins with rifting between AFR and ANT at about 167.2 Ma and ends short before the eastern tip of the Falkland Plateau (SAM) clears the continental margin of AFR at about 100 Ma and a deep water circulation between the South Atlantic and the Indian Ocean is established.

[29] In Figures 16 and 17, spreading directions and rates for the SAM-ANT and AFR-ANT spreading regimes are

shown. These yield valuable information on the dynamics of the plate motions and are referred to in the forthcoming discussion of the different stages of the breakup of Gondwana. The displayed spreading directions and rates were calculated by rotating a point on the well-observed magnetic anomaly C34 step by step about consecutive stage poles until the closure of the corresponding ocean basin is reached.

5.1. Early Stages: 167.2 Ma and Older

[30] The 167.2 Ma reconstruction (Figure 11) shows the configuration of the continents within Gondwana after an initial phase of east-west oriented rifting between AFR and ANT has occurred. This is referred to as stage 1 in the breakup of Gondwana by *Cox* [1992]. The existence and timing of this early rifting event is documented in the occurrence of the north-south oriented Lebombo and Rooi-Rand dike swarms (~190 Ma), parallel to the Lebombo Mountains in southeast Africa [*Reeves*, 2000]. The emplacement of these dikes occurred shortly before the eruption of the Karoo volcanic suite at 183 Ma [*Reeves and de Wit*, 2000; *Storey et al.*, 2001].

[31] For this time, the position of ANT with respect to AFR is defined by extrapolation of the 155 Ma rotation parameters in the AFR-ANT spreading regime until a closure of the Mozambique Basin–Riiser-Larsen Sea is obtained. According to the trend in the spreading direction as seen on Figure 16 for ages younger than 155 Ma and a modelled spreading half rate of more than 21 mm/yr by *Jokat et al.* [2003a], the AFR-ANT spreading system is extrapolated using a spreading direction of about 34°E and a half rate of about 21.5 mm/yr. Further constraints on the relative position of ANT with respect to AFR, before seafloor spreading in the Riiser-Larsen Sea and Mozambique Basin began, are provided by onshore geology. The Archean Grunehogna Craton in East ANT is interpreted to be a fragment of the Zimbabwe-Kaapval Craton (proto-Kalahari Craton) in southeast AFR for at least Late Mesoproterozoic times [*Peters et al.*, 1991; *Jacobs et al.*, 2003; *Jacobs and Thomas*, 2004]. In late Neoproterozoic/Early Paleozoic time (between 650 and 500 Ma), various parts of proto-East and West Gondwana formed the East African–Antarctic orogen by continental collision [*Jacobs and Thomas*, 2004]. The Grunehogna Craton became part of what today is East ANT and remained fixed in its Gondwana position until the beginning of Gondwana breakup (<183 Ma). Maybe during this orogeny, recently described by an Himalayan-type indenter-escape tectonics model by *Jacobs and Thomas* [2004], a zone of weakness formed in the eastern part of the proto-Kalahari Craton facilitating the complete detachment of the Grunehogna craton during Gondwana breakup [*Jacobs and Thomas*, 2004]. Another anchor for the initial position between AFR and ANT, as shown in Figure 11, is provided by the correlation of the Beattie Anomaly in southern AFR with the Sverdrupfjella-Kirvanveggen anomaly in ANT [*Corner and Groenewald*, 1991; *Corner et al.*, 1991]. As discussed by *Jokat et al.* [2003a], both magnetically similar features may belong to the Grenville age (1.1 Ga) Namaqua-Natal-Maud Belt that is continuous in southern and eastern Africa and parts of Dronning Maud Land [*Groenewald et al.*, 1991].

[32] In our new model, north-south oriented rifting and subsequent seafloor spreading in the Somali Basin and the conjugate Mozambique Basin and Riiser-Larsen Sea began about 15 Ma after the stage 1 rifting between East and West Gondwana occurred. The existence of the early rifting event was proposed by *Cox* [1992]. No direct information regarding the exact timing of the onset of north-south rifting and the transition to seafloor spreading was available from data used in this study. However, it is possible to infer the timing of these events given knowledge of the oldest seafloor spreading anomalies in the corresponding ocean basins. In the Somali Basin, these are dated as M22 (152 Ma) [*Segoufin and Patriat*, 1980; *Cochran*, 1988] or possibly even older (M25, 157 Ma), as proposed by *Rabinowitz et al.* [1983]. The oldest magnetic anomaly in the Mozambique Basin–Riiser-Larsen Sea was tentatively dated as M24 (155 Ma) [*Jokat et al.*, 2003a] off the coast of central Dronning Maud Land, giving rise to the suggestion that rifting started in these ocean basins almost simultaneously between 170 Ma and 160 Ma. *Jokat et al.* [2003a] presented a spreading model for the opening of the Mozambique Basin–Riiser-Larsen Sea, with half rates between 20 and 25 mm/yr, from calculation of synthetic anomaly sequences for the Riiser-Larsen Sea. Accordingly, a half rate of 22 mm/yr was used to extrapolate the AFR-ANT spreading system in the refined model presented here (Figure 17). Consequently, rifting in the Mozambique Basin–Riiser-Larsen Sea starts at about 167.2 Ma.

[33] Early stages of stretching and basin development take place in the Weddell Sea region and between SAM and AFR contemporaneously with initial rifting events between AFR and ANT in the Mozambique Basin and Riiser-Larsen Sea (Figure 11). The Antarctic Peninsula (ANP) is moving in a southwesterly direction from a position closer to ANT than today's, which results in highly stretched continental curst beneath the Filchner-Ronne Shelf [*Hübscher et al.*, 1996; *Hunter et al.*, 1996; *Leitchenkov and Kudryavtzev*, 2000]. A ratio of stretched to unstretched crust of 2.5 was used for the Filchner-Ronne Shelf to reconstruct the initial position of ANP with respect to ANT. Stretching factors of 1.5–3.0 are proposed by *Hübscher et al.* [1996] and *Leitchenkov and Kudryavtzev* [2000].

[34] Rifting between ANP and ANT is accompanied by a westward motion of southernmost SAM, namely, Patagonia, with respect to AFR and the Maurice Ewing Bank, which results in stretching and extension in the Falkland Plateau Basin [*Lorenzo and Mutter*, 1988; *Marshall*, 1994; *Platt and Philip*, 1995]. From a detailed synthesis of single-channel and multichannel seismic data and interpretation of Deep Sea Drilling Project borehole data (leg 36 and 71), *Lorenzo and Mutter* [1988] proposed a crustal extension ratio beneath the Falkland Plateau of 140–280%. This ratio has been used to constrain the extension in the Falkland Plateau Basin between 167.2 Ma and 130 Ma. An alternative position for the Maurice Ewing Bank within the Falkland Plateau is given for 167.2 Ma (Figure 11, light grey), based on a position proposed by *Storey et al.* [1999]. This allows an increased size for any potential continental material in the Falkland Plateau, or for a more easterly Jurassic position of the Falkland Islands as proposed by *Adie* [1952], *Taylor and Shaw* [1989], *Marshall* [1994], and *Storey et al.* [1999].

[35] Intracontinental deformations in AFR or SAM have to be introduced for reconstructing SAM with respect to AFR, as suggested by *Burk and Dewey* [1974], *Unternehr et al.* [1988], *Fairhead* [1988], *Nürnberg and Müller* [1991], *Lawver et al.* [1998], and *Macdonald et al.* [2003]. The necessary deformations are extensions and transcurrent movements, which are attested to by dikes or faults and graben systems on both continents. To portray these complex deformations, SAM is subdivided into four individual blocks, as proposed by *Nürnberg and Müller* [1991]. The subplates used by Nürnberg and Müller are the (northern) South America subplate, the Paraná, Salado, and Colorado subplates. Additionally, a Patagonia subplate is used, which is bound to the north by the Colorado subplate and that moves along the Gastre Fault System [*Rapela and Pankhurst*, 1992]. Since only rough estimates of the possible amount of extension or displacement exist for these movements [*Unternehr et al.*, 1988; *Sibuet et al.*, 1984; *Rapela and Pankhurst*, 1992], intracontinental deformations in SAM are kept to a minimum throughout this model. In our 167 Ma reconstruction, Patagonia is shifted for 345 km to the east, relative to SAM, to avoid any overlap of the northern tip of ANP onto southernmost SAM or the Falkland Plateau. Dextral transcurrent movements of up to 500 km were already suggested by *Rapela and Pankhurst* [1992].

5.2. Weddell Sea Opening: 147.0 Ma

[36] After about 20 Myr of stretching and rifting in the Filchner-Ronne Shelf and the Falkland Plateau Basin, the first true ocean floor is created in the southern Weddell Sea at about 147.0 Ma (M20) (Figure 12). The predrift position of the southern boundary of the Falkland Plateau with respect to the coast of Dronning Maud Land and the Filchner-Ronne Shelf is defined by extrapolation of the rotation parameters for the SAM-ANT spreading system, as explained above and shown in Figures 16 and 17. The seamounts of Polarstern Bank also formed during the initial stages of seafloor spreading, and reflect the general direction of plate motions during this early phase of Weddell Sea opening [*Jokat et al.*, 1996]. The strike of this bathymetric high and its associated magnetic anomaly aligns almost perpendicular to the rotated magnetic anomaly C34.

[37] Stretching and extension in the Filchner-Ronne Shelf may have stopped and the ANP reached its present-day position relative to East ANT at 147.0 Ma. So far, there exists no unique evidence for or against the argument that stretching in the Filchner-Ronne Shelf occurred at the same time as seafloor spreading in the Weddell Sea. However, stretching continued in the Falkland Plateau until the Lower Cretaceous [*Lorenzo and Mutter*, 1988]. While extensional forces were active in the Falkland Plateau, Patagonia was still subject to forces acting in a westerly direction, resulting in continued dextral shear along the Gastre Fault system [*Rapela and Pankhurst*, 1992]. The position of AFR with respect to ANT at 147.0 Ma is constrained by the close proximity of anomaly M22 (~152.1 Ma) in the Mozambique Basin and M21 (~149.7 Ma) in the Riiser-Larsen Sea.

5.3. Early Opening of the South Atlantic Ocean: 140.0–130.0 Ma

[38] The ongoing opening of the Weddell Sea finally leads to the complete development of an east-west oriented spreading system along the coast of western Dronning Maud Land, by ridge crest propagation from southwest to northeast up to about 10°E [*Jokat et al.*, 2003a]. This led to the final separation of SAM and the Falkland Plateau from ANT at around M12 (135 Ma) (Figures 13 and 14). Between AFR and ANT, north-south oriented spreading continued during this time, as defined by magnetic anomalies M16 (141.5 Ma) and M12 (135.8 Ma) in the Mozambique Basin and M16n (140.4 Ma) and M11 (133.1 Ma) in the Riiser-Larsen Sea.

[39] The final opening of the southern South Atlantic Ocean between SAM and AFR is related to the extrusion of seaward dipping reflector sequences (SDRS) along the volcanic passive margins of SAM and AFR and is shown in the 130 Ma reconstruction in Figure 14 [*Gladczenko et al.*, 1997; *Hinz et al.*, 1999]. The occurrence of SDRS correlates with the appearance of Anomaly G along the coast lines of both continents [*Rabinowitz and LaBrecque*, 1979]. In the southern Natal Valley and its conjugate, the Georgia Basin, the first ocean floor was already created by 130 Ma. Magnetic anomaly M10 (130 Ma) on both continental margins was used to constrain the position of the Falkland Plateau with respect to AFR. The spreading centers between SAM-ANT and AFR-ANT are defined through the rotation of magnetic anomaly C34 (83 Ma) onto older anomalies in the Weddell Sea and the correlation of magnetic anomaly M10 (130 Ma) in the Mozambique Basin with anomaly M11 (133.8 Ma) in the Riiser-Larsen Sea.

5.4. Complete Opening of the South Atlantic Ocean: 118.0 and Younger

[40] Finally, the reconstruction for 118.0 Ma (M0) (Figure 15) shows the ongoing opening of the South Atlantic Ocean. Between 110 Ma and 100 Ma, the Falkland Plateau clears the southwestern tip of AFR and opens a deep water connection between the South Atlantic and the southwest Indian Ocean [*Lawver et al.*, 1992]. The Mozambique Ridge has already rifted off the coast of central Dronning Maud Land in the Lazarev Sea (~122 Ma) and gave the way free for ocean currents to establish between the southwest Indian Ocean and the Weddell Sea. The ocean gateway between SAM and ANP is still closed and probably blocked by the South Orkney block [*Lawver et al.*, 1992].

[41] The rotations for the 118.0 Ma and 83.0 Ma reconstructions (the latter is not shown here) are well constrained by magnetic anomalies in the Riiser-Larsen Sea and Mozambique Basin, the southern Natal Basin, Georgia, Cape, and Argentine basins. The reconstruction parameters of *Martin et al.* [1982] and *Shaw and Cande* [1990] are used to define the relative position of SAM with respect to AFR for these ages (see Tables 2 and 3 for rotation parameters). These rotations are in good agreement with the constraints for the AFR-ANT and SAM-ANT spreading systems, as deduced from magnetic anomaly data.

6. Discussion

[42] The new model for the Mesozoic breakup of Gondwana has significant consequences on the configuration and movement of the continents and continental fragments during the early stages of Gondwana breakup. In

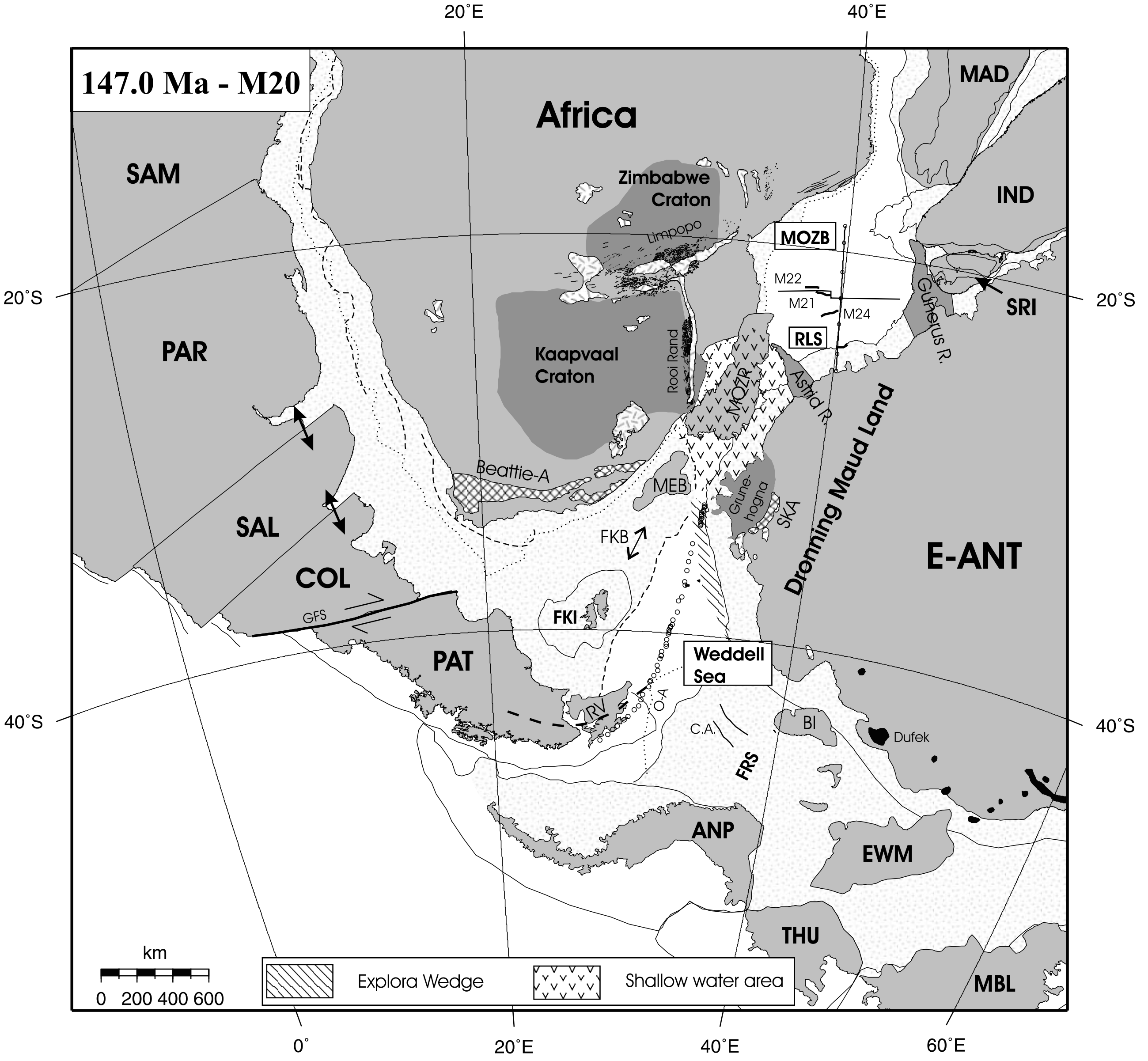

Figure 12. The 147 Ma (M20) reconstruction. Seafloor spreading in the Riiser-Larsen Sea and Mozambique Basin has already begun, with the oldest identified magnetic anomaly north of central Dronning Maud Land identified as M24 (155 Ma) by *Jokat et al.* [2003a]. In the Weddell Sea, rifting between Patagonia and the Antarctic Peninsula created the eastern continental margins of the Antarctic Peninsula. The initial spreading axis in the southern Weddell Sea may have been located in the Rocas Verdes Basin in southern Patagonia and propagated eastward from there to the west coast of Dronning Maud Land. From this time on, there are three separate basins developing independently during the breakup of Gondwana. These basins are the Somali Basin, the Mozambique Basin–Riiser-Larsen Sea, and the Weddell Sea Basin.

sections 6.1–6.6, the key features of this model and their implications on regional tectonics and geology will be discussed in greater detail.

6.1. Early Movements in the Weddell Sea

[43] Before rifting and seafloor spreading in the Weddell Sea area began (>167.2 Ma, Figure 11), Patagonia, the ANP, East ANT and AFR enclosed a basin comprising continental crust of the Filchner-Ronne Shelf, the Falkland Plateau, the Falkland Islands block and the Maurice Ewing Bank. This basin was subject to intense stretching and crustal thinning contemporaneous with the initial stages of north-south oriented rifting between AFR and ANT in the conjugate Mozambique Basin and Riiser-Larsen Sea and between AFR and Madagascar in the Somali Basin. These three basins were developing independently since the early stages of Gondwana breakup and indicate the differential movements of the major continents AFR, ANT and SAM since that time [*Jokat et al.*, 2003a].

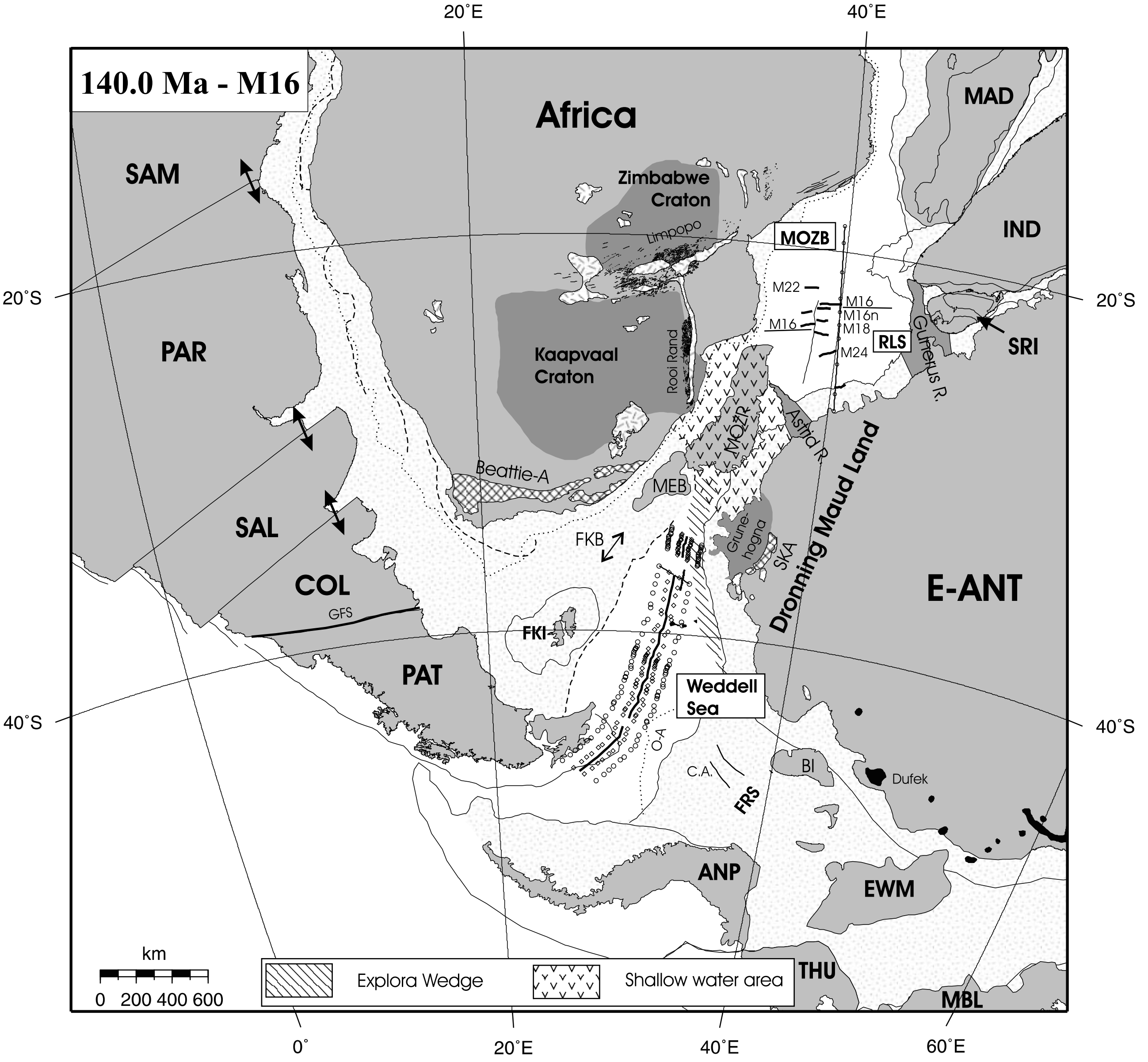

Figure 13. The 140 Ma (M16) reconstruction. Spreading in the Riiser-Larsen Sea and Mozambique Basin continues in an almost north-south direction while the opening of the Weddell Sea occurs in a northwest-southeast direction (in a reference frame with AFR fixed). These differential spreading directions result in a continuous extensional regime between SAM and AFR and also lead to further extension in the Falkland Plateau Basin between the Falkland Islands and Maurice Ewing Bank. No deep ocean connection exists at this time between the Mozambique Basin and the Weddell Sea Basin. The ancient core of the Mozambique Ridge may have prevented any deep water circulation so that only shallow water, or even subaerial conditions, prevailed in what today is the Lazarev Sea.

[44] Stretching in the Falkland Plateau Basin and the Filchner-Ronne Shelf resulted in an eastward motion of the ANP and southernmost SAM (Patagonia), including the Falkland Islands, away from AFR, the Maurice Ewing Bank and East ANT. *Marshall* [1994] proposed a continuous north-south striking spreading center being active in the Falkland Plateau Basin and Weddell Sea Basin between 175–155 Ma. Although we do not follow this interpretation exactly, a period of combined extension in these two basins during the initial phases of rifting in the Weddell Sea area is suggested. To a lesser degree, but oriented in a more northeast-southwest direction, this extension can be followed to the north where intracontinental deformation between the Colorado, Salado and Paraná subplates occurred. This tectonic activity resulted in extension between these blocks and AFR. It could be that the later opening of the South Atlantic Ocean between SAM and AFR was the final result of the same extensional forces that had started to act during the first stages of Gondwana breakup between 170 Ma and 160 Ma.

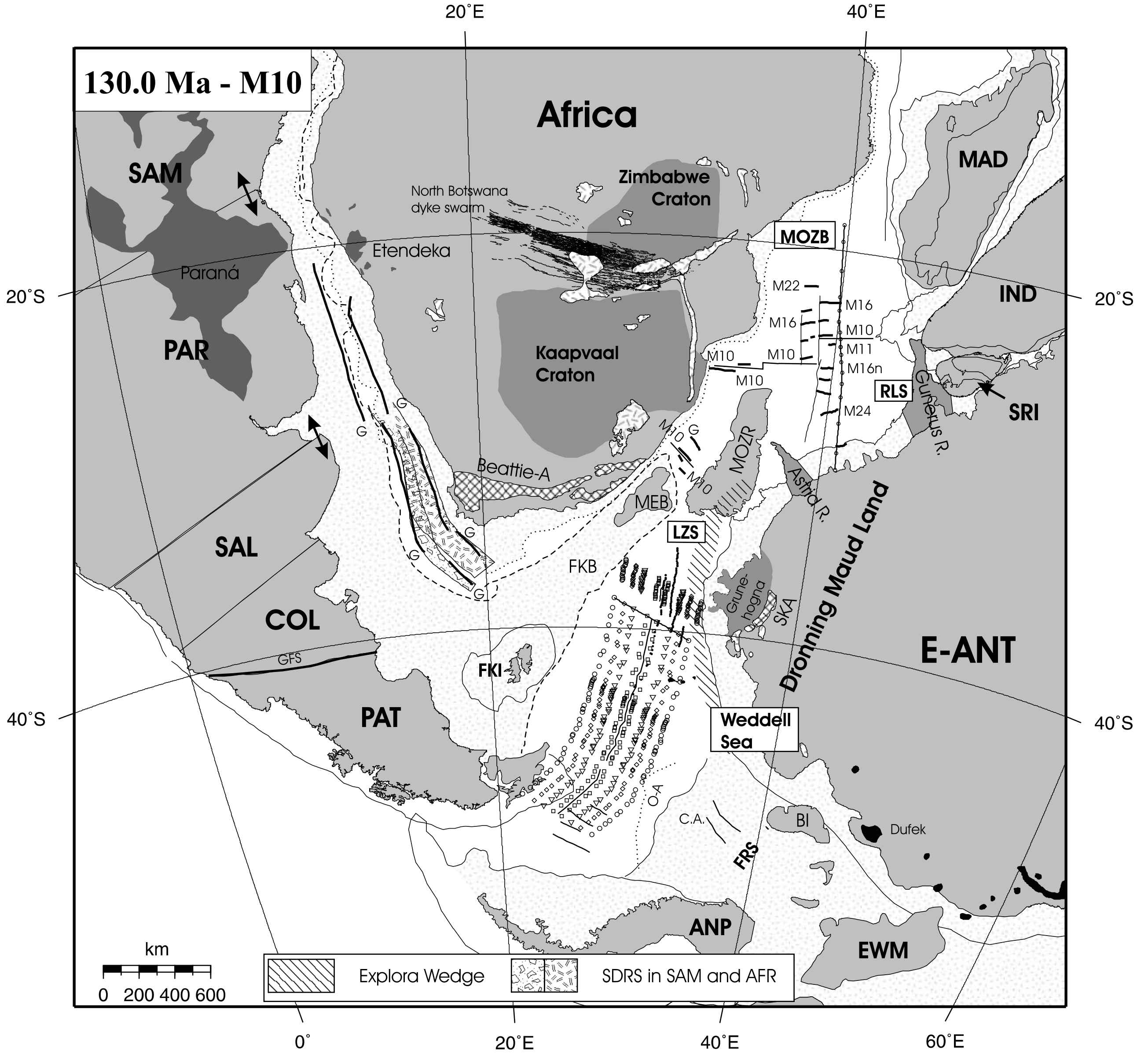

Figure 14. The 130 Ma (M10) reconstruction. While the Riiser-Larsen Sea, Mozambique Basin, and Weddell Sea Basin are developing further, the first ocean floor or seaward dipping reflector sequences in the South Atlantic between South America and Africa are formed. Seafloor spreading also started in the southern and northern Natal Valley. Differential movements between Patagonia and the Colorado block in South America are finished, and only farther north do intracontinental deformations still take place between the Salado and Paraná blocks and the northern part of South America. The latter movement is related to the emplacement of the Paraná-Etendeka volcanics between 138 Ma and 132 Ma [*Courtillot et al.*, 1999]. In the Lazarev Sea, there is still no deep water connection between the southwest Indian Ocean and the Weddell Sea. The Mozambique Ridge is still attached to Antarctica, preventing any deep water passing through from one ocean basin to the other.

[45] During this early phase of extension of the Filchner-Ronne Shelf and Falkland Plateau, relative southward motion of ANT was faster than the relative southwestward motion of Patagonia, resulting in dextral-transtensional shear between ANT (i.e., the Filchner Ronne Shelf) and the Falkland Plateau (Figure 11). In this way, a line of crustal weakness may have formed across the Weddell Sea that was later reactivated as a spreading center between SAM and ANT.

[46] Extension between ANP and Patagonia resulted in rifting and partial separation of ANT and ANP from the SAM continent shortly before the creation of the first ocean floor in the southern Weddell Sea (Figures 11 and 12). This early separation led to the formation of a nonvolcanic rifted margin along the east coast of the ANP [*Ghidella and*

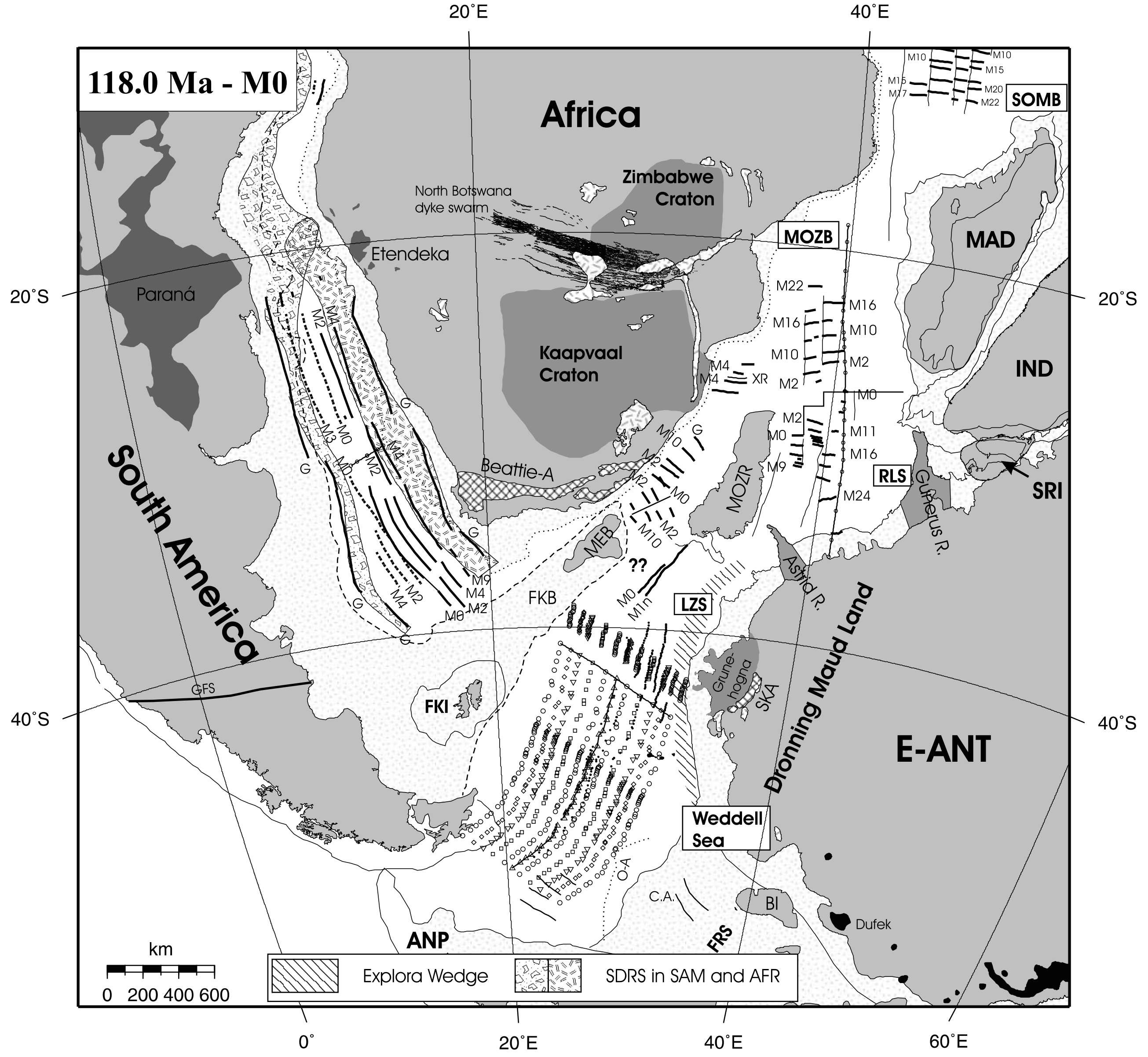

Figure 15. The 118 Ma (M0) reconstruction. The spreading system in the South Atlantic between SAM and AFR has developed completely. A deep water connection between the southwest Indian Ocean and the Weddell Sea became established once the Mozambique Ridge cleared the coast of central Dronning Maud Land. Intracontinental deformation in SAM is no longer occurring and the Falkland Plateau, including the Falkland Islands and the Maurice Ewing Bank, behaves as a single rigid plate with respect to SAM.

LaBrecque, 1997]. The conjugate side, along the west coast of Patagonia, may have been subducted beneath SAM during the Cretaceous as part of a long lasting and still continuing history of subduction along this continental margin. At the time of rifting between ANP and Patagonia (167.2–140 Ma) the Rocas Verdes Basin had also formed in southernmost SAM [*Dalziel and Elliot*, 1982]. The rotated synthetic isochron for 147 Ma (M20) overlaps onto the SAM continent (Figure 12), suggesting that this basin may have been the site were the Weddell Sea rift originated. The initial rift propagated eastward resulting in the formation of the Orion magnetic anomaly [*LaBrecque et al.*, 1986] along the northern limit of the COT in the southern Weddell Sea (Figure 12). Farther east, along the coast of western Dronning Maud Land, the further propagation of this rift between 150 Ma and 138 Ma led to the extrusion of large volumes of magma to form the Explora Wedge, which can be seen as a sequence of seaward dipping reflectors (SDRS) in seismic data [*Hinz*, 1981; *Hinz and Krause*, 1982]. Extrusion would have occurred diachronously, from southwest to northeast along the coast of Dronning Maud Land, following the general direction of the opening of the Weddell Sea from southwest to northeast [*Jokat et al.*, 2003a]. The age of formation of the SDRS that this model suggests (150–

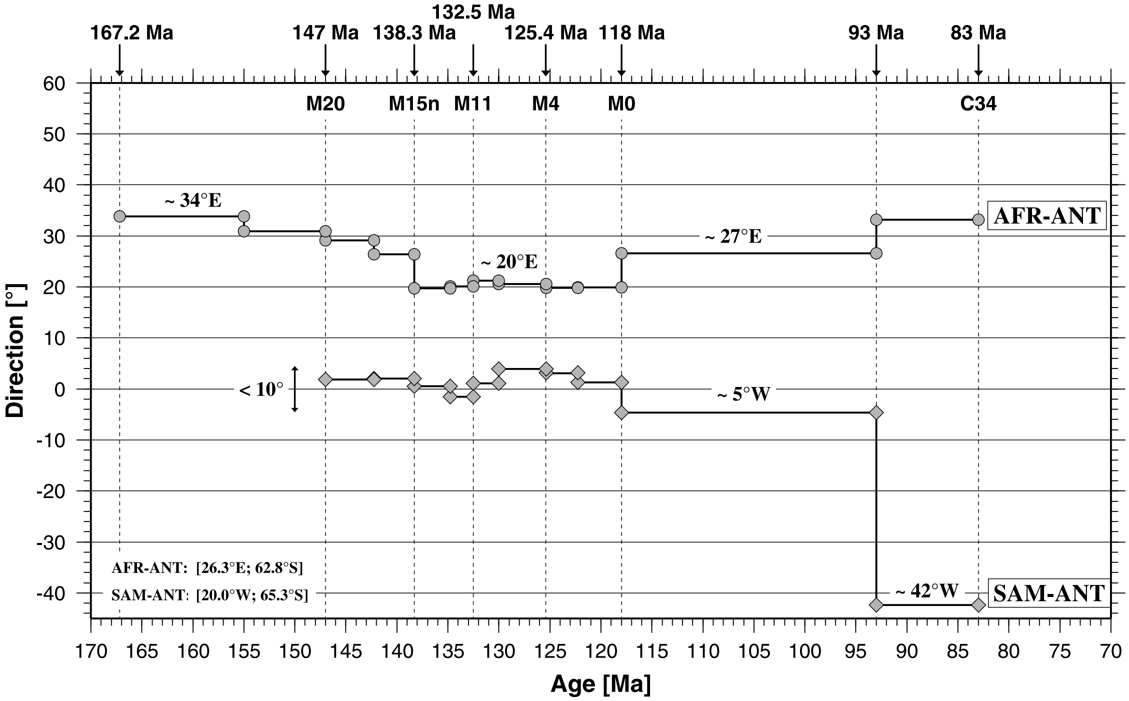

Figure 16. Spreading directions for the AFR-ANT and SAM-ANT spreading regimes (in an ANT reference frame) as calculated for a point on magnetic anomaly C34 that is successively rotated back in time until the closure of the corresponding ocean basin is reached. The almost constant spreading direction in the SAM-ANT spreading system, with a variation of less than 10° between 147 Ma and 93 Ma, is obvious. Spreading in the AFR-ANT spreading regime starts with a direction of about 34°W around 167.2 Ma and successively decreases to about 20°W until 118 Ma (M0). Whereas the SAM-ANT spreading system experiences a dramatic change in spreading direction during the pole change at 93 Ma [*Livermore and Hunter*, 1996], this change is not that prominent in the AFR-ANT spreading system.

138 Ma) conflicts with data published by other authors and will be discussed in greater detail in section 6.2.

6.2. Explora Wedge and the Karoo-Ferrar Large Igneous Events

[47] The plume-related Karoo and Ferrar volcanism in AFR and ANT is now commonly accepted to have occurred at around 183 Ma [*Encarnacion et al.*, 1996; *Duncan et al.*, 1997; *Elliot and Fleming*, 2000; *Reeves and de Wit*, 2000; *Storey et al.*, 2001]. Its exact relation in time and space to the breakup of Gondwana in the Weddell Sea and the Riiser-Larsen Sea, though, is still a point of discussion [*Jokat et al.*, 2003a]. According to *Cox* [1992] and *Elliot and Fleming* [2000] the Explora Wedge formed as the conjugate part of the Lebombo monocline that is part of the Karoo volcanics in AFR, and assign a similar age to it. This is confirmed by an analysis of regional aeromagnetic data in the southern Weddell Sea of *Johnson et al.* [1992] and *Hunter et al.* [1996]. They estimated the age of the Explora Wedge from a southward continuation of the Explora Anomaly, which is in parts the magnetic expression of the Explora Wedge, across Berkner Island to the Dufek Massif. Using the dates of intrusions in the Dufek Massif (185 ± 2.4 Ma, after *Brewer et al.* [1996]) and a dolerite sill in Dronning Maud Land (182.1 ± 1.9 Ma), *Johnson et al.* [1992] and *Hunter et al.* [1996] suggested an approximate age of 182 Ma for the formation of the Explora Wedge. However, the volcanic sequences in the Weddell Sea have not yet been drilled, and so no definite age for their formation is known.

[48] In this study an approximate age of 150–138 Ma is proposed for the formation of the Explora Wedge on the basis of the well-defined age of the magnetic anomalies in the eastern Weddell Sea. This is more than 30 Myr younger than previously suggested. According to *Hinz* [1981] and *Mutter* [1985], SDRS are formed as precursors to the development of a spreading ridge. A close relation in time between the emplacement of the SDRS and the onset of seafloor spreading has been found along many rifted margins [*White and McKenzie*, 1989; *Courtillot et al.*, 1999]. The best studied SDRS are those of the southeastern margin of Greenland and northwestern margin of Norway at the Vøring Plateau (Ocean Drilling Program (ODP) legs 152 and 104, respectively). There, direct correlations between the age of drilled sections of SDRS and the estimated onset of seafloor spreading could be made, suggesting a time delay of only 2 to 5 Myr [*Courtillot et al.*, 1999]. Inferring a similar genesis for the SDRS along the west coast of Dronning Maud Land, and using the magnetic anomaly identifications as presented in this study, an age range of 150 Ma to 138 Ma is assumed for their emplacement. This timing post dates the 183 Ma Dufek Massif [*Behrendt et al.*, 1981; *Johnson et al.*, 1992; *Hunter et al.*, 1996] and the emplacement of the Karoo and Ferrar volcanics by more than 30 Myr. This leads to the conclusion that there is no direct link between the plume related volcanism in AFR and

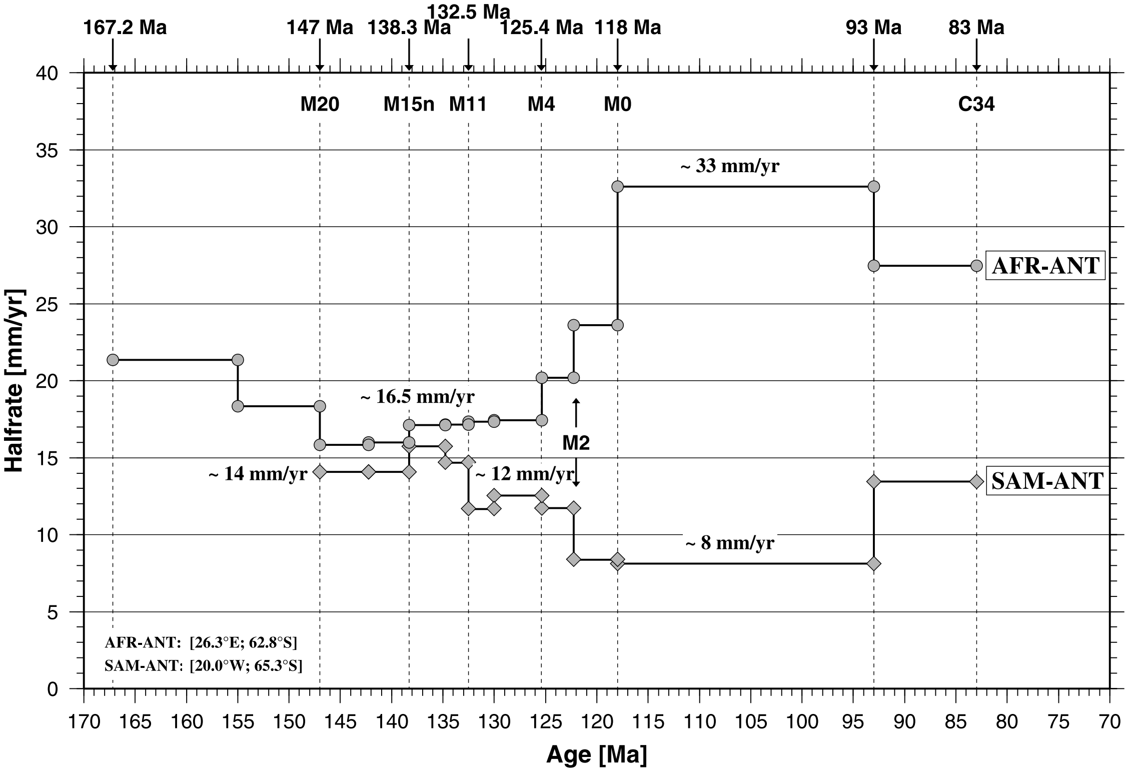

Figure 17. Spreading rates for the AFR-ANT and SAM-ANT spreading regimes (in an ANT reference frame). The calculations are the same as for the spreading directions in Figure 16. Spreading rates in the SAM-ANT regime vary between 12 and 16 mm/yr in the time span from the beginning of seafloor spreading north of the Orion Anomaly until the drop in spreading rate to a value of about 8 mm/yr around chron M2 (122 Ma). This is the age determined for the magnetic expression of Anomaly T. The 93 Ma change in the pole of rotation also has its expression in spreading rates with an increase from 8 mm/yr to a value of 13.5 mm/yr. Spreading rates in the AFR-ANT spreading corridor start with a value of about 22 mm/yr and decrease to about 16.5 mm/yr until M4 (125 Ma). From then on, the rate increases rapidly to about 33 mm/yr for the time span between M0 (118 Ma) and 93 Ma. It should be noted that spreading rates and spreading directions calculated for the time between M0 (118 Ma) and C34y (83 Ma) depend heavily on the time chosen for rotation.

ANT and the opening of the Weddell Sea and the emplacement of the Explora Wedge, as already noted by *Jokat et al.* [2003a].

6.3. Explora Escarpment

[49] As the separation of SAM and ANT continues, the Explora Escarpment along the west coast of Dronning Maud Land (Figure 1) forms at about 147–130 Ma. *Lawver et al.* [1992] interpret this steep bathymetric step as an expression of early strike-slip movements between East and West Gondwana (200–150 Ma). This interpretation is not supported by the model presented here. From interpretations of seismic data, it is evident that the Explora Escarpment formed after the emplacement of the SDRS [*Miller et al.*, 1990; *Kaul*, 1991]. According to this and the age suggested above for the formation of the SDRS (155–138 Ma), the Explora Escarpment must be more than 10 Myr younger than suggested by *Lawver et al.* [1992]. One possible mechanism for the formation of the escarpment that does not involve large strike-slip motions was put forward by *Kaul* [1991]. In his work, the steep bathymetric step formed along a normal fault during Early Cretaceous times, which would correlate with the final separation of the Falkland Plateau from East ANT.

6.4. Anomaly T

[50] After the Falkland Plateau cleared the coast of Dronning Maud Land, spreading rates in the Weddell Sea dropped to less than 10 mm/yr around magnetic chron M2 (122.3 Ma) (Figure 17). Anomaly T occurs between the identification of magnetic anomalies M1n (118.7 Ma) and M3 (123.0 Ma) in the Weddell Sea, suggesting it has an age of about 119–123 Ma. *Rogenhagen and Jokat* [2002] suggest that Anomaly T may be the expression of the transition between oceanic lithosphere formed at fast and slow spreading rates, according to the interpretation of seismic data that show a smooth basement topography to the south of Anomaly T and a rough basement topography to the north. Recent studies along the ultraslow Gakkel Ridge in the Arctic and comparative work on the Southwest Indian Ridge provide new interpretations of basement ridges in the vicinity of slow and ultraslow spreading ridges

[*Jokat et al.*, 2003a; *Dick et al.*, 2003]. *Jokat et al.* [2003b] conclude that off-axis basement ridges are common for ocean floor formed at half spreading rates of less than 7 mm/yr. Such basement ridges are interpreted as a result of focused and increased melt supply in the ultraslow spreading regime. In the Weddell Sea, we encounter spreading velocities of 8 mm/yr north of Anomaly T, which is within the range of ultraslow rates (<20 mm/yr full rate). Thus, if the increased basement roughness north of Anomaly T [*Rogenhagen and Jokat*, 2002] and the observed gravity anomalies are correlated with the existence of basement ridges like those along the Gakkel Ridge and the Southwest Indian Ridge, it could be concluded that Anomaly T marks a transition between a slow spreading regime to the south and an ultraslow spreading regime to the north.

6.5. Mozambique Ridge

[51] The role and position of the Mozambique Ridge during the breakup of Gondwana is of crucial importance for an understanding of how and when a deep water connection between the Southwest Indian Ocean and the South Atlantic Ocean first became established. The Mozambique Ridge forms a large submarine plateau and is suggested to be composed in part of continental fragments embedded within oceanic crust [*Mougenot et al.*, 1991; *Ben-Avraham et al.*, 1995]. However, its prebreakup position and subsequent kinematic history is only sparsely known [*Ben-Avraham et al.*, 1995; *Tikku et al.*, 2002]. From a detailed study of satellite-derived free-air gravity data and shipborne magnetic data, *Tikku et al.* [2002] inferred an extinct spreading center in the northern Natal Valley, which was active in separating the Mozambique Ridge from AFR between M11 (133.0 Ma) and 125.3 Ma. The poles of rotation from this study and a predrift position of the Mozambique Ridge as presented by *Marks and Tikku* [2001] were combined with the model parameters listed in Tables 2 and 3 and correlated with the relative positions of AFR and ANT through time.

[52] The possible position of the Mozambique Ridge shown in the predrift reconstruction (167.2 Ma, Figure 11) is that proposed by *Marks and Tikku* [2001]. For this and the following reconstructions, the outline of the maximum size of the continental core of the Mozambique Ridge, as inferred from free-air gravity data [*Sandwell and Smith*, 1997], is used. The configuration shown in Figure 11 implies, on the one hand, that the Mozambique Ridge behaved as an independent microplate even prior to the existence of the extinct spreading ridge in the northern Natal Valley and, on the other hand, that a significant amount of extension in central Mozambique and onshore Dronning Maud Land occurred prior to the separation of AFR and ANT. Both these requirements were discussed by *Marks and Tikku* [2001], *Cox* [1992], and *Tikku et al.* [2002].

[53] For the 147 Ma, 140 Ma, and 130 Ma reconstructions (Figures 12, 13, and 14), the position of the Mozambique Ridge was interpolated and adjusted from the reconstructions of *Marks and Tikku* [2001], and *Tikku et al.* [2002]. As shown in Figures 12–14, the Mozambique Ridge fits almost exactly in the gap between the Maurice Ewing Bank to the west and the Astrid Ridge to the east. Both these features are assumed to consist, at least partially, of a continental core [*Ludwig*, 1983; *Roeser et al.*, 1996] and hence would have formed, together with the Mozambique Ridge, a continuous barrier to deep water circulation between the Indian Ocean and the Weddell Sea at this time. *Mutterlose and Wise* [1990] presented evidence for anaerobic to dysaerobic bottom water conditions on the continental slope north of Dronning Maud Land during Valanginian-Hauterivian (138–124 Ma) times from analyses of Lower Cretaceous nannofossils in cores from ODP Leg 113. Accordingly, *Jokat et al.* [2003a] suggested the existence of a shallow water or even subaerial basin between AFR and ANT at about 145 Ma. The proposed position of the Mozambique Ridge at 147–130 Ma supports this interpretation, assuming rifting and seafloor spreading was active in the Mozambique plain and the northern Natal Valley at least since at about 147 Ma.

[54] According to *Tikku et al.* [2002], seafloor spreading in the northern Natal Valley stopped at about 125.3 Ma. Thus, in the 118 Ma reconstruction (Figure 15), the Mozambique Ridge is shown in its present-day position with respect to AFR. By this time, the ridge had rifted off the coast of Dronning Maud Land and was moving away from it in a northeasterly direction. Although there is no direct evidence for the exact age when the Mozambique Ridge and ANT separated, indirect hints come from an interpretation of magnetic anomalies in the Lazarev Sea [*Jokat et al.*, 2003a] (Figure 2). If the lineated east-west striking magnetic anomalies in the Lazarev Sea are interpreted as anomaly M0 (118 Ma) and M1n (120 Ma), as suggested by *Jokat et al.* [2003a], the Mozambique Ridge must have cleared its position in the Lazarev Sea by 122.0 Ma, in agreement with the 118 Ma reconstruction shown in Figure 15. However, some uncertainty still exists about the configuration of the ridge systems that were active in the Lazarev Sea at this time (area marked by question mark in Figure 15). On the basis of the east-west strike of the magnetic anomalies in the Lazarev Sea, conjugate seafloor spreading anomalies would be expected south of the Maurice Ewing Bank, but this ocean floor no longer exists due to subduction at the South Sandwich trench. Rifting between the Mozambique Ridge and ANT should have formed seafloor spreading anomalies parallel to the ridge axis in a northeast-southwest direction. However, only sparse data exist in these regions, and no such seafloor spreading anomalies could so far be identified in the eastern Lazarev Sea, or south of the Mozambique Ridge. Maybe any magnetic anomalies in the eastern Lazarev Sea are overprinted by the large Maud Rise complex.

6.6. New Model Compared to Other Published Data

[55] Compared to other published models, the model for the opening of the Weddell Sea, as presented in this study, is constrained by unequivocally dated magnetic anomaly identifications and puts strong constraints on the age of the oldest ocean floor in the southern Weddell Sea. The deduced Gondwana breakup model has major differences and improvements compared to other published models. An overview of the most significant differences and improvements compared to some of them is given below:

[56] In the Gondwana breakup reconstructions of *Lawver et al.* [1992], the earliest movements in the Weddell Sea are described as a consequence of north-south oriented movements between rigid East and West Gondwana plates. This

entails simple strike-slip motions along the western coast of Dronning Maud Land and in the southern Weddell Sea. Large strike-slip motions between rigid East and West Gondwana are not encountered in the new model presented in this paper. Stretching and extension takes place in the Weddell Sea Basin and between SAM and AFR since the early stages of Gondwana breakup, which rules out the assumption of two rigid (East and West) Gondwana plates.

[57] Spreading directions proposed in the model of *Ghidella et al.* [2002] are very similar to those presented in this model. However, Ghidella et al.'s 146 Ma and 160 Ma reconstructions were only tentatively dated due to weak constraints on the age of the oldest ocean floor. These dates are revised in the new model presented here by about 13 Myr, suggesting an age of 147 Ma for the oldest ocean floor in the southern Weddell Sea.

[58] In the same way, the age for the initiation of seafloor spreading, as presented by *Livermore and Hunter* [1996], differs by 18 Ma from the one presented here. Similar to *Lawver et al.* [1992], they assume rigid East and West Gondwana motions for the early stages of Gondwana breakup, which is not supported by the new model.

[59] The timing and position of the initial phase of separation between SAM and ANT in the Weddell Sea, as presented by *Kovacs et al.* [2002], is similar to that presented here. However, no evidence can be found in the high-resolution magnetic anomaly data along the coast of western Dronning Maud Land for the suggested subsequent phase of east-west oriented spreading. The constant spreading directions shown in Figure 17 agree with the east-west directed strike of the magnetic anomalies shown in Figure 5 and exclude a sudden change in spreading direction at any time during the opening of the Weddell Sea.

[60] While *Jokat et al.* [2003a] concentrate on the presentation and interpretation of the new magnetic anomaly data in the eastern Weddell Sea, Lazarev Sea and Riiser-Larsen Sea, in this study, the interpretation of magnetic anomalies in the Weddell Sea is extended farther west by the correlation with other published data from the western and central Weddell Sea. *Jokat et al.*'s [2003a] newly derived model for the breakup of Gondwana describes any movements in the Weddell Sea area between SAM and ANT only as far as they can directly be deduced from the newly presented magnetic database. The model presented here is a continued and refined model of the one presented by *Jokat et al.* [2003a] including a detailed description of the early movements in the Weddell Sea area shortly before and during the initial stages of Gondwana breakup.

7. Conclusion

[61] A refined plate tectonic model for the opening of the Weddell Sea between South America and Antarctica and the Mesozoic breakup of Gondwana in the South Atlantic region is presented in this paper. The rotation parameters for the seafloor spreading history between South America and Antarctica are based on well-constrained ages for the ocean floor in the Weddell Sea. These are combined with published data for the spreading systems between South America and Africa and Africa and Antarctica and a revised set of finite rotations is determined that describes the early breakup of Gondwana between South America, Africa, and Antarctica.

[62] The new model provides parameters already for the earliest movements taking place in the Weddell Sea region while Africa and Antarctica start to separate. This includes extensional movements between the Antarctic Peninsula and the East Antarctic craton between 167 Ma and 147 Ma, and within the Falkland Plateau, separating Patagonia from Africa and the Maurice Ewing Bank. Extensional forces between South America and Africa are already active in the Weddell Sea region at the same time when rifting in the conjugate Mozambique Basin and Riiser-Larsen Sea, and the Somali Basin occurred. Thus there were three separate basins, the Weddell Sea, Mozambique Basin and Riiser-Larsen Sea, and the Somali Basin, developing independently at this time.

[63] The continental margin along the east coast of the Antarctic Peninsula probably formed during those initial stages of Gondwana breakup as a result of rifting between the Antarctic Peninsula and Patagonia. The opening of the Weddell Sea starts at around 147 Ma in the southernmost part of the Weddell Sea. This is 10 to 15 Myr later than previously suggested by other published models. As a consequence of this revised age for the opening of the Weddell Sea, an age of about 150 Ma to 138 Ma is suggested for the formation of the seaward dipping reflector sequences, the Explora Wedge, along the west coast of Dronning Maud Land. After the formation of the Explora Wedge the initial opening in the southern Weddell Sea starts in a NNW direction at slow spreading rates (~12–14 mm/yr) and drops down to ultraslow spreading rates at about 122 Ma (M2).

[64] In the frame of the Gondwana breakup model presented here, possible paleopositions and movements of the Mozambique Ridge are verified. The assumption that the Mozambique Ridge once acted as an independent continental fragment was used to infer its position throughout the complete Gondwana breakup process. Thereafter, the development of a deep water connection between the Indian and the South Atlantic Ocean occurred not before 122 Ma. Before this time the Mozambique Ridge, Astrid Ridge and the Maurice Ewing Bank formed a continental barrier between the oceans in the west and in the east. Uncertainties, however, exist about the origin and the initial position of the Mozambique Ridge within Gondwana and the precise date and geometry of its separation from the Antarctic continent.

[65] **Acknowledgments.** All the calculations done within this work were performed with a MATLAB code (The MathWorks Inc.) written by the author. Figures were prepared with GMT (Generic Mapping Tools). We thank Robert Duncan, Dietmar Müller, and an anonymous reviewer for their constructive comments and reviews.

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