More free publications from Archimer

Art. N° 72
Contribution COB N° 67

The American Association of Petroleum Geologists Bulletin
V. 56, No. 6 (June 1972), P. 991-1007, 11 Figs., 3 Tables

Marginal Fracture Zones as Structural Framework of Continental Margins in South Atlantic Ocean[1]

JEAN FRANCHETEAU[2] and XAVIER LE PICHON[2]
29N-Brest, France

Abstract – A plate tectonic model of the early opening of the South Atlantic is used to describe the structural framework of the continental margins and adjacent oceanic and coastal areas on both sides of the ocean. It is proposed that major offsets of the continental margins necessarily induce the subsidence of coastal basins where fracture zones intersect the continents. The configuration of the accreting plate-margin boundary gradually developed throughout the opening of the ocean after Late Jurassic time. –

Introduction

We consider that the South Atlantic Ocean was created by the drift of Africa and South America and that the separation of South America and Africa began about 130 m.y. ago (Maxwell *et al.*, 1970). Actual rifting, or at least invasion of the sea, may have begun earlier, as indicated by the existence of Tithonian marine strata south of São Salvador, Brazil (L. de Loczy, personal commun.), but the main separation probably did not begin before Early Cretaceous. We adopt the predrift reconstruction of Bullard *et al.* (1965), because it can be reproduced accurately and has been shown to be compatible with a wealth of geologic and geophysical data (*e.g.*, Hurley *et al.*, 1967; Hurley, 1968). The success of this reconstruction shows that the drift has not been accompanied by any significant deformation of the continents and that the opening of the South Atlantic should be discussed in terms of rigid plates. We consequently use the plate tectonic hypothesis to determine the precise geometry of the early opening following Le Pichon and Hayes (1971) and to investigate how much the structural framework of the continental margins is controlled by this geometry of opening. In particular, we will attempt to show that the margin offsets which result in the formation of marginal fracture zones in the adjacent ocean basins induce the formation of coastal basins on the adjacent shelf and continent. However, there are two major difficulties in this attempt: (1) the fracture zones in the South Atlantic are not well known, especially near their heavily sedimented continental margin ends; (2) it is difficult to obtain a good review of the geology of the coastal basins from the published literature. In particular, we have no access to confidential oil industry survey results and obviously cannot take them into account. However, the rigor of our kinematic model leads to predictions which can be easily verified, and we hope that this preliminary attempt will lead to fruitful discussions and eventually to release of some oil industry geologic data. We want to stress that this paper is concerned only with the opening between Africa and South America during the latest post-Triassic phase of continental drift.

Model

On a spherical earth, the relative movement of two rigid plates can be represented at any given time by movement about a pole of rotation. Le Pichon and Hayes (1971) have suggested that the mechanical constraints imposed by the continental segments of the lithosphere when continents first split apart are much stronger than the constraints imposed by the thin oceanic lithosphere produced at a normal accreting plate margin. The initial relative motion of the plates is stabilized and proceeds about the same pole of rotation during the early phase of opening. Peculiar marginal fracture ridges are built as extensions of the important offsets of the continental margins. These marginal ridges are later modified by sedimentary processes but are very good markers of the geometry of early opening of an ocean created by the split of two continents. Consequently, this model provides a direct approach to the determination of the parameters of initial rotation. Using this model, Le Pichon and Hayes computed the best fit pole of early opening of the

[1] Manuscript received, July 23, 1971; revised and accepted, October 5, 1971. Contribution no. 67 of the Groupe Scientifique of the Centre Océanologique de Bretagne.
[2] Centre Océanologique de Bretagne, B.P. 337.
We are grateful to D. P. McKenzie and J. G. Sclater for sending us a paper in advance of publication, to M. Magnier for communication of an unpublished bathymetric map. We thank D. Carré, Y. Potard, and N. Uchard for assistance in editing the manuscript.
K. Beurlen, P. R. Boyer, L. W. Butler, N. K. Grant, A. Hallam, W. J. Ludwig, M. Magnier, and Tj. H. van Andel provided helpful comments. G. Pautot and R. Hekinian communicated preliminary results of a cruise across Walvis Ridge.
© 1972. The American Association of Petroleum Geologists. All rights reserved.

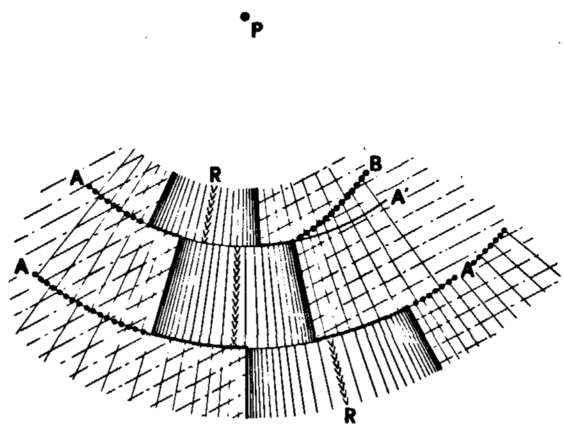


FIG. 1—Highly schematic diagram showing how early opening induces formation of coastal basins. Opening occurs about pole *P*. Accreting plate margin is *R*. Increasing subsidence away from *R* of plates covered by oceanic crust is shown by closer ruling. On continent, coupled to adjacent ocean floor, subsidence increases toward margins. Hinge or normal faulting occurs along prolongation of offset margins (small circles *A*) and may be influenced by preexisting line of weakness as in *B*. Thus coastal basins are limited by prolongations of transform faults.

South Atlantic at 21.5° N lat., 14.0° W long., in a reference frame attached to Africa. In the computation, equatorial fracture ridges (St. Paul, Romanche, and Chain) on both sides of the Mid-Atlantic Ridge were used exclusively. Yet, the model applies to the whole South Atlantic, for the Falkland Plateau northern scarp and the Falkland fracture zone, as well as the northern scarps of the Walvis and Rio Grande ridges, also are small circles about this pole of early opening. The pole, however, only describes the relative movement of the African and South American plates and does not apply north of Cape Palmas at the boundary of the Ivory Coast and Liberia or north of Cape Orange at the boundary of Brazil and French Guiana. For example, the Guinea fracture zone, farther north, is within the African-North American plates system.

Accurate knowledge of the parameters of initial opening is very helpful in understanding the structural framework imposed on the continental margins during their creation. Some offsets of the continental margins are transform faults during the early opening and must coincide with small circles about the pole of rotation. Large marginal fracture ridges, built on ocean floor, extend away from these continental margin offsets along the same small circles. In addition, as the ocean widens by accretion of new lithosphere, the sea floor becomes more distant from the accreting plate margin and progressively subsides. The adjacent continental margin, which is coupled to the oceanic lithosphere, tends to subside with it. The subsidence is a direct function of the distance to the corresponding segment of accreting plate margin, because it is controlled by the thermal inertia of the lithosphere. Therefore, the thermal contrast on each side of a fracture zone with a large offset is important, and fracture zones act as regions of decoupling for blocks which have differential vertical movements (Fig. 1). The resulting differential subsidence of parts of continental margins will lead to the formation of shelf and coastal basins, open toward the sea, and approximately limited by the prolongations of the margin offsets and corresponding fracture zones. The rigidity of the plates requires that the subsidence of the basins along the same plate margin begins simultaneously. However, the invasion of the sea is probably not simultaneous, but progresses from one or both ends of the rift. Subsequently, as the ocean widens and the margins subside, heavy terrigenous sedimentation may take place and result in a significant advance of the continental margin between two closely spaced marginal fractures, thus creating an extension of the continental coastal basins on the oceanic crust.

Wilson (1965) has defined transform faults as lines of pure slip between two plates; therefore, the motion associated with such faults conserves crust. A ridge-ridge transform fault ends abruptly against the two offset crests of ridge. Therefore, its inactive prolongations should end abruptly against the continental margin, which is a fossil plate boundary at the time of the initial rift. However, the process of differential subsidence of the margins, which we just described, results in the creation of normal faults or hinge faults within the continents along the prolongations of the oceanic transform faults (Fig. 1). These hinge faults therefore will limit coastal basins. Furthermore, as Wilson (1965, p. 344) noted, "If a continent in which there exists faults or lines of weakness splits into two parts, the new tension fractures, or transform faults, may trail and be affected by the existing faults." The normal or hinge faults created in the coastal areas by differential subsidence of the margins may therefore rejuvenate these old lines of weakness. The lines of weakness, however, even if they are reactivated during drift, could have directions very different from the early opening transform directions. Le Pichon *et al.* (1971b) have proposed to call structures which tend to organize themselves along small circles of opening "transform directions." It should be stressed that, if our reasoning is correct, no significant horizontal motion should have occurred along the continental transform directions during the course of drift. This is indeed demonstrated by Bullard *et al.*'s (1965) fit.

In Figure 2, Africa arbitrarily has been held fixed, and two rotations have been applied to South America and its adjoining sea floor (see Table 1). The resulting relative positions of the continents are approximately those 80 to 90 m.y. ago, near the end of the first phase of opening (Le Pichon and Hayes, 1971). According to McKenzie and Sclater (1971), the earthquake epicenters associated with the Mid-Atlantic Ridge (Barazangi and Dorman, 1969) also have been rotated, thus defining the probable location of the rift at the same time (Table 1). Theoretical flow lines in this model are small circles about a pole at 21.5°N lat., 14.0°W long. and are shown in Figure 2. Table 2 gives the azimuths predicted for flow lines at their intersections with the continental margins on both sides of the Atlantic. Where fracture zones exist, they should have the azimuth given in the table.

We have made a systematic examination of the available geologic, geophysical, and bathymetric data to identify the major directions. These transform directions generally are clearly associated with an offset of the margins and can be related directly to present offsets of the rift, as revealed by seismic, magnetic, and/or bathymetric data. These transform directions and their corresponding active transform faults (Table 3) give strong support to the model.

A casual examination of Figure 2 confirms that, on a large scale, Le Pichon and Hayes' pole of early opening accounts satisfactorily for the trend of the Romanche fracture zone (21.1° circle) and that of the ridge connecting the island of Trindade to the Brazilian margin (40.4°). The northern east-west edge of the Walvis Ridge (47°), the Falkland Plateau scarp (68°), as well as the southeastern continental margin of South Africa (68°), all follow closely the trends predicted from the study of equatorial fracture zones. The east-west northern scarp of the Rio Grande rise follows only approximately the 48° circle.

We are aware that there are errors inherent in the model which stem from (1) errors in determination of the pole of rotation resulting from inadequate knowledge of the trends of the fracture zones and imprecision in the predrift reconstruction of the continents, (2) imperfections in the rigidity of plates, and (3) existence of processes other than those related to early drift active in modifying the structures of the margins.

The results show that the well-defined structural trends related to the opening of the ocean conform closely to predicted transform directions everywhere within 50° of latitude. This demonstrates that the first two causes of error are negligible with respect to the third. In fact, although it is generally easy to recognize the trend of a fracture zone or subsiding trough, it commonly is difficult to determine the precise location of the fault along which differential movement takes place. Thus, in the following discussion, the trend of the structures is more important than their exact location.

Equatorial Transform Directions

The eastern end of St. Paul fracture zone (18.65° circle) is parallel with a small circle and follows closely the Ivory Coast continental margin, which it intersects just west of Abidjan (Fig. 3). This fracture zone may have been important in shaping the narrow Ivory Coast basin within the Precambrian cratons (Spengler and Delteil, 1966). Similarly, the Romanche fracture zone lies along a small circle (21.1°) which parallels the continental margin along a steep WSW-ENE escarpment called Ivory Coast-Ghana ridge (Arens *et al.*, 1971). This ridge is particularly prominent in reflection profiles and appears as a basement uplift faulted on the south (Arens *et al.*, 1971). The extension of the Romanche fracture zone passes just south of Accra and marks the northwest boundary of the Dahomey or western Benin basin filled with Cretaceous and Tertiary sediments in common with most sedimentary basins along the West African coast (Reyre, 1966; Grant, 1969; Fig. 3). The important NNE-SSW Buem-Togo thrust zone, which formed during the Pan-African orogeny, is associated with mafic and ultramafic rocks and even alpine-type peridotites. This thrust zone marks a major boundary between two Precambrian cratons (Grant, 1969) and was, according to McCurry (1971), the locus of a collision between two lithospheric plates during the Pan-African orogeny (Fig. 3). The Early Cretaceous opening of the South Atlantic Ocean apparently was not influenced by this colliding plate boundary, an ancient line of weakness, which has since been reactivated as evidenced by its seismic activity. Similarly, the roughly parallel Adamawa-Cameroun-São Tomé volcanic line, which has been active since Late Cretaceous time (see Reyre, 1966), is a reactivation of an old line of weakness during the second phase of opening of the Atlantic. Its trend does

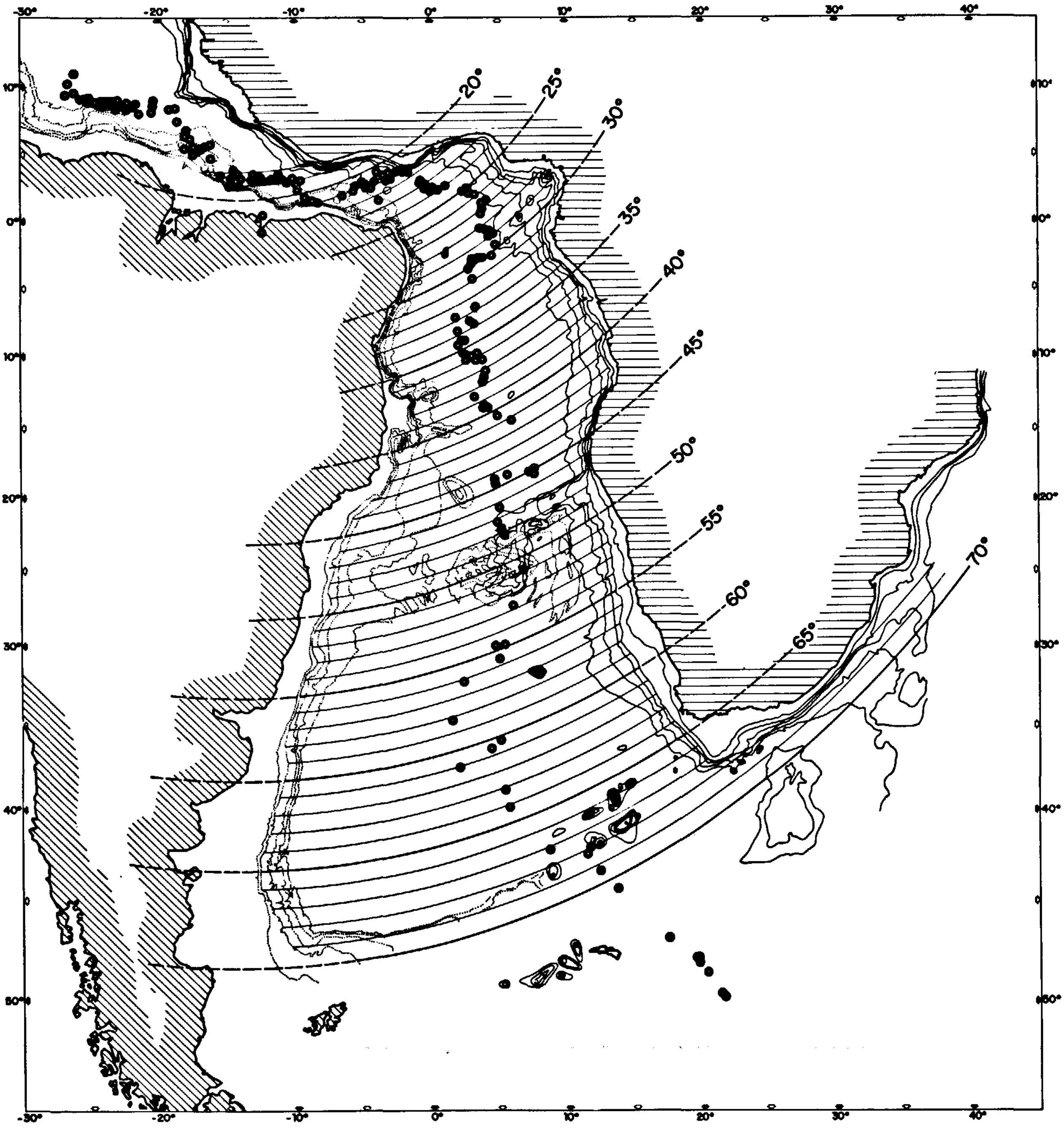


FIG. 2—Relative positions of South American and African plates in Late Cretaceous near end of first phase of opening. Rotated epicenters after Barazangi and Dorman (1969). Dotted lines are bathymetry on South American plate (south of 29°S lat. after Lonardi and Ewing, 1971; north of 29°S lat. after U.S. Navy Hydrog. Office, 1968). Continuous lines are bathymetry on African plate (north of 27°S lat. after Comm. Carte Géologique Monde, 1960, and Assoc. African Geol. Surveys, 1968; south of Walvis Ridge after E. S. W. Simpson and E. Forder, unpub. map). Contours shown at 200; 1,000; 2,000; 3,000; and 4,000 m. Flow lines about early pole are at 1° intervals.

not conform to the early opening trend. However, the Buem-Togo thrust zone and the Adamawa-Cameroun lines intersect the African margin at the same points as the Romanche and 27° fracture zones, respectively.

The eastern part of Chain fracture zone (23.2°) is not apparent in Figure 2, but it is well known from the Mid-Atlantic Ridge crest to 5°W long. According to the data of Arens *et al.* (1971), a buried segment extends eastward to at least 1.5° W long. The Chain fracture zone would, in this model, intersect Africa east of Lagos (Fig. 3) at the limit between the Dahomey and Benue troughs (Grant, 1969; Wright, 1968) where as much as 5 km of Upper Cretaceous (Santonian to Aptian) sediments accumulated (see McConnell, 1969; Reyment, 1965). Apparently, outbuilding of the Niger delta has been controlled by the Chain marginal fracture ridge on the north and a fracture zone on the south that corresponds to the important Pernambuco shear zone of Brazil (Beurlen, 1970; see Table 3).

These fracture zones probably acted as dams for the delta sediments. Thus, the continental extensions of the three major equatorial fracture zones mark the edge of where pronounced subsidence occurred in the Early Cretaceous and where true marine sediments were deposited in

Table 1. Rotations Used For Figure 1

Plate	Lat.	Long.	Rotation Angle[1]
S. America			
first[2]	44.0	-30.6	+57.0
then[3]	21.5	-14.0	-26.3
equivalent to[4]	63.2	-36.7	+35.26
Earthquakes	63.2	-36.7	+17 63
Africa		Not Rotated	

[1] Positive rotation of moving plate about pole listed is in anti-clockwise sense, viewed from above pole.
[2] Fit of 500-fm contours (Bullard *et al.*, 1965).
[3] Early rotation of South America (in frame attached to Africa) corresponding to the last stage of development (about 80 m.y.) of the marginal fracture ridges according to Le Pichon and Hayes (1971).
[4] Rotation applied to South America to obtain its position as shown in Figure 1. This rotation is the total post-80 m.y. rotation.

Table 2. Directions of Early Opening Fracture Zones at Selected Points of Margins

SOUTH AMERICA					AFRICA				
Location	Lat.	Long.	Colat.* (Degrees)	Azimuth**	Location	Lat.	Long.	Colat.* (Degrees)	Azimuth**
Near Cayenne	5.0	-52.0	18.2	309.5	Southern Liberia	5.0	-9.0	17.2	74.1
Mouth of Amazon	0.0	-50.0	21.3	297.3	Libreville	0.0	+9.0	31.1	45.2
Areia Branca	-5.0	-37.0	24.0	263.2	South of Pointe Noire	-5.0	+12.0	36.8	47.0
Maceió	-10.0	-36.0	29.1	262.4	South of Luanda	-10.0	+13.0	41.2	50.1
Ilhéus	-15.0	-39.0	33.8	268.5	North of Moçâmedes	-15.0	+12.0	44.5	54.4
Vitória	-20.0	-40.0	38.8	270.2	South of Cape Fria	-20.0	+13.0	49.2	56.1
North of Paranaguá	-25.0	-48.0	44.5	281.0	North of Lüderitz	-25.0	+15.0	54.4	56.3
East of Pôrto Alegre	-30.0	-50.0	49.8	282.6	South of Wreck Point	-30.0	+17.0	59.5	56.2
La Plata	-35.0	-58.0	56.5	290.7	Durban	-30.0	+31.0	67.3	44.5
South of Bahía Blanca	-40.0	-62.0	62.3	293.7	West of Cape Town	-34.0	+18.0	63.3	56.5
North of Golfo San Jorge	-45.0	-66.0	68.1	296.7	East of Port Elizabeth	-34.0	+27.0	67.8	48.8
Santa Cruz	-50.0	-68.0	73.1	297.8					
Cabo San Diego	-55.0	-65.0	76.8	294.4					

*Distance to early-opening pole at 18.8°N lat., 39.9°W long. in South American frame, and 21.5°N lat., 14.0°W long. in African (Le Pichon and Hayes, 1971).

**Azimuth is direction of early flow lines counted east from north.

the Albian-Aptian, and the limits of coastal basins which are filled with Late Jurassic to Holocene sediments (Hourcq, 1966).

A good discussion of this problem by Burke (1969) showed the importance of oceanic fracture zones in controlling the distribution of Cretaceous and Tertiary sedimentary basins in western equatorial Africa. However, Burke suggested that the extension of Chain fracture zone passes near Accra, whereas we have shown that this is the Romanche fracture; Burke also shows the extension of the Romanche fracture zone along the border of the Ivory Coast basin, whereas we have shown that it is the St. Paul fracture.

On the South American side, the three major equatorial fracture zones also mark the limits of Cretaceous coastal basin (Beurlen, 1970; see Table 3, Figs. 4, 5). The St. Paul fracture zone passes north and is presumed to be the northern limit on the continental shelf of the large Cretaceous basin just east of the mouth of the Amazon (Beurlen, 1970, Fig. 57). In this basin, 4,000 m of sediments accumulated beginning in the Albian, and the first marine sediments are Maestrichtian. The Romanche fracture zone is the northern limit of the Cretaceous coastal basins of Maranhão (Fig. 4), which are filled with as much as 8 km of sediments. These two Brazilian basins (São Luis and Barreirinhas), like the Dahomey or western Benin basin, have been created by normal faulting and have had their sedimentation controlled by the same structural high on the north. Also, the Chain transform direction which follows Atol das Rocas and Fernando de Noronha marks the northern boundary of a coastal basin filled with Turonian and younger sediments, the Apodi Plateau basin (Fig. 5), which would be the homolog of the Benue trough.

Transform Directions Between Equatorial Fracture Zones and Walvis-Rio Grande Fracture

South of the Niger delta, the Cameroun basin seems to be bounded by the 27° fracture zone on the north and the Ascension fracture zone (30°) on the south (Fig. 3). Figure 6 and Table 2 show the correspondence between the Ogooué-Gabon basin on the African side and the Sergipe-Alagoas and Recôncavo basins on the Brazilian side (see Beurlen, 1970, Fig. 49).

A detailed bathymetric map of the continental shelf and slope off Angola (M. Magnier, personal commun.) has been used to show that, in detail, the model accounts for the trend of the prominent bathymetric offsets (Fig. 7). The fracture zone we postulate north of Luanda (40.4°) would

Table 3. Correspondence Between Rift and Margins Offsets

FZ Name	Rift Axis	Rift Offset	Distance to Early Pole (Degrees)	Africa	South America	Margin Offset
St. Paul	0.8°N, 27.5°W	L (600)	18.65	Northern limit of Ivory Coast basin	Northern limit of basin east of mouth of Amazon River	L (500)
Romanche	0.7°S, 20.1°W	L (800)	21.10	Northern limit Dahomey basin	Northern limit of Maranhão basins	L (500?)
Chain	1.5°S, 14.5°W	L (200)	23.2	Northern limit of Benue trough and Niger delta	Northern limit of Apodi Plateau basin	L (150)
?	3°S, 12°W?		27.0	Southern limit of Niger delta	Opposite Pernambuco shear zone	
Ascension	8°S, 14°W	R (300)	30.0	Northern limit of Ogooué basin	Southern limit of Sergipe basin	R (300)
	10°S, 13°W	R	32.5	Southern limit of Ogooué basin	Southern limit of Recôncavo basin and northern limit of Almada basin	
Near St. Helena	15°S, 13°W	L	36.5	Within Congo basin	Submarine ridge east of Prado	L (100?)
	18.5°S, 12.5°W	L	40.4	Northern limit of *Cuanza basin*	Trinidade Rise	R (100)
	20°S, 12°W	L	42.5	Southern limit(?) of Cuanza basin	Northern limit of São Paulo embayment	R (100)
	21.5°s, 12°W	R (100)	43.3-44.9	Southern limit of Benguela basin	Within São Paulo embayment	R (100)
	26°S, 14°W	R (?)	47.0-48.0	Northern limit of Walvis Ridge	Southern limit of São Paulo plateau and embayment and northern limit of Rio Grande Rise	
	29°S, 13°W	R	50.0		Northern limit of Pelotas basin	R (150)
	33°S, 15°W	R (?)	53.6	Within SW African coastal basin	Southern limit of Pelotas basin	R (150)
Near Tristan da Cunha	37°S, 18°W	R (300)	56.5	Southern limit of *SW African coastal basin*	Northern limit of Rio Salado basin	R
Near Gough	41°S, 16°W	L (200)	61.0	Southern limit of Cape Town-Orange River basin	Northern limit of Bahía Blanca basin	R (?)
Falkland	47°S, 11°W	L (small)	68.0	Southern limit of southeastern continental margin	Northern limit of Falkland Plateau and San Jorge basin	L (1250)
	50°S, 8°W		71.0	Limit Transkei basin-Mozambique Ridge	Southern limit of Falkland Plateau	R (?)

*R for right lateral, L for left lateral; offset in km within parentheses; distance in degrees.

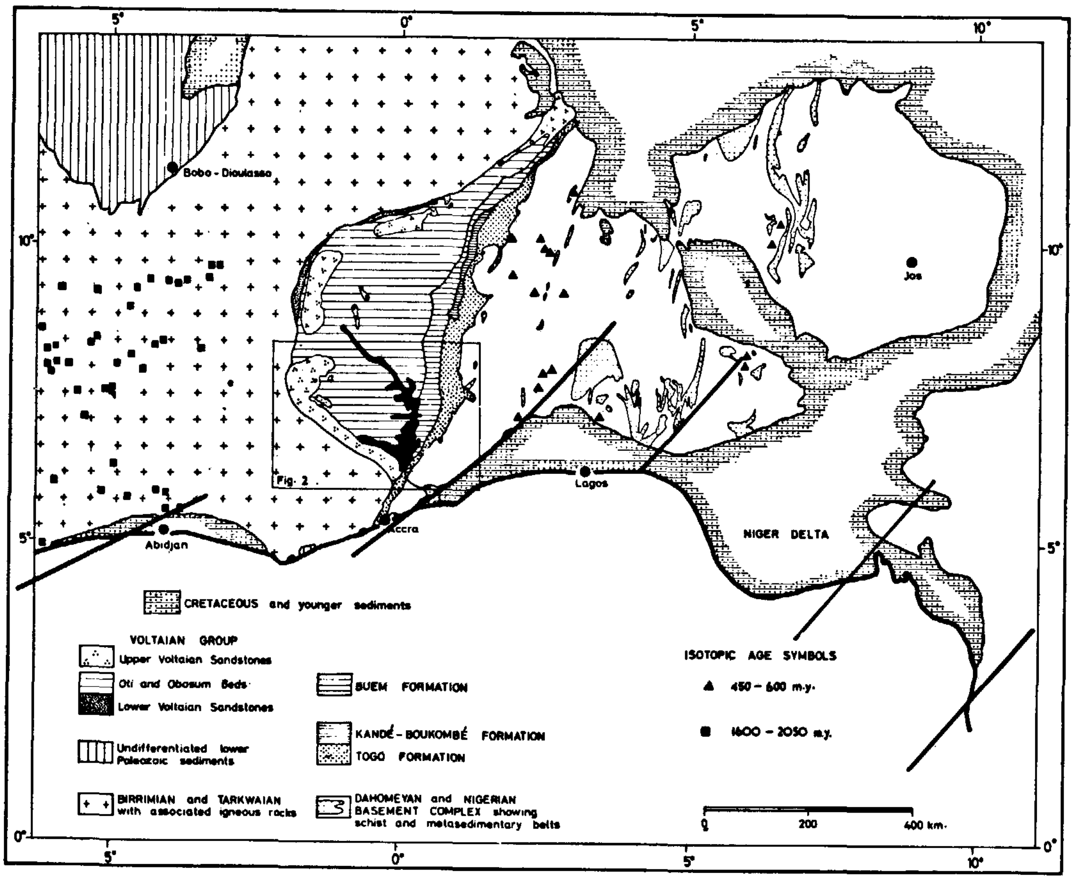


FIG. 3—Geology of eastern margin of West African craton after Grant (1969). Prolongation of major fracture zones within continent has been added. From west to east: St. Paul (18.65°), Romanche (21.1°), Chain (23.2°), 27°, and Ascension (30°).

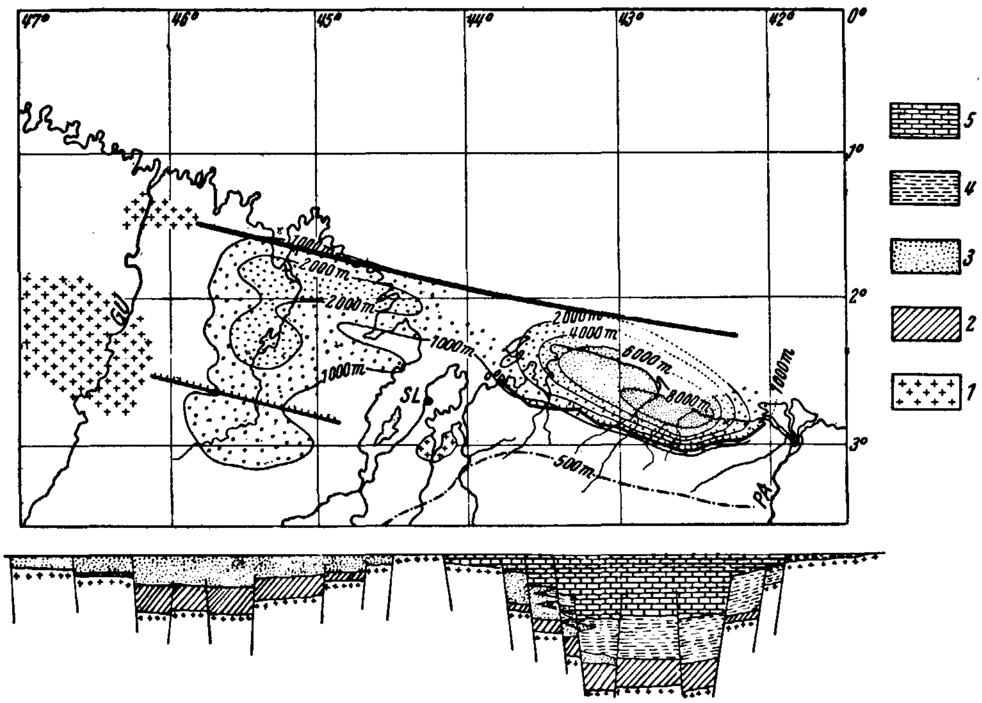


FIG. 4—Isopach map of Maranhão basins after Beurlen (1970). Prolongation of Romanche fracture zone (21.1°) has been added. Note parallelism between predicted direction and faults and elongation of basins. Thickness in meters. *1*, crystalline rocks; *2*, Paleozoic; *3*, nonmarine Albian and Aptian; *4*, marine Albian; *5*, marine Upper Cretaceous; *SL*, São Luis; *Gu*, Gurupi River; *PA*, Parnaiba River.

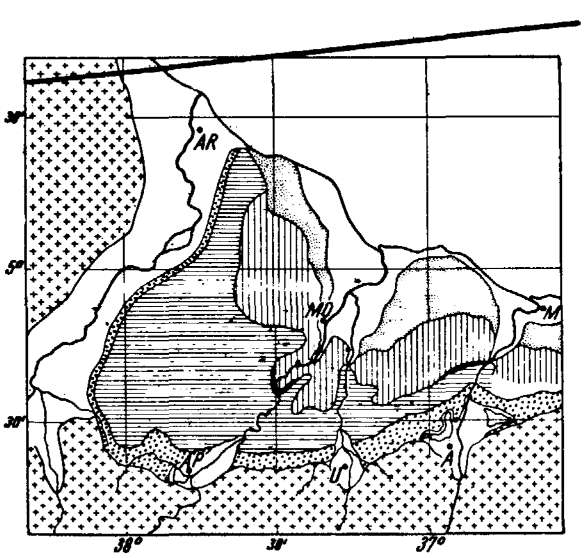


FIG. 5—Geologic map of Apodi Plateau basin in Brazil (after Beurlen, 1970). Note parallelism between Chain fracture zone (23.2°) prolongation (dark line) and southern edge of basin. Crosses are crystalline rocks; large dots, Açu sandstone; horizontal lines, Turonian limestones; vertical lines, Senonian limestones; fine dots, early Tertiary; white, Quaternary; *AR*, Aracati; *MO*, Mossoro; *M*, Macau; *AP*, Apodi; *U*, Upanema; *A*, Açu.

be a structural limit for the important Cuanza basin, which has accumulated more than 3,500 m of sediments since the Neocomian (Brognon and Verrier, 1966). This fracture zone finds its counterpart in the submarine ridge extending from the island of Trindade to Brazil. The isopach maps of Brognon and Verrier (1966) suggest that there may be, north of Luanda, an important barrier which acted as a dam for the post-Aptian sediments. The southern limit of the Cuanza basin corresponds to an offset of the margin off Novo Redondo (42.5°, Fig. 7)[3]. This northeast-southwest offset of the African margin is compatible with the pronounced east-west trend of the 5+ km/sec basement complex just south of Rio de Janeiro (Ewing *et al.*, 1969; Figs. 8, 9). The 42.5° "Novo Redondo fracture zone" corresponds to the northern limit of what Butler (1970) termed the "São Paulo embayment." This coastal basin is beneath the continental shelf between Rio de Janeiro and São Paulo, and is filled with more than 4 km of Cretaceous and younger sediments (Butler, 1970; Leyden *et al.*, 1971). A seismic

[3] In the Cuvo region, just north of Novo Redondo, important volcanic activity (basalts and andesites) began in the Neocomian (see Reyre, 1966).

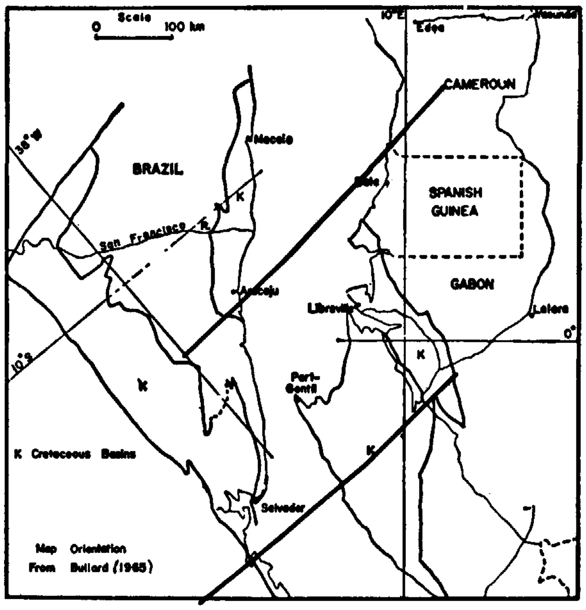
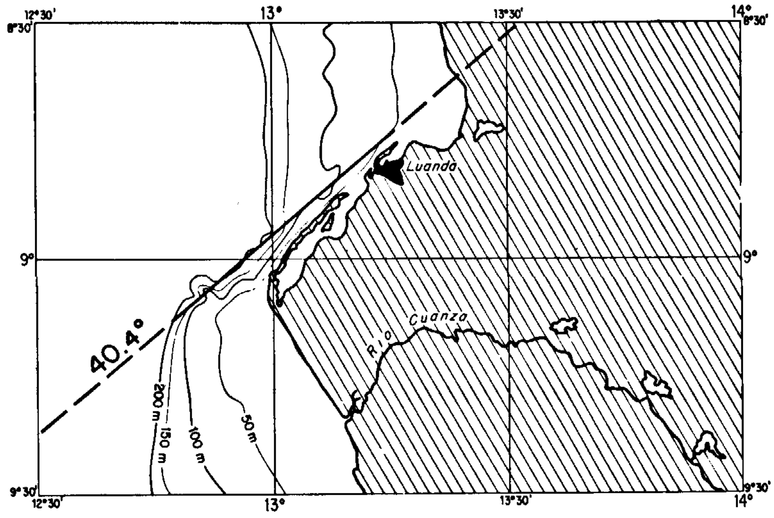


FIG. 6—Cretaceous basins in Brazil and Gabon are shown in Bullard *et al.* (1965) reconstruction (after Allard and Hurst, 1969). Ascension (30°) and 32.5° fracture zones roughly bound parts of three coastal basins (Gabon, Sergipe-Alagoas, and Recôncavo).

reflection survey of the shallow structure of the São Paulo embayment by Butler (1970) has revealed the probable presence of diapirs and suggests a complete analogy in the history of this embayment and the Cuanza basin. The southern limit of the São Paulo embayment is marked by the 47° fracture zone (Figs. 2, 9), which corresponds to the Walvis-Rio Grande fracture. Within this embayment two other offsets exist—near 43.3° and 44.9° in Figure 9. The 43.3° circle, on the African side (Fig. 7), is an important offset that marks the southern limit of the Benguela basin.

Walvis and Rio Grande Ridges

The Walvis and Rio Grande ridges are the two largest bathymetric features in the South Atlantic Ocean; yet they are not related to major offsets of the continental margins. Wilson (1965) first suggested a "hot-spot" origin for these features. Morgan (1971) recently revived the hypothesis. The apparent obliquely diverging trends of these two features would be due to drifting of both plates toward the north with respect to the deeper hot-spot source. Actually, Figure 2 shows that both features are made of east-west sections roughly parallel with small circles of opening, and ending abruptly against north-south sections roughly perpendicular to small circles of opening. In particular, the northern scarp of Walvis Ridge follows exactly the 47° circle of Figure 2. A recent ship cruise of the Centre Océanologique de Bretagne has confirmed that the Walvis Ridge consists of a linear double ridge, with a central trough filled with sediments. Dredges have brought back pillow lava basalts from the northernmost ridge. The northern scarp of Rio Grande ridge follows approximately the 48° circle. Le Pichon *et al.* (1966) have shown that it is a sharp basement wall, with numerous outcrops of late Mesozoic and Cenozoic sediments, on top of which pillow lavas have been photographed. South of this wall, the main part of the rise is made by a pile of stratified, apparently terrigenous sediments, in which Lonardi and Ewing (1971) have recognized Layer A, which is probably of Eocene age. North of the scarp, Plate 1 of Lonardi and Ewing (1971) clearly shows fracture zones which parallel it, between 47 and 48° (Fig. 2). Also, the north-south sections of Rio Grande and Walvis are parallel in Figure 2 and do not diverge from each other as would be implied by a hot-spot origin. Thus, the hot-spot origin of both ridges seems to us untenable and may have originated from using an inaccurate, highly simplified bathymetry. The east-west-trending northern scarps of Walvis and Rio Grande ridges most probably are related to major fracture zones



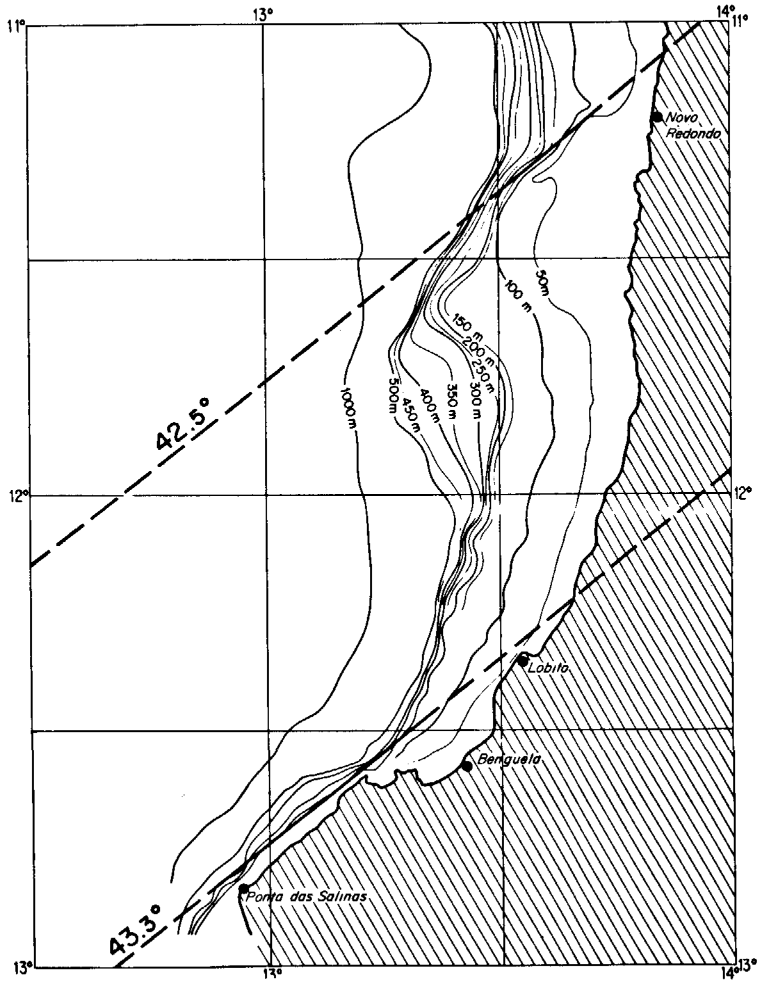


FIG. 7—Bathymetric maps off Angola (M. Magnier, personal commun.). Note agreement between predicted trends of margin offsets and actual trends.

which were active during the first phase of opening, between Early Cretaceous and 80 m.y. ago, and the north-south sections may be related to a readjustment of the crust at the time when the pole of opening shifted north (Le Pichon and Hayes, 1971). Thus, we feel that both north-south segments probably were produced at the same time.

Yet (Fig. 2), the north-south segment of the Rio Grande ridge is close to the African margin, whereas the equivalent north-south part of the Walvis Ridge is along the rotated epicenter belt. There is no symmetry between the ocean basins on each side of the rotated epicenter belt, or between the two north-south segments. Most probably an eastward shift of the Mid-Atlantic Ridge has occurred since the creation of the rise (Le Pichon, 1968).

The fact that the northern scarp of Rio Grande Rise (48° circle) corresponds to the southern scarp of Walvis Ridge, and not to its northern part, is not explained by the model. Further, the difference in structure of the Rio Grande Rise and the Walvis Ridge is not explained by the model. The Rio Grande Rise is composed of three units: (1) an east-west trending unit, (2) a north-south basement scarp, and (3) a unit which is a thick pile of stratified sediments on top of south-dipping basement. We propose herewith a hypothetical explanation for these differences which can be easily checked by examination of data already collected by several institutions.

Figure 10 shows the proposed hypothetical reconstruction. It is assumed that the Rio Grande Rise originally fitted south of the São Paulo plateau and embayment. Units 1 and 2 of the Rio Grande Rise appear to be the homolog of the east-west and north-south parts of Walvis Ridge. The north-south walls of Walvis Ridge and Rio Grande Rise now lie at roughly the same distance from the margins. Inspection of the detailed bathymetry in Plate 1 of Lonardi and Ewing (1971) shows more clearly than our Figure 10 that there is a good morphologic fit of unit 3 of the Rio Grande Rise south of the São Paulo plateau between two steep WNW-ESE escarpments. Thus, according to this hypothesis, unit 3 of the Rio Grande Rise was a part of the Brazilian continental rise during the early opening. We will not discuss this hypothesis, but will simply note facts which provide some support to this model.

1. Samples of early Eocene "turbidites" have been dredged from the summit of unit 3 of the Rio Grande Rise, in 800-m water depth (Le Pichon *et al.*, 1966).

2. Leyden *et al.* (1971) reported the results of a seismic refraction survey in this area. They showed that the structure of the region where the Rio Grande Rise is supposed to have fitted is typically oceanic whereas just northwest the São Paulo plateau is a typical continental rise.

3. The steep WNW-ESE basement scarp, 800-1,000 m high, which is supposed to have bounded unit 3 of the Rio Grande Rise on the north before its detachment from the Brazilian margin, has a topographic, magnetic, and seismic structure typical of a fracture zone (Leyden *et al.*, 1972; Lonardi and Ewing, 1971, Plate 1).

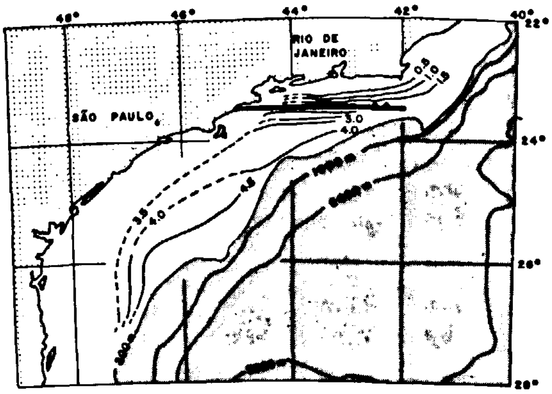


FIG. 8—Depth to basement (km) off southern Brazil over São Paulo embayment (after Ewing *et al.*, 1969, with 42.5° fracture zone added).

The Walvis fracture zone (47°) intersects the African coast just north of Cape Fria. In southern Angola, a volcanic lineament active in the Cretaceous and Miocene, where post-Triassic and pre-Late Cretaceous volcanic manifestations also are found (Reyre, 1966), lies roughly in the prolongation of the Walvis Ridge and extends far into the African continent. Along this major lineament, products of deep origin (alkaline ring dikes, carbonatites, kimberlites) are emplaced between the Wealdian and Albian (see Reyre, 1966). On the Brazilian side, the prolongation of the Rio Grande fracture zone (48° circle in Fig. 8) is parallel with the WNW-ESE axis of the Paraná basin (the Torres syncline; see Butler, 1970), where a sequence of Paleozoic and Mesozoic sediments is capped by the extensive Serra

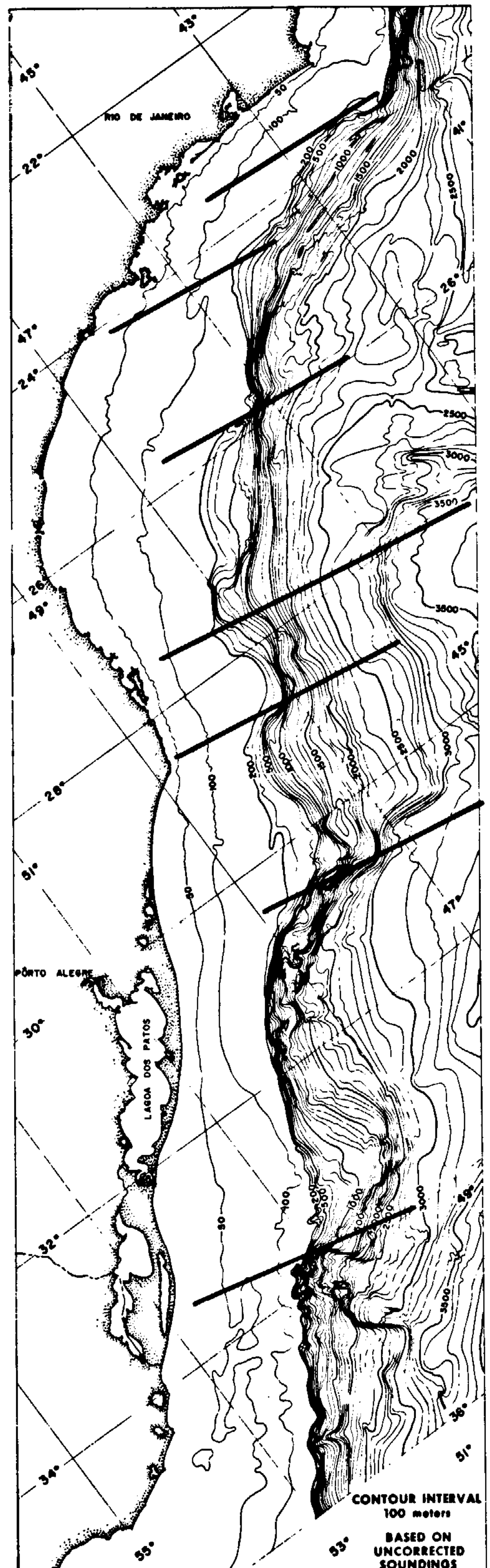


FIG. 9—Bathymetric map of continental margin of southern Brazil and Uruguay (after Butler, 1970). From north to south the following fracture zones have been drawn: 42.5°, 43.3°, 44.9°, Walvis (47°), Rio Grande (48°), 50°, and 53.6°.

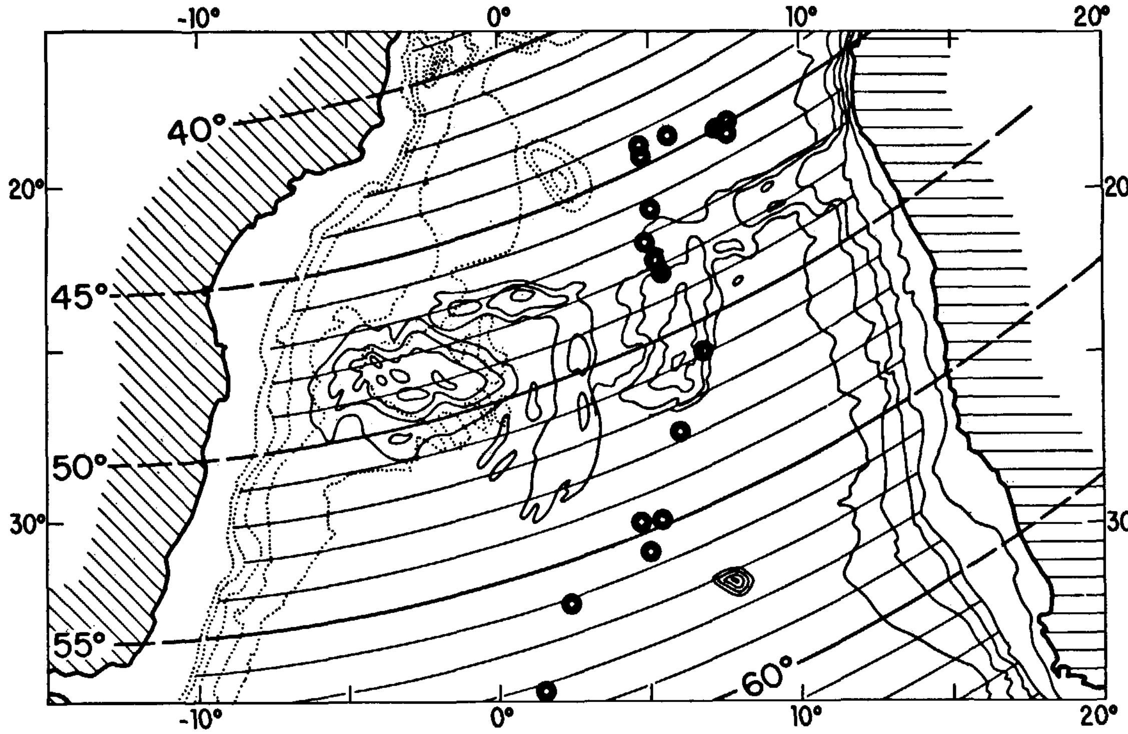


FIG. 10—Hypothetical reconstruction of Rio Grande Rise during early opening. Fit has been made by eye.

Geral plateau basalts, of Early Cretaceous age (120–130 m.y.; Amaral *et al.*, 1966).

Studies to compare the structures and geologic histories of the east-west and north-south parts of the Walvis and Rio Grande ridges would be advantageous. In particular, the JOIDES drillings 21 and 22 show that the east-west part of Rio Grande Rise was originally a shallow region which began to subside during the Campanian. There is no evidence, however, that the rise ever subsided below the carbonate compensation depth (Maxwell *et al.*, 1970). Similar drilling of the corresponding east-west segment of Walvis Ridge and on the north-south segments of both ridges is required. In any case, it is clear that the open ocean existed south of the Walvis-Rio Grande fracture earlier than north of it.

To summarize, we believe that the Walvis and Rio Grande ridges are composite structures. The east-west segments are part of a major transform fault whereas the north-south segments may be related to major crustal readjustment when the pole of rotation shifted, probably about 80 m.y. ago. The third unit of the Rio Grande Rise probably was part of the Brazilian continental rise. However, it is puzzling that the large size of the fracture zone does not correspond to a large continental offset.

Transform Directions South of Walvis and Rio Grande Ridges

A contour map of the top of probable basement (Ludwig *et al.*, 1968a) for the Argentine continental margin delineates the location and extent of major coastal basins (Fig. 11). Series of NW-SE to WNW-ESE basins, such as the Salado basin south of the Rio de la Plata (56.5° circle in Fig. 2), Bahía Blanca (or Colorado) basin near 40°S (61° circle in Fig. 2), San Jorge basin in the Gulf of San Jorge (68° circle in Fig. 2), and the Malvinas basin south of the Falkland Islands, have their long axes along the predicted transform directions (Fig. 11). Zambrano and Urien (1970) have discussed the history and structural framework of these basins. According to these authors, the basins began to subside and accumulate sediments in the late Jurassic-Early Cretaceous. The basins have the same tectonic pattern and are probably grabens originated by a pattern of northwest-southeast-trending faults. The block faulting responsible for the creation of the basins (and the extension of mafic rocks in Uruguay and Argentina) was probably the expression of the incipient breakup between the South American and African plates along the flow lines we have shown.

If the early-opening pole is correct, we should expect to find important structural features associated with the African continental margin as African counterparts of the Argentine basins. The only Atlantic coastal basin with Cretaceous or Tertiary sediments south of Walvis Ridge is just north of Lüderitz (South-West Africa) around 25°S lat. (Reyre, 1966). This African basin is the homolog of the Pelotas basin of southern Brazil and Uruguay described by Butler (1970). The 56.5° small circle, which corresponds to the Argentine Salado basin, intersects the African coast near 28-29°S lat. Fuller (1971) suggested there is a line of old weakness in this vicinity (his line *b* in the Orange River-Kheis) marked by extensive Mesozoic Stormberg volcanic activity, which would have controlled the emplacement of kimberlites.

In our model, the Bahía Blanca basin is the counterpart of the southern part of the Cape Town-Orange River basin over the south African continental shelf, described by Bryan and Simpson (1971).

The 68° small circle, which approximates the trend of the San Jorge basin, is parallel with the Falkland Plateau northern escarpment. Le Pichon *et al.* (1971a) have described this scarp as a 2,900-m high wall which forms the southern boundary of the Argentine basin. East of 40°W long., a linear basement structure (the Falkland fracture zone) marks the continuation of the Falkland scarp. This fracture zone can be traced to 28°W long., where it abruptly ends against a north-south segment, as in the case of Walvis and Rio Grande ridges. On the African side, a line of seamounts which is part of the Cape Rise follows the 68° circle. These seamounts may have been emplaced along a former transform fault during the early opening of the South Atlantic. If the model is correct, future bathymetric surveys in the Cape Rise region should reveal major northeast-southwest ridges and lines of seamounts.

The steep linear southeast African continental margin between Durban and the Agulhas Bank is very well approximated by the 68° circle (Fig. 2). We believe this is strong, but not definitive, evidence for placing the southeastern boundary of the African plate along this margin during the early stage of opening of the South Atlantic. However, it is not known if the part of the South American plate which was lying south of this boundary was oceanic or continental in character. An oceanic area next to southern South America, South Africa, and northwest Antarctica has been advocated by Crowell and Frakes (1968) to account for the facies distributions of late Paleozoic glacial deposits. In Dietz and Sproll's (1970) reconstruction, the fit of Africa and Antarctica leaves most of the linear continental margin between Durban and Agulhas Bank bounded on the south by a gap. The solution of this problem of the oceanic gap lies in the true nature of the crust of the Falkland Plateau, *i.e.*, whether it was part of the Gondwanaland continent, or whether it has been built on oceanic crust.

According to Ewing *et al.* (1971) the Falkland Plateau, east of the Falkland Islands, is an extension of the South American continent. The plateau is shown by them to consist of a thick wedge-shaped body of sediments dipping and thickening toward the south. The basement has a velocity close to 6 km/sec, like that determined for continental basement on the Argentine shelf (Ludwig *et al.*, 1968a). The southern limit of this continental block corresponds to the Falkland trough, where the sediments lie on oceanic crust (Ewing *et al.*, 1971), and its eastern limit probably corresponds to 40°W long.

If we accept these results, the southeastern Africa continental margin from southwest of Cape Agulhas to near Durban represents an ancient line of shear between continental parts of the African and South American plates. The Transkei basin, between South Africa and the Mozambique Ridge, would be truly oceanic, as shown by seismic refraction measurements (Ludwig *et al.*, 1968b; Green and Hales, 1966), and its age would be Early to middle Cretaceous. It is also unlikely that the Agulhas Plateau represents a *microcontinent*, because the inclusion of the Falkland Plateau in the reconstructions of Bullard *et al.* (1965) and Dietz and Sproll (1970) leaves very few gaps.

M. Ewing *et al.* (1969) reported that cores of Cenomanian age (90-100 m.y.) were recovered from the Agulhas Plateau. This age is compatible with a drift origin for the Transkei basin, starting in Early Cretaceous time. In this interpretation, the Transkei basin is structurally part of the Atlantic Ocean, and the age of its floor should increase toward the northeast.

Evolution of Shape of Accreting Plate Margin During Opening of Ocean

In Figure 2 we have rotated the epicenters associated with the South Atlantic ridge to show the approximate position of the accreting plate margin near the end of the early phase of opening, in Late Cretaceous time. For this we implicitly make the assumptions that (1) the shape of the accreting plate margin has remained invariant; (2) spreading has proceeded symmetrically since that time, *i.e.*, the same surface of crust has

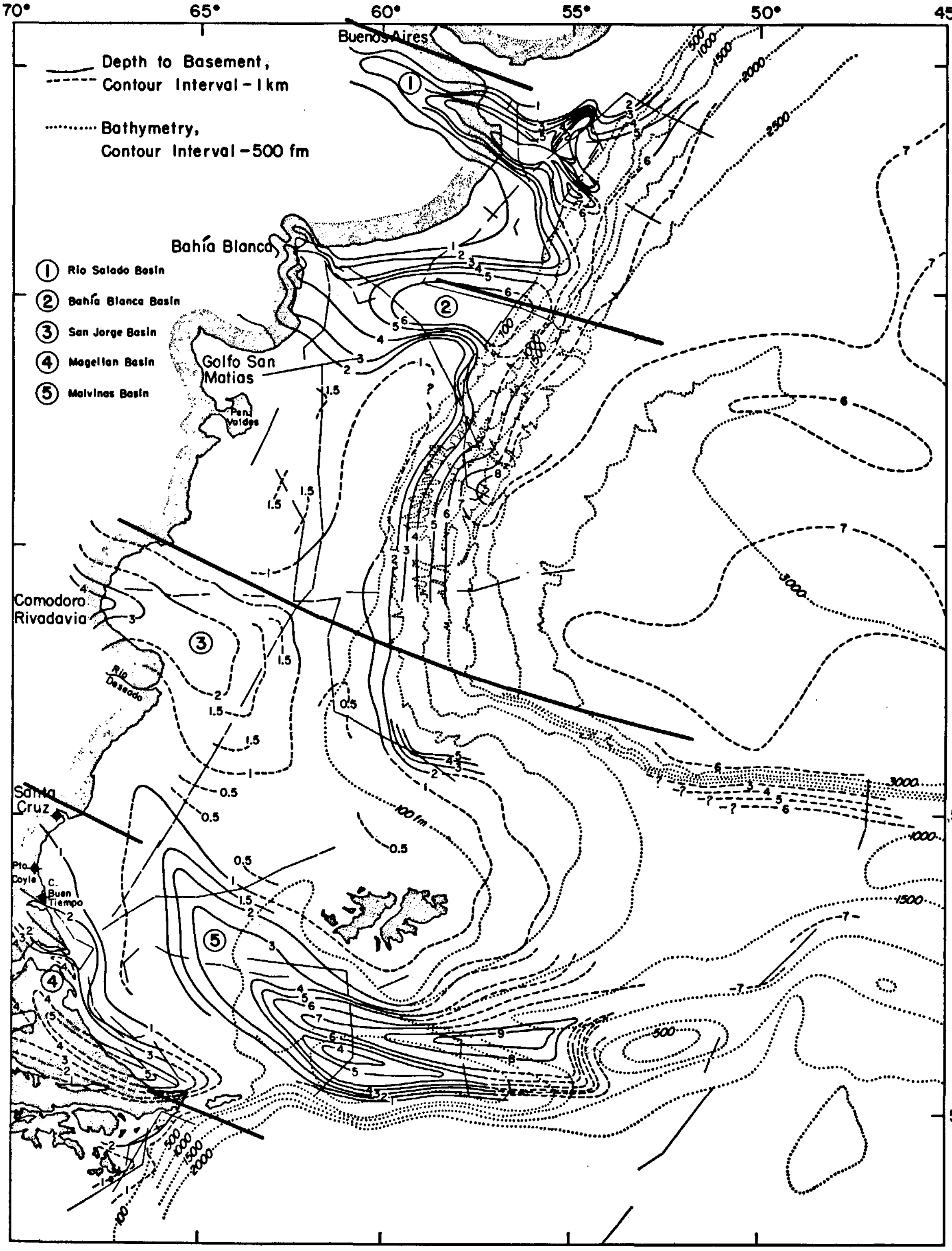


Fig. 11—Map of basement depth off Argentina (after Ludwig *et al.*, 1968a). Transform directions from north to south are: 56.5°, 61°, 68°. Two directions (73.1° and 76.8°) at bottom of figure are not related to present rift offsets. Note striking agreement between predicted trends and actual trends.

been produced on either side; and (3) the plate margin has never jumped in position.

McKenzie and Sclater (1971) have shown that the present shape of the accreting plate margin, as defined by the epicenters, does not deviate by more than 200 km from the Bullard *et al.* (1965) shape of the initial rift. Second-order deformation of this shape has been produced by at least two successive, widely different finite rotations during the opening. Thus, McKenzie and Sclater's test shows that the shape of the plate margin is inherited from the initial break and that the major rift and margin offsets are in fair correspondence. It also shows that the ridge, as an average and to a first approximation, has held a central position with respect to the margins.

In general, the second-order deformation of the accreting plate-margin shape seems to be produced by jumps in position and not by asymmetric spreading. For example, in Figure 2, the 68° Falkland fracture zone must have been the location of a very large offset of the ridge crest in the initial phase of opening, if our interpretation is correct. This offset may have been of the order of 1,000 km or more, yet the present offset does not exceed 200 km. The rift south of the 68° circle must have jumped eastward at the end of the first phase of opening. Figure 2 shows that, in general, south of the 45° small circle, the epicenter belt lies closer to the American margin; between the 40° and 30° circles it lies closer to the American margin; and between 30° and 21° it lies closer to Africa again. Whether this second-order asymmetry is always related to jumps of the rift cannot be determined with the data available.

Conclusion

Our data suggest that the structural framework of the continental margins on both sides of the South Atlantic has been controlled principally by the offsets and marginal ridges created by the initial openings. As was realized by Reyre (1966, p. 272), "l'essentiel est de souligner le rôle que ces transversales profondes franchissant les frontières océaniques, paraissent jouer dans la localisation des bassins sédimentaires côtiers" (the essential point is to emphasize the role which these deep transverse features, crossing the ocean borders, seem to play in localizing the coastal sedimentary basins). Each of these coastal basins seems to be bordered by structural highs in the prolongation of oceanic fracture zones along what we have called "transform directions," which correspond exactly on both sides of the Atlantic.

Our model has predictive values for many poorly known features, such as offsets of margins, fracture zones, age and nature of sea floor south of Africa, composite nature of the Walvis and Rio Grande ridges, significance of the Falkland Plateau, *etc.*

Finally, we have described the second-order deformation of the accreting plate margin throughout the opening of the ocean and related it to probable jumps in the rift position at the time when there was a significant change in the position of the pole of opening.

References Cited

Allard, G. O., and V. J. Hurst, 1969, Brazil-Gabon geologic link supports continental drift: Science, v. 163, p. 528-532.

Amaral, G., U. G. Cordani, K. Kawashita, and J. H. Reynolds, 1966, Potassium-argon dates of basaltic rocks from southern Brazil: Geochim. et Cosmochim. Acta, v. 30, p. 159-189.

Arens, G., J. R. Delteil, P. Valéry, B. Damotte, L. Montadert, and P. Patriat, 1971, The continental margin off the Ivory Coast and Ghana, *in* The geology of the east Atlantic continental margin; Pt. 4, Africa: Great Britain Inst. Geol. Sci. Rept., no. 70/16, p. 61-78.

Association of African Geological Surveys-UNESCO, 1968, International tectonic map of Africa, sheets 4, 5, 8: Paris, scale 1:5,000,000.

Barazangi, M., and J. Dorman, 1969, World seismicity maps compiled from ESSA, Coast and Geodetic Survey epicenter data, 1961-1967: Seismol. Soc. America Bull., v. 59, p. 369-380.

Beurlen, K., 1970, Geologie von Brasilien: Berlin-Stuttgart, Gebrüder Borntraeger, 444 p.

Brognon, G., and G. R. Verrier, 1966, Tectonique et sédimentation dans le bassin du Cuanza, *in* Sedimentary basins of the African coast; Pt. 1, Atlantic Coast: Paris, Internat. Union Geol. Sci.-Assoc. African Geol. Surveys, p. 207-252.

Bryan, G. M., and E. S. W. Simpson, 1971, Seismic refraction measurements on the continental shelf between Orange River and Cape Town, *in* The geology of the East Atlantic continental margin; Pt. 4, Africa: Great Britain Inst. Geol. Sci. Rept., no. 70/16, p. 187-198.

Bullard, E., J. E. Everett, and A. G. Smith, 1965, The fit of the continents around the Atlantic, *in* Symposium on continental drift: Royal Soc. London Philos. Trans., v. 258, p. 41-51.

Burke, K., 1969, Seismic areas of the Guinea Coast where Atlantic fracture zones reach Africa: Nature, v. 222, p. 655-657.

Butler, L. W., 1970, Shallow structure of the continental margin, southern Brazil and Uruguay: Geol. Soc. America Bull., v. 81, p. 1079-1096.

Commission de la Carte Geologique du Monde, Sous Commission de la Carte Tectonique du Monde, 1960, Carte tectonique internationale du monde, sheet 6: 21st Internat. Geol. Cong., Copenhagen, scale 1:15,000,000.

Crowell, J. C., and L. A. Frakes, 1968, Late Paleozoic glacial facies and the origin of the South Atlantic Ocean: 23d Internat. Geol. Cong., Czechoslovakia, Rept. Proc., sec. 13, p. 291-302.

Dickson, G. O., W. C. Pitman, III, and J. R. Heirtzler, 1968, Magnetic anomalies in the South Atlantic and ocean floor spreading: Jour. Geophys. Research, v. 73, p. 2087-2100.

Dietz, R. S., and W. P. Sproll, 1970, Fit between Africa and Antarctica: a continental drift reconstruction: Science, v. 167, p. 1612-1614.

Ewing, J., R. Leyden, and M. Ewing, 1969, Refraction shooting with expendable sonobuoys: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 174-181.

——— W. J. Ludwig, M. E. Ewing, and S. L. Eittreim, 1971, Structure of the Scotia sea and Falkland Plateau: Jour. Geophys. Research, v. 76, p. 7118-7137.

Marginal Fracture Zones as Structural Framework

Ewing, M., S. Eittreim, M. Truchan, and J. I. Ewing, 1969, Sediment distribution in the Indian Ocean: Deep-Sea Research, v. 16, p. 231-248.

Fuller, A. O., 1971, South Atlantic fracture zones and lines of old weakness in southern Africa: Nature, Physical Science, v. 231, p. 84-85.

Grant, N. K., 1969, The late Precambrian to early Paleozoic Pan-African orogeny in Ghana, Togo, Dahomey, and Nigeria: Geol. Soc. America Bull., v. 80, p. 45-56.

Green, R. W. E., and A. L. Hales, 1966, Seismic refraction measurements in the southwestern Indian Ocean: Jour. Geophys. Research, v. 71, p. 1637-1647.

Heirtzler, J. R., and X. Le Pichon, 1965, Crustal structure of the mid-ocean ridges. 3, Magnetic anomalies over the Mid-Atlantic Ridge: Jour. Geophys. Research, v. 70, p. 4013-4033.

——— G. O. Dickson, E. M. Herron, W. C. Pitman, III, and X. Le Pichon, 1968, Marine magnetic anomalies, geomagnetic field reversals and motions of the ocean floor and continents: Jour. Geophys. Research, v. 73, p. 2119-2136.

Hourcq, V., 1966, Les grands traits de la géologie des bassins côtiers du groupe équatorial, *in* Sedimentary basins of the African coast; Pt. 1, Atlantic Coast: Paris, Internat. Union Geol. Sci.-Assoc. African Geol. Surveys, p. 163-170.

Hurley, P. M., 1968, The confirmation of continental drift: Sci. American, v. 218, p. 52-64.

——— F. F. M. de Almeida, G. C. Melcher, U. G. Cordani, J. R. Rand, K. Kawashita, P. Vandoros, W. H. Pinson, Jr., and H. W. Fairbairn, 1967, Test of continental drift by comparison of radiometric ages: Science, v. 157, p. 495-500.

Le Pichon, X., 1968, Sea-floor spreading and continental drift: Jour. Geophys. Research, v. 73, p. 3661-3697.

——— and D. E. Hayes, 1971, Marginal offsets, fracture zones and the early opening of the South Atlantic: Jour. Geophys. Research, v. 76, p. 6283-6293.

——— S. L. Eittreim, and W. J. Ludwig, 1971a, Sediment transport and distribution in the Argentine basin, 1, Antarctic bottom current passage through the Falkland fracture zone, *in* Physics and chemistry of the earth, v. 8: London, Pergamon Press, p. 1-28.

——— T. Saito, and J. Ewing, 1966, Mesozoic and Cenozoic sedimentary rocks from Rio Grande rise (abs.): Geol. Soc. America Ann. Mtg. Program (San Francisco), p. 121; 1968, Geol. Soc. America Spec. Paper 101, p. 121.

——— J. Bonnin, J. Francheteau, and J. C. Sibuet, 1971b, Une hypothèse d'évolution tectonique du golfe de Gascogne, *in* L'histoire structurale du golfe de Gascogne: Inst. Français Pétrole Pub., Collection Colloques et Séminaires, v. 22, pt. 2, chapter 6(11), p. 1-44. Paris, Editions Technip.

Leyden, R., W. J. Ludwig, and M. Ewing, 1971, Structure of the continental margin off Punta del Este, Uruguay, and Rio de Janeiro, Brazil: Am. Association Petroleum Geologists Bull., v. 55, p. 2161-2173.

Lonardi, A. G., and M. Ewing, 1971, Sediment transport and distribution in the Argentine basin. 4. Bathymetry of the continental margin, Argentine basin and other related provinces. Canyons and sources of sediments, *in* Physics and chemistry of the earth, v. 8: London, Pergamon Press, p. 79-121.

Ludwig, W. J., J. I. Ewing, and M. Ewing, 1968a, Structure of Argentine continental margin: Am. Assoc. Petroleum Geologists Bull., v. 52, p. 2337-2368.

——— J. E. Nafe, E. S. W. Simpson, S. Sacks, 1968b, Seismic-refraction measurements on the southeast African continental margin: Jour. Geophys. Research, v. 73, p. 3707-3719.

Maxwell, A. E., R. P. Von Herzen, K. J. Hsu, J. E. Andrews, T. Saito, S. F. Percival, Jr., E. D. Milow, and R. E. Boyce, 1970, Deep sea drilling in the South Atlantic: Science, v. 168, p. 1047-1059.

McConnell, R. B., 1969, Fundamental fault zones in the Guiana and West African shields in relation to presumed axes of Atlantic spreading: Geol. Soc. America Bull., v. 80, p. 1775-1782.

McCurry, P., 1971, Plate tectonics and the Pan-African orogeny in Nigeria: Nature, v. 229, p. 154-155.

McKenzie, D. P., and J. G. Sclater, 1971, The evolution of the Indian Ocean since the Late Cretaceous: Royal Astron. Soc. Geophys. Jour., v. 25, p. 437-528.

Morgan, W. J., 1971, Convection plumes in the lower mantle: Nature, v. 230, p. 42-43.

Reyment, R. A., 1965, Aspects of the geology of Nigeria; the stratigraphy of the Cretaceous and Cenozoic deposits: Ibadan, Ibadan Univ. Press, 145 p.

Reyre, D., 1966, Particularités géologiques des bassins côtiers de l'ouest Africain, *in* Sedimentary basins of the African coast; Pt. 1, Atlantic Coast: Paris, Internat. Union Geol. Sci.-Assoc. African Geol. Surveys, p. 253-304.

Spengler, A. de, and J. R. Delteil, 1966, Le bassin secondaire-tertiaire de Côte d'Ivoire, *in* Sedimentary basins of the African coast, Pt. 1, Atlantic Coast: Paris, Internat. Union Geol. Sci.-Assoc. African Geol. Surveys, p. 99-113.

U.S. Navy Hydrographic Office, 1968, The world: U.S. Navy Hydrog. Office, scale 1:12,233,000 at equator.

Wilson, J. T., 1965, A new class of faults and their bearing on continental drift: Nature, v. 207, p. 343-347.

Wright, J. B., 1968, South Atlantic continental drift and the Benue trough: Tectonophysics. v. 6, p. 301-310.

Zambrano, J. J., and C. M. Urien, 1970, Geological outline of the basins in southern Argentina and their continuation off the Atlantic shore: Jour. Geophys. Research, v. 75, p. 1363-1396.