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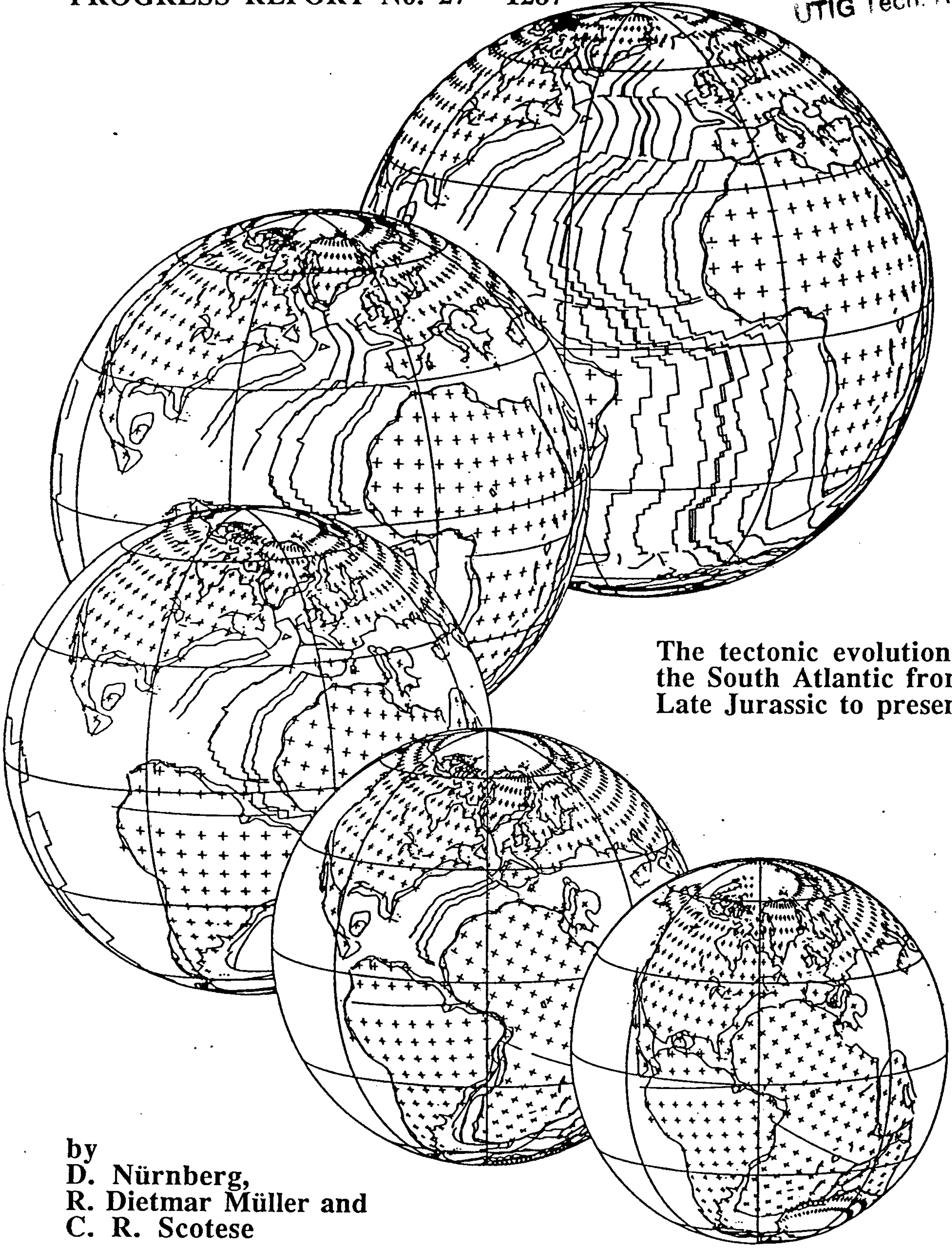

The tectonic evolution of the South Atlantic from Late Jurassic to present

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Abstract

The breakup of the continents around the South Atlantic was characterized by a stepwise, northward-propagating rift system, beginning in the southernmost South Atlantic. 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-Andean Cochabamba deformation zone, 2. within marginal basins in South America (Salado, Colorado basins), 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 predicts 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-Andean Cochabamba line. Between Chron M4 and Chron M0 (118.7 Ma) rifting propagated into the Benue Trough and Niger Rift, inducing rift and strike slip motion. After Chron M0 (118.7 Ma), 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, as shown in our set of revised seafloor spreading isochrons.

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 & LaBrecque, 1979, Pindel et al., 1982). Only few plate models for the early opening history of the South Atlantic to present day have been published. Dickson et al. (1968) showed 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 and published finite rotation poles between North America and Africa (Pitman & Talwani, 1972). 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 breakup history. Previous fit reconstructions of 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 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 modified from a recent compilation of magnetic anomaly picks in the South Atlantic (Cande et al., in prep., Rabinowitz & LaBrecque, 1979, Barker, 1979, Martin et al., 1982). Satellite altimetry data, in addition, provide useful constraints for evaluating the position and the direction of fracture zone lineaments. Seasat data were used to evaluate finite rotation poles by comparing the strike of Seasat lineations with small circles calculated from stage poles.

We combined magnetic anomaly data with Satellite altimetry data to derive an improved tectonic database for the South Atlantic. Using the 3D graphic capabilities of an interactive Evans and Sutherland computer system, we used this database to obtain a high resolution plate kinematic model for the South Atlantic (Figs. 12 to 20). The rotation parameters and tectonic database for this model are on the magnetic tape distributed with this update.

Database

1. Magnetic anomaly data

A new compilation of magnetic anomaly picks and lineations in the South Atlantic (Cande et al., in prep., see also Barker, 1979, LaBrecque & Hayes, 1979, Rabinowitz & LaBrecque, 1979, Martin et al., 1982) was used to construct isochrons of seafloor spreading (Fig. 1 and 2). Ages of magnetic anomalies were taken from the timescale of Kent & Gradstein (1986). Magnetic anomaly pick locations for A34 to A3 correspond to the young end of the normal polarity interval (Cande et al., in prep.). In the Agulhas Basin (Barker, 1979, LaBrecque & Hayes, 1979), picks are defined by the old end of the normal polarity interval. Magnetic anomaly data in the Agulhas Basin was partly reinterpreted using profiles from Barker (1979) and LaBrecque & Hayes (1979).

2. Satellite altimetry data

A tectonic fabric map for the South Atlantic ocean floor (Gahagan et al., in prep.) was derived from Seasat altimetry data used in the form of the "along track deflection of the vertical" (Sandwell 1984) (Fig. 1). The processing technique of the Seasat data is discussed in Gahagan et al. (in prep., see POMP Progress Report No. 32). Geosat altimetry data alone was used to better identify fracture zone locations in the Agulhas Basin.

Methods

1. Tectonic fabric map

The tectonic fabric map of the South Atlantic (Fig. 1), based on the first derivative of the measured sea surface, delineates features such as fracture zones, volcanic ridges, marginal basins and seamounts. Outlined blue and red lines represent positive and negative steep slopes in the geoid as viewed to northeast, whereas hatched areas reflect broad zones of geoid anomalies. A discussion of how to determine the location of fracture zones from these linear geoid features is found in POMP Progress Report No. 21-0687 (Müller et al., 1987). The common occurence of closely spaced pairs of red and blue Seasat lineations indicates that fracture zone central valleys are the most prominent features of South Atlantic fracture zones.

Most Seasat lineations in the South Atlantic are interrupted and discontinuous. The data in the Argentine, Brazil, Cape and Angola Basins are especially sparse. Nevertheless, some prominent fracture zones show relatively continuous pairs of red and blue lineations, which can be traced nearly from one continental margin to the other. The locations of less prominent fracture zones were derived from offsets in lines of magnetic anomalies, from Seasat altimetry data and by comparison to younger and older isochrons.

2. Derivation of rotation poles

Cande et al. (in prep.) calculated 45 finite rotation poles between Chron A34 and Chron A3, each representing an average time interval of less than 2 Ma. Most of Cande et al.'s (in prep.) poles satisfy the data constraints. The poles for magnetic anomalies 6a, 6c, 11, 16, 20, 25, however, were slightly modified. We used the "Hierarchical Tectonic Analysis" method (Ross & Scotese, in press) to determine new finite rotation poles by fitting pairs of corresponding magnetic anomalies and pairs of Seasat lineation trends that belong to prominent fracture zones. Stage poles, calculated from these finite rotation poles, were used to derive small circles for every stage. These small circles should parallel Seasat lineations for each specific stage (Table 2). If small circles and Seasat lineations deviated significantly, we improved the finite rotation poles (Table 1).

In addition to finite rotation poles fitting magnetic lineations for Chron A34 to Chron A3, finite poles of rotation for Chron M0, Chron M4, and the fit reconstruction 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 in the southernmost South Atlantic published by Rabinowitz & LaBrecque (1979), Martin et al. (1982) and Cande et al. (in prep.).

3. Construction of isochrons and fracture zones

The method of constructing seafloor spreading isochrons is described in POMP Progress Report No. 21-0687 (Müller et al., 1987). Isochrons are shown for Chrons 3, 5, 5a, 5c, 6, 6a, 6c, 7, 9, 11, 13, 16, 18, 20, 21, 22, 24, 25, 27, 30, 32, 33 and 34 (Fig. 1). In addition, synthetic flowlines of fracture zones for each stage have been constructed along corresponding small circles.

Geological and geophysical constraints for the fit reconstruction

Onshore geologic data, the oceanic/continental crust boundary, the shape of the Guinea and Demarara plateaus, and equatorial fracture zone extensions on the continental shelves (POMP Progress Report No. 22-0787) were used as tie points for the fit reconstruction. Upper Cretaceous magnetic anomaly data in the southern South Atlantic were used to constrain the early opening phase.

1. Onshore geologic data

The Precambrian Pernambuco lineament in Brazil and the Cameroon volcanic line in Africa, both reactivated during the initial phase of the South Atlantic opening, are assumed to have a common origin (Emery & Uchupi, 1984).

2. Oceanic/continental crust boundary

The continental margins of South America and Africa have not been palinspastically restored yet, so we used the oceanic/continental crust boundary (OCB) of Emery & Uchupi (1984). The OCB on the South American side was slightly modified between 20°S and 30°S according to Seasat altimetry data. Emery & Uchupi (1984) mapped the seaward edge of the South American salt basins as the OCB. However, Seasat lineations give clear evidence for a large part of the salt being deposited or mobilized onto oceanic crust.

3. Guinea and Demara Plateaus

A gap between the Guinea and Demarara plateaus before Aptian times is unlikely (Jones 1987, Mascle & Blarez, 1987). The fracture zone pattern and the interpretation of deep water sediments in the equatorial Atlantic from seismic stratigraphy do not permit a gap between the African and Brazilian margins during the lower Cretaceous opening of the South Atlantic.

4. Extensions of fracture zones on continental shelves

Four prominent fracture zones, the St. Paul (AA'), Romanche (BB') and Chain (CC') fracture zones in the equatorial and the Ascension fracture zone (DD') in the northernmost South Atlantic as interpreted from Seasat altimetry data, can be traced from the South American to the African continental margin (Fig. 1). A detailed description of these fracture zones is given in POMP Progress Report No. 22-0787 (Nürnberg et al. 1987).

Fit position of the continents around the South Atlantic

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 assuming intracontinental deformation during the initial opening of the South Atlantic. In accordance with geological and geophysical data, we propose rift motion combined with minor strike slip movement along three intracontinental zones of weakness:

1. Benue Trough / Niger Rift system in Africa interpreted from gravity studies (Fairhead, in press, Fairhead & Okereke, 1987),
2. Intracontinental deformation zone within South America proposed by Unternehr et al. (in press) extending from the Parana and Chacos Basin volcanics to the Andean Cochabamba-Santa Cruz Bend,
3. Marginal basins in South America (Salado and Colorado Basins), whose sedimentary fill and fault pattern indicate intensive rifting processes (Urien & Zambrano, 1974).

Movements along these deformation zones are considered to have taken place simultaneously with the breakup of the continents.

1. Rift motion in Africa

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 (Fig. 3). According to Fairhead (in press) 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. During the Neocomian, the trough was not an effective depo-center (Castro, 1987). 50 km of strike slip motion are proposed by Fairhead (in press). The Benue Trough is assumed to belong to a post-Jurassic intracontinental plate boundary (Pindel & Dewey, 1982, Pindel et al., 1985, Fairhead, in press) between northwestern Africa and southern Africa together with the Gongola and Niger Rift, which are thought to be the inland extensions of the Benue Trough blanketed by a thick Cenozoic sediment cover (Fairhead, in press) (Fig. 4). Pindel & 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, in press), is assumed to not have any activity during the early opening of the South Atlantic. According to Fairhead (in press), the Central African Shear Zone (CASZ) extends about 2000 km across Africa from the Gulf of Guinea through Cameroon, Chad, and the Central African Republic into Sudan (Fig. 4). A rejuvenation of this Precambrian lineament in Late Cretaceous/early Tertiary times (Fairhead, in press) has dextral displacement (Ngangom, 1983, Cornacchia & Dars, 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). Only a faster motion of the African subplate north of the CASZ relative to the eastward moving southern African plate could explain dextral shear, which may have been caused by a compressional stress regime between northeastern and southern Africa. This, however, does not affect the fit reconstruction.

2. Intracontinental deformation zones in South America

Parana Basin-Andean Cochabamba/Santa Cruz Bend shear zone

Unternehr et al. (in press) propose an intraplate deformation zone within South America extending from the South American Parana and Chacos Basins to the Andean Cochabamba / Santa Cruz Bend (Fig. 5). 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. Although direct geological evidence is rare (see POMP Project Report No. 22-0787), Unternehr et al. (in press) suggest 150 km of dextral strike slip motion along this proposed second order plate boundary.

Rift basins within South America

According to Urien & 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 & 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 Upper Jurassic (Urien & Zambrano, 1974) support the model of rift movements in both basins during the early opening phase of the South Atlantic (Fig. 6,7, and 8).

3. How we derived our fit

We started with a fit reconstruction of the equatorial Atlantic (Table 1), which matches the Guinea and Demarara Plateaus as well as equatorial fracture zone extensions interpreted from Seasat altimetry data (see POMP Project Report 22-0787). 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 75 km of rifting, 50 km of sinistral shear movement 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 (in press) and Fairhead & Okereke (1987). The opening of the Benue Trough and Niger Rift implies a compressional phase in North Africa. Geologic data for which were not available to us. The proposed rotation results in a large overlap of the African and South American oceanic/continental 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 (Fig. 9) consist of a series of half grabens, characterized by a rift phase sedimentation that started during the late Jurassic/early Cretaceous (Castro, 1987), usually with pre-Aptian sediments (Fig. 10). Tectonic activity and sedimentation in these basins ceased during the lower 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 a 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-Cochabamba intracontinental deformation zone outlined by Unternehr et al (in press). As the amounts for strike slip and rift motion along this line are very uncertain, we tried to minimize the amount of motion to 50-60 km of rifting and 40-50 km of strike slip. Hence, we imply less tectonic movement along this deformation zone than Sibuet et al. (1984) and Unternehr et al. (in press), 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 fit very well. In order to close a still remaining 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 40 km and 60 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. 12).

South Atlantic opening

1. The initial opening: a propagating rift system

Starting from the fit reconstruction already described, we suggest a stepwise, northward-propagating rift for the South Atlantic (Fig. 12-16). 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 (Urien & Zambrano, 1973) supports this assumption. At about 130 Ma, rifting combined with dextral strike slip motion is assumed to have started along the Parana Basin - Andean Cochabamba/Santa Cruz Bend deformation zone proposed by Unternehr et al. (in press). 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 be 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). The extension south of the equatorial Atlantic was taken up by continental stretching and sinistral strike slip motion in the Benue Trough/Niger Rift System, which is in accordance with Fairhead & Okereke (1987) and Fairhead (in press). A compressional phase in the equatorial Atlantic, proposed earlier by Rabinowitz & LaBrecque (1979), is not evident (Castro, 1987) (Fig. 11). At Chron M0 (118.7 Ma) movements along the Parana Basin - Andean Cochabamba / Santa Cruz Bend deformation zone ceased, having generated 50 to 60 km of crustal extension and 40 to 50 km of dextral shear.

After Chron M0 (118.7 Ma), the equatorial Atlantic began to open, connecting the South and Central Atlantic. While intracontinental movements within Africa continued until about Chron A34 (84 Ma) (Fairhead & Okereke, 1987, Castro, 1987), rifting in the Salado and Colorado Basins is assumed to have ceased at about Chron M4 (126.5 Ma), having generated 40 km and 60 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 A34 (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.

2. South Atlantic seafloor spreading since Chron A34

The subsequent opening of the South Atlantic since Chron A34 is characterized by simple divergence of two continental plates (Fig. 17-20). This simple spreading history is complicated by ridge jumps, fracture zone jumps as well as variations in seafloor spreading rate and direction. These reorganizations are reflected in the isochron map (Fig. 1).

Ridge jumps

The most obvious ridge jump in the South Atlantic occurred along the Falkland/Agulhas Fracture Zone (FAFZ). Magnetic anomaly picks from Chron M10 to Chron M0 time, discovered 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).

The interpretation of magnetic anomaly data in the Agulhas Basin lead Labrecque & Hayes (1979) to the assumption of a short-lived, independently acting Malvinas Plate existing between Chron A34 and Chron A31. 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) (Fig. 21), and may have caused convergence of the two plates along the northeastern Georgia Rise. Thus, 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 & Hayes, 1979).

A reinterpretation of Agulhas Basin magnetic anomaly data (J.-Y. Royer, pers. comm.) in combination with Geosat altimetry data, however, does not support the existence of the Malvinas Plate. According to our interpretation, the Agulhas Basin isochrons trend NW-SE with fracture zones parallel to the FAFZ (Fig. 1). Stage poles fitting the A34, A33 and A32 magnetic anomaly picks in the Agulhas Basin have the same small circles as the South Atlantic spreading center at that time. Thus, magnetic anomaly lineations in the Agulhas Basin as well as in the South Atlantic north of the FAFZ were generated by the same spreading system.

We propose that seafloor spreading in the Agulhas Basin was initiated at Chron A34 time and stopped at approximately Chron A28 time. Subsequently, the spreading ridge jumped westward creating the Meteor Rise and the Islas Orcadas Rise between Chron A27 and Chron A25. Since Chron A24, isochrons up to Chron A3 are generated successively in the South Atlantic south of the FAFZ.

A second prominent ridge crest jump took place south of the Rio Grande Rise (LaBrecque & Brozena, in press), leaving a 200 km long fossil spreading center at Chron A32 time (Cande et al, in prep.). After Chron A32, this spreading center jumped eastward.

Fracture zone jumps

Our interpretation of magnetic anomaly data and satellite-derived tectonic fabric maps reveals two fracture zone jumps in the South Atlantic. Between Chron A21 (48.8 Ma) and Chron A20 (44.7 Ma), the Tristan de Cunha Fracture Zone jumped slightly to the north at 29°S, 28°W. This tectonic event coincided with increasing spreading rates during this time, probably due to a global plate reorganization event around Chron A21.

A second minor fracture zone jump took place east of the Rio Grande Rise at 33°S, 22°W in the vicinity of the fossil spreading center described above. Here, the fracture zone jumped slightly to the south between Chron A16 (38.1 Ma) and Chron A13 (35.3 Ma). A change in South Atlantic spreading direction is observed at this time as well.

Variations in seafloor spreading half-rates

In Fig. 22, we show spreading half-rates for the South Atlantic opening history along two synthetic flowlines starting at two points along the Mid-Atlantic ridge (0.5N, 25.1W and 39.9S, 16.7W). Spreading half-rates were calculated using the finite rotation poles in Table 1 and the poles of Cande et al.'s (in prep.) plate tectonic model (Fig. 23). 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 A34 (84 Ma), spreading half-rates increased to a maximum of 28-38 mm/yr at Chron A34. From this time, half-rates gradually decreased, reaching a minimum of about 14-16 mm/yr (Chron A27 to A25) in the early Cenozoic. This period of slow spreading lasted from about Chron A30 (66.7 Ma) to Chron A21 (48.8 Ma), coincident with slow convergence between the Nazca and the South American plates (Pardo-Casas & Molnar, 1987). A sudden increase of spreading half-rates to 25-29 mm/yr at Chron 20 (44.7 Ma) 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 highly dependent on the accuracy of the magnetic polarity timescale. Therefore, the interpretation of small scale fluctuations in spreading rates is difficult to support (Cande et al, in prep.). Either they represent real fluctuations or inaccuracies in the magnetic polarity timescale. 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. Acording to Cande et al. (in prep.), spreading rates have been about 7% faster on the west flank of the South Atlantic than on the east flank since Chron A34, although this asymmetry in spreading rate cannot be regarded as spatially or temporally uniform (Cande et al., in prep.).

Variations in spreading direction

In Fig. 22, we also show spreading directions for the South Atlantic along two synthetic flowlines starting at two points along the spreading axis (0.5N, 25.1W and 39.9S, 16.7W) corresponding to the finite rotation poles in Table 1. In Fig. 23 we calculated spreading directions for the plate tectonic model of Cande et al. (in prep.).

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 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 Seasat lineations and are expressed in the reorientations of the spreading direction in Fig. 22, as well as in the isochrons (Fig. 1). 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).

Identifications of Fracture zones

The simple model of fracture zones represented by steps in the basement 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.

Since closely spaced pairs of red and blue Seasat lineations are characteristic of the South Atlantic, we assume central bathymetric valleys rather than basement steps to be the most common morphologic 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 & Rabinowitz, 1981). However, only a few continuous pairs of red and blue Seasat lineations allow us to follow 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.

An interesting observation made after carefully examining the data is that the distribution and number of fracture zones is a function of spreading velocity. During the fast spreading between Chron A34 and Chron A32, only a few fracture zones could be identified (Fig. 24). For crust created during the slow spreading time after Chron A30, many additional fracture zones are observed, confirmed by offsets in the magnetic anomaly picks and Seasat lineations. This increased number of fracture zones lasted until approximately Chron A20, when spreading rates again accelerated. After Chron A20, several fracture zones disappear or decrease their offset. This interval of reduced spreading rate coincides with a noticeable increasing in basement roughness, which may be attributed to an increase in the age offset across the fracture zones as spreading slows down (Cande et al., in prep.). A cooler and necessarily more brittle oceanic plate during periods of slow spreading may explain the increasing amount of fracture zones.

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Table 1: Finite reconstruction poles for the following South American and African subplates with respect to Africa and South America, respectively: South America (201), Parana Plate (202), Salado Plate (290), Colorado Plate (291), southern Africa (701), northwestern Africa (714)

Mobil Plate	Age	Lat.	Long.	Angle	Ref. Plate	Description
201	3.88	60.00	-39.00	1.21	701	! SAM-AFR AN 3 CANDE et al.1987
201	8.92	60.00	-39.00	3.15	701	! SAM-AFR AN 5 CANDE et al.1987
201	11.55	59.50	-38.00	4.05	701	! SAM-AFR AN 5A CANDE et al.1987
201	16.22	59.50	-38.00	5.75	701	! SAM-AFR AN 5C CANDE et al.1987
201	19.35	59.50	-38.00	7.05	701	! SAM-AFR AN 6 CANDE et al.1987
201	20.88	59.50	-37.75	7.60	701	! SAM-AFR AN 6A CANDE modified
201	23.27	59.50	-37.00	8.80	701	! SAM-AFR AN 6C CANDE modified
201	25.50	59.00	-36.00	9.50	701	! SAM-AFR AN 7 CANDE et al.1987
201	28.15	58.00	-35.00	10.55	701	! SAM-AFR AN 9 CANDE et al.1987
201	31.23	57.00	-34.50	11.60	701	! SAM-AFR AN 11 CANDE modified
201	35.29	57.50	-34.00	13.38	701	! SAM-AFR AN 13 CANDE et al.1987
201	38.10	57.00	-33.25	14.40	701	! SAM-AFR AN 16 CANDE modified
201	41.29	57.50	-32.50	15.80	701	! SAM-AFR AN 18 CANDE et al.1987
201	44.66	57.50	-31.75	17.60	701	! SAM-AFR AN 20 CANDE modified
201	48.75	58.50	-31.50	19.07	701	! SAM-AFR AN 21 CANDE et al.1987
201	51.95	59.00	-31.50	20.10	701	! SAM-AFR AN 22 CANDE et al.1987
201	55.14	60.00	-32.00	21.20	701	! SAM-AFR AN 24 CANDE et al.1987
201	58.64	61.50	-32.50	22.30	701	! SAM-AFR AN 25 CANDE modified
201	63.03	62.50	-33.00	23.55	701	! SAM-AFR AN 27 CANDE et al.1987
201	65.50	63.00	-33.30	24.30	701	! SAM-AFR AN 29 CANDE et al.1987
201	66.74	63.00	-33.30	24.70	701	! SAM-AFR AN 30 CANDE et al.1987
201	71.37	63.00	-33.50	26.60	701	! SAM-AFR AN 32 CANDE et al.1987
201	74.30	63.00	-33.50	27.90	701	! SAM-AFR AN 33 CANDE et al.1987
201	80.17	63.00	-34.00	31.00	701	! SAM-AFR AN 33R CANDE et al.1987
201	84.00	61.75	-34.00	33.50	701	! SAM-AFR AN 34 CANDE et al.1987
201	118.70	51.66	-33.05	52.71	701	! SAM-AFR M0
201	121.00	50.09	-31.92	53.36	701	! SAM-AFR M2
201	126.50	49.99	-31.19	54.35	701	! SAM-AFR M4
201	150.00	49.99	-31.19	54.35	701	! SAM-AFR FIT
201	245.00	50.57	-32.02	53.00	701	! SAM-AFR
202	118.7	0.00	0.00	0.00	201	! PARANA PLATE-SAM M0
202	126.5	6.66	-68.00	0.60	201	! PARANA PLATE-SAM M4
202	131.5	6.66	-68.00	1.00	201	! PARANA PLATE-SAM M10
202	245.0	6.66	-68.00	1.00	201	! PARANA PLATE-SAM
290	126.5	0.00	0.00	0.00	202	! SALADO SUBPLATE-PARANA PLATE M4
290	150.0	-16.77	-64.57	1.42	202	! SALADO SUBPLATE-PARANA PLATE FIT
290	245.0	0.0	0.0	0.0	202	! SALADO SUBPLATE-PARANA PLATE
291	126.5	0.00	0.00	0.00	202	! COLORADO SUBPLATE-PARANA PLATE M4
291	150.0	-23.41	-66.05	3.30	202	! COLORADO SUBPLATE-PARANA PLATE
291	245.0	0.0	0.0	0.0	202	! COLORADO SUBPLATE-PARANA PLATE
714	84.0	0.00	0.00	0.00	701	! NWAFR-SAFR A34
714	118.7	19.56	8.66	2.55	701	! NWAFR-SAFR M0
714	118.7	53.38	-35.08	-50.96	201	! NWAFR-SAM M0
714	245.0	53.38	-35.08	-50.96	201	! NWAFR-SAM FIT

Table 2: Finite rotation poles and stage poles for the South Atlantic used in our model.

MOB. plate: 201, REF. plate: 701

Data points where directions & rates of spreading are calculated :
2 .45 -25.11 -39.94 -16.70

These points are on ISOCHRON# 0 and PLATE ID# 201

<u>Finite rotations</u> :

Chron	Age	Lat.	Long.	Angle	!	
0	.00	.00	.00	.00	!	PRESENT-DAY
3	3.90	60.00	-39.00	1.21	!	SAM-AFR AN 3 CANDE et al.1987
5	8.90	60.00	-39.00	3.15	!	SAM-AFR AN 5 CANDE et al.1987
51	11.60	59.50	-38.50	4.05	!	SAM-AFR AN 5A CANDE et al.1987
53	16.20	59.50	-38.00	5.75	!	SAM-AFR AN 5C CANDE et al.1987
6	19.40	59.50	-38.00	7.05	!	SAM-AFR AN 6 CANDE et al.1987
61	20.90	59.50	-37.75	7.60	!	SAM-AFR AN 6A CANDE et al.1987
63	23.30	59.50	-37.00	8.80	!	SAM-AFR AN 6C CANDE et al.1987
7	25.50	59.00	-36.00	9.50	!	SAM-AFR AN 7 CANDE et al.1987
9	28.20	58.00	-35.00	10.55	!	SAM-AFR AN 9 CANDE et al.1987
11	31.20	57.00	-34.50	11.60	!	SAM-AFR AN 11 CANDE et al.1987
13	35.30	57.50	-34.00	13.38	!	SAM-AFR AN 13 CANDE et al.1987
16	38.10	57.00	-33.25	14.40	!	SAM-AFR AN 16 CANDE et al.1987
18	41.30	57.50	-32.50	15.80	!	SAM-AFR AN 18 CANDE et al.1987
20	44.70	57.50	-31.75	17.60	!	SAM-AFR AN 20 CANDE et al.1987
21	48.80	58.50	-31.50	19.07	!	SAM-AFR AN 21 CANDE et al.1987
22	52.00	59.00	-31.50	20.10	!	SAM-AFR AN 22 CANDE et al.1987
24	55.10	60.00	-32.00	21.20	!	SAM-AFR AN 24 CANDE et al.1987
25	58.60	61.50	-32.50	22.30	!	SAM-AFR AN 25 CANDE et al.1987
27	63.00	62.50	-33.00	23.55	!	SAM-AFR AN 27 CANDE et al.1987
30	66.70	63.00	-33.30	24.70	!	SAM-AFR AN 30 CANDE et al.1987
32	71.40	63.00	-33.50	26.60	!	SAM-AFR AN 32 CANDE et al.1987
33	74.30	63.00	-33.50	27.90	!	SAM-AFR AN 33 CANDE et al.1987
333	80.20	63.00	-34.00	31.00	!	SAM-AFR AN 33R CANDE et al.1987
34	84.00	61.75	-34.00	33.50	!	SAM-AFR AN 34 CANDE et al.1987

<u>Stage poles for plate 201</u>

A1	A2	T1	DT	Lat	Lon	Angle	Dist	V	Dir	Dist	V	Dir
0	3	.00	3.90	60.0	-39.0	1.21	61.	30.	82.	102.	34.	79.
3	5	3.90	5.00	60.0	-39.0	1.94	61.	38.	82.	102.	42.	79.
5	51	8.90	2.70	57.7	-37.0	.90	58.	31.	83.	99.	37.	80.
51	53	11.60	4.60	59.5	-36.8	1.70	60.	35.	84.	101.	40.	81.
53	6	16.20	3.20	59.5	-38.0	1.30	60.	39.	84.	101.	44.	81.
6	61	19.40	1.50	59.5	-34.6	.55	60.	35.	86.	101.	40.	83.
61	63	20.90	2.40	59.3	-32.3	1.20	59.	48.	88.	100.	55.	84.
63	7	23.30	2.20	52.0	-26.6	.71	52.	28.	92.	93.	36.	87.
7	9	25.50	2.70	48.5	-29.4	1.07	48.	33.	90.	89.	44.	86.
9	11	28.20	3.00	46.8	-32.2	1.07	47.	29.	88.	88.	40.	84.
11	13	31.20	4.10	60.4	-29.7	1.78	60.	42.	90.	101.	47.	87.
13	16	35.30	2.80	49.7	-26.5	1.03	50.	31.	94.	90.	41.	89.
16	18	38.10	3.20	61.5	-22.3	1.41	62.	43.	95.	102.	48.	92.
18	20	41.30	3.40	56.7	-25.4	1.80	57.	49.	94.	97.	58.	91.
20	21	44.70	4.10	69.6	-21.5	1.50	70.	38.	94.	110.	38.	92.
21	22	48.80	3.20	68.0	-27.3	1.04	68.	34.	92.	109.	34.	91.
22	24	52.00	3.10	78.2	-37.7	1.16	78.	41.	89.	119.	36.	88.

24	25	55.10	3.50	88.0	-8.7	1.24	88.	39.	91.	129.	31.	91.
25	27	58.60	4.40	80.0	-35.9	1.32	80.	33.	90.	121.	29.	89.
27	30	63.00	3.70	73.5	-35.3	1.17	73.	34.	90.	114.	32.	89.
30	32	66.70	4.70	63.2	-36.0	1.90	63.	40.	90.	104.	44.	88.
32	33	71.40	2.90	62.9	-33.5	1.30	63.	44.	92.	104.	48.	90.
33	333	74.30	5.90	63.5	-38.4	3.10	63.	52.	90.	104.	57.	88.
333	34	80.20	3.80	47.3	-40.3	2.59	47.	56.	89.	88.	76.	87.

Stage poles for plate 701

A1	A2	T1	DT	Lat	Lon	Angle	Dist	V	Dir	Dist	V	Dir
0	3	.00	3.90	60.0	-39.0	-1.21	61.	-30.	262.	102.	-34.	259.
3	5	3.90	5.00	60.0	-39.0	-1.94	61.	-38.	262.	102.	-42.	258.
5	51	8.90	2.70	57.8	-36.7	-.90	58.	-31.	262.	99.	-37.	258.
51	53	11.60	4.60	59.6	-36.8	-1.70	60.	-35.	262.	101.	-40.	259.
53	6	16.20	3.20	59.5	-38.0	-1.30	60.	-39.	261.	101.	-44.	257.
6	61	19.40	1.50	59.7	-34.5	-.55	60.	-35.	263.	101.	-40.	259.
61	63	20.90	2.40	59.7	-32.3	-1.20	59.	-48.	264.	100.	-55.	260.
63	7	23.30	2.20	52.9	-24.7	-.71	52.	-28.	267.	93.	-36.	262.
7	9	25.50	2.70	49.1	-26.7	-1.07	48.	-33.	265.	89.	-44.	260.
9	11	28.20	3.00	47.3	-29.2	-1.07	47.	-29.	262.	88.	-40.	257.
11	13	31.20	4.10	60.9	-31.2	-1.78	60.	-42.	264.	101.	-47.	259.
13	16	35.30	2.80	50.8	-23.7	-1.03	50.	-31.	267.	90.	-41.	260.
16	18	38.10	3.20	62.8	-25.0	-1.41	62.	-43.	267.	102.	-48.	262.
18	20	41.30	3.40	57.8	-25.2	-1.80	57.	-49.	266.	97.	-58.	260.
20	21	44.70	4.10	70.3	-32.6	-1.50	70.	-38.	265.	110.	-38.	261.
21	22	48.80	3.20	68.0	-35.7	-1.04	68.	-34.	263.	109.	-34.	258.
22	24	52.00	3.10	74.7	-61.5	-1.16	78.	-41.	259.	119.	-36.	255.
24	25	55.10	3.50	80.3	-103.3	-1.24	88.	-39.	260.	129.	-31.	258.
25	27	58.60	4.40	76.3	-66.1	-1.32	80.	-33.	259.	121.	-29.	256.
27	30	63.00	3.70	71.7	-48.8	-1.17	73.	-34.	259.	114.	-32.	256.
30	32	66.70	4.70	62.7	-36.0	-1.90	63.	-40.	259.	104.	-44.	254.
32	33	71.40	2.90	62.9	-33.5	-1.30	63.	-44.	260.	104.	-48.	255.
33	333	74.30	5.90	62.4	-38.2	-3.10	63.	-52.	257.	104.	-57.	253.
333	34	80.20	3.80	47.3	-27.7	-2.59	47.	-56.	255.	88.	-76.	250.

Table 2 (cont.)

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 MOB. plate: 201, REF. plate: 701

 Data points where directions & rates of spreading are calculated :
   2    .45 -25.11 -39.94 -16.70

   These points are on ISOCHRON#   0  and PLATE ID# 201

 Finite rotations :
  Chron Age     Lat.  Long.   Angle
   333  80.20  63.00 -34.00  31.00  ! SAM-AFR AN 33R CANDE et al.1987
    34  84.00  61.75 -34.00  33.50  ! SAM-AFR AN 34 CANDE et al.1987
   100 118.70  51.66 -33.05  52.71  ! SAM-AFR M0
   104 126.50  49.99 -31.19  54.35  ! SAM-AFR M4

 Stage poles for plate 201
  A1   A2     T1     DT          Lat    Lon    Angle     Dist   V  Dir    Dist   V  Dir

 333  34   80.20  3.80         47.3  -40.3    2.59      47.  56.  89.    88.  76.  87.
  34 100   84.00 34.70         36.2  -41.2   20.53      36.  39.  88.    77.  64.  87.
 100 104  118.70  7.80          2.8  -25.9    2.46      20.  12. 175.    48.  26. 125.

 Stage poles for plate 701

  A1   A2     T1     DT          Lat    Lon    Angle     Dist   V  Dir    Dist   V  Dir

 333  34   80.20  3.80         47.3  -27.7   -2.59      47. -56. 255.    88. -76. 250.
  34 100   84.00 34.70         36.7  -23.2  -20.53      36. -39. 253.    77. -64. 248.
 100 104  118.70  7.80         17.1   11.4   -2.46      20. -12. -37.    48. -26. 267.
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Fig. 1: Tectonic fabric map from Seasat altimetry data, isochrons, synthetic flowlines of fracture zones and magnetic anomaly picks in the South Atlantic. The tectonic fabric of the South Atlantic is taken from Gahagan et al. (in prep.). The isochrons are based on magnetic anomaly data from Cande et al. (in prep.), Rabinowitz & LaBrecque (1979), LaBrecque & Hayes (1979), Barker (1979) and Martin et al. (1982). The boundaries between oceanic and continental crust are taken from Emery & Uchupi (1984). Plate identification numbers: 701 - southern Africa, 714 - northwestern Africa, 201 - South America, 202 - Parana Plate, 290 - Salado Plate, 291 - Colorado Plate. Fracture zone extensions on the continental shelves: AA' - St. Paul Fz, BB' - Romanche Fz, CC' - Chain Fz, DD' - Ascension Fz.

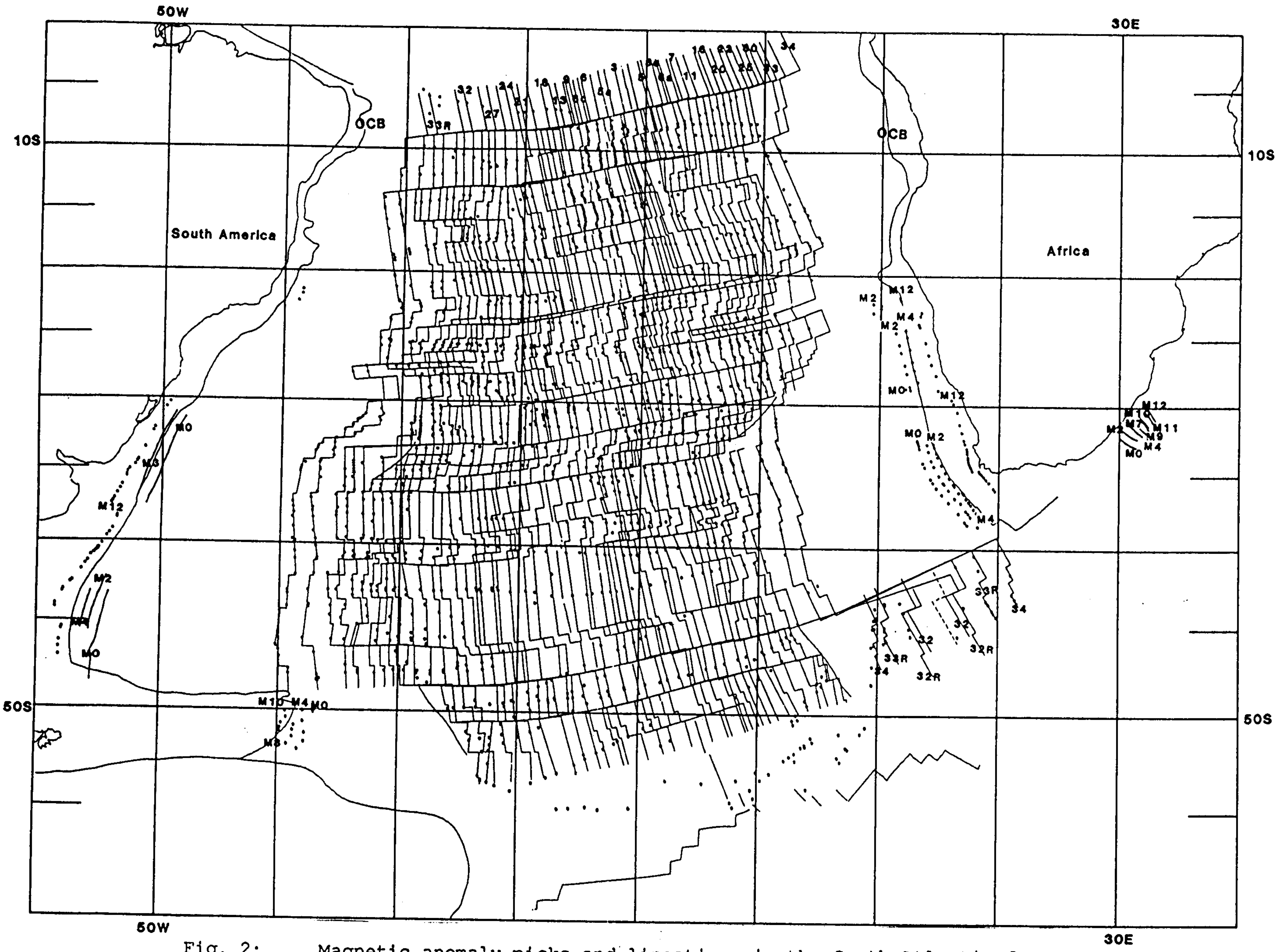


Fig. 2: Magnetic anomaly picks and lineations in the South Atlantic from Cande et al. (in prep.), Rabinowitz & LaBrecque (1979), LaBrecque & Hayes (1979), Barker (1979), Martin et al. (1982). Isochrons are from Nürnberg et al. (this paper).

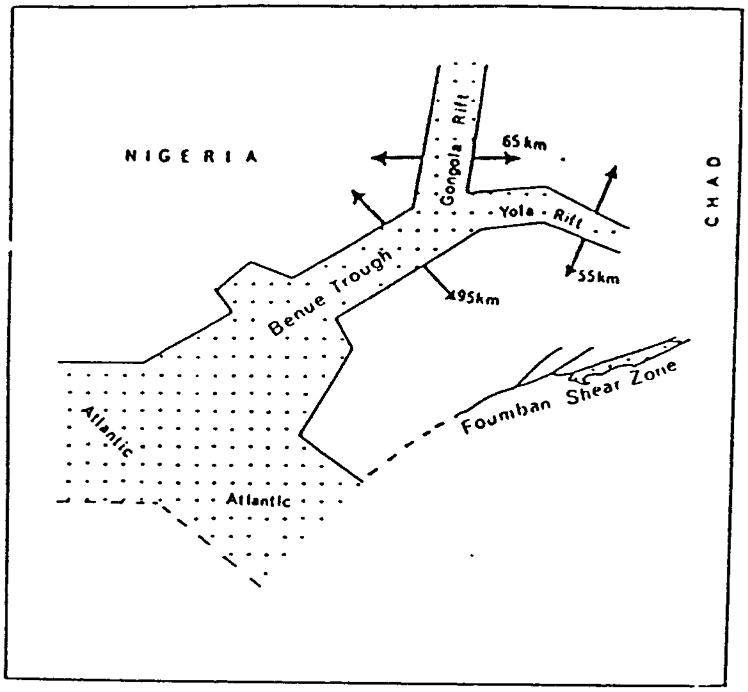


Fig. 3: Tectonic model of the West African rift system showing the amount of crustal extension deduced for each arm of the rift system (from Fairhead & Okereke, 1987)

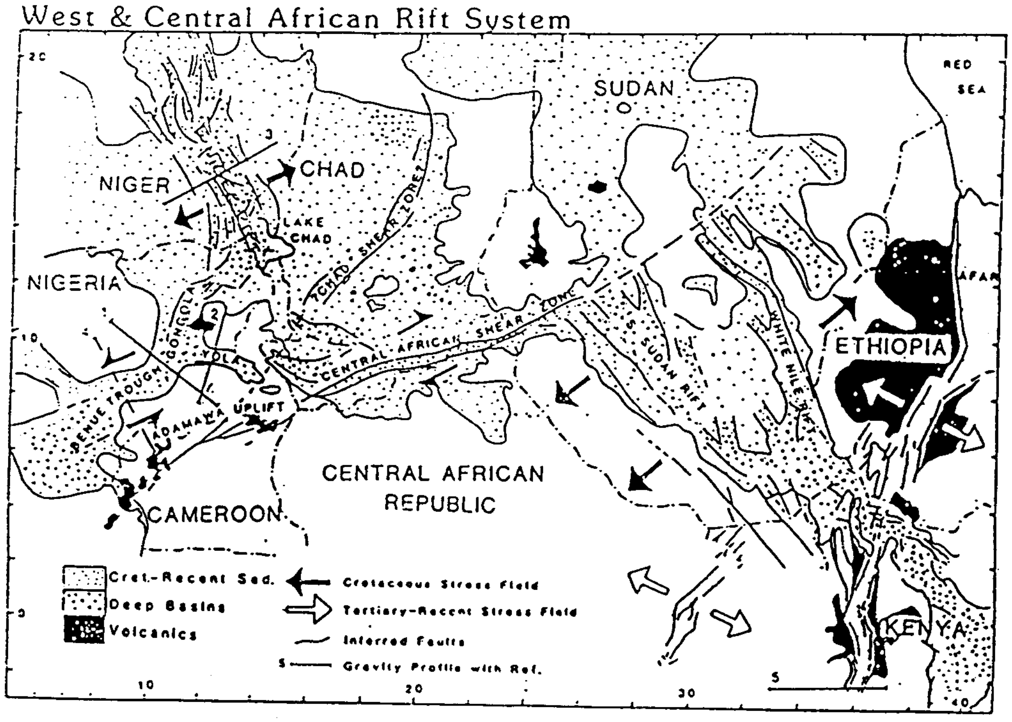


Fig. 4: Tectonic model of the West and Central African Rift System (from Fairhead, in prep.).

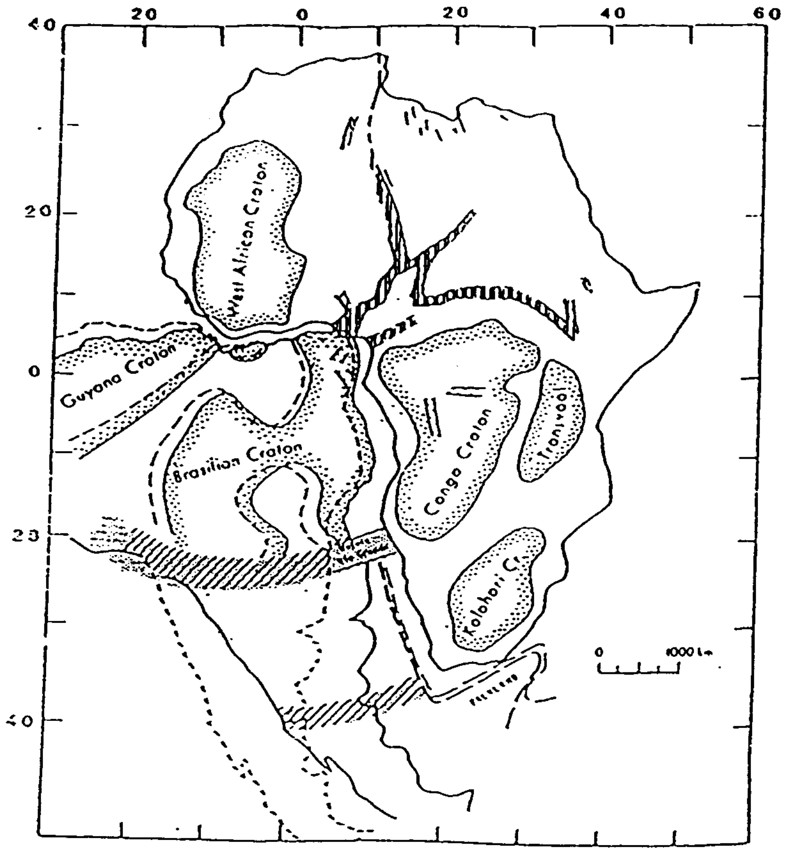


Fig. 5: Initial fit from Curie (1983) showing Africa in its present position and shape. The hatched line delineates the position of South America after relative motion between the northern and southern subplates has taken place along the proposed Parana-Cochabamba second order plate boundary (shaded area), whereas the solid line outlines the pre-deformational position of the southern subplate of South America. The second shaded area shows another possible second order plate boundary north of the Falklands (from Unternehr et al., in press).

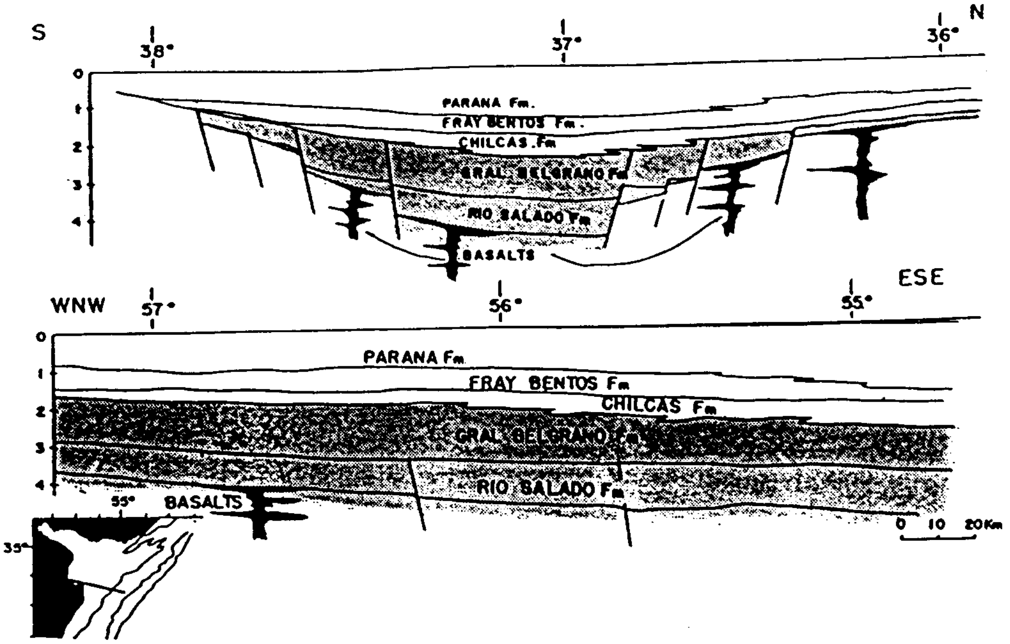


Fig. 6: Cross sections of the Salado Basin. Vertical scale in km; Mesozoic formations in grey (from Urien & Zambrano, 1973).

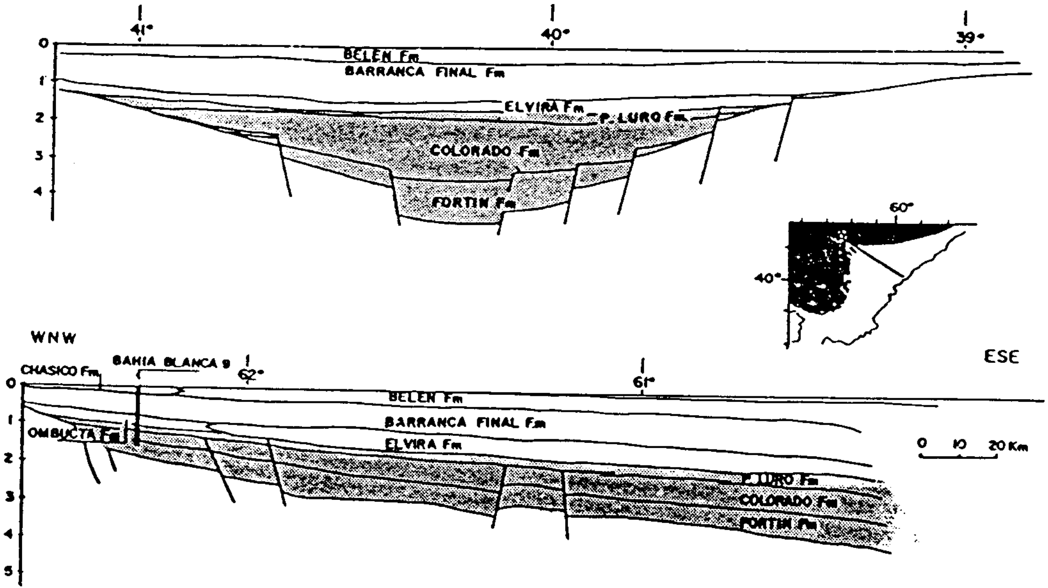
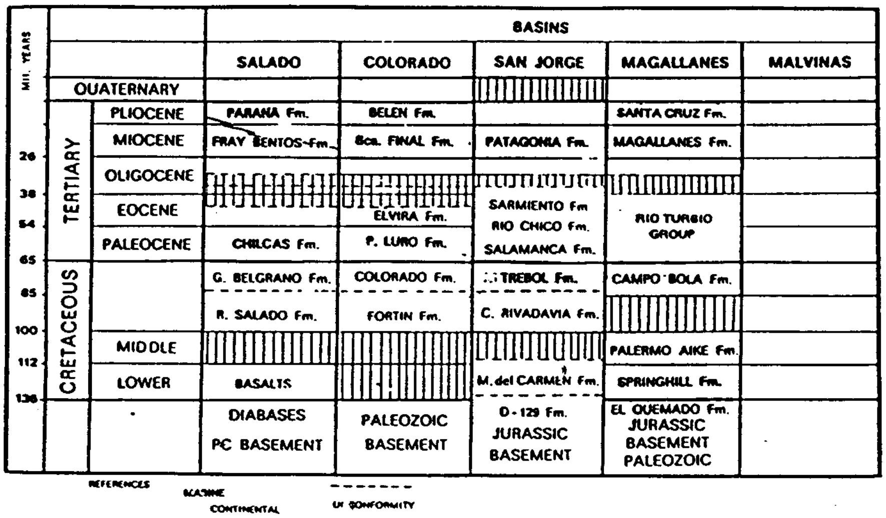


Fig. 7: Cross sections of the Colorado Basin. Vertical scale in km; Mesozoic formations in grey (from Urien & Zambrano, 1973).



MIL. YEARS			BASINS				
			SALADO	COLORADO	SAN JORGE	MAGALLANES	MALVINAS
	QUATERNARY				▥		
	TERTIARY	PLIOCENE	PARANA Fm.	BELEN Fm.		SANTA CRUZ Fm.	
		MIOCENE	FRAY BENTOS Fm.	Bca. FINAL Fm.	PATAGONIA Fm.	MAGALLANES Fm.	
26		OLIGOCENE	▥	▥	▥	▥	
38		EOCENE	▥	▥ ELVIRA Fm.	SARMIENTO Fm RIO CHICO Fm. SALAMANCA Fm.	RIO TURBIO GROUP	
54		PALEOCENE	CHILCAS Fm.	P. LURO Fm.			
65	CRETACEOUS		G. BELGRANO Fm.	COLORADO Fm.	TREBOL Fm.	CAMPO BOLA Fm.	
85			R. SALADO Fm.	FORTIN Fm.	C. RIVADAVIA Fm.	▥	
100		MIDDLE	▥	▥	▥	PALERMO AIKE Fm.	
112		LOWER	BASALTS	▥	M. del CARMEN Fm.	SPRINGHILL Fm.	
136			DIABASES PC BASEMENT	PALEOZOIC BASEMENT	D-129 Fm. JURASSIC BASEMENT	EL QUEMADO Fm. JURASSIC BASEMENT PALEOZOIC	

REFERENCES
MARINE
CONTINENTAL
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Fig. 8: Schematic stratigraphic columns for the Salado and Colorado basins (from Urien & Zambrano, 1973)

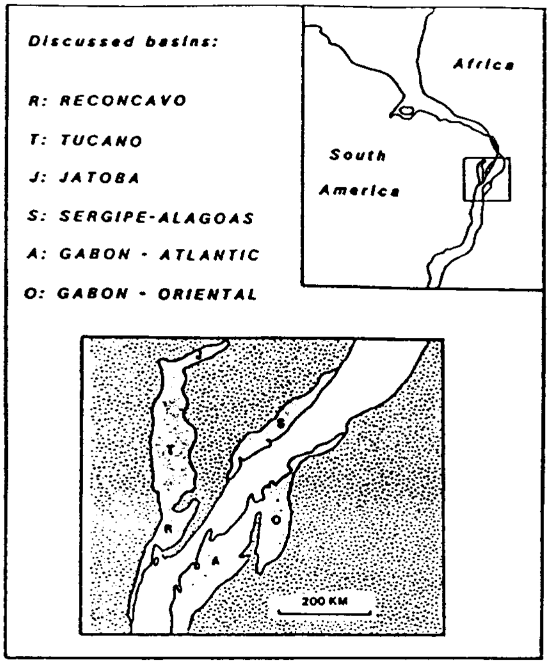

Fig. 9: Location map of the Reconcavo and Tucano basins in northeast Brazil. Stippled: Phanerozoic sediments; hatched: Precambrian basement (from Castro, 1987).

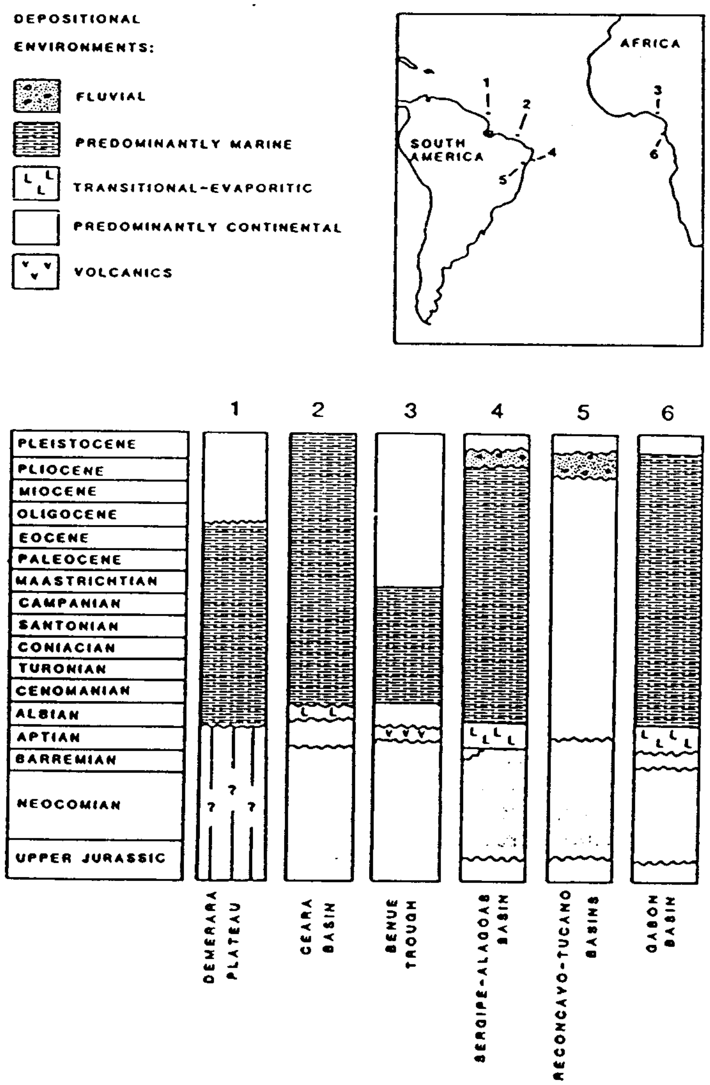

Fig. 10: Schematic stratigraphic columns from different areas in northeastern Brazil mentioned in the text (from Castro, 1987)

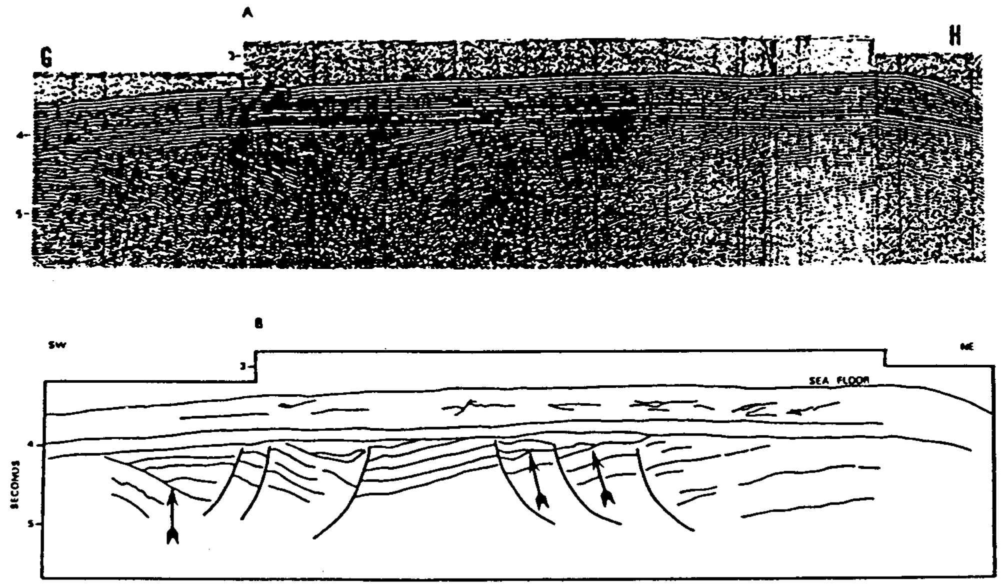

Fig. 11: Seismic profile across the Demarara Plateau (from Hayes et al., 1972) and interpreted line drawing of profile. Arrows point to indications of growth of downthrown blocks The extensional style of the pre-Albian unconformity section is evident (from Castro, 1987).

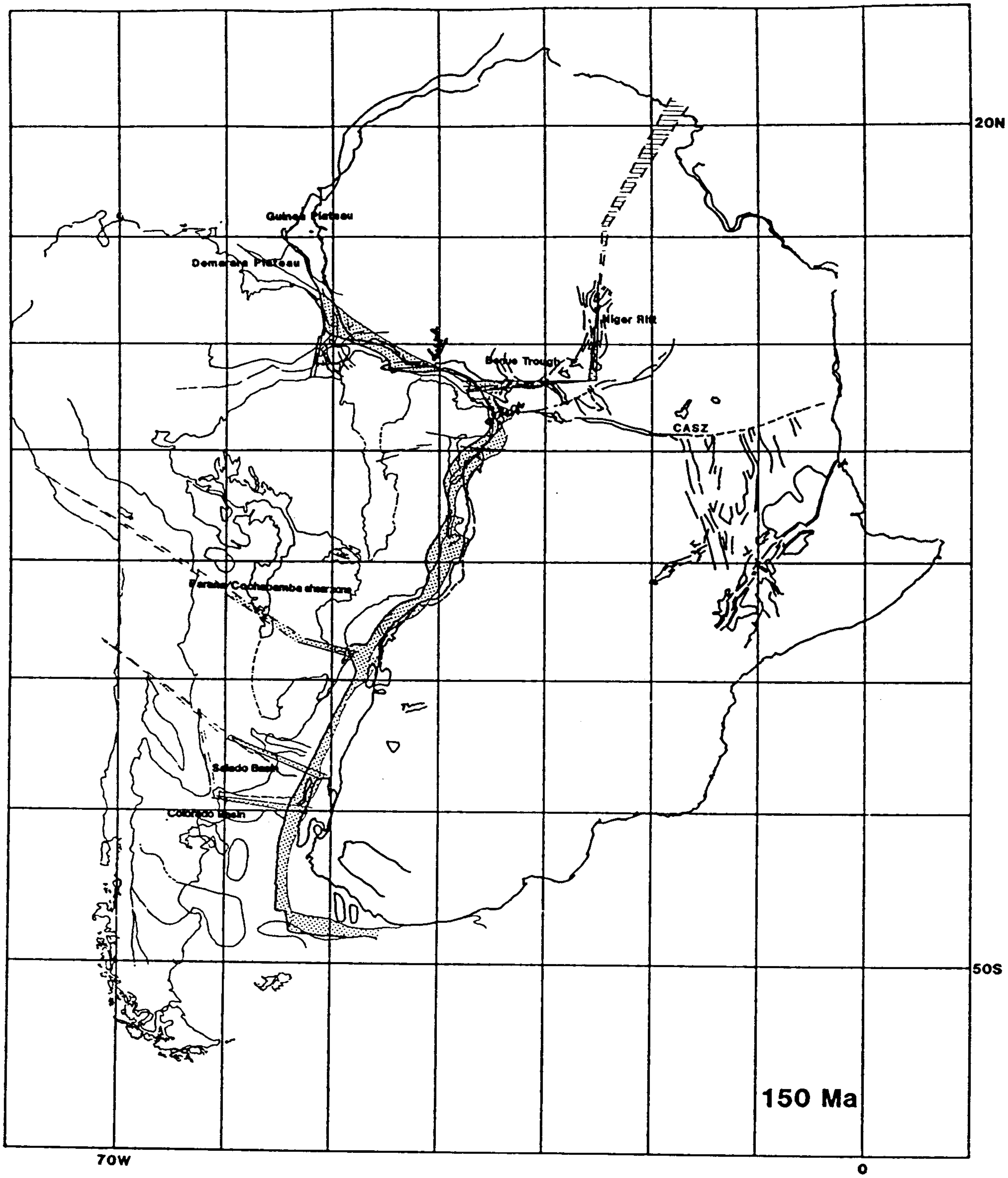

Fig. 12: 150 Ma (Tithonian)

A predrift reconstruction for the South Atlantic without considerable gaps or overlaps between the continental margins of Africa and South America can only be derived by use of a nonrigid plate model. A model of a stepwise northward propagating rift is in good accordance with geological data from the continents. Our model predicts northward 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/Andean Cochabamba 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 (stippled areas) is shown by overlaps of hypothetical subplate-boundaries. Overlaps of continental margins are also stippled, whereas gaps between continental margins and gaps between subplate-boundaries are hatched. Arrows indicate current activitiy along intracontinental deformation zones.

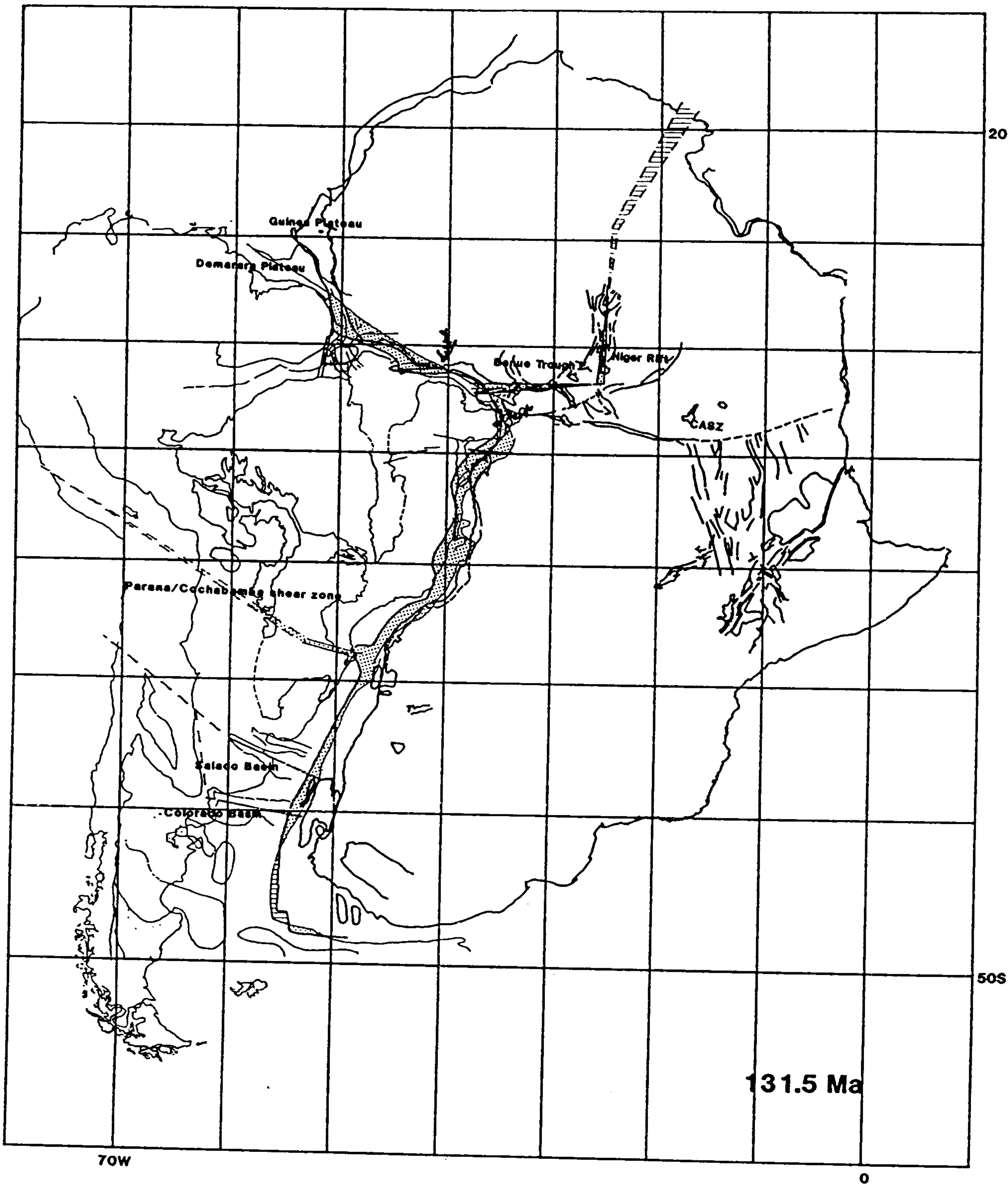

Fig. 13: **130 Ma (Hauterivian)**

At approximately 130 Ma (Hauterive), 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 & Zambrano, 1973) support this assumption.

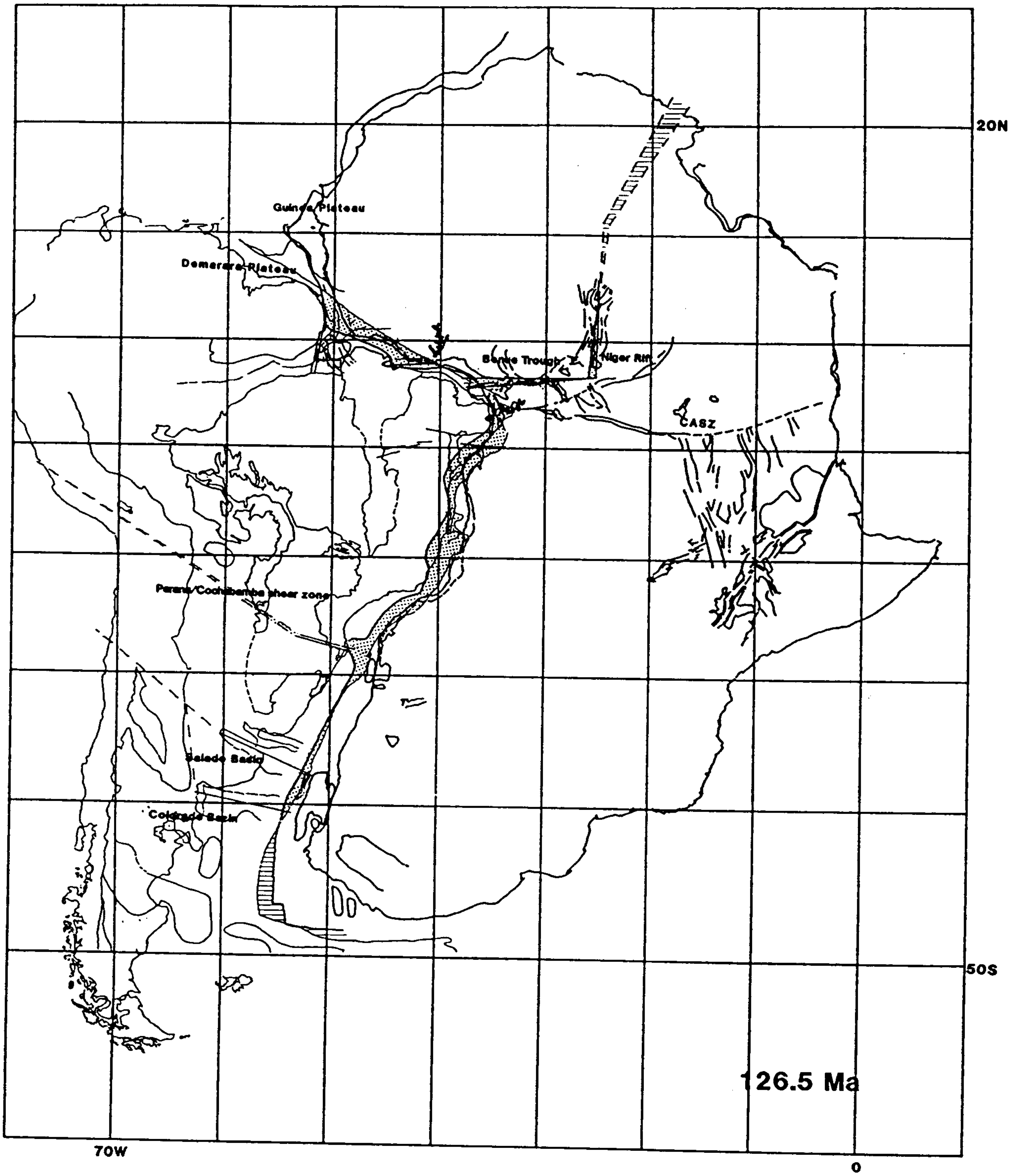

Fig. 14: **Chron M4 (126.5 Ma, Hauterivian)**

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/Cochabamba 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 40 km and 60 km of crustal extension in the Salado Basin and Colorado Basin, respectively, and 20 to 30 km of dextral strike slip in both basins.

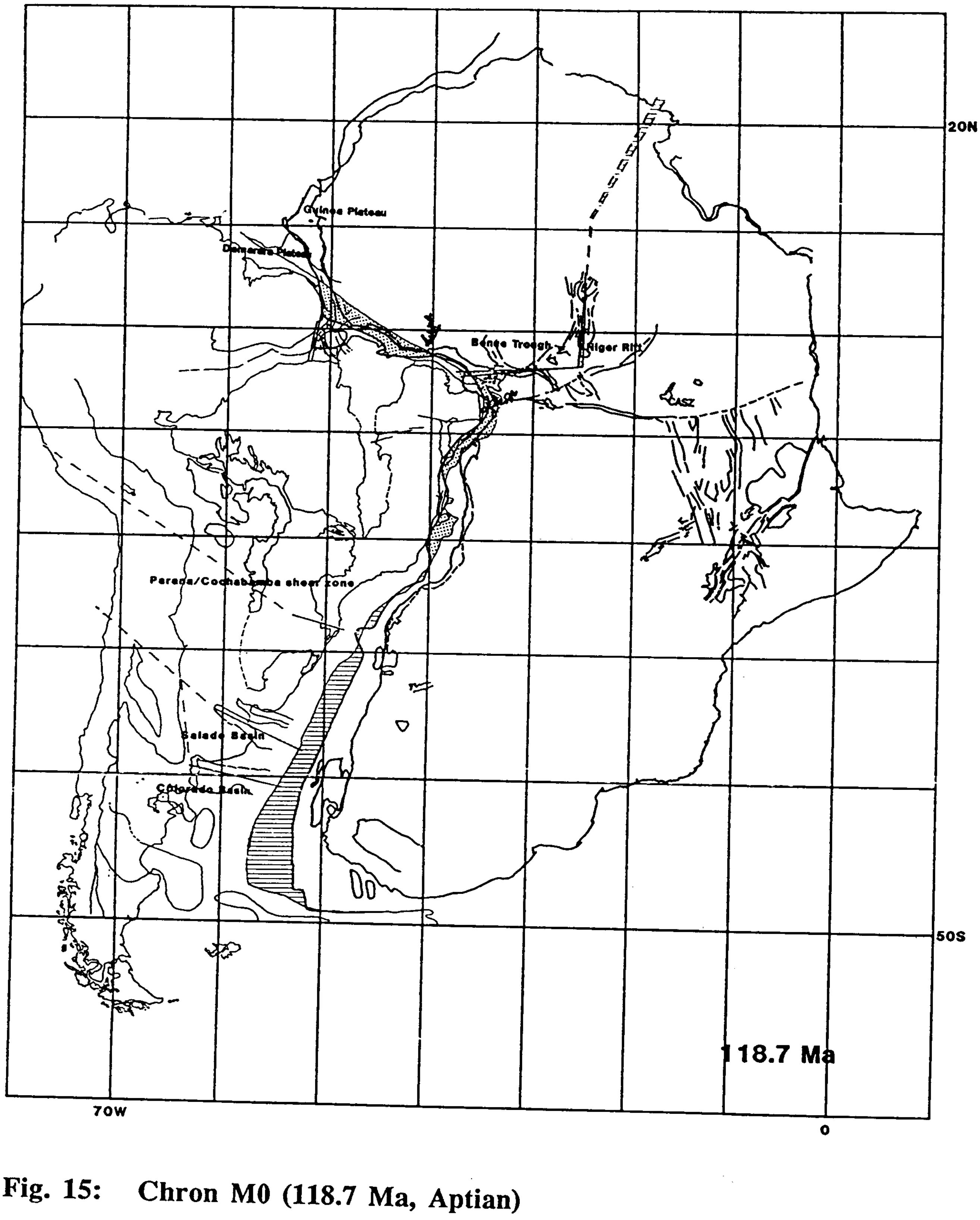

Fig. 15: Chron M0 (118.7 Ma, Aptian)

Between Chrons M4 and M0, rifting propagated northward into the Benue Trough. The Benue Trough/Niger Rift system constitutes a large Cretaceous rift/sinistral strike slip system that was active until about 80 Ma (Fairhead & Okereke 1987). At Chron M0 movements along the Parana-Andean Cochabamba deformation zone ceased, having generated 50 to 60 km of crustal extension and 40 to 50 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).

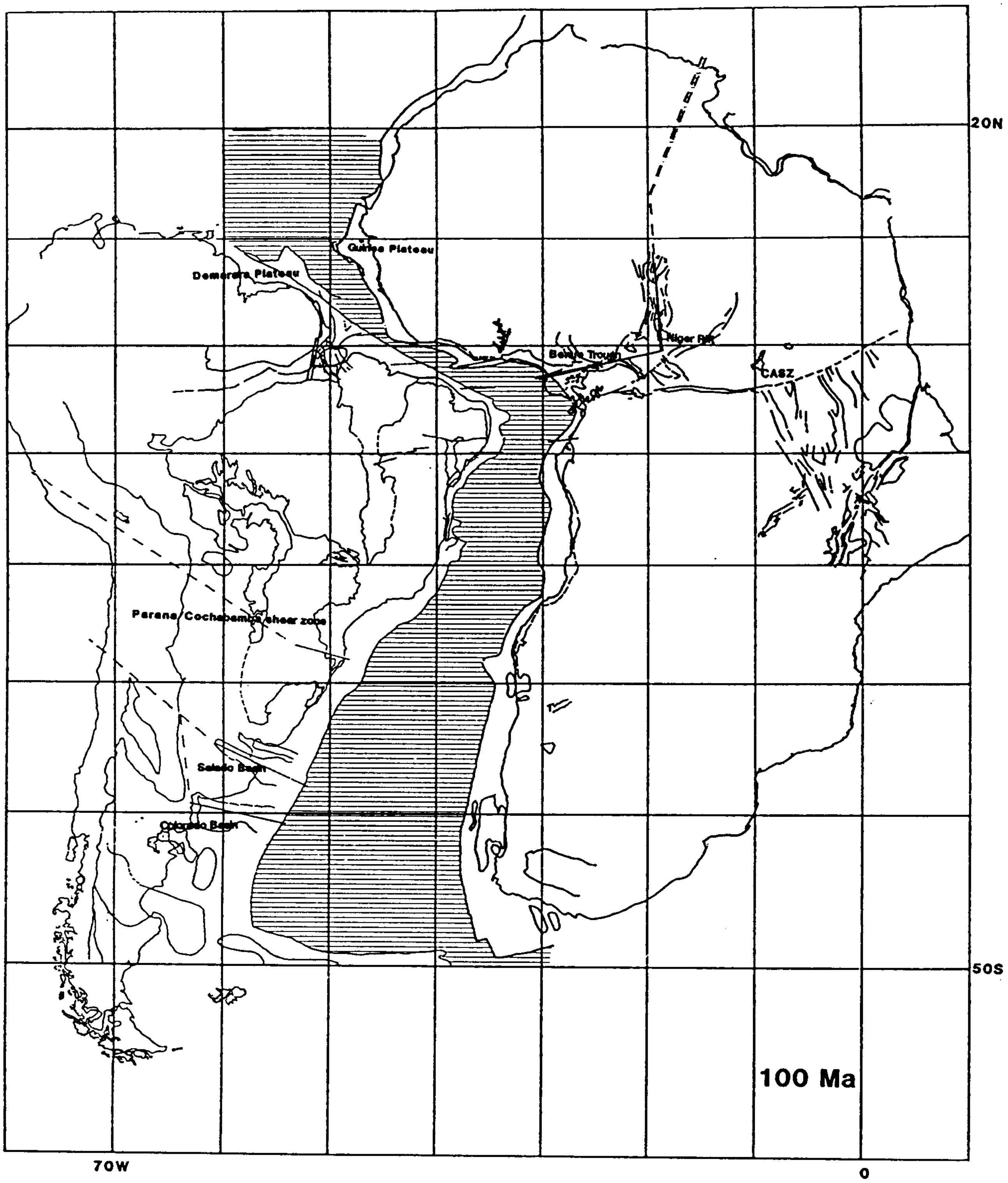

Fig. 16: 100 Ma (Albian)

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 Cretaceous).

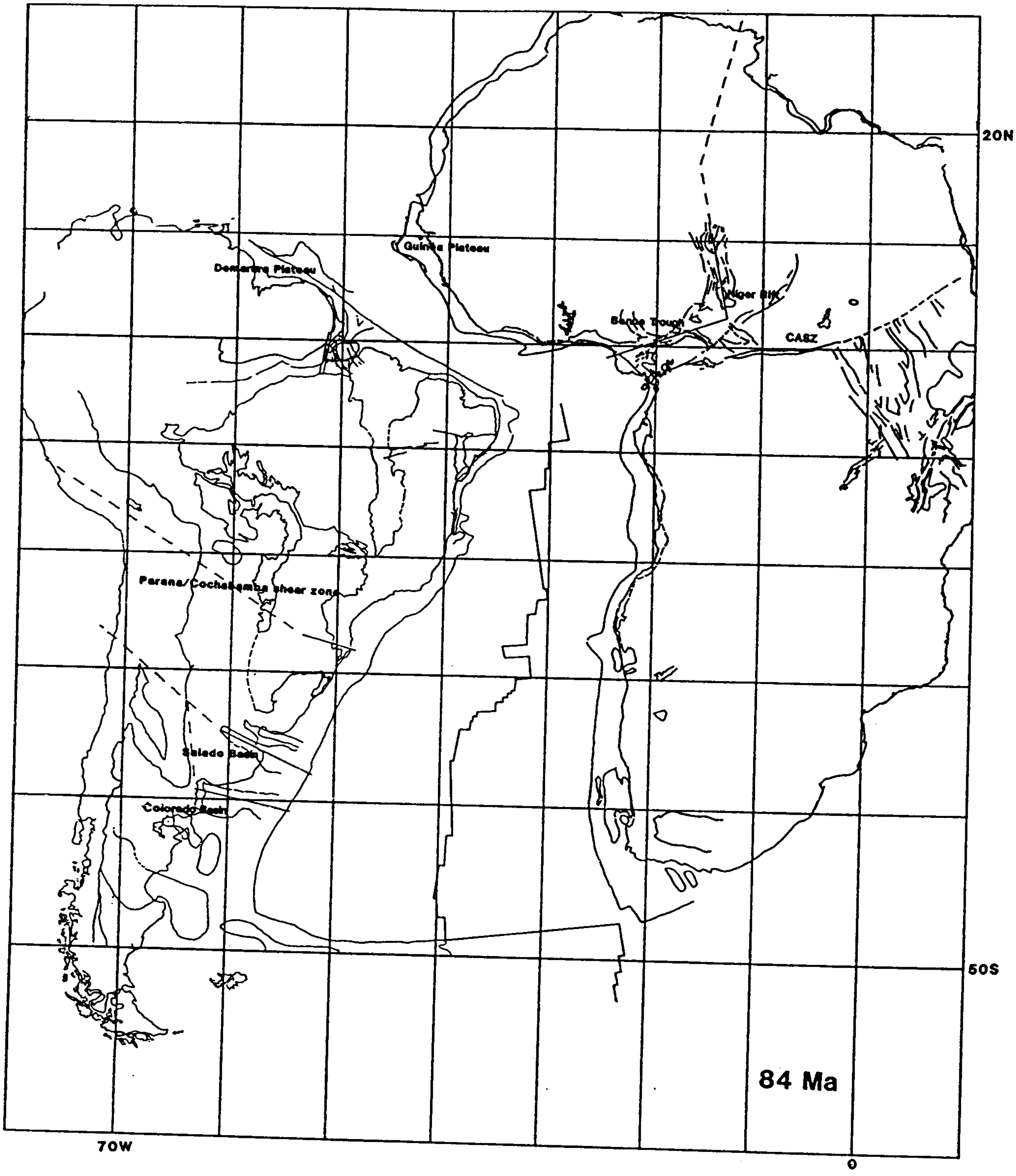

Fig. 17: **Chron 34 (84 Ma, Campanian)**

Intracontinental movements ceased within Africa at approximately Chron 34 (84 Ma). In accordance with Fairhead & Okereke (1987), we propose 75 km of rifting combined with 50 km of strike slip motion in the Benue Trough. After Chron 34, the South Atlantic is assumed to have opened as a two plate system.

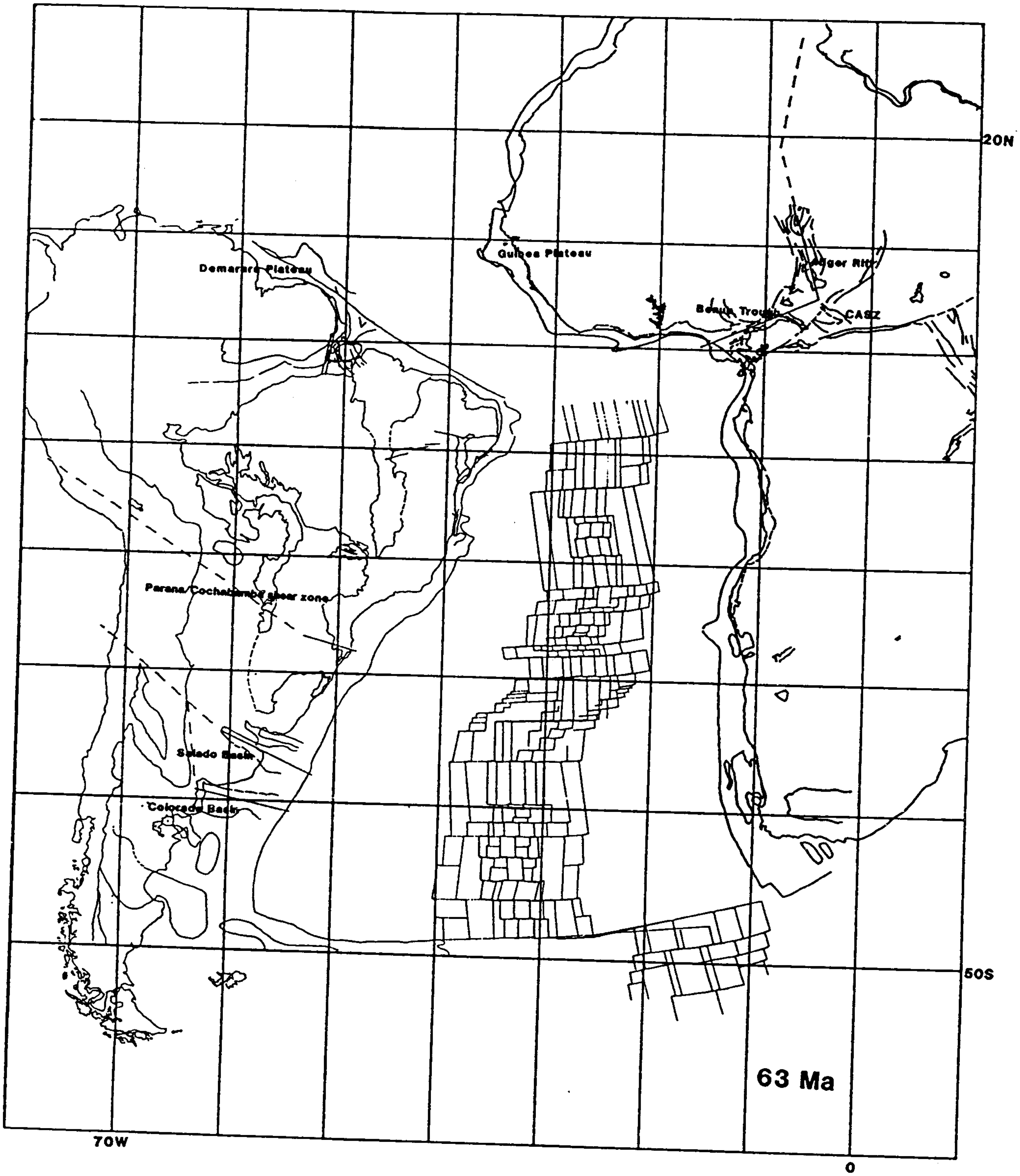

Fig. 18: Chron 27 (63Ma)

The subsequent opening of the South Atlantic since Chron 34 (84 Ma) has been characterized by simple divergence of two continental 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.

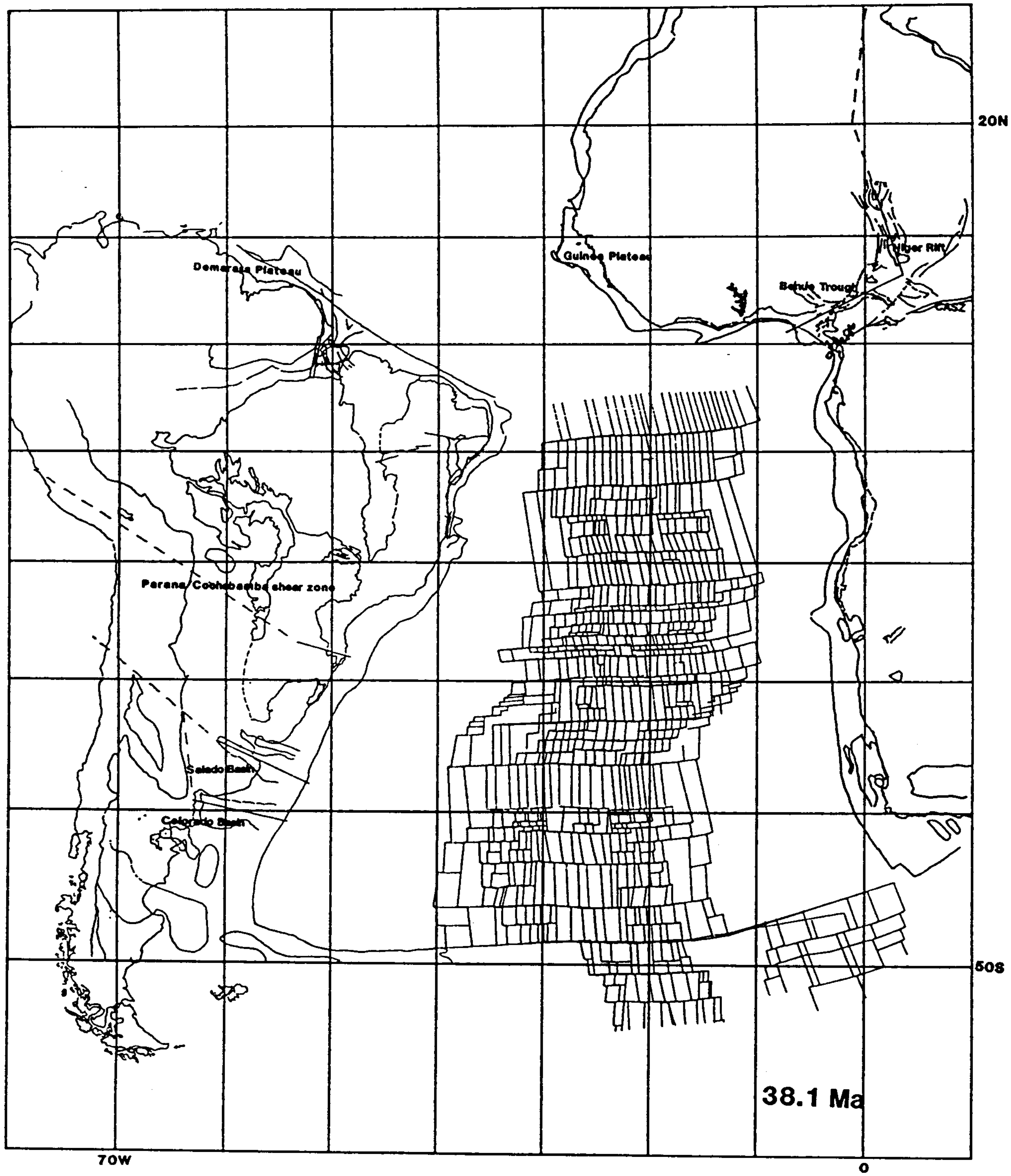

Fig. 19: **Chron 16 (38.1 Ma)**

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).

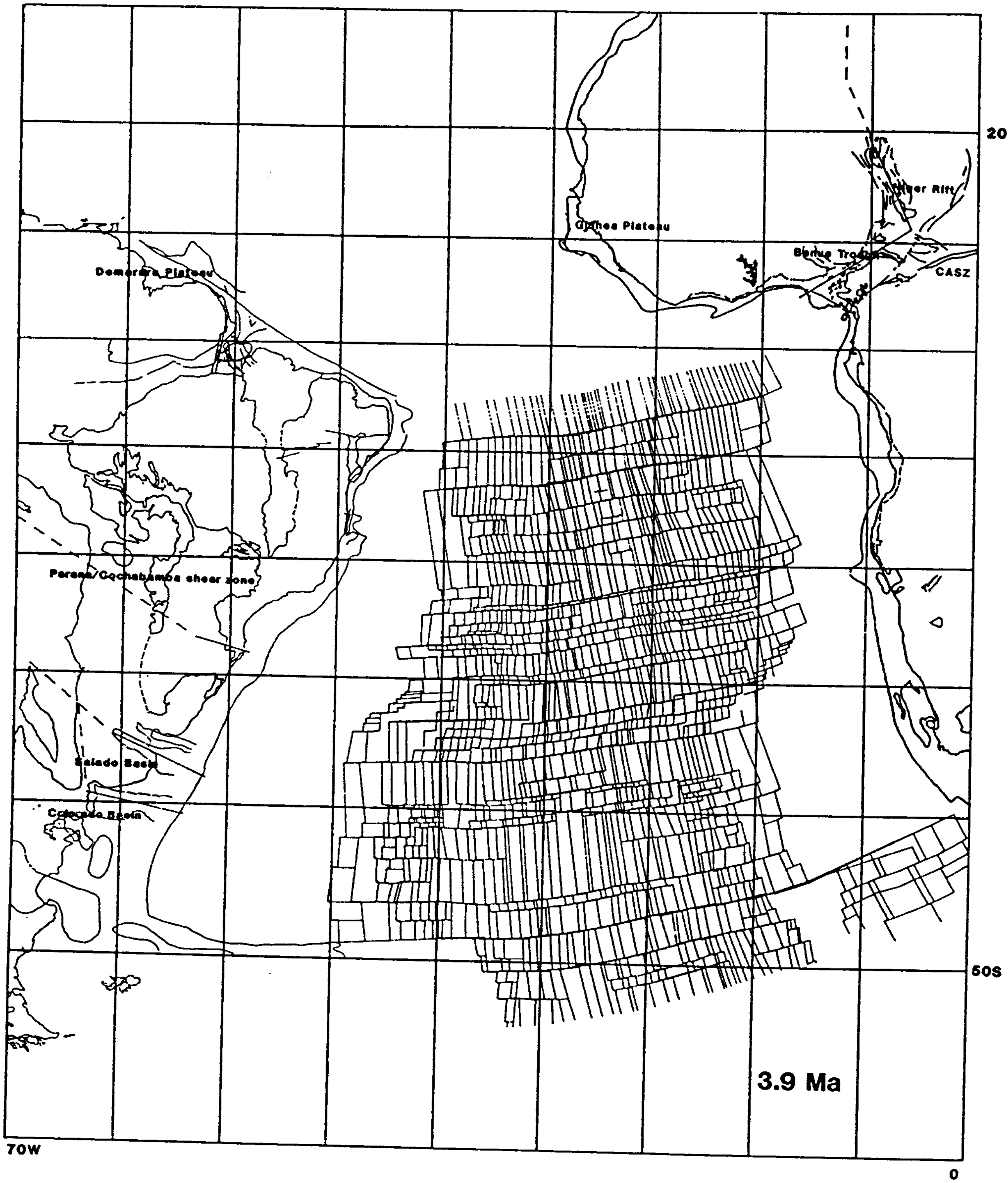

Fig. 20: Chron 3 (3.9 Ma)

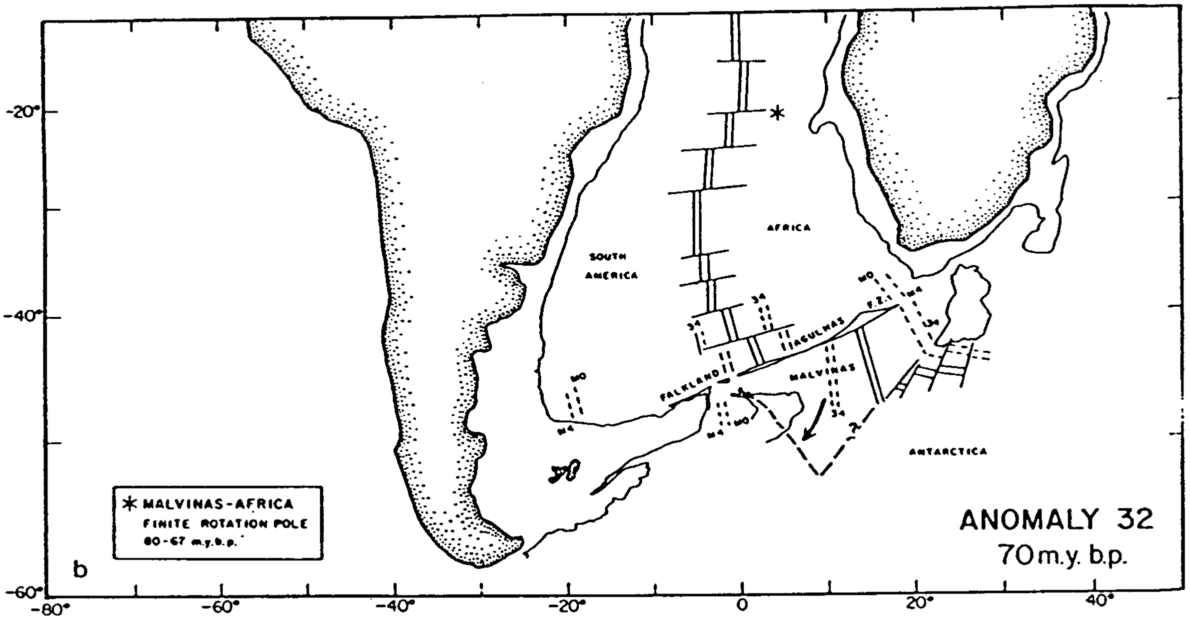

Fig. 21: Reconstruction at Paleocene time (Chron A32) displaying formation of Malvinas plate with compressive relative motion with South American plate about instanteneous pole near northern tip of northeastern Georgia Rise (from LaBrecque & Hayes, 1979).

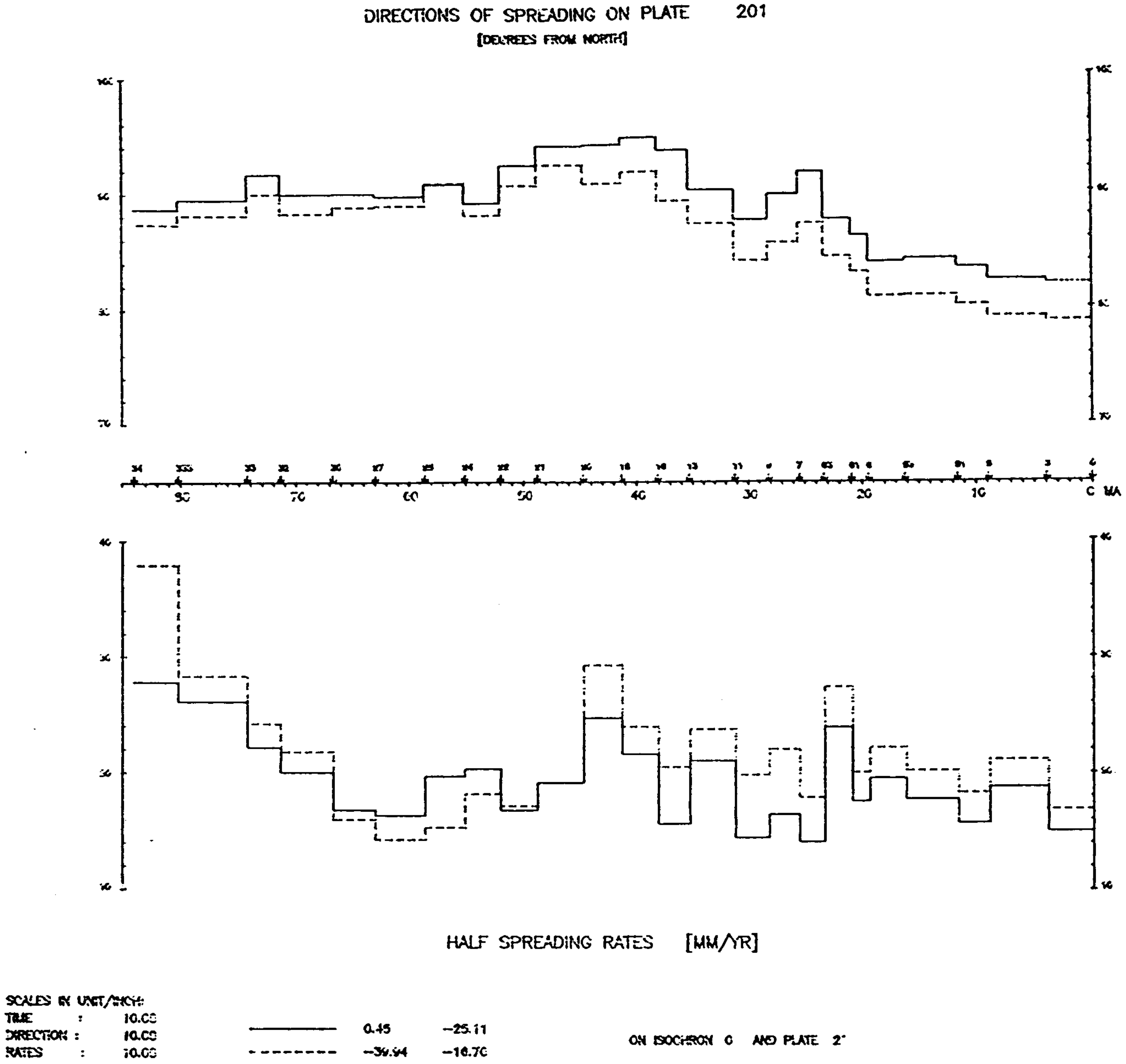

Fig. 22: Histograms showing spreading half-rates and spreading directions according to finite rotation poles in Table 2 (modified plate tectonic model of Cande et al. (in prep.)

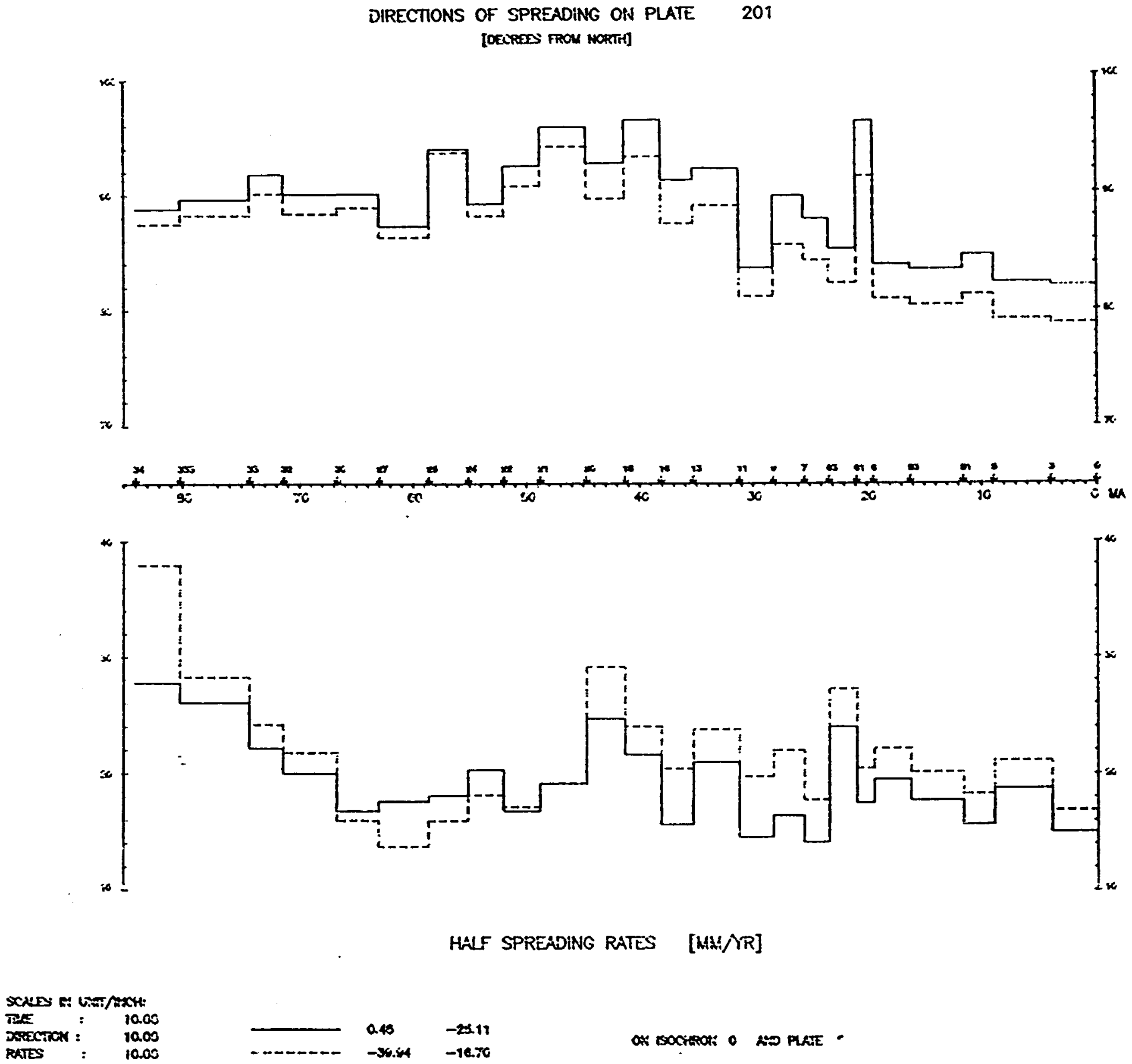

Fig. 23: Histograms showing spreading half-rates and spreading directions according to Cande et al.'s (in prep.) plate tectonic model