Geophysical Journal International

Geophys. J. Int. (2016) **206,** 835–844 doi: 10.1093/gji/ggw147
Advance Access publication 2016 April 14
GJI Marine geosciences and applied geophysics

Early seafloor spreading in the South Atlantic: new evidence for M-series magnetochrons north of the Rio Grande Fracture Zone

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Accepted 2016 April 12. Received 2016 April 8; in original form 2015 August 8

SUMMARY

Recent tectonic reconstructions of the South Atlantic have partitioned the ocean basin into several segments based upon one or more proposed intraplate South American deformation zones. In several of these reconstructions, opening of the southern segment(s) by seafloor spreading prior to Aptian-Albian time is accompanied by contemporaneous strike-slip motion along an intraplate boundary extending southeastward from the Andean Cochabamba—Santa Cruz bend to the Rio Grande Fracture Zone (RGFZ). We have examined new magnetic data over the Pelotas, Santos and Campos Basins, offshore Argentina and Brazil, acquired by ION-GXT in tandem with long-offset, long record seismic reflection data, and identified seafloor spreading anomalies M4, M3, M2 and M0 (∼131, ∼129, ∼128 and ∼125 Ma). Integrating these results with our earlier work, we have been able to correlate magnetochrons M4, M3, M2 and M0 north and south of the RGFZ on the South American margin, and north and south of the Walvis Ridge on the African side. Our results are therefore inconsistent with diachronous opening models that involve substantial continental strike-slip motion north of RGFZ during M4 to M0 time. Although the ocean basin may have opened from south to north, our results indicate that seafloor spreading began north of the RGFZ earlier than previously proposed.

Key words: Satellite gravity; Marine magnetics; Continental margins: divergent; Atlantic Ocean.

INTRODUCTION

After their seminal paper, linking seafloor spreading to magnetic data (Vine & Matthews 1963), nearly all the early attempts to correlate seafloor spreading anomalies over the South Atlantic were limited to the region south of the Rio Grande Fracture Zone (RGFZ, Mascle & Phillips 1972; Larson & Ladd 1973; Ladd *et al.* 1973; Ladd 1974; Rabinowitz 1976; LaBrecque & Rabinowitz 1977; Barker 1979; LaBrecque & Hayes 1979; Rabinowitz & LaBrecque 1979; Martin *et al.* 1982). However, although limited by data coverage, Cande & Rabinowitz (1978, 1979) were able to map M0 and M3 north of RGFZ from six widely spaced magnetic anomaly profiles offshore Brazil, and from three profiles offshore Angola. In their thorough study of magnetic data south of RGFZ, Rabinowitz & LaBrecque (1979) identified M0 and M4 over both flanks of the ocean basin from the RGFZ south to the Falkland Plateau/Ewing Bank in the west, and from the Walvis Ridge (and RGFZ) to the Cape of Good Hope in the east. In the southernmost portions of these margins, they identified older magnetochrons M9–M11, but note that amplitudes decrease northward and conclude that this decrease is '. . . probably related to reduced magnetization of the oceanic crust' (p. 5979). More recently, and with some variation, other workers (Nurnberg & Muller 1991; Hall & Bird 2007; Moulin *et al.* 2009; Bird & Hall 2010b; Hall *et al.* 2014; Perez-Diaz & Eagles 2014) have since identified M-series magnetochrons that are consistent with those of Rabinowitz & LaBrecque (1979). Moulin *et al.* (2009), combined the older M9–M11 chrons and G anomaly of Rabinowitz & LaBrecque (1979) into a new group that they call Large Marginal Anomalies.

Much of the difficulty in determining the early opening history of the South Atlantic is the absence of seafloor spreading anomalies. The Cretaceous Magnetic Quiet Zone (CMQZ) occurred between Chrons C34 (84 Ma) and M0 (126 Ma), and the break-up of the South Atlantic occurred roughly between 130 and 110 Ma. However, Granot & Dyment (2015) have recently correlated magnetic anomalies within the CMQZ that they suggested are related to magnetic field intensity variations. They interpreted a change in plate motion between South America and Africa at 100 Ma, and their work might help with further studies on the opening of the South Atlantic, particularly north of our study area and the equatorial region of the South Atlantic.

Research carried out between 1965 and 2006, describing the earliest kinematic evolution of the South Atlantic Ocean, was tabulated by Moulin *et al.* (2009). Combining their summary with recent work (Eagles 2007; Torsvik *et al.* 2009; Perez-Diaz & Eagles 2014), total South Atlantic reconstruction times range from 130 Ma to over 150 Ma (Late Jurassic to Aptian), with calculated rotation poles centred near 50.9°N, 34.6°W and an average rotation angle

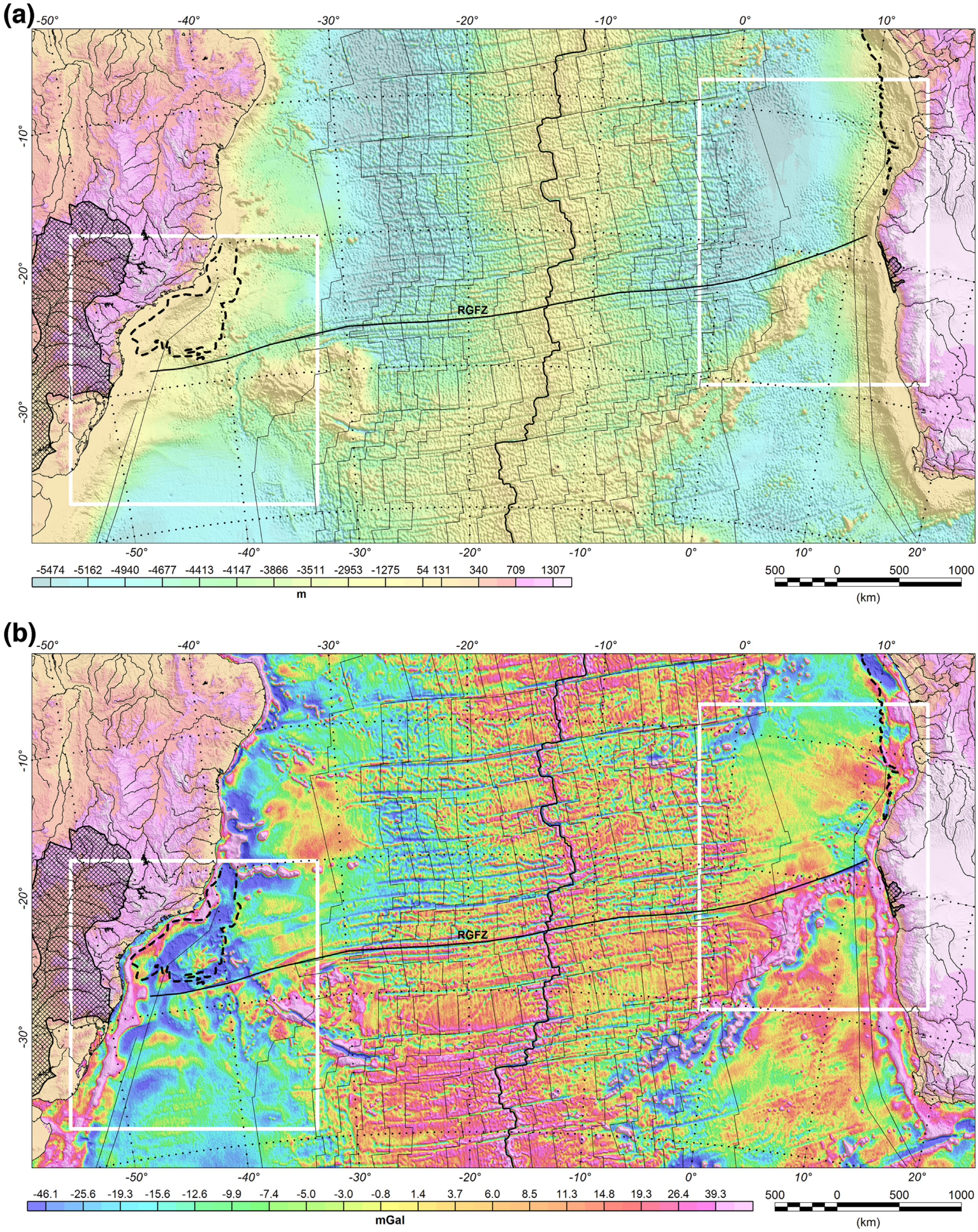

Figure 1. Central South Atlantic Ocean topography (a) (ETOPO1, Smith & Sandwell 1997), satellite-derived free air gravity anomalies (b), and calculated Bouguer gravity anomalies (c) (offshore gravity only, Sandwell *et al.* 2014). Outlines of salt deposition limits (dashed black); Rio Grande Fracture Zone ('RGFZ') and Mid-Atlantic ridge (thick black); geomagnetic isochrons (Muller *et al.* 1997, thin black); Parana and Etendeka flood basalt regions onshore South America and Africa, respectively (hachured black areas); Figs 2 and 3 South America and Africa, respectively (white boxes).

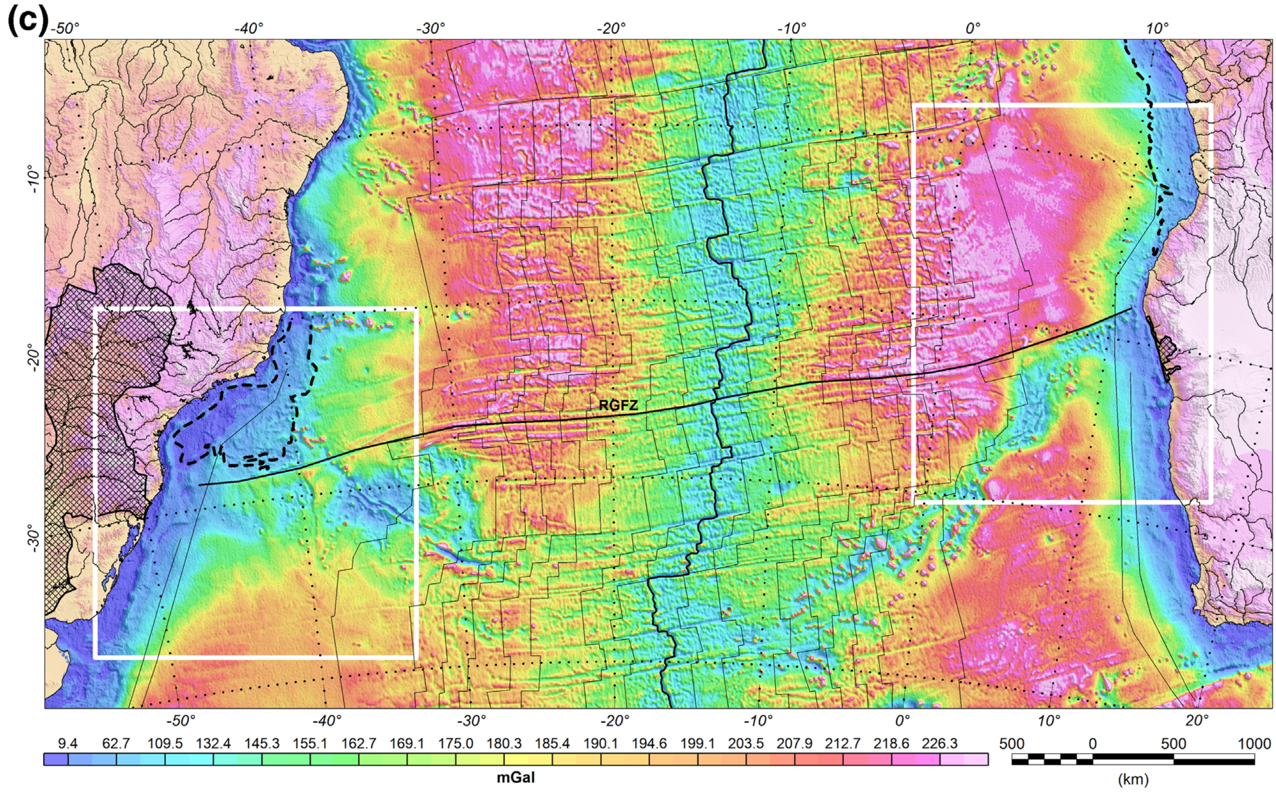

Figure 1 – (*Continued.*)

of 55.1° (respective standard deviations: 4°, 3° and 3°). Our results differ slightly, total reconstruction pole for M4 (130.6 Ma), 45.5° N, 32.9 W° and 54° rotation (Bird & Hall 2010, 2010ab and Hall & Bird 2007, 2009), because we included M4 chrons north of the RGFZ in our calculations.

Recent tectonic reconstructions of the South Atlantic suggest that the ocean basin evolved by diachronous motion along one or more intraplate continental deformation zones, oriented east–west to southeast–northwest, in South America (Unternehr *et al.* 1988; Nurnberg & Muller 1991; Eyles & Eyles 1993; Schettino & Scotese 2005; Koenig & Jokat 2006; Eagles 2007; Moulin *et al.* 2009; Torsvik *et al.* 2009; Perez-Diaz & Eagles 2014). Right-lateral motion along faults in these zones allowed the northward progression of seafloor spreading in the South Atlantic Ocean. One of the proposed faults extends from RGFZ on the east coast of Brazil, northwest to the Andean Cochabamba—Santa Cruz bend in central Bolivia. If, as the South Atlantic opened, right lateral motion continued in this fault zone after M4 time (∼131 Ma), then oceanic crust produced during this interval south of RGFZ should be absent to the north.

Using satellite-derived gravity data to identify oceanic fracture zones (Fig. 1, Sandwell *et al.* 2014), and new marine magnetic anomaly data acquired over the South American margin north of the RGFZ together with existing data, we have identified M4, M3, M2 and M0 anomalies above the salt canopy of the Santos and Campos Basins, offshore Brazil (Fig. 2). In addition, we have identified the same M-series anomalies along the African margin north of the Walvis Ridge to ∼9°S (Fig. 3). Combining these results with our earlier work over offshore Angola (Hall & Bird 2007) we have calculated new total reconstruction poles for the early evolution of the South Atlantic Ocean (Table 1). Any motion along the proposed intracontinental transform boundary, extending coast-to-coast through central South America in line with RGFZ (Schettino & Scotese 2005; Koenig & Jokat 2006; Eagles 2007; Moulin *et al.* 2009; Torsvik *et al.* 2009; Perez-Diaz & Eagles 2014), is inconsistent with our results. The existence of M4, M3, M2 and M0 magnetochrons located north and south of RGFZ indicates coeval seafloor accretion across this fracture zone.

DATA

In addition to the new marine magnetic anomaly data acquired by ION-GXT in tandem with their South Atlantic BasinSPAN™ long-offset, long-record seismic reflection programs, we have utilized open-file data that are downloadable from two internet sources: (1) the National Oceanic and Atmospheric Administration's National Geophysical Data Center (NGDC, www.ngdc.noaa.gov) and (2) Scripps Institute of Oceanography, University of California San Diego (scripps.ucsd.edu). Magnetic anomaly profiles (GEODAS Marine Geophysical Trackline Data: gravity, magnetics and bathymetry), ETOPO1global relief model (1 arcmin grid), and TerrainBase global topography (5 arcmin grid) are available from NGDC (Amante & Eakins 2009). Recently updated satellite-derived free air gravity anomalies (1 arcmin grid, Sandwell *et al.* 2014) are available from Scripps (Figs 1–3).

METHODS

Residual gravity

We calculated residual Bouguer gravity anomalies by 7 km upward continuation of satellite-derived Bouguer gravity anomalies, and then subtracting this upward continued grid from the original grid (Figs 2 and 3). We calculated Bouguer anomalies

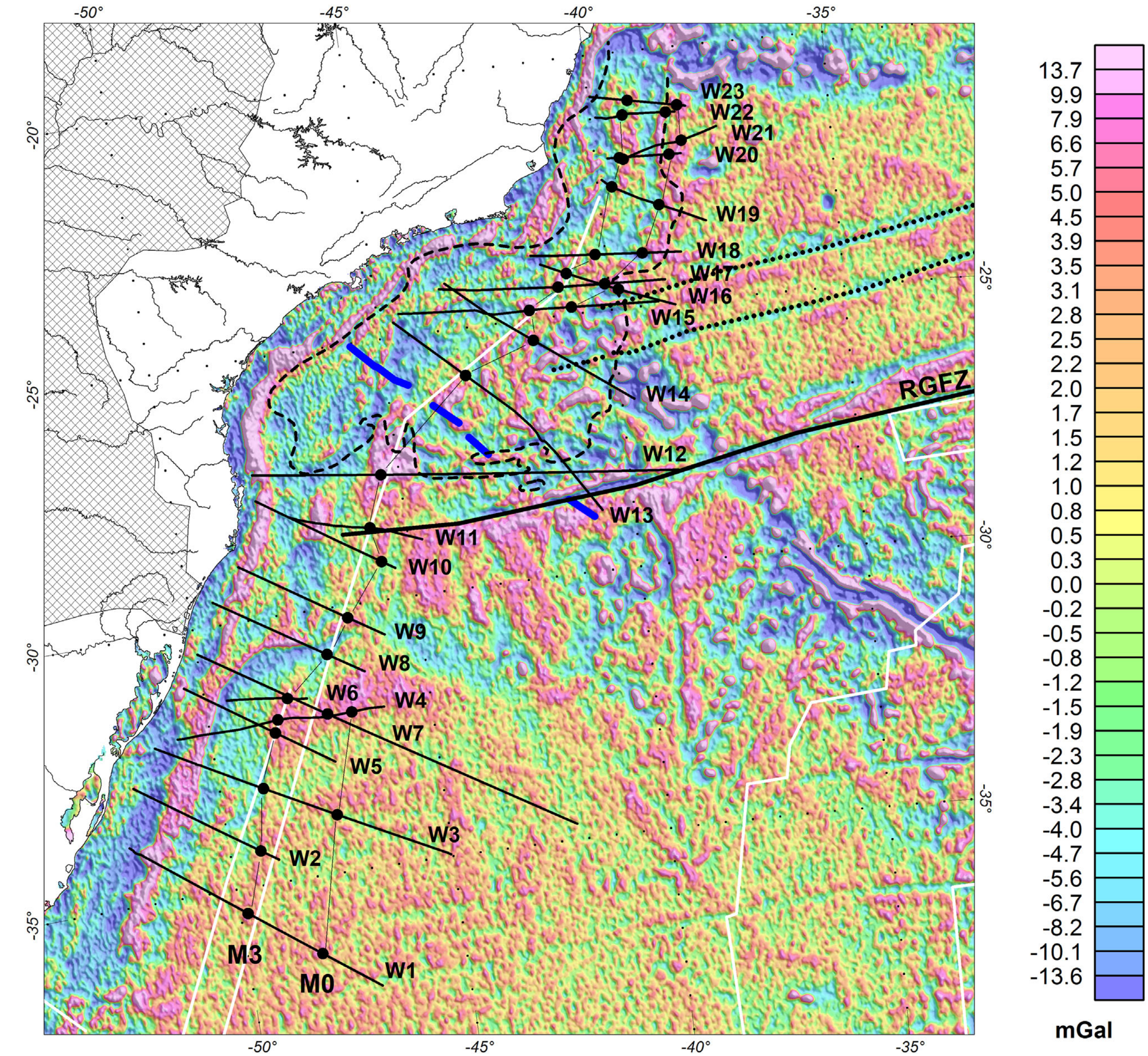

Figure 2. Residual satellite-derived Bouguer gravity anomalies offshore South America (Sandwell *et al.* 2014); Residual = (Bouguer) – (7 km upward continued Bouguer); Marine magnetic profiles locations in Fig. 4 ('W', black); M0 and M3 magnetochron picks (black circles) connected by thin black lines; Leyden *et al.* (1971) seismic refraction experiment location (thick blue); Outline of salt deposition limit (dashed black); Rio Grande Fracture Zone ('RGFZ', heavy black); Geomagnetic isochrons (Muller *et al.* 1997, white); Parana flood basalt region onshore South America (hachured black area); trace of unnamed fracture zones north of RGFZ (dotted lines).

(Fig. 1c) after assuming a water bottom density of 2.0 g cc^{-1} then adding 0.97 g cc^{-1} density to the water column. Note that we used TerrainBase topography offshore, which was generated using 100 per cent depth-soundings, rather than ETOPO1, which was generated using depth-soundings and gravity data. The resulting grid displays shorter wavelength anomalies at the expense of longer wavelengths, and allows for the identification of subtle anomalies associated with fracture zones and seafloor spreading centres.

Poles of rotation

Oceanic transform faults, and their off-axis traces, are fracture zones (FZ) that roughly coincide with flowlines that describe the relative motions between two lithospheric plates. The off-axis sections of fracture zones are fossil transform faults and therefore indicate that oceanic crust must exist at least on one side of the fracture zone. The intersections of flow lines mapped along FZs with identified magnetic lineations (described below) are control points that were used to compute total reconstruction poles from 131 Ma to the present for South American and African plates (Table 1) by modifying the method described by Engebretson *et al.* (1984) and Bird (2004). A computer program builds a 101 × 101 matrix of trial rotation poles where the central seed pole is defined by the user who also chooses the initial space between matrix nodes. The program averages reconstruction rotation angles between the two sets of control points and each of the trial poles in the matrix, then errors between reconstructed points are minimized with a best fit

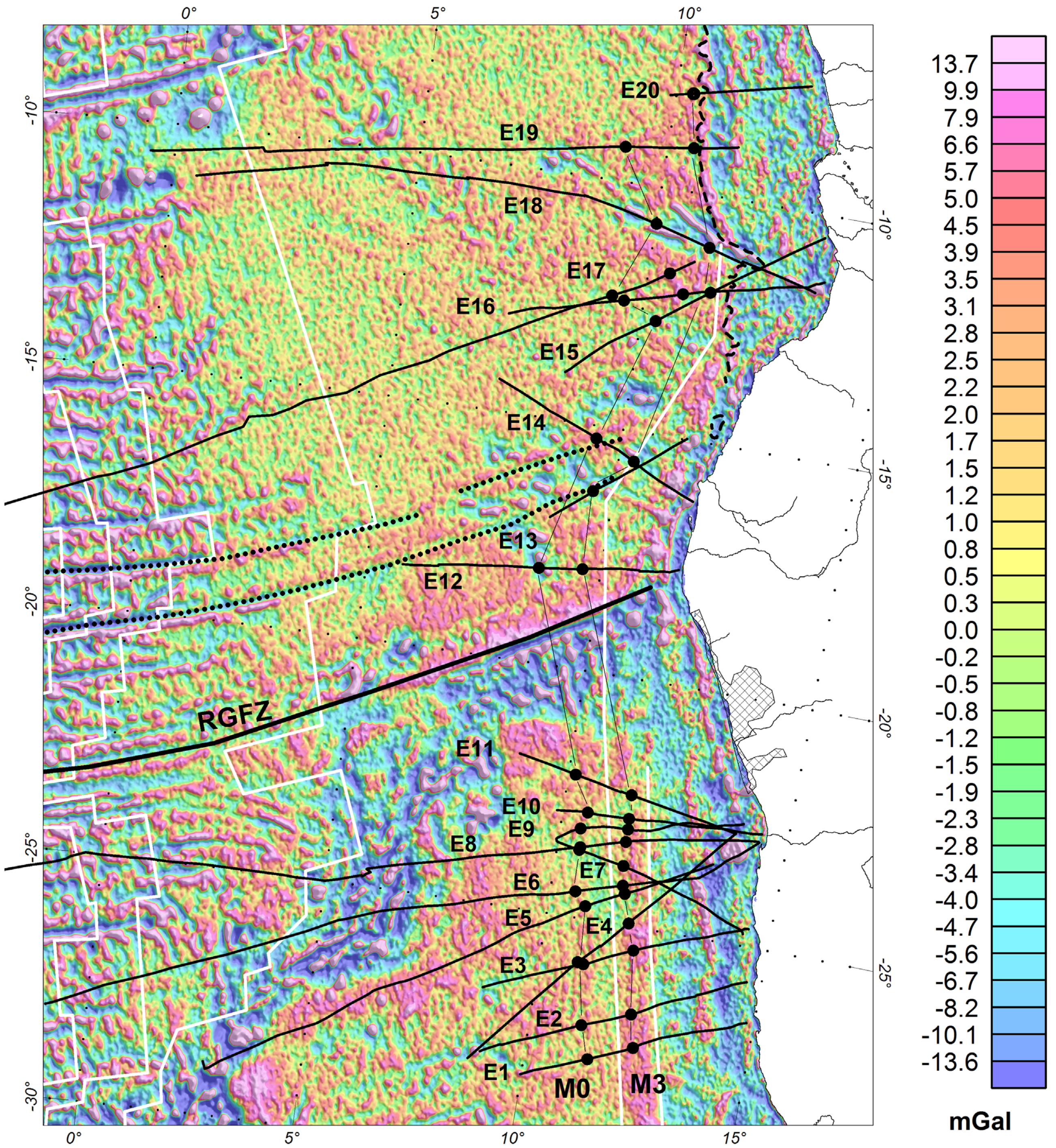

Figure 3. Residual satellite-derived Bouguer gravity anomalies offshore Africa (Sandwell *et al.* 2014); Residual = (Bouguer) – (7 km upward continued Bouguer); Marine magnetic profile data (thin black), profiles locations displayed in Fig. 4 ('E', black); M0 and M3 magnetochron picks (black circles) connected by thin black lines; Outline of salt deposition limit (dashed black); Rio Grande Fracture Zone ('RGFZ', heavy black); Geomagnetic isochrons (Muller *et al.* 1997, white); Parana flood basalt region onshore South America (hachured black area); trace of unnamed fracture zones north of RGFZ (dotted lines).

pole and rotation angle are returned by the program. These results are then used as a new seed pole with smaller matrix increment, and so on (Bird 2004). Stage poles were calculated between mapped chrons and the Mid-Atlantic Ridge for each flank of the ocean basin, and then summed to determine the total reconstruction poles. RMS rotation errors for M0 and M4 were 1.94° and 1.92°, respectively.

Magnetic lineations

Ship track magnetic data crossing the African and South American margins were examined for evidence of linear anomaly patterns. Profiles based on GEODAS data have various orientations and were projected along a uniform azimuth related to flow line directions predicted from rotation poles. Newly acquired magnetic data from ION-GXT were acquired along parallel profiles oriented along

Table 1. Total reconstruction poles for South America relative to Africa: M0 and M4 (this study), C34–C5 (Bird & Hall 2010b).

Chron	Age	Lat	Lon	Rot
C5	9.8	72.4	–49.7	4.3
C6	18.7	64.0	–40.8	7.1
C13	33.2	53.1	–31.6	13.9
C18	38.6	55.8	–32.1	16.5
C21	45.7	55.1	–30.7	19.6
C25	57.1	57.7	–30.4	22.4
C31	68.4	54.4	–29.0	24.9
C34	83.6	59.4	–34.2	33.6
M0	125.9	43.4	–32.2	52.2
M4	130.6	45.5	–33.0	54.0

either NW–SE or E–W. We compared feature-to-feature correlations between adjacent tracks over each margin in order to carefully map magnetic lineations. Prominent magnetic anomalies that displayed the best line to line continuity along each margin were then compared with those predicted by seafloor spreading models based upon the geomagnetic reversal time scale of Gradstein *et al.* (2014). Several geomagnetic reversal time scales have been proposed for the Late Jurassic–Early Cretaceous portion of the time scale (e.g. Channell *et al*. 1995; Gradstein *et al*. 2005; Tominaga & Sager 2010; Malinverno *et al.* 2012; Gradstein *et al.* 2014). Although most of these time scales are somewhat similar to each other, we have used the time scale of Gradstein *et al.* (2014) on the basis that it is the most recent time scale widely adopted by the scientific community. Distinctive magnetic anomalies identified included those associated with magnetochrons M4, M3, M2 and M0 (i.e. 130.6, 129.1, 128.7 and 125.9 Ma, respectively).

RESULTS

We have updated our earlier calculations (Hall & Bird 2007; Bird & Hall 2010b) after adding new, high quality magnetic data over the Santos and Campos Basins, offshore Brazil. We estimated the relative positions of the two plates for times corresponding to M4, M2 and M0 by holding the African Plate fixed, and rotating the South American Plate counter-clockwise for three individual times between 130.6 and 125.9 Ma (Table 1). These total reconstruction poles are supported by new marine magnetic anomaly data, integrated with open-file marine magnetic anomaly data, to identify and map, line-by-line, Mesozoic magnetochrons north of the RGFZ, offshore Brazil, Angola and the Congo. Several prominent magnetic features with amplitudes of ∼250–300 nT can be successfully correlated along both margins (Fig. 4). Seafloor spreading models show that these prominent features correlate well with those associated with anomalies M4, M3, M2 and M0 (Fig. 5).

South American margin

Magnetic anomaly maps over the South American margin between 38°S and 45°S (Max *et al.* 1999; Schreckenberger 2001) show linear anomalies roughly parallel to the coast. Over the Argentinian margin near 43°S these anomalies have been identified as those associated with magnetochrons M0–M10 (Schreckenberger 2001). Further north from 38°S to 31°S (i.e. immediately south of RGFZ) Rabinowitz & LaBrecque (1979) identified anomalies associated with magnetochrons M0 and M3. North of RGFZ, Cande & Rabinowitz (1978) examined several, sparsely distributed profiles and were able to map linear features that they tentatively identified as either M0 or M3. With our newly acquired, more extensive magnetic data we are able to continue the correlations of Rabinowitz & LaBrecque (1979) and Cande & Rabinowitz (1978) northwards to at least 21°S with better resolution and greater confidence. The new data extend south of RGFZ to ∼34°S where they overlap some of the northernmost profiles used by Rabinowitz & LaBrecque (1979). For example, their Profile 105 coincides almost exactly with profile W3 (Fig. 4b). North of RGFZ magnetic anomalies with amplitudes of 200–400 nT can be well correlated from profile to profile (Fig. 4b). North of the RGFZ magnetic anomaly amplitudes remain substantial (200–350 nT) and similar well-correlated features can be traced over many profiles as far north as ∼21°S (Fig. 4a).

African margin

Magnetic anomalies over the African margin near Cape Town (∼34°S) have been identified by Rabinowitz & LaBrecque (1979), and recently by Hall *et al.* (2014), as those associated with magnetochrons M11 to M0. Several of these magnetic anomalies can be followed from profile-to-profile northwards from Cape Town to just south of the Walvis Ridge (∼23°S, Fig. 4d). Specifically, anomalies M4, M3 and M0 can be confidently identified. Many of the profiles shown in Fig. 4(d) are the same as those used by Rabinowitz & LaBrecque (1979). For example, profiles E1, E4 and E6 correspond to profiles 9, 6 and 5, respectively. North of the Walvis Ridge, near 12°S, Profile E15 displays a well-defined minimum that is identified as M0 (Fig. 4c). Amplitudes of the anomalies east of this minimum along this profile are generally less than the M-series anomalies identified further south along the margin, nevertheless the overall character of the anomalies allows us to correlate several features including M2, M3 and a peak roughly 50 km further east that we interpret as M4. Further north, near 9°S, anomaly amplitudes are reduced but feature-to-feature correlation can still be mapped although with less confidence. We have tentatively identified the dominant peak on profile E20, which is taken from Contrucci *et al.* (2004), as M4 based upon its similarity to the feature identified as M4 on both profile E15 and profile E16 (Fig. 4c).

Seafloor Spreading Models

A seafloor spreading model for the African margin is shown in Fig. 5(a). The model involves spreading between M0 and M4 at a rate of 28 mm yr^{-1}. This rate fits well with profiles E6 and E8, but appears to be slightly too small for profile E15 and E16. Anomalies M2 and G on Profile E6 (Fig. 5a) are those identified by Rabinowitz & LaBrecque (1979) for their profile 5. The observed data correlate well with the anomalies predicted by the seafloor spreading model demonstrating that spreading was underway by M4 time (130.6 Ma) as far north as 9°S.

A seafloor spreading model for the South American margin in the vicinity of RGFZ is shown in Fig. 5(b). The model involves spreading for the M-series between M0 and M3 at a rate of 29 mm a^{-1}, roughly the same as that for the spreading model over the African margin. Features identified as M0 and M3 can be traced with confidence north of RGFZ over the Campos/Santos Basin area, to the northern limit of the new high quality magnetic data near 21°S.

South Atlantic reconstruction

Fig. 6 shows South American M3 chron picks rotated and mapped over African M3 chron picks using a pole determined by linear

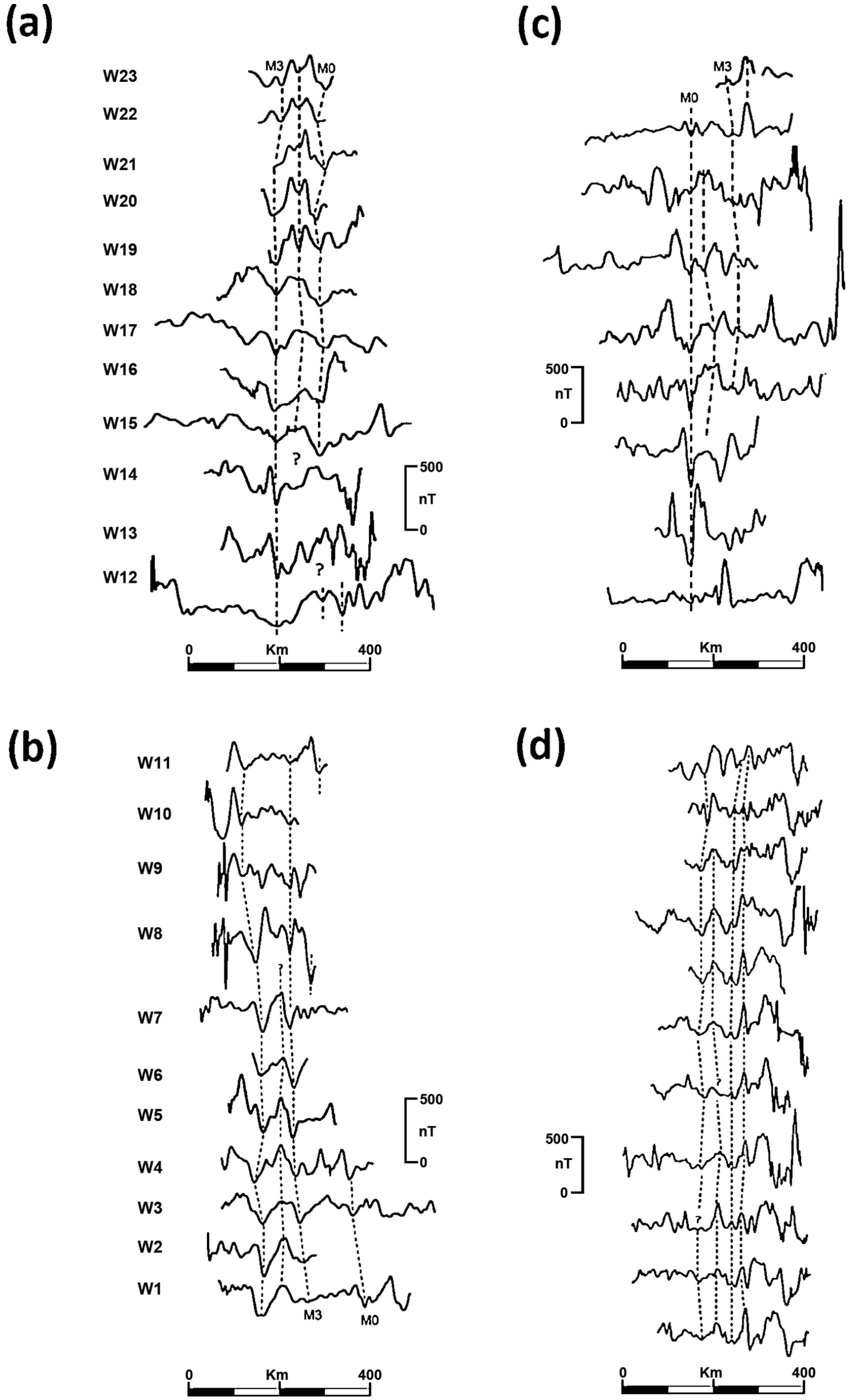

Figure 4. Total intensity magnetic anomaly profiles over the Atlantic margins of South America (a) north of, and (b) south of the Rio Grande Rise and of Africa (c) north of, and (d) south of the Walvis Ridge. Location of profiles shown in Figs 2 and 3. All profiles over Africa (E1–E20), and profiles W4, W6, W11, W16 and W21, are from public sources.

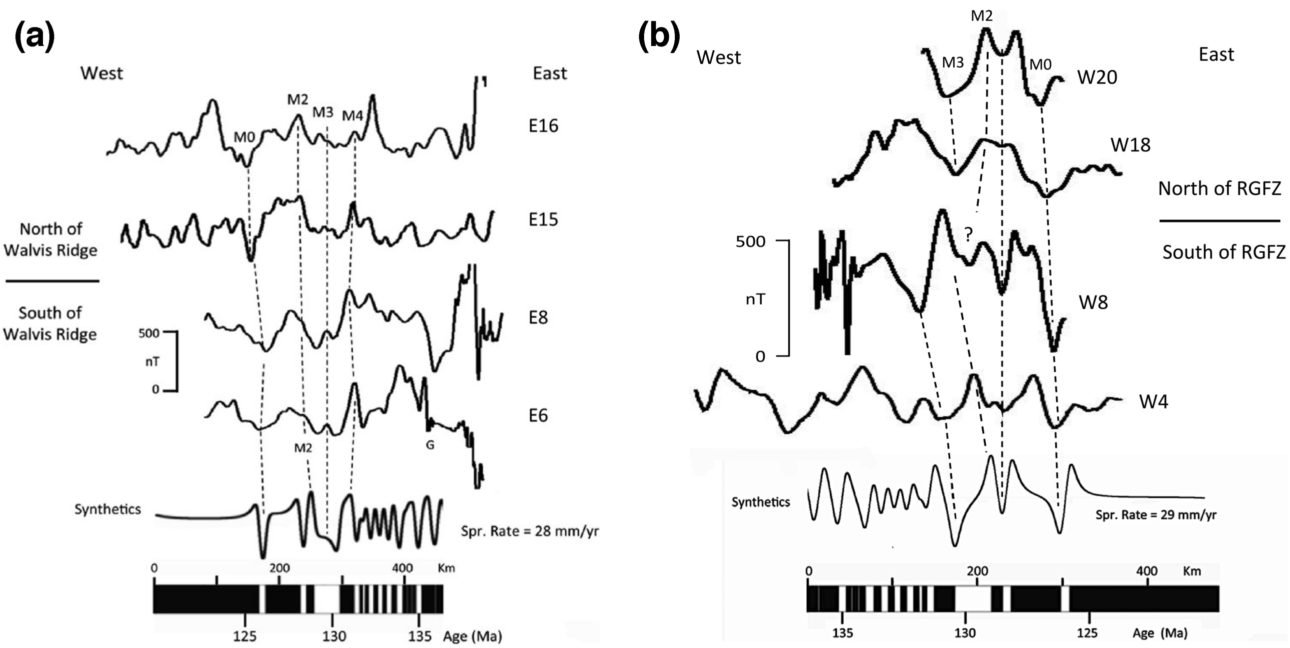

Figure 5. Correlation of observed magnetic anomaly profiles with synthetic seafloor spreading models for the (a) African and (b) South American margins. Seafloor spreading anomalies M0–M4 based upon the magnetic polarity reversal scale of Gradstein *et al.* (2014).

interpolation between our M0 and M4 total reconstruction poles: 44.70°N, 32.68°W and 53.92° rotation (∼129 Ma). Overall, the chron picks lie midway between South American and African 1 km isobaths, however the northernmost sets of chron picks lie closer to the Brazilian margin suggesting asymmetry spreading and/or possible ridge jumps in this segment of the South Atlantic rift.

DISCUSSION

Crystalline crust north of the RGFZ

The subtle expression of unnamed oceanic fracture zones can be traced from free air gravity anomalies north of RGFZ, westward from the Mid-Atlantic Ridge to just east of the Sao Paulo Plateau (Fig. 2). The same fracture zones can be traced eastward from the Mid-Atlantic Ridge to anomalies we identify as M0, about 180 km offshore Angola (Fig. 3). The extent of these fracture zones on either side of the ridge indicate that seafloor spreading was coeval, and that if Mesozoic chrons are observed on one side of the ocean basin, then they must also exist on the other side, provided no ridge jumps occurred during early seafloor spreading. We further note that these fracture zones on the western flank of the ocean basin extend landward beneath the seaward limit of the Campos salt nappe, indicating that the salt extends over oceanic crust,

Early investigators were divided regarding the nature of the crust beneath the Sao Paulo Plateau. Based on seismic refraction data, which showed the deepest crustal layer with velocities ranging from 6.1 to 6.6 km s^{-1}, Leyden *et al.* (1971) concluded that the plateau was composed of continental crust. However, Kumar & Gamboa (1979) interpreted seismic reflection and refraction data, as well as data from Deep Sea Drilling Project site 356 as evidence that the plateau was underlain by oceanic crust. More recently, long-offset, long-record reflection seismic data suggests that the plateau is a thin continental fragment that was rafted away from the mainland during the earliest opening of the ocean basin (Kumar *et al.* 2012).

Early opening of the South Atlantic ocean basin

Several workers have proposed diachronous opening of the South Atlantic ocean basin facilitated by motion along intracontinental deformation zones through South America (Unternehr *et al.* 1988; Nurnberg & Muller 1991; Schettino & Scotese 2005; Koenig & Jokat 2006; Eagles 2007; Moulin *et al.* 2009; Torsvik *et al.* 2009; Perez-Diaz & Eagles 2014). Others suggest that these displacements of continental blocks are not necessary to explain the early opening of the South Atlantic (Heine *et al.* 2013; Quirk *et al.* 2013). Heine *et al.* (2013) proposed a three-phase model with initial E–W extension from 140 Ma to approximately 126 Ma, intermediate equatorial Atlantic strain localization and lithospheric weakening, followed by NE–SW extension through the final break-up of western Gondwana around 113 Ma. They suggested that the conjugate Brazil and Angola pre-salt basins were formed during the initial slow E–W spreading, and subsequent extension lead to seafloor spreading south and north of the Santos–Benguela margins segment, where the final break between South American and Africa occurred. Quirk *et al.* (2013) also suggested that the final location of break-up between South American and Africa was the Santos–Benguela margins segment, and that it was facilitated by the Tristan da Cuhna mantle plume which delayed the onset of marine conditions and resulted in subaerial seafloor spreading. Their model required break-up at 123 Ma with initial seafloor spreading at 2.4 cm a^{-1}. Quirk *et al.* (2013) rejected the existence of transcontinental strike-slip zones, but suggested that a NW–SE lithospheric lineament influenced the magmatic history of the region before and after break-up.

The diachronous models, particularly regarding our work near RGFZ, rely upon limited evidence of seafloor spreading anomalies north of the RGFZ. For example, Moulin *et al.* (2009) suggested that seafloor accretion began at M7 (132 Ma) south of RGFZ, and that South Atlantic breakup with Africa did not occur north of RGFZ until Aptian-Albian time (113 Ma). They cite Unternehr *et al.* (1988) and proposed that as much as 150 km of dextral shear occurred along a continental strike-slip fault that extended southeastward from the Andean Cochabamba–Santa Cruz bend to the RGFZ (Fig. 7).

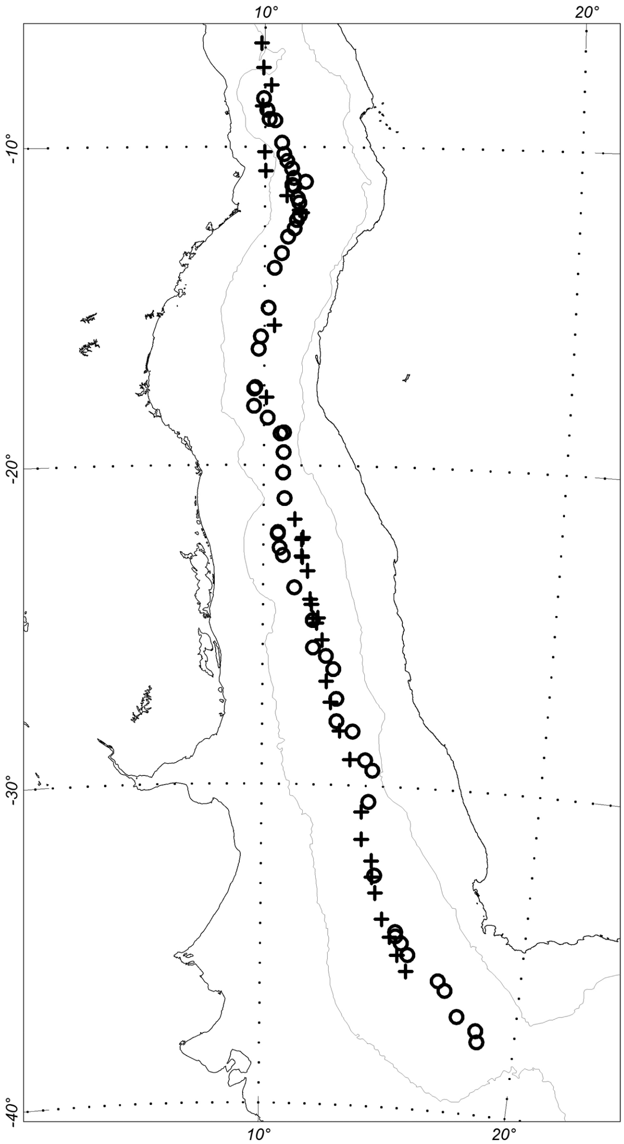

Figure 6. South Atlantic reconstruction for M3 time (∼129 Ma). South American M3 picks are open circles, and African M3 picks are '+' symbols. One km isobaths contours for South American and Africa are plotted.

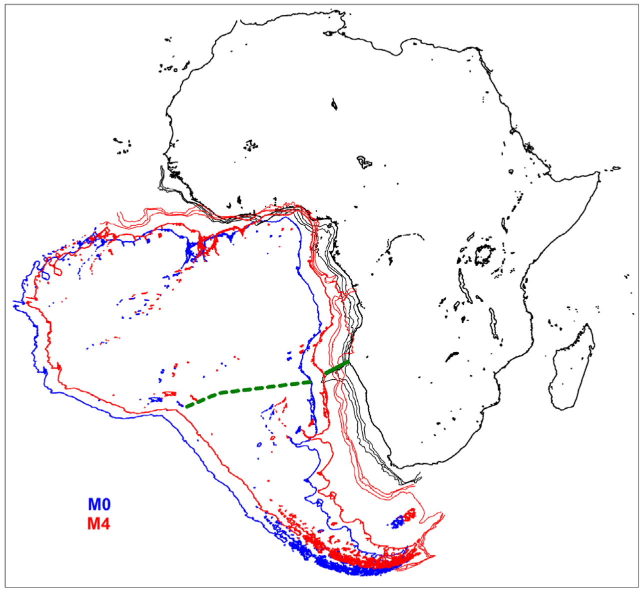

Figure 7. Reconstruction of South America relative to fixed Africa for M0 (124.6 Ma, blue) and M4 (129.8 Ma, red) (Gradstein *et al.* 2014); Early Rio Grande fracture zone (green); proposed continent transform location (Moulin *et al.* 2009, dashed green). One, two and three km isobaths for Africa and M4-positioned South America (black and red contours).

However, the reported geological evidence for this transform is from an, '… interpretation of remote sensing data (F. Bénard, private communication, 1986)', and warns that extensive basalt flows make, 'direct field evidence extremely difficult to obtain' (Unternehr *et al.* 1988, p. 175). Eyles & Eyles (1993) suggested that asymmetric distribution of volcanics and dike swarms in the Parana Basin are evidence of an intraplate boundary.

Similar to Heine *et al.* (2013) and Quirk *et al.* (2013), our results are inconsistent with diachronous spreading models that require South America–Africa motion north of RGFZ to be the result of movement along a continental strike-slip zone during the interval M3 to M0. Instead our results indicate that M3 through M0 seafloor spreading north of RGFZ was coeval with seafloor spreading south of RGFZ. Furthermore, the absence of any significant offset in these magnetic lineations is strong evidence that there was no significant movement along the proposed fault after M4 (∼130 Ma). Our seafloor models for M3 to M0 show very little change in the spreading rate (∼28 mm a^{-1}) along the African margin between Cape Town and 12°S consistent with our rotation pole which is located about 80° (ranges from 70° to 90°) from both the African and South American margins. This suggests that the conditions for crustal extension and seafloor spreading during this time did not vary significantly along the margins between areas north and south of the RGFZ.

CONCLUSIONS

Integration of new magnetic data acquired over the Brazilian margin, with the recent high quality satellite gravity data (Sandwell *et al.* 2014) and our earlier work along the South American and African margins supports the following:

(1) Identification and mapping of M4, M3, M2 and M0 north and south of the RGFZ on both western and eastern flanks of the South Atlantic basin.
(2) Delineation of unnamed fracture zones north of RGFZ indicative of the early formation of oceanic crust,
(3) Location of the westerly limit of these unnamed fracture zones beneath the seaward limit of the Campos salt nappe, consistent with the presence of oceanic crust beneath the salt, and
(4) Calculation of revised total reconstruction rotation poles for South America and Africa for M4 and M0.

These results are inconsistent with tectonic reconstruction models that require strike-slip motion along an intraplate continental deformation zone in South America from the Andean Cochabamba–Santa Cruz bend to RGFZ that continued until Aptian-Albian time (∼113 Ma).

ACKNOWLEDGEMENTS

We thank ION-GXT for allowing us to interpret, and present here, high-resolution magnetic data acquired in-tandem with their South

Atlantic BasinSPAN™ projects. Open-file data presented are available on-line from institutions described under Data.

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