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The tectonic evolution of the South Atlantic from Late Jurassic to present

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ABSTRACT

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An improved tectonic database for the South Atlantic has been compiled by combining magnetic anomaly, Geosat altimetry, and onshore geologic data. We used this database to obtain a revised plate-kinematic model. Starting with a new fit-reconstruction for the continents around the South Atlantic, we present a high-resolution isochron map from Chron M4 to present.

Fit reconstructions of South America and Africa that require rigid continental plates result in substantial misfits either in the southern South Atlantic or in the equatorial Atlantic. To achieve a fit without gaps, we assume a combination of complex rift and strike-slip movements: (1) along the South American Parana–Chacos Basin deformation zone, (2) within marginal basins in South America (Salado, Colorado Basin), and (3) along the Benue Trough/Niger Rift system in Africa. These faults are presumed to have been active before or during the breakup of the continents.

Our model describes a successive "unzipping" of rift zones starting in the southern South Atlantic. Between 150 Ma (Tithonian) and approximately 130 Ma (Hauterivian), rifting propagated to 38°S, causing tectonic movements within the Colorado and Salado basins. Subsequently, between 130 Ma and Chron M4 (126.5 Ma), the tip of the South Atlantic rift moved to 28°S, resulting in intracontinental deformation along the Parana–Chacos Basin deformation zone. Between Chron M4 and Chron MO (118.7 Ma) rifting propagated into the Benue Trough and Niger Rift, inducing rift and strike-slip motion. After Chron MO, the equatorial Atlantic began to open, while rifting and strike-slip motion still occurred in the Benue Trough and Niger Rift. Since Chron 34 (84 Ma), the opening of the South Atlantic is characterized by simple divergence of two rigid continental plates.

Introduction

No plate tectonic model has been published to date that describes the opening of the South Atlantic from fit position to present day. A large number of fit reconstructions have been proposed (e.g., Bullard et al., 1965; Rabinowitz and LaBrecque, 1979; Pindell and Dewey, 1982; Unternehr et al., 1988). Only few plate models for the early opening history of the South Atlantic to present day have been published. Dickson et al. (1968) constructed the first isochrons for the South Atlantic. Ladd (1974) determined the relative motion of South America with respect to Africa from Early Cretaceous to present day from the magnetic anomaly pattern. Ladd's isochrons for the South Atlantic were improved by Larson et al. (1985), who incorporated Seasat altimetry data in addition to the magnetic anomalies to determine ridge crest offsets and locations of poorly known fracture zones.

Here, we present a revised plate tectonic model for the South Atlantic from fit reconstruction to present day that includes a review of the Triassic/Jurassic continental tectonic development of Africa and South America significant for the early

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breakup history. Previous fit reconstructions of the continents around the South Atlantic, which assumed rigid plates for South America and Africa, result in substantial misfits either in the southernmost South Atlantic or in the equatorial Atlantic. The assumption of a combination of complex rift and strike-slip motions within the African and the South American plates during breakup improves the fit of the continents around the South Atlantic and implies a northward propagating rift starting in the southernmost South Atlantic.

The subsequent relative motion history between South America and Africa is derived from a recent compilation of magnetic anomaly picks in the South Atlantic (Cande et al., 1988; Rabinowitz and LaBrecque, 1979; Barker, 1979; Martin et al., 1982). Ages of magnetic anomalies were taken from the timescale of Kent and Gradstein (1986). Satellite altimetry data, in addition, provide useful constraints for determining the position and the direction of fracture zone lineaments and allow to evaluate finite rotation poles by comparing the strike of lineations in the short wavelength gravity field with small circles calculated from stage poles.

Tectonic setting

The bathymetric chart (Gebco) (see Fig. 2) shows all major bathymetric features in the South Atlantic. The depth increases fairly symmetrically from the Mid-Atlantic ridge to both African and South American sides, interrupted by the Rio Grande Rise, the Walvis Ridge, the Meteor Rise, the Islas Orcadas Rise, Ascension and Discovery Island. The Argentine, Brazil, Cape, and Angola basins are the deepest areas in the South Atlantic exhibiting the greatest sediment thicknesses of max. 6000 m.

The opening of the South Atlantic is characterized by simple divergence of the African and South American plates, which are separated at the Mid-Atlantic ridge and have passive continental margins. Both the oceanic parts of the South American and African plates came into existence during the initial phase of seafloor spreading in the Early Cretaceous, since the oldest clearly identifiable magnetic anomaly on oceanic crust of both plates is M4 (126.5 Ma). Rabinowitz and LaBrecque (1979) identified older anomalies back to anomaly M12 (135.6 Ma) on the continental shelves of Africa and South America, assuming the generation of large basalt flows on continental crust during the initial stage of rifting.

From the Late Cretaceous to the present, the spreading history of the South Atlantic is defined fairly well (Cande et al., 1988). However, the older oceanic crust created during the Cretaceous Quiet Period (around 118.7 Ma to 84 Ma) has no magnetic signature. By means of satellite altimetry data, Cande et al. (1988) traced fracture zones over large distances. Major fracture zones appear to be double (Ascension Fz., Bode Verde Fz.), triple (Rio de Janeiro Fz.), or even quadruple (Rio Grande Fz.) offset fracture zones (Cande et al., 1988). According to these authors, there is an increase in the number and amplitude of fracture zone anomalies in Seasat altimeter data during the period of slow spreading between Chron 30 and Chron 23. Correspondingly, the number of fracture zones is decreasing during times of fast spreading.

The most obvious ridge crest jump in the South Atlantic occurred along the Falkland/Agulhas Fracture Zone (FAFZ). Magnetic anomaly picks from Chron M10 to Chron M0 time, identified in the Natal Valley (Martin et al., 1982), are offset by 1400 km from their equivalents in the southern Cape Basin. The location and orientation of these picks and their counterparts in the Georgia Basin indicate that the South Atlantic spreading system extends about 600 km south of the FAFZ from its inception (Barker, 1979). According to Barker (1979), the original offset of the ridge crest was eliminated by three westward ridge crest jumps creating narrow rough-topped ridges (Meteor Rise, Islas Orcadas Rise, Agulhas Plateau).

A second prominent ridge crest jump took place south of the Rio Grande Rise (LaBrecque and Brozena, in press), leaving a 200 km long fossil spreading center at Chron 32 time (Cande et al., 1988). After Chron 32, this spreading center jumped eastward. According to LaBrecque and Gorini (in prep.) the Serra Geral–Rio Grande hot spot trail is characterized by three major periods of volcanic effusion. Each volcanic event was followed by rift propagation events, the latest of

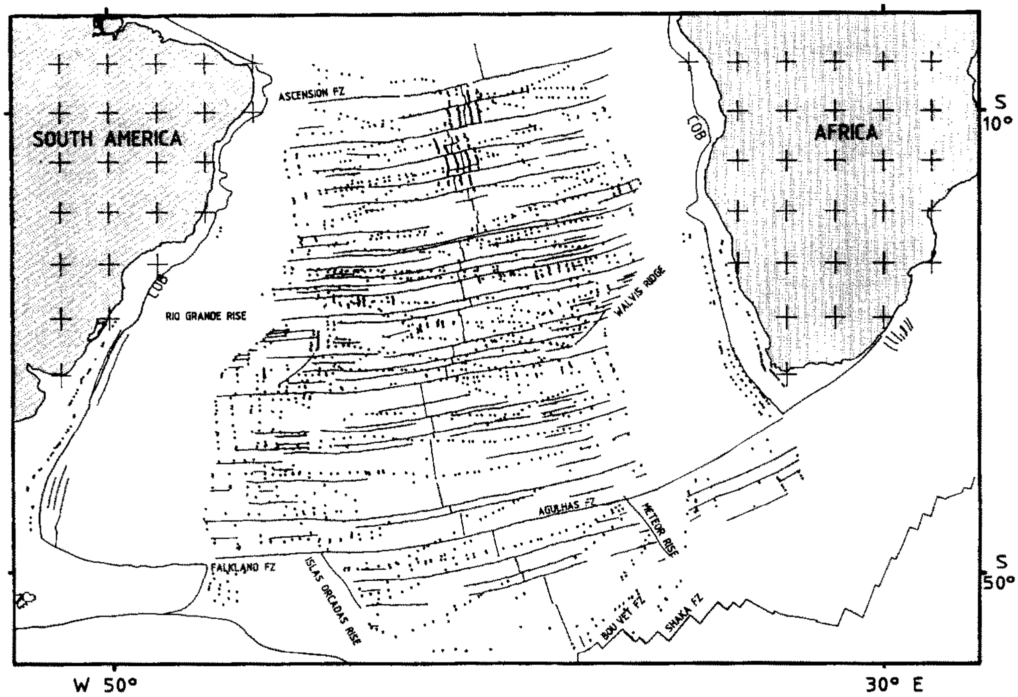


Fig. 1. Tectonic map for the South Atlantic showing magnetic anomaly data and tectonic flowlines constructed by using the rotation poles in Table 1. Flowlines were plotted where fracture zones can be identified from Geosat gravity signals and/or offsets of magnetic picks. Magnetic anomaly picks and lineations are taken from Cande et al. (1988), Rabinowitz and LaBrecque (1979), LaBrecque and Hayes (1979), Barker (1979) and Martin et al. (1982). The location of the ridge axis is based on a combination of magnetic and topographic profiles and GEBCO (Cande et al., 1988).

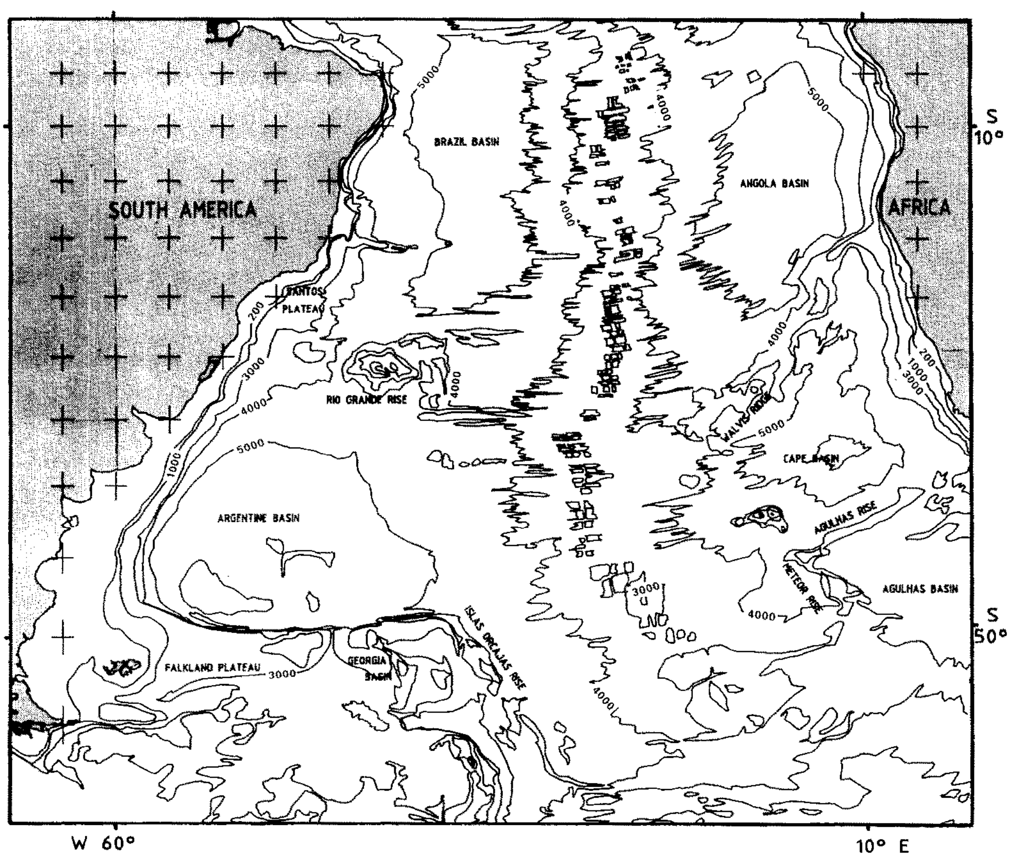


Fig. 2. Bathymetry (in meters) and major tectonic features of the South Atlantic Ocean (from GEBCO, version 5.0).

which corresponds to the fossil spreading center at Chron 32 time.

The interpretation of magnetic anomaly data in the Agulhas Basin led LaBrecque and Hayes (1979) to the assumption of a short-lived, independently acting Malvinas Plate existing between Chron 34 and Chron 31. Their model predicts a late Cretaceous clockwise rotation of this plate with respect to South America, resulting from a change in the relative motion of Africa with respect to South America (Ladd, 1974). This rotation caused convergence of the Malvinas and the South American plates along the northeastern Georgia Rise. This oceanic rise, created simultaneously with the Malvinas Plate, would have been the site of subduction of up to 200 km of the Malvinas Plate (LaBrecque and Hayes, 1979).

Methods

Magnetic anomaly data and bathymetry

In order to derive an improved tectonic database for the South Atlantic Ocean we combined magnetic anomaly data and satellite altimetry data. The most recent compilation of magnetic anomaly picks and lineations in the South Atlantic (Cande et al., 1988; see also Barker, 1979; LaBrecque and Hayes 1979; Rabinowitz and LaBrecque, 1979; Martin et al., 1982) (Fig. 1) was used to construct isochrons of seafloor spreading. Magnetic anomaly pick locations for Chron 34 to 3 correspond to the young end of the normal polarity interval (Cande et al., 1988). In the Agulhas Basin (Barker, 1979; LaBrecque and Hayes, 1979), picks are defined by the old end of the normal polarity interval. Magnetic anomaly data in the Agulhas Basin were partly reinterpreted (J.-Y., Royer, pers. commun., 1987) using profiles from Barker (1979) and LaBrecque and Hayes (1979).

Since detailed bathymetric data of the South Atlantic fracture zones are still sparse (Fig. 2), the true trends of fracture zones in the South Atlantic are only known in parts. By using satellite altimetry data, we have derived tectonic flowlines of fracture zones over large parts of the South Atlantic ocean floor.

Satellite altimetry data

Satellite altimetry data have been shown to be a powerful tool to locate tectonic features on the ocean floor and to trace tectonic lineations (Sandwell and Schubert, 1982; Sailer and Okal, 1983; Okal and Razenave, 1985; Haxby, 1987; Shaw, 1987; Cande et al., 1988; Shaw and Cande, 1990; Craig and Sandwell, 1988; Müller et al., in press). In this work, we used altimetry data derived by Geosat (GEOdesy SATellite). This satellite began its unclassified Exact Repeat Mission (ERM) in October, 1987, and operated during the entire Austral summer 1987–1988. The Geosat data reached a higher degree of accuracy in comparison to the older Seasat data from 1978, since it achieved an accuracy of 3.5 cm for significant wave heights of 2 m (McConathy and Kilgus, 1987; MacArthur et al., 1987), 2.9 times better than the 10 cm accuracy of Seasat data for wave heights less than 20 m (Tapley et al., 1982). Geosat has an equatorial track spacing of 164 km (McConathy and Kilgus, 1987), since it was placed in the unclassified 17 day ERM. Twenty-two of these Geosat altimeter repeat cycles were stacked to improve the data accuracy and coverage.

Fortunately, Geosat could record geoid signals in high southern latitudes in contrast to Seasat, which was mainly due to the sea ice minimum around Antarctica during the Austral summer (Royer et al., in press). To identify tectonic flowlines by Geosat altimetry data, we used the ascending (those going SE–NW) (Fig. 3) and descending (those going NE–SW) (Fig. 4) satellite passes. Since the tectonic features, which generate the flowlines, exhibit relatively short wavelengths in the geoid, we used the slope of the geoid rather than the geoid itself. This slope, or the first derivative of the geoid, is called the deflection of the vertical and is plotted perpendicular to the ground tracks. Moreover, wavelengths shorter than 19.8 km and greater than 4000 km were removed using a Gaussian filter for two reasons: because they are below the threshold of noise or because they are related to deep-seated gravity anomalies and thermal convection and therefore do not reflect the actual bathymetry. Due to the measuring technique, tectonic features on the ocean floor must be separated by at least 32 km (McConathy and Kilgus, 1987) in order to be recognizable for the satellite.

Deflection of the vertical chart (DOV)

To construct a tectonic fabric chart of the South Atlantic ocean floor, plots of the deflection of the vertical along track at Gebco scale were interpreted by tracing peaks, respectively troughs of the deflection of the vertical from track to track. The resulting lineations were traced on the basis of polarity, amplitude and character (Mayes, 1988) (Fig. 5). Lineations of this chart at least cross three tracks (Fig. 6).

Though the interpretation of the deflection of the vertical plots exhibit many continuous lineations over wide areas of the South Atlantic, a direct correlation to fracture zones is problematic, since gravity signatures of fracture zones vary with spreading rate (Shaw and Cande, 1987). Thus, we rather used the satellite altimetry data to predict seafloor spreading directions by determining tectonic flowlines than determining the locations of fracture zones themselves. Since these flowlines show the direction of relative plate motion, they can be used just as the fracture zone identifications as constraints for plate tectonic reconstructions.

The simple model of fracture zones represented by steps in the basement (Fig. 5c) is seldomly in accordance with bathymetric and gravimetric data over fracture zones (Collette, 1986) Actually, fracture zones exhibit a more complex morphology mostly due to variations in seafloor spreading velocity and direction, as well as age offset. The common occurrence of closely spaced pairs of lineations indicating maximum positive respectively negative slopes in the geoid shows that fracture zone central valleys rather than basement

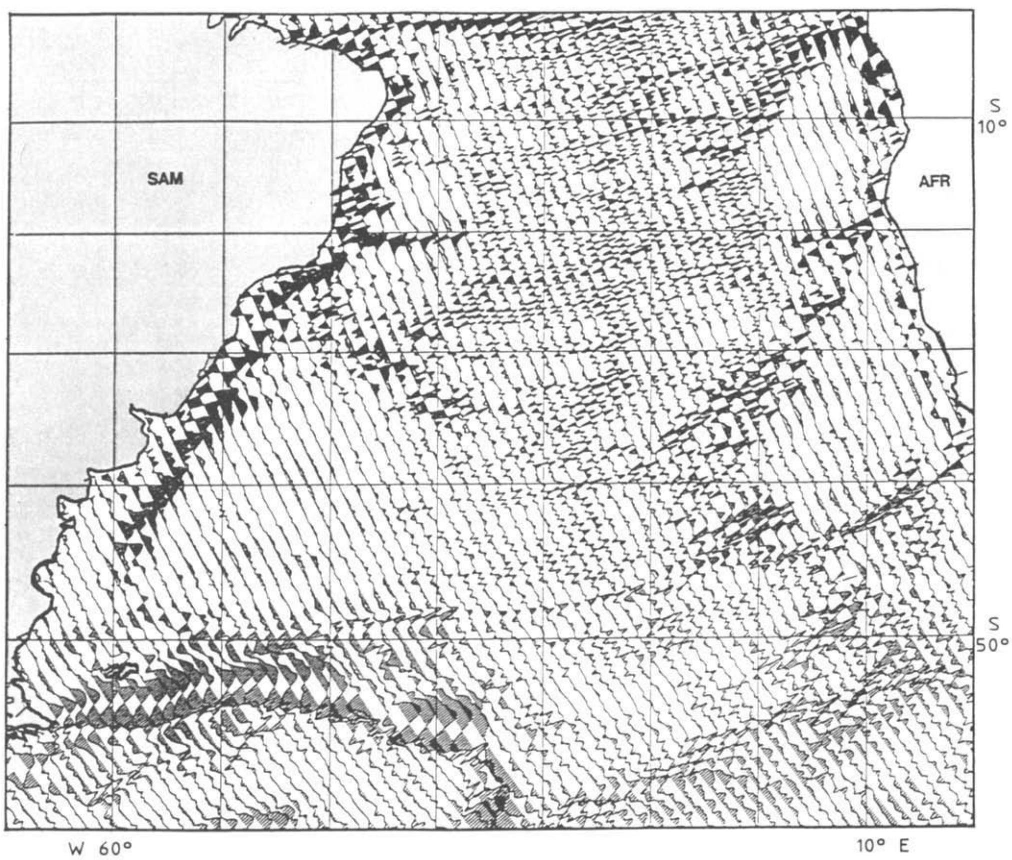


Fig. 3. Deflection of the vertical (DOV), plotted perpendicular to track, ascending passes (going SE–NW), in the South Atlantic Ocean.

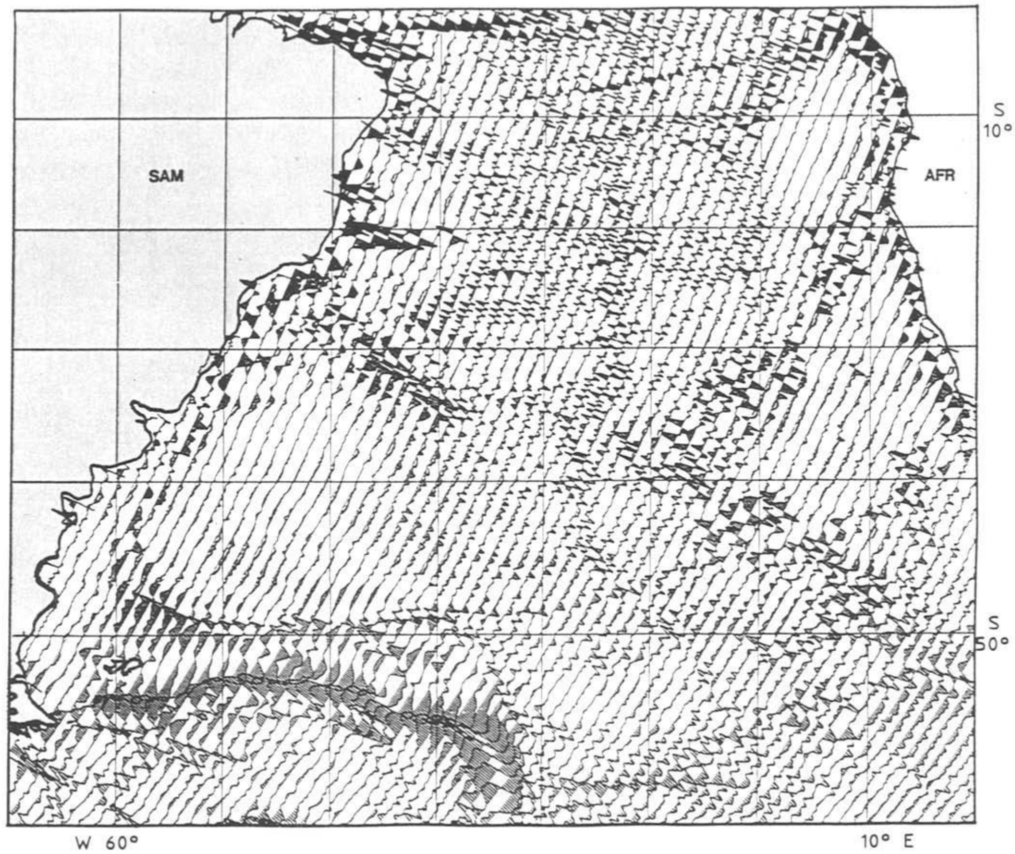


Fig. 4. Deflection of the vertical (DOV), plotted perpendicular to track, descending passes (going NE–SW), in the South Atlantic Ocean.

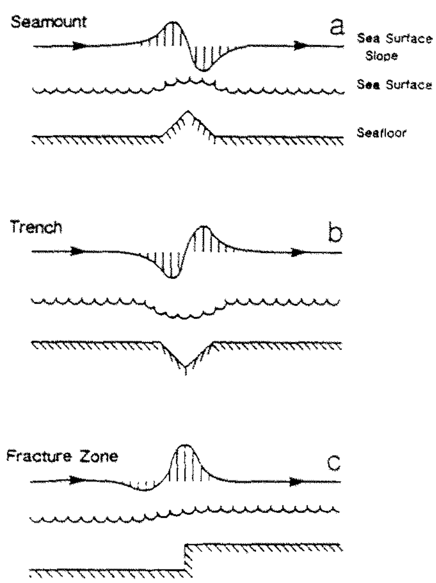


Fig. 5. Geoid anomaly and deflection of the vertical (slope of the geoid) signal for a seamount (a), trough (b) and fracture zone (c) (from Sandwell, 1984).

steps are the most prominent features of South Atlantic fracture zones. Gravity and bathymetric measurements along the Rio Grande Fracture Zone reveal the troughlike nature of this fracture zone (Gamboa and Rabinowitz, 1981). However, only a few continuous Geosat lineations allow us to trace fracture zones over long distances. This applies to the Ascension, Bode Verde, Rio de Janeiro, Rio Grande, Tristan de Cunha, Gough and Falkland/Agulhas fracture zones. The data in the Argentine, Brazil, Cape and Angola Basin are sparse, probably due to the thick sediment cover.

As Mayes (1988) could show for the Eltanian Fracture Zone in the Southeast Pacific, the Geosat lineations correlate well with the bathymetric fracture zone identification of the Eltanian fracture zone system from the Gebco charts (Mammerickx et al., 1984; Falcomer and Tharp, 1984). However, the deflection of the vertical chart gives more

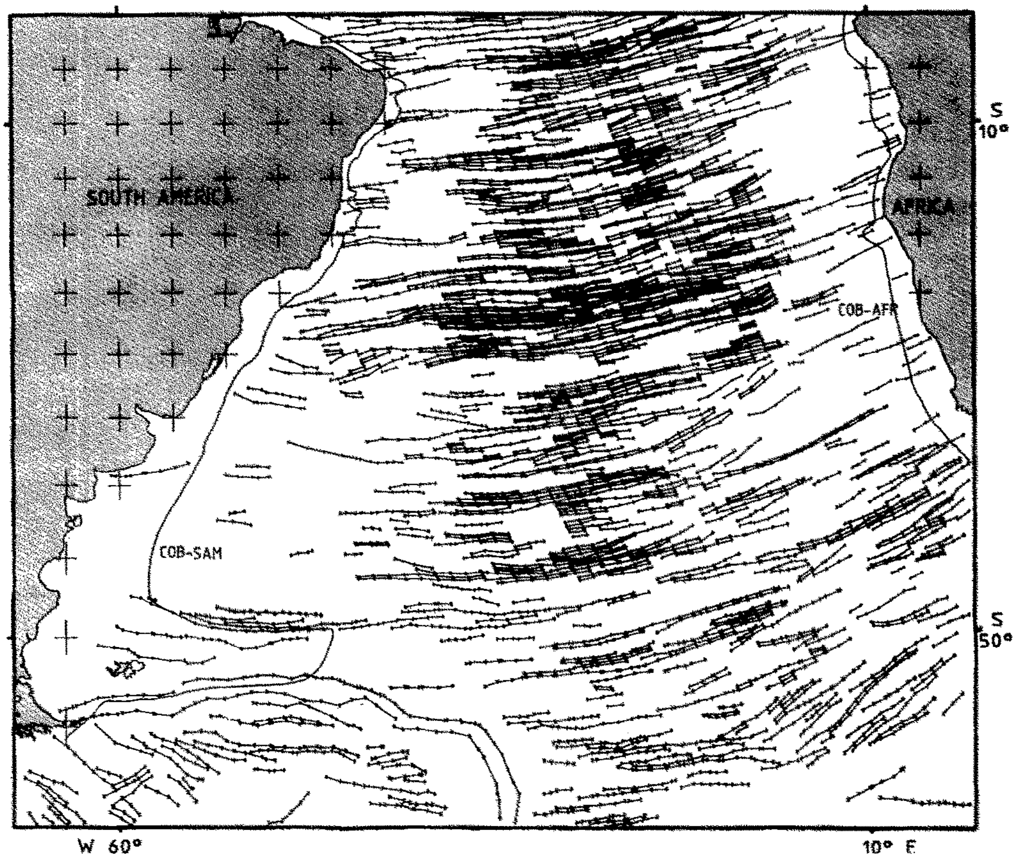


Fig. 6. Tectonic fabric lineations derived from the deflection of the vertical for the South Atlantic Ocean. Symbols indicate ground track crossings. + = points of maximum positive slope (traveling from south to north); ■ = points of maximum negative slope.

detail for the trends of the fracture zones. Müller et al. (in press) showed that the basement trough of the Kane Fracture Zone in the Central Atlantic correlates within ±5 km in average with the corresponding trough in the geoid. In the South Atlantic, the Geosat lineations slightly deviate from the bathymetric fracture zone identifications from Gebco, especially on the African plate. We refer this to the sparse ship track coverage in the South Atlantic resulting in incorrect bathymetry identification.

Tectonic fabric of the South Atlantic Ocean

To reconstruct a high-resolution tectonic history of the South Atlantic, we combined the magnetic data with the Geosat lineations. We used the most prominent deflection of the vertical lineations in combination with the magnetic data base for the purpose of calculating new finite poles of rotation and proving already published poles. The tectonic flowlines of the Ascension, Bode Verde, Rio de Janeiro, Rio Grande, Falkland/Agulhas fracture zones constrain the spreading direction better than bathymetric identifications.

An Evans and Sutherland PS300 interactive graphics computer system was used to reconstruct plate motions through time. Magnetic anomaly picks and lineations, deflection of the vertical lineations, continental margins and tectonic data on the continents were displayed in an orthographic projection. After assigning the digitized data to individual plate tectonic elements, or plates, they can be rotated independently around their poles of rotation relative to any other plate displayed on the sphere. Plate rotations are constrained by the best visual fit of all data. We used the "Hierarchical tectonic analysis" method (Ross and Scotese, 1988) to determine the plate positions to their relative positions in the past.

Cande et al. (1988) calculated 45 finite rotation poles between Chron 34 and Chron 3, each representing an average time interval of less than 2 Ma. The finite pole of rotation for a plate pair is the Euler pole, which rotates one plate to the reference plate from the present day relative position to its past position. Most of Cande et al.'s (1988) poles satisfy the data constraints. The poles for magnetic anomalies 6a, 6c, 11, 16, 20, 25, however, were slightly modified. The relative motion be-

TABLE 1

Finite reconstruction poles for the following South American and African subplates distinguished in the text with respect to Africa and South America, respectively: South America (SAM), Parana Subplate (PAR), Colordo Subplate (COL), Salado Subplate (SAL), southern Africa (AFR), northwestern Africa (NWAFR) *

Mobil Plate	Age (Ma)	Lat. (°)	Long. (°)	Angle (°)	Ref. Plate	Description
SAM	3.88	60.00	−39.00	1.21	AFR	SAM-AFR AN 3
SAM	8.92	60.00	−39.00	3.15	AFR	SAM-AFR AN 5
SAM	11.55	59.50	−38.00	4.05	AFR	SAM-AFR AN 5A
SAM	16.22	59.50	−38.00	5.75	AFR	SAM-AFR AN 5C
SAM	19.35	59.50	−38.00	7.05	AFR	SAM-AFR AN 6
SAM	20.88	59.50	−37.75	7.60	AFR	SAM-AFR AN 6A
SAM	23.27	59.50	−37.00	8.80	AFR	SAM-AFR AN 6C
SAM	25.50	59.00	−36.00	9.50	AFR	SAM-AFR AN 7
SAM	28.15	58.00	−35.00	10.55	AFR	SAM-AFR AN 9
SAM	31.23	57.00	−34.50	11.60	AFR	SAM-AFR AN 11
SAM	35.29	57.50	−34.00	13.38	AFR	SAM-AFR AN 13
SAM	38.10	57.00	−33.25	14.40	AFR	SAM-AFR AN 16
SAM	41.29	57.50	−32.50	15.80	AFR	SAM-AFR AN 18
SAM	44.66	57.50	−31.75	17.60	AFR	SAM-AFR AN 20
SAM	48.75	58.50	−31.50	19.07	AFR	SAM-AFR AN 21
SAM	51.95	59.00	−31.50	20.10	AFR	SAM-AFR AN 22
SAM	55.14	60.00	−32.00	21.20	AFR	SAM-AFR AN 24
SAM	58.64	61.50	−32.50	22.30	AFR	SAM-AFR AN 25
SAM	63.03	62.50	−33.00	23.55	AFR	SAM-AFR AN 27
SAM	65.50	63.00	−33.30	24.30	AFR	SAM-AFR AN 29
SAM	66.74	63.00	−33.30	24.70	AFR	SAM-AFR AN 30
SAM	71.37	63.00	−33.50	26.60	AFR	SAM-AFR AN 32
SAM	74.30	63.00	−33.50	27.90	AFR	SAM-AFR AN 33
SAM	80.17	63.00	−34.00	31.00	AFR	SAM-AFR AN 33R
SAM	118.70	51.60	−35.00	52.92	AFR	SAM-AFR AN M0
SAM	126.50	50.40	−33.50	54.42	AFR	SAM-AFR AN M4
SAM	131.50	50.00	−32.50	55.08	AFR	SAM-AFR
PAR	118.70	0.00	0.00	0.00	SAM	PAR-SAM M0
PAR	131.50	−15.20	−73.20	1.48	SAM	PAR-SAM
SAL	126.50	0.00	0.00	0.00	PAR	SAL-PAR M4
SAL	131.50	−32.20	−64.50	0.73	PAR	SAL-PAR
SAL	150.00	−32.20	−64.50	1.18	PAR	SAL-PAR
COL	126.50	0.00	0.00	0.00	PAR	COL-PAR M4
COL	150.00	−18.00	−73.20	1.05	PAR	COL-PAR
NWA	84.00	0.00	0.00	0.00	AFR	NWA-SAFR A34
NWA	118.70	16.50	6.70	−1.15	AFR	NWA-SAFR M0
NWA	118.70	50.80	−34.20	−53.69	SAM	NWA-SAM M0

* Finite rotation poles between Chron 34 and Chron 3 are from Cande et al. (1988). Poles for magnetic anomalies 6a, 6c, 11, 16, 20, 25, however, were slightly modified.

tween plates for a discrete period of time, or stage, is defined by stage poles. The sum of a series of stage poles equals a finite pole of rotation. In order to test the accuracy and self-consistency of the finite poles of Cande et al. (1988), we calculated spreading rates, directions and stage poles for the South American–African plate pair. These parameters, plotted against time, give us a visual control of consistency and smoothness of changes in plate orientation and rate. Stage poles calculated from the finite rotation poles were used to derive small circles for every stage. These small circles should parallel Geosat lineations for each specific stage. If small circles and Geosat lineations deviated significantly, we modified the finite rotation poles. Shaw and Cande (1990) have developed an inversion method that jointly uses fracture zone and magnetic anomaly location data to solve for rotation parameters. They computed finite rotation poles and their uncertainties for 11 times between Chron 34 and present day based on Seasat altimetry and magnetic anomaly data. Although this time period is covered by our reconstructions as well, the focus of this paper is the early opening of the South Atlantic from the Late Jurassic to the Late Cretaceous (Chron 34) and the construction of a high-resolution isochron chart.

Finite poles of rotation for Chron M4 and M0 were derived by taking into account intracontinental deformation within South America and Africa during the early opening phase of the South Atlantic (Table 1). For the M0 and M4 poles, we considered magnetic anomaly picks and lineations

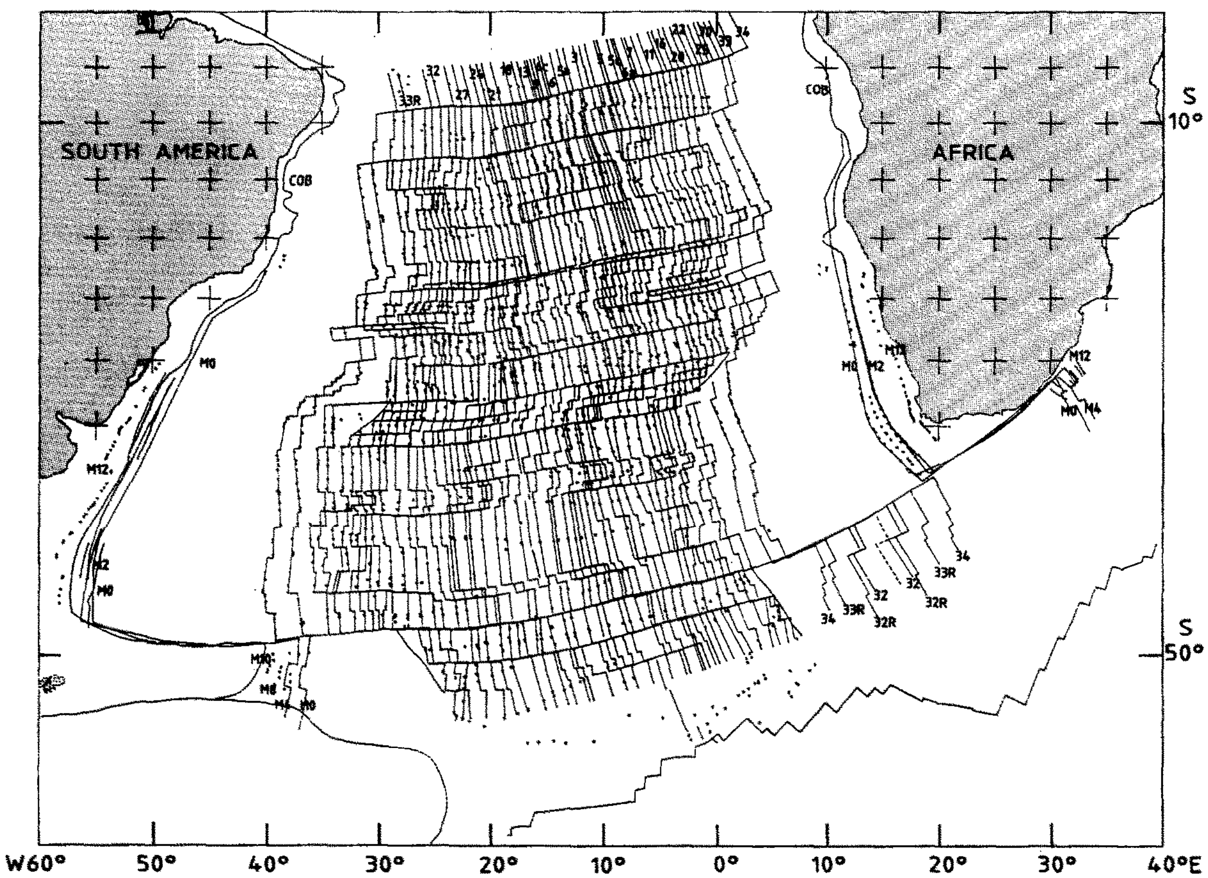


Fig. 7. Isochron chart for the South Atlantic Ocean based on the magnetic anomaly data compilation of Cande et al. (1988), Rabinowitz and LaBrecque (1979), LaBrecque and Hayes (1979), Barker (1979) and Martin et al. (1982). The ridge axis is from Cande et al. (1988), the continental/oceanic crust boundary is modified after Emery and Uchupi (1984).

in the southernmost South Atlantic published by Rabinowitz and LaBrecque (1979), Martin et al. (1982) and Cande et al. (1988).

Constructing isochrons and synthetic flowlines

To derive an isochron map for the South Atlantic, we plotted small circles for the entire length of the ridge in 1° intervals for every single stage. Small circles should parallel Geosat lineations for each specific stage. If small circles and Geosat lineations deviated significantly, we improved the finite pole of rotation (Table 1). Then, the small circles, the matched magnetic anomaly picks and lineations with additional constraints from "paleo-ridges" constructed for younger stages, were used to draw the spreading centers for a particular reconstruction. The position of fracture zones offsetting the "paleo-ridge" were constrained by deflection of the vertical lineations. The resulting fossil spreading centers are assigned to their respective plate and are used as isochrons. They were rotated to each side of the present spreading center, resulting in a self-consistent und symmetric model of seafloor-spreading isochrons (Fig. 7). Isochrons are shown for Chrons 3, 5, 5a, 6, 6a, 6c, 7, 9, 11, 13, 16, 18, 20, 21, 22, 24, 25, 27, 30, 32, 33, 34, M0 and M4. In addition, synthetic flowlines of fracture zones for each stage have been constructed along corresponding small circles.

The isochron map shows a high-resolution pattern for the spreading history from Chron M4 to present day, reflecting clearly the changing amounts of fracture zone offsets through time. M-anomalies, however, are sparse, M4-anomaly picks falling together with the continental/oceanic crust boundary (COB) of Emery and Uchupi (1984), indicating first seafloor spreading with the generation of oceanic crust around M4 (126.5 Ma). These magnetic anomalies do not reach further north than 25°S in the vicinity of the Walvis Ridge–Rio Grande Rise complex. Older M-anomalies identified by Rabinowitz and LaBrecque (1979) lie landwards of the COB. This can be interpreted as the generation of large basaltic flows intersecting the continental crust during the initial rifting phase (Rabinowitz and LaBrecque, 1979). The oldest M-anomalies in the South Atlantic are M12 (135.6 Ma)

The initial opening of the South Atlantic: a new fit model

Previous fit reconstructions of the continents around the South Atlantic, which assumed rigid plates for South America and Africa, result in substantial misfits either in the southernmost South Atlantic or in the equatorial Atlantic (Bullard et al. 1965). To account for that Rabinowitz and LaBrecque (1979) proposed a major compressional episode (~ 200 km) between the Demarara Plateau and the Guinean margin, synchronous with the opening of the southern domain. However, evidence for such a compressional phase is scarce. Vink (1982) proposed that differential stretching of conjugate margins as the rift propagates accounts for the misfit problems.

To achieve a fit reconstruction without significant gaps and overlaps, we included a combination of complex intracontinental rift and strike-slip movements assumed to have been active before or during the breakup of the continents. The amplitude of intraplate deformation within South America and Africa, however, is directly related to the tightness of the fit reconstruction. The tighter the fit, the larger the deformation to be considered. Onshore geologic data, the continental/oceanic crust boundary, the shape of the Guinea and Demarara plateaus, and equatorial fracture zone extensions on the continental shelves were used as tie points for the fit reconstruction. Late Cretaceous magnetic anomaly data in the southern South Atlantic were used to constrain the early opening phase.

As palinspastically restored continental margins of South America and Africa are not available to date, we used the continental/oceanic crust boundary (COB) of Emery and Uchupi (1984). The COB on the South American side is slightly modified between 20°S and 30°S using Seasat altimetry data (Gahagan et al., 1988). Emery and Uchupi (1984) mapped the seaward edge of the South American salt basins as the COB. However, Seasat lineations give clear evidence for a large part of the salt being deposited or mobilized onto oceanic crust. According to LaBrecque and Zitellini (in prep.), the COB in the southernmost part of the South Atlantic is more likely a transition zone of 150 km in width. This transition zone is bounded landwards by magnetic anomaly G of Rabinowitz and LaBrecque (1979) and seawards by magnetic anomaly M4, which generally coincides with Emery and Uchupi's (1984) COB. The transition from 100% continental to 100% oceanic crust probably occurs within a zone of 30 km (LaBrecque and Zitellini, in prep).

Geosat altimetry data as well as bathymetric interpretation from Gebco reveal the COB of Emery and Uchupi (1984) along the Agulhas transform margin to be incorrect. Since the South Atlantic fit reconstruction highly depends on the accurate fit of the Falkland and Agulhas fracture zones, we modified the COB according to Geosat and Gebco. According to W.W. Hay and C.N. Wold (pers. commun., 1990), over long distances the 200 m and 2000 m isobaths best reflect the pre-rift margins of South America and Africa. This would imply approximately 100 km of stretching or a factor of 3. Using these pre-rift margins would reduce the existing overlaps in the fit-reconstruction (see Fig. 9) significantly.

A gap between the Guinea and Demarara plateaus before Aptian times is unlikely (Jones, 1987; Mascle and Blarez, 1987; Popoff et al., 1989a,b). The fracture zone pattern and the interpretation of deep water sediments in the equatorial Atlantic from seismic stratigraphy do not

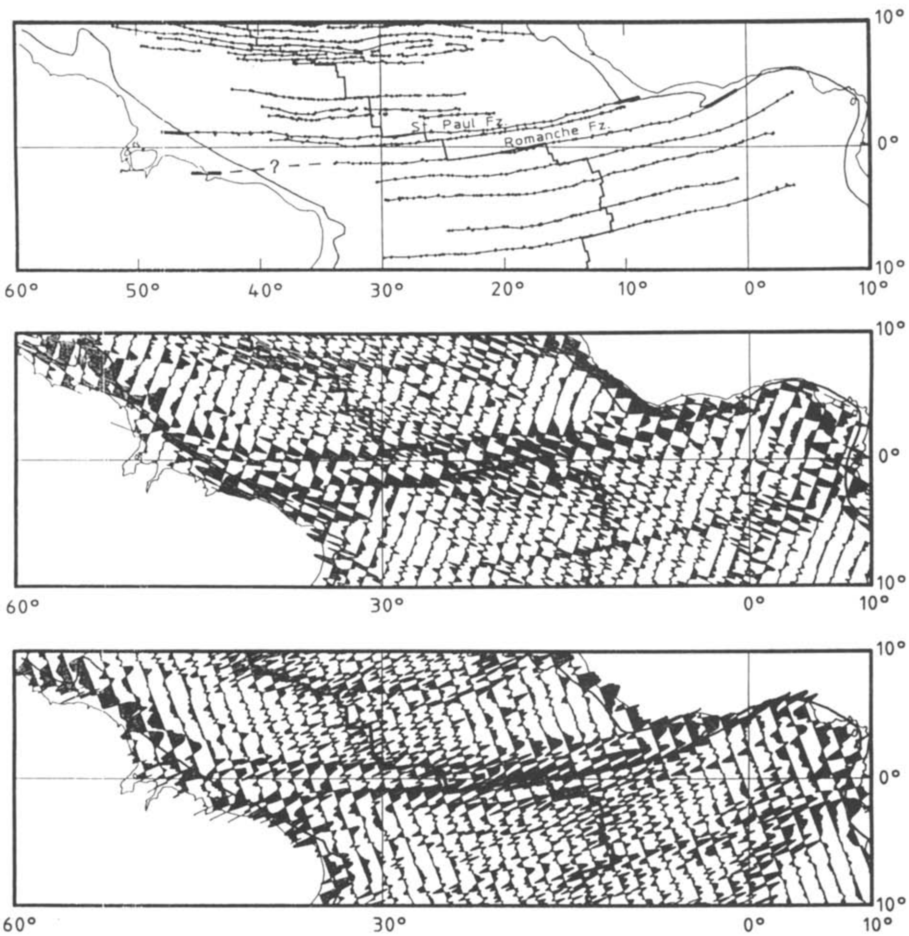


Fig. 8. Interpretation of two prominent fracture zones in the equatorial Atlantic from Geosat and Seasat altimetry data (Fig. 8a): St. Paul Fz. and Romanche Fz. (AA' and BB' respectively in Figs. 9–13). The fracture zone extensions to the continental shelves serve as tiepoints for the fit reconstruction of South America and Northwest Africa. (b) and (c) show the descending and ascending passes of the deflection of the vertical (DOV), respectively, plotted perpendicular to track.

permit a gap between the African and Brazilian margins during the early Cretaceous opening of the South Atlantic. Thus, we attempt to obtain a close fit of these plateaus until the opening of the equatorial Atlantic.

Two prominent fracture zones, the St. Paul (*AA′* in Figs. 9–13) and Romanche (*BB′* in Figs. 9–13) fracture zones in the equatorial Atlantic, as interpreted from Geosat and Seasat altimetry data and magnetic pics, can be traced from the Brazilian to the African continental margins (Fig. 8). The western extension of the St. Paul Fracture Zone runs into the mouth of the Amazon River, the eastern extension intersects the African continent directly beneath Cape Palmas (Ivory Coast Basin), where it is in line with the general strike of the coastline eastwards of Cape Palmas. The western end of the Romanche Fracture Zone is tentatively interpreted to correspond to the Parnaiba Ridge, whereas on the west coast of Africa there is clear evidence that the fracture zone roughly bounds the northwestern edge of the Dahomey Basin.

Gravity and magnetic anomalies along the Agulhas Plateau and the Falkland Plateau indicate rapid transitions from continental to oceanic crust (Scrutton, 1976; Rabinowitz et al., 1976). There is no evidence for faulting parallel to the Agulhas continental margin (R.A. Scrutton, pers. commun., 1990) implying predominantly strike-slip without rifting along the Falkland-Agulhas Fracture Zone.

Intracontinental deformation zones in Africa and South America

A fit reconstruction for the South Atlantic without considerable gaps or overlaps between the African and South American continental margins can only be derived by including intracontinental deformation during the initial opening of the South Atlantic in both continents as proposed by Burke and Dewey (1974), Unternehr et al. (1988) and Conceicao et al. (1988). The possibility of deformations diffusely distributed throughout a plate originally proposed by Burke and Dewey (1974) can be excluded (Martin et al., 1982). The deformations are most probably restricted along belts of limited extension (Unternehr et al., 1988; Olivet et al., 1984). In accordance with geological and geophysical data, we propose rift motion combined with minor strike-slip movement along three intracontinental zones of weakness. Movements along these deformation zones are considered to have taken place simultaneously with the breakup of the continents.

Rift motion in Africa: Benue Trough / Niger Rift system

Gravity measurements along the Benue Trough and Gongola Rift in Nigeria reveal positive gravity anomalies, which may be due to simple lithospheric stretching (Fairhead and Okereke, 1987). Maximum possible crustal extension is assumed to have reached 95 km, 65 km, and 55 km in the Benue Trough, Gongola Rift and Yola Rift, respectively. According to Fairhead (1988), Maurin et al. (1986), Benkhelil (1982), Benkhelil et al. (1988) and Allix and Popoff (1983), the Benue Trough is a sinistral wrench fault zone consisting of a series of *en echelon* basins with thick successions of marine Cretaceous (Aptian) to younger (Maastrichtian?) sediments. The Benue Trough is considered to be a failed arm of a R.R.F. triple junction situated in the Gulf of Guinea (Burke et al., 1971; Burke and Dewey, 1974; Popoff, 1988; Popoff et al., 1989a). During the Neocomian, the trough was not an effective depo-center (Castro, 1987). Sixty kilometers of strike-slip motion are proposed by Fairhead (1988). The Benue Trough is assumed to belong to a post-Jurassic intracontinental plate boundary (Pindell and Dewey, 1982; Fairhead, 1988; Pindell et al., 1988) between northwestern Africa and southern Africa together with the Gongola and Niger rifts, which are thought to be the inland extensions of the Benue Trough blanketed by a thick Cenozoic sediment cover (Fairhead, 1988). Pindell and Dewey (1982) propose that the northwestern part of Africa and South America behaved as one plate until the opening of the equatorial Atlantic after Chron M0 (118.7 Ma).

A second intracontinental deformation zone within Africa, the Central African Shear Zone (Fairhead, 1988), is assumed to not have been active during the early opening of the South Atlantic. According to Fairhead (1988), the Central

African Shear Zone (*CASZ* in Fig. 9) extends about 2000 km across Africa from the Gulf of Guinea through Cameroon, Chad and the Central African Republic into Sudan. A rejuvenation of this Precambrian lineament in Late Cretaceous/ Early Tertiary times (Fairhead, 1988) has dextral displacement (Ngangom, 1983; Cornacchia and bars, 1983) generating narrow subsiding rift basins infilled with Cretaceous and Tertiary sediments. A dextral strike-slip motion, however, contradicts the predominantly sinistral and extensional stress regime in the northern part of the South Atlantic during the early stages of oceanic evolution (Castro, 1987).

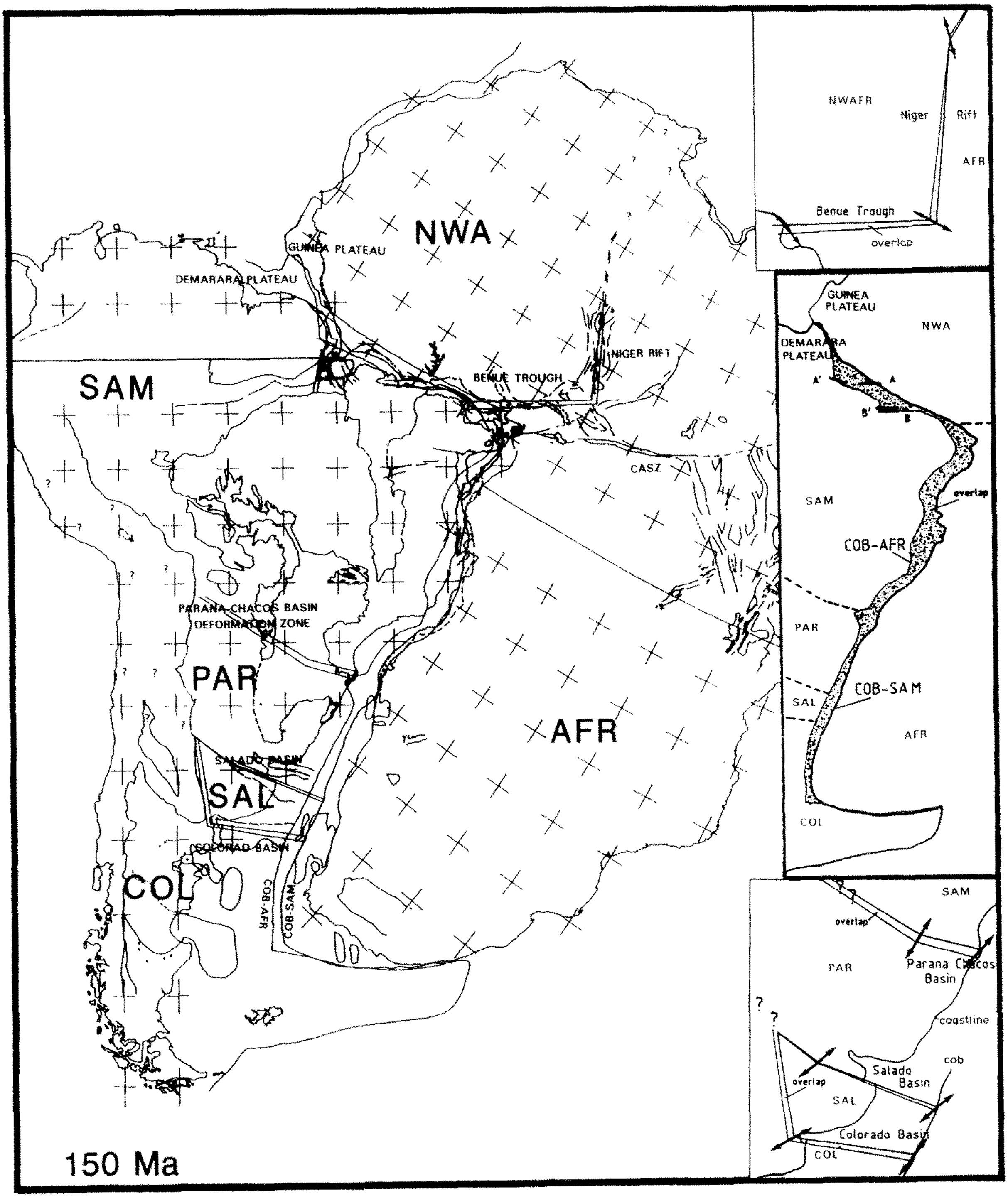
Intracontinental deformation zones in South America

Parana and Chacos Basin shear zone. Unternehr et al. (1988) propose an intraplate deformation zone within South America extending from the South America Parana and Chacos Basin to the Andean Cochabamba–Santa Cruz bend. According to Sibuet et al. (1984), widespread basalt flows in the Parana Basin (120 Ma, Barremian) may belong to a failed rift arm of a triple junction on the South American plate that was active during the Late Jurassic and Early Cretaceous and resulted in 100 km of N–S extension. The Serra Geral volcanism created approximately 790,000 km^3 of basalt distributed over an area of 2,000,000 km^2. The preferred average age is assigned to 130 Ma (LaBrecque and Gorini, in prep.). Although direct geological evidence is rare due to most extensive basalt flows covering older geological structures (Campos et al., 1974), Unternehr et al. (1988) suggest 150 km of dextral strike-slip motion along this proposed second order plate boundary. In our reconstructions, we include the idea of rift and shear movements within the South American Parana and Chacos Basin. However, the existence of a second order plate boundary proposed by Unternehr et al. (1988) reaching from the Parana Basin to the Andean Cochabamba/Santa Cruz Bend remains partly speculative though remote sensing data in this area reveal supporting evidence (Unternehr et al., 1988).

Rift basins within South America. According to Urien and Zambrano (1974), the tectonic evolution of the Salado and Colorado Basins in South America may be explained by rifting processes perpendicular to the South Atlantic rift during the initial opening of the South Atlantic. Both marginal basins are open to the South Atlantic Ocean and show E–W, NE–SW and NW–SE structural trends (Urien and Zambrano, 1974). The post-upper Jurassic sediment fill (Cretaceous nonmarine sediments) the presence of basalts in the Salado Basin, as well as the inception of faulting during the Middle and Late Jurassic (Urien and Zambrano, 1974) support the model of rift movements in both basins during the early opening phase of the South Atlantic.

How we derived the fit of continents around the South Atlantic

We started with a fit reconstruction of the equatorial Atlantic (Table 1), which matches the Guinea and Demara Plateaus as well as equatorial fracture zone extensions interpreted from Geosat and Seasat altimetry data, bathymetric and magnetic data. This reconstruction avoids any gap in the equatorial Atlantic. Subsequently, we applied a rotation, which restores southern Africa relative to northwestern Africa, closing the Benue Trough (Table 1). This movement implies 50–60 km of rifting, 40–50 km of sinistral shear in the Benue Trough and the same amount of rifting in the Niger Rift since the initial opening of the South Atlantic, which is in accordance with Fairhead (1988) and Fairhead and Okereke (1987). Avbovbo et al. (1986) show evidence for rifting in the Chad Basin of northeastern Nigeria during Late Cretaceous times. Minor folding is assumed to have resulted from subsidence of the basement-controlled graben along existing fault/fracture planes. The proposed rotation results in a large overlap of the African and South American continental/ oceanic crust boundaries between 5°S and 12°S. The amount of continental overlap, however, could be reduced by considering crustal extension in northeastern Brazil during the very early separation of Brazil and Gabon. The N–S striking Reconcavo and Tucano basins consist of a series of half-grabens, characterized by a rift phase sedimentation that started during the Jurassic/early Cretaceous (Castro, 1987) usually with pre-Aptian sediments. Tectonic activity and sedimentation in these basins ceased during the early Cretaceous (Castro, 1987). According to Castro (1987), the South Atlantic marginal basins in Gabon and Brazil including the Reconcavo and Tucano basins



were created and developed under a regime of predominantly extensional stresses. Palinspastically restoring these basins in our fit reconstruction would result in less overlap of the South American and African continental margins in this region.

Having closed the Benue Trough, a gap still remains in the southern South Atlantic. This gap is partly closed by rotating southern South America eastward (Table 1) along the Parana Basin intracontinental deformation zone. As the amounts for strike-slip and rift motion along this line are very uncertain, we tried to minimize the amount of motion to 60–70 km of rifting and 20–30 km of strike-slip. Hence, we imply less tectonic movement along this deformation zone than Sibuet et al. (1984) and Unternehr et al. (1988) who assume 100 km of rifting and 150 km of strike-slip, respectively. By including dextral motion along this deformation zone in our model, the M-anomaly picks between the Rio Grande Rise and the Salado Basin (Rabinowitz and LaBrecque, 1979) fit fairly well. In order to close a remaining small gap in the southernmost South Atlantic, we rotated the southernmost tip of South America clockwise to Africa closing the Salado and Colorado basins. This rotation implies 20–25 km and 40–45 km of crustal extension within the Salado and Colorado Basins, respectively, and 20–30 km of strike-slip motion in both basins since middle Jurassic times. The final result is a fit of the continents around the South Atlantic without any gaps or unreasonable amounts of overlap that is consistant with and constrained by geologic data (Fig. 9).

Plate tectonic reconstructions

The initial opening of the South Atlantic: a propagating rift system

Starting from the fit reconstruction already described, we suggest a stepwise, northward-propagating rift for the South Atlantic (Figs. 9–13). A first rift phase is tentatively dated as 150 Ma (Tithonian) to 130 Ma (Hauterivian). This rift propagated from the southernmost tip of the South Atlantic to about 38°S in the vicinity of the Salado Basin. This rifting phase caused continental stretching and minor dextral strike-slip motion within the Colorado and Salado basins. The post-upper Jurassic sediment fill as well as the inception of faulting between Middle and Upper Jurassic lines (Urien and Zambrano, 1973) supports this assumption. At about 130 Ma, rifting combined with dextral strike-slip motion is assumed to have started along the Parana/Chacos Basin deformation zone. We infer that this strike-slip motion was related to further northward propagation of rifting in the South Atlantic up to 28°S. North of this rift, Africa and South America are assumed to have been rigidly attached until Chron M4 (126.5 Ma).

Between Chron M4 (126.5 Ma) and Chron M0 (118.7 Ma) rifting propagated northward into the Benue Trough. There is no evidence for opening in the equatorial Atlantic before Aptian time (118.7 Ma) (Jones, 1987; Castro, 1987; Mascle et al., 1988). The extension south of the equatorial Atlantic was taken up by continental stretching

Fig. 9. 150 Ma (Tithonian). A pre-drift reconstruction for the South Atlantic without considerable gaps or overlaps between the continental margins of Africa and South America can only be derived by applying a nonrigid plate model. A model of a stepwise northward propagating rift is in good accordance with geological and geophysical data from the continents. Our model predicts a rift propagation in several steps giving rise to intracontinental deformation at the northernmost rift extensions. Intracontinental deformation is assumed to have taken place within the South American marginal Salado and Colorado basins and along the South American Parana/Chacos Basin deformation zone. In Africa, rifting and strike-slip motion in the Benue Trough and Niger Rift are assumed to have been active since the early opening of the South Atlantic until approximately 80 Ma. The inferred amount of continental stretching along the deformation zones is shown by overlaps of hypothetical subplate-boundaries (stippled areas in insets). Overlaps of continental margins are also stippled, whereas gaps between continental margins and gaps between subplate-boundaries are hatched (see insets). Plate identification numbers: *AFR* = southern Africa, *NWA* = northwestern Africa, *SAM* = South America, *PAR* = Parana Plate, *SAL* = Salado Plate, *COL* = Colorado Plate.

and sinistral strike-slip motion in the Benue Trough/Niger Rift system in accordance with Fairhead and Okereke (1987) and Fairhead (1988). No evidence is present for a compressional phase in the equatorial Atlantic (Castro, 1987; Mascle et al., 1988) as proposed by Rabinowitz and

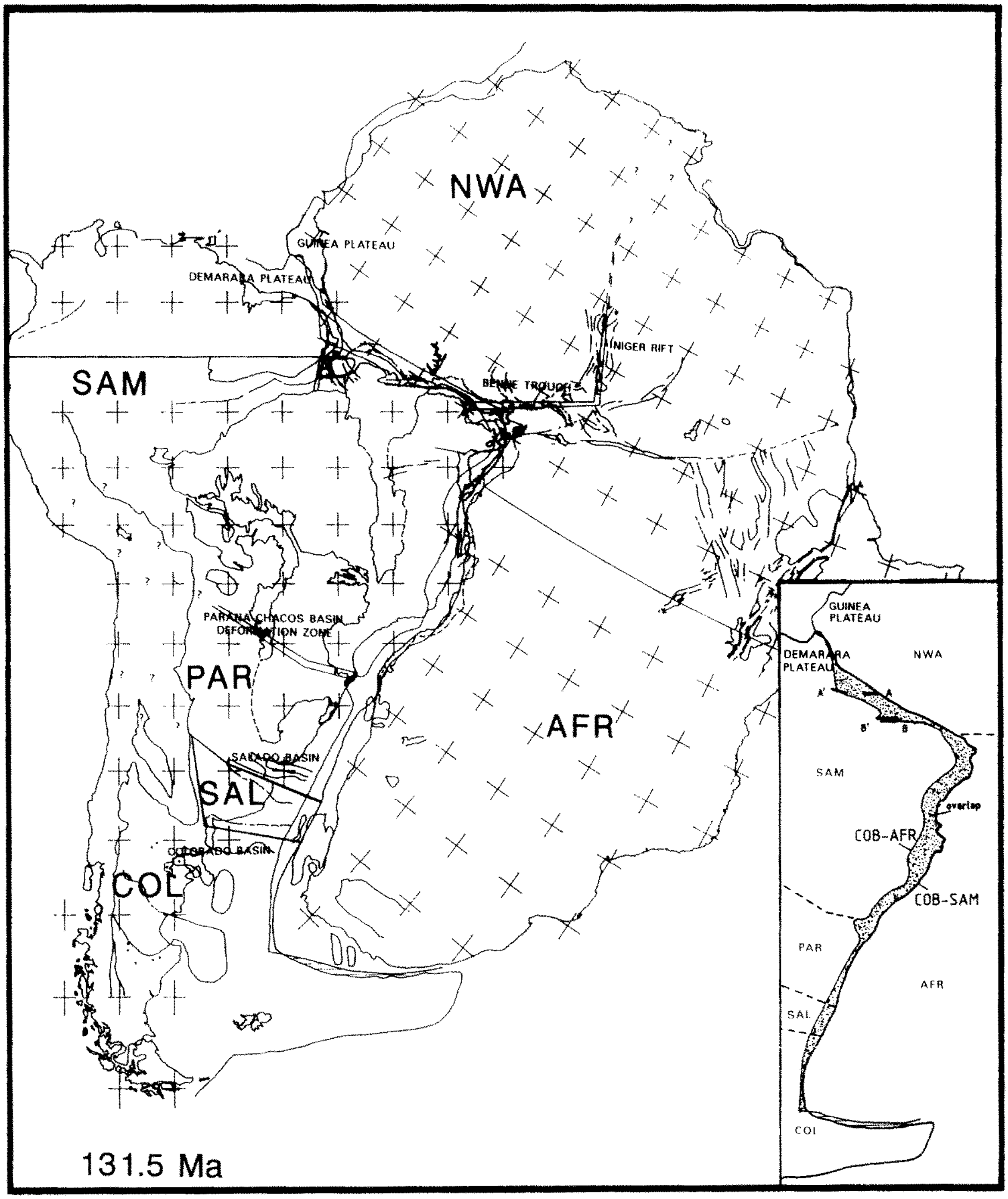


Fig. 10. 130 Ma (Hauterivian). At approximately 130 Ma (Hauterivian), the South Atlantic rift propagated to about 38°S, in the vicinity of the Salado Basin. This rifting phase has caused continental stretching and minor dextral strike-slip motion within the Salado and Colorado basins since approximately 150 Ma (Tithonian). The post-upper Jurassic sediment fill as well as the inception of faulting between the Middle and Late Jurassic (Urien and Zambrano, 1973) support this assumption. For legend see Fig. 9.

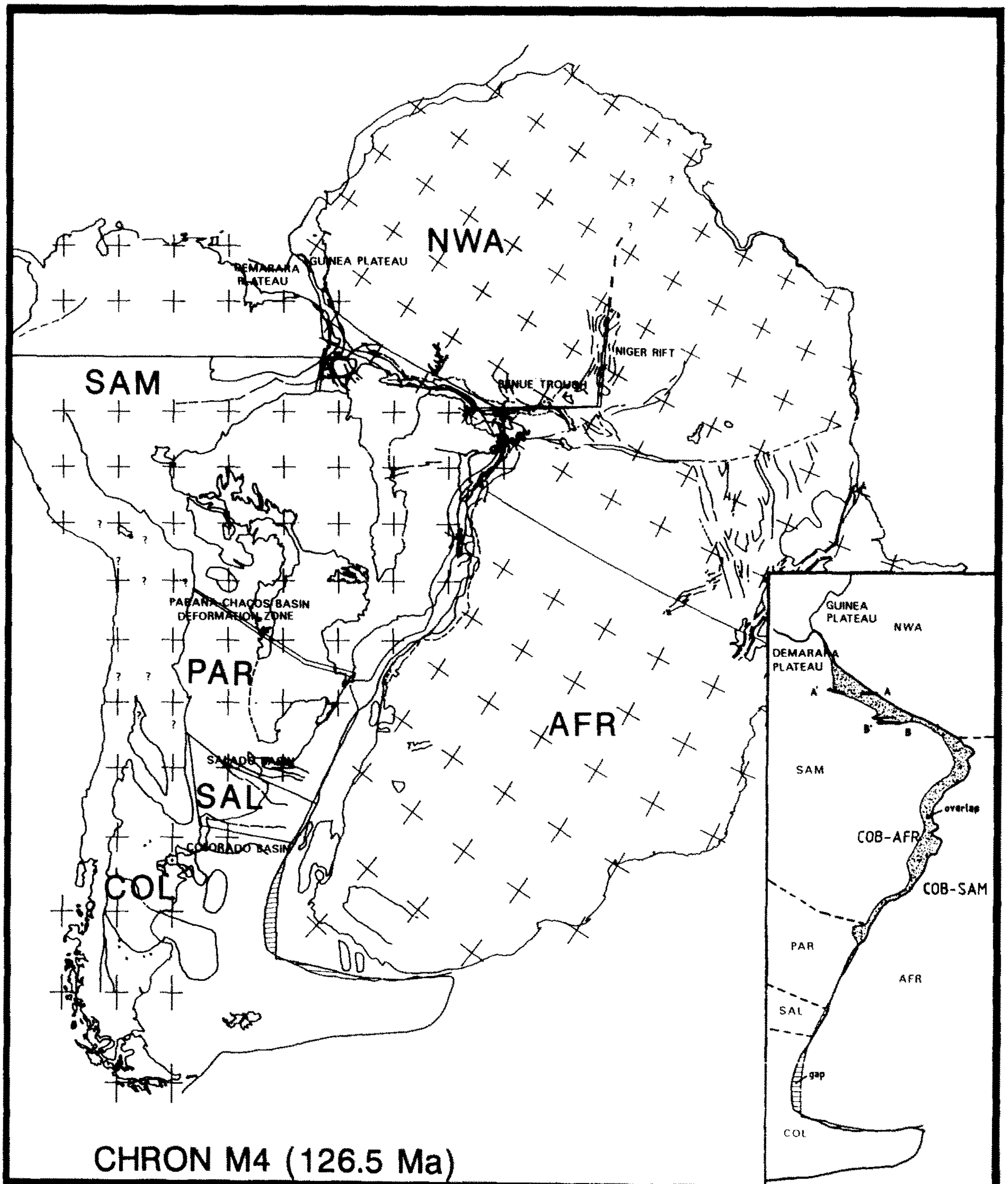


Fig. 11. Chron M4 (126.5 Ma, Hauterivian). The further northward propagation of South Atlantic rifting between 130 Ma (Hauterive) and Chron M4 (126.5 Ma) induced rifting combined with strike-slip motion along the Parana/Chacos Basin deformation zone in South America. At Chron M4, seafloor spreading has propagated up to 28°S. Rifting and strike-slip motion in the Salado and Colorado basins ceased at about Chron M4 (126.5 Ma) having generated 20–25 km and 40–45 km of crustal extension in the Salado Basin and Colorado Basin, respectively and 20 to 30 km of dextral strike-slip in both basins. For figure captions see Fig. 9.

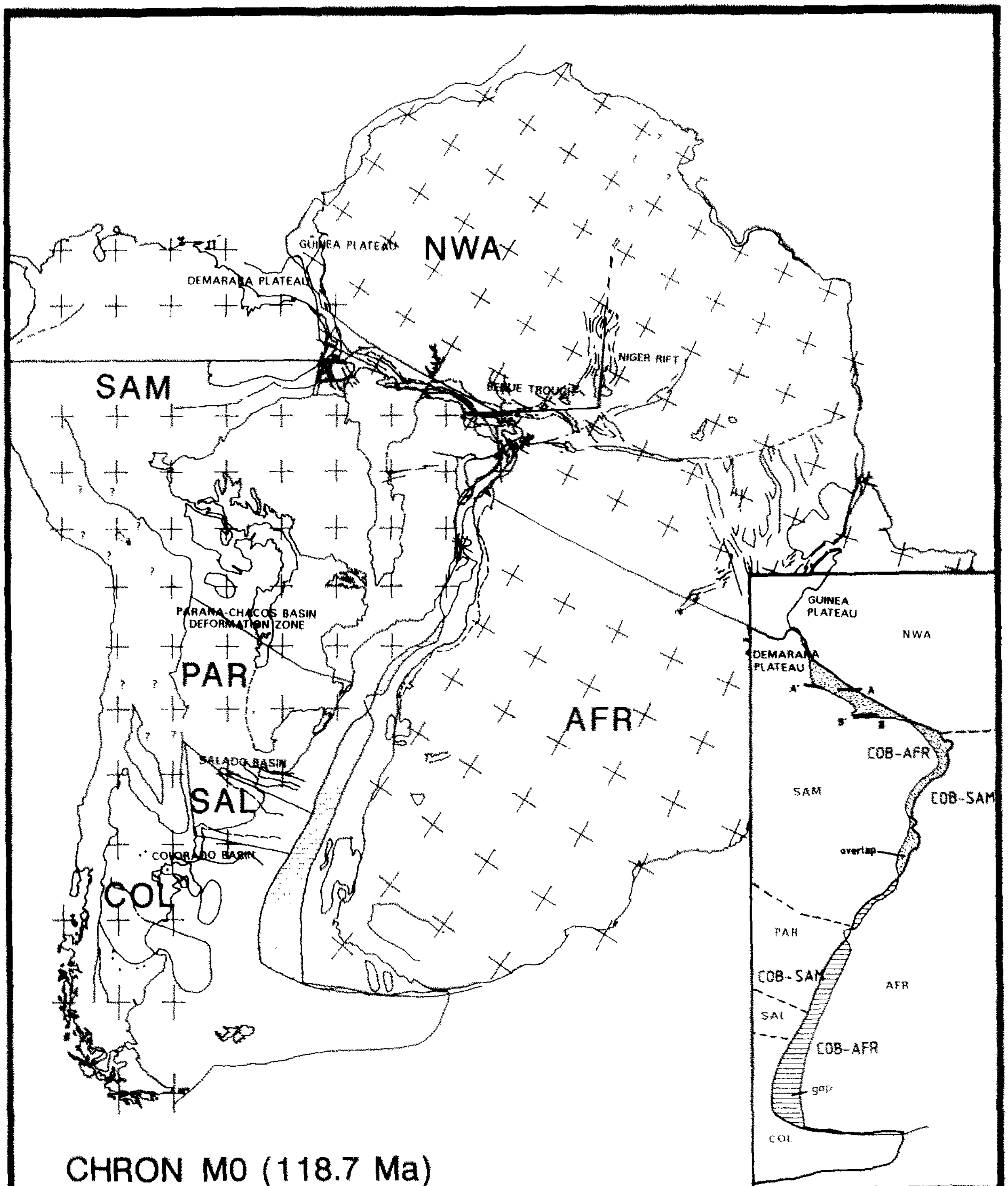


Fig. 12. Chron M0 (118.7 Ma, Aptian). Between Chrons M4 and M0, rifting propagated northward into the Benue Trough. The Benue Trough/Niger Rift system constitutes a large Crétaceous rift/sinistral strike-slip system that was active until 80 Ma B.P. (Fairhead and Okereke, 1987). At Chron M0 movements along the Parana/Chacos Basin deformation zone ceased, having generated 60 to 70 km of crustal extension and 20 to 30 km of dextral shear. Africa was still rigidly attached to South America in the equatorial Atlantic, since there is no evidence for sediments older than Aptian (Jones, 1987). For legend see Fig. 9.

LaBrecque (1979). At Chron M0 (118.7 Ma) movements along the Parana/Chacos Basin deformation zone ceased, having generated 60 to 70 km of crustal extension and 20 to 30 km of dextral shear.

After Chron M0 (118.7 Ma), the equatorial

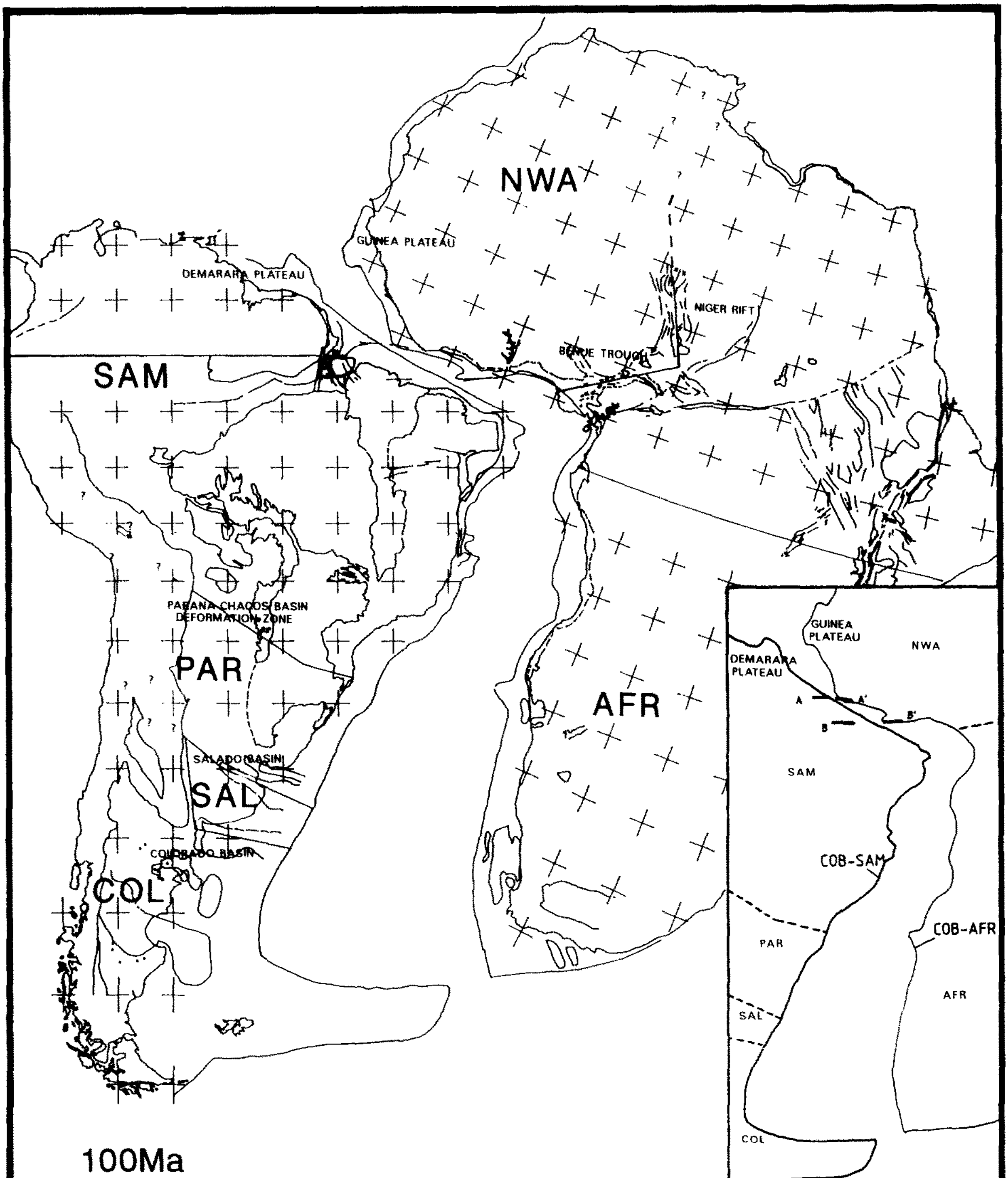


Fig. 13. 100 Ma (Albian). After Chron M0, the equatorial Atlantic began to open, connecting the South and Central Atlantic. Subsequently, South America behaved as a rigid plate, while intracontinental deformation in Africa was active until approximately 80 Ma (Late Crétaceous). For legend see Fig. 9.

Atlantic began to open. According to Mascle et al. (1988) continental rifting in the equatorial Atlantic resulted in the creation of small divergent basins in Aptian times characterized by thinned continental crust. Not until Late Albian to Early Cenomanian times (ca. 100 Ma), small oceanic

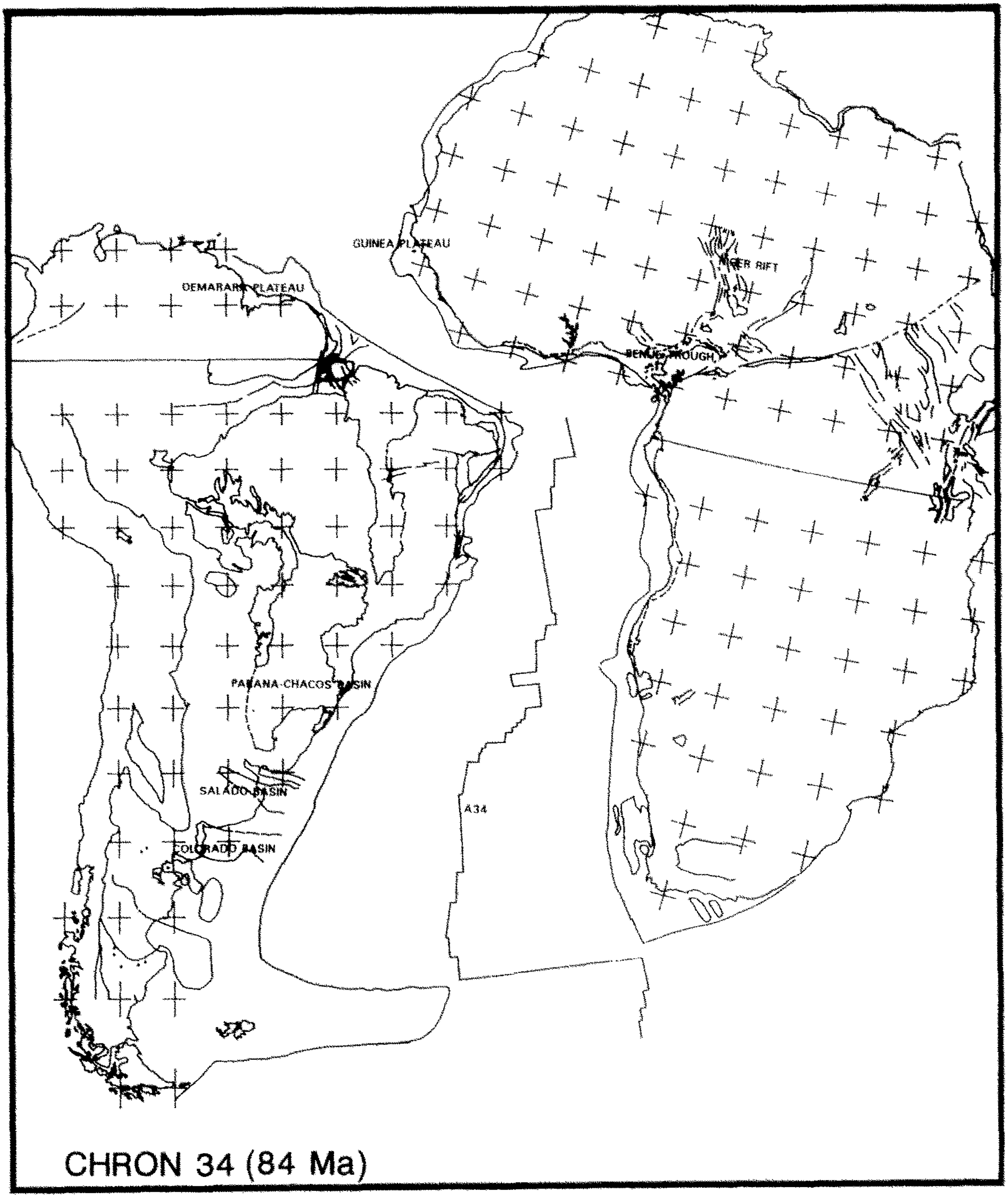


Fig. 14. Chron 34 (84 Ma, Campanian). Intracontinental movements ceased within Africa at approximately Chron 34 (84 Ma). In accordance with Fairhead and Okereke (1987), we propose 50–60 km of rifting combined with 40–50 km of sinistral strike-slip motion in the Benue Trough. After Chron 34, the South Atlantic is assumed to have opened as a two plate system.

basins were created establishing the final breach between the continental crusts of Brazil and Africa (Mascle et al., 1988; Popoff et al., 1989a). Paleo-current interconnection between the Central and the South Atlantic was established around Upper Albian times documented from the presence of

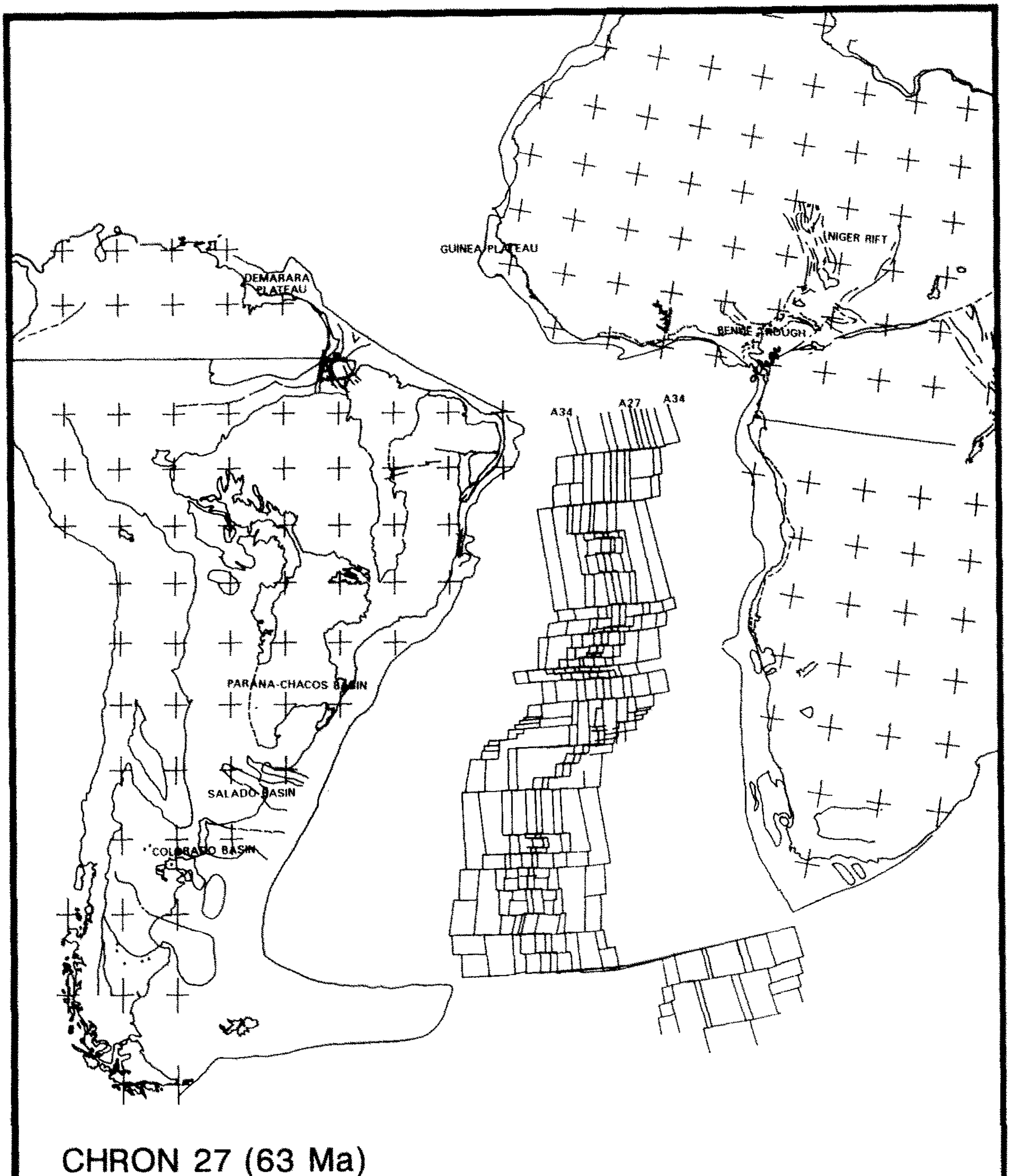


Fig. 15. Chron 27 (63Ma). The subsequent opening of the South Atlantic since Chron 34 (84 Ma) has been characterized by simple divergence of two continentel plates. At approximately Chron 27 (63 Ma), seafloor spreading rates reached a minimum during a period of slow spreading between Chron 30 (66.7 Ma) and Chron 20 (44.7 Ma), resulting in the creation of many new fracture zones.

Atlantic and Thethysian faunas (Wiedmann, 1978).

While intracontinental movements within Africa continued until about Chron 34 (84 Ma) (Fairhead and Okereke, 1987; Castro, 1987), rifting in the Salado and Colorado basins is assumed to have ceased at about Chron M4 (126.5 Ma),

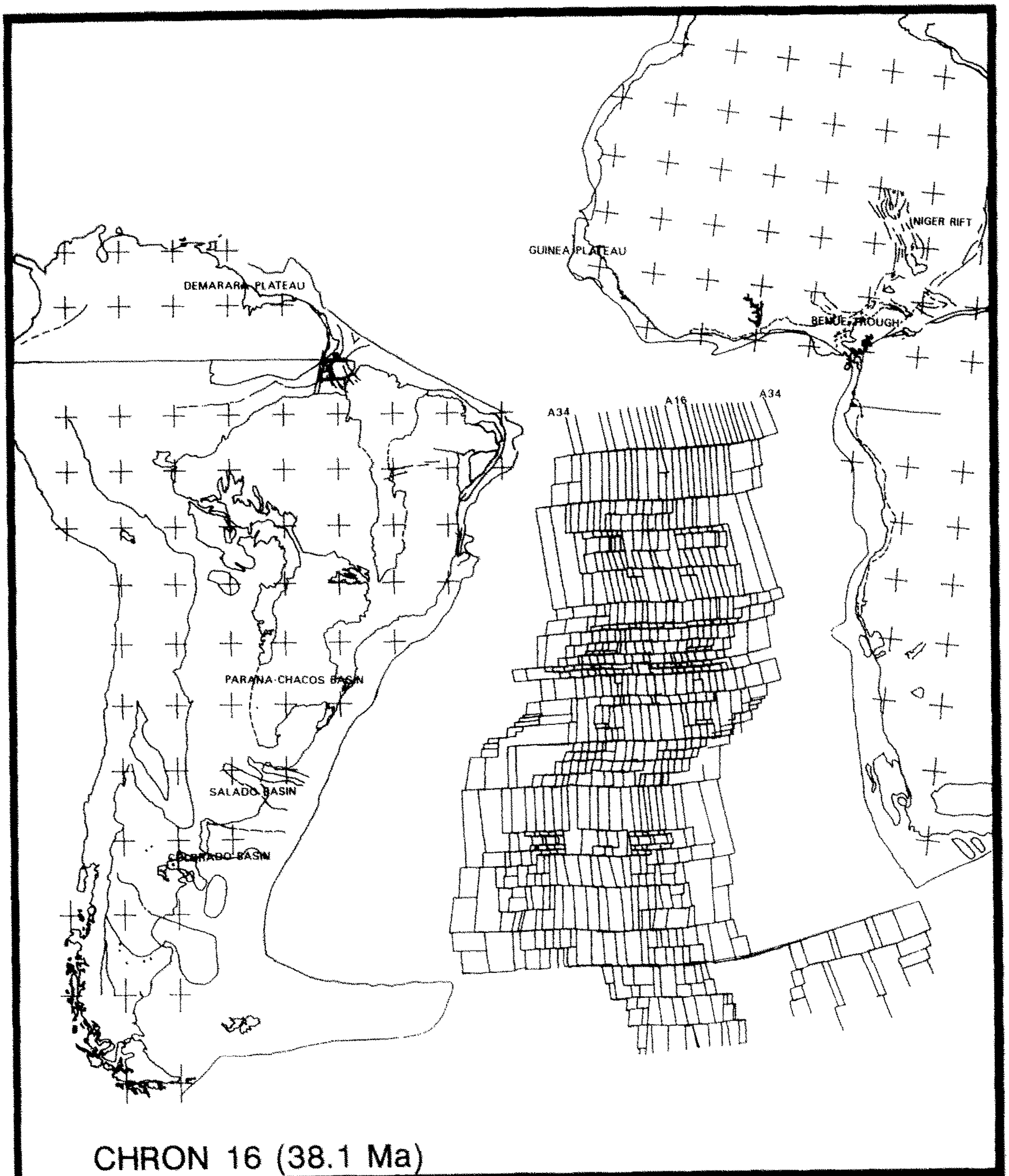


Fig. 16. Chron 16 (38.1 Ma). After Chron 20 (44.7 Ma), South Atlantic spreading rates accelerated, resulting in a decreasing number of fracture zones. A subtle S-shaped curve of the fracture zones throughout the Atlantic indicates a change in spreading direction during Eocene time at approximately Chron 16 (38.1 Ma).

having generated 20–25 km and 40–45 km of crustal extension in the Salado Basin and Colorado Basin, respectively, and 20 to 30 km of dextral strike-slip in both basins. Since Chron 34 (84 Ma) the South Atlantic has opened as a two plate system. The strike-slip/rift zones present during various times at the northernmost end of the propagating rift can be regarded as stress buffers that prevented the translation of compression into the region north of the rotation pole.

South Atlantic seafloor spreading since Chron 34

The subsequent opening of the South Atlantic since Chron 34 is characterized by simple divergence of two plates (Figs. 14–16). This simple spreading history is complicated by minor ridge jumps, fracture zone jumps as well as variations in seafloor spreading rate and direction. These reorganizations are reflected in the isochron map (Fig. 7).

In Fig. 17 we show spreading half-rates for the South Atlantic opening history along two synthetic flowlines starting at two points along the Mid-Atlantic ridge (0.5° N, 25.1° W and 39.9° S, 16.7° W). Spreading half rates were calculated using the finite rotation poles in Table 1. Fine scale fluctuations of half spreading rates in these graphs indicate considerable variations in seafloor spreading during the South Atlantic opening.

Between Chron M4 (126.5 Ma) and Chron 34 (84 Ma) spreading half rates increased to a maximum of 28–38 mm/yr at Chron 34. From this time, half rates gradually decreased, reaching a minimum of about 14–16 mm/yr (Chron 27 to 25) in the early Cenozoic. This period of slow spreading lasted from about Chron 30 (66.7 Ma) to Chron 21 (48.3 Ma), coincident with slow con-

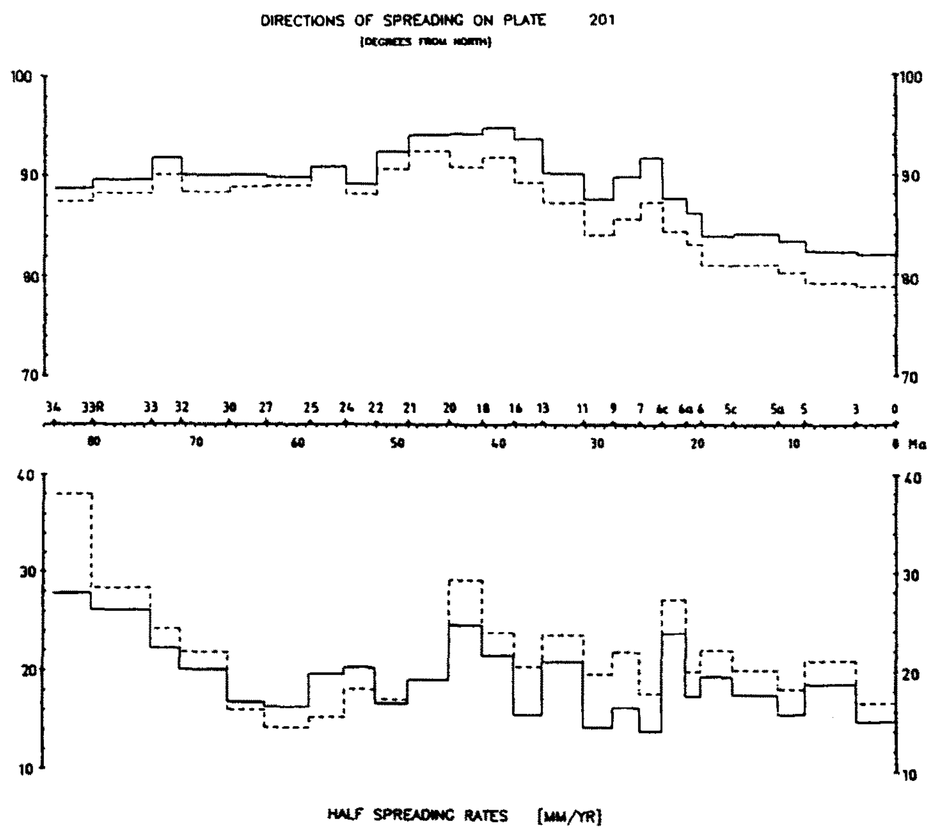


Fig. 17. Histograms showing spreading half-rates and spreading directions according to finite rotation poles in Table 1 (modified plate tectonic model of Cande et al., 1988). Spreading rates and directions are calculated along two synthetic flowlines starting at two points along the Mid-Atlantic ridge (0.5° N, 25.1° W—solid line; 39.9° S, 16.7° W—dashed line).

vergence between the Nazca and the South American plates (Pardo-Casas and Molnar, 1987) and resulting in the creation of many new fracture zones. An increase of spreading half-rates to 25–29 mm/yr at Chron 20 (44.7 Ma) resulting in a decreasing number of fracture zones is followed by fine scale fluctuations until present day, which, in general, show a decreasing trend.

The accuracy of the spreading history presented here is dependent on the accuracy of the magnetic polarity time-scale. Therefore, the interpretation of small-scale fluctuations in spreading rates is difficult (Cande et al., 1988). Either they represent real fluctuations or inaccuracies in the magnetic polarity time scale. However, a high-resolution aeromagnetic survey of the Mid-Atlantic ridge south of Ascension Island reveals short-term fluctuations in seafloor spreading (Brozena, 1986). A total opening rate of 47.4 km/Ma at 7 Ma is followed by decreasing rates down to 35 km/Ma at 2 Ma (Brozena, 1986).

In general, the magnetic anomaly pattern of the South Atlantic indicates asymmetrical spreading. According to Cande et al. (1988), spreading rates have been about 7% faster on the west flank of the South Atlantic than on the east flank since Chron 34, although this asymmetry in spreading rate cannot be regarded as spatially or temporally uniform (Cande et al., 1988).

In Fig. 17 we also show spreading directions in the South Atlantic along two synthetic flowlines starting at two points along the spreading axis corresponding to the finite rotation poles in Table 1. The ideal graphs of spreading direction versus time between times of reorganizations are assumed to be smooth curves, implying that the spreading history of an ocean basin is an evolutionary, gradual process. The slight modifications we have made to Cande et al.'s (1988) finite rotation poles smooth the spreading direction curve of the South Atlantic considerably and do not imply rapid changes in spreading direction, except at distinct events of plate tectonic reorganizations.

Important changes in spreading direction are documented in the flowline pattern revealed by Geosat lineations and are expressed in the reorientations of the spreading direction in Fig. 17, as well as in the isochrons (Fig. 7). For example, a subtle S-shaped curve of the fracture zones throughout the South Atlantic indicate changes in spreading direction during the Early Cretaceous (at about Chron 32) and during Eocene times (at about Chron 16).

Conclusions

In this study, we present a conclusive model for the tectonic evolution of the South Atlantic from Late Jurassic to present that is consistent with all available geological and geophysical data. To improve previous fit-reconstructions of the continents around the South Atlantic, we assume nonrigidity of continental plates. Large intracontinental deformation zones within South America and Africa are suggested to have been active during the breakup of these continents.

We propose a stepwise northward propagating rift for the South Atlantic. In the first rift phase between 150 and 130 Ma the rift propagated from the southernmost tip of South America to about 38°S, causing continental stretching and dextral strike-slip motion within the South American Salado and Colorado basins. This tectonic activity did not cease before Chron M4, having generated 20–25 km and 40–45 km of crustal extension in the Salado Basin and Colorado Basin, respectively, and 20–30 km of dextral displacement in both basins. At about 130 Ma, rift and strike-slip motion started along the South American Parana/Chacos Basin deformation zone related to further northward propagation of the South Atlantic rift up to 28°S. North of this rift, Africa and South America are assumed to have been rigidly attached until Chron M4. Between Chron M4 and Chron M0 rifting propagated northward into the Benue Trough. The equatorial Atlantic did not open before Aptian time (118.7 Ma). Thus, the extension generated in the South Atlantic had to be taken up by continental stretching and sinistral strike-slip motion in the Benue Trough/Niger Rift system. Tectonic activity along the Parana/Chacos Basin deformation zone ceased at Chron MO, having generated 60–70 km of crustal extension and 20–30 km of dextral shear. After Chron MO, the equatorial Atlantic began to open, while intracontinental movements within Africa continued until about Chron 34. Since then, the South Atlantic opened as a simple two plate system.

By combining magnetic anomaly picks, Geosat altimetry data and onshore geologic data we have constructed a selfconsistant model for the early opening of the South Atlantic as well as a high-resolution isochron chart for the South Atlantic ocean floor that shows variable fracture zone spacing through time as well as subtle changes in spreading direction. The series of finite rotation poles proposed in this paper results in a plate-kinematic model without severe, short-term changes in directions of relative plate motions as proposed previously. Hence our results for the time interval from Chron 34 to present day concur with Shaw and Cande's (1990) conclusion that available data do not support a model of erratic changes in sea floor spreading directions in the South Atlantic.

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