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Chapter 14

THE AGE OF THE SOUTH ATLANTIC

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I. INTRODUCTION

This paper attempts to further delineate the pattern of continental drift that has taken place in the South Atlantic since mid-Mesozoic time. The history presented is based on the analysis of the magnetic anomaly pattern associated with the mid-Atlantic ridge which indicates the age of the basement rock and may be used to determine to a first approximation the pattern of drift between the continental masses that surround the Atlantic.

In the theory of sea-floor spreading it is assumed that continental drift in the Atlantic has taken place because the surrounding continents have been passively rafted away from the mid-Atlantic ridge (Heezen, 1960; Hess, 1962, 1968; Dietz, 1961, 1968). This implies that the Atlantic margins of the continents were not deformed and, in particular, not underthrust as drifting occurred. South America plus the oceanic crust between its eastern margin and the axis of the mid-Atlantic ridge has drifted as a single rigid crustal plate. Africa plus the oceanic crust between its western margin and the mid-Atlantic ridge axis has also drifted as a single rigid crustal plate. The mid-Atlantic ridge

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is an accretionary margin where new oceanic crust is created and welded to the drifting plates by igneous processes involving the upper mantle and crust of the earth. The mid-Atlantic ridge is an axis of symmetry because roughly equal amounts of new crust are welded to the African and South American plates.

Vine and Matthews (1963) pointed out that sea-floor spreading gives rise to a pattern of magnetic anomalies bilaterally symmetric with respect to the mid-ocean ridge axis. This magnetic field pattern arises from within the basaltic oceanic crust which is composed of alternate bands of normally and reversely magnetized rock. These bands, which parallel the mid-Atlantic ridge crest, vary in width depending on the rate of spreading and the length of the corresponding time interval of normal or reversed polarity of the earth's magnetic field.

Time scales giving the history of reversals of the earth's field back to 80 m.y. (Late Cretaceous) have been derived by Vine (1966) and Heirtzler *et al.* (1968) from the magnetic anomaly patterns in the South Atlantic, Indian, and Pacific oceans. The time scales where obtained by comparing the magnetic anomaly pattern across the ridge axis with the known magnetic reversal chronology of Cox *et al.* (1963) and Dalrymple *et al.* (1967) for the past 3.4 m.y. With the assumption of a constant spreading rate, Heirtzler *et al.* extrapolated the reversal pattern back to 80 m.y. and assigned numbers 1–32 to the major characteristic anomalies for this time interval.

Evidence that substantiates the general validity of the time scales has come as a result of the *Joides* deep-sea drilling project in the South Atlantic (Maxwell *et al.*, 1970). Cores that bottomed on basalt were obtained at eight sites. The magnetically predicted age of the basement at these sites had been obtained by identification of the anomalies at these sites and correlation of these anomalies with the time scale of Heirtzler *et al.* Ages obtained by paleontologic dating of the basal sediment agree remarkably with those predicted. These data are shown in Fig. 1. The crosses indicate the age obtained at each drilling site, and the x axis gives the distance of each drilling site from the ridge axis. The straight line is the age predicted from the magnetic anomaly time scale of Heirzler *et al.* The hole locations are shown in Fig. 8.

For any spreading ridge, the time sequence of reversals gives rise to a unique pattern of magnetic anomalies which depends on the spreading rate, the present geographic location of the ridge, and the geographic location at the time of formation. Dickson (1967) and Dickson *et al.* (1968) have identified this pattern in the South Atlantic. With additional data now available, a more detailed determination of the anomaly lineation pattern has been made. Once the magnetic lineations have been identified, the age of basement is inferred. Since each anomaly lineation arises from a strip of crust that was formed simultaneously at the ridge axis, each anomaly lineation defines a former plate margin. Thus by simply fitting together anomaly lineations of the same age but

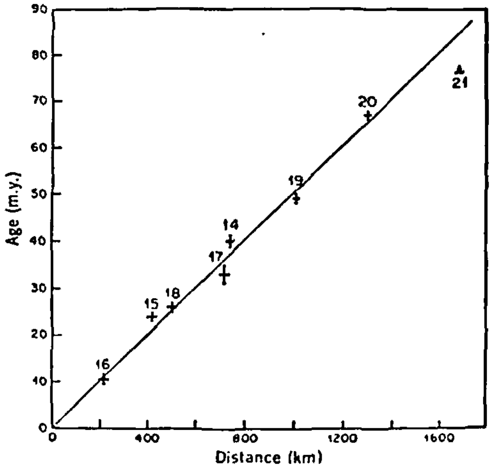


Fig. 1. The age of the sediments immediately above basalt (presumed to be basement) for the *Joides* holes 14–21 is shown plotted against distance from the ridge axis (see Fig. 8 for location). The line is the age predicted from magnetic anomalies vs. distance (Heirtzler *et al.*, 1968).

from opposite sides of the ridge a picture of the ocean and configuration of the bounding continents at that time may be determined. A sequence of such pictures describes the pattern of spreading that has taken place in the South Atlantic (Fig. 11).

By use of the *Joides* results in the North Atlantic and the analysis of magmetic anomalies made by Pitman *et al.* (1971) and Pitman and Talwani (1972) in the North Atlantic, we may develop a generalized magnetic time scale extending beyond the Late Cretaceous to the Late Jurassic. Comparison of the generalized pattern to be found in the South Atlantic with that found in the North Atlantic enables us to make a reasonable estimate of the initiation of drift in the South Atlantic.

II. THE MAGNETIC PATTERN IN THE SOUTH ATLANTIC

A. Data Reduction

Figure 2 shows the area of the South Atlantic studied and ships' tracks for which magnetic data were available. The shipboard data were collected by the *R/V Vema* and *R/V Conrad* of the Lamont–Doherty Geological Observatory and the *A. R. A. Azpiola* of the Argentine Hydrographic Office. In addition we have used aeromagnetic data collected by the U. S. Navy Project Magnet.

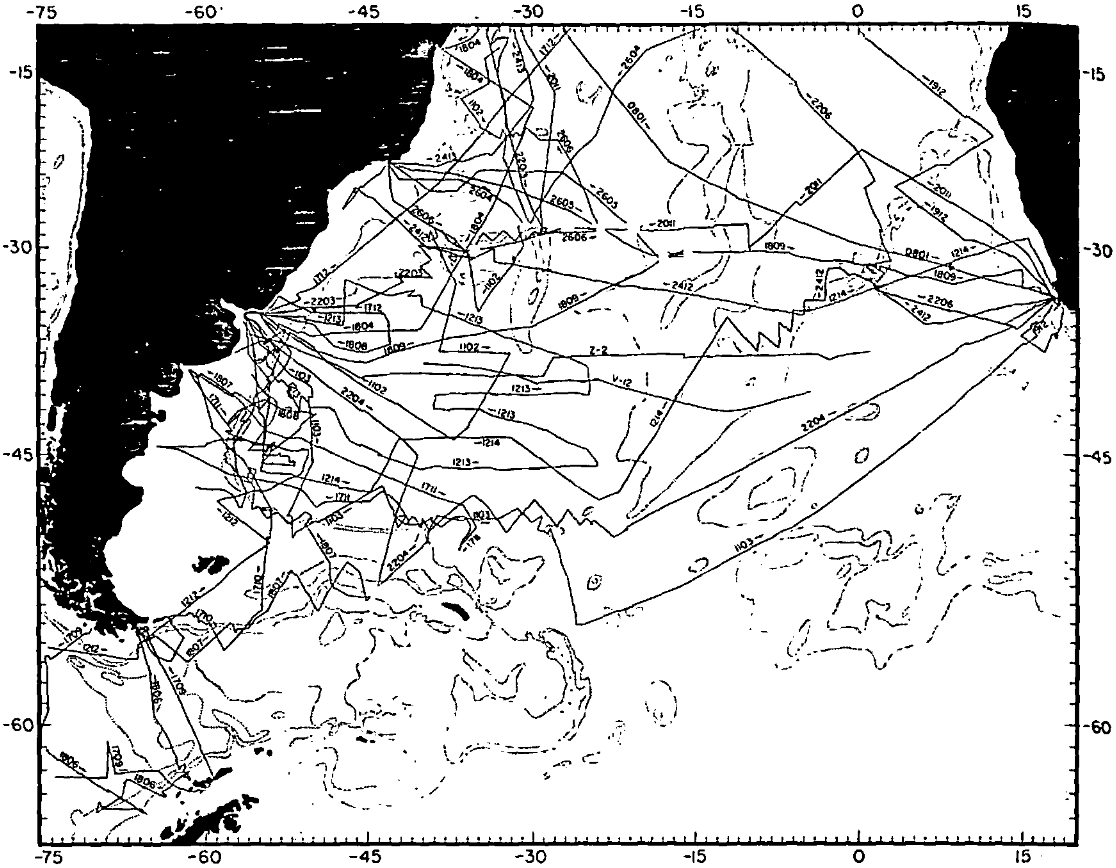
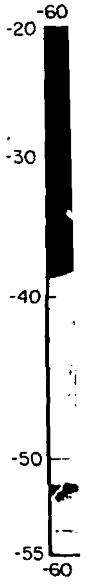


Fig. 2. Ships' tracks are shown along which total intensity magnetic and bathymetric data were available. The designation Z-2 indicates the track of the *A. R. A. Zapiola* of the Argentine Hydrographic Office. All other tracks are of the *R/V Vema* and *R/V Conrad* of the Lamont-Doherthy Geological Observatory.

Both proton precession and fluxgate magnetometers were used, and the data were recorded in analog fashion and later digitized. The regional field was removed using a digital computer and a spherical harmonic expansion of the earth's main field with coefficients of Cain *et al.* (1964).

B. Identification and Correlation of the Anomalies

Figure 3 shows some anomaly profiles plotted along the tracks. The track line serves as the zero reference level. The epicenters delineate the ridge axis and associated fracture zones. The magnetic anomaly amplitudes have been plotted perpendicular to the track line with positive values northward. Figure 4 (adapted from Dickson, 1967, and Dickson *et al.*, 1968) shows mag-



netic anomaly profiles that have been projected along an azimuth of 90° to simulate a perpendicular traverse of the ridge axis. Correlations are shown using the anomaly numbering system of Pitman *et al.* (1968). These correlations have been discussed in detail by Dickson (1967) and Dickson *et al.* (1968), so only brief mention of these correlations will be made now.

Figure 4 shows the general linearity of the magnetic pattern across the the mid-Atlantic ridge. At the top of the figure two profiles across the East Pacific rise in the North Pacific are shown, the one on the right is the same data as the left-hand profile, but is shown in mirror image to demonstrate the similarity that exists between the magnetic profiles across the ridges of different oceans. The most readily correlatable anomalies in these profiles are the axial anomaly and anomalies 5, 12, 13, 20, and 21.

No clear correlations can be made in the vicinity of the Walvis ridge because its own magnetic pattern strikes across the trend of the mid-Atlantic ridge anomaly pattern (see Figs. 5a and 8). There are some lineations in the Cape Basin between the Walvis ridge and the Southwest African margin. West of the mid-Atlantic ridge the anomalies can be correlated as far as the Rio Grande rise in the 2011 and 1809 profiles and to the eastern margin of the

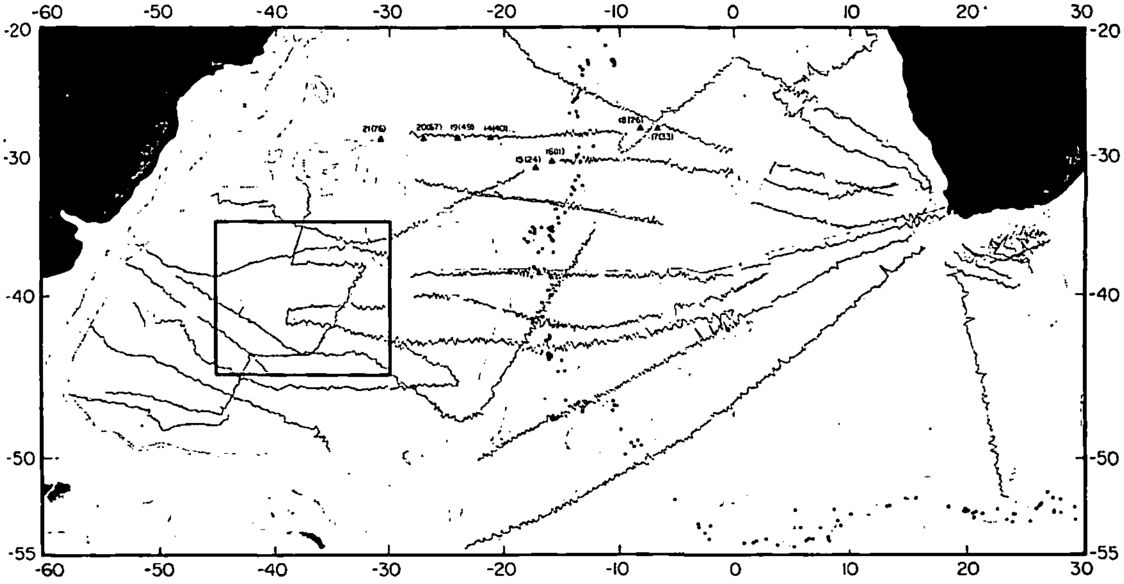


Fig. 3. Magnetic anomalies along selected ships' tracks are shown. The track line is the zero reference level. Anomaly amplitude is plotted perpendicular to the track with positive northward. The enclosed area in the Argentine basin is shown at a larger scale in Fig. 6a. The seismic epicenters are from Barazangi and Dorman (1969) and Sykes (personal communication). The location of South Atlantic *Joides* drill holes are shown as triangles. The hole number with the inferred basement age in m.y.b.p. in parenthesis are shown beside the triangle.

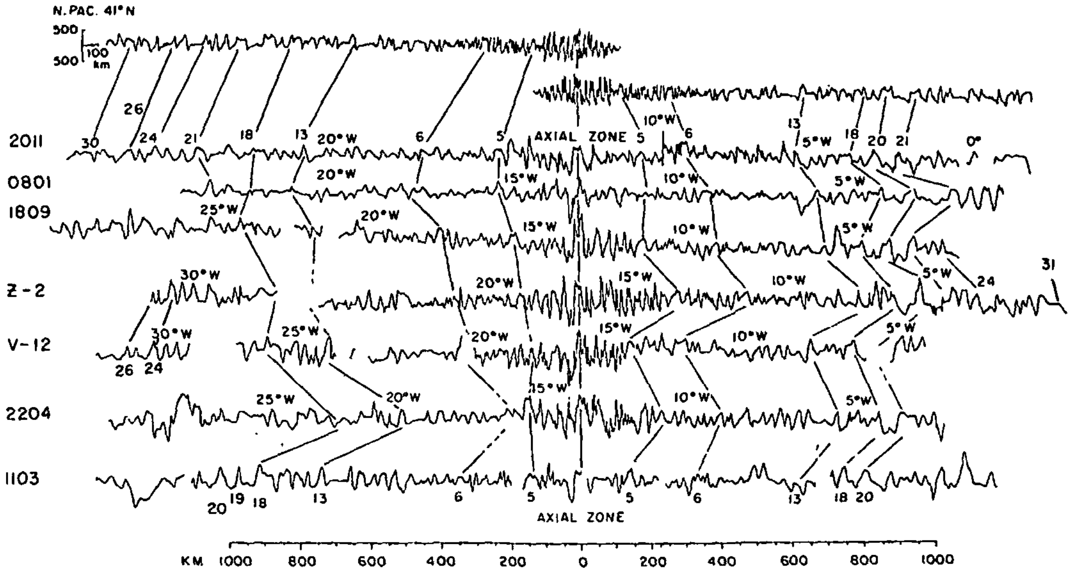


Fig. 4. Projected magnetic anomaly profiles across the South Atlantic are shown. Key anomaly correlations are indicated and numbered according to the system of Pitman *et al.* (1968). Track locations are given in Fig. 2. The longitude along selected profiles is given.

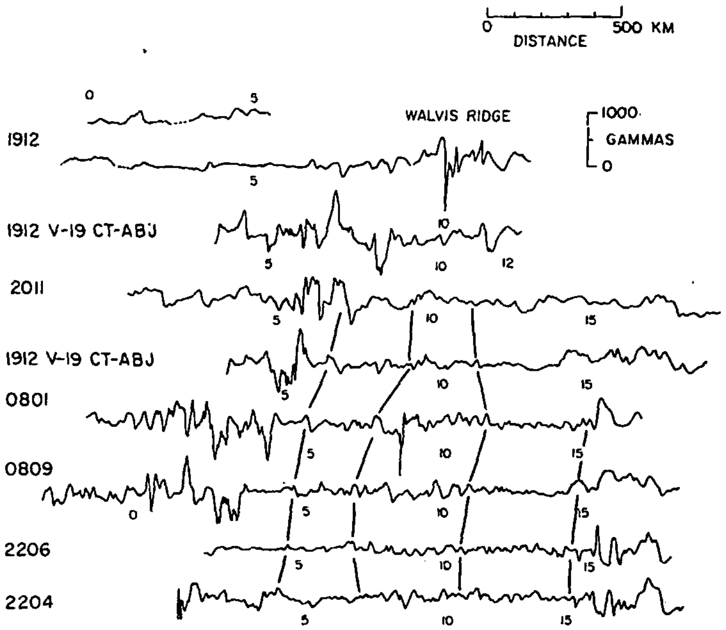


Fig. 5a. Magnetic profiles from the eastern South Atlantic. Numbers to the left refer to ship tracks in Fig. 2. Numbers along the profile are east longitude.

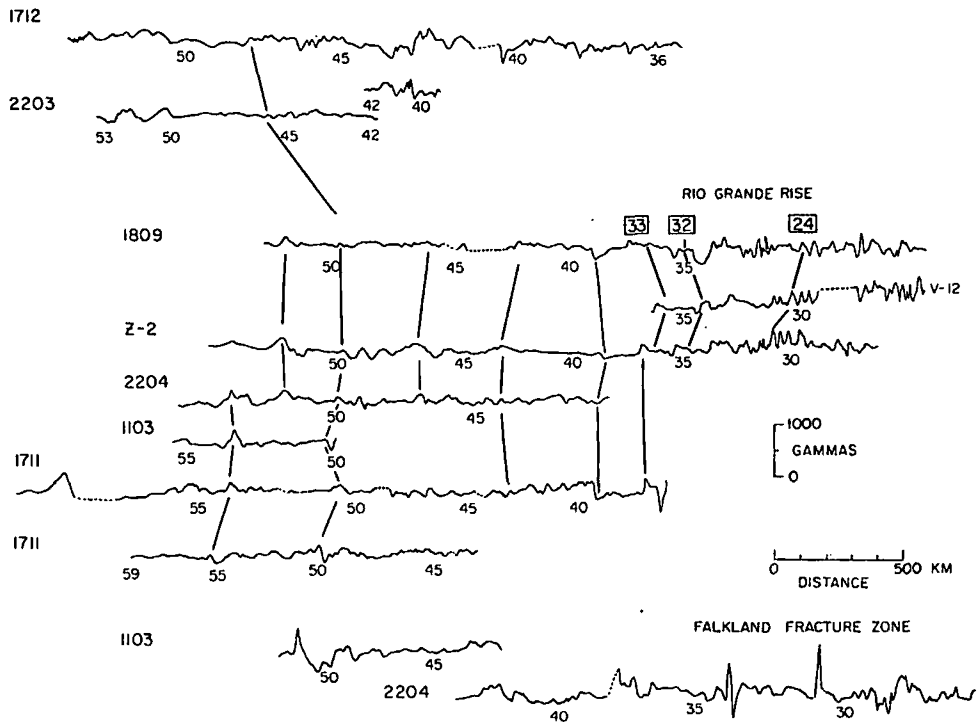


Fig. 5b. Magnetic profiles from the western South Atlantic are shown. Magnetic anomaly numbers are enclosed in squares. The additional numbers are longitude (west) along the profiles.

Argentine basin in the V-12 and Z-2 profiles. There is also some evidence of a lineation pattern within the Argentine basin eastward of the continental slope off Argentina (see Fig. 5b).

Anomaly 31 was the oldest anomaly that Dickson (1967) and Dickson *et al.* (1968) were able to correlate in the western South Atlantic. With the additional data, anomaly 32, an anomaly we will call 33, and a quiet zone may be found to the south and southwest of the Rio Grande rise. The anomaly here called 33 (see Fig. 6a) did not appear in the numbering system of Pitman *et al.* (1968) and thus was not assigned an age by Heirtzler *et al.* (1968). Immediately westward of anomaly 33 in the western South Atlantic the amplitude of the anomalies is distinctly subdued. This zone extends to the Argentine shelf (Figs. 3, 5, and 6a) (Mascle, J., and Phillips, J. D., 1972).

In the eastern South Atlantic the oldest anomaly that Dickson (1967) and Dickson *et al.* (1968) were able to correlate in the vicinity of the Walvis ridge is 24. Just south and east of the Walvis ridge anomalies out to 30 were identified. With additional data we have been able to correlate through anomaly 33 to the south and north of the Walvis ridge (Fig. 8).

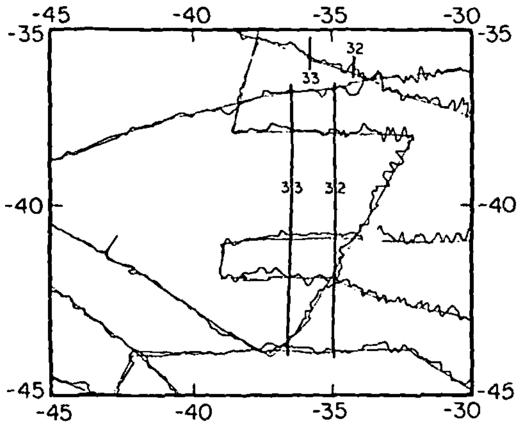


Fig. 6a. Enlarged portion of Fig. 3 showing correlations of magnetic anomalies at the edge of the quiet zone in the Argentine basin.

South of the Walvis Ridge and east of anomaly 31 there are several step-like anomalies, east of which is a quiet zone. Between the eastern margin of the quiet zone and the continental margin is a region of incoherent anomalies. The ridge runs across the trend of the pattern, and its anomaly pattern appears complex. Correlations along the ridge are not obvious and certainly there is no evidence of symmetry. This indicates that the Walvis ridge has not been an axis of sea-floor spreading.

Passing over the Walvis ridge into the Cape basin the magnetic field becomes much quieter (Fig. 5a). Some correlations can be made in the Cape basin, although the anomalous field has a more subdued character.

C. The Age of the Floor of the South Atlantic Ocean

As has been already noted, the amplitude of the magnetic anomalies is subdued in the flanking basins of the South Atlantic and few correlations could be made between profiles. Helsley and Steiner (1968), by an analysis of Cretaceous paleomagnetic data, concluded that during the Cretaceous period there were long intervals of dominantly normal magnetic polarity, although there were magnetic polarity reversals in the lowermost and uppermost Cretaceous. It is obvious that any oceanic crust created by the spreading process during long periods of constant magnetic polarity would lack a lineation pattern (except, perhaps, low-amplitude anomalies due to intensity variations). Helsley and Steiner suggested that this in fact explained the magnetically quiet region that exists west of anomaly 32 on the lower flanks of the East Pacific rise. Figure 6b (adopted from Raff, 1966, and Helsley and Steiner, 1968) shows this transition in the North Pacific. Anomalies 32 and 33 are indicated. Note the striking similarity between the transition shown in this figure and that shown in Fig. 6a from the South Atlantic. The same negative anomaly beyond 33 is found in both cases followed by a region of subdued magnetic anomalies. (Anomalies 32 and 33 of Fig. 6b appear to be of much lower amplitude than those of Fig. 6a; this is simply because of the difference in scales used in the figures.) As discussed previously this region extends to the Argentine shelf. The few tentatively correlated anomalies within this zone may represent short polarity events within the Cretaceous or may be due to intensity variations.

In the North Atlantic, Pitman *et al.* (1971) and Pitman and Talwani (1972) have shown that between Africa and North America (Fig. 7) the following type of magnetic pattern exists. The sequence of anomalies from 1 to 31 extends outward from the axis of the mid-Atlantic ridge on both flanks. Anomalies 32 and 33 may be identified in several places. Shoreward from this region on either flank is a zone of more subdued anomalies. Correlations in this region have not been made even with quite close track spacing (Anderson *et al.*, 1969; Vogt *et al.*, 1970). The basement of this region is rough (Holcombe, 1971) and may well be the cause of the low-amplitude anomalies that do occur. Pitman and Talwani (1972) have correlated this zone with the Cretaceous period

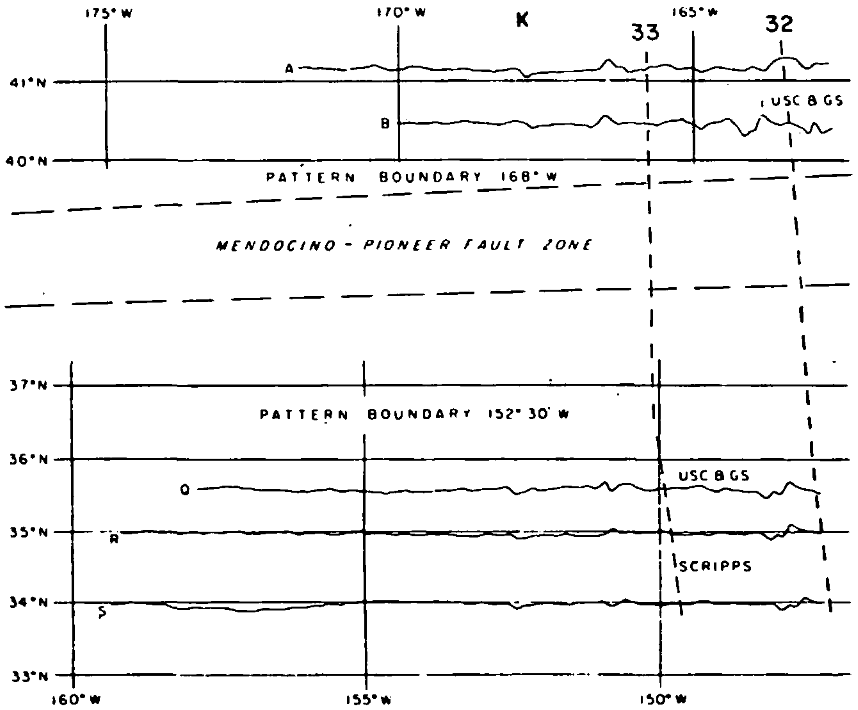


Fig. 6b. Magnetic anomalies from the North Pacific after Raff (1966) and Helsley and Steiner (1968).

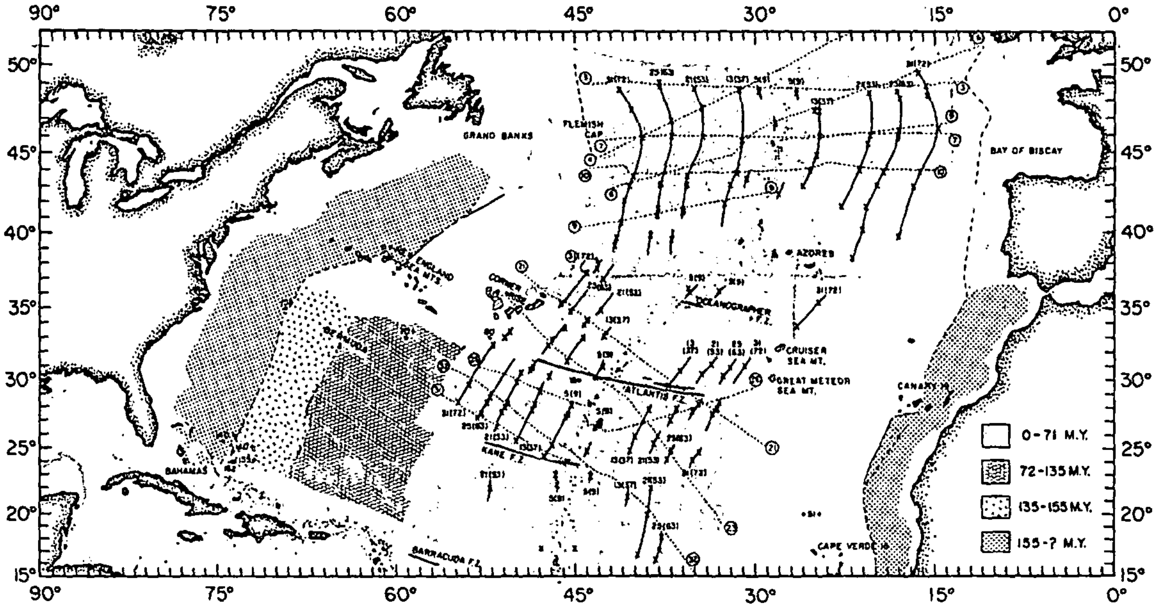


Fig. 7. North Atlantic is shown. Lineations for some key anomalies younger than 72 m.y.b.p. are shown. The anomaly numbers are given; the age of the anomalies is shown in parenthesis (m.y.b.p.) (Heirtzler *et al.*, 1968). The location of *Joides* drill holes are shown as dots with the age in m.y. shown beside the dot. The plus sign beside the age indicates that the drilling did not reach basement. The seismic epicenters defining the axis of the ridge and the associated transform faults are from Barazangi and Dorman (1969).

of dominantly normal magnetic polarity. Still further landward is the Keathley sequence of magnetic anomalies (Anderson *et al.*, 1969; Vogt *et al.*, 1970; Emery *et al.*, 1970). Pitman and Talwani (1972) have proposed that this sequence represents spreading from 155 to 135 m.y. The conclusion is based on interpolation between the oldest lineation that may be defined by the Cenozoic patterns and *Joides* hole 105, dated at about 155 m.y. (Ewing *et al.*, 1970). This hole is at the landward edge of the Keathley sequence. Landward of the Keathley sequence is another zone of subdued anomalies called the quiet zone (Heirtzler and Hayes, 1968). The boundary between the quiet zone and the Keathley sequence is called the quiet-zone boundary. Various hypotheses have been offered to explain this quiet zone (Heirtzler and Hayes, 1967; Drake *et al.*, 1968; Nafe and Drake, 1969; Vogt *et al.*, 1970). However, the fact that the quiet-zone boundary that lies off of the west coast of Africa may be fitted against the quiet-zone boundary that lies off of the east coast of the United States suggests that this boundary represents an isochron (Pitman and Talwani, 1972). de Boer (1968) has proposed that the Upper Triassic may have been a period of dominantly normal magnetic polarity, and Burek (1970) thinks that this may extend into the Jurassic. Thus a most likely explanation for the quiet zone is that it represents the Upper Triassic–Middle Jurassic period during which there were no magnetic polarity reversals.

Thus from the North Atlantic we may infer the following general pattern of polarity reversals: (1) 0–77 m.y., frequent reversals, distinct magnetic anomaly pattern; (2) 77–135 m.y., infrequent reversals (perhaps only intensity variations), no distinct pattern of magnetic anomalies; anomalies that do exist are quite subdued and most probably due to intensity variations, petrologic contrasts, and bathymetric effects; (3) 135–155 m.y., frequent reversals resulting in a distinct anomaly pattern; (4) 155–? m.y., again no reversals and as a result no distinct magnetic anomaly pattern. These zonations are shown in Fig. 7. Hayes and Pitman (1970) have found the same zonation in the North Pacific. We may now compare this rough time scale to the South Atlantic (Fig. 8). The fact that no distinct pattern of anomalies similar to the Keathley sequence appears implies that active spreading and consequently active drift began subsequent to about 135 m.y. This is in agreement with the paleomagnetic evidence of Vilas and Valencio (1970) who concluded that the initiation of drift occurred somewhere between Late Triassic and Middle Cretaceous. Maxwell *et al.* (1970) also proposed a similar age of separation based on extrapolation of the *Joides* results. Using geologic arguments Allard and Hurst (1969) surmised that separation must have occurred sometime in the Middle Cretaceous. The radiometric age of the Kaoko basalts of Southwest Africa range from 136 to 114 m.y. (Siedner and Miller, 1968). The basalts of Serra Geral, Brazil, are of the same age (Amaral *et al.*, 1966). Features of this type are regarded as having been caused by extension accompanying initial rifting.

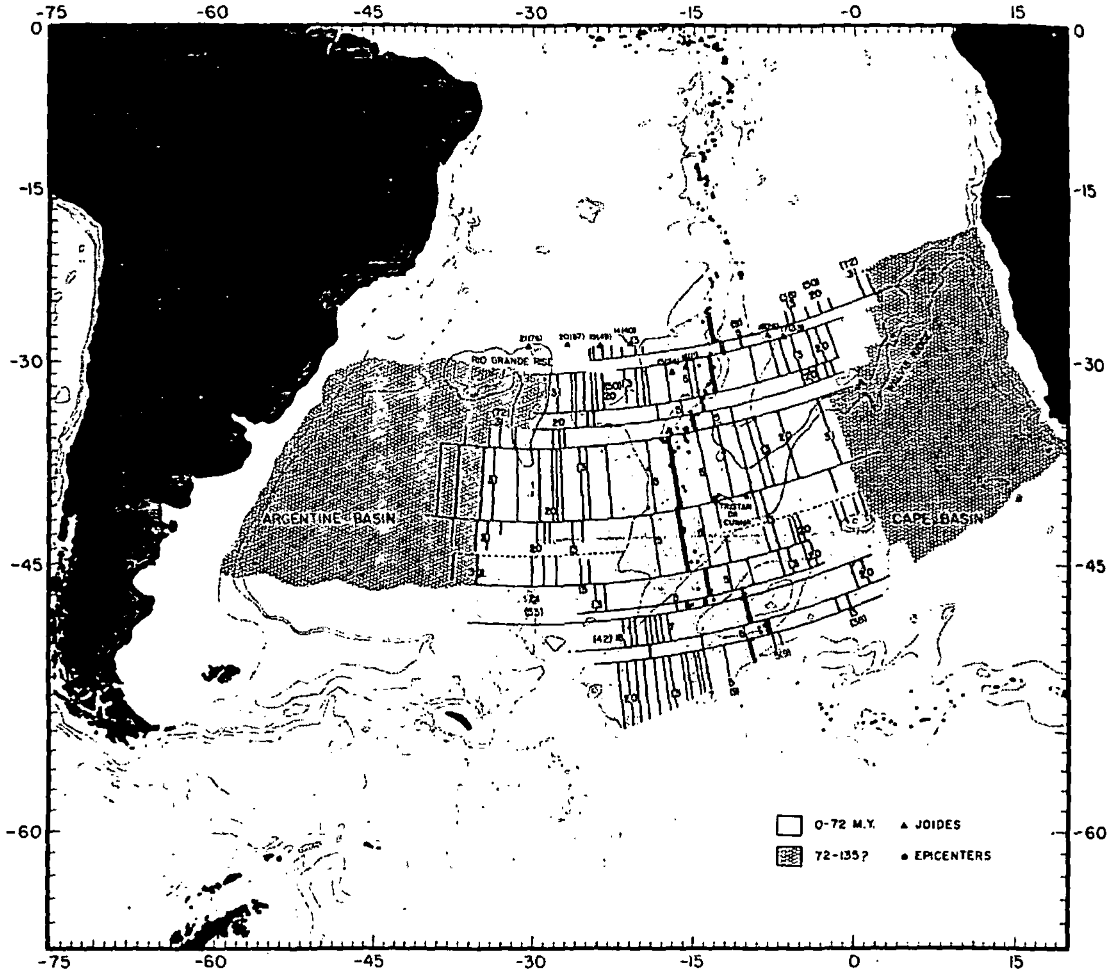


Fig. 8. Generalized magnetic lineation map for the South Atlantic. Magnetic anomaly numbers are shown with ages in m.y. in parenthesis. The location of *Joides* holes is indicated with triangles. The hole number with ages in m.y. in parenthesis is also given. The seismic epicenters are from Barazangi and Dorman (1969) and Sykes (personal communication). Curved lines are fracture zones drawn as small circles about Bullard's pole at lat 44° N, long 30° W.

III. EVOLUTION OF THE SOUTH ATLANTIC

A. Sea-Floor Spreading

Given the above constraints we may now attempt to synthesize a model for the evolution of the Atlantic, south of the Azores. Pitman and Talwani (1972) have devised an evolutionary history of the North Atlantic by fitting together magnetic lineations of the same age, but from opposite sides of the ridge axis, similar to the way in which Bullard *et al.* (1965) fitted continental margins. Ladd and Pitman (in preparation) have fitted together magnetic anomaly lineations of the same age in the South Atlantic. The model is shown in Figs. 9, 10, and 11. The relative paleopositions of Africa and North America are from Pitman and Talwani (1972). The original unrifted configuration of the continents is assumed to be that of Bullard *et al.* (1965).

The initial rifting (Fig. 9) separated Laurasia from Gondwana. Africa and South America separated from North America at about 180 m.y. (Dietz and Holden, 1970; Pitman and Talwani, 1972). This suggests the presence of a Late Triassic spreading ridge west of South America, connected to the Triassic mid-Atlantic ridge by a system of ridges and transform faults, perhaps along what is now the southern border of the Gulf of Mexico and perhaps extending through what is now the region of Central America. This mode of spreading would have continued until the latest Jurassic or the earliest Cretaceous (approximately 135 m.y.). At this time rifting between South America and Africa took the form of active sea-floor spreading. The ridge transform fault system that linked the mid-Atlantic ridge to the Pacific ridge from the Late Triassic to the Late Jurassic may have continued to be active since North America and South America appear to have been moving away from Africa as independent plates.

South America might then have had an active spreading ridge offshore from both its eastern and western margin as it does today. The spreading

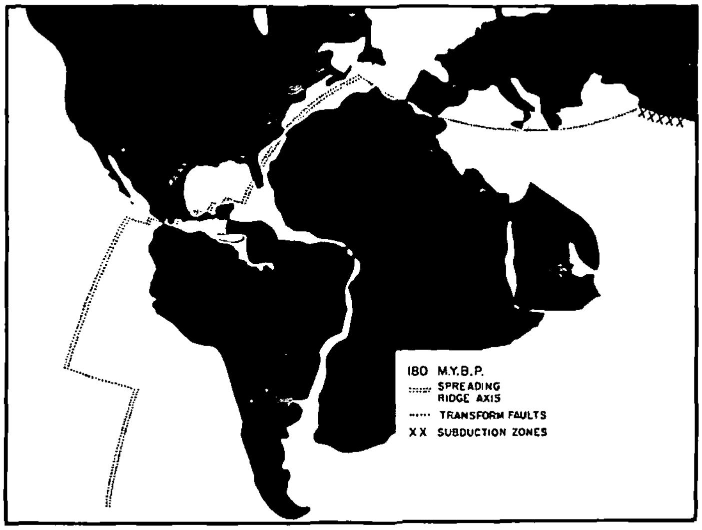


Fig. 9. The Atlantic 180 m.y.b.p. at the initiation of rifting between Gondwana and Laurasia. The fit of the continents is that of Bullard *et al.* (1965).

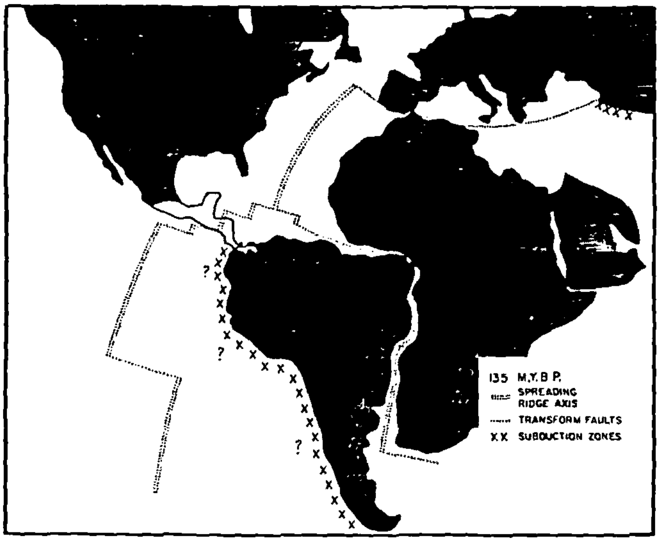


Fig. 10. The Atlantic at approximately 130 m.y.b.p. The relative position of Europe–North America and South America–Africa is that of Bullard *et al.* (1965).

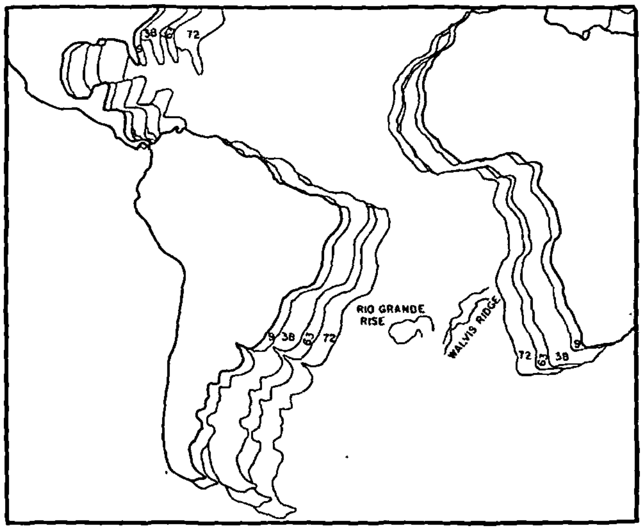


Fig. 11. An inferred sequence of relative paleogeographic positions for Africa, South America, and North America for several ages ranging from 72 to 9 m.y.b.p. The Walvis ridge and Rio Grande rise have been plotted with respect to the configuration of the continents at 71 m.y.b.p. The relative paleogeographic positions of North America and Africa are from Pitman and Talwani (1972); those of Africa and South America are from Ladd and Pitman (in preparation).

in the South Atlantic passively rafted the bounding continents. There was no underthrusting along the Atlantic margins. It is possible that the underthrusting along the western margin of South America may have begun at about the time that the South Atlantic began to open. This conclusion is given some support by the fact that andesite volcanism appears in the southern Andes in the Late Jurassic (Katz, 1963). In Fig. 11 the evolution of the Atlantic from 135 m.y. to the present is shown. All paleogeographic positions are shown relative to the axis of the South Atlantic branch of the mid-ocean ridge system.

B. Mantle Hot Spots

The Walvis ridge and Rio Grande rise are the most puzzling features of the South Atlantic. Wilson (1963 and 1965), Dietz and Holden (1970), and Morgan (1971) have suggested that the Walvis ridge and perhaps the Rio Grande rise were generated by spreading plates moving relative to a mantle hot spot or convective plume. Wilson proposed that the Hawaiian Islands were also formed as the Pacific plate moved over a mantle hot spot. The proposition seems most plausible in this latter case. The Hawaiian Islands form a nearly linear chain that cuts obliquely across magnetic lineations and fracture zones without offsetting either (Hayes and Pitman, 1970). They consist of volcanics extruded on the crust, and decrease in age to the southeast (Wilson, 1965). Neither the Walvis ridge nor the Rio Grande rise have such a systematic appearance. The Walvis ridge appears to be offset by fracture zones. The northern limb is asymmetric with a steep southeasterly facing scarp. The Rio Grande rise extends east–west with a southerly extending branch at the eastern end. The existence of this southerly limb as a genetic part of the Rio Grande rise is still questionable. Bathymetric profiles in this region show a rise in the rough basement but do not indicate a feature of the size or character of the east–west limb (Lonardi and Ewing, 1971; Connary, 1972).

The mantle hot spot that formed (and is still forming) the Hawaiian island chain has been far from any actively spreading ridge axis. Although the region is cut by the Molokai and Murray fracture zones this section of the plate was so distant from the active ridge axis when it traversed the hot spot that these fracture zones may not have been fundamental structural weaknesses in the crust. The Hawaiian island chain thus follows a smooth curve indicative of linear relative motion between the plate and the hot spot. As noted above the Walvis ridge, on the other hand, is rather sinuous and appears to be offset by fracture zones (see Fig. 8). The currently active Walvis ridge hot spot, presumed to be beneath Tristan da Cunha Island (Wilson, 1963, 1965; Dietz and Holden, 1970; Morgan, 1971), is located quite near the ridge axis. If the hot spot has always been at or near the ridge axis, the magma would obviously be extruded to the surface via convenient zones of weakness such as the axial rift and/or active transform faults. Thus, even if the path of motion of the Walvis ridge hot spot was linear relative to the plate the surficial expression as a chain of extrusives might have a steplike appearance. Both the Rio Grande rise and the Walvis ridge have long northern segments (Fig. 8). On the Rio Grande rise this segment trends slightly south of west. On the Walvis ridge this segment (which joins the African coast) trends southwest–northeast. Further to the south the trend of the Walvis ridge becomes nearly southerly, as does the easternmost limb of the Rio Grande rise. This apparent change in trend has been explained by Dietz and Holden (1970) as indicating a change in the direction of relative motion of the plates vs. the mantle hot spot. From the generalized anomaly trends shown in Fig. 8 it can be inferred that this change occurred about 80 m.y. ago. A rather contradictory observation with regard to the origin of the Rio Grande rise and the Walvis ridge has been made by LePichon and Hayes (1971). They have shown that the northern limbs of both the Walvis ridge and the Rio Grande rise lie along a small circle of presumed relative motion implying a fracture-zone origin.

Evidence from *Joides* drilling (Maxwell *et al.*, 1970) suggests that the Rio Grande rise was a shallow feature by the Late Cretaceous. This is not in contradiction with the ages of basement predicted by the magnetic anomalies. Segments of the Walvis ridge are known from core data to have been uplifted prior to the Paleocene (Ewing *et al.*, 1966). We may perhaps presume that the northern segment of the Walvis ridge was uplifted by the Late Cretaceous. LePichon and Hayes (1971) have shown that if the South Atlantic is closed up to its Late Cretaceous size, the Walvis ridge–Rio Grande rise would form a natural barrier to circulation of bottom water between the southern South Atlantic and the northern South Atlantic. The North Atlantic may have been isolated from the South Atlantic by ridges along the extensions of equatorial fracture zones. They have suggested that this may account for the Cretaceous salt basins on the coasts of South America and Africa between the equator and lat 30° S. Defant (1961) and Ewing *et al.* (1966) pointed out that the Walvis ridge and Rio Grande rise at present form a somewhat effective barrier to deep circulation. In the Fig. 11 reconstruction of the South Atlantic, the Walvis ridge and Rio Grande rise have been rotated back with the continents that they adjoin at 71 m.y. It can be seen that these features are separated by only a narrow gap. This gap would have been filled by the axial region of the ridge. Anomaly 31 (*Joides* site 20) was just being generated. In fact, the *Joides* results indicate that this portion of the crust did not subside to the carbonate compensation depth until 38 m.y., suggesting that the ridge and its flanks plus the Rio Grande rise and Walvis ridge formed an effective barrier until that time. The only route for deep-water circulation between the northern and southern South Atlantic may have been a narrow pass through the Rio Grande rise called Rio Grande gap (LePichon *et al.*, 1971).

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NOTE ADDED IN PROOF

Recent work by Larson and Pitman (1972) has revised the estimate of the duration of the Keathley sequence. On the basis of JOIDES drilling, they now place the range of the Keathley sequence from 148 to 110 m.y.b.p. instead of 155 to 135 m.y. This would place the initiation of sea-floor spreading in the South Atlantic at 127 ± 2 m.y. since recent work by Larson and Ladd (in preparation) has shown that anomalies M1 to M12 of the Keathley sequence exist just west of Cape Town.

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