New angles on South Atlantic opening

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SUMMARY

Existing models of relative motion between the South America and Africa plates significantly misrepresent the azimuth of Lower Cretaceous seafloor spreading in the South Atlantic Ocean. An improved model is derived from fits of fracture zones, magnetic reversal anomalies, and the edges of a rifted large igneous province at the Northeast Georgia Rise and Agulhas Plateau. An absolute date for this rifting event is not known but, by assuming least change in spreading rates during magnetic chron C34, rifting can be estimated to have occurred at ∼100 Ma. This modelling demands a plate divergence history that involves diachronous opening of the South Atlantic, consistent with published estimates of the ages of break-up from sedimentary basins on the South American and African passive margins. The diachronous opening lasts approximately 40 Myr, during which time it must be accommodated by significant intracontinental deformation. A reconstruction using the intra-C34 rotation also illustrates the earliest possibility for direct deep-water connection between the Central and South Atlantic Oceans. One further consequence of this model is that a total reconstruction derived from it and closure of the Central Atlantic between North America and Africa suggests that the Venezuelan and Gulf of Mexico basins may be conjugates formed during the earliest opening of the Central Atlantic, and not separate marginal basins.

Key words: Caribbean, continental deformation, fracture zones, Gulf of Mexico, plate tectonics, South Atlantic.

INTRODUCTION

West Gondwana broke up to form South America and Africa when rifting and seafloor spreading formed the South Atlantic Ocean in Early Cretaceous times. The development of this ocean is the oldest and best-known problem in global tectonics, inspired by maps that show its complementary bounding coastlines. This problem was the subject of the first computer-assisted statistical reconstruction, when Bullard *et al.* (1965) used a least-squares technique to produce an iconic fit of submarine contours. Later studies aimed to refine the Bullard fit using related techniques and other markers, for example the piercing points of prominent fracture zones (FZs) at the equatorial Atlantic continental margins, prominent sheared continental margins in the equatorial and southern Atlantic, and geophysical definitions of the continent–ocean boundaries (Le Pichon & Hayes 1971; Sibuet & Mascle 1978; Rabinowitz & LaBrecque 1979).

The recognition of Early Cretaceous-aged magnetic anomaly isochrons in the southernmost South Atlantic spawned reconstructions that used the Bullard fit rotation as a starting point to define finite rotations (e.g. Rabinowitz & LaBrecque 1979; Martin *et al.* 1981). These new rotations, as well as the observation that the anomalies disappear northwards in the South Atlantic, led to a suspicion that the continent–ocean boundaries are not isochrons. Oil industry and academic data have shown that the break-up

unconformities occur in significantly younger strata in the north than in the south, confirming this suspicion. Consequently, deformation zones in South America and West Africa were identified or implied to accommodate the northward-propagating break-up (Pindell & Dewey 1982; Fairhead & Okereke 1987; Unternehr *et al.* 1988). Movements on these deformation zones were modelled to produce a tighter fit at closure, by introducing continental microplate or 'block' rotations, resulting in further additions to the Bullard family of fits (e.g. Unternehr *et al.* 1988; Nürnberg & Müller 1991; Lawver *et al.* 1999; Schettino & Scotese 2005).

Here I detail a modelling experiment to describe Cretaceous South Atlantic seafloor spreading. Ignoring the Bullard family of poles to start with, the experiment provides a set of finite rotation parameters based on a large set of available geometrical constraints that accurately depict seafloor-spreading processes in the earliest South Atlantic Ocean. By doing so, it is possible to optimize the accuracy of a reconstruction of the continental margins at the time of their break-up, which occurred immediately before this spreading. After showing that the opening of the South Atlantic was diachronous and that it occurred within a two-plate system, the timing and magnitude of deformation in continental accommodation zones is predicted from the rotations, rather than estimated for the purposes of refining the continental margin fits. Finally, some consequences of the new rotations for Caribbean tectonics are introduced.
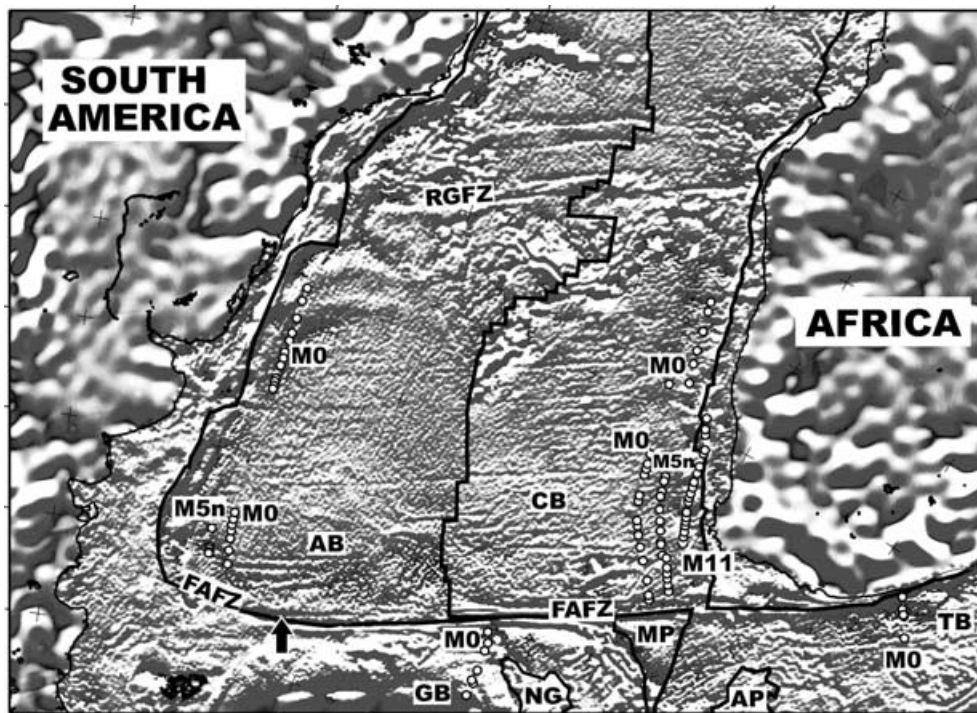
Figure 1. C34y (84 Ma) reconstruction of free-air gravity anomalies (Sandwell & Smith 1997) illuminated from an angle of 10° west of north. White circles: magnetic anomaly picks (Rabinowitz & LaBrecque 1979; Martin *et al.* 1982; Reznikov *et al.* 2005, other picks exist in later literature but do not significantly extend this set). Africa fixed in its present-day position. AB: Argentine Basin; AP: Agulhas Plateau; CB: Cape Basin; FAFZ: Falkland-Agulhas Fracture Zone; GB: Georgia Basin; MP: Malvinas Plate (from Marks & Stock 2001); NG: Northeast Georgia Rise; RGFZ: Rio Grande Fracture Zone; TB: Transkei Basin. Black arrow: intersection between FAFZ and an intraoceanic FZ. Thick black lines: mid-ocean ridge at C34y and continent-ocean boundaries.

FRACTURE ZONES AND ISOCHRONS IN THE SOUTH ATLANTIC

For models of relative plate motions, the azimuths and lengths of segments of FZs are powerful constraints that are independent of and complementary to magnetic anomaly isochrons. Satellite-derived free-air gravity data can be used to identify FZs, whose presence gives rise to linear anomalies that can be traced over thousands of kilometres. These constraints have never been fully used in studies of Early Cretaceous South Atlantic plate motions, despite the fact that a large number of linear gravity anomalies are evident in Sandwell & Smith's (1997) satellite-derived gravity field there (Fig. 1). Magnetic isochrons in the Argentine and Cape basins (Rabinowitz & LaBrecque 1979) show some of these anomalies to coincide with short fossil ridge-crest offsets that existed since break-up, reinforcing their interpretation as FZ traces. The parallelism of the anomalies shows that the offsets did not migrate appreciably along the ridge axis with respect to one another, meaning that the related FZs are reliable indicators of spreading directions that can be modelled as segments of small circles about stage poles that describe the opening of the South Atlantic.

Throughout the South Atlantic, a subtle change in FZ curvature about halfway through the long normal-polarity anomaly C34 documents a spreading direction change at some time (here termed C34i) between 124.5 and 84 Ma (I use the timescale of Gradstein *et al.* (2004) throughout). Rabinowitz & LaBrecque (1979) also noted this change in a single FZ in the Argentine basin and suggested a rotation ('P_{R2}') to describe it.

There is no magnetic reversal isochron to constrain or date C34i. Some studies used the seaward edges of Aptian salt basins in the central South Atlantic as intra-C34 isochrons (e.g. Rabinowitz &

LaBrecque 1979), but the reliability of these features is disputed (Jackson *et al.* 2000). An alternative isochron lies south of the Falkland–Agulhas FZ: The rifted edges of the Northeast Georgia Rise and Agulhas Plateau, which can be defined using satellite-derived gravity or bathymetric data. These fragments of a large igneous province separated from one another and Maud Rise, in the Weddell Sea, at plate boundaries between the South America, Africa, and Antarctica plates during chron C34 (Kristoffersen & LaBrecque 1991; Gohl & Uenzelmann-Neben 2001). Marks & Tikku (2001) extrapolated pre-C34 rotation parameters to derive an intra-C34 rotation, E, that aligns the Northeast Georgia Rise and Agulhas Plateau. Although other small plates are thought to have moved independently in this region, their motion either pre-dated the formation of the Northeast Georgia Rise and Agulhas Plateau (Tikku *et al.* 2002), or did not involve them (Marks & Stock 2001), so that the plateaus were always situated on the South America and Africa plates and can be used to reconstruct them (Figs 1 and 2).

FINITE ROTATIONS FOR SOUTH AMERICA–AFRICA PLATE MOTION

Although the Bullard family of reconstruction rotations produce reasonable fits of the rifted South American and African margins and magnetic anomaly isochrons, the flowlines they define are more strongly curved between the continental margins and anomaly C34y than the FZs are (Figs 1 and 2). This observation means that stage rotations in the Bullard family cannot be accurate for describing seafloor-spreading processes immediately following break-up. As well as the non-isochron nature of the continent–ocean boundaries, another reason for this is the difficulty involved in depicting
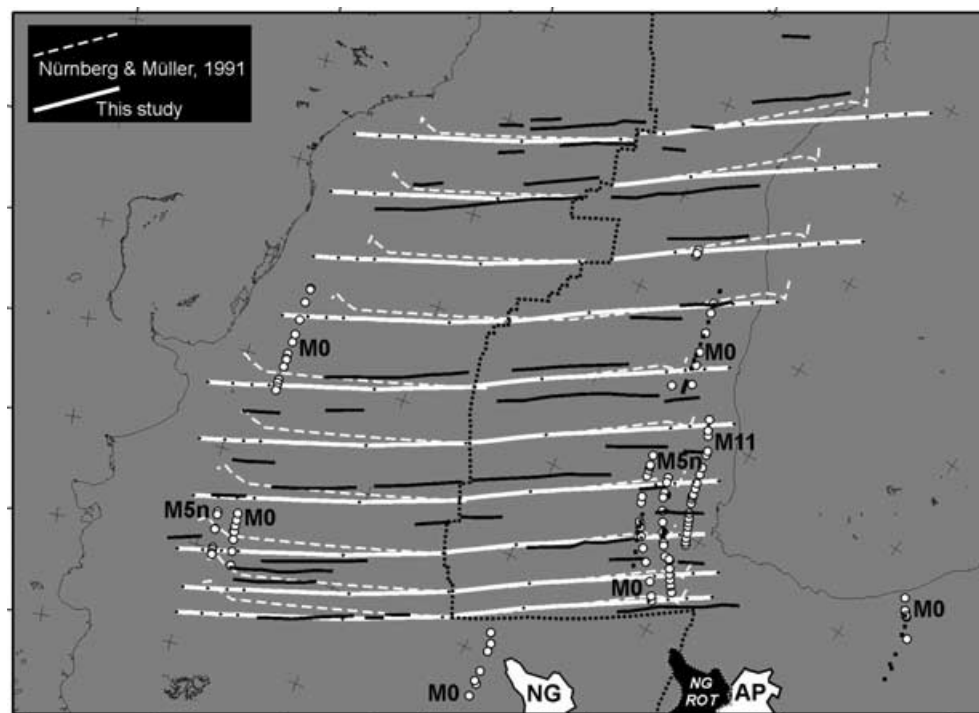
Figure 2. Visual fits of isochron data in the southern South Atlantic plotted over a C34y reconstruction. Synthetic flowlines predicted by new rotations (white lines), and by a previously published set (white dashed lines), are shown compared to gravity expressions of FZs (black lines). White circles: magnetic anomaly picks. Black squares: rotated South American magnetic anomaly picks. AP: Agulhas Plateau (white); NG: Northeast Georgia Rise (white) in their C34y positions. *NG ROT*: Northeast Georgia Rise (black) in its reconstructed position fitting to AP at C34i.

the azimuths of the fossil ridge-offset transforms in the Cape and Argentine basins, whose offset is not much greater than their width across strike. Instead, many of the Bullard family rotations take their azimuthal constraint from the sheared continental margins bounding the Falkland–Agulhas FZ off Argentina and South Africa. Fig. 1 shows that the strike of the Falkland FZ intersects that of intraoceanic FZs in the Argentine Basin, which means that it cannot have responded to South America–Africa plate motion in the same way as those FZs did. Consistent with this, Upper Jurassic–Valanginian rifting, and great thicknesses of younger strata, in the deep Outeniqua (Dingle *et al.* 1983) and Falkland Plateau (Richards *et al.* 1996) basins on the Falkland–Agulhas FZ's continental flanks shows that the FZ accommodated significant extensional strain during the opening of the South Atlantic. The Falkland–Agulhas FZ is not, therefore, a simple strike-slip fault that expresses relative plate motion directions in terms of its map trace. Consequently, realignments of segments of the Falkland–Agulhas FZ that do not take this extension into account cannot be expected to accurately reconstruct the opening of the South Atlantic.

The pattern of intraoceanic FZs in the Cape and Argentine basins is better reconstructed by rotations about a new set of Euler poles that are situated further north than those in the Bullard family (Table 1). I undertook simultaneous visual fitting of FZ-related gravity anomalies and magnetic isochron data to derive the rotations in Table 1. In order to be able to use constraints from FZs formed at short offsets, I fitted the FZ data to synthetic flowlines in a procedure analogous to the post-C34 South Atlantic study of Shaw & Cande (1990). I omitted seafloor-spreading anomalies marginwards of M0 in the Georgia and Natal Valley basins (Martin *et al.* 1982; Reznikov *et al.* 2005), due to the possibility of their having formed at a ridge between the South America plate and a Mozambique Ridge microplate (Tikku

Table 1. New finite rotation parameters. All rotations are right handed. FIT denotes the rotation for fitting the segments of the continental margins south of the accommodation zone in the Colorado Basin. Older magnetic anomaly timescales and the studies that use them refer to chron M5n and the corresponding magnetic anomaly as M4.

Latitude	Longitude	Angle	Age (Ma)	Chron
South America with respect to Africa				
59.0	−37.0	41.3	∼100	C34i
56.8	−37.9	53.7	124.61	M0
56.5	−38.4	55.6	130.28	M5n
56.3	−38.8	57.5	∼136	M11
56.1	−39.0	60.0	150?	FIT

et al. 2002). There are no identifications of anomaly M11 on the South America plate, making it likely that those on the Africa plate are related to processes occurring during stretching prior to seafloor spreading (Austin & Uchupi 1982). Because of this, the rotation parameters for chron M11 were derived using stage rotations of the African-side anomaly M11 identifications to those of M5n and M0, and the adopted date for the M11 rotation (136 Ma) is unlikely to be particularly accurate.

Figs 2 and 3 show the results of this process. Fig. 2 shows fits of magnetic anomaly isochron picks and of the conjugate rifted margins (defined from satellite-derived gravity data) of the Northeast Georgia Rise and Agulhas Plateau as well as of some FZs to model flowlines. Fig. 3 shows the fit of model flowlines, along with flowlines about Shaw & Cande's (1990) Euler poles, to the entire set of South Atlantic FZs south of the Marathon and Mercurius FZs, which misfitting flowlines show did not form between the South America
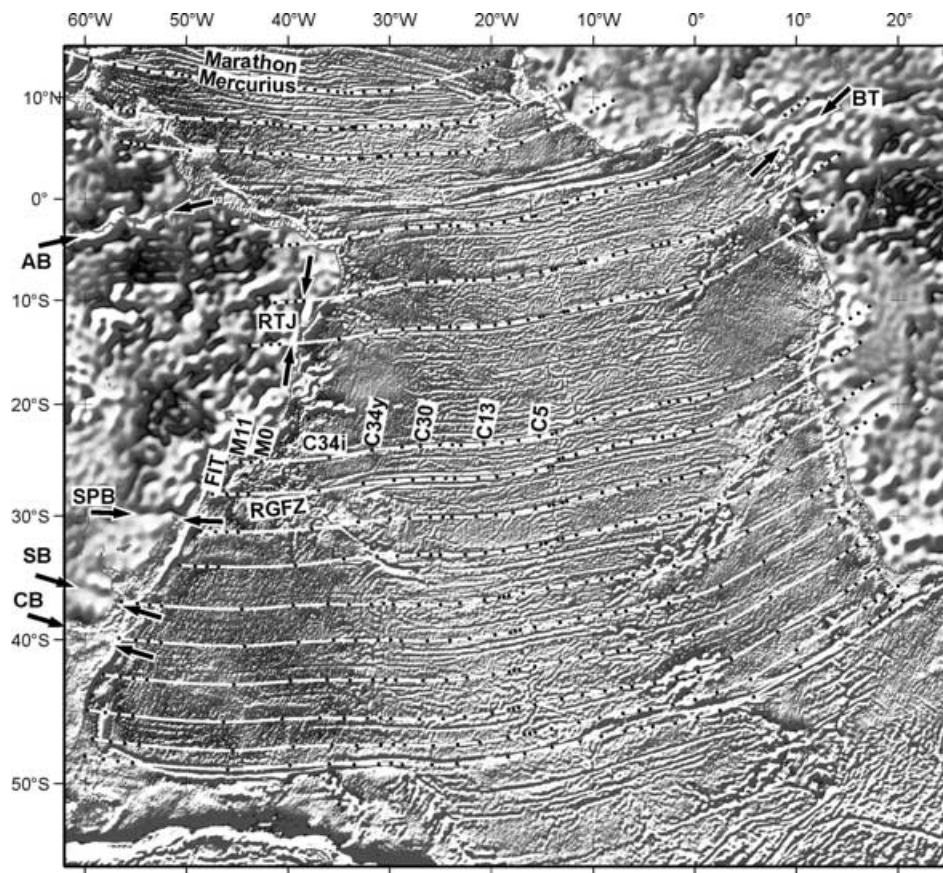
Figure 3. Flowlines predicted by the rotations in Table 1 and those of Shaw & Cande (1990) for later times, compared to FZs in illuminated satellite-derived free-air gravity data (Sandwell & Smith 1997). Points on the flowlines indicate constrained rotations, some labelled. RGFZ: Rio Grande Fracture Zone. Black arrows: gravity anomalies associated with some of the accommodation zones discussed in the text: AB: Amazon Basin; BG, Benue Trough; CB, Colorado Basin; RTJ, Recôncavo–Tucano–Jatobá basin system; SB: Salado Basin; SPB, southern Paraná Basin.

and Africa plates. Fig. 4 locates the new Euler poles in comparison to some Euler poles of the Bullard family.

At present, continental extension usually occurs at slower rates than seafloor spreading. With this in mind, if integrated pre-M5n extension in the Cape and Argentine basins was about half as fast as the seafloor spreading that followed it, a date of 150 Ma (Upper Jurassic) can be adopted for the 'FIT' reconstruction parameters and the start of stretching there. Similarly, it is possible to estimate a date for the C34i direction change by employing parsimony in consideration of spreading rates. Based on uniformly smooth basement in seismic reflection records (e.g. Rabinowitz & LaBrecque 1979), it is reasonable to assume that during C34 spreading rates did not drop below 25 mma^{-1} (Bird & Pockalny 1994). Using this assumption, and by allowing the spreading rate to change at M0, C34i, and C34y, then the range of possible dates for C34i is 102–96 Ma. Dates in this range overlap with estimates of the age of main volcanism at the Agulhas Plateau and Northeast Georgia Rise (Kristoffersen & LaBrecque 1991; Gohl & Uenzelmann-Neben 2001). Minimum change in spreading rate, at about 28 mma^{-1} throughout C34, occurs if C34i dates to 99.7 Ma. This date is similar to Marks & Tikku's (2001) 96 Ma for their rotation E, which was based on extrapolation of spreading rates in the South Atlantic and Southwest Indian oceans.

Various considerations combine to provide a high degree of confidence in the new rotations. In general, because of the greater numbers of data and increased curvature in the target figures, sets of
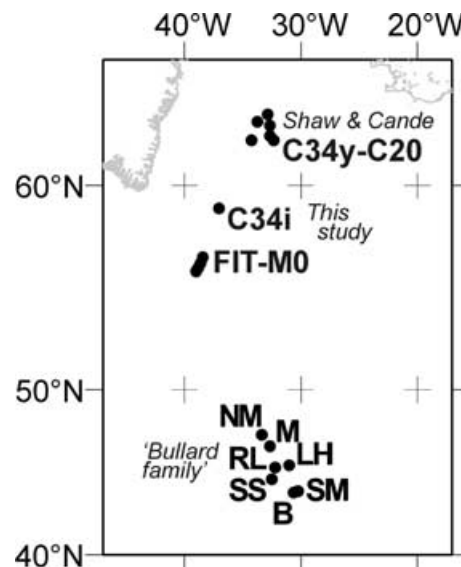

Figure 4. Comparison of the total reconstruction poles of this study and Shaw & Cande (1990) to some of the Bullard family for the fit of South America or a South American microplate to Africa (B: Bullard *et al.* 1965; LH: Le Pichon & Hayes 1971; M: Martin *et al.* 1981; NM: Nürnberg & Müller 1991 (Colorado microplate); RL: Rabinowitz & LaBrecque 1979 and Unternehr *et al.* 1988 (southern South America microplate); SM: Sibuet & Mascle 1978 and SS: Schettino & Scotese 2005 (Patagonia terrane)).

rotation parameters are more reliable when they are based on complementary data sets describing longer ancient plate boundaries. As such, these rotations, derived using FZs from over 6500 km of the South Atlantic and magnetic isochrons as long as 2300 km in the Cape and Argentine basins, are likely to be more reliable than those that are based solely on the magnetic isochrons. By the same consideration, the C34i and FIT rotations, which each include constraints from a large number of FZs but only a very short isochron, are the least reliable within Table 1. A further indicator of the reliability of a sequence of finite rotations is a stable sequence of stage poles calculated from it, based on the assumption that major plate motion is steady and not interrupted by abrupt large changes, which would show up as big stage pole jumps. The stage pole sequence defined from the flowline modelling indeed shows smooth migration, with successive poles separated by distances of $\sim$150 km, and 350 km over the C34 period, whereas the Bullard family of poles require large jumps ($>$3000 km) over C34. With the rotation angles held fixed, rotations about Euler poles positioned more than $\pm 1°$ away from those in Table 1 produce visually unacceptable fits to FZs. Larger uncertainty bounds are imaginable if the rotation angle would be allowed to vary.

SOME IMPLICATIONS OF THE REVISED MODEL

Intracontinental deformation

Using the new set of finite rotations for South Atlantic opening, full closure of the Argentine and Cape basins with rigid South America and Africa plates produces a considerable northward-increasing overlap, which is illustrated in Figs 2 and 3 by the steady northward increase in the overlap between the flowlines and continental margins. Within the informal confidence bounds estimated above, it is impossible to produce a simultaneous fit of the FZ and magnetic isochron constraints that does not result in this kind of overlap. This means either that the overlap indicates how one or both of the FZ and magnetic anomaly data sets is seriously and falsely interpreted, or that a tectonic explanation must be sought for the overlap. Given that the gravity anomalies identified as FZs form an oceanwide copolar set of lineations, and that the magnetic anomalies of the Cape and Argentine basins have been independently inspected and identified by numerous workers (Rabinowitz & LaBrecque 1979; Austin & Uchupi 1982; Nürnberg & Müller 1991; Max *et al.* 1999; Bauer *et al.* 2000), problems with either data set seem quite unlikely. Hence, in this section, I explore the implications of the overlap in terms of plate tectonic processes.

Fig. 3 shows that, with the exception of the Rio Grande FZ, the entire set of South Atlantic FZs is well matched by flowlines all the way to the continent-ocean boundaries. In the spreading corridors bounding this FZ, the flowline overlap of $\sim$800 km is confined to the African flank, consistent with the eastwards ridge jump identified by Rabinowitz & LaBrecque (1979). This jump would have transferred African seafloor to the South America plate, including segments of the Rio Grande FZ, and is the likely reason for the misfits between that FZ and the model flowlines. The otherwise good FZ fits oceanwide are most simply interpreted as showing that only two plates were involved in the opening of the South Atlantic and that the action of smaller independently moving plates during seafloor spreading can thus be ruled out as a cause for the overlap.

Overlaps also occur in the Bullard family of reconstructions, and have long been attributed to northward-propagating opening of the South Atlantic (Hey & Vogt 1977; Pindell & Dewey 1982; Vink 1982; Nürnberg & Müller 1991). Along with estimates of the positions of the continent–ocean boundaries (e.g. Nürnberg & Müller 1991; Lawver *et al.* 1999; Dickson *et al.* 2003), the seafloor-spreading history implied by the new rotation parameters of Table 1 can be used to date this propagation by reconstructing non-overlapping segments of the opposing continental margins. In this way, I produced non-overlapping fits for seven segments of the South Atlantic margins (Fig. 5) using finite rotations interpolated between the rotations of Table 1. The ages of these interpolated rotations define a sequence (Fig. 6) in which the South Atlantic opens by northward propagation of a spreading centre between two plates over a period of around 40 Myr. This sequence is consistent with some estimates of the time of break-up in basins on the segments' passive margins, based on identifications of prominent break-up unconformities (Bennett & Rusk 2002; Chang *et al.* 1992; Dailly *et al.* 2002; Guiraud & Maurin 1992; Karner & Driscoll 1998; Lawrence *et al.* 2002; Teisserenc & Villemin 1989).

Vink (1982) suggested that the northward propagation of South Atlantic opening was accommodated by variable amounts of stretching of its passive margins prior to break-up. Although extensional basins on the passive margins do have variable widths and stretching factors (e.g. Davison 1997), the observed variability is not consistent with the overlap implied by the new fit reconstruction parameters. Instead, I suggest that known continental deformation zones accommodated the northward propagation as short-lived parts of the South America–Africa plate boundary. This idea simplifies the suggestions of various authors that the observed movements on these zones are evidence for minor ($<$200 km) independent rotations of continental microplates that might be employed to improve the fit of South Atlantic reconstructions (Pindell & Dewey 1982; Fairhead & Okereke 1987; Unternehr *et al.* 1988; Uliana *et al.* 1989).

The propagation sequence in Fig. 6 is accommodated at five known South American basins and deformation zones, and one previously unidentified deformation zone (coinciding with an E–W free-air gravity lineament at $\sim$30°S in the southern Paraná basin; Figs 3 and 5). The complete traces of these zones are not well known, as many are buried or follow strike-slip trends (e.g. compare Unternehr *et al.* 1988; Pindell & Dewey 1982; Nürnberg & Müller 1991; Jaques 2003); the linkages shown in Fig. 5 are largely speculation and the continuations to the active western margin of South America are arbitrary. Gravity anomalies associated with some of the zones appear to continue into Africa (Fig. 5) suggesting that some deformation may also have occurred there. In the case of the Benue Trough, there is good geological evidence to support this possibility (e.g. Pindell & Dewey 1982; Fairhead & Okereke 1987), although no movement on it has been used to produce Figs 5 and 6. Elsewhere, these observations may indicate instead that deformation exploited existing pre-break-up aged structures that happened to cross the South Atlantic rift zone.

Because the deformation zones are envisaged as having accommodated movements that can be modelled using Table 1, it is possible to predict the timing and nature of tectonism on them and compare them to published geological observations. Firstly, the ages of the interpolated rotations for fitting margin segments suggest that the accommodation zones were active in the periods 150–142 Ma (Colorado Basin–Macachin Trough); 142–133 Ma (Salado Basin–General Levalle Basin); 133–125 Ma (southern Paraná basin–Aimara Basin); 125–120 Ma (São Francisco River Lineament); 120–118 Ma (Recôncavo–Tucano–Jatobá and Solimões–Amazon–Marajó basin systems), and 118–111 Ma (Solimões–Amazon–Marajó basin system and/or Benue Trough). These dates
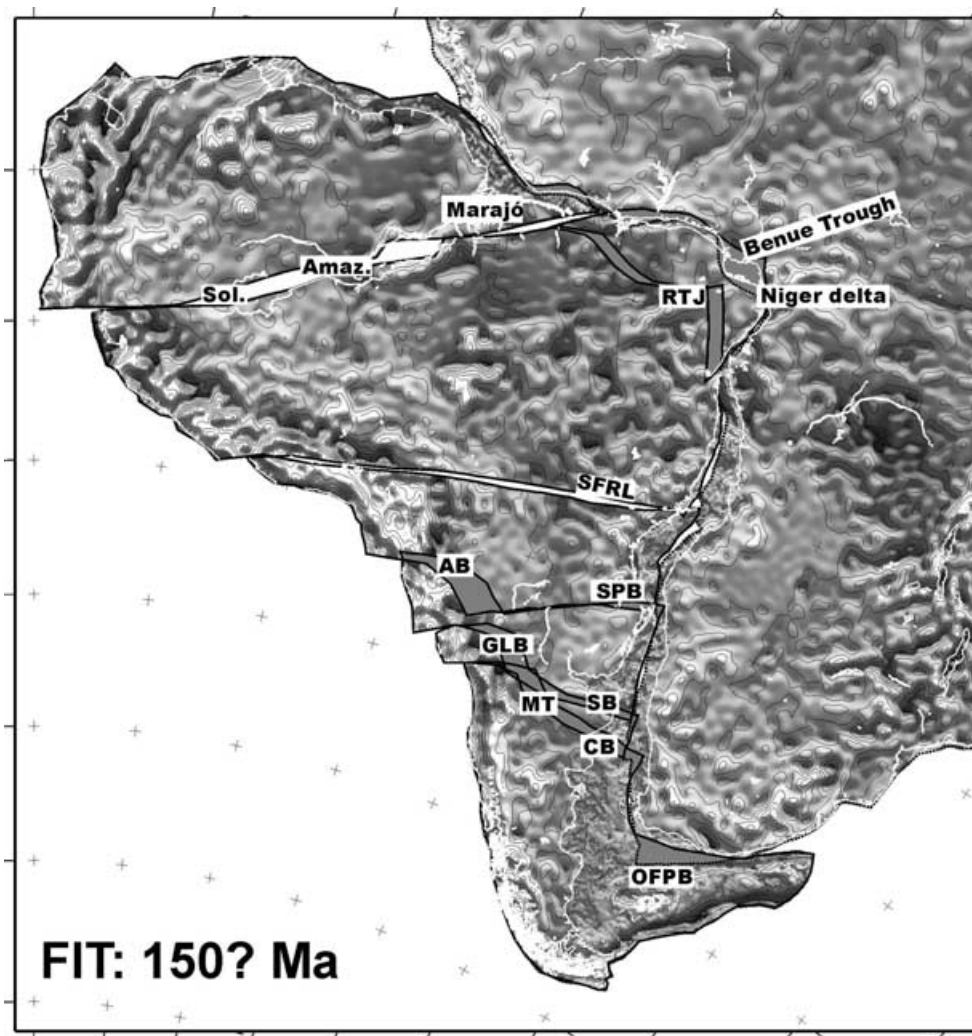
Figure 5. Model reconstruction of free-air gravity anomalies (Sandwell & Smith 1997) of Africa and South America immediately before the start of break-up in the south. Africa is held fixed in its present-day position. White lines: present-day coasts (for reference). Mid-grey: overlaps that may indicate stretching during break-up or later shelf progradation (e.g. Niger delta). AB: Aimara Basin, Amaz.: Amazon Basin, CB: Colorado Basin, GLB: General Levalle Basin, Marajó: Marajó Basin, MT: Macachin Trough, OTFB: Outeniqua and Falkland Plateau basins, RTJ: Recôncavo–Tucano–Jatobá basins, SB: Salado Basin, SFRL: São Francisco River Lineament, Sol.: Solimões Basin, SPB: lineament in southern Paraná Basin.

are undoubtedly given with too much precision, because they are subject to errors related to the uncertainties in the rotations of Table 1, and in the dates of FIT and C34i. Nonetheless, these errors are far smaller than the usually stratigraphic uncertainty in the dating of tectonism in the South American basins and deformation zones. Despite this, nearly all of the named features are known to have been tectonically active during Late Jurassic and/or Early Cretaceous times (Urien & Zambrano 1973; Chang *et al.* 1992; Costa *et al.* 2001; Fairhead & Okereke 1987; Saadi *et al.* 2002; Webster *et al.* 2004; Franke *et al.* 2006), consistent with their initiation, adoption, or reactivation as accommodation zones. Only the tectonic history of the lineament in the southern Paraná basin is not known, although the Rio Grande and Ponta Grossa arches bounding it to the north and south are known to have been uplifted in Early Cretaceous times (Ernesto *et al.* 1999).

Secondly, the predicted senses of motion on the accommodation zones are also broadly confirmed in the literature. Overall, in South America the modelled differential movements during the period of northward propagation are oriented WNW–ESE (present-day coordinates). The simplest conceivable accommodation zone is thus an ESE-striking dextral strike-slip fault zone, of which several are suggested by field work in Argentina, Uruguay, and southern Brazil (Uliana *et al.* 1989; Ernesto *et al.* 1999). A component of extension would be expected on accommodation zones with strikes oriented more NW–SE, as is the case for the Colorado, Salado, and General Levalle basins, and Macachin Trough (Urien & Zambrano 1973; Webster *et al.* 2004; Franke *et al.* 2006), and compressional components would be expected on more W–E oriented accommodation zones, as is the case with the Amazon Basin (Costa *et al.* 2001). Each phase of northward propagation requires the related South American accommodation zone to take up about 200 km of relative motion. Unfortunately, there are no reliable geological estimates of the amounts of movement on these features, making an evaluation of this aspect of the model impossible.

Opening of the equatorial Atlantic gateway

Using the new set of rotation parameters, the sheared equatorial continental margins of the South Atlantic part at chron C34i (Fig. 6).
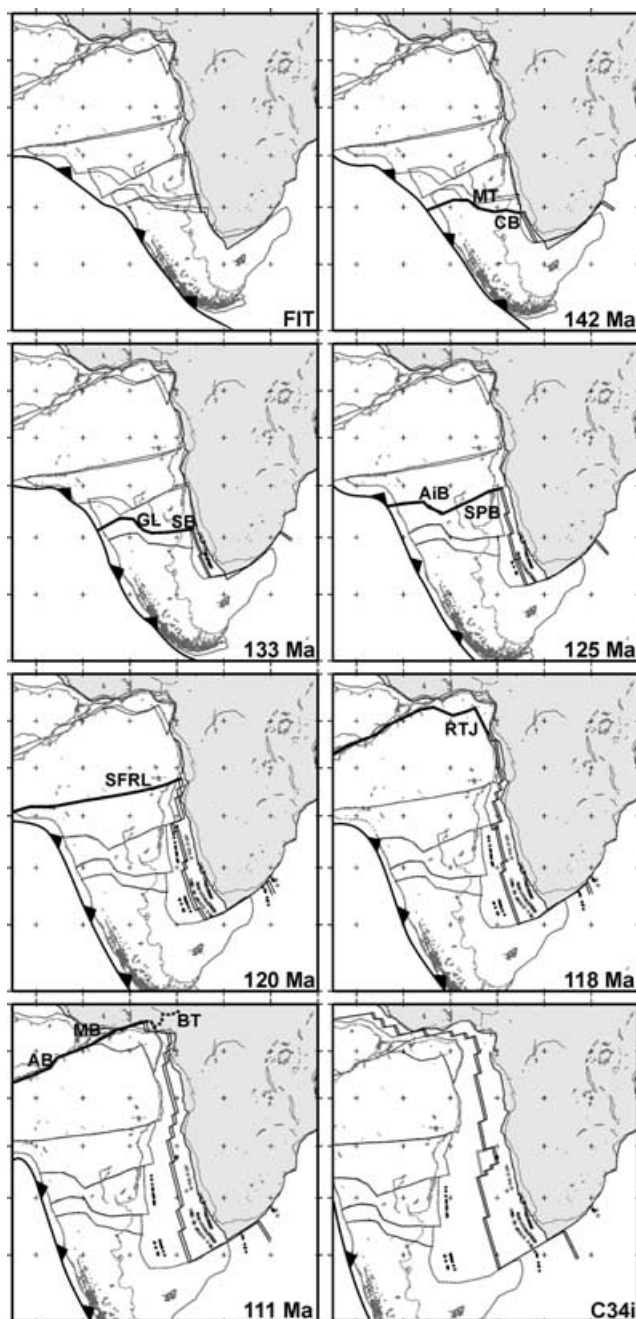
Figure 6. Reconstructions detailing northward propagation of South Atlantic seafloor spreading (double line; segmentation simplified) and accommodation zones. Thick grey line in C34i panel: suggested abandoned ridge crest after ridge jump (true age of ridge jump is uncertain because of lack of magnetic anomaly isochron constraints). Discs: magnetic anomaly picks. All rotations interpolated from those in Table 1. AB: Amazon Basin; AiB: Aimara Basin; BT: Benue Trough; CB: Colorado Basin; GL: General Levalle Basin; MB Marajó Basin; MT: Macachin Trough; RTJ: Recôncavo–Tucano–Jatobá basin system; SB: Salado Basin; SFRL: São Francisco River Lineament; SPB: lineament at southern edge of Paraná Basin.

If the suggested date of 100 Ma for this chron is correct, then this places a maximum boundary on the age of possible development of a deep-water gateway between the North Atlantic and South Atlantic oceans in Early Cenomanian times. Based on geological observations, deep-water connection may, however, have occurred still later

(Wagner & Pletsch 1999), perhaps depending on the possible presence of transverse ridges and trapped slivers of continental material in the young gateway (Bonatti 1996).

DISCUSSION: EARLY TECTONICS OF THE CARIBBEAN REGION

Although the continental margin segment fits are similar in the new and Bullard family reconstructions, accurate modelling of FZ azimuths in the South Atlantic requires larger offsets on intracontinental deformation zones. Regardless of whether these zones were situated in South America or Africa, or both, their action gives rise to a reconstruction of South America and Africa that is very different to its predecessors. The difference is well seen in the north, where South America and North America parted from Africa during Pangea break-up (Fig. 7). With South America and North America positioned relative to Africa according to the new fit parameters and those of Roest *et al.* (1992), a much tighter reconstruction of the northern South America and Gulf of Mexico–Florida margins is achieved, whereas previous reconstructions featured a large underlap.

The new placement of South America strongly suggests that seafloor spreading in the proto-Caribbean ocean occurred at a single ridge between the North America and West Gondwana plates, with the Gulf of Mexico forming on its northern flank. The simplest interpretation of the present-day Venezuela Basin would be as having been formed on the conjugate flank, but some versions of later Caribbean events, which are the subject of controversy, would require the floor of this basin to have been subducted beneath a Caribbean plate introduced from the Pacific (e.g. Pindell *et al.* 1988). In either case, our knowledge of Early Caribbean plate tectonics can be greatly simplified, as until now there had been a requirement for microplates defining the Venezuela and Gulf of Mexico basins as two separate locations of Late Jurassic seafloor spreading in the region, one each side of the Yucatan Peninsula (e.g. Hall *et al.* 1982; Meschede & Frisch 1998; Bird *et al.* 2005). Yucatan, as suggested by Anderson & Schmidt (1983), may instead have subsequently assumed its present position by strike-slip movements along the Mojave–Sonoro Megashear.

CONCLUSIONS

A new model of seafloor spreading in the South Atlantic is based on full and simultaneous fitting of FZs, as seen in gravity data, and of magnetic and other isochrons. As such, it is more reliable than foregoing models, which fitted only subsets of the FZ data set, or their piercing points with the continental margins, and which assumed that those margins, or great lengths of them, were isochrons. The new rotations require that the onset of seafloor-spreading propagated from south to north throughout the entire length of the ocean in a process that lasted around 40 Myr. This process in turn requires substantial intracontinental deformation to have occurred in South America and/or Africa. The geological histories of the deformation zones suggested to fulfil this role, although consistent with their having done so, are generally poorly known. Improvements to our knowledge of the timing and amount of deformation in these zones offer the best opportunities to reject, confirm, or refine the model presented here. One wider consequence of this model is the simplification it offers to what is known of the early history of the Caribbean.
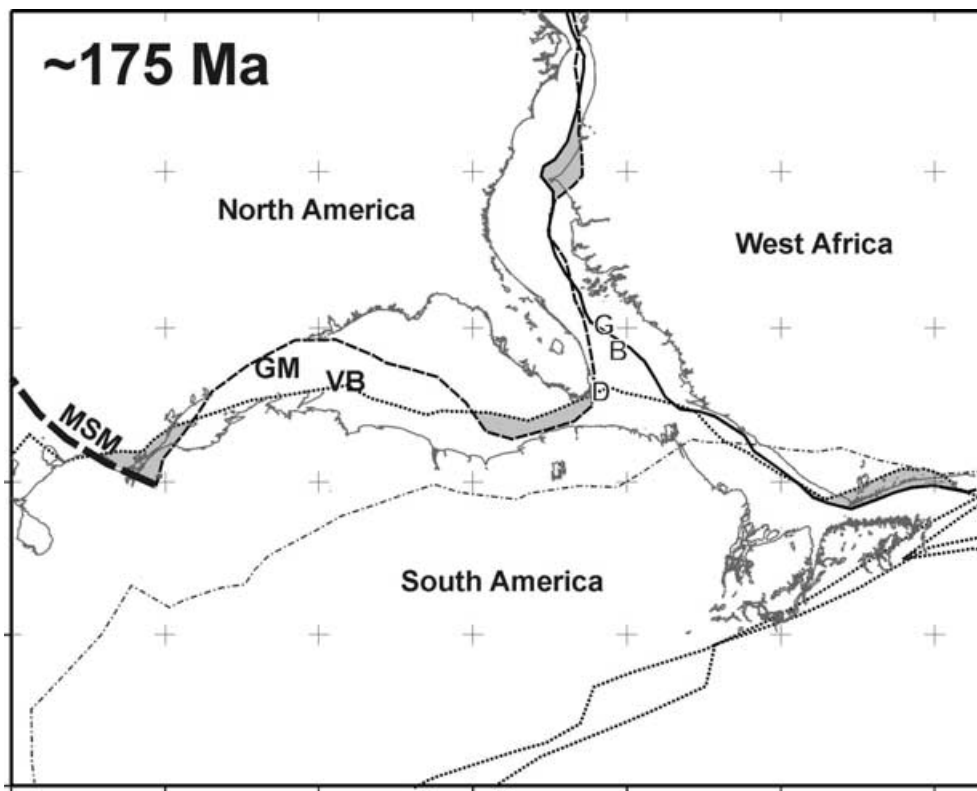
Figure 7. Reconstruction of the Caribbean region at ~175 Ma, before opening of the South and Central Atlantic Oceans. Rotations are with respect to a fixed Africa, for South America as in Table 1, and for North America after Roest *et al.* (1992). B, D, G: the Bahamas Platform, Demerara and Guinea Marginal Plateaus, all of which bear great thicknesses of Cretaceous sediments deposited onto either oceanic or thinned continental crust (Freeman-Lynde & Ryan 1987; Benklehil *et al.* 1995) and whose dispositions in a closed Atlantic are, therefore, not known and not shown; GM: Gulf of Mexico; MSM: Mojave-Sonora Megashear; VB: Venezuela Basin. Grey fill: areas of overlap between the African (solid black line), South American (dotted black lines) and North American (dashed black lines) continental edges. Dot-dash line: South America continental edge as fit by Nürnberg & Müller (1991). Mid-grey: overlaps.

ACKNOWLEDGMENTS

REFERENCES

Anderson, T.H. & Schmidt, V.A., 1983. The evolution of Middle America and the Gulf of Mexico-Caribbean Sea region during Mesozoic time, *Geol. Soc. Am. Bull.,* **94,** 941–966.

Austin, J.A. & Uchupi, E., 1982. Continental-oceanic crustal transition off Southwest Africa, *AAPG Bull.,* **66**(9), 1328–1347.

Bauer, K. et al., 2000. Deep structure of the Namibia continental margin as derived from integrated geophysical studies, *J. geophys. Res.,* **105**(B11), 25 829–25 854.

Benklehil, J., Mascle, J. & Tricart, P., 1995. The Guinea continental margin: an example of a structurally complex transform margin, *Tectonophysics,* **248,** 117–137.

Bennett, K.C. & Rusk, D., 2002. Regional 2D seismic interpretation and exploration potential of offshore deepwater Sierra Leone and Liberia, West Africa, *The Leading Edge,* **21,** 1118–1124.

Bird, D.E., Burke, K., Hall, S.A. & Casey, J.F., 2005. Gulf of Mexico tectonic history: hotspot tracks, crustal boundaries and early salt distribution, *AAPG Bull.,* **89,** 311–328.

Bird, R.T. & Pockalny, R.A., 1994. Late Cretaceous and Cenozoic seafloor and oceanic basement roughness: spreading rate, crustal age and sediment thickness correlations, *Earth planet Sci. Lett.,* **123,** 239–254.

Bonatti, E., 1996. Anomalous opening of the Equatorial Atlantic due to an equatorial mantle thermal minimum, *Earth planet. Sci. Lett,* **143,** 147–160.

Bullard, E., Everett, J.E. & Smith, A.G., 1965. The fit of the continents around the Atlantic, *Phil. Trans. Roy. Soc. Lond., A,* **258,** 41–51.

Chang, H.K., Kowsmann, R.O., Figueiredo, A.M. F. & Bender, A.A., 1992, Tectonics and stratigraphy of the East Brazil Rift system: an overview, *Tectonophysics,* **213,** 97–138.

Costa, J.B.S., Bemerguy, R.L., Hasui, Y. & Borges, M. da S., 2001. Tectonics and paleogeography along the Amazon river, *J. South Am. Earth Sci.,* **14,** 335–347.

Dailly, P., Lowry, P., Goh, K. & Monson, G., 2002. Exploration and development of Ceiba Field, Rio Muni Basin, Southern Equatorial Guinea, *The Leading Edge,* **21,** 1140–1146.

Davison, I., 1997, Wide and narrow margins of the Brazilian South Atlantic, *J. geol. Soc. Lond.,* **154,** 471–476.

Dickson, W.G., Fryklund, R.E., Odegard, M.E. & Green, C.M., 2003. Constraints for plate reconstruction using gravity data—implications for source and reservoir distribution in Brazilian and West African margin basins, *Mar. Pet. Geol.,* **20,** 309–322.

Dingle, R.V., Siesser, W.G. & Newton, A.R., 1983. *Mesozoic and Tertiary Geology of Southern Africa*, A.A. Balkema, Rotterdam.

Ernesto, M., Raposo, M.I.B., Marques, L.S., Renne, P.R., Diogo, L.A. & de Min, A., 1999. Paleomagnetism, geochemistry and ^{40}Ar/^{39}Ar dating of the North-eastern Paraná Magmatic Province: tectonic implications, *J. Geodyn.,* **28,** 321–340.

Fairhead, J.D. & Okereke, C.S., 1987. A regional gravity study of the West African rift system in Nigeria and Cameroon and its tectonic interpretation, *Tectonophysics,* **143,** 141–159.

Franke, D., Neben, S., Schreckenberger, B., Schulze, A., Stiller, M. & Krawczyk, C.M., 2006. Crustal structure across the Colorado Basin, offshore Argentina, *Geophys. J. Int.,* **165,** 850–864, doi:10.1111/j.1365-246X.2006.02907.x

Freeman-Lynde, R.P. & Ryan, W.B.F., 1987. Subsidence history of the Bahama Escarpment and the nature of the crust underlying the Bahamas, *Earth planet. Sci. Lett.,* **84,** 457–470.

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

Gradstein, F.M. et al., 2004. *A Geologic Time Scale 2004,* Cambridge University Press, Cambridge, 589 pages.

Guiraud, R. & Maurin, J.C., 1992. Early Cretaceous rifts of western and central Africa, *Tectonophysics,* **213,** 153–168.

Hall, D.J., Cavanaugh, T.D., Watkins, K.S. & Macmillen, K.J., 1982. The rotational origin of the Gulf of Mexico based on regional gravity data, in *Studies in continental margin geology: AAPG Memoir*, **Vol. 34,** pp. 115–126, eds Watkins, J.S. & Drake, C.L.

Hey, R.N. & Vogt, P.R., 1977. Spreading center jumps and sub-axial asthenosphere flow near the Galapagos hotspot, *Tectonophysics,* **37,** 41–52.

Jackson, M.P.A., Cramez, C. & Fonck, J.-M., 2000. Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins: implications for salt tectonics and source rocks, *Mar. Pet. Geol.,* **17,** 477–498.

Jaques, J.M., 2003. A tectonostratigraphic synthesis of the sub-Andean basins: inferences on the position of South American intraplate accommodation zones and their control on South Atlantic opening, *J. geol. Soc. Lond.,* **160,** 703–717.

Karner, G.D. & Driscoll, N.W., 1998. Tectonic setting of the Marnes-Noires/Falcao source rocks of the Congo and Angolan continental margins, *AAPG Bull.,* **82,** 1928.

Kristoffersen, Y. & LaBrecque, J., 1991. On the tectonic history and origin on the Northeast Georgia Rise, *Proc. ODP, Scient. Res.,* **114,** 23–38.

Lawrence, S.R., Munday, S. & Bray, R., 2002. Regional geology and geophysics of the eastern Gulf of Guinea (Niger Delta to Rio Muni), *The Leading Edge,* **21,** 1112–1117.

Lawver, L.A., Gahagan, L.M. & Dalziel, I.W.D., 1999. A tight fit—Early Mesozoic Gondwana, a plate reconstruction perspective, *Mem. Natl. Inst. Polar Res.* Spec. Issue 53, 214–229.

Le Pichon, X. & Hayes, D.E., 1971. Marginal offsets, fracture zones and the early opening of the South Atlantic, *J. geophys. Res.,* **76,** 6283–6293.

Marks, K.M. & Stock, J.M., 2001. Evolution of the Malvinas plate south of Africa, *Mar. Geophys. Res.,* **22,** 289–302.

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

Martin, A.K., Hartnady, C.J. N. & Goodlad, S.W., 1981. A revised fit of South America and South Central Africa, *Earth planet. Sci. Lett.,* **54,** 293–305.

Martin, A.K., Goodlad, S.W., Hartnady, C.J.N. & du Plessis, A., 1982. Cretaceous paleopositions of the Falkland Plateau relative to southern Africa using Mesozoic seafloor spreading anomalies, *Geophys. J. R. astr. Soc.,* **71,** 567–579.

Max, M.D., Ghidella, M., Kovacs, L., Paterlini, M. & Valladares, J.A., 1999, Geology of the Argentine continental shelf and margin from aeromagnetic survey data, *Mar. Pet. Geol.,* **16,** 41–64.

Meschede, M. & Frisch, W., 1998, A plate tectonic model for the Mesozoic and Early Cenozoic history of the Caribbean plate, *Tectonophysics,* **296,** 269–291.

Nürnberg, D. & Müller, R.D., 1991. The tectonic evolution of the South Atlantic from Late Jurassic to present, *Tectonophysics,* **191,** 27–53.

Pindell, J.L. & Dewey, J.F., 1982. Permo-Triassic reconstruction of Western Pangea and the evolution of the Gulf of Mexico/Caribbean domain, *Tectonics,* **1,** 179–211.

Pindell, J.L., Cande, S.C., Pitman, W.C. III, Rowley, D.B., Dewey, J.F., LaBrecque, J. & Haxby, W., 1988. A plate-kinematic framework for models of Caribbean evolution, *Tectonophysics,* **155,** 121–138.

Rabinowitz, P.D. & LaBrecque, J., 1979. The Mesozoic South Atlantic ocean and evolution of its continental margins, *J. geophys. Res.,* **84,** 5973–6002.

Reznikov, M., Ben-Avraham, Z., Hartnady, C. & Niemi, T.M., 2005. Structure of the Transkei Basin and Natal Valley, Southwest Indian Ocean, from seismic reflection and potential field data, *Tectonophysics,* **397,** 127–141.

Richards, P.C., Gatliff, R.W., Quinn, M.F., Williamson, P. & Fannin, N.G.T., 1996. The geological evolution of the Falkland Islands continental shelf, in *Weddell Sea Tectonics and Gondwana Break-up*, **Vol. 108,** pp. 105–128, eds Storey, B.C., King, E.C. & Livermore, R.A., Geol. Soc. London Spec. Pub.

Roest, W.R., Dañobeitia, J.J., Verhoef, J. & Collette, B.J., 1992. Magnetic anomalies in the Canary Basin and the Mesozoic evolution of the Central North Atlantic. *Mar. Geophys. Res.,* **14,** 1–24.

Saadi, A., Machette, M.N., Haller, K.M., Dart, R.L., Bradley, L.-A. & de Souza, A.M.P.D., 2002. Map and database of Quaternary faults and lineaments in Brazil, USGS Open File Report 02–230, Denver.

Sandwell, D.T. & Smith, W.H.F., 1997. Marine gravity from Geosat and ERS-1 satellite altimetry, *J. geophys. Res.,* **102,** 10 039–10 054.

Schettino, A. & Scotese, C.R., 2005. Apparent polar wander paths for the major continents (200 Ma to the present day): a paleomagnetic reference frame for global plate tectonic reconstructions, *Geophys. J. Int.,* **163,** 727–759, doi:10.1111/j.1365-246X.2005.02638.x

Shaw, P.R. & Cande, S.C., 1990. High-resolution inversion for south Atlantic plate kinematics using joint altimeter and magnetic anomaly data, *J. geophys. Res.,* **95,** 2625–2644.

Sibuet, J.-C. & Mascle, J., 1978. Plate kinematic implications of Atlantic equatorial fracture zones, *J. geophys. Res.,* **83,** 3401–3421.

Teisserenc, P. & Villemin, J., 1989. Sedimentary basins of Gabon—geology and oil systems, in *Divergent/passive margin basins: AAPG Memoir*, **Vol. 48,** pp. 117–199, eds. Edwards, J.D. & Santogrossi, P.A.

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

Uliana, M.A., Biddle, K.T. & Cerdan, J., 1989. Mesozoic extension and the formation of Argentine sedimentary basins, in *Extensional Tectonics and Stratigraphy of the North Atlantic Margins, AAPG Memoir*, **Vol. 46,** eds Tankard, A.J. & Balkwill, H.R.

Unternehr, P., Curie, D., Olivet, J.L., Goslin, J. & Beuzart, P., 1988. South Atlantic fits and intraplate boundaries in Africa and South America, *Tectonophysics,* **155,** 169–179.

Urien, C.M. & Zambrano, J.J., 1973. The geology of the basins of the Argentine continental margin and Malvinas Plateau: in *The Ocean Basins and Margins; the South Atlantic*, eds Nairn, A.E.M. & Stehli, F.G., Plenum Press, New York.

Vink, G.E., 1982. Continental rifting and the implications for plate tectonic reconstructions, *J. geophys. Res.,* **87,** 10 677–10 688.

Wagner, T. & Pletsch, T., 1999. Tectono-sedimentary controls on Cretaceous black shale deposition along the opening of the Equatorial Atlantic Gateway (ODP Leg 159), in *The oil and gas habitats of the South Atlantic: Geological Society London Special Publication*, **Vol. 153,** pp. 241–265, eds Cameron, N.R., Bate, R.H. & Clure, V.S.

Webster, R.E., Chebli, G.A. & Fischer, J.F., 2004. General Levalle basin, Argentina: A frontier Lower Cretaceous rift basin, *AAPG Bulletin,* **88,** 627–652, 10.1306/01070403014