AGU PUBLICATIONS

Tectonics

RESEARCH ARTICLE
10.1002/2014TC003644

Key Points:

- Seafloor spreading data constrain South Atlantic growth
- Ocean grew by divergence of two plates
- Diachronous breakup accommodated by intracontinental deformation at all scales

Supporting Information:

- Readme
- Animation S1
- Figure S1
- Figure S2
- Figure S3

Correspondence to:
L. Pérez-Díaz,
l.perezdiaz@es.rhul.ac.uk

Citation:
Pérez-Díaz, L., and G. Eagles (2014), Constraining South Atlantic growth with seafloor spreading data, *Tectonics*, *33*, doi:10.1002/2014TC003644.

Received 10 JUN 2014
Accepted 29 AUG 2014
Accepted article online 5 SEP 2014

Constraining South Atlantic growth with seafloor spreading data

Lucía Pérez-Díaz[1] and Graeme Eagles[2]

[1]Royal Holloway, University of London, Egham, UK, [2]Alfred Wegener Institute, Helmholtz Centre for Polar und Marine Research, Bremerhaven, Germany

Abstract Recent models of South Atlantic opening history focus on early plate divergence by incorporating intracontinental deformation, which is poorly constrained. Aiming to avoid the uncertainties in this approach, we model the entire divergence history with a joint inversion for seafloor spreading data. For this history, the pre-Campanian motion parameters are the first to feature formal uncertainty estimates. We date the onset of spreading at 138 Ma, with movement along intracontinental accommodation zones leading to the assembly of South America by 123 Ma and Africa by 106 Ma. Part of the ridge in the Agulhas Basin jumped westward soon afterward toward the Bouvet plume, initiating the motion of a short-lived Malvinas Plate. The NE Georgia and Maud rises and Agulhas Plateau formed as a large igneous province over the plume. Farther north, part of the ridge jumped eastward toward the Tristan plume around 94–93 Ma but seems not to have resulted in independent plate motion. Our results show that the South Atlantic grew by diachronous breakup of continents on just two plates. Cretaceous intracontinental deformation in South America and Africa can be interpreted in terms of the accommodation of stress associated with northward propagation of this process. The pattern of accommodation is usually envisaged as focusing all of the strain in narrow belts. With our rotations, a commonly used set of such belts accounts instead for just 42–67% of the implied total strain. We suggest that the remainder was accommodated at all scales within the continental interiors and the extended continental margins.

1. Introduction

Investigations of the evolution of ancient divergent plate boundary zones, including those necessary for resource exploration purposes, are beginning to work toward quantifying and depicting their nonrigidity and its consequences [e.g., *Williams et al*., 2011]. This requires not only the quantification of material displacement fields and plate boundary forces but also the stresses transmitted by these forces to deforming regions inside the continents. Within such a context, defining accurate sets of rotations for the bounding rigid bodies at times during margin development becomes increasingly important, as does quantifying the uncertainties in them. Traditionally, this is led from geometric fits of the products of margin development, which include the continent-ocean boundaries and contemporary basins and shear zones in the continental interiors and margins [e.g., *Bullard et al*., 1965; *Rabinowitz and LaBrecque*, 1979; *Nürnberg and Müller*, 1991; *Moulin et al*., 2010]. As well as not being simple markers of rigid plate divergence, features like these are difficult to portray consistently at high resolution and are not interpreted unanimously, making it impossible to objectively compare the rotations and models based on them.

In an alternative approach, the model presented here provides an estimate of South Atlantic opening from Valanginian to present, optimized to describe the shapes and distributions of fracture zones and seafloor isochrons. In comparison to the contents of continent-ocean transition zones, these features are simpler to identify unequivocally in the South Atlantic, and with more tightly constrained locations, making it possible to provide formal uncertainty estimates for rotations describing pre-Campanian plate motions there. Interpretations of kinematic markers in continent-ocean transition zones and intracontinental tectonic zones thus do not drive the modeling process. The model can therefore be used as a predictive tool for the study of those features. The model is further depicted and discussed with reference to a 1 My resolution animated reconstruction of gridded free-air gravity anomalies.

1.1. Previous Work

It is no surprise that the opening of the South Atlantic Ocean is one of the most extensively researched problems in global tectonics. After all, the similarities between the coastlines of Africa and South America

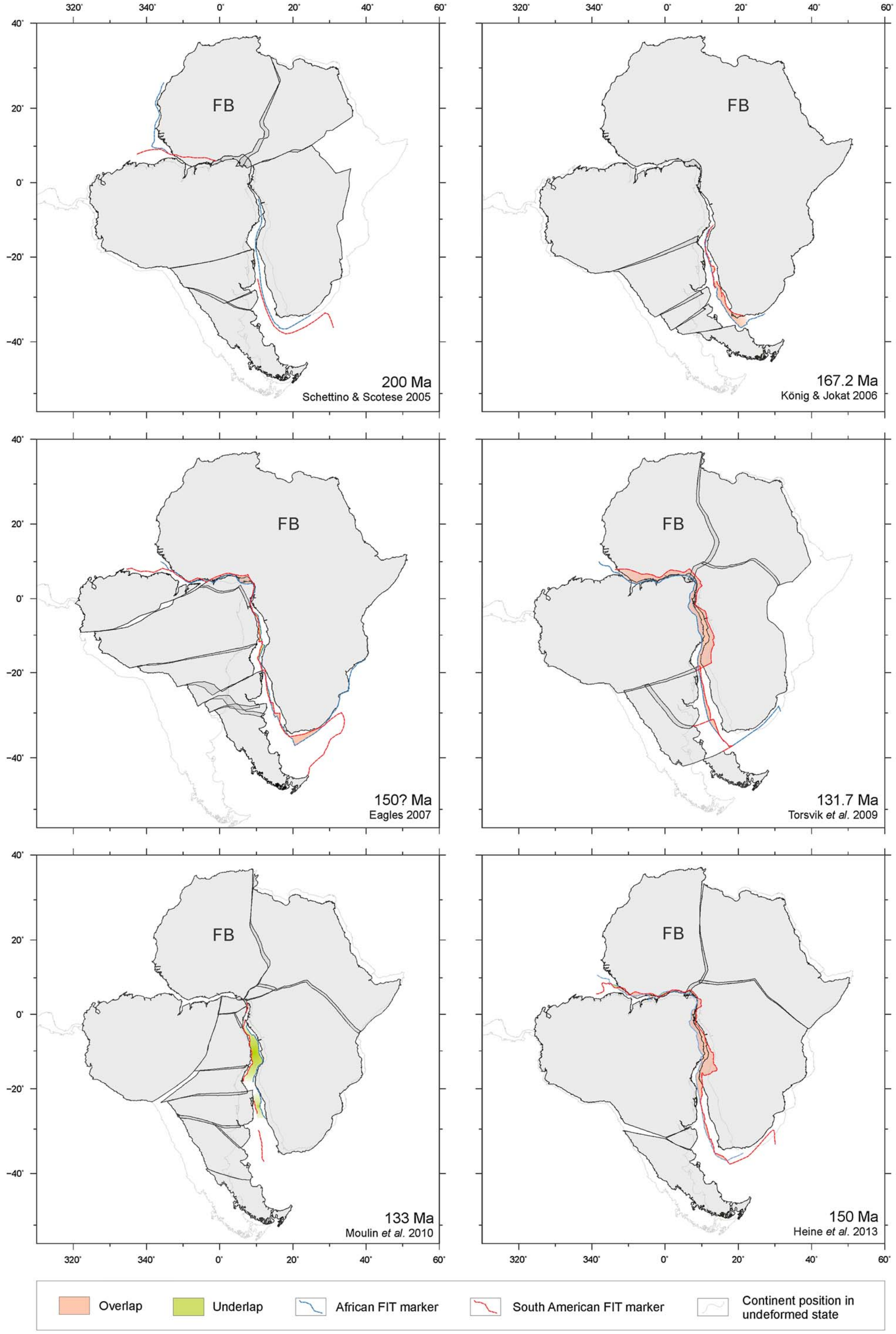

Figure 1. Simplified view of some recent South Atlantic reconstructions showing the variety of interpretations of intracontinental accommodation zones and continent-ocean boundaries [*Schettino and Scotese*, 2005; *König and Jokat*, 2006; *Eagles*, 2007; *Torsvik et al*., 2009; *Moulin et al*., 2010; *Heine et al*., 2013]. FB: fixed block.

inspired the basic foundations of plate tectonic theory. Many models have seen the light since *Bullard et al*. [1965] broke new ground with their computer-assisted reconstruction. Some of these are summarized in Figure 1. In recent years, driven by the oil and gas industry's move into deeper water exploration, attention has been focussed on describing the early stages of continental separation.

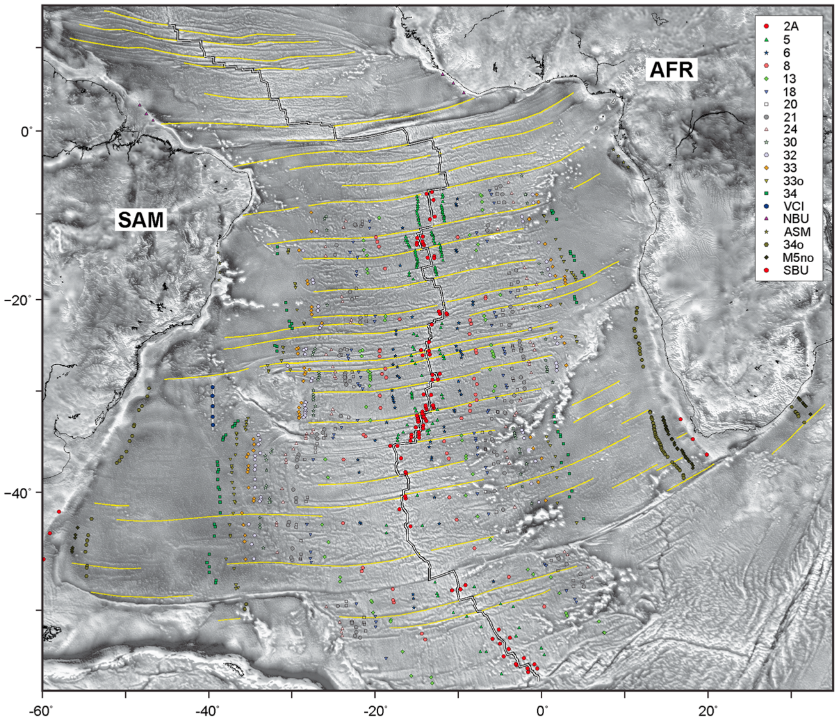

Figure 2. Isochron data set displayed over satellite-derived free-air gravity data set from *Sandwell and Smith* [2009]. Positions along fracture zones have been picked at 10 km intervals (small yellow triangles).

Because the shapes of the bounding continents are clearly recognizable throughout Figure 1, it is also clear that there is general agreement about the South Atlantic Ocean being the result, at first order, of the divergence of two large plates. Agreement also exists in that this divergence started earlier in the south than in the north. Evidence for Cretaceous internal deformation of Africa and South America has long been interpreted in terms of the accommodation of stress related to this northward propagation. In any given location, the timing, sense, amount, and even the occurrence of this deformation may be subjects of debate. Despite this, it is widely taken as motivation for invoking motions of small plates bearing continental blocks in order to reduce gaps, overlaps, and misalignments of the reconstructed extended continental margins. *Heine et al*. [2013] present what is probably the most sophisticated study of this kind by reviewing, developing, and balancing plausible models for the effects of stretching in a set of intracontinental accommodation zones and on the extended continental margins.

This approach assumes that knowledge about the locations of, and motion across, the margins and intracontinental accommodation zones can be described at a level of accuracy that, once propagated through the model to constrain the fit and motion of locations of other such features in it, is still less than the uncertainties in the new locations and their motions. With continent-ocean transition zones in the South Atlantic typically 50 to 150 km wide, and the continental interiors still not completely explored for the products of lithospheric extension, this assumption is unlikely to have been met. Perhaps the best illustration of this is the failure of a large number of studies of this kind to reach consensus on the detailed earliest opening history of the South Atlantic [*Aslanian et al*., 2009; *Torsvik et al*., 2009; *Moulin et al*., 2010; *Heine et al*., 2013].

In an alternative approach, *Eagles* [2007] used a visual-fit model to suggest that South Atlantic opening was conceptually far simpler than it had come to be viewed in the previous 40 years. He demonstrated that the patterns of fracture zone (FZ) traces and magnetic anomalies in the ocean floor could be expressed in terms of the divergence of just two plates. This could not be the case if the ocean margins had acquired their present-day shapes by the rotation of independent plates bearing them during the breakup process. The finite rotation poles he determined for the plates' prebreakup locations lie farther north than in all previous studies, which had been led from margin-based fit criteria. *Font et al*. [2009] showed that this more northerly location is preferable for reconstructing the apparent polar wander paths of mid-Cretaceous (~100 Ma) rocks in South America and Africa.

Table 1. Finite Rotation Parameters and Confidence Regions for South Atlantic Reconstructions[a]

		Rotation Parameters (deg)			95% Confidence Ellipsoid, 1σ, Great Circle (deg)			
Chron	Age (Ma)	Lon.	Lat.	Ang.	Axis 1	Axis 2	Axis 3	Azimuth
2A	2.581	−37.03	56.97	0.75	0.60	0.07	0.03	113.83
5	9.987	−34.81	54.07	3.16	0.85	0.18	0.02	105.01
6	18.748	−33.59	53.63	7.02	0.40	0.08	0.04	103.96
8	25.295	−32.74	53.66	9.95	0.29	0.06	0.05	102.73
13	33.266	−31.82	54.85	13.37	0.22	0.05	0.04	101.49
18	38.032	−31.46	56.19	15.77	0.22	0.05	0.04	101.13
20	41.590	−31.06	57.02	17.60	0.21	0.05	0.03	100.92
21	45.346	−30.88	58.27	19.12	0.20	0.04	0.03	101.10
24	52.648	−32.07	61.28	21.23	0.17	0.04	0.03	103.71
30	65.861	−32.49	62.21	24.73	0.14	0.03	0.03	103.55
32	70.961	−32.56	61.85	26.56	0.17	0.04	0.03	102.96
33	73.577	−32.62	61.64	27.92	0.15	0.04	0.03	102.42
33o	79.543	−33.19	61.14	30.97	0.13	0.03	0.03	103.41
34	84.000	−33.85	60.74	33.42	0.12	0.03	0.03	105.28
VCI	92.500	−35.15	59.96	37.84	0.13	0.10	0.02	128.62
NBU	103.000	−38.97	61.56	43.35	0.13	0.09	0.02	94.62
ASM	119.500	−40.06	58.83	51.36	0.11	0.06	0.02	102.09
34o	124.610	−39.88	57.40	53.47	0.11	0.03	0.02	109.45
M5no	130.800	−40.04	57.36	55.89	0.14	0.04	0.03	113.49
SBU	138.000	−39.28	56.23	59.58	0.46	0.08	0.06	123.45

[a] Ages are assigned to NBU, ASM, VCI, and SBU such that the rotations produce minimum change in seafloor spreading rates through the CNS.

Here, *Eagles*'s [2007] experiment is expanded as a quantitative South Atlantic opening model based on seafloor spreading data. The advantages of the new experiment are that it provides the first continuous least squares model description of plate motions from the separation of the continental margins until the present day, an increase in detail to include four stages of motion through the Cretaceous normal polarity superchron (CNS), and a full set of 95% confidence regions. The model results reiterate that a two-plate opening history with substantial intracontinental deformation is the most economical way to describe seafloor data from the South Atlantic. Using this history as a framework, we present a model for the timings of conjugate margin divergence and tectonic processes in the better documented intracontinental basins and deformation belts of South America and Africa. Furthermore, we discuss the model in terms of the distribution and partitioning of intracontinental strain during continental breakup.

2. Finite Rotation Model for the South Atlantic

The growth of the South Atlantic Ocean is modeled using the joint inversion technique of *Nankivell* [1997] as described by *Eagles* [2004] and *Livermore et al*. [2005]. The locations of 20 finite rotation poles and angles of rotation about them are resolved by minimizing the misfits of sets of small and great circle segments to the locations of fracture zones and isochron data in the ocean.

2.1. Data Set

The inversion data set (Figure 2) in the South Atlantic is based on several sources. All of our magnetic isochron picks are labeled and dated according to the magnetic reversal anomaly timescale of *Gradstein et al*. [2004] (Table 1). The magnetic isochron data set is derived from a set of magnetic anomaly profiles varying in vintage and density. This results in an uneven coverage of isochrons, which in some spreading corridors are defined from just one or two ship track crossings. Picks of isochrons younger than chron C34y are taken from *Nankivell*'s [1997] thesis, whose data set was an iteration on those of *Cande et al*. [1988] and *Shaw and Cande* [1990]. Despite this data set's age, few more recent magnetic data are available for the region. With the exception of chron C33 (for which both the old and young ends are picked), picks are taken from the younger edges of the isochrons. Identifications of the old edge of the CNS and anomaly M5n have been made following *Eagles* [2007], adding to his data set with picks from profiles newly published by *Moulin et al*. [2010]. Both of these old isochrons run oblique to the continental margins in the Cape and Argentine basins, where they merge with a prominent marginal magnetic anomaly that has been related to the presence of seaward dipping basalt bodies [*Rabinowitz and LaBrecque*, 1979; *Bauer et al*., 2000].

In addition, we constructed four nonmagnetic isochrons, none of which are intended to precisely constrain prerift plate margin geometries. Instead, they are introduced in order to allow the model to fit a greater number of small circle segments to the picked fracture zones throughout the CNS. This makes it possible to depict more detailed changes in the plate divergence vector in Aptian-Cenomanian times. These nonmagnetic isochrons are the following:

1. An abandoned mid-ocean ridge segment in the South American Plate south of the Rio Grande Rise, which we interpret at the gravity signal related to the bathymetric trough known as the Vema Channel. The ridge jump is evidenced by the strong asymmetry of accreted oceanic crust in the spreading corridor occupied by the trough. Measured from the present-day ridge crest to the continental slopes, this corridor is as much as 800 km wider on the South American Plate. Most of this difference is expressed in the variable width of the CNS magnetic anomaly, within which the channel lies. These observations imply an eastward relocation, or relocations, totaling 400 km, of the mid-ocean ridge in the spreading corridor during CNS times. The isochron picked from the putative ridge jump scar is named the "Vema Channel Isochron" or VCI.
2. The gravity anomaly highs outlining the continental shelf edges off Liberia and north of the Amazon in the South Atlantic Ocean. The highs are sampled along short segments of the margin bordering a single-spreading corridor, in order to ensure that they do not represent diachronous markers formed during the mid-ocean ridge's northward propagation. We refer to this isochron as NBU (Northern Break-Up).
3. The gravity anomaly highs outlining the continental shelf edges in the southern parts of the Cape and Argentine basins in the South Atlantic Ocean. This feature too is defined along a short segment of the margin in order to ensure an isochronous nature. We name it SBU (Southern Break-Up).
4. The gravity anomaly highs at the continental shelf edges of the Rio Muni/Gabon and Jacuipe margin basins, which are characterized by the presence of a prominent post-middle Aptian ($<$120 Ma) salt layer [*Rabinowitz and LaBrecque*, 1979]. This isochron is named ASM for "Aptian Salt Margin."

In total, the combined set of magnetic and nonmagnetic isochrons provides constraints on plate divergence from 788 individual point rotations. The smallest number of constraining isochron rotations is 5 (for VCI), and the greatest is 99 (for chron 5).

We digitized fracture zones along linear gravity anomaly troughs and steps with points at 10 km intervals, using the newest version of *Sandwell and Smith*'s [2009] data set. The set of FZs is selected to avoid segments that have been transferred between plates as a result of ridge jumps (e.g., the Florianopolis and Falkland-Agulhas FZs) or that record cross-axial strain at long-offset transform faults (e.g., the Falkland-Agulhas and Romanche FZs). Not all FZs evident in the gravity are sampled, as doing so would overpopulate the FZ data set. The chosen set maximizes the accuracy of our results by sampling records from the longest possible paleolength of the plate boundary. The resulting number of FZ crossings is 8336.

2.2. Method

The modeling procedure was straightforward. Where possible, isochron data were constrained to fit with their conjugates. A smaller number of isochron picks were allowed to rotate to nonconjugate targets because of the absence of conjugate data. Most important among these are the picks for VCI and the southernmost segments of M5n, in the Cape Basin and northern Natal Valley. A starting set of rotations was taken or interpolated from either *Nankivell* [1997] for post-C34 rotations or *Eagles* [2007] for earlier ones. With the data set shown, the procedure converges on a solution after a few tens of iterations. The solution appears robust in that very similar results can be achieved by approaching it from other starting rotation sets based on more southerly rotation poles [e.g., *Bullard et al*., 1965; *Rabinowitz and LaBrecque*, 1979; *Nürnberg and Müller*, 1991; *Moulin et al*., 2010].

2.3. Results

Figure 3 presents the solution as a set of visual fits of rotated isochron picks to target great circle segments and synthetic ridge-crest flowlines lines to fracture zone picks. The procedure reduced the misfits to a mean and standard deviation of 1.1 and 22.5 km for isochron data and 0.1 and 11.6 km for FZ data. If outliers are neglected under the assumption that the misfits should adopt Gaussian distributions, the population statistics are 1.0/16.4 km for isochron data and 0.2/8.0 km for FZ data.

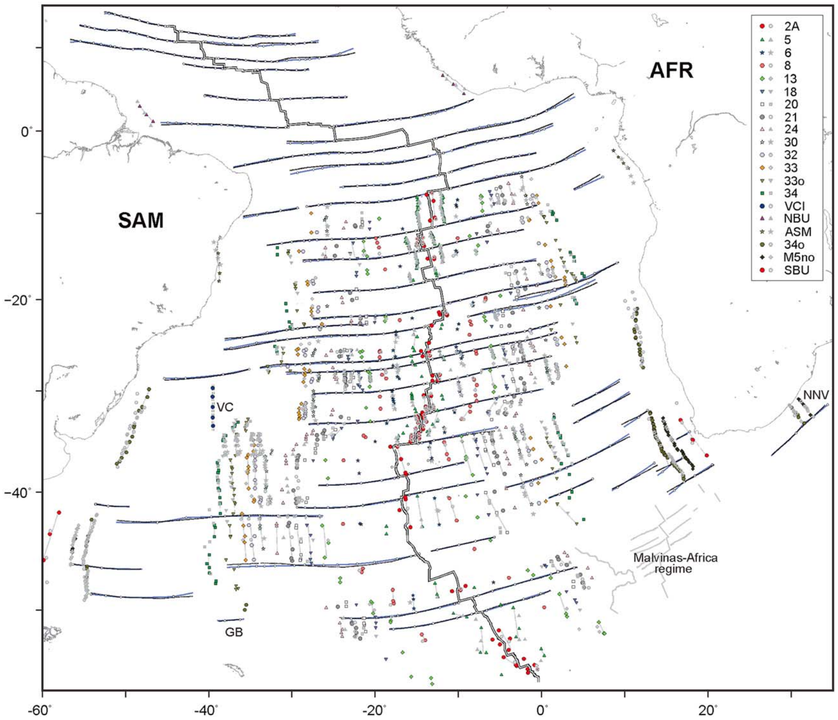

Figure 3. Visual representation of the finite rotation model results. Thin grey lines represent the target great circle segments to which groups of isochron picks are rotated. Faint grey outline symbols: rotated isochron picks; blue outlines with white discs: synthetic flow lines with flow points defined by half-finite rotations. GB: Georgia Basin; NNV: Northern Natal Valley; and VC: Vema Channel.

The values derived from FZ data are typical for the technique, but the isochron misfits are slightly more broadly distributed than in models of other similarly aged regions [e.g., *Eagles and König*, 2008]. The broad distribution of isochron misfits may be attributable to the relatively large number of instances in which great circle targets are defined from just two isochron picks in a corridor. The validity of such targets is strongly dependent on both picks being accurately located and reliably identified.

Within the FZ data set, the most poorly fitting flowline segments tend to be the longer ones located within the oldest part of the CNS on the African Plate. There is no systematic distribution of these misfits that would lead to the suspicion that a third or further plates had acted during the formation of the modeled seafloor. Instead, we suspect that the poor fits are a result of the failure of the procedure to fully capture a pattern of continuously changing curvature from the small number of CNS-aged flow line segments available to the model.

Table 1 and Figure 4 locate the rotation poles from the model within 95% confidence ellipses generated using covariance matrices built from the rotation parameters and misfit populations in the solution. Even within the confidence regions, none of the determined rotations overlaps with any of the “Bullard Family” [*Eagles*, 2007] of full-fit rotations that concentrate on optimizing continental margin fits. Instead, the new rotations occur about a set of poles that occupy a narrow region in the North Atlantic, for the most part smoothly migrating about a point southeast of Greenland but with inflections at chrons NBU, VCI, and C30. The NBU inflection is related to the changing strike of FZs in seafloor formed during the later part of the CNS. Its severity may be an artifact related to the small number of FZ segments that the model is forced to use to depict the change. The C30 inflection is more reliably depicted from shorter stages accompanied by a spreading rate decrease, as noted, for example, by *Cande et al.* [1988], *Shaw and Cande* [1990], and *Nankivell* [1997].

Figure 5 compares our model explicitly to others in the South Atlantic using sets of full synthetic ridge crest flow lines calculated in them. The largest differences between the sets of synthetic flow lines appear at their oldest ends as a result of the independent motions of various small plates that have been invoked to explain the evidence for Cretaceous deformation in the African and South American continental interiors. None of the complexity implied by these invocations is reflected in the shapes of the FZs nearest the coastlines. Farther offshore, most of the models do a reasonable job of describing the equatorial Atlantic Ocean. This is because a great proportion of the equatorial seafloor formed at times for which the plate motion can be characterized by magnetic isochron data. Farther south, where this is not the case because most or all of the seafloor formed during the CNS, larger differences can be seen. The flow lines show greater similarity overall on the African Plate because, with Africa universally taken as the fixed plate for finite rotation modeling, the stage rotations from which the flowlines are calculated are computationally closely related to the finite rotations. The stage pole for the moving South American Plate, however, moves with the plate by half of the preceding finite rotation. Our technique, which uses explicit constraints from modeling stage rotations for the ridge crest, more faithfully reproduces the shapes of FZs on the South American Plate.

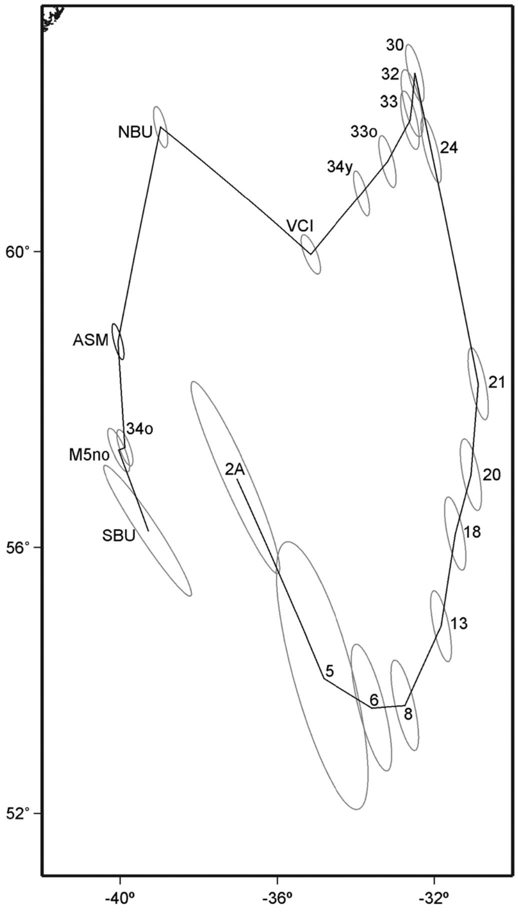

Figure 4. Location of the finite rotation poles and their 95% confidence ellipses as defined in the model.

3. Animation Method

Our animated reconstruction illustrates a tectonic history that we have interpreted from the rotations in Table 1. The animation shows the plate motions resulting in the opening of the South Atlantic Ocean, as well as a set of motions on accommodation zones that enable the rotations to produce a plausible set of fits of continental margin segments.

Individual still frames at 1 My intervals are shown in sequence to produce a high-resolution reconstruction of the ocean's development from 138 Ma to present. Each frame shows the locations of *Sandwell and Smith*'s [2009] free-air gravity data with respect to the portion of South America north of the Amazon River. To build the frames, a set of masks is digitized (Figure 6), outlining snapshots of internally rigid crustal areas that have moved as parts of the African and South American plates at 1 My intervals between 138 Ma and present. In addition, we digitized 39 masks for the outline of the Malvinas Plate, a short-lived oceanic plate that formed in late Cretaceous times in the Agulhas Basin [*Marks and Stock*, 2001]. In the oceans, each of these outlines parallels the nearest known magnetic anomaly isochron from the data set used in the inversion, showing offsets where they intersect fracture zones as depicted by the free-air gravity data. Where magnetic isochron data are nonexistent or scarce, we base our outlines on synthetic isochrons generated by rotating the active ridge crest into the plate interior by the appropriate finite half rotation. In the continental interiors, the masks follow a set of Cretaceous-aged tectonic features whose assignment and depiction we outline next.

With these plate contours as cropping templates, data are extracted from *Sandwell and Smith*'s [2009] free-air gravity set. These data are then rotated to their reconstructed positions using Generic Mapping Tools's *grdrotater* command [*Wessel and Smith*, 1998] and rotations interpolated from the parameters in Table 1.

4. Description of the New Animation

Producing plate kinematic reconstructions under the constraints of the rotation parameters in Table 1 involves four interdependent interpretive steps.

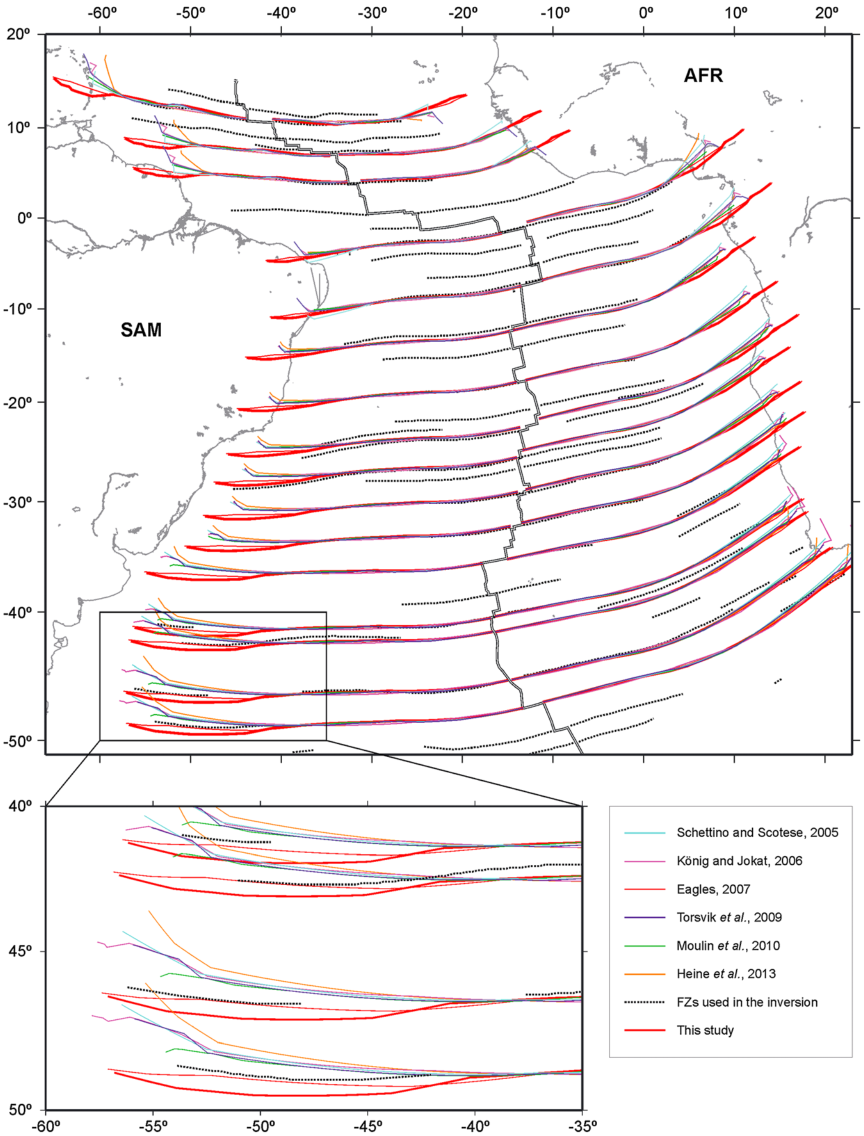

Figure 5. Comparison of synthetic flow lines in various models of South Atlantic opening to FZ traces in the seafloor [*Schettino and Scotese*, 2005; *König and Jokat*, 2006; *Eagles*, 2007; *Torsvik et al*., 2009; *Moulin et al*., 2010; *Heine et al*., 2013; this study].

First and second, breakup boundaries and corresponding breakup dates need to be chosen for conjugate continental margin segments. For breakup boundaries, various features of the continent-ocean transition zones might be interpreted from deep-seismic soundings, gravity and magnetic anomaly data, and onshore geology. Candidate features include ancient rift-boundary faults, which may locate the inward edge of extended continental crust, or more distal products of continental extension such as exhumed peridotite ridges or seaward dipping basalt flows [*Moulin et al*., 2010]. With dynamic and kinematic processes in continental rift zones being the subject of much ongoing work, there is as yet no consensus on which of these features might best approximate a breakup marker in any particular segment of any particular margin. Furthermore, variable data quality and availability means that the locations of these features are mapped with variable precision. All of this uncertainty is difficult or impossible to quantify. We can only estimate that the combined positional-interpretational uncertainty for breakup markers may be in the region of 50–100 km. Dates for breakup markers are also subject to uncertainty because they are generally derived indirectly from dating of breakup unconformities in margin basins. These uncertainties also have measured and interpretational components that come from the dating method used, the choice of which regional surface to label as a breakup unconformity, and their authors' understanding of what

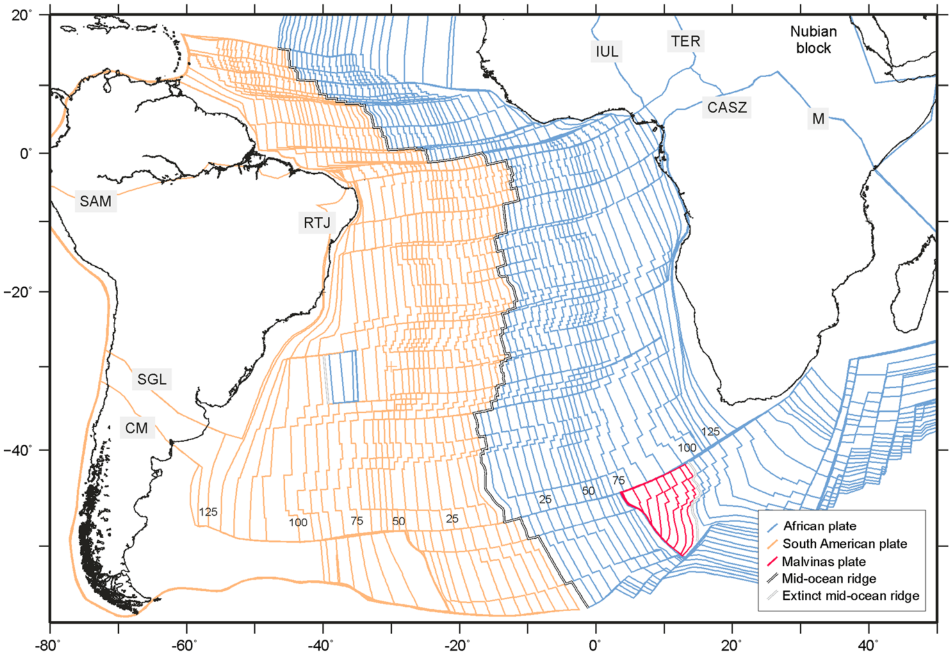

Figure 6. Plate masks used in the animation. AR: Anza Rift; CASZ: Central African Shear Zone; CM: Colorado Basin-Macachín Trough; IUL: Iullemeden Basin; MR: Muglad Rift; RTJ: Recôncavo-Tucano-Jatobá basin system; SAM: Solimões-Amazon-Marajó; SGL: Salado-General Levalle; and TER: Termit Basin. Blue outlines on the South American Plate represent the portion of crust transferred from the African Plate as a result of the Vema Channel ridge jump.

process the unconformity represents. Most of this is difficult to quantify as well. Our estimate for the accuracy of breakup dates is ±3 My.

The breakup markers we use for the model are based on the free-air gravity anomaly that forms over the continental slope. This anomaly is typically around 100 km wide. Together with crustal-scale seismic data, modeling of this anomaly shows that it is undoubtedly contributed to by divergence-related features such as the presence of thick sediment wedges and, in some cases, lower crustal high-velocity bodies that might modify its meaning and applicability as a breakup marker in any given setting [e.g., *Unternehr et al.*, 2010; *Franke et al.*, 2006; *Watts and Fairhead*, 1999]. We chose the gravity anomaly for its ubiquity in the satellite-derived data set of *Sandwell and Smith* [2009], but because of its width, the variety of possible sources, and the large uncertainties estimated above, we do not consider any part of it to consistently represent a definitive breakup marker. The anomalies are fitted visually within the estimated uncertainty using rotations interpolated from Table 1 for their adopted age of breakup. An advantage of this approach is that it prevents the effects of the large uncertainties in the breakup marker's location and age from propagating any further into the model than the spreading corridors bordering the interpreted margin segments.

It has been argued that intracontinental correlations of Proterozoic high-angle shear zones between neighboring segments of the South American or African plates might serve to fine-tune continental margin fits [*Pindell and Dewey*, 1982; *Moulin et al.*, 2010]. However, we are not yet aware of any situation in which such correlations are sufficiently robust or finely characterized across the continental shelves to justify doing so.

It has long been recognized [*Burke and Dewey*, 1974; *Fairhead*, 1988; *Unternehr et al.*, 1988] that intracontinental deformation can be surmised from the occurrence of unacceptable misfits of breakup markers on the continental margins. This surmise is also possible with the considerations and rotations introduced above. Hence, the third and fourth interpretational steps involve making a number of decisions about the existence and location of intracontinental tectonic zones and their periods of activity. Here, there are feedbacks with the first two steps, as estimates of the timing of activity on an accommodation zone should not disagree with estimates of the timing of activity in the margin segments linked to it. Managing this requires a familiarity with the literature on Mesozoic deformation in the interiors of Africa and South America [e.g., *Guiraud and Maurin*, 1992; *Jacques*, 2003]. We summarize this literature in Figures 7–9. Figures 7 and 8 show that a great variety of features has been suggested to have accommodated relative plate motions in the

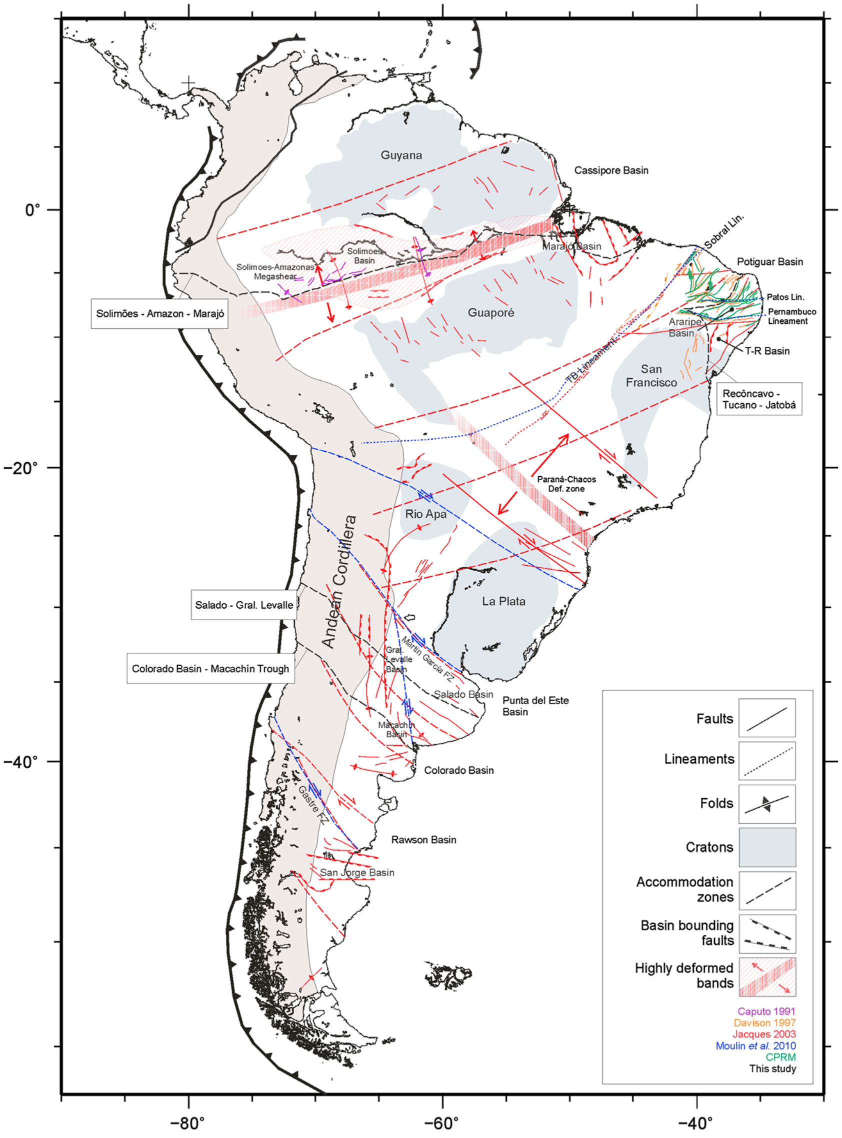

Figure 7. Compilation of Cretaceous intracontinental deformation zones in South America, as proposed in published literature [*Caputo*, 1991; *Davison*, 1997; *Jacques*, 2003; *Moulin et al*., 2010; this study]. Accommodation zones used in this study are labeled and shown as thick dashed lines.

interiors of Africa and South America during Cretaceous times. Those studies that intend to use these features in the quantification of plate reconstructions tend to concentrate on a smaller subset of them, subdividing the continents into a handful of large rigid blocks between prominent shear zones and sedimentary basins [e.g., *Moulin et al*., 2010; *Heine et al*., 2013]. In contrast, regional tectonic studies and paleogeographic atlases tend to identify a greater variety and number of features, including, for example, dyke swarms, arches, and broad deformation zones that imply more fragmented continental interiors [e.g., *Jacques*, 2003; *Guiraud et al*., 2000]. Figure 9 shows that the tectonostratigraphy of sedimentary basins in these accommodation zones is only very broadly constrained. The stratigraphy could be taken to justify assumptions of either simultaneous or sequential rift phases in the basins. Many of the accompanying shear zones, faults, and arches can only be dated with a precision that suggests their involvement in South Atlantic opening.

Figures 7–9 make clear that the uncertainties involved in identifying a set of these accommodation zones for any purpose are large, perhaps the largest of all we consider, because evidence for their existence can be slight, equivocal, or conceivably even absent, and few of them are precisely dated. As we noted above, the assumption of accurate knowledge about intracontinental strain is not a suitable basis on which to lead a

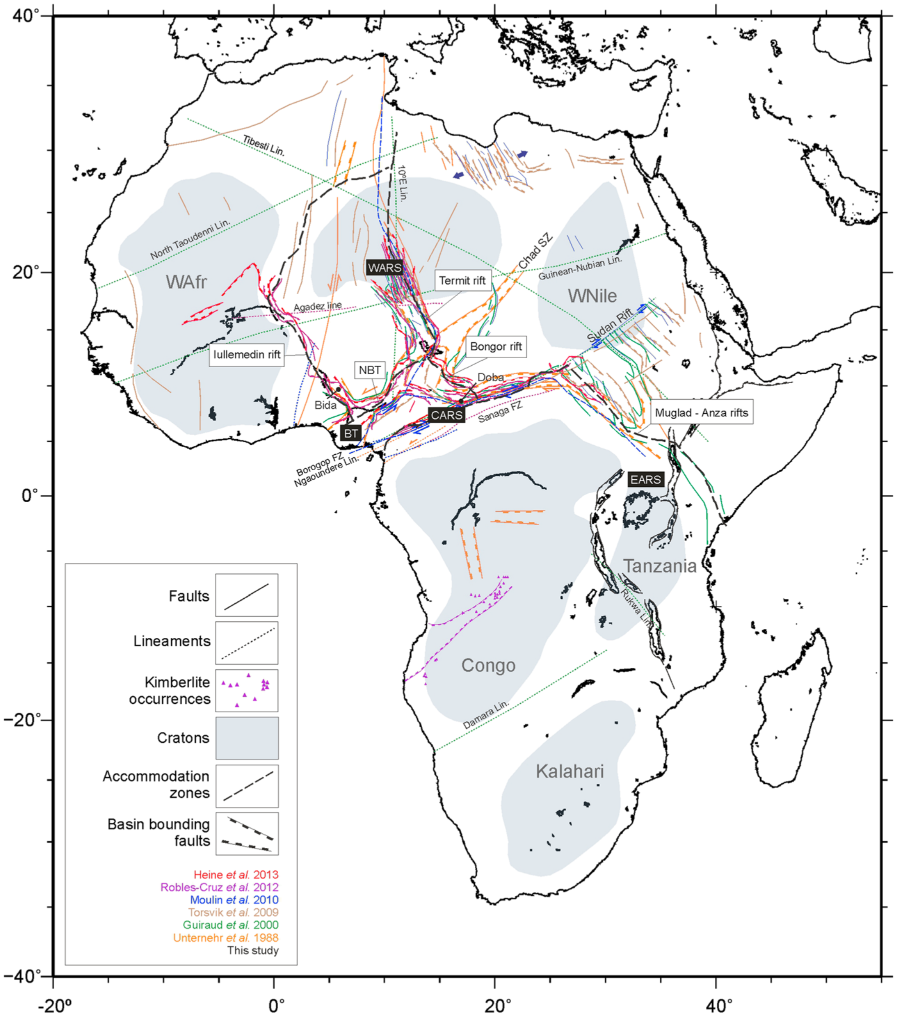

Figure 8. Compilation of Cretaceous intracontinental deformation zones in Africa, as proposed in published literature [*Heine et al.*, 2013; *Robles-Cruz et al.*, 2012; *Moulin et al.*, 2010; *Torsvik et al.*, 2009; *Guiraud et al.*, 2000; *Unternehr et al.*, 1988; this study]. BT: Benue Trough; CARS: Central African Shear Zone; EARS: East African Rift System; NBT: Northern Benue Trough; and WARS: West African Rift System. Accommodation zones used in this study are labeled and shown as thick dashed lines.

reconstruction effort by determining Euler rotations from its products. In contrast, an advantage of our approach is that we are only concerned with portraying those products using a set of rotations determined independently of them. Clearly, even working with a single set of governing rotations, there is plenty of leeway for producing a variety of total fit reconstructions using this four-step process. This will remain the case until the tectonostratigraphy of the Cretaceous basins in Africa and South America is known in more detail. For now, in being constrained by an optimally-robust bounding kinematic framework, our approach abstracts and so helps focus attention on the processes acting immediately prior to and during breakup. This is useful, because those processes have become a source of uncertainty and disagreement in reconstructions of the South Atlantic during the past couple of decades.

4.1. Accommodation Zones

As noted above, opinions vary greatly about which continental areas deformed in response to the stresses generated prior to and during the northward propagation of the South Atlantic mid-ocean ridge. In the following, a set of new reconstructions based on one application of the considerations detailed before is presented. The new set of reconstructions differs from those of *Eagles* [2007] in using a set of intra-African accommodation zones as well as South American ones (Figures 10–14). This set consists of some, but not all,

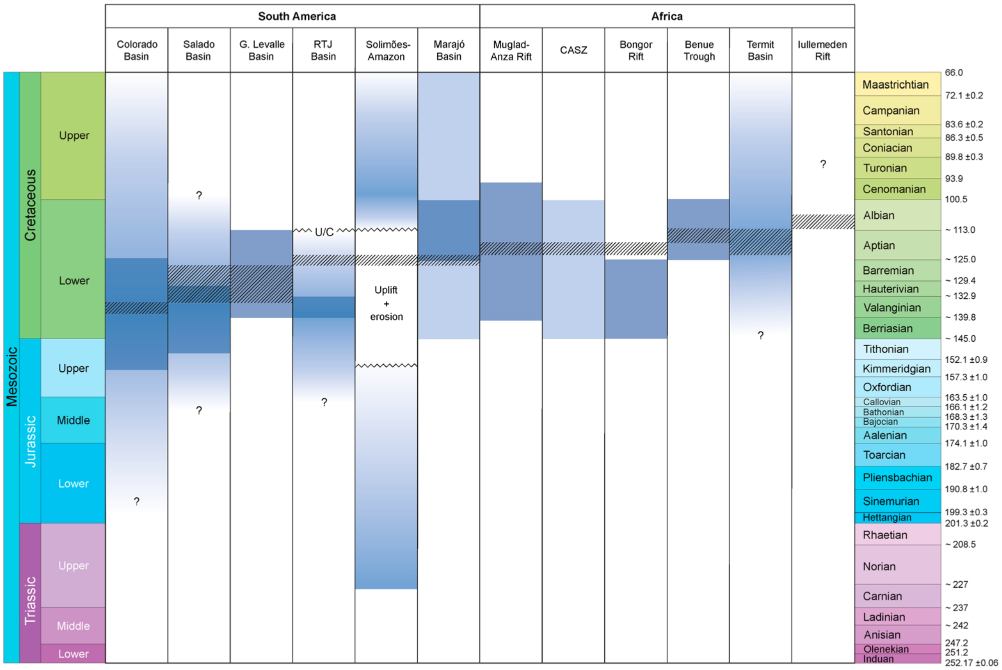

Figure 9. Chronostratigraphy of proposed intracontinental deformation zones in South America and Africa. Light fill: stratigraphic range of basin fill. Dark fill: range of rift phase sedimentation (where proposed). Hachured: rift phases implied by the rotations of Table 1 as applied in Figures 10–14 and the animation. RTJ: Recôncavo-Tucano-Jatobá Basins; U/C: Unconformity.

of the suggested accommodation zones of Figures 7 and 8. We introduce these accommodating features briefly here.

In South America we have chosen to use four deformation zones, all of which have been suggested in the past on the basis of geological observations (Figure 6). These are from south to north (1) Colorado Basin-Macachín Trough, (2) Salado-General Levalle basins, (3) Recôncavo-Tucano-Jatobá basins, and (4) Solimões-Amazon-Marajó basins (Figure 7).

The trends of the Colorado and Salado basins have led authors to speculate about their formation and evolution. Both basins have been interpreted often as aulacogens: failed arms of triple-rift systems formed in early South Atlantic three-plate systems. The presence of upper Jurassic-lower Cretaceous basalt intrusions in both basins is consistent with such an interpretation [*Urien and Zambrano*, 1973; *Franke et al.*, 2006; *Torsvik et al.*, 2009; *Pángaro and Ramos*, 2012]. Others consider them to be the expression of an earlier extensional event during which the reactivation of older basement structures exerted determining control over the resultant trend of the basin [*Pángaro and Ramos*, 2012; *Autin et al.*, 2013]. A third hypothesis describes the Colorado basin as a pull-apart structure, resulting from strike-slip dominated extension contemporary to the opening of the southern South Atlantic [*Nürnberg and Müller*, 1991].

Our accommodation zones in the Colorado and Salado basins continue toward the northwest via the Macachín graben and General Levalle basin. The Macachín graben is described as a NW trending belt of transtensional subsidence whose genesis may be explained by rifting [*Tankard et al.*, 1995]. The General Levalle basin has been interpreted as the result of the reactivation, during Early Cretaceous times, of a Paleozoic suture zone, again in a transtensional sense [*Webster et al.*, 2004]. The basin fill has been dated as of Lower Cretaceous to Aptian age [*Urien and Zambrano*, 1973; *Webster et al.*, 2004].

The Recôncavo-Tucano-Jatobá system is recorded in the literature as an aborted intracontinental rift that opened in Late Jurassic to Early Cretaceous times as a response to South Atlantic rifting penetrating northward between Brazil and Gabon. Once more, the basin architectures and evolution are thought to be conditioned by the presence of preexisting structures in the basement [*Milani and Davison*, 1988]. Rifting along these basins stopped during Aptian-Albian times and is marked in the sedimentary record by a postrift unconformity of upper Aptian age. This change has been speculated to have occurred in

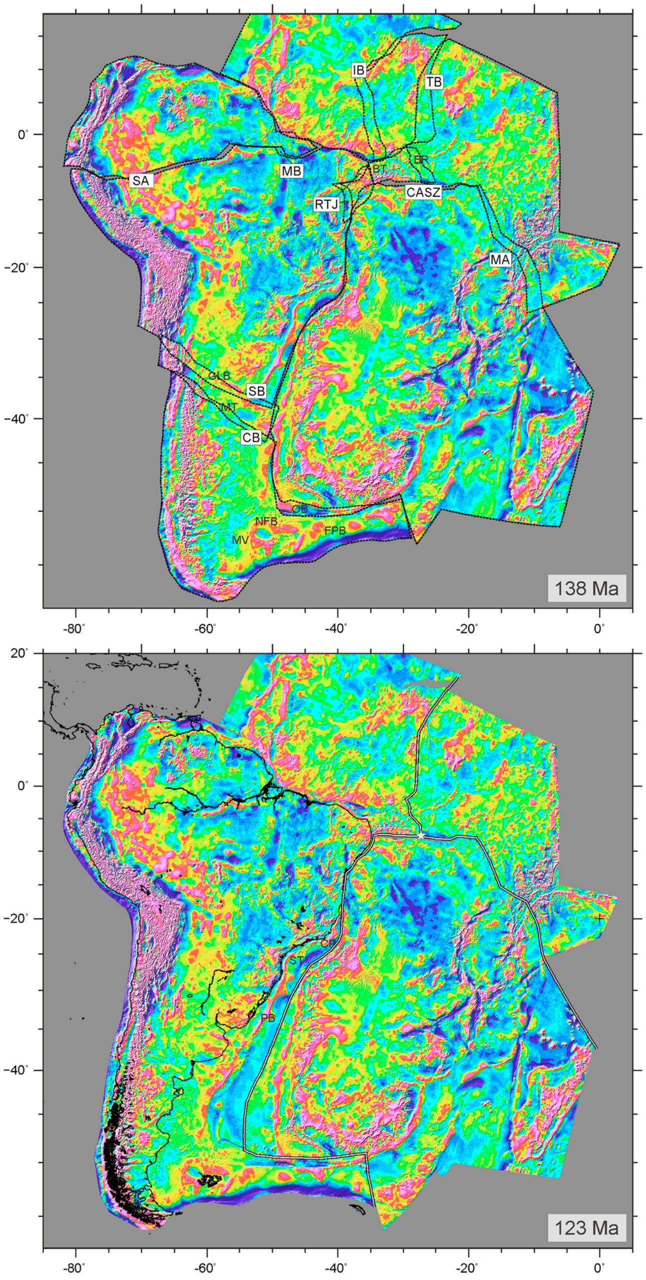

Figure 10. (top) Initial continental block configuration immediately prior to seafloor spreading. (bottom) Plate configuration at 123 Ma, showing an assembled South America and the onset of intracontinental deformation in Africa. Reconstructions use satellite free-air gravity anomaly data from *Sandwell and Smith* [2009]. See text for more details. BT: Benue Trough; BR: Bongor Rift; CASZ: Central African Shear Zone; CB: Colorado Basin; CP: Campos Basin; FPB: Falkland Plateau Basin; GLB: General Levalle Basin; IB: Iullemeden Basin; MA: Muglad-Anza Rift; MB: Marajó Basin; MT: Macachín Trough; MV: Malvinas Basin; NFB: North Falkland Basin; PB: Pelotas Basin; RTJ: Recôncavo-Tucano-Jatobá Basin; SA: Solimões-Amazon Basins; SB: Salado Basin; ST: Santos Basin; and TB: Termit Basin.

response to a change in extension direction of the South Atlantic rift from oblique to margin normal [*Castro*, 1987; *Milani and Davison*, 1988; *Macdonald et al*., 2003].

Our model also uses a dextral transpressional plate boundary along the Solimões-Amazon basins [*Caputo*, 1991; *De Matos and Brown*, 1992; *Almeida et al*., 2000]. Uplift and erosion related to the action of this short-lived plate boundary can be interpreted from the absence of a Triassic to Upper Cretaceous sedimentary succession in the Amazonas-Solimões basin. Farther east, where this boundary bends into a NE orientation in the Marajó Basin, extensional or transtensional motion can be implied from the basin's Aptian-Albian rift sequence [*Costa et al*., 2001].

Cretaceous extension is better documented in Africa than South America. It is generally accepted that major structural features, namely, the central and West African rift systems, accommodated deformation during Cretaceous times. Movement within these rift systems is evidenced, for example, by the presence of extensional basins trending perpendicular to the Central African Shear Zone (CASZ) [*Fairhead*, 1988; *Fairhead and Binks*, 1991, and references therein; *Guiraud et al*., 2005]. However, the timing, magnitude, and plate tectonic context of these movements continue to be a matter of debate. *Guiraud and Maurin* [1992] determine two main extensional events on each of these rift zones. The first, dated Berriasian-Early Aptian, affected basins in the Gulf of Guinea, Chad, Sudan, Kenya, and Niger and occurred prior to separation of the Borborema Province from what is now the mouth of the Benue Trough and the Niger Delta. The second event, which took place during the Late Aptian-Albian, resulted in the development of pull-apart basins from Benue to southern Chad and further growth of the basins along the Central African Shear Zone. The findings of *Guiraud and Maurin* [1992] were corroborated by studies of magmatism dating the onset of crustal extension for the Central

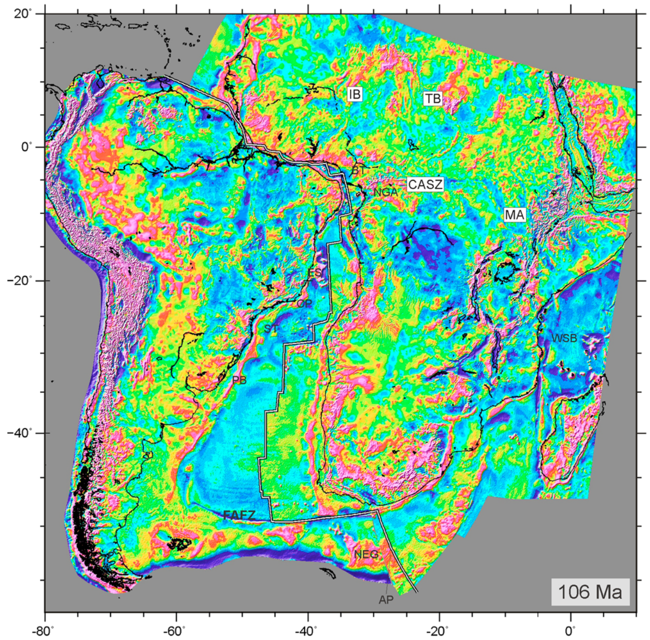

Figure 11. Plate configuration at 106 Ma, showing the South Atlantic plate boundary separating complete modern-like African and South American continents for the first time. Data as in Figure 10. See text for more details. AP: Agulhas Plateau; BT: Benue Trough; CASZ: Central African Shear Zone; CP: Campos Basin; ES: Espirito Santo Basin; FAFZ: Falkland-Agulhas Fracture Zone; IB: Iullemeden Basin; MA: Muglad-Anza Rift; NEG: northeast Georgia Rise; NGA: Ngaoundere Lineament; PB: Pelotas Basin; ST: Santos Basin; TB: Termit Basin; and WSB: West Somali Basin.

African Rift System as having followed the breakup of Gondwana with a later reactivation during mid-Cretaceous times [*Loule and Pospisil*, 2013].

In the reconstructions presented here, the four accommodation zones chosen within continental Africa are (1) Iullemeden rift, (2) Termit-Bongor rift, (3) Termit-Northern Benue Trough, and (4) CASZ-Muglad-Anza rift (Figure 8). As a result, Africa is divided into five blocks, the movements of four of which we interpret to result from intracontinental deformation conditioned by the northward propagating South Atlantic plate boundary. The fifth block moves independently of South American-African plate motion on the NE margin of the opening Muglad-Anza rift. The Muglad-Anza rifting is not necessary to achieve an improvement to the fits of any of the South Atlantic margin segments. We depict it in order to illustrate an alternative to the widely used suggestion that the Muglad-Anza rift basin system played a role in accommodating South Atlantic opening-related stress [e.g., *Heine et al*., 2013]. Given the rift zone's explicit connection to the Indian Ocean via the East African margin, we alternatively suggest that it opened in response to the accommodation of stresses transmitted to the interior of Africa from the early opening of the Indian Ocean.

The Benue trough is a Y-shaped Cretaceous sedimentary basin that trends NE into the interior of Africa from the Niger Delta. It has been speculated that the Benue trough is an aulacogen formed in Aptian to early Albian times by failure of a ridge-ridge-ridge triple junction with the Gulf of Guinea and South Atlantic [*Burke et al*., 1971; *Burke and Dewey*, 1974]. In detail, the basin's structure seems to be better explained in terms of left-lateral strike slip combined with an extensional component [*Benkhelil*, 1989; *Fairhead*, 1988; *Unternehr et al*., 1988; *Nürnberg and Müller*, 1991]. The main rift phase seems to have started in Albian times, but there is evidence for a later small compressional episode of Santonian age, marked by unconformities in the sedimentary record and related by some to the first stages of Africa-Arabian-Eurasian plate collision [*Benkhelil*, 1989; *Guiraud et al*., 2005]. The proximity of the Cameroon volcanic line and its similarity to the Y shape of the Benue basin has led some to speculate on the role of a mantle plume in the basin's development. According to these speculations, activity of the plume beneath the Benue trough would have ceased during Santonian times, after which clockwise rotation of Africa would result in its repositioning under the Cameroon line where volcanism started at around 65 Ma. Removal of a heat source from beneath the Benue Trough would have contributed to its Santonian subsidence and folding episode [*Fitton*, 1980; *Fairhead*, 1988; *Unternehr et al*., 1988; *Nürnberg and Müller*, 1991; *Coulon et al*., 1996; *Shemang et al*., 2001; *Basile et al*., 2005; *Ngako et al*., 2006; *Olade*, 2009].

The Benue trough deformation zone continues farther east into Africa along the CASZ. The CASZ is a wrench fault system whose development started in Early Cretaceous times, being dominated by sinistral tectonics between 130 and 74 Ma and later rejuvenated with dextral displacement [*Fairhead*, 1988]. Toward the western part of the CASZ lies the Ngaoundere lineament, a basement feature that was reactivated in Early

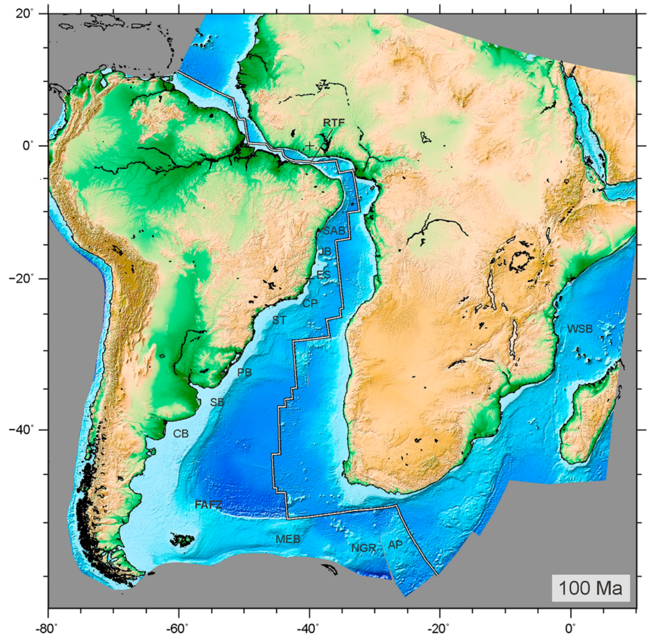

Figure 12. Initial stages of equatorial opening; 100 Ma reconstruction using present-day bathymetry and topography data from *Amante and Eakins* [2009]. AP: Agulhas Plateau; CB: Colorado Basin; CP: Campos Basin; ES: Espirito Santo Basin; FAFZ: Falkland-Agulhas Fracture Zone; JB: Jequitinhonha Basin; MEB: Maurice Ewing Bank; NGR: northeast Georgia Rise; PB: Pelotas Basin; RTF: transform fault that led to formation of the Romanche FZ. SAB: Sergipe-Alagoas Basin; SB: Salado Basin; ST: Santos Basin; and WSB: West Somali Basin.

Cretaceous and later in Cenozoic times as a dextral strike-slip fault [*Browne and Fairhead*, 1983]. The lineament can be correlated on predrift reconstructions with the Pernambuco lineament in Brazil. The existence of Cretaceous volcanic rocks and mylonite zones in Cameroon supports the interpretation of this lineament as a weakened zone in the lithosphere, explaining its many reactivations during changes in the African stress regime [*Browne and Fairhead*, 1983; *Benkhelil*, 1989; *Fairhead*, 1988; *Genik*, 1992; *Guiraud and Maurin*, 1992].

The strike-slip component of strain on the CASZ and in the Benue Trough was transformed into extension in a system of basins that splay off or offset them [*Fairhead*, 1988; *Genik*, 1992; *Guiraud and Maurin*, 1992]. Examples of this transformation are the Bongor rift, a NNW-SSE extensional trough active from Neocomian to Barremian, and the Termit basin, which trends NW-SE along the western edge of the Nubian block and was active in Cretaceous times [*Genik*, 1992]. North of the Termit basin, our accommodation zone follows a series of lineaments whose history is very poorly known, such as Amguid-Gassil-Touil-Algeria and 10°E lineaments [*Guiraud and Maurin*, 1992].

4.2. From SBU to the Assembly of South America (138 to 123 Ma)

Figure 10 (top) shows our model's initial continental block configuration immediately prior to the onset of seafloor spreading between the Falkland Plateau and southern Africa. Extension at this point is depicted in the southern Cape and Argentine basins and farther south in the Outeniqua and Falkland Plateau basins. Although not shown, the Malvinas and North Falkland basins are also thought to have been active during this period, having commenced rifting in mid-Jurassic times [*Richards and Fannin*, 1997; *Bransden et al.*, 1999; *Baristeas et al.*, 2013]. Farther north, the opening of these basins and the ensuing early stages of seafloor spreading are accommodated by motion along the most southerly accommodation zones, in the Colorado Basin-Macachín Trough (138–134 Ma) and Salado-General Levalle basins (134–126 Ma). The model timings for these accommodation zones are supported by the broadly constrained published ages for the basins' sedimentary infills, which range from Late Jurassic to Early Cretaceous [*Urien and Zambrano*, 1973; *Bushnell et al.*, 2000; *Webster et al.*, 2004; *Franke et al.*, 2006; *Autin et al.*, 2013]. The role played by the Colorado and Salado basins, as sequential and short-lived loci of an evolving boundary between two plates, is not the same as that of classical aulacogens whose evolution involves three simultaneously active rifts between three plates [e.g., *Burke et al.*, 1971; *Burke and Dewey*, 1974; *Burke*, 1976].

This earliest map and the start of the animation are for 138 Ma, in the earliest Valanginian. The date is a young, and therefore conservative, example of several estimates of the time when the South American and African parts of Gondwana started diverging. Breakup unconformities are undoubtedly oldest in the south, occurring in the Valanginian sequence of the Outeniqua Basin [*Roux*, 1997] and near the base of the Barremian sequence south of the Walvis Ridge (~131 Ma) [*Brown*, 1995; *Jungslager*, 1999]. These are consistent with the identified magnetic anomalies in the Cape and Argentine basins, which start with M5n (131–130 Ma; Barremian). The

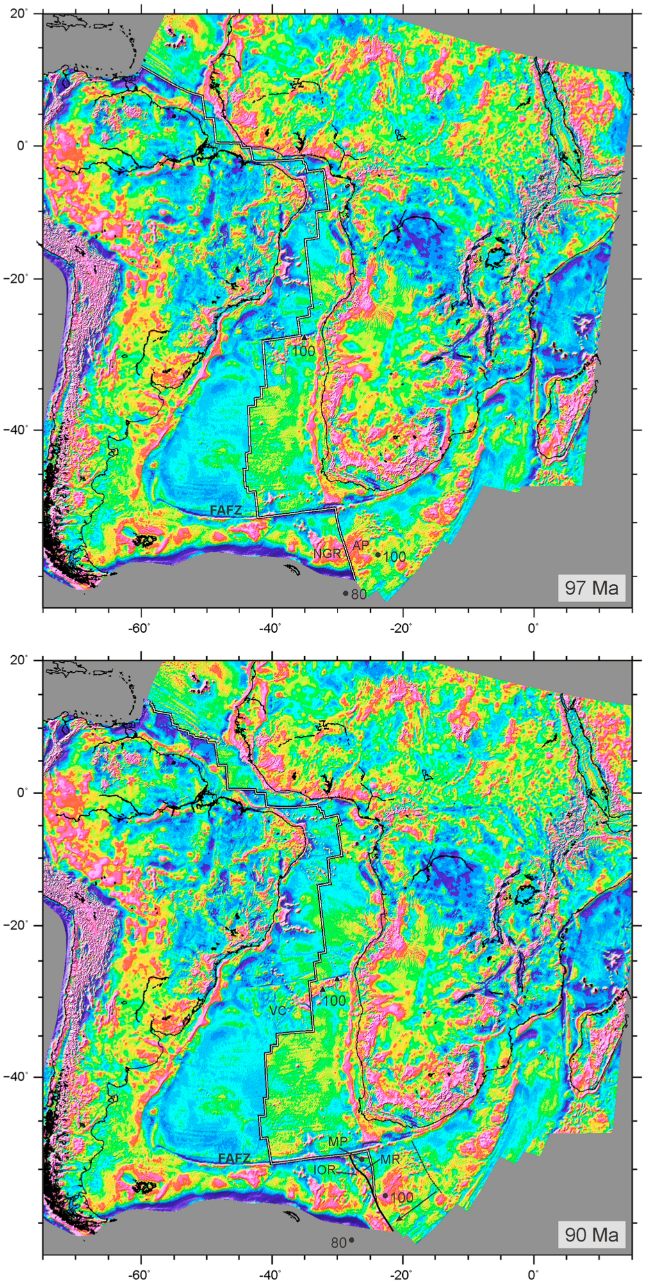

Figure 13. Plate configuration at (top) 97 and (bottom) 90 Ma, showing the formation of the SOLIP and the inception of the Malvinas Plate. AP: Agulhas Plateau; FAFZ: Falkland-Agulhas Fracture Zone; IOR: Islas Orcadas Rise; MR: Meteor Rise; NEG: northeast Georgia Rise; MP: Malvinas Plate; and VC: Vema Chanel. Black circles: reconstructed positions of the Bouvet plume at 100 and 80 Ma (rotations from *Doubrovine et al.* [2012]). Small black triangles with numbers: dated occurrences of volcanism on the Walvis Ridge [*O'Connor and Duncan*, 1990]. Data as in Figure 10. See text for more details.

duration of continental stretching that preceded formation of these unconformities is less well known. Syn-rift sediments in the Outeniqua and Orange basins date from Oxfordian-Kimmeridgian times (~157 Ma) [*Light et al.*, 1993; *Roux*, 1997]. Conventionally, this phase has been assumed to have occurred in an E-W oriented stress field related to the divergence of the bounding African and South American plates. It has been shown that changes in the azimuth of seafloor spreading in the Weddell Sea would have been very sensitive to the initiation of this South American-African divergence if both occurred as motions in a three-plate circuit with Antarctica and that two such changes occurred prior to South Atlantic oceanization [*Eagles and Vaughan*, 2009]. However, the record of spreading in the Weddell Sea is notoriously difficult to date unequivocally. *Eagles* [2010] shows how the central Scotia Sea contains a preserved conjugate to the Weddell Sea in which magnetic anomaly azimuths change at M19, possibly dating the later of the two Weddell Sea changes and with it the onset of South Atlantic plate divergence, to ~146 Ma. Conversely, *Heine et al.* [2013] suggest initial development of the South Atlantic rift basins in a NE-SW oriented stress field related to the established motion of the Antarctic Plate with respect to South America and Africa, referring to studies that suggest rift zones are more likely to successfully transition to seafloor spreading if they are oriented oblique to the stress field [*Brune et al.*, 2012; *Heine and Brune*, 2014]. This NE-SW motion and associated stress field date back to at least 165 Ma and possibly as far as 183 Ma (Toarcian-Callovian) [*Leinweber and Jokat*, 2012; *Eagles and König*, 2008].

The early phase of South Atlantic opening sees the emplacement of the Paraná-Etendeka large igneous province, the initial magmatic expression of the Tristan plume, at around 130 Ma [*O'Connor and Duncan*, 1990]. *Torsvik et al.* [2009] have argued that the event constitutes a precursor to seafloor spreading. The

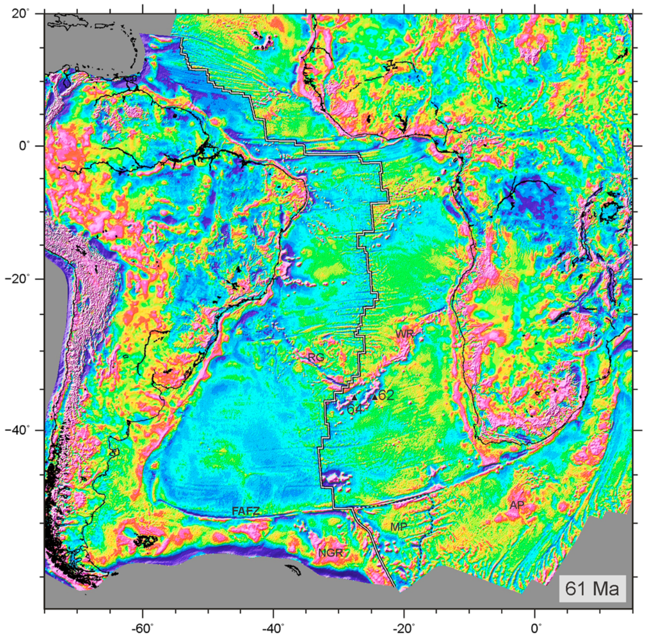

Figure 14. The 61 Ma reconstruction, showing termination of the Malvinas Plate resulting in abandonment of mid-ocean ridge in the Agulhas Basin (centered on 15°W, 50°S) and the South Atlantic reverting to a two-plate system. Data and symbols as in Figures 10 and 13. See text for more details. AP: Agulhas Plateau; FAFZ: Falkland-Agulhas Fracture Zone; MP: Malvinas Plate; NGR: northeast Georgia Rise; RG: Rio Grande Rise; and WR: Walvis Ridge. Small black triangles with numbers: dated occurrences of volcanism on the Walvis Ridge [*O'Connor et al.*, 2012].

enhanced geothermal gradient associated with this volcanism is thought to have been a key factor in hydrocarbon generation in the southern segment of the South Atlantic, most of which occurred during Cretaceous times [*Chaboureau et al.*, 2012].

Between 126 and 123 Ma, the western movement of the assembled Uruguay, Salado, and Colorado blocks results in extensional deformation along the Recôncavo-Tucano-Jatobá basins as well as transpressional-transtensional movements along the Solimões-Amazon-Marajó accommodation zone [*Caputo*, 1991; *De Matos and Brown*, 1992; *Almeida et al.*, 2000; *Costa et al.*, 2001].

Asmus and Ponte [1973] date the most significant deformation episode in the marginal basins of Brazil (Pelotas, Santos, Campos, Espirito Santo, Jequitinhonha, Recôncavo, and Sergipe-Alagoas) to be pre-Aptian, coinciding with our estimated time of seafloor spreading between Gabon and Brazil and the need for intracontinental accommodation north of it. Early Aptian preevaporitic sequences are widespread between the Santos and Sergipe-Alagoas basins (as well as their African conjugates) [*Franks and Nairn*, 1973], indicating restricted lagoon conditions and hypersalinity most likely imposed by local tectonic barriers. Evaporitic deposition continued as the basins widened, with one of the thickest sequences being deposited during upper Aptian times [*Chaboureau et al.*, 2012]. To allow for this thick sequence to be deposited, it is suspected that volcanic and dynamic topography centered on the Walvis Ridge-Rio Grande Rise, and generated in response to the continued presence of the Tristan plume, formed a regional barrier between the northern and southern parts of the evolving South Atlantic Ocean [*Behrmann et al.*, 2011].

4.3. Assembly of Africa (123 to 106 Ma)

By 123 Ma (Figure 10, bottom), activity ceases in the South American accommodation zones and switches to their African counterparts. As noted above, we depict the eastern part of Africa as moving in response to stresses generated in the circuit with the Indian Plate. The fossil oceanic plate boundary in the West Somali Basin is the most obvious link to that circuit, with its western end lying close to the SE end of the Muglad-Anza rift [*Reeves et al.*, 1987]. Spreading ceased in the West Somali Basin at either 125 Ma [*Segoufin and Patriat*, 1980; *Cochran*, 1988] or 134 Ma [*Rabinowitz et al.*, 1983; *Eagles and König*, 2008]. Our animation's depiction of the Muglad-Anza rift is more consistent with the more recent extinction age, but the basin fill's first rift cycle (140–95 Ma) [*McHargue et al.*, 1992] is too loosely constrained to unequivocally support either interpretation. We consider it possible that the early Cretaceous phase of tectonic activity in the West African Rift System (WARS) records the further-field effects of the same stresses and that the later phase was a consequence of South Atlantic spreading-related stresses that rejuvenated the same structures [*Genik*, 1992; *Scotese et al.*, 1988].

As part of this rejuvenation, by mid-Aptian (123 to 118 Ma) our model shows a short-lived plate boundary running along the CASZ and experiencing around 145 km of sinistral strike slip (Ngaoundere lineament) [*Browne and Fairhead*, 1983; *Benkhelil*, 1989; *Fairhead*, 1988; *Genik*, 1992; *Guiraud and Maurin*, 1992]. During upper Albian times, left-lateral strike slip focuses on the northern part of the Benue trough, along with the second, “Atlantic”, phase of development of the Termit basin.

Near the Aptian-Albian transition the accommodating plate boundary moves from the Termit basin to the Iullemeden basin. Extension on the present-day shelf is thus able to focus on the segment of the Gulf of Guinea east of the southern end of this boundary. Marine incursion into the Gulf of Guinea and northeast Brazil basins during late Aptian/early Albian is evidenced by the presence of the first marine sequences in the sedimentary record [*Fairhead and Binks*, 1991; *Basile et al*., 2005].

4.4. Opening of Equatorial and High-Latitude Gateways to the South Atlantic

Figures 11–13 detail how the South Atlantic started to become progressively connected to the Cretaceous world ocean by the opening of gateways at its northern and southern ends in the period 106–97 Ma. In the continental interiors, intracontinental deformation of Africa in response to South Atlantic propagation-related stresses ceased at the beginning of this period. Africa was not assembled in its present form until much later, however, because of extension in the Red Sea, Gulf of Aden, and East African Rift System.

In the far south, the continental eastern end of the Falkland Plateau, at Maurice Ewing Bank, separates from the Agulhas platform at the southern end of the African continental margin at ~106 Ma (Figure 11). Southeast of the separation point, the NE Georgia Rise and Agulhas Plateau are juxtaposed at ~97 Ma (Figure 13, top). Together with Maud Rise on the Antarctic Plate, they form a tight cluster of bathymetric features. All three have been related to excess volcanism, based on drilling results [*Schandl et al*., 1990; *Kristoffersen and LaBrecque*, 1991] or seismic structure [*Parsiegla et al*., 2008]. The clustering at ~97 Ma suggests that they formed as a single Albian-Cenomanian Southern Ocean large igneous province (SOLIP). SOLIP is located nearly 450 km closer to the C34o isochron on the South American Plate than on the African Plate and so may have started to form in the interior of the South American Plate. Furthermore, the width of CNS seafloor in which the Agulhas Plateau is embedded is much greater than its apparent conjugate with the NE Georgia Rise, suggesting that at some point during the CNS the plate boundary jumped toward the South American Plate. The plume head at which SOLIP formed may have been the target for this jump. At 97 Ma, the Bouvet Plume reconstructs to the region beneath SOLIP [*Doubrovine et al*., 2012]. Despite SOLIP having initiated off axis on the South American Plate, the ridge jump means that it would have spent at least some of its lifetime as an on-axis feature, making it potentially analogous to Iceland at the present day. Together with the presence of only Campanian and younger sediments at Maud Rise and the NE Georgia Rise [*Huber and Watkins*, 1992], the analogy suggests that much of SOLIP may have been subaerial for the period ~105–85 Ma. Consequently, the South Atlantic may have remained as a semiconfined basin until Santonian times.

Farther north, the reconstruction suggests that shallow and intermediate-depth water circulation across the equatorial area could have started at 100 Ma (Figure 12), with the development shortly afterward of a deep water gateway between the North and South Atlantic Oceans (Cenomanian-Turonian). These events would have involved, over a period of several million years, continent-continent and then continent-ocean transform motions resulting in the production of sheared continental margins in West Africa and Brazil. Transtensional pull-apart basins can be expected to have formed along both margins, separated by highs that would have acted as structural barriers to deep water exchange. This interpretation finds support in the work of *Wagner and Pletsch* [1999], derived from oceanic drilling off the coast of Ghana and along the Romanche FZ (Ocean Drilling Program Leg 159). They date the early opening stage of the equatorial Atlantic to middle Albian or earlier (as recorded in drill cores by the transition from freshwater lake to marine delta sediments), with midwater exchange taking place during late Albian-early Cenomanian. *Friedrich and Erbacher* [2006], *Friedrich et al*. [2012], and *Murphy and Thomas* [2013] also give geochemical, sedimentological, and faunal evidence for initial shallow water open circulation starting in Albian times.

Figure 12 illustrates a moment of shallow water exchange, following which the gateway widens to a fully open state over the following few million years until Late Cretaceous. *Wagner and Pletsch* [1999] suggest that fully open oceanic conditions were established in the equatorial Atlantic gateway by sometime between Turonian and Danian (94–62 Ma). This might be narrowed somewhat by noting that the smooth migration of the finite rotation pole between chrons VCI and C30 (~91.5–65.5 Ma) implies a period of steady oblique divergence in the equatorial Atlantic. This is also consistent with studies based on stable isotope data, sediment composition, and foraminiferal assemblages that date the opening of the equatorial Atlantic as late

Table 2. Rotation Parameters, Malvinas Plate[a]

	This Study			*Marks and Stock* [2001]		
Age (Ma)	Lon.	Lat.	Ang.	Lon.	Lat.	Ang.
71	−13.32	17.84	3.13	−23.00	25.00	2.90
79	−15.19	20.45	7.14	−17.00	25.00	6.80
84	−17.18	25.38	9.83	−17.00	25.00	9.50
96	−26.79	42.90	16.39	-	-	-

[a] Rotations for the Malvinas Plate with respect to a fixed African Plate.

Turonian to Campanian [*Friedrich and Erbacher*, 2006; *Friedrich et al*., 2012; *Murphy and Thomas*, 2013]. With the ongoing presence of the Tristan plume in the mantle below the central southern Atlantic, however, the Rio Grande Rise-Walvis Ridge pair may have played a role in ongoing restricted water exchange between the North and South Atlantic [*Behrmann et al*., 2011]. Subsidence of the ridge is suggested only to have allowed deep water exchange by early Campanian (83 Ma) times [*Robinson et al*., 2010] or even 65–58 Ma [*Voigt et al*., 2013].

4.5. The Short Life of a Small Plate in the South Atlantic (80 Ma to Present)

Some of the interior basins of Africa reveal evidence for a compressional event in Santonian times (~86–84 Ma). Between 90 and 70 Ma, a pulse of alkaline magmatism affected southern Africa [*Moore et al*., 2008]. It might be argued that the two episodes were responses to a single change in stress regime. The compression event has been related to the initial stages of Alpine convergence at the north of the continent [*Benkhelil*, 1989; *Guiraud et al*., 2005]. Figure 13 shows that an additional influence on the stress field by this time would have been the introduction of shear stress forces on newly formed long-offset transform faults on the equatorial Atlantic plate boundary.

This period also saw the production of the seafloor that gives the best evidence for the action of a separate Malvinas Plate in the Agulhas Basin south of South Africa (Figure 13, bottom). Of the available presentations of this evidence, our model is most consistent with the findings of *Marks and Stock* [2001], who determine the necessity for a Malvinas Plate on the basis of combined magnetic anomaly and FZ orientation data, together with the presence of the abandoned extinct ridge that separated it from the African Plate. They place the onset of the plate's motion to a time between M0 and 34y and its incorporation into the African Plate at chron 27o. Above, we showed evidence for a reorganization of the plate boundary in the Agulhas basin by an ~97 Ma ridge jump or migration toward the site of excess volcanism that built the SOLIP. We envisage that the inception of the Malvinas Plate may have accompanied this change, perhaps in response to local changes in the stress field related to the accompanying shortening of the Falkland-Agulhas FZ.

Our rotations (Table 2) for the Malvinas Plate are based on Marks and Stock's, with small alterations and additions in order to improve the fit of the plate's northern edge to the Falkland-Agulhas fracture zone and to show the onset of its motion within the SOLIP at 96 Ma. Like *Marks and Stock* [2001], we interpret the western boundary of the plate at the Islas Orcadas-Meteor rise seamounts to have accommodated only slight oblique convergence, rather than a destructive boundary at the NE Georgia Rise [*Labrecque and Hayes*, 1979]. At 61 Ma (Figure 14), the Malvinas Plate is incorporated into the African Plate as a result of a farther westward ridge jump along the Falkland-Agulhas FZ and abandonment of the Malvinas-Africa ridge crest in the Agulhas basin [*Marks and Stock*, 2001]. Consequently, South Atlantic opening reverts to being a two-plate divergence process. By 61 Ma the plate divergence rate has also slowed considerably. This may be reflected in the development of a number of new transform faults along the ridge crest. This slowdown coincides with evidence for the arrival of the Deccan plume beneath the Indian-African plate boundary, by which it has been argued that the plume contributed to a slowdown of the African Plate's motion over the mantle at 70–45 Ma, by turning the asthenosphere into an uphill slope [*Cande and Stegman*, 2011; *van Hinsbergen et al*., 2011]. Furthermore, the slowdown of the African Plate with respect to the mantle would have had an effect on the forces acting on transform faults, which would undergo compression. This could have played a role in the very large ridge jump happening along the Falkland-Agulhas FZ, which resulted in the abandonment of the Malvinas-Africa spreading center.

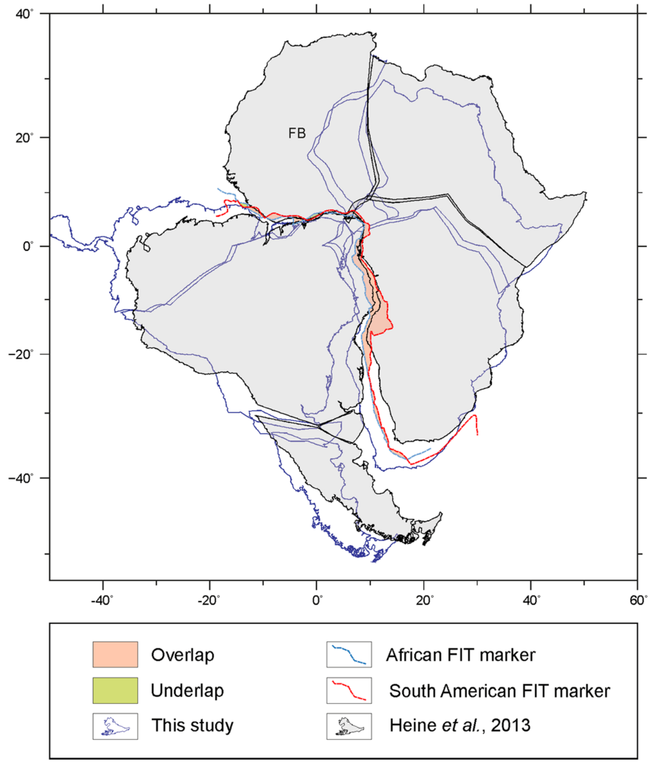

Figure 15. Comparison of full-fit reconstructions of the continents bounding the South Atlantic Ocean produced (i) using our rotations and a subset of continental accommodation zones from Figures 7 and 8 and (ii) by *Heine et al.* [2013] with the assumption that all stress related to the northward propagation of the South Atlantic was expressed in quantified extension of sedimentary basins in a similar set of accommodation zones. FB: Fixed block.

5. Discussion

Despite the variety of geological and geophysical data interpretations of the Cretaceous interior tectonics of South America and Africa (Figures 7 and 8), plate tectonic forward modeling that utilizes these interpretations consistently assumes that all of the continental plate-linked deformation was focused on a small number of narrow fault-bounded belts [e.g., *Nürnberg and Müller*, 1991; *Moulin et al.*, 2010; *Heine et al.*, 2013]. With estimates of the proportion of aseismic strain in broad deforming regions around ~30% [e.g., *Tassone et al.*, 2012], this assumption is clearly unsound. When working forward to plate reconstructions with this assumption, the general failure of the studies to agree on the locations and identities of accommodation zones, and therefore precise margin fits, should come as no surprise.

Similarly, when working toward depicting intracontinental deformation from tightly constrained rotations, as we have done, it is unreasonable to expect that all of the strain implied by plate divergence ought to be depicted in reconstruction overlaps at well-defined basins and tectonic belts. Added to this, a point comes in the consideration of continental deformation, in either direction, at which uncertainty in the existence or kinematics of a deformation zone becomes too large to justify its use as constraints in a reconstruction. Studies that take this approach are therefore all moderated by some reference to the quality, and quantity, of the geological or geophysical information on which accommodation zone interpretations are based. The reconstructions in Figures 10–14 are no exception to the moderation process. They use a relatively small number of accommodation zones that are relatively well known to generate margin fits within our adopted error bounds for the locations of breakup margin segments. They do so by the application of rotations interpolated within the sequence shown in Table 1 and without recourse to ad hoc adjustments to improve those fits. As such, we consider the reconstructions self-consistent and plausible but by no means a definitive picture of the intracontinental strain evolution.

Despite this, the models do offer a starting point for conservative further consideration of the accommodating strain pattern during South Atlantic opening. A wide range of evidence exists for mid-Cretaceous deformation of the continental interiors outside of our chosen accommodation zones, suggesting as one might expect that not all of the stress associated with northward propagation of the South Atlantic Ocean was accommodated in them (Figures 7 and 8). If this were the case, then the motions implied for the zones in Figures 10–14 would tend to be systematic overestimates, as *Moulin et al.* [2010] and *Heine et al.* [2013] noted for accommodation zones used by *Eagles* [2007]. Figure 15 illustrates, and Table 3 quantifies, these overestimates for our model in simple terms with respect to published depictions and estimates of relative motion in the accommodation zones from geological and geophysical indicators. From Table 3, the sedimentary basins in our chosen set of deformation zones account for a maximum of 42–67% of the

Table 3. Comparison of Basin Extension Estimates[a]

Basin Name	Estimated Extension, km/Reference	Model Overlap (km) (This Study)	Proportion Overlap Unaccounted for
Bongor/Doba	31/*Heine et al.* [2013]	136	77%
Termit	60/*Fairhead* [1988]	260	62%
Termit	27–98/*Heine et al.* [2013]		
Bida/Iullemeden	28/*Heine et al.* [2013]	170	83%
Benue Trough	95/*Fairhead* [1988]	26	0%
Benue Trough	10–50/*Unternehr et al.* [1988]		0%
Recôn.-Tucano	27–35/*Milani and Davison* [1988]	125	72–78%
Jatobá	42–65/(ave. of other estimates)	99	28–55%
Colorado	106/*Heine et al.* [2013]	70	0%
Marajó	42–65/(ave. of other estimates)	46	0–2%
Salado	65/*Heine et al.* [2013]	75	0%
TOTAL	426–684	1019	33–58

[a] Muglad Basin does not contribute to totals as we consider it not to have extended in response to South Atlantic-related stresses.

intracontinental extensional strain implied by fits of continental margin segments with the rotations in Table 1. In the following, we refer to the remaining 33–58% as “discrepant extensional strain.”

If all of our model’s discrepant extensional strain were accommodated on a single extra intracontinental deformation zone, then that zone would reconstruct with an overlap implying extension in the region of 336–591 km. Such a feature clearly does not exist, although other narrow deformation zones have been suggested in the literature. Based on typical extension values for the basins in Table 3, the addition of two further narrow zones might account for 100 km of the total overlap implied by the discrepant strain. Candidates might include the fault zones proposed in the Paraná and Chacos basins or the numerous Cretaceous basins of the Borborema Province farther north [*Nürnberg and Müller*, 1991; *Eagles*, 2007; *Torsvik et al.*, 2009; *Moulin et al.*, 2010; *Heine et al.*, 2013; *Von Gosen and Loske*, 2004].

The Transbrasiliano lineament is another feature widely suggested to have accommodated relative plate motion in Cretaceous times, usually by translation of crustal blocks along strike-slip faults [*Pérez-Gussinyé et al.*, 2007; *Moulin et al.*, 2010]. The timing and amount of such motion on the lineament are debated. Most recently, *Heine et al.* [2013] pointed out that no extensional or compressional features have been documented in published geological and geophysical data, as would be expected at restraining and releasing bends and step overs during strike-slip movement along the lineament’s sinuous trace [*Cunningham and Mann*, 2007]. They concluded that the lineament is an unlikely candidate for a “missing” narrow zone of high strain in South America. Similarly, although our rotations suggest that the lineament would have experienced extension across its axis, there is no evidence for concomitant sedimentary basin formation. The presence of Cretaceous kimberlites and other alkaline volcanic centers along the lineament’s length can, on the other hand, be seen as consistent with small degrees of partial melting during limited extensional thinning of the lithosphere [*Sonoki and Garda*, 1988; *Silva et al.*, 1995; *Pereria and Fuck*, 2005; *Kaminsky et al.*, 2009]. Similar interpretations can be made concerning alkaline volcanism along lineaments in South America such as the Ponta Grossa and Ponta Porã arches [*Gomes et al.*, 2011a, 2011b] and Asunción Rift [*Velázquez et al.*, 2011] and in Africa, such as the Lucapa graben [*De Boorder*, 1982; *Pereira et al.*, 2003]. Alkaline melts tend to be related to continental extension at factors of less than 2.0 [*McKenzie and Bickle*, 1988], such that a number of moderate strain features might be evoked to account for more of the discrepant strain. In terms of overlap from discrepant strain, 25 such 20 km wide features on each side of the South Atlantic might account for 100 km at stretching factors of 1.1 or 200 km at stretching factors of 1.2.

At an even finer scale, intraplate seismicity shows that continents undergo slow and slight deformation in response to stress transmitted across them from plate boundaries. The distribution of this seismicity is not confined to prominent preexisting structures and tectonic zones but is instead widely scattered, making it seem likely that large areas of the continents experience strain. South America and Africa in Cretaceous times would have been no different. This notion of distributed deformation is not new in South Atlantic studies but has not been explicitly accounted for [e.g., *Nürnberg and Müller*, 1991]. If the entire overlap due to our determined extensional discrepant strain was evenly distributed through the interiors of the continents bounding the South Atlantic, then each kilometer-wide swath of the continent perpendicular to the plate boundary would have to have stretched by an average of less than 100 m. In assumed 50–150 km wide extended continental margins, the associated distributed stretching factor would be in the region of 1.002–1.0007. Distributed like this, and even more so over a continental-scale deforming region, it is likely that much of the propagation-related strain could remain undetectable without detailed study of individual pre-Cretaceous faults.

These considerations suggest that it is reasonable to hypothesize that stress associated with the northward propagation of the South Atlantic ridge as the South American and African plates formed and separated was accommodated at sites spread throughout the interiors of the two continents, whose specific nature would depend on rheological heterogeneity. The resulting strain is likely to be evident at all scales, with perhaps only a little more than half taken up on narrow, short-lived, prominent plate boundary segments like the WARS or Colorado and Salado basins.

6. Conclusions

Here we present a new plate kinematic model describing the opening history of the South Atlantic from Valanginian to present, as constrained by seafloor spreading features, which overlap with or often predate the breakup process owing to the ocean's strongly diachronous opening. These features are easier to interpret unequivocally for the South Atlantic than are breakup markers found within continent-ocean transition zones. Furthermore, this approach prevents the larger uncertainties in relative plate motions determined from intracontinental tectonic features from propagating long distances into the plate kinematic model.

The model provides a plausible history for the evolution of the South Atlantic Ocean, putting features such as the Vema Channel, Malvinas Plate, NE Georgia Rise, and Agulhas Plateau into context by offering explanations for their formation and evolution, as follows:

1. Continental separation starts at the latest by 138 Ma. During the first stages of opening, intracontinental deformation focuses on South America, leading to opening of the Colorado, Salado, and General Levalle basins. As extension penetrates between Brazil and Gabon, a transpressional-transtensional boundary becomes active through the Amazon-Solimões-Marajó basins. From the assembly of South America at 123 Ma, intracontinental deformation focuses on African deformation belts. Accommodation of South Atlantic propagation-related stresses in the continental interiors ceases at 106 Ma.
2. Shallow and intermediate-depth water exchange across the equatorial Atlantic was possible since 100 Ma, with the development of a deep water gateway over the following few millions of years. Owing to the action of the Tristan plume in the central southern Atlantic, volcanism that built the Rio Grande-Walvis Ridge pair might have played a role in delaying or restricting water exchange until their subsidence.
3. The Agulhas Plateau-NE Georgia Rise and Maud Rise are portrayed as a single large igneous province formed over the Bouvet mantle plume, to which part of the mid-ocean ridge south of the Falkland-Agulhas FZ jumped at ~97 Ma. A further consequence of this ridge jump may have been inception of the short-lived Malvinas Plate in response to changes in the regional stress field brought associated with the changing length of the transform fault on the Falkland-Agulhas FZ.
4. By 61 Ma, a farther westward ridge jump along the Falkland-Agulhas FZ sees the Malvinas Plate cease to move independently. South Atlantic spreading reverts to a two-plate divergence process. This coincides with a slowdown in African Plate motion, which has elsewhere been related to arrival of the Deccan plume beneath its boundary with the Indian plate [*Cande and Stegman*, 2011]. Malvinas Plate extinction may be related to forces transmitted across transform faults in the southern South Atlantic during the slowdown.

Finally, we are able to avoid circularity by analyzing continental extension linked to the northward propagation of seafloor spreading in the South Atlantic without making assumptions about those processes for the purposes of modeling that propagation. Our considerations show that the stresses generated within the surrounding continental interiors during the northward propagation of seafloor spreading seem to have been accommodated not only by movements on narrow continent-wide deformation belts but also by smaller-scale processes approximating distributed deformation.

Acknowledgments
Data for this paper were obtained from NOAA's Marine Geophysical Trackline Database (magnetic anomaly profiles), the Scripps Institution of Oceanography, University of California (free-air gravity data), and the Global Seafloor Fabric and Magnetic Lineation Data Base Project (magnetic anomaly picks). We are grateful to Royal Holloway University of London and the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research for funding. Both authors would like to thank the COMPASS consortium for travel funding support and Jo Whittaker for her constructive and careful review of the manuscript.

References

Almeida, F., B. B. Neves, and C. D. R. Carneiro (2000), The origin and evolution of the South American Platform, *Earth Sci. Rev.*, *50*, 77–111, doi:10.1016/S0012-8252(99)00072-0.

Amante, C., and B. W. Eakins (2009), ETOPO1 1 Arc-minute global relief model: Procedures, data sources and analysis, *NOAA Tech. Memo. NESDIS NGDC-24*, 19 pp., Natl. Geophys. Data Cent., Boulder, Colo.

Aslanian, D., et al. (2009), Brazilian and African passive margins of the Central Segment of the South Atlantic Ocean: Kinematic constraints, *Tectonophysics*, *468*(1–4), 98–112, doi:10.1016/j.tecto.2008.12.016.

Asmus, H. E., and F. C. Ponte (1973), The Brazilian marginal basins, in *The Ocean Basins and Its Margins*, vol. 1, edited by A. E. M. Nairn and F. G. Stehli, pp. 87–133, The South Atlantic, Plenum Press, New York.

Autin, J., et al. (2013), Colorado Basin 3D structure and evolution, Argentine passive margin, *Tectonophysics*, *604*, 264–279, doi:10.1016/j.tecto.2013.05.019.

Baristeas, N., Z. Anka, R. di Primio, J. F. Rodriguez, D. Marchal, and F. Dominguez (2013), New insights into the tectono-stratigraphic evolution of the Malvinas Basin, offshore of the southernmost Argentinean continental margin, *Tectonophysics*, *604*, 280–295, doi:10.1016/j.tecto.2013.06.009.

Basile, C., J. Mascle, and R. Guiraud (2005), Phanerozoic geological evolution of the Equatorial Atlantic domain, *J. Afr. Earth Sci.*, *43*(1–3), 275–282, doi:10.1016/j.jafrearsci.2005.07.011.

Bauer, K., S. Neben, B. Schreckenberger, R. Emmermann, K. Hinz, N. Fechner, K. Gohl, A. Schulze, R. B. Trumbull, and K. Weber (2000), Deep structure of the Namibia continental margin as derived from integrated geophysical studies, *J. Geophys. Res.*, *105*, 25,829–25,853, doi:10.1029/2000JB900227.

Behrmann, J. H., A. Shulgin, and A. Prokoph (2011), High resolution bathymetric survey on the NW slope of Walvis Ridge, offshore Namibia, in *Berichte der Naturforschenden Gesellschaft zu Freiburg i*, pp. 97–110, Breisgau. Aedificatio-Verlag, Freiburg.

Benkhelil, J. (1989), The origin and evolution of the Cretaceous Benue Trough (Nigeria), *J. Afr. Earth. Sci.*, *8*(2–4), 251–282, doi:10.1016/S0899-5362(89)80028-4.

Bransden, P. J. E., P. Burges, M. J. Durham, and J. G. Hall (1999), Evidence for multi-phase rifting in the North Falklands Basin, *Geol. Soc. London, Spec. Pubs.*, *153*(1), 425–443, doi:10.1144/GSL.SP.1999.153.01.26.

Brown, L. F. (1995), Sequence Stratigraphy in offshore South African divergent basins, in *AAPG Studies in Geology*, vol. 41, 184 pp., Am. Assoc. Petrol. Geol., Tulsa, Okla.

Browne, S., and J. Fairhead (1983), Gravity study of the Central African Rift System: A model of continental disruption 1. The Ngaoundere and Abu Gabra rifts, *Tectonophysics*, *94*, 187–203, doi:10.1016/0040-1951(83)90016-1.

Brune, S., A. A. Popov, and S. V. Sobolev (2012), Modeling suggests that oblique extension facilitates rifting and continental break-up, *J. Geophys. Res.*, *117*, B08402, doi:10.1029/2011JB008860.

Bullard, E., J. E. Everett, and A. G. Smith (1965), The fit of the continents around the Atlantic, *Philos. Trans. R. Soc. London A: Mathematical, Physical and Engineering Sciences*, *258*(1088), 41–51.

Burke, K. (1976), Development of graben associated with initial ruptures of the Atlantic Ocean, in *Sedimentary Basins of Continental Margins and Cratons*, edited by M. H. P. Bott, *Tectonophysics*, *36*, 93–112.

Burke, K., and J. Dewey (1974), Two plates in Africa during the Cretaceous?, *Nature*, *249*, 313–316, doi:10.1038/249313a0.

Burke, K., T. Dessauvagie, and A. Whiteman (1971), Opening of the Gulf of Guinea and geological history of the Benue depression and Niger delta, *Nature*, *233*, 51–55, doi:10.1038/physci233051a0.

Bushnell, D. C., J. E. Baldi, F. H. Bettini, H. Franzin, E. Kovas, R. Marinelli, and G. J. Wartenburg (2000), Petroleum systems analysis of the eastern Colorado Basin, offshore northern Argentina, in *Petroleum Systems of South Atlantic Margins*, edited by M. R. Mello and B. J. Katz, *Mem. Am. Assoc. Petrol. Geol.*, *73*, 403–415.

Cande, S. C., and D. R. Stegman (2011), Indian and African Plate motions driven by the push force of the Reunion plume head, *Nature*, *475*, 47–52, doi:10.1038/nature10174.

Cande, S. C., J. L. Labrecque, and W. F. Haxby (1988), Plate kinematics of the South Atlantic: Chron C34 to present, *J. Geophys. Res.*, *93*, 13,479–13,492, doi:10.1029/JB093iB11p13479.

Caputo, M. V. (1991), Solimões megashear: Intraplate tectonics in northwestern Brazil, *Geology*, *19*(3), 246–249, doi:10.1130/0091-7613(1991)019<0246:SEMITI>2.3.CO;2.

Castro, A. C., Jr. (1987), The northeastern Brazil and Gabon basins: A double rifting system associated with multiple crustal detachment surfaces, *Tectonics*, *6*, 727–738, doi:10.1029/TC006i006p00727.

Chaboureau, A.-C., Y. Donnadieu, P. Sepulchre, C. Robin, F. Guillocheau, and S. Rohais (2012), The Aptian evaporites of the South Atlantic: A climatic paradox?, *Clim. Past*, *8*(3), 1047–1058, doi:10.5194/cp-8-1047-2012.

Cochran, J. R. (1988), Somali Basin, Chain Ridge, and origin of the Northern Somali Basin gravity and geoid low, *J. Geophys. Res.*, *93*, 11,985–12,008, doi:10.1029/JB093iB10p11985.

Costa, J., R. L. Bemerguy, Y. Hasui, and M. da Silva Borges (2001), Tectonics and paleogeography along the Amazon River, *J. South Am. Earth Sci.*, *14*, 335–347, doi:10.1016/S0895-9811(01)00025-6.

Coulon, C., P. Vidal, and C. Dupuy (1996), The Mesozoic to early Cenozoic magmatism of the Benue Trough (Nigeria): Geochemical evidence for the involvement of the St. Helena plume, *J. Petrol.*, *37*(6), 1341–1358, doi:10.1093/petrology/37.6.1341.

Cunningham, W. D., and P. Mann (2007), Tectonics of strike-slip restraining and releasing bends, *Geol. Soc. London Spec. Publ.*, *290*(1), 1–12, doi:10.1144/SP290.1.

Davison, I. (1997), Wide and narrow margins of the Brazilian South Atlantic, *J. Geol. Soc.*, *154*, 471–476, doi:10.1144/gsjgs.154.3.0471.

De Boorder, H. (1982), Deep-reaching fracture zones in the crystalline basement surrounding the West Congo System and their control of mineralization in Angola and Gabon, *Geoexploration*, *20*, 259–273, doi:10.1016/0016-7142(82)90025-4.

De Matos, R. M. D., and L. D. Brown (1992), Deep seismic profile of the Amazonian craton [northern Brazil], *Tectonics*, *11*, 621–633, doi:10.1029/91TC03091.

Doubrovine, P. V., B. Steinberger, and T. H. Torsvik (2012), Absolute plate motions in a reference frame defined by moving hot spots in the Pacific, Atlantic, and Indian oceans, *J. Geophys. Res.*, *117*, B09101, doi:10.1029/2011JB009072.

Eagles, G. (2004), Tectonic evolution of the Antarctic-Phoenix plate system since 15 Ma, *Earth Planet. Sci. Lett.*, *217*, 97–109, doi:10.1016/S0012-821X(03)00584-3.

Eagles, G. (2007), New angles on South Atlantic opening, *Geophys. J. Int.*, *168*(1), 353–361, doi:10.1111/j.1365-246X.2006.03206.x.

Eagles, G. (2010), The age and origin of the central Scotia Sea, *Geophys. J. Int.*, *183*(2), 587–600, doi:10.1111/j.1365-246X.2010.04781.x.

Eagles, G., and M. König (2008), A model of plate kinematics in Gondwana breakup, *Geophys. J. Int.*, *173*(2), 703–717, doi:10.1111/j.1365-246X.2008.03753.x.

Eagles, G., and A. P. M. Vaughan (2009), Gondwana breakup and plate kinematics: Business as usual, *Geophys. Res. Lett.*, *36*, L10302, doi:10.1029/2009GL037552.

Fairhead, J. D. (1988), Mesozoic plate tectonic reconstructions of the central South Atlantic Ocean: The role of the West and Central African rift system, *Tectonophysics*, *155*(1–4), 181–191, doi:10.1016/0040-1951(88)90265-X.

Fairhead, J., and R. Binks (1991), Differential opening of the Central and South Atlantic Oceans and the opening of the West African rift system, *Tectonophysics*, *187*, 191–203, doi:10.1016/0040-1951(91)90419-S.

Fitton, J. G. (1980), The Benue trough and Cameroon line—A migrating rift system in West Africa, *Earth Planet. Sci. Lett.*, *51*(1), 132–138, doi:10.1016/0012-821X(80)90261-7.

Font, E., M. Ernesto, P. F. Silva, P. B. Correia, and M. A. L. Nascimento (2009), Palaeomagnetism, rock magnetism and AMS of the Cabo Magmatic Province, NE Brazil, and the opening of South Atlantic, *Geophys. J. Int.*, *179*(2), 905–922, doi:10.1111/j.1365-246X.2009.04333.x.

Franke, D., S. Neben, B. Schreckenberger, A. Schulze, M. Stiller, and M. Krawczyk (2006), Crustal structure across the Colorado Basin, offshore Argentina, *Geophys. J. Int.*, *165*(3), 850–864, doi:10.1111/j.1365-246X.2006.02907.x.

Franks, S., and A.-E.-M. Nairn (1973), The equatorial marginal basins of West Africa, in *The Ocean Basins and Its Margins*, vol. 1, edited by A. E. M. Nairn and F. G. Stehli, pp. 301–350, The South Atlantic Plenum Press, New York.

Friedrich, O., and J. Erbacher (2006), Benthic foraminiferal assemblages from Demerara Rise (ODP Leg 207, western tropical Atlantic): Possible evidence for a progressive opening of the Equatorial Atlantic Gateway, *Cretaceous Res.*, *27*(3), 377–397, doi:10.1016/j.cretres.2005.07.006.

Friedrich, O., R. D. Norris, and J. Erbacher (2012), Evolution of middle to Late Cretaceous oceans—A 55 m.y. record of Earth's temperature and carbon cycle, *Geology*, *40*, 107–110, doi:10.1130/G32701.1.

Genik, G. J. (1992), Regional framework, structural and petroleum aspects of rift basins in Niger, Chad and the Central African Republic (CAR), *Tectonophysics*, *213*(1–2), 169–185, doi:10.1016/0040-1951(92)90257-7.

Gomes, C. B., E. Ruberti, P. Comin-Chiaramonti, and R. G. Azzone (2011a), Alkaline magmatism in the Ponta Grossa Arch, SE Brazil: A review, *J. South Am. Earth Sci.*, *32*, 152–168, doi:10.1016/j.jsames.2011.05.003.

Gomes, C. B., V. F. Velázquez, R. G. Azzone, and G. S. Paula (2011b), Alkaline magmatism in the Amambay area, NE Paraguay: The Cerro Sarambí complex, *J. South Am. Earth Sci.*, *32*, 75–95, doi:10.1016/j.jsames.2011.04.004.

Gradstein, F. M., et al. (2004), *A Geologic Time Scale*, Cambridge Univ. Press, Cambridge, U. K.

Guiraud, R., and J.-C. Maurin (1992), Early Cretaceous rifts of Western and Central Africa: An overview, *Tectonophysics*, *213*(1–2), 153–168, doi:10.1016/0040-1951(92)90256-6.

Guiraud, R., M. Doumnang, S. Carretier, and S. Dominguez (2000), Evidence for a 6000 km length NW-SE-striking lineament in northern Africa: The TIbesti lineament, *J. Geol. Soc.*, *157*, 897–900, doi:10.1144/jgs.157.5.897.

Guiraud, R., W. Bosworth, J. Thierry, and A. Delplanque (2005), Phanerozoic geological evolution of Northern and Central Africa: An overview, *J. African Earth Sci.*, *43*, 83–143, doi:10.1016/j.jafrearsci.2005.07.017.

Heine, C., and S. Brune (2014), Oblique rifting of the Equatorial Atlantic: Why there is no Saharan Atlantic Ocean, *Geology*, *42*, 211–214, doi:10.1130/G35082.1.

Heine, C., J. Zoethout, and R. D. Müller (2013), Kinematics of the South Atlantic rift, *Solid Earth Discuss.*, *5*(1), 41–116, doi:10.5194/sed-5-41-2013.

Huber, B. T., and D. K. Watkins (1992), Biogeography of Campanian-Maastrichtian calcareous plankton in the region of the Southern Ocean: Paleogeographic and paleoclimatic implications, in *The Antarctic Paleoenvironment: A Perspective on Global Change*, *Antarct. Res. Ser.*, vol. 56, edited by J. P. Kennett and D. A. Warnke, pp. 31–60, AGU, Washington, D. C.

Jacques, 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. London*, *160*, 703–717, doi:10.1144/0016-764902-089.

Jungslager, E. H. A. (1999), Petroleum habitats of the Atlantic margin of South Africa, in *The Oil and Gas Habitats of the South Atlantic*, edited by N. R. Cameron, R. H. Bate, and V. S. Clure, *Geol. Soc. London Spec. Publ.*, *153*, 153–168.

Kaminsky, F. V., S. M. Sablukov, S. I. Sablukova, and O. D. Zakharchenko (2009), The Fazenda Largo off-craton kimberlites of Piauí State, Brazil, *J. South Am. Earth Sci.*, *28*, 288–303.

König, M., and W. Jokat (2006), The Mesozoic breakup of the Weddell Sea, *J. Geophys. Res.*, *111*, B12102, doi:10.1029/2005JB004035.

Kristoffersen, Y., and J. LaBrecque (1991), On the tectonic history and origin on the Northeast Georgia Rise, *Proc. ODP Sci. Results*, *114*, 23–38.

Labrecque, J. L., and D. E. Hayes (1979), Seafloor spreading history of the Agulhas Basin, *Earth Planet. Sci. Lett.*, *45*(2), 411–428, doi:10.1016/0012-821X(79)90140-7.

Leinweber, V. T., and W. Jokat (2012), The Jurassic history of the Africa-Antarctica corridor—New constraints from magnetic data on the conjugate continental margins, *Tectonophysics*, *530–531*, 87–101, doi:10.1016/j.tecto.2011.11.008.

Light, M. P. R., M. P. Maslanyj, R. J. Greenwood, and N. L. Banks (1993), Seismic sequence stratigraphy and tectonics offshore Namibia, *Geol. Soc. London Spec. Publ.*, *71*, 163–191, doi:10.1144/GSL.SP.1993.071.01.08.

Livermore, R. A., A. P. Nankivell, G. Eagles, and P. Morris (2005), Paleogene opening of Drake Passage, *Earth Planet. Sci. Lett.*, *236*, 459–470, doi:10.1016/j.epsl.2005.03.027.

Loule, J.-P., and L. Pospisil (2013), Geophysical evidence of Cretaceous volcanics in Logone Birni Basin (Northern Cameroon), Central Africa, and consequences for the West and Central African Rift System, *Tectonophysics*, *583*, 88–100, doi:10.1016/j.tecto.2012.10.021.

Macdonald, D., et al. (2003), Mesozoic break-up of SW Gondwana: Implications for regional hydrocarbon potential of the southern South Atlantic, *Mar. Pet. Geol.*, *20*(3–4), 287–308, doi:10.1016/S0264-8172(03)00045-X.

Marks, K. M., and J. M. Stock (2001), Evolution of the Malvinas Plate south of Africa, *Mar. Geophys. Res.*, *22*(4), 289–302, doi:10.1023/A:1014638325616.

McHargue, T. R., T. L. Heidrick, and J. E. Livingston (1992), Tectonostratigraphic development of the Interior Sudan rifts Central Africa, *Tectonophysics*, *213*, 187–202, doi:10.1016/0040-1951(92)90258-8.

McKenzie, D., and M. J. Bickle (1988), The volume and composition of melt generated by extension of the lithosphere, *J. Petrol.*, *29*, 625–679, doi:10.1093/petrology/29.3.625.

Milani, E., and I. Davison (1988), Basement control and transfer tectonics in the Recôncavo-Tucano-Jatobá rift, northeast Brazil, *Tectonophysics*, *154*, 41–70, doi:10.1016/0040-1951(88)90227-2.

Moore, A., T. Blenkinsop, and F. Cotterill (2008), Controls on post-Gondwana alkaline volcanism in Southern Africa, *Earth Planet. Sci. Lett.*, *268*(1–2), 151–164, doi:10.1016/j.epsl.2008.01.007.

Moulin, M., D. Aslanian, and P. Unternehr (2010), A new starting point for the South and Equatorial Atlantic Ocean, *Earth Sci. Rev.*, *98*(1–2), 1–37, doi:10.1016/j.earscirev.2009.08.001.

Murphy, D. P., and D. J. Thomas (2013), The evolution of Late Cretaceous deep-ocean circulation in the Atlantic basins: Neodymium isotope evidence from South Atlantic drill sites for tectonic controls, *Geochem. Geophys. Geosyst.*, *14*, 1–18, doi:10.1002/2013GC004889.

Nankivell, A. P. (1997), Tectonic Evolution of the Southern Ocean between Antarctica, South America and Africa over the last 84 Ma, PhD thesis, Oxford Univ., Oxford, U. K.

Ngako, V., E. Njonfang, F. T. Aka, P. Affaton, and J. M. Nnange (2006), The North-South Paleozoic to Quaternary trend of alkaline magmatism from Niger-Nigeria to Cameroon: Complex interaction between hotspots and Precambrian faults, *J. African Earth Sci.*, *45*(3), 241–256, doi:10.1016/j.jafrearsci.2006.03.003.

Nürnberg, D., and R. D. Müller (1991), The tectonic evolution of the South Atlantic from Late Jurassic to present, *Tectonophysics*, *191*(1–2), 27–53, doi:10.1016/0040-1951(91)90231-G.

O'Connor, J. M., and R. A. Duncan (1990), Evolution of the Walvis Ridge-Rio Grande Rise Hot Spot System: Implications for African and South American Plate motions over plumes, *J. Geophys. Res.*, *95*, 17,475–17,502, doi:10.1029/JB095iB11p17475.

O'Connor, J. M., et al. (2012), Hotspot trails in the South Atlantic controlled by plume and plate tectonic processes, *Nat. Geosci.*, *5*(10), 735–738, doi:10.1038/ngeo1583.

Olade, M. A. (2009), Evolution of Nigeria's Benue Trough (Aulacogen): A tectonic model, *Geol. Mag.*, *112*(06), 575, doi:10.1017/S001675680003898X.

Pángaro, F., and V. Ramos (2012), Paleozoic crustal blocks of onshore and offshore central Argentina: New pieces of the southwestern Gondwana collage and their role in the accretion of Patagonia and the evolution of Mesozoic south Atlantic sedimentary basins, *Mar. Pet. Geol.*, *37*(1), 162–183, doi:10.1016/j.marpetgeo.2012.05.010.

Parsiegla, N., K. Gohl, and G. Uenzelmann-Neben (2008), The Agulhas Plateau: Structure and evolution of a large igneous province, *Geophys. J. Int.*, *174*(1), 336–350, doi:10.1111/j.1365-246X.2008.03808.x.

Pereira, E., J. Rodrigues, and B. Reis (2003), Synopsis of Lunda geology, NE Angola: Implications for diamond exploration, *Comun. Inst. Geol. E Mineiro*, *90*, 189–212.

Pereria, R. S., and R. A. Fuck (2005), Archean nuclei and the distribution of kimberlite and related rocks in the São Francisco Craton, Brazil, *Revista Brasileira de Geociências*, *35*, 93–104.

Pérez-Gussinyé, M., A. R. Lowry, and A. B. Watts (2007), Effective elastic thickness of South America and its implications for intracontinental deformation, *Geochem. Geophys. Geosyst.*, *8*, Q05009, doi:10.1029/2006GC001511.

Pindell, J., and J. F. Dewey (1982), Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico and Caribbean region, *Tectonics*, *1*(2), 179–211, doi:10.1029/TC001i002p00179.

Rabinowitz, P. D., and J. LaBrecque (1979), The Mesozoic South Atlantic Ocean and evolution of its continental margins, *J. Geophys. Res.*, *84*, 5973–6002, doi:10.1029/JB084iB11p05973.

Rabinowitz, P. D., M. F. Coffin, and D. Falvey (1983), The separation of Madagascar and Africa, *Science*, *220*, 67–69, doi:10.1126/science.220.4592.67.

Reeves, C. V., F. M. Karanja, and I. N. MacLeod (1987), Geophysical evidence for a failed Jurassic rift and triple-junction in Kenya, *Earth Planet. Sci. Lett.*, *81*(2–3), 299–311, doi:10.1016/0012-821X(87)90166-X.

Richards, P. C., and N. G. T. Fannin (1997), Geology of the North Falkland Basin, *J. Pet. Geol.*, *20*, 165–183, doi:10.1111/j.1747-5457.1997.tb00771.x.

Robinson, S. A., D. P. Murphy, D. Vance, and D. J. Thomas (2010), Formation of 'Southern Component Water' in the Late Cretaceous: Evidence from Nd-isotopes, *Geology*, *38*(10), 871–874, doi:10.1130/G31165.1.

Robles-Cruz, S. E., J. C. Melgarejo, S. Galí, and M. Escayola (2012), Major and trace-element compositions of indicator minerals that occur as Macro- and Megacrysts, and of xenoliths, from kimberlites in Northeastern Angola, *Minerals*, (2)*4*, 318–337, doi:10.3390/min2040318.

Roux, J. (1997), Potential outlined in Southern Outeniqua Basin off South Africa, *Oil Gas J.*, *21*, 87–91.

Sandwell, D. T., and W. H. F. Smith (2009), Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge segmentation versus spreading rate, *J. Geophys. Res.*, *114*, B01411, doi:10.1029/2008JB006008.

Schandl, E. S., M. P. Gorton, and F. J. Wicks (1990), Mineralogy and geochemistry of alkali basalts from Maud Rise, Weddell Sea, Antarctica, in *Proceedings ODP, Science Results*, vol. 113, edited by P. F. Barker *et al*., pp. 5–14, Ocean Drilling Program, College Station, Tex.

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

Scotese, C. R., L. M. Gahagan, and R. L. Larson (1988), Plate tectonic reconstructions of the Cretaceous and Cenozoic ocean basins, *Tectonophysics*, *155*(1–4), 27–48, doi:10.1016/0040-1951(88)90259-4.

Segoufin, J., and P. Patriat (1980), Existence d'anomalies mésozoiques dans le basin de Somalie: Implication pour les relations Afrique-Antarctique-Madagascar, *C. R. Acad. Sci.*, *291*, 85–88.

Shaw, P. R., and S. C. Cande (1990), High-resolution inversion for South Atlantic plate kinematics using joint altimeter and magnetic anomaly data, *J. Geophys. Res.*, *95*, 2625–2644, doi:10.1029/JB095iB03p02625.

Shemang, E. M., C. O. Ajayi, and W. R. Jacoby (2001), A magmatic failed rift beneath the Gongola arm of the upper Benue trough, Nigeria?, *J. Geodyn.*, *32*(3), 355–371, doi:10.1016/S0264-3707(01)00034-5.

Silva, A. M., F. Chemale Jr., R. M. Kuyumjian, and L. Heaman (1995), Mafic dyke swarms of Quadrilátero Ferrífero and southern Espinhaço Minas Gerais, Brazil, *Revista Brasileira de Geociências*, *25*, 124–137.

Sonoki, I. K., and G. M. Garda (1988), K-Ar ages of alkaline rocks from southern Brazil and eastern Paraguay: Compilation and adaptation to new decay constants, *Boletim IG-USP Série Científica*, *19*, 63–85.

Tankard, A. J., et al. (1995), Structural and tectonic controls of basin evolution in southwestern Gondwana during the Phanerozoic, in *Petroleum Basins of South America*, edited by A. J. Tankard, S. Suarez, and H. J. Welsink, *Mem. Am. Assoc. Pet. Geol.*, *62*, 5–52.

Tassone, T. R., S. P. Holford, R. R. Hillis, and A. K. Tuitt (2012), Quantifying Neogene plate-boundary controlled uplift and deformation of the southern Australian margin, *Geol. Soc. London Spec. Publ.*, *367*, 91–110, doi:10.1144/SP367.7.

Torsvik, T. H., S. Rousse, C. Labails, and M. A. Smethurst (2009), A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin, *Geophys. J. Int.*, *177*(3), 1315–1333, doi:10.1111/j.1365-246X.2009.04137.x.

Unternehr, P., D. Curie, J. L. Olivet, J. Goslin, and P. Beuzart (1988), South Atlantic fits and intrastate boundaries in Africa and South America, *Tectonophysics*, *155*, 169–179, doi:10.1016/0040-1951(88)90264-8.

Unternehr, P., G. Péron-Pinvidic, G. Manatschal, and E. Sutra (2010), Hyper-extended crust in the South Atlantic: In search of a model, *Pet. Geosci.*, *16*, 207–215, doi:10.1144/1354-079309-904.

Urien, C. M., and J. J. Zambrano (1973), The geology of the basins of the Argentine continental margin and Malvinas Plateau, in *The Ocean Basins and Its Margins*, vol. 1, edited by A. E. M. Nairn and F. G. Stehli, pp. 301–350, The South Atlantic Plenum Press, New York, doi:10.1007/978-1-4684-3030-1_4.

Van Hinsbergen, D. J. J., B. Steinberger, P. V. Doubrovine, and R. Gassmöller (2011), Acceleration and deceleration of India-Asia convergence since the Cretaceous: Roles of mantle plumes and continental collision, *J. Geophys. Res.*, *116*, B06101, doi:10.1029/2010JB008051.

Velázquez, V. F., C. Riccomini, C. D. B. Gomes, and J. Kirk (2011), The Cretaceous alkaline dyke swarm in the central segment of the Asunción Rift, Eastern Paraguay: Its regional distribution, mechanism of emplacement, and tectonic significance, *J. Geol. Res.*, *2011*, 1–18, doi:10.1155/2011/946701.

Voigt, S., et al. (2013), Tectonically restricted deep-ocean circulation at the end of the Cretaceous greenhouse, *Earth Planet. Sci. Lett.*, *369–370*, 169–177, doi:10.1016/j.epsl.2013.03.019.

Von Gosen, W., and W. Loske (2004), Tectonic history of the Calcatapul Formation, Chubut province, Argentina, and the "Gastre fault system", *J. South Am. Earth Sci.*, *18*(1), 73–88, doi:10.1016/j.jsames.2004.08.007.

Wagner, T., and T. Pletsch (1999), Tectono-sedimentary controls on Cretaceous black shale deposition along the opening Equatorial Atlantic Gateway (ODP Leg 159), *Geol. Soc. London Spec. Publ.*, *153*(1), 241–265, doi:10.1144/GSL.SP.1999.153.01.15.

Watts, A. B., and J. D. Fairhead (1999), A process-oriented approach to modelling the gravity signature of continental margins, *Leading Edge*, *18*, 258–263.

Webster, R. E., G. A. Chebli, and J. F. Fisher (2004), General Levalle basin, Argentina: A frontier lower Cretaceous rift basin, *Am. Assoc. Petrol. Geol. Bull.*, *88*(5), 627–652, doi:10.1306/01070403014.

Wessel, P., and W. H. F. Smith (1998), New, improved version of generic mapping tools released, *Eos Trans. AGU*, *79*(47), 579, doi:10.1029/98EO00426.

Williams, S. E., J. M. Whittaker, and R. D. Müller (2011), Full-fit, palinspastic reconstruction of the conjugate Australian-Antarctic margins, *Tectonics*, *30*, TC6012, doi:10.1029/2011TC002912.