AN ABSTRACT OF THE THESIS OF

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Title: TECTONIC EVOLUTION OF THE WALVIS RIDGE AND WEST AFRICAN MARGIN, SOUTH ATLANTIC OCEAN

Abstract approved: Redacted for privacy
Tjeerd H. van Andel

The opening of the South Atlantic between 140 and 90 m. y. B. P. occurred about two poles of rotation. The initial pole of rotation was maintained until Africa and South America were completely separated. The subsequent removal of restraints imposed by the pre-existing structure of Africa and South America on the early spreading direction permitted a northward migration of the pole of rotation and concomitant reorientation of spreading direction.

The NNE trending Cameroon-Gabon and southern Angola coastlines which offset the generally SSE trend of the west African margin between 5°N and the Walvis Ridge are proposed as initial transform offsets of the South Atlantic proto-rift. Location of these initial offsets was controlled by lineations of the Precambrian/Early Paleozoic belts of thermotectonic activity which occur between older, stable cratonic nuclei of Gondwana. Shorter offsets of the continental

margin south of the Walvis Ridge and the two major offsets of the west African coastline north of the Walvis Ridge define a pole of rotation at 5°N, 26°W for the initial South Atlantic opening.

A set of magnetic anomaly lineations near the continental margins of Angola and southwest Africa is described and named the Benguela sequence. These anomalies were formed during the initial phase of spreading and are displaced right-laterally almost 1000 kilometers across an extension of the continental offset along the southern Angola margin. This offset is named the Benguela Fracture Zone. The Benguela anomalies are correlated with anomalies of the Lynch sequence in the western North Atlantic. The change in direction between the two pre-Cenozoic phases of South Atlantic spreading is dated at roughly 120 m.y. B.P. based upon an extrapolation of the ages of anomalies in the Lynch sequence to the time of reorientation in the South Atlantic. Formation of the South Atlantic quiet zones occurred by sea-floor spreading about a pole of rotation at 21.5°N, 14.0°W during the second phase of opening.

The present structure of the Walvis Ridge is controlled by nearly orthogonal NE and NW trending faults shown by seismic reflection profiling. The NE trending set of faults approximate small circles of the pole of rotation at 21.5°N, 14.0°W and appear to offset the Walvis Ridge topography in a right-lateral sense. Reorientation of spreading would have produced extension across the Benguela

Fracture Zone; development of short offset spreading centers along the Benguela Fracture Zone during this reorientation is proposed to explain the right-lateral offsets of the Walvis Ridge topography. Lack of geophysical information on the lower crustal structure prevents a direct explanation of the present elevation of the Walvis Ridge. However the Walvis Ridge is probably underlain by a low density root produced by alteration of the lower crust and upper mantle materials beneath the Benguela Fracture Zone which began during the spreading reorientation. Asymmetric spreading over the Walvis Ridge may have permitted the zone of crustal accretion to remain near the older Benguela Fracture Zone long enough to allow the creation of an anomalously broad low-density root which is responsible for the uplift of the Walvis Ridge.

Tectonic Evolution of the Walvis Ridge and West African Margin, South Atlantic Ocean

by

Timothy Robert Baumgartner

A THESIS

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Typed by Linda Wille for Timothy Robert Baumgartner

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"To study history means submitting to chaos and nevertheless retaining faith in order and meaning."

Father Jacobus to Joseph Knecht
in The Glass Bead Game
by Herman Hesse

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INTRODUCTION

The Walvis Ridge is a sinuous elevation of the ocean floor linking the continental margin of South-West Africa with the flank of the mid-ocean ridge of the South Atlantic. Except for one earthquake (Stover, 1968) just south of the Walvis Ridge, it is aseismic, a relic of crustal processes operating as Africa and South America separated. This paper traces the evolution of the Walvis Ridge within the framework of the Pre-Cenozoic history of the South Atlantic.

The concept of seafloor spreading (Hess, 1962; Dietz, 1961) has been broadened with the formulation of plate tectonics by McKenzie and Parker (1967), Morgan (1968), and LePichon (1968). Most of the earth's seismicity, tectonism and orogenesis can be explained by movement along the boundaries of a number of rigid plates which are in motion with respect to each other. Symmetric magnetic anomaly patterns about mid-ocean ridges resulted from reversals of the earth's magnetic field during accretion at plate boundaries (Vine and Matthews, 1963; Vine, 1966). Using these anomaly lineations as crustal isochrons and the strikes of transform faults (Wilson, 1965) as flow lines, past configurations of continents and the resultant shapes of ocean basins can be reconstructed (Pitman and Talwani, 1972; McKenzie and Sclater, 1971). The relative plate motions required for these reconstructions can be described by finite poles and angles of rotation.

The spreading history of the South Atlantic from latest Cretaceous to the present is relatively well known from studies of the magnetic anomalies and from Deep Sea Drilling (Dickson and others, 1968; Heirtzler and others, 1968; Maxwell and others, 1970). Mascle and Phillips (1972a) have related symmetric magnetic quiet zones in the South Atlantic to seafloor spreading during a period of normal polarity in the late Cretaceous. LePichon (1968) pointed out that the opening of the South Atlantic must have occurred about at least two successive poles. Assuming the present pole of rotation (58°N, 37°W) to be valid for the entire Cenozoic, an average pre-Cenozoic pole at 35°N, 21°W is needed to satisfy the reconstruction of Gondwana by Bullard and others (1965). Small circles about this early pole approximately parallel the northern scarps of the Walvis Ridge, Rio Grande Rise, and Falkland Plateau. LePichon and Hayes (1971) proposed a model for the development of continental margin offsets and associated ridges and fracture zones in the South Atlantic. They believe that the evolution of the entire South Atlantic between 140 and 80 m. y. ago can be described by a pole of rotation at 21.5°N, 14.0°W, derived from equatorial fracture ridges (St. Paul, Romanche and Chain). More recently Francheteau and LePichon (1972) fitted structural trends along the South American and African margins (considered by them as original transform directions) to flow lines of this early pole of opening. Although small circles about this pole do agree with the scarps along the northern boundaries of the Walvis Ridge, Rio Grande Rise and Falkland Plateau, they do not coincide with the major continental offsets of the African margin along the Cameroon-Gabon and Angola-South West Africa coasts.

LePichon (1968) notes that, given an underlying state of stress, a thick lithosphere should break along zones of internal weakness and that patterns of oceanic opening may be determined by pre-existing structure. It is likely that the initial opening of the South Atlantic was controlled by major structural boundaries within the Gondwanan lithosphere. These boundaries were the loci of episodic orogeny and tectonic rejuvenation throughout the Precambrian, and their effect on the later tectonic evolution of Africa is well documented (Clifford, 1968, 1970). This paper examines the history of the South Atlantic in an attempt to relate the effects superimposed by the pre-existing basement of Gondwana to the creation of the adjacent seafloor and concomitant evolution of the Walvis Ridge. Magnetic anomalies in the eastern Angola and Cape basins and on the continental rise off Africa, described in this paper, yield a seafloor spreading pattern which is consistent with the directions of major internal weaknesses in Africa. The structure of the Walvis Ridge is interpreted with the assumption that rifting took place along these continental zones of weakness.

DATA SOURCES AND CONTROL

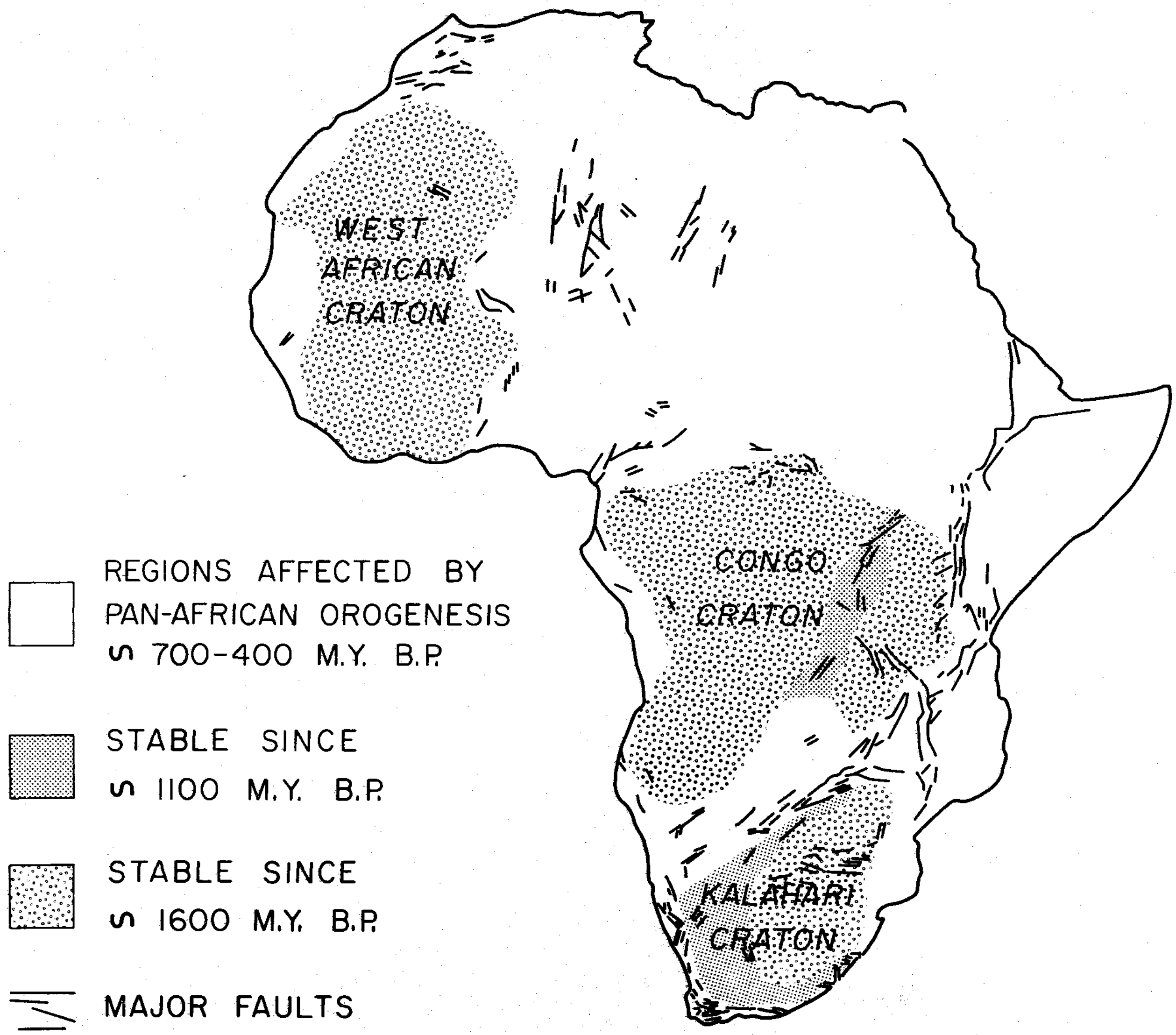
The data for this study were collected on expeditions from various institutions and include underway measurements of bathymetry, magnetics and seismic reflection. Magnetic data were recorded on Legs 8 and 9 of the CIRCE Expedition from Scripps Institution of Oceanography, Leg 4 of cruise 99 of R.V. Chain from Woods Hole Oceanographic Institute, the R.V. Conrad cruise 1313 of Lamont-Doherty Geological Observatory, and traverses 2, 71, 204, and 205 of the Department of Geology of the University of Cape Town, South Africa. Aeromagnetic data from PROJECT MAGNET flights (Mascle and Phillips, 1972a) of the U.S. Naval Oceanographic Office were also utilized. Continuous depth and seismic reflection profiles used in the study are from the CIRCE 8 and Chain 99/4 cruises.

All magnetic measurements were made with a proton precession, Varian magnetometer. Magnetic anomaly profiles were obtained by elimination of the regional field using the IGRF coefficients (Cain and others, 1968). Seismic reflection profiles were made on CIRCE 8 with a 10 cubic-inch airgun and on Chain 99/4 by firing a 40 cubic-inch airgun and 100,000 joule sparker synchronously. Primary navigation during all cruises except those of the University of Cape Town was achieved by satellite navigation. The South African traverses utilized celestial navigation.

STRUCTURAL CONTROL OF THE WEST AFRICAN MARGIN

During the breakup and dispersal of Gondwana, Africa acted as a single crustal block. However, Precambrian and early Paleozoic belts of orogenesis and syntectonic radiometric rejuvenation indicate a long preceding period of mobility throughout mid-continental regions of the African basement. Subsequently, since the early Paleozoic, deformation of rocks has occurred only along the continental periphery, in the Cape Fold Belt, the Mauritanides and the Atlas Mountains. Within the African interior, great sedimentary basins began forming during the time spanning the Precambrian/Paleozoic boundary. The development of these sedimentary basins persisted throughout the Paleozoic and Mesozoic into the Tertiary, masking large regions of the Precambrian basement with sediments but leaving the outer rims of the interior basins exposed. In recent years, extensive work in radiometric dating of African rocks exposed above the platform cover has provided a chronologic framework for the evolution of African Precambrian and early Paleozoic structural and stratigraphic provinces. Radiometric dates of the Precambrian and early Cambrian basement fall into four groups which broadly reflect times of orogenesis and thermal overprinting. These are >2100 m. y., 2050-1600 m. y., 1050-850 m. y. and 700-400 m. y. (Clifford, 1970). This progression of activity resulted in the

FIGURE 1: Structural-orogenic units of Africa (after Clifford, 1970).


WEST AFRICAN CRATON
CONGO CRATON
KALAHARI CRATON
REGIONS AFFECTED BY PAN-AFRICAN OROGENESIS ~ 700-400 M.Y. B.P.
STABLE SINCE ~ 1100 M.Y. B.P.
STABLE SINCE ~ 1600 M.Y. B.P.
MAJOR FAULTS

successive blocking-out of three major, stable cratonic nuclei (Figure 1). The regions of the West African, Congo and Kalahari nuclei were stabilized by approximately 1600 m. y. ago, although orogenesis after 1100 m. y. ago increased the area of the Kalahari craton and divided the Congo craton. Structural differentiation of the African basement culminated between 700-400 m. y. ago in a widespread thermotectonic episode called the Pan-African event by Kennedy (1965). Orogeny and rejuvenation by thermal overprinting of the Pan-African event affected almost the entire continent outside the stable cratonic nuclei. By the end of this event, the stable cratons were surrounded by long, sinuous belts of rocks with a mega-tectonic grain produced by folding of geosynclinal sediments, widespread metamorphism of older schists and gneisses, and syntectonic emplacement of granites (Clifford, 1968). These tectonic and metamorphic lineations are generally parallel to the strike of the Pan-African belts.

Clifford (1968) notes that all major fault systems of the Phanerozoic except the Western Rift Valley, are located within zones of Pan-African rocks. Wilson's (1965) concept of transform faulting predicts that a proto-rift through continental crust would prefer pre-existing lines of weakness. It seems reasonable that the structural heterogeneity developed throughout the Precambrian should have determined the initial rifting configuration between Africa and

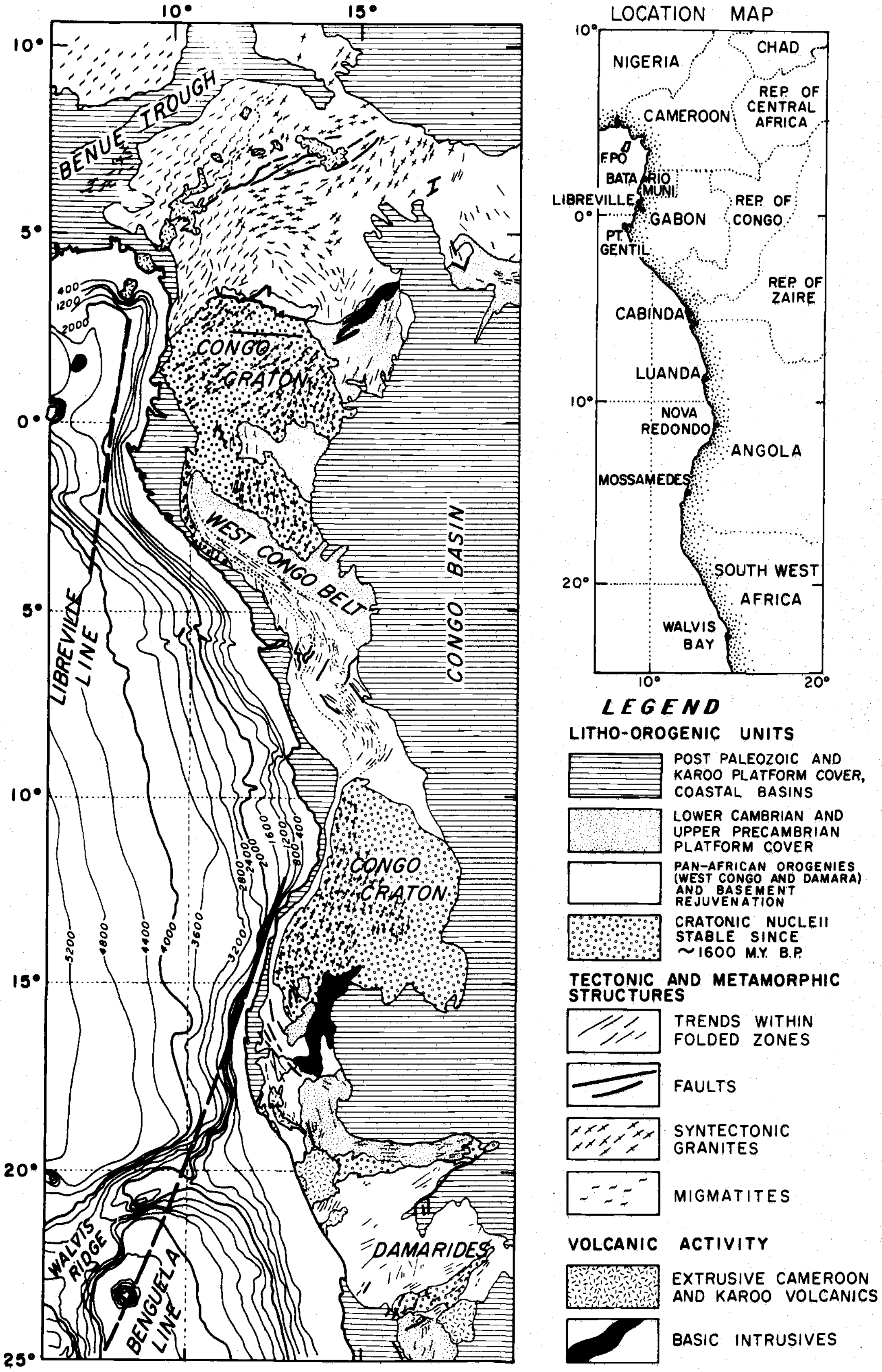
South America.

LePichon and Hayes (1971) predict the existence of fracture ridges within rifted continental margins which are inferred counterparts of fracture zones along mid-ocean ridges. Francheteau and LePichon (1972) attempted to locate such fracture ridges by the association of structural and bathymetric trends with offsets of the South American and African margins. Their search concentrated on trends that agree with the pole of rotation for the early South Atlantic obtained by LePichon and Hayes (1971). However, a gravity survey of the Angola margin (Rabinowitz, 1972) has cast doubt on the fracture ridges postulated there by Francheteau and LePichon. Rabinowitz points out that geophysical data from many inactive continental margins do confirm or support the presence of basement ridges (Drake and others, 1959; Rabinowitz and Talwani, 1969; Ewing and others, 1963; Emery and others, 1970), and Burk (1968) suggests that these ridges mark the initiation of seafloor spreading. However, the extent to which these ridges represent transform shearing, block faulting of the margin or any other process which might be associated with rifting, is still not well understood.

Four major trends along the continental margin between Cameroon and South Africa agree with onshore tectonic and metamorphic lineations within the basement regions affected by the Pan-African rejuvenation. I have called these the Libreville, Benguela, Luderitz and Cape Town lines (Figures 2 and 3). Both the Libreville and Benguela lines are directly juxtaposed to Pan-African belts, and follow along lobes of the Congo craton. The Luderitz and Cape Town lines lie along bathymetric trends extending off the continental shelf to the continental rise.

Within Cameroon, south and east of the Cameroon volcanics and north of the Congo craton, tectonic and metamorphic lineations trend between N10°E and N20°E near the coastline (Figure 2). Here the migmatite lineations and folded belts are more ancient structures that were rejuvenated during the Pan-African event. Away from the coast, these NNE lineations bend to the east around the Congo craton and branch south. The Cameroon volcanics near the coast are emplaced within the Pan-African zone along a boundary zone which marks a slight convergence of the migmatite lineations. To the east, these volcanics lie along a fault system which itself is apparently controlled by the trend of the Precambrian migmatites and syntectonic granites. The base of the continental slope (2000 meter contour) from 3°N to 1°S, along the Cameroon and Gabon coasts is parallel to onshore Pan-African migmatite lineations and fold axes which bend around the Congo craton. Although the coastline cuts through cratonic rocks from Bata to Point Gentil, the spatial relation of the Pan-African zone to the Congo craton suggests that the border of the Pan-African rocks extends under the continental terrace to the south-

FIGURE 2: Location of Libreville and Benguela lines along west African margin. Tectonic map simplified from UNESCO-ASGA (1969) 1:500,000 International Tectonic Map of Africa. Bathymetry from Uchupi (1971).



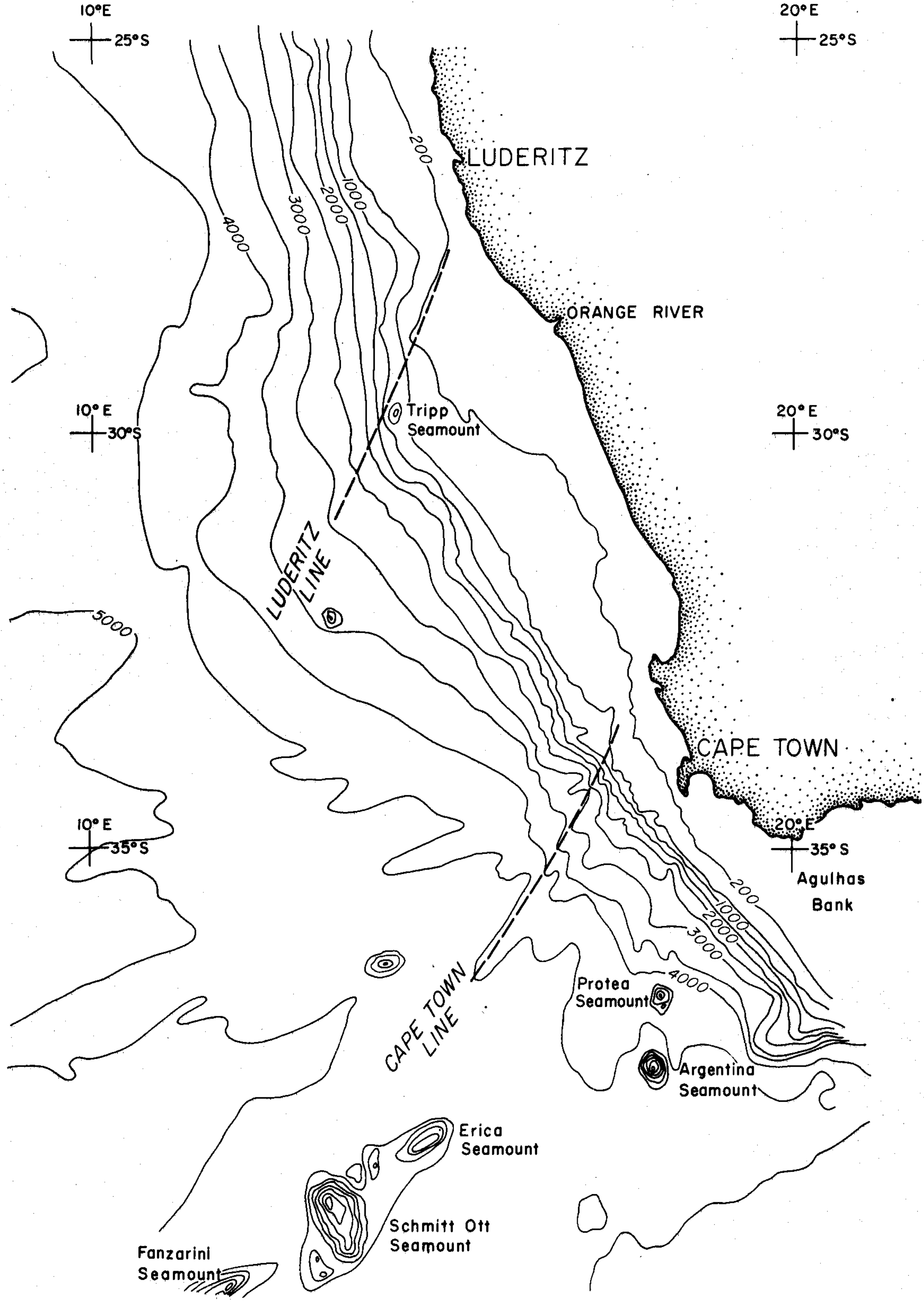
10°
15°
10°
5°
0°
5°
10°
15°
20°
25°
BENUE TROUGH
CONGO CRATON
WEST CONGO BELT
CONGO BASIN
LIBREVILLE LINE
CONGO CRATON
WALVIS RIDGE
BENGUELA LINE
DAMARIDES
400
1200
2000
5200
4800
4400
4000
3600
3200
2800
2400
2000
1600
1200
800
400
LOCATION MAP
NIGERIA
CHAD
REP. OF CENTRAL AFRICA
CAMEROON
F.PO
BATA
RIO MUNI
LIBREVILLE
GABON
REP. OF CONGO
PT. GENTIL
REP. OF ZAIRE
CABINDA
LUANDA
NOVA REDONDO
ANGOLA
MOSSAMEDES
SOUTH WEST AFRICA
WALVIS BAY
10°
20°
LEGEND
LITHO-OROGENIC UNITS
POST PALEOZOIC AND KAROO PLATFORM COVER, COASTAL BASINS
LOWER CAMBRIAN AND UPPER PRECAMBRIAN PLATFORM COVER
PAN-AFRICAN OROGENIES (WEST CONGO AND DAMARA) AND BASEMENT REJUVENATION
CRATONIC NUCLEII STABLE SINCE ~1600 M.Y. B.P.
TECTONIC AND METAMORPHIC STRUCTURES
TRENDS WITHIN FOLDED ZONES
FAULTS
SYNTECTONIC GRANITES
MIGMATITES
VOLCANIC ACTIVITY
EXTRUSIVE CAMEROON AND KAROO VOLCANICS
BASIC INTRUSIVES

west. Recent work by Pautot and others (1973) has shown that the salt diapir limit of the Gabon Basin follows the 2000 meter contour between 1°N and 3°S. They suggest a relationship to a fracture zone trend that is postulated by Burke (1969) which reaches the continent at 2°N near Bata with a strike of N45°E. It is reasonable to assume that the northwestern limit of salt deposition was controlled by a fracture zone, but the trend and location are more probably those of the Libreville line (Figure 2). Although this fracture zone is thought to have limited the extent of evaporite sedimentation, neither Pautot and others (1973) nor Leyden and others (1972) have found evidence for a NNE trending basement ridge in seismic reflection profiles across the slope break. Possibly, a once existing basement ridge may have subsided and gradually disappeared beneath the sediments of the continental slope and rise. Hurley and Rand (1969) show that a small cratonic nucleus in northwestern Brazil has broken from the Congo craton. However, between this small cratonic nucleus and the Brazil margin, there is a northeast-southwest trending province dated 400-800 m. y. B. P., which is the counterpart of the Pan-African rejuvenation. This evidence points to an approximate strike of N10°E for the direction of shearing along the Libreville line. This line follows the 2000 meter contour until it breaks to the southeast off Gabon. The Cameroon volcanics south of 7°N which describe a slightly different direction than the Libreville line, lie along a boundary within the Pan-African belt itself where the Pan-African metamorphic lineations converge. An extension of the Libreville line landward would meet this boundary at a low angle. Since the Cameroon volcanoes probably did not develop until the Neogene (Burke and others, 1971), they may represent a reactivation of stresses along slightly different Pan-African directions than those from which the initial South Atlantic rifting developed.

The coastline of Angola, from Nova Redondo to Mossamedes, skirts the edge of the Congo craton (Figure 2). The zone of Pan-African rejuvenation lies within a narrow band along the edge of the craton and follows earlier Precambrian trends of syntectonic granite emplacement within the Congo craton of southern Angola. The opposing coastline of Brazil (Bullard and others, 1965) along the Sao Paulo embayment lies within the much wider Paraiba metamorphic belt which is also dated as 500-700 m. y. B. P. (Cordani and others, 1968) and is dominated by structural lineations which were parallel to the Pan-African trends in Angola when the two continents were joined. Off Angola a double band of isostatic gravity highs extends southwestward from 9°S to the Walvis Ridge (Rabinowitz, Figure 5, 1972). The axial trend of these anomalies is N20°E, although the seaward gravity high is offset by minor north-south trends. The western gravity high approximates the upper continental slope which has an average trend of N19°E. Between 10°S and 15°S, the trend of the Pan-African zone also averages N20°E. From comparison with a study of the Norwegian margin by Talwani and Eldholm (1972) Rabinowitz concludes that the seaward gravity high marks the oceanic-continental boundary and that the eastern gravity belt may be a hinge line for subsidence within the Precambrian rocks. Seismic reflection data over the Walvis Ridge-continental slope join, discussed later, record an uplifted basement block which is associated with the seaward free-air gravity anomaly (Rabinowitz, Figure 4, 1972). Basement fault scarps parallel to this block cross the more EW topographic trend of the Walvis Ridge here. Strikes of these faults are parallel to the axes of the positive gravity anomalies described by Rabinowitz. The Benguela line in Figure 2 is parallel to the axial trend of the double band gravity highs, to the Pan-African trend, and the general trend of the continental slope. The strike of this line represents the logical direction for transform shearing along the southern Angola margin. It is again noteworthy that the belt of salt diapirism south of 11°S defined by Pautot and others (1973) is nearly parallel to the Benguela line. However, its seaward limit appears to extend slightly beyond the Benguela line to the west.

The Libreville and Benguela lines occur where Pan-African belts abruptly change directions conforming to the boundaries of cratonic nuclei. This is not true for the Luderitz and Cape Town

FIGURE 3: Location of Luderitz and Cape Town lines along the southwest African margin. Bathymetry after Simpson and Forder (1967).

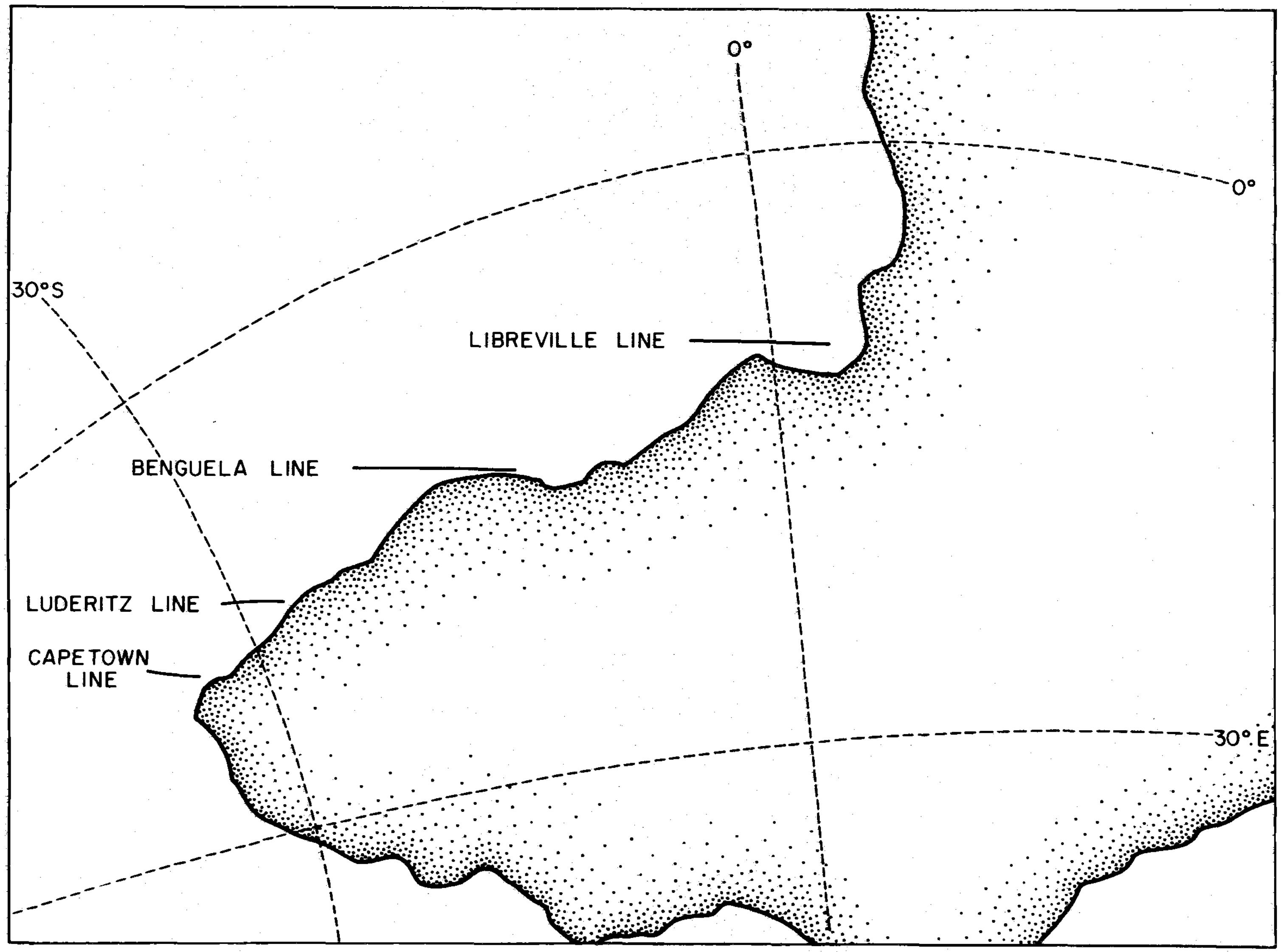

10°E
25°S
20°E
25°S
LUDERITZ
200
1000
2000
3000
4000
ORANGE RIVER
10° E
30°S
20° E
30°S
Tripp
Seamount
LUDERITZ
LINE
5000
CAPE TOWN
10° E
35°S
20° E
35° S
Agulhas
Bank
200
1000
2000
3000
4000
CAPE TOWN
LINE
Protea
Seamount
Argentina
Seamount
Erica
Seamount
Schmitt Ott
Seamount
Fanzarini
Seamount

lines (Figure 3). Although the Pan-African Damara belt north of Luderitz curves southwestward following the Kalahari craton, this segment of the coastline has no major offsets like those bordering the Congo craton. Rather, the Luderitz and Cape Town lines are recognized by regional offsets of the continental margin bathymetry, which are analogous to more local offsets of the shelf break between Walvis Bay and Cape Town. Although it is not displayed well in Figure 3, van Andel and Calvert (1971) and Dingle (1973) have noted a regular scalloped morphology of the continental shelf and suggested both erosional processes and tectonic control for its origin. Near 27.5°S, the continental shelf break along the 200 meter contour turns abruptly into a southwestern trend which continues to the 3000 meter contour. Paralleling this offset of the shelf break to the southwest, a fault scarp has been mapped by Dingle (1973, Figure 7) between the 200 meter and 500 meter contours. At 33.5°S a narrow topographic high extends from the continental shelf to the 4500 meter contour (Figure 3). This lineation borders the NE-SW trending Cape Canyon incised across the continental shelf (Dingle, 1973, Figure 7). The residual magnetic anomaly pattern off southwestern Africa (Simpson and Du Plessis, 1968, Figure 4) exhibits a general northwesterly trend. Inner and outer belts of high amplitude (up to 500 gammas) positive anomalies parallel the continental shelf break. A northeasterly cross trend is imposed on the primary direction of these belts between Walvis Bay and Luderitz, which Simpson and Du Plessis suggest is due to offshore extensions of Damaran rocks with high magnetic susceptibilities. The NE trending shelf break segments mapped by van Andel and Calvert (1971) (included in Figure 6 for reference) fall along the three prominent positive magnetic cross trends and appear to reflect a magnetic edge effect across faults which must control the morphology of the continental shelf and slope there. The bathymetric lineations used as control for the Luderitz and Cape Town lines in Figure 3 occur along offsets of the outer positive magnetic belt. This evidence indicates that the structure of the African continental margin from the Walvis Ridge to Cape Town is controlled by NE-SW offsets of the basement even though there are no onshore tectonic or metamorphic lineations of this orientation within the Pan-African basement. The free-air gravity map of Simpson and Du Plessis (1968, Figure 5) shows a positive belt of gravity highs which follow the upper continental slope between Walvis Bay and Cape Town. Although the axis of this belt is offset right-laterally as is the shelf break, there are only very weak northeasterly trends of the kind that might be associated with fracture ridges along transform directions. Seismic reflection (Simpson, 1971) and sonobuoy refraction data (Bryan and Simpson, 1971) between Luderitz and Cape Town yield no evidence for basement ridges, although a discontinuity in the basement below the Cape

Canyon suggests faulting. Considering Rabinowitz's conclusions for the structure of the Angola margin, it is likely that the positive gravity belt along the slope marks the boundary between continental and oceanic crust. Nevertheless, lateral offsets of the continental crust, represented by the Luderitz and Cape Town lines, are strongly indicated, and these features are considered to be the directions of initial transform shear south of the Walvis Ridge.

The Libreville, Benguela, Luderitz and Cape Town lines fall along small circles of a pole located at 5°N, 26°W. A Mercator projection of Africa (Figure 4) with its pole shifted to these coordinates, demonstrates the parallelism of these four lines and suggests a mutual origin related to the initial rotation between Africa and South America. If this is true, these lines are parallel to, if not actually coincident with, early Cretaceous fracture zones created along the Atlantic proto-rift. These fractures appear to have had a controlling influence on the present morphology and history of sedimentation along the continental margin from the Gulf of Guinea to the tip of South Africa.

FIGURE 4: Libreville, Benguela, Luderitz and Cape Town lines along the west African margin: Mercator projection shifted to pole at 5°N, 26°W. The fit of these postulated lines of shear may be compared to small circles about this pole since all parallels of the pole are horizontal in this projection. Dashed lines are parallels and meridians about present geographic north pole.


0°
0°
30°S
LIBREVILLE LINE
BENGUELA LINE
LUDERITZ LINE
CAPETOWN LINE
30° E

PRE-CENOZOIC MAGNETICS AND SPREADING HISTORY

Two sets of magnetic lineations are present within an area bounded by 5°S, 40°S, 0°E and the African margin. The landward set of anomalies, called here the Benguela sequence, is thought to reflect spreading along a direction parallel to the Benguela line. The seaward set includes the magnetic quiet zone (van Andel and Moore, 1970; Mascle and Phillips, 1972a) and anomalies to the west within the Heirtzler sequence (Heirtzler and others, 1968).

The Benguela sequence has been constructed from correlations between magnetic profiles taken on Chain 99/4, CIRCE 8, CIRCE 9, Conrad 1313, and South Africa cruises 2, 71, 204 and 205 north and south of the Walvis Ridge. Profiles over the Walvis Ridge show that the magnetic signature is disturbed by basement structure and morphology. For simplicity, these profiles are omitted from the presentation except for one Walvis Ridge crossing on Chain 99/4. Most of these profiles are oriented northeast-southwest, making it possible to observe magnetic lineations nearly perpendicular to the strike of the Benguela offset. The more east-west oriented profiles (CIRCE 9, South Africa 204, 205 and the north-south segment of Chain 99/4) were projected to an azimuth of 035°.

After projection of the profiles, visual comparisons of the relative number, sequence, and amplitudes of the maxima and

FIGURE 5: Correlation of Benguela anomalies along ship tracks shown in inset. Correlations are made between multiple peak anomaly groups rather than between individual anomalies. The anomaly groups are identified by Roman numerals which correspond to the linear bands on Figure 6. Anomaly profiles of CIRCE 9, the north-south segment of Chain 99/4, and South Africa 204 and 205 are projected to 035° to improve identification. Fracture zones shown as continuous lines to aid comparison with Figure 6. Stippled tone indicates anomalies not related to seafloor spreading. Scarps along the continental shelf interpreted as faults are noted by F on the magnetic profiles. The magnetic profiles are arranged in relative geographic position from north to south; their relative east-west positions are shifted slightly to permit easier visual tracking of anomalies. Parallels (below baselines) and meridians (above baselines) are shown by tick marks every four degrees. SM indicates seamount anomaly.

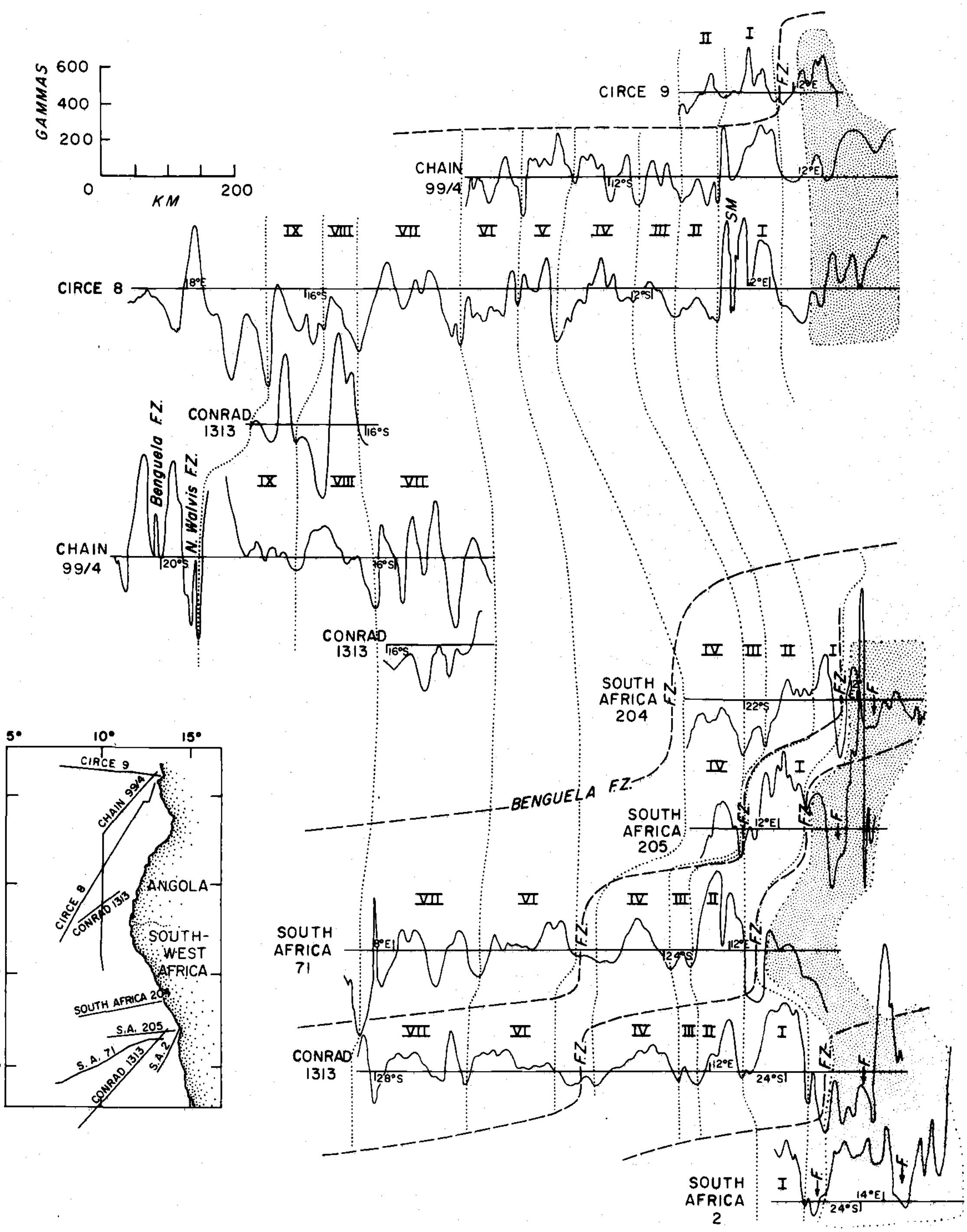
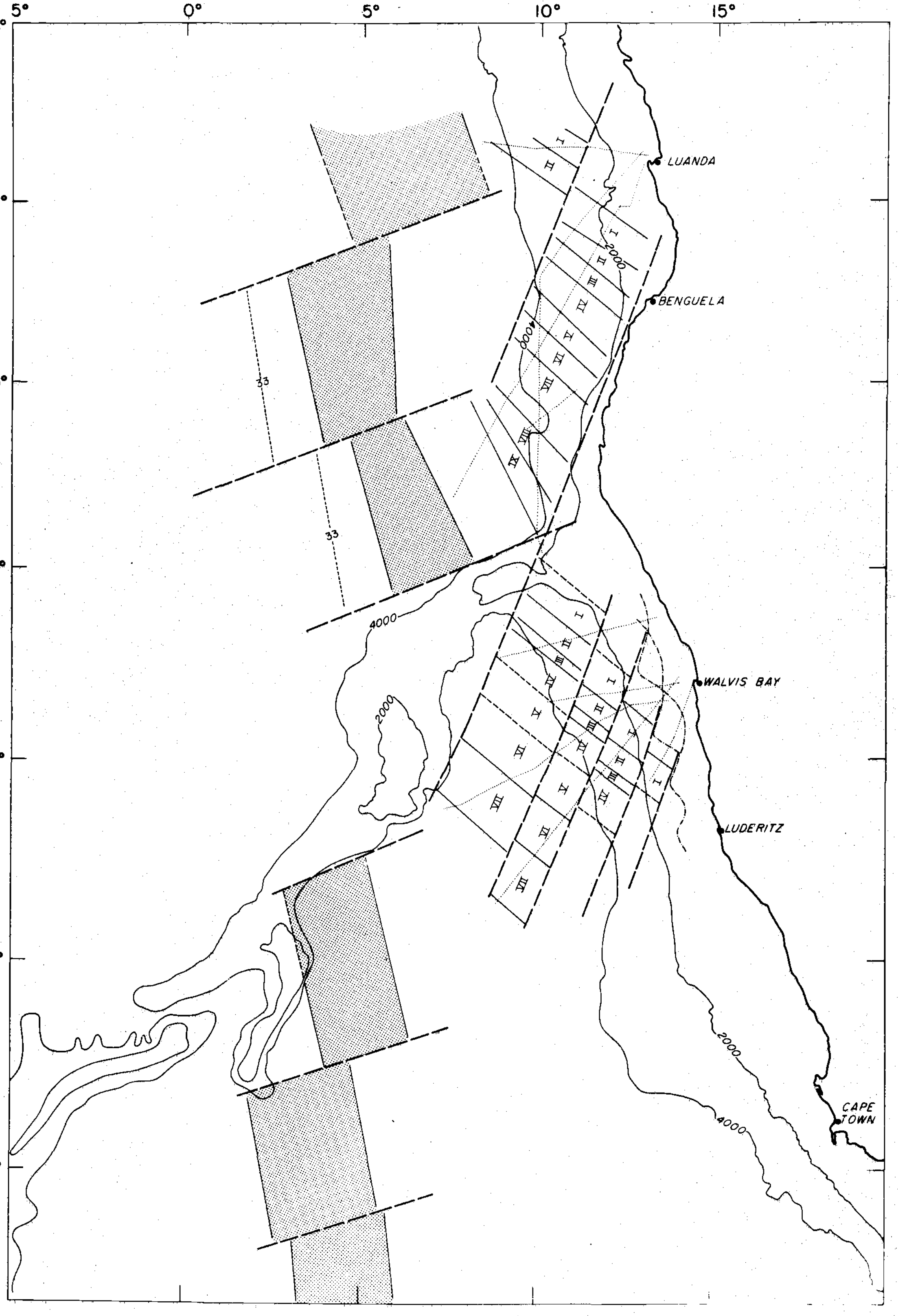

GAMMAS
600
400
200
0
KM
200
CIRCE 9
CHAIN 99/4
CIRCE 8
CONRAD 1313
CHAIN 99/4
CONRAD 1313
Benguela F.Z.
N. Walvis F.Z.
SM
BENGUELA F.Z.
SOUTH AFRICA 204
SOUTH AFRICA 205
SOUTH AFRICA 71
CONRAD 1313
SOUTH AFRICA 2
ANGOLA
SOUTH-WEST AFRICA
CIRCE 9
CHAIN 99/4
CIRCE 8
CONRAD 1313
SOUTH AFRICA 204
S.A. 205
S.A. 71
CONRAD 1313
S.A. 2

FIGURE 6: Map of Benguela anomaly correlations in Figure 5 plotted along ship tracks which are shown as light stippled lines. Fracture zones shown as heavy dashed lines. Scarps marking continental shelf breaks mapped by van Andel and Calvert (1971) and Simpson and Du Plessis (1968) between 20°S and 27°S drawn with narrow dot-dash lines. Magnetic quiet zones, shown as grey stippled pattern, and anomaly 33 taken from Figure 8. 2000 and 4000 meter contours from Uchupi (1971).


5°
0°
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25°
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LUANDA
BENGUELA
WALVIS BAY
LUDERITZ
CAPE TOWN
2000
4000
33
33

minima were made. The correlations are shown in Figure 5 as bands of multiple peak anomaly belts and identified with Roman numberals which begin with the oldest. Figure 6 is a map of the anomaly belts plotted along the ship tracks.

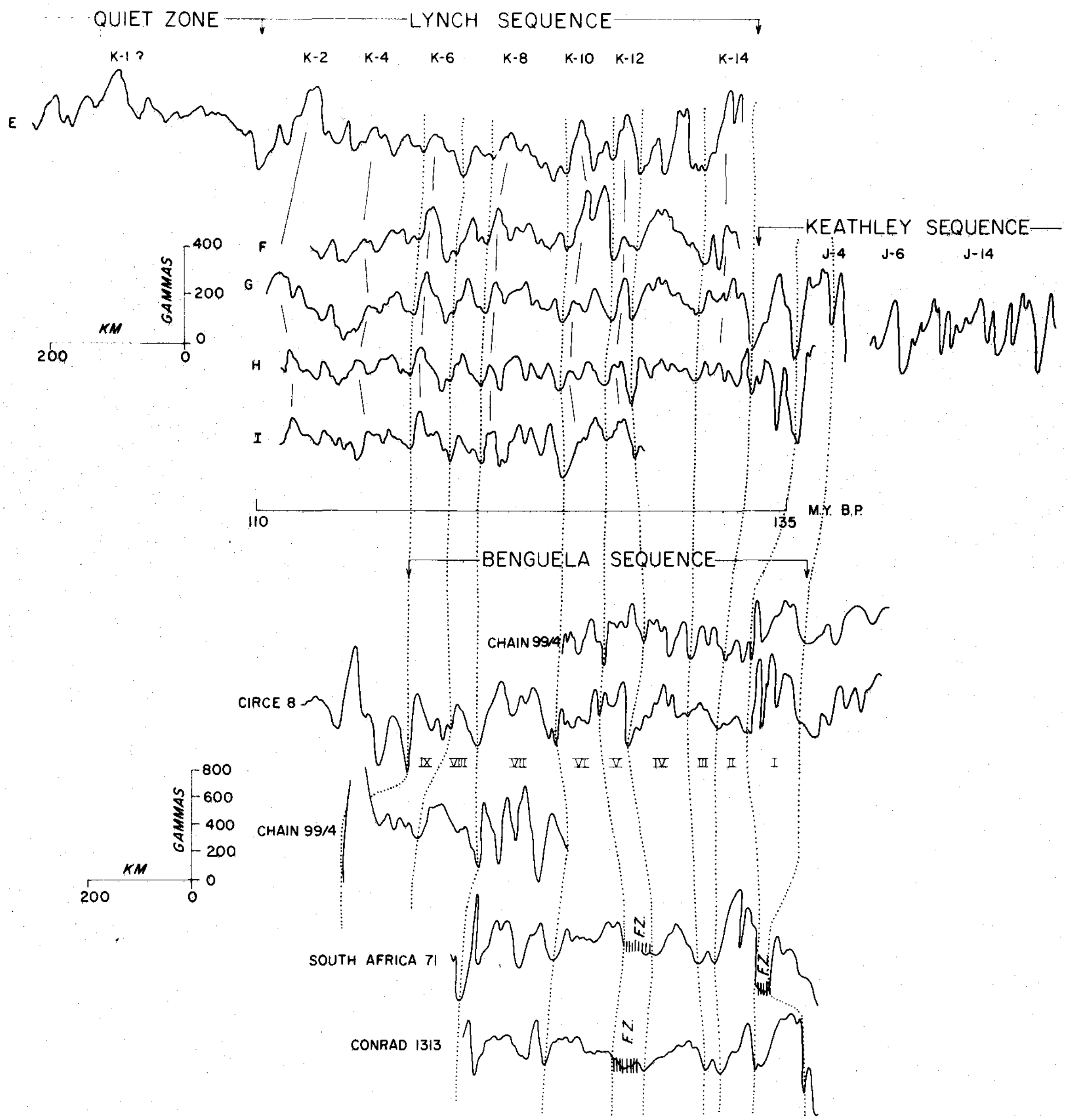
The best overall correlation of the anomalies is between the longer Chain 99/4 and CIRCE 8 profiles north of the Walvis Ridge. These anomalies include those recognized by Von Herzen and others (1972) from CIRCE 8, CIRCE 9, Chain 99/4 and Chain 99/3 in a small area north of 12°S. A right-lateral magnetic offset of nearly 1000 kilometers across the Benguela line yields further evidence for a major fracture zone along the Angola margin here (Figure 6). Below the Benguela fracture zone the anomaly correlations are complicated by numerous crossings of three closely spaced fracture zones (Figure 6). Only profile South Africa 2, south of the Walvis Ridge, does not cross any fracture zones. In this region van Andel and Calvert (1971) mapped three NE-SW offsets of the NW-SE scarp which marks the shelf break. These offsets of the shelf edge appear to extend seaward and displace the magnetic anomalies. South Africa 204 and 71 and Conrad 1313 show large amplitude negative anomalies where these tracks cross the NE-SW striking offsets of the shelf. Where the seaward extensions of the fracture zones cross magnetic profiles South Africa 71 and Conrad 1313 they show significant changes in magnetic signature with subdued and slightly negative anomalies. The South Africa 71 crossing of the seaward fracture zone is wide and more pronounced, probably because the track line crosses it at a low angle. The single fracture zone mapped above the Benguela line, north of the Walvis Ridge, would meet the shoreline near 6°S if extended to the northeast. Onshore, the fold trends within the West Congo orogenic belt of Pan-African age make an almost 90° change in strike (Figure 2) east of Cabinda. This fracture zone appears to be an initial offset of the continental margin that may have been directly influenced by the structural trends of the Pan-African basement as along the Libreville and Benguela lines. Rabinowitz (1972) notes that the magnetic offset mapped initially by Von Herzen and others (1972) lies along a wide gravity high which may suggest an underlying basement ridge associated with shearing along the fracture zone.

Magnetic anomalies related to the structure of the continental margin, indicated by the stippled tone in Figure 5, show no coherent pattern of lineation. Baumgartner and van Andel (1971) and Von Herzen and others (1972) have related the shoreward anomalies at 9°S to northwesterly basement ridges extending from the continent. South of 20°S, there are strong negative anomalies over the SE-NW trending shelf scarps between the right-laterally offset NE-SW scarps. Thus the SE-NW striking scarps are thought to be hinge faults along which subsidence of the continental margin occurred between the fracture zone offsets. These scarps are noted in Figure 6 also.

The strike of the Benguela anomalies is best determined by the lineations north of the Walvis Ridge on the two long tracklines which do not cross fracture zones. Here the strike is generally N45°W except for anomaly IX, which strikes N25°W.

Vogt and Johnson (1971) have established an anomaly sequence (Lynch sequence) in the western North Atlantic between the Keathley (Vogt and others, 1971) and Heirtzler magnetic sequences. The boundary between the Keathley and the Lynch sequences lies along the 135 m. y. B. P. isochron of Pitman and Talwani (1972). This isochron is based on extrapolated spreading rates since no JOIDES holes penetrate to basement within this area. Comparisons of anomalies from the Keathley, Lynch and Benguela sequences are shown in Figure 7. No dates are available for the Benguela anomalies, but since B-I must be contemporaneous with the initiation of spreading in the South Atlantic, a rough upper age limit can be assigned. Although postulated dates for this event vary from 200 m. y. B. P. to 90 m. y. B. P., the most reasonable estimates fall around the Jurassic/Cretaceous boundary (140 to 130 m. y. B. P.). Dietz and Holden (1972) assume 135 m. y. B. P., which agrees with radiometric dating of the Kaoko basalts (136 to 114 m. y. B. P.) of Southwest Africa (Siedner and Miller, 1968) and Serra Geral lavas of Brazil of the same age (Amaral and others, 1966). Deep Sea Drilling data in

FIGURE 7: Correlation of magnetic anomalies in the western North Atlantic (Lynch and Keathley sequences) from Vogt and Johnson (1971) and in the eastern South Atlantic (Benguela sequence). Note differences in scales for each region. Time ticks shown for Keathley and Lynch sequences based on 135 m. y. isochron in western North Atlantic and onset of Late Cretaceous magnetic quiet period.


QUIET ZONE
LYNCH SEQUENCE
K-1 ?
K-2
K-4
K-6
K-8
K-10
K-12
K-14
E
F
G
H
I
KEATHLEY SEQUENCE
J-4
J-6
J-14
400
200
0
GAMMAS
KM
200
0
110
135
M.Y. B.P.
BENGUELA SEQUENCE
CHAIN 99/4
CIRCE 8
IX VIII VII VI V IV III II I
800
600
400
200
0
GAMMAS
KM
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CHAIN 99/4
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the South Atlantic yield an extrapolated date for opening near 130 m. y. B. P. (Maxwell and others, 1970). LePichon and Hayes (1971) chose 140 m. y. B. P. as the initiation of spreading. Therefore an age between 140 and 130 m. y. B. P. has been assumed for B-I. Thus, it is reasonable to assume that the Lynch and Benguela sequences were initiated at the same time and correlation of their anomalies should be possible.

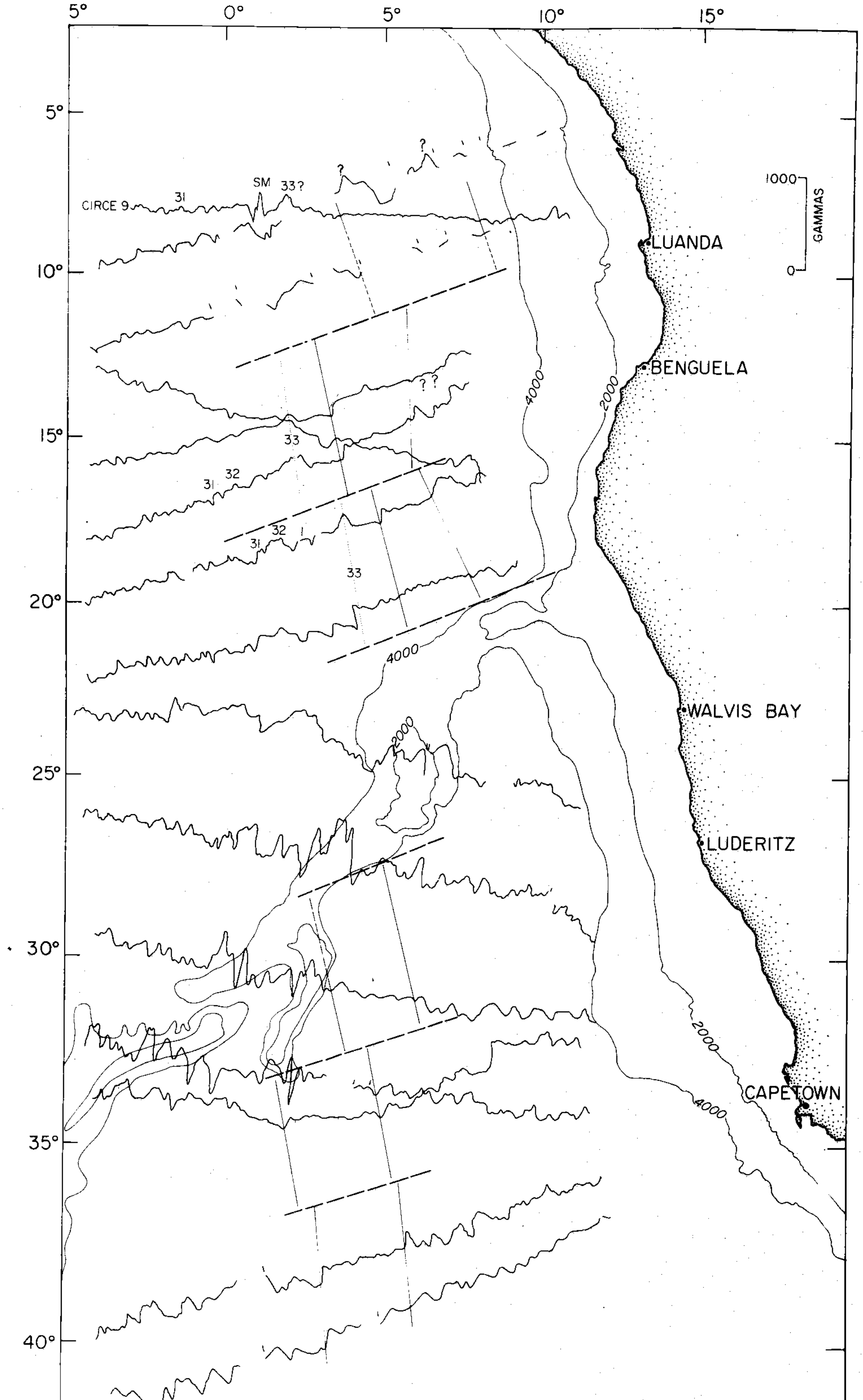
The Lynch sequence lies approximately 14° to 20° north of the Cretaceous magnetic equator (determined from a continental North America paleomagnetic pole at 70°N, 170°W; Larochelle, 1969) while the Mesozoic paleolatitudes of Angola and South West Africa, (McElhinny and others, 1968) are between 20° and 30°S. Accordingly, the larger amplitudes of the Benguela anomalies suggest a higher paleolatitude than the Lynch anomalies. Because the profiles are reversed and from different hemispheres, the shapes of anomalies should be asymmetric with respect to one another. This asymmetry is pronounced in the anomaly band IV between the CIRCE 8, Conrad 1313 profiles and the G, F profiles in the North Atlantic. Both sets of anomalies have approximately symmetric orientations to magnetic north (Lynch, N30°E; Benguela, N45°W).

The end of the Lynch anomaly sequence has been placed at 90 m. y. by Vogt and Johnson (1971). Since they note, however, that the Lynch sequence is terminated by the onset of a period of uniform magnetic polarity, 110 m. y. B. P. might be a more reasonable date because this quiet magnetic zone can be interpreted as the Upper Cretaceous Mercanton Interval of normal polarity (McElhinny and Burek, 1971) which began around 110 m. y. B. P.

Recently, Larson and Pitman (1972) presented a global synthesis of the Mesozoic geomagnetic time scale based on lineations in the North Pacific. They correlate with good reason the Keathley sequence to the Hawaiian lineations, but suggest that the Keathley sequence occupies the interval from 155 to 110 m. y. B. P., and they question the validity of the Lynch anomalies as polarity reversals. Instead, they suggest that the Lynch anomalies result from bathymetric trends and/or changes in the paleofield intensity. However, the Lynch survey was made parallel to bathymetric and presumably structural trends to avoid crossing fracture zones. The only track which does cross structural trends is that part of profile E (Figure 7) which is over the quiet zone. Following Ladd (1973), Larson and Pitman (1972) conclude that spreading in the South Atlantic began during the Upper Cretaceous quiet period, around 110 m. y. B. P. However, radiometric data all point to 140 to 130 m. y. B. P. as the age of opening and the biostratigraphy of African coastal basins also suggests an opening date earlier than 110 m. y. B. P. Basal units within the Gabon, Congo and Cuanza basins are all pre-Aptian (>110 m. y.) (Belmonte and others, 1965). In the Gabon and Congo basins, the lower sediments are Neocomian (>120 m. y.) and perhaps older. These facts conflict with Larson and Pitman's timing of the Hawaiian and Keathley sequences, which requires that the Keathley sequence end at 110 m. y. B. P. The reasonable correlation between the Benguela and Lynch anomalies further supports the validity of the Lynch anomalies and makes Vogt and others (1971) and Vogt and Johnson's (1971) date for the boundary between the Keathley and Lynch sequences more reasonable. It seems unlikely that the Lynch anomalies lie over crust generated during a period of uniform magnetic polarity, but the discrepancy between Larson and Pitman's results and the existence of the Benguela and Lynch anomalies will remain until further work can resolve it.

van Andel and Moore (1970) and Mascle and Phillips (1972a) have described abyssal magnetic quiet zones in the South Atlantic and the latter concluded that they are the result of seafloor spreading during the Upper Cretaceous interval of normal polarity. Unfortunately, the boundaries of the zones are inadequately known. Mascle and Phillips' chart (1972, Figure 5) suggests that the smooth zones are continuous but non-linear areas, with sharp kinks in the two African sequences. Such sharp changes in trend might be caused by lateral offsets resulting from fracture zones. Mascle and Phillips (1972a) used data from PROJECT MAGNET flights (Mascle and Phillips, 1972b. Figure 8 shows a preliminary reinterpretation

FIGURE 8: Location of Angola Basin and Cape Basin magnetic quiet zone boundaries along PROJECT MAGNET flight lines (Mascle and Phillips, 1972a) and CIRCE 9 ship track. Lineation of anomaly 33 indicated by light stippled line. Identification of anomalies 31 and 32 provided for reference to Heritzler sequence. Postulated fracture zone offsets shown by heavy dashed lines. Tick marks along PROJECT MAGNET lines indicate changes in course. Vertical scale of CIRCE 9 is approximately one-half that of the PROJECT MAGNET profiles shown on figure. Bathymetry from Uchupi (1971). SM indicates seamount anomaly.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CIRCE 9
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SM
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32
1
4000
2000
1000
0
GAMMAS
LUANDA
BENGUELA
WALVIS BAY
LUDERITZ
CAPETOWN

of the same data for the eastern South Atlantic plus the CIRCE 9 profile from van Andel and Heath (1970), with probable fracture zone offsets of the quiet zones. The most significant feature is a right lateral offset across the Walvis Ridge, suggesting that fracture zones border the more east-west trending segments of the ridge.

The quiet zone segment best defined by the PROJECT MAGNET lines lies between 13°S and the Walvis Ridge, just west of the Benguela anomalies. The western edge of this segment is marked by a pronounced negative anomaly which strikes N12°W and is slightly offset in a left-lateral sense. The eastern edge of the quiet zone diverges both northward near 13°S and southward towards the Walvis Ridge. The reason is not understood but may be related to a change in direction of spreading that took place during the transition from the Benguela lineations to the quiet zone. North of 10°S, the quiet zone along the CIRCE 9 profile is much wider than anywhere else. PROJECT MAGNET data in this region are inadequate, however, to confirm this abrupt widening.

Irving and Couillard (1973), compiling continental magnetic reversal data from 165 to 65 m. y. B. P., concluded that the best compromise between land and marine data sets limits of 110 and 83 m. y. B. P. for the Cretaceous normal polarity interval. However, there remains some uncertainty about the younger age limit of the magnetic quiet zone. The 83 m. y. limit corresponds to the last positive magnetic anomaly (33) of the Heirtzler sequence. Anomaly 33 (Figure 8; Mascle and Phillips, 1972a, Figure 4) is separated from the quiet zone by a smooth section of the magnetic profiles which is shorter than the quiet zone. This short smooth section is distinguished from the quiet zone mapped by Mascle and Phillips (1972a) by the existence of a sharp negative anomaly along the western boundary of the quiet zone. This short smooth interval, separated from the quiet period, is recognizable not only in the South Atlantic, but also in the North Atlantic (Vogt and others, 1971, Figure 3), and Pacific (Raff, 1966, Figure 2). The sharp negative anomaly bordering the younger edge of quiet zones in the Atlantic and Pacific probably represents a reversal near 90 m. y. B. P. observed by Russian investigators (Pecherski and Khramov, 1973), and pointed out by Creer (1971). Thus, the quiet zone most likely ends at this 90 m. y. reversal and anomaly 33 lies near 83 m. y. B. P.

The change in strike between the Benguela anomalies and the western edge of the quiet zone represents a marked change in spreading direction. Reorientation appears to have begun near the end of anomaly lineation VII of the Benguela sequence. If we assume that the spreading rate was constant in the North Atlantic while the Lynch anomalies were forming, it is possible to date the position in the Lynch sequence which corresponds to the end of B-VII time and the change in spreading direction as approximately 120 m. y. B. P.

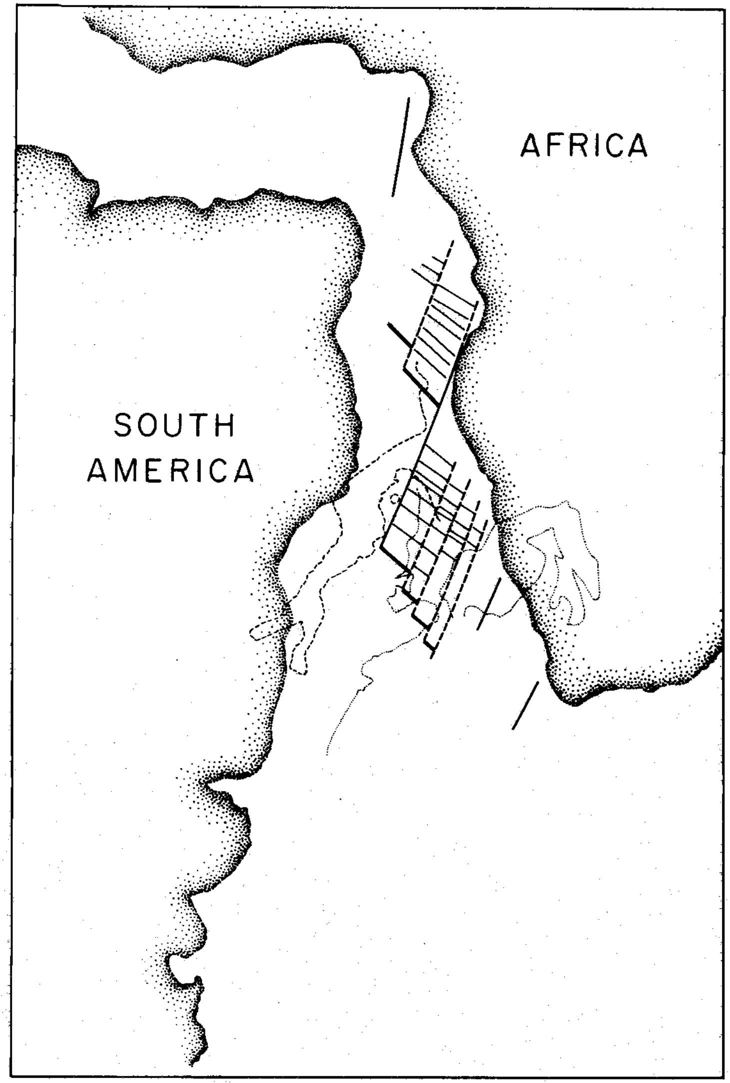
By 90 m. y. B. P., the reorientation to a new pole of rotation was complete.

LePichon (1968) showed that the South Atlantic must have opened in at least two episodes of spreading defined by two poles of rotation in order to reconcile the fit of South America and Africa (Bullard and others, 1965) with the present rotation. The change in strike between the Benguela lineations and the Angola Basin quiet zone requires a shift in the pole of rotation between 140 and 90 m. y. B. P. The earliest pole is defined by the strikes of the fracture zones along the African margin. The second pole is the same as that used by Francheteau and LePichon (1972) for their initial opening (140 to 80 m. y. B. P.), which was determined from the strikes of projected bathymetric trends of the equatorial South Atlantic. Small circles around this second pole fit the northern scarps of the Walvis Ridge, Rio Grande Rise and Falkland Plateau. The two episodes of spreading are shown in forward time sequence in Figure 9, beginning from the fit of the 500 fathom contours of South America and Africa of Bullard and others (1965). All rotations are made by moving the South American plate and leaving Africa fixed. Table 1 summarizes the rotations.

The angles of rotation were determined by rotating South America away from Africa so that 1) the western edge of Benguela anomaly belt VII lies along an approximately median position

FIGURE 9A 120 m. y. B. P. reconstruction (end of B-VII anomaly) of South Atlantic obtained by rotation of South America away from Africa (Table 1). Heavy solid lines are the Libreville, Benguela, Luderitz and Cape Town lines interpreted as fracture zones. Anomalies of Benguela sequence on African plate where known from trackline coverage on Figure 6. Odd numbered anomaly groups are shown by stippled tone. Heavy dashed lines are fracture zones through Benguela sequence. Stippled line is 4000 meter contour of the margin and Rio Grande Rise on South American plate. Light dashed line is 4000 meter contour of margin and Walvis Ridge on African plate. Contours from Uchupi (1971).

FIGURE 9B 90 m. y. B. P. reconstruction (end of Upper Cretaceous magnetic quiet period) of South Atlantic obtained by second rotation of South America from Africa (Table 1). Magnetic quiet zone (Mascle and Phillips, 1972a) shown as horizontal lines on South American plate and dots on African plate. All other symbols same as on Figure 9A.


AFRICA
SOUTH
AMERICA

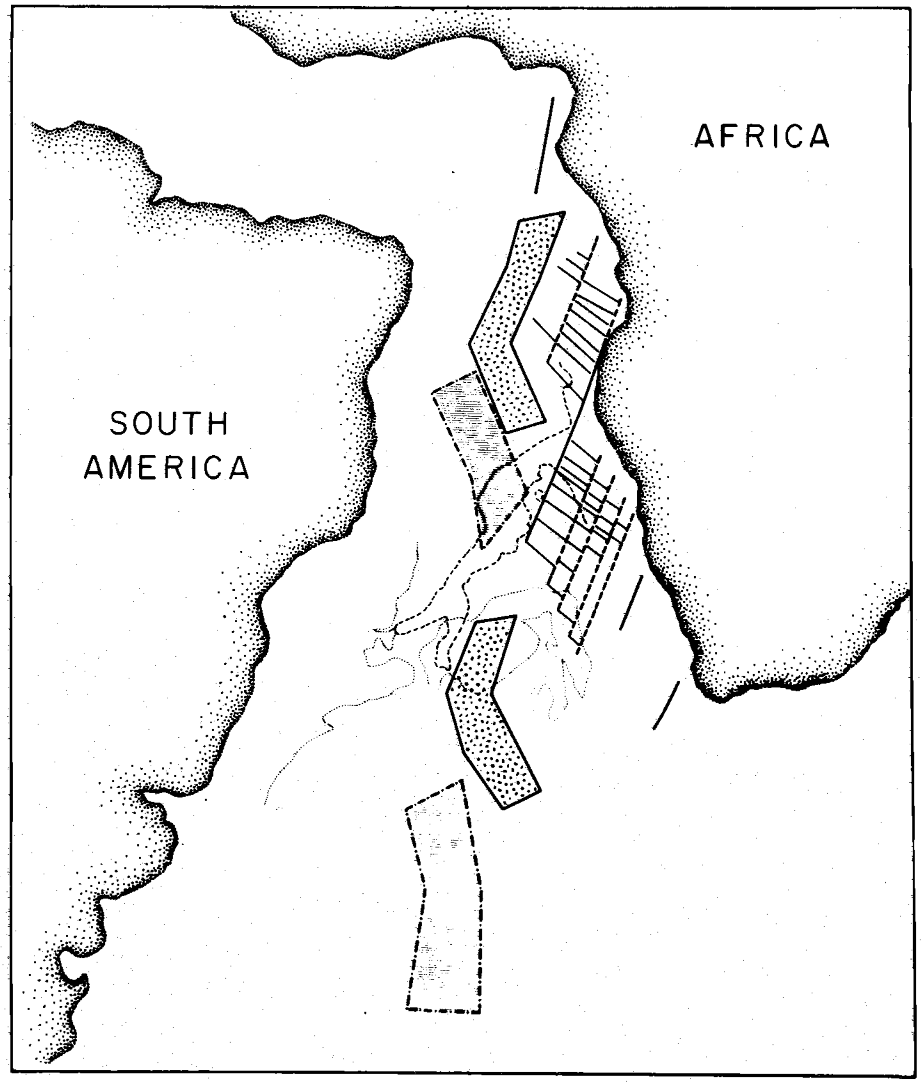

AFRICA
SOUTH
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TABLE 1

Rotations used for Figures 9 and 13

Plate	Pole Lat.	Pole Long.	Rotation Angle
South America			
Fit of 500 fm contours[2]	44.0	-30.6	+57.0
120 m.y. B.P. reconstruction[3]	5.0	-26.0	-19.5
90 m.y. B.P. reconstruction[4]	21.5	-14.0	-12.0
Equivalent to[5]	69.0	-11.0	+35.0
Fit of Mid-Atlantic Ridge to 90 m.y. B.P. reconstruction[6]	69.0	-11.0	-17.5
Africa	Not rotated		

[1]Positive rotation of plate is in counter-clockwise sense looking down at pole.

[2]Bullard and others' (1965) fit of South America and Africa.

[3]End of B-VII time, Figure 9A.

[4]End of Cretaceous normal polarity period, Figure 9B.

[5]Total post-90 m.y. rotation.

[6]Position of Mid-Atlantic Ridge crest on Figure 13. This rotation follows rotation about pole at 21.5°N, 14.0°W; Mid-Atlantic Ridge is fixed to South America plate during rotation.

(Figure 9A) and 2) the seaward boundaries of the African and South American quiet zones coincide (Figure 9B). The boundaries of the magnetic quiet zones of Figure 9B are those mapped by Mascle and Phillips (1972a).

These rotations do not necessarily describe the pattern of movement, but only the relative motions required to fit the isochronous boundaries on each plate separated by an active ridge. Because of lack of data the reconstructions are only approximations to successive configurations of the early South Atlantic. There are no data off South America to establish the existence of a set of anomalies comparable to the Benguela sequence, and symmetric spreading during this period has been assumed. The second rotation permits a test of fit between two magnetic boundaries across the spreading ridge. Mascle and Phillips note that the quiet zone south of the Rio Grande Rise is approximately 15% wider than its complement south of the Walvis Ridge when measured along small circles drawn about the rotational pole of Bullard and others (1965). The reconstruction of Figure 9B indicates that the greater width of the Argentine Basin zone follows from its increased distance from the pole at 21.5°N, 14.0°W. The remaining rotation required to place South America in its present position is -35.0 about 69.0°N, 11.0°W. This pole disagrees with the present poles of rotation (62°N, 36°W or 58°N, 37°W) for the South Atlantic determined by Morgan (1968) and

LePichon (1968). Since this is an average pole for the entire Cenozoic and Late Cretaceous, however, this difference would not seem to be significant.

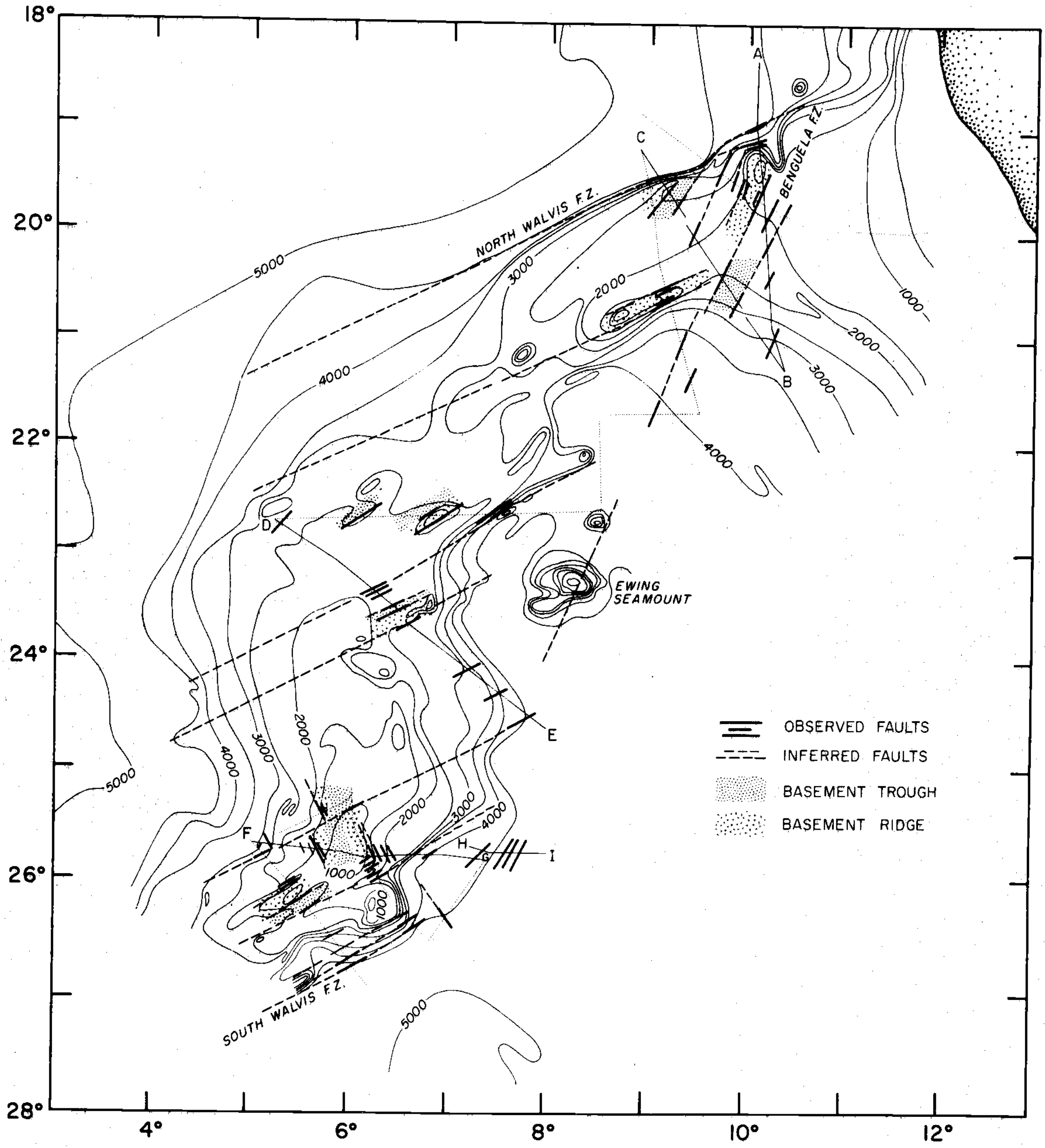
RELIEF AND STRUCTURE OF THE WALVIS RIDGE

Data for the structural study of the Walvis Ridge come from continuous depth and seismic reflection recordings of the R. V. *Chain* 99/4 and CIRCE 8 cruises. The area of study covered by these cruises lies within 4°E to 11°E and 18°S to 27°S (Figure 10) and contains six *Chain* 99/4 traverses across the Walvis Ridge north of 25°S and a star-shaped CIRCE 8 survey within the southern portion of the study area that includes six lines of seismic reflection data. Another CIRCE 8 line crosses the Walvis Ridge where it joins the continental margin. This material and data of the University of Cape Town (Simpson and Forder, unpublished map, 1967) were used for the bathymetric base map of Figure 10. The bathymetry of the inner margin facing southeast and northeast towards Africa has been considerably improved by the addition of the *Chain* 99/4 and CIRCE 8 tracklines.

The seismic reflection data within the study area provide coverage that is rather widely spaced yet detailed enough to yield a tentative structural map of the upper section of oceanic crust. Profiles representative of the structural character of the Ridge are shown in Figure 11.

Based on the general outline of the Walvis Ridge as well as dominant topographic trends of its uplands, the Walvis Ridge can be

FIGURE 10 Basement structure of the Walvis Ridge east of 4°E superimposed on bathymetry. Structural interpretation based on seismic reflection data from ship tracks of the Chain 99/4 and CIRCE 8 cruises which are shown as light stippled or solid lines. Seismic profiles in Figure 12 were recorded along the lettered solid tracklines and selected to be representative of the structural character of the Walvis Ridge. Bathymetric base map contoured from data of Simpson and Forder (1967) with the addition of depth profiles taken along each of the Chain 99/4 and CIRCE 8 ship tracks. Contours are in uncorrected meters.



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NORTH WALVIS F.Z.
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SOUTH WALVIS F.Z.
EWING SEAMOUNT
5000
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A
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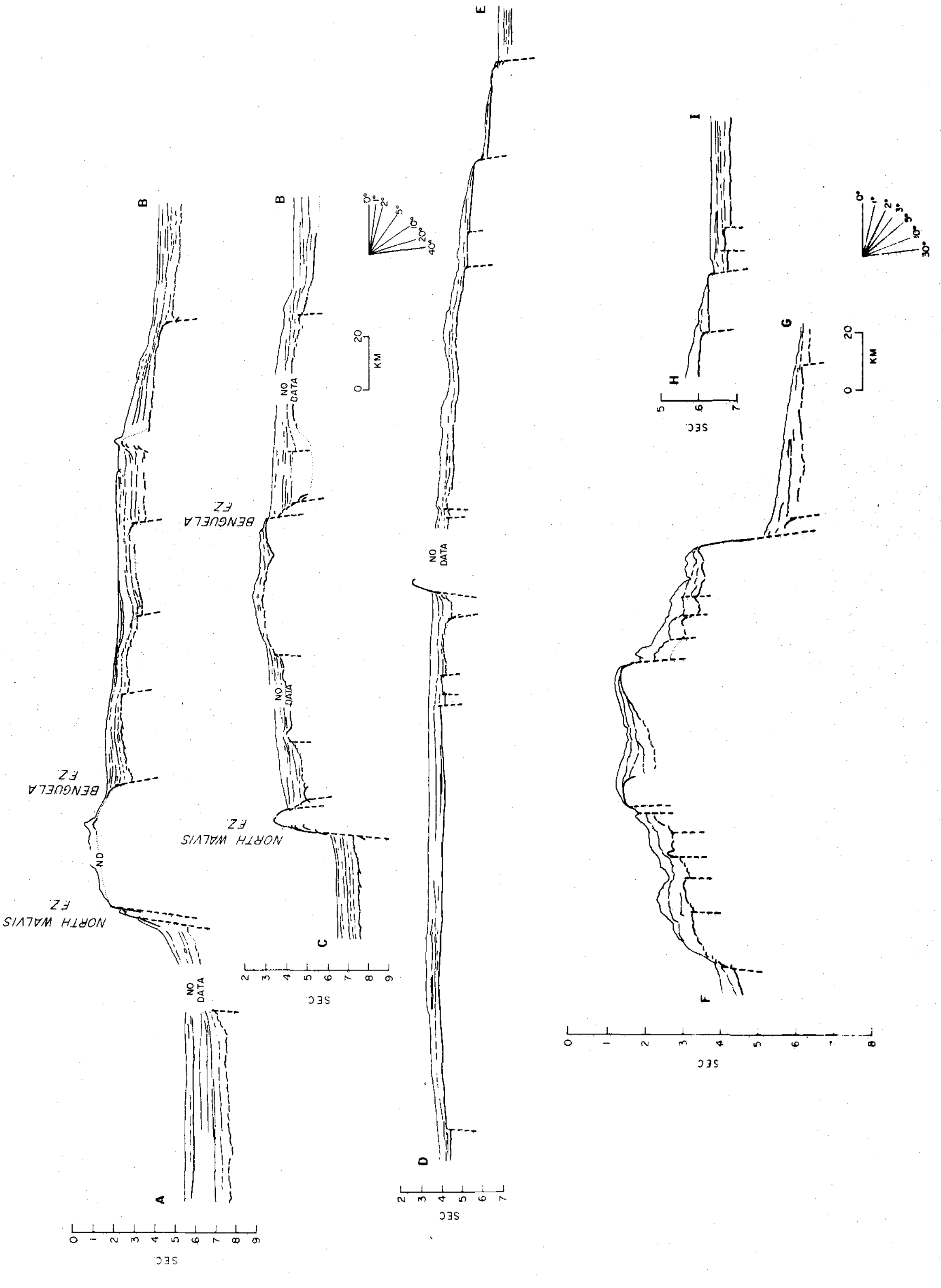
I
OBSERVED FAULTS
INFERRED FAULTS
BASEMENT TROUGH
BASEMENT RIDGE

subdivided into three segments. Between the continental margin and 23°S, the relief trends nearly N60°E. From 23°S to 25.5°S the dominant topographic trend is N25°W although minor relief associated with faulting strikes N60°E. South of 25.5°S the dominant trend changes again to approximately N60°E. These regions are referred to respectively as the northern, central and southern segments. The central segment, with a width of about 300 kilometers, is the broadest part of the Walvis Ridge which narrows to under 170 kilometers in the northern segment. Small ridges with a surface relief of 500 to 1500 meters occur over the Ridge uplands. They are linear and in most places parallel the major bathymetric trends. The inner margin of the Walvis Ridge consists of topographic scarps which are approximately perpendicular to each other and give it a blocky appearance. The outer margin of the Ridge, has a more broadly curved outline between 8°E, 20°S and 5°E, 25.5°S, but this contrast with the inner margin may be more apparent than real because of inadequate bathymetric control. To the northeast and southwest of this wide arc, the trends are more nearly parallel to those of the inner margin.

Reflection profiles (Figure 11) show that the acoustic basement consists of discontinuous, hummocky reflectors indicating that the basement is volcanic. The smooth appearance of the acoustic basement in the central part of the ridge may be due either to a hard

FIGURE 11 Line drawings of seismic reflection profiles across Walvis Ridge. Locations shown in Figure 11. Profiles AB, BC, DE from Chain 99/4; vertical exaggeration approximately 8. Profiles FG and HI from CIRCE 8; vertical exaggeration approximately 14. Vertical scales in two-way reflection time. Horizontal scales approximate. Acoustic basement shown with thicker line than overlying reflectors. Fault interpretations indicated by heavy dotted lines.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sediment layer such as chert, or to the presence of smoothly layered extrusives, since Deep Sea Drilling data indicate that extrusive basaltic basement can be quite smooth (Ewing and others, 1972).

Faults on the reflection profiles commonly affect only the basement, but some faulting extends upwards into the sedimentary reflectors. Sedimentation appears to have been largely controlled by deposition within structural troughs and by erosion or non-deposition over the more exposed basement ridges and flat regions of basement of the central segment. Even with this smoothing effect of sedimentation, the Walvis Ridge topography strongly reflects the underlying system of basement faulting. Figure 10 shows the interpretation of basement structure derived from reflection data and topography.

The structural framework of the upper oceanic crust here is controlled by three sets of faults. The first set is associated with the Benguela Fracture Zone and strikes generally N25°E. The remaining two sets strike approximately N60°E and N25°W. These latter faults control the topographic expression of the Walvis Ridge. Along the northern boundary of the northern segment of the Ridge, the N60°E set of faults disrupts the trend of the Benguela Fracture Zone. The following discussion considers these three sets of faults and associated structural features in more detail.

The Benguela Fracture Zone is defined by the seismic reflection data as approximately 135 kilometers wide in the region where the Walvis Ridge joins the continental margin. Within this zone, parallel and sub-parallel faulting is associated with basement ridges and troughs. The faults are completely buried by sediments and, on Figure 10 with its 500 m contour interval, have little or no surface topographic expression. The faults can be recognized by vertical offsets of the basement. The major offset denoted as the Benguela Fracture Zone on profiles AB and BC strikes N25°E. All faults on these two profiles, except those forming the outer northern boundary scarp, are part of the Benguela set. The Benguela structures appear to end at the northern boundary of the Walvis Ridge. Along this northern boundary two prominent basement ridges are uplifted along scarps which strike N65°E (Figure 10, Figure 11, profiles AB, BD). However, south of this boundary, the basement ridges trend approximately S25°W along faults of the Benguela set. Between these two basement ridges, a small topographic indentation of the Ridge boundary occurs near 9.5°E, 19.3°S along an intersection of N25°E Benguela faults and N60°E boundary faults.

South of 22°S, the identification of the Benguela Fracture Zone is uncertain. Along the flank of the inner margin of the southern segment, near 26°S, 7-8°W, of the Walvis Ridge, the edge of a wide fault terrace strikes nearly N25°E. The faults along which this terrace is uplifted are shown in profile HI. They may be related to the Benguela Fracture Zone, but they do not extend northward through the Cape Basin across profile DE. However, the location and alignment of the Ewing Seamount and a smaller one north of it suggest that their formation was controlled by the Benguela Fracture Zone.

The discussion now focuses on the two sets of faults which strike N60°E and N25°W and dominate the structural framework of the Walvis Ridge. The Ridge itself appears to consist of a series of crustal blocks offset right-laterally along the N60°E set. The large right-lateral offset of the magnetic quiet zones to the north and south of the Walvis Ridge (Figure 8) indicates that this faulting is related to transform shearing. The most prominent examples of the N60°E set on Figure 11 are the North Walvis Fracture Zone of profiles AB and BC, and the exposed high basement scarp approximately 70 kilometers from the eastern end of profile FG. Within the central segment of the Ridge, the structural features on profile DE between 22°S and 23°S lie along extensions of the nearby boundary scarps. In the southern segment, a high basement ridge and trough near 5.5°E, 26.25°S run along the topographic axis but are connected to the N60°E boundary scarp which occurs between 25°S and 26°S. Where seismic data are lacking, the linear relief of the Walvis Ridge uplands indicates that the major faults, which form SE-facing boundary scarps along the inner margin, continue southwestward across the Ridge. The two positive basement blocks centered on profile FG have been uplifted along faults of the N25°W set. The basement high to the west appears to be offset right-laterally at 5.75°E, 25.5°S across a fault extending from the N60°E boundary fault between 24.5°S and 25°S. There are no seismic data over the area in which a similarly offset eastern block should be found. However, the observed eastern block appears to be terminated to the north by down-faulting.

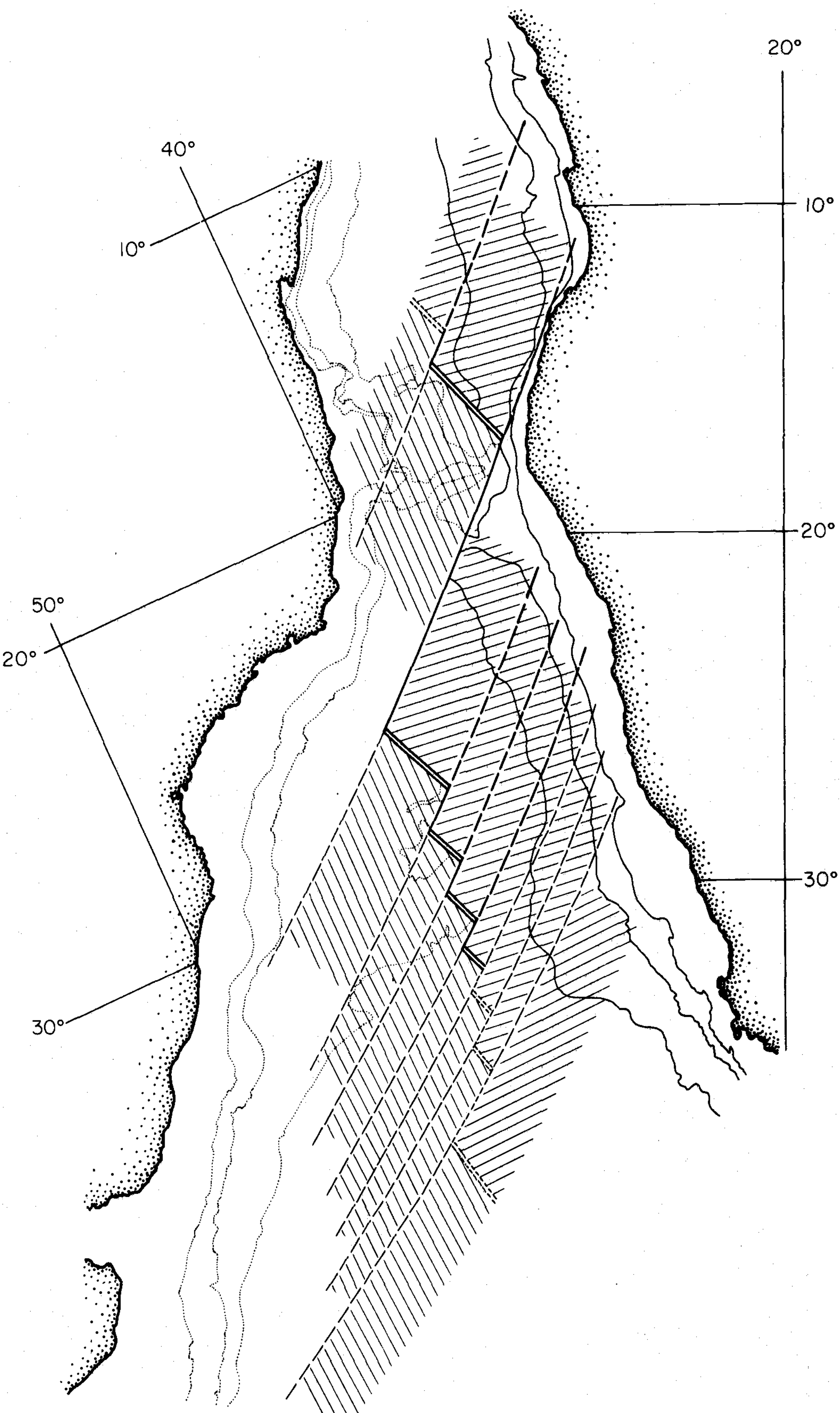
van Andel and Heath (1970) pointed out the existence of numerous normal faults over the eastern flank of the Mid-Atlantic Ridge, which parallel the ridge crest and are nearly orthogonal to intervening fracture zone offsets. The NW-NE orthogonal structure of the Walvis Ridge outside the region affected by the Benguela structures, is strikingly similar to the inherited tectonic fabric of the volcanic layer 2 within a laterally offset, spreading sea floor. The perpendicular faults through the Walvis Ridge suggest a similar origin for its structure.

TECTONIC EVOLUTION OF THE WALVIS RIDGE

I have argued above, using lineations of the Gondwanan zones of weakness as well as an interpretation of magnetic lineations off the Angolan and South West African continental margin, that the initial opening of the South Atlantic occurred about a pole at 5°N, 26°W. The magnetic data suggest that a significant reorientation of spreading direction occurred somewhat before the onset of the Upper Cretaceous interval of uniform magnetic polarity.

The initial spreading direction south of Luanda, Angola, was oriented approximately S25°W along the long transform shear called here the Benguela Fracture Zone. The spreading axis began to reorient after formation of anomaly group B-VII. A little earlier, near the end of B-VI time, the edges of the South America and African continents had become completely separated. The continental blocks must have remained together longest, along the Benguela Fracture Zone since this was the largest initial offset between the two continents. Once the two continents were no longer juxtaposed, the rotational pole moved northward. This suggests that location of the initial pole of rotation for the South Atlantic opening was controlled by the pre-existing structure of Gondwana. Figure 12 shows the configuration of spreading centers and fracture zones at approximately 120 m. y. B. P. in the South Atlantic. It is based on

FIGURE 12 Paleotectonic interpretation of early South Atlantic opening (approximately 120 m. y. B. P.). Seafloor spreading elements based on extrapolation of data from Figure 9A. Ridge crests shown by double solid and dashed lines, transform faults by single heavy lines and short dashed lines. Inactive fracture zones shown by heavy dashed lines and lighter dashed lines. Oceanic crust depicted by diagonal lines. 400, 2000, and 4000 meter contours of South American (stippled lines) and African (solid lines) plates from Uchupi (1971).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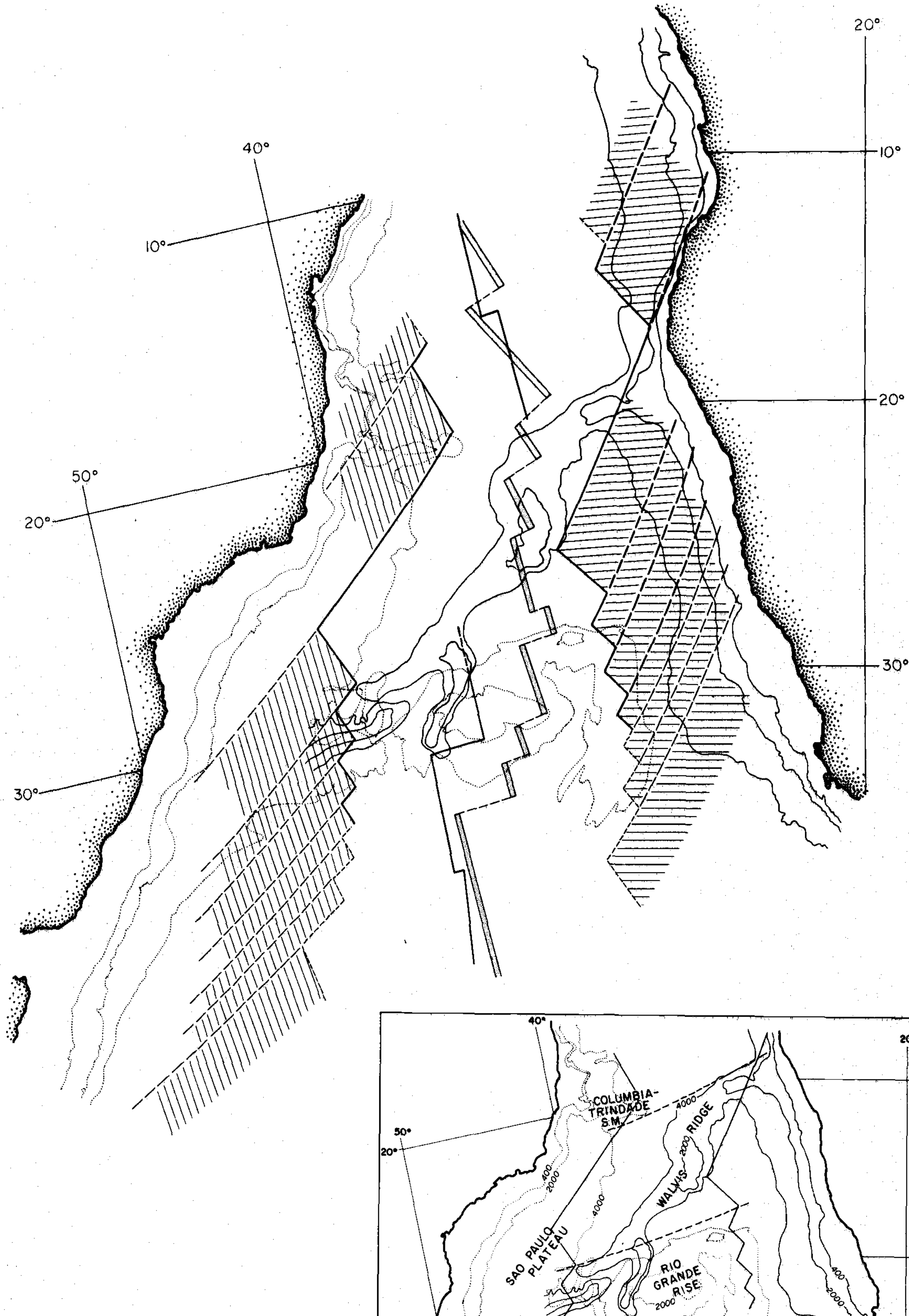
extrapolation of the data in Figure 6 and the rotation of Figure 9A. The reconstruction of Figure 12 shows that the tectonics of the early opening phase of the South Atlantic were dominated by long linear shear elements separated by short rifting segments. Lachenbruch and Thompson (1972) have shown that resistance to shearing may be less than resistance offered to rifting; hence the configuration for the initial spreading phase is quite plausible. Studies of the tectonics of the Gulf of California and the Gulf of Aden, both geologically very young rifted basins, show a very similar pattern of initial separation of continental crust, predominatly along _en echelon_ shears separated by shorter spreading ridge segments.

Figure 13 shows the amount of crust generated by 90 m. y. B. P., beyond the 120 m. y. B. P. plate boundaries. The approximate position of the accreting African plate margin at 90 m. y. B. P. is indicated by the seaward boundary of the Angola and Cape Basin magnetic quiet zones. The position of the spreading center across the latitudes of most of the Walvis Ridge is unknown. The evolutionary relationship of the Walvis Ridge and Rio Grande Rise is shown by overlapping bathymetry of the South American and African plates. The fit of the Walvis Ridge between the EW trending Columbia-Trindade seamount chain along 20°S off Brazil and the Rio Grande Rise to the south is striking. The Columbia-Trindade seamount chain is nearly aligned with the northern boundary of the Walvis

FIGURE 13 Opening of South Atlantic at the end of Upper Cretaceous period of uniform polarity (approximately 90 m. y. B. P.). Position of 90 m. y. plate boundary estimated by seaward boundaries of the Angola and Cape Basin magnetic quiet zone; shown by heavy solid and dashed lines. Grey stippled tone within double solid lines depicts present Mid-Atlantic Ridge crest rotated back to 90 m. y. position (Table 1). Configuration of present ridge crest based on positions of earthquake epicenters (Stover, 1968) and Ladd and others (1973) South Atlantic chart of magnetic anomalies. Pre-120 m. y. oceanic crust from Figure 12. Inset shows 120 m. y. boundaries and small circles about pole at 21.5°N, 14°W.


COLUMBIA-TRINDADE S.M.
WALVIS RIDGE
SAO PAULO PLATEAU
RIO GRANDE RISE

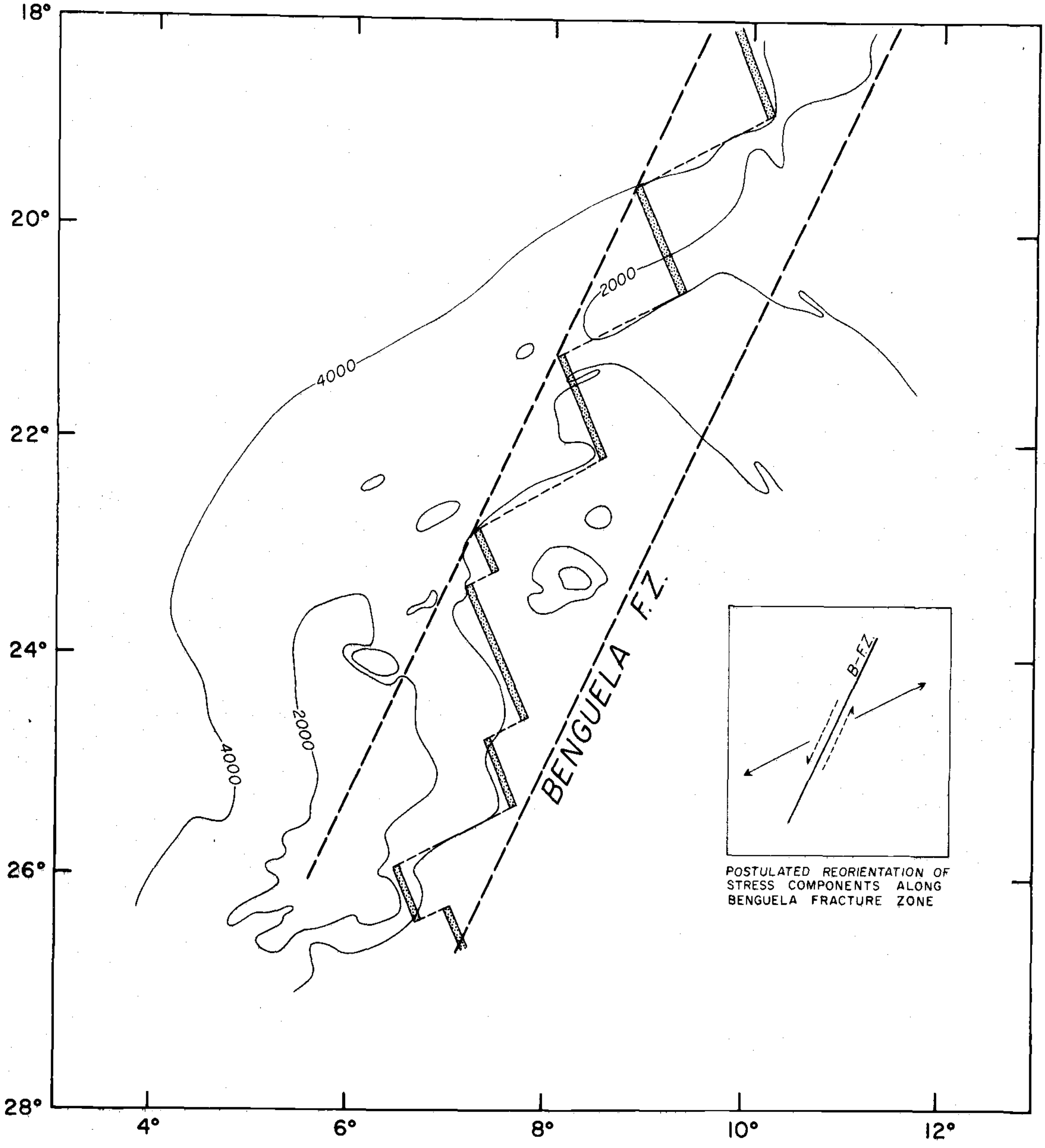
Ridge along a small circle of the rotational pole (21.5°N, 14°W). The northern scarp of the Rio Grande Rise is likewise aligned with the furthest western projection of the Walvis Ridge shown, beyond the point where it splits into two narrow ridge segments. Figure 13 also includes the present configuration of the Mid-Atlantic Ridge crest which has been rotated using the poles and angles shown in Table 1. North of the Walvis Ridge and south of the Rio Grande Rise the present rotated ridge crest is centered near the 90 m.y. B.P. plate boundary. Deviations of the present ridge crest from this plate margin suggests asymmetric spreading or an eastward jump of the spreading centers after 90 m.y. These deviations are discussed in more detail later.

Interpretation of the Walvis Ridge structure suggests that it consists of crustal blocks offset right-laterally along N60°E trending fracture zones which extend through the Ridge and border it to the north and south. The high NW and SE-facing boundary scarps as well as the N60°E striking basement ridges and troughs over the Walvis Ridge uplands may be explained as secondary tectonic features related to vertical movements along en echelon fracture zones. Vertical movements play a significant role in the dynamics of fracture zones (van Andel, 1971), possibly resulting from low density roots of altered mantle material beneath them as suggested by gravity and seismic refraction data for the Mendocino (Dehlinger and others, 1970) and the Rivera Fracture Zones (Gumma, 1973). Since the N60°E faults generally disturb only the basement, uplift of the Walvis Ridge must have occurred very early in its history.

The North Walvis Fracture Zone (Figure 11) along the northern boundary of the Walvis Ridge strikes generally N65°E between 7°E and 11°E, and cuts across the N25°E structures within the Benguela Fracture Zone (Figure 10). This scarp is relatively straight except between 9°E and 10.5°E where its linearity is interrupted by crossing the Benguela zone, suggesting that the Benguela structures formed prior to the N60°E trending faults. Formation of the northern boundary fault then must have required breaking through the older Benguela Fracture Zone. According to Menard and Atwater (1969), a reorientation of the sense postulated here should result in a leaky fracture zone with slow transverse spreading, not in a break through older crust. However, the Ascension Fracture Zone shows a similar anomalous break through older crust (van Andel and others, 1973).

Projection of the boundaries of the Benguela Fracture Zone from the structures between the Walvis Ridge and continental margin to the southwest, shows that the orthogonal boundary scarps of the inner Walvis Ridge margin lie within its breadth (Figure 14). The boundary scarps may thus mark the configuration of the spreading and transform offsets which formed as tension began to rift apart

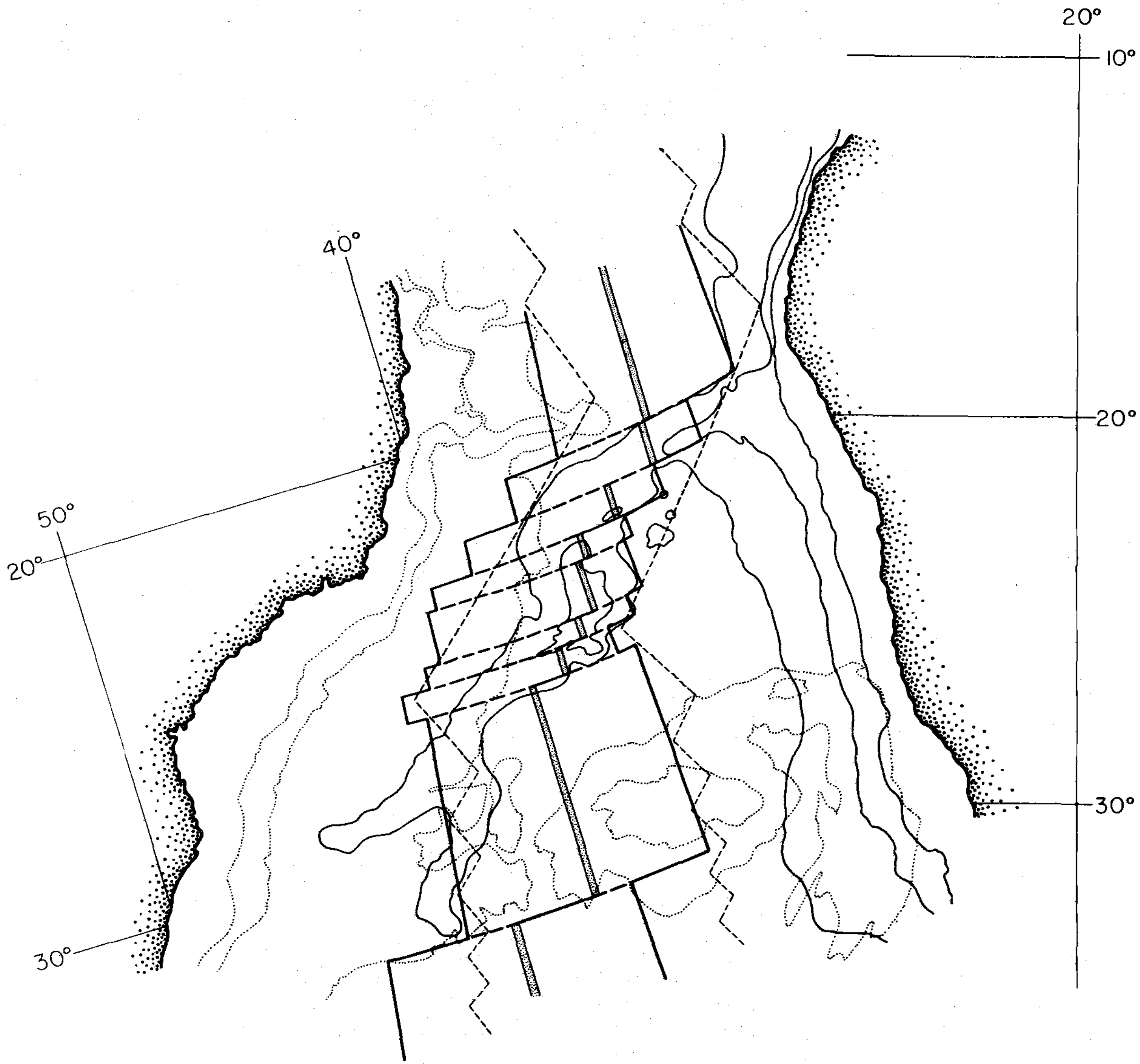
FIGURE 14 Postulated reorientation of short spreading centers within Benguela Fracture Zone during the 120 m. y. spreading reorientation. Benguela Fracture Zone boundaries estimated from width of faulted zone trending N25°E near junction of Walvis Ridge and continental margin, and projected to the southwest. N25°W trending boundary scarps along inner margin of Walvis Ridge interpreted as initial spreading centers. 2000 and 4000 meter contours of Walvis Ridge included for reference. The inset diagram shows reorientation of stress components acting on the Benguela Fracture Zone at the earth's surface.



POSTULATED REORIENTATION OF STRESS COMPONENTS ALONG BENGUELA FRACTURE ZONE the Benguela Fracture Zone during the reorientation. The difference in spreading directions between the Benguela and Walvis Ridge Fracture Zones is 40 degrees. This dramatic reorientation may have precluded a leaky fracture zone from developing along the Benguela Fracture Zone and instead permitted short spreading centers to develop almost immediately.

The model for the tectonic evolution of the Walvis Ridge (Figure 15) hypothesizes asymmetric spreading of the short spreading segments to account for the eastward deviation of the present rotated Mid-Atlantic Ridge crest with respect to the 120 m. y. plate boundaries. The asymmetric spreading is postulated here only for the crust on which the Walvis Ridge is located. Whether the continued eastward deviation of the present ridge crest is related to asymmetric spreading over the Rio Grande Rise or to a jumping ridge crest is not known. The hypothesis of asymmetric spreading over the Walvis Ridge is supported by the continuing proximity of the spreading axes to their initial loci along the Benguela Fracture Zone. The extreme width and length of the offset of the Benguela Fracture Zone may have created a stationary zone of weakness within the lithosphere along which spreading was preferred. Thus the spreading rate for the African plate may have been very slow or close to zero, allowing the spreading axes to remain for some time near this postulated zone of weakness. The

FIGURE 15 Proposed model for tectonic evolution of the Walvis Ridge. Short dashed line shows 120 m. y. plate boundaries separated by 7° opening about pole at 21.5°N, 14.0°W. Heavy solid lines show position of plate boundary after spreading reorientation at 120 m. y. B. P. To the north and south of the Walvis Ridge the new spreading centers have jumped to the west of the original 120 m. y. plate boundary breaking off triangular and jagged crustal blocks which are now part of the African plate. Spreading reorientation across the present Walvis Ridge occurred within the Benguela Fracture Zone (Figure 14). Fractured zones fall along small circles of the rotational pole and coincide with the set of N60°E faults across the Walvis Ridge. Asymmetric spreading postulated for crust over the Walvis Ridge; elsewhere the model assumes symmetric spreading, although this may not be true for crust over Rio Grande Rise. 400, 2000 and 4000 meter contours shown by stippled lines on South American plate and solid lines on African Plate. Bathymetry of Walvis Ridge and Rio Grande Rise continued across plate boundary. Bathymetry from Uchupi (1971) except Walvis Ridge contours taken from Figure 10.



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combination of asymmetric spreading ridge segments and closely spaced transform faults at the margin of this older fracture zone may have permitted deep alteration of underlying mantle, and the formation of a broad low density root. If the elevation of the Walvis Ridge occurred very early in its history as suggested above, then the Ridge must presently be in isostatic compensation.

North and south of the Walvis Ridge, the 90 m. y. plate boundary (Figure 13) is off center to the west with respect to the 120 m. y. boundaries. The linear EW trends of the Columbia-Trindade seamount chain and the continental rise south of the Sao Paulo Plateau both lie within the pre-120 m. y. South American plate in which spreading was oriented much more NE-SW. These observations suggest that during reorientation the spreading center jumped to the west and broke off triangular and jagged blocks of older crust which must now be part of the African plate north and south of the Walvis Ridge (Figure 15). If this is true, then the 90 m. y. plate margin is centered between the older adjusted ridge crests. The trend and location of the 90 m. y. boundary on the African plate north of the Walvis Ridge on Figure 16 conflicts slightly with the magnetic anomaly lineation B-IX in Figure 6. Since correlation of the B-IX anomalies between the CIRCE 8 and Chain 99/4 (Figure 5) is poor, the trend of the adjusted plate margin here is probably more like that shown in Figure 15. The postulated jumps of the spreading centers as well as the formation of short spreading segments within the Benguela Fracture Zone during the first change in spreading direction suggest an instantaneous reorientation of the spreading axes as well as the transform faults.

Additional work is needed to clarify the tectonic relationship between the Walvis Ridge and the Rio Grande Rise. The tectonic model shows that a large section of the Walvis Ridge had been generated before most of the Rio Grande Rise began to form. The evolution proposed here indicates also a more southern path of drift for the Rio Grande Rise than has been previously proposed (LePichon and Hayes, 1971; Francheteau and LePichon, 1972).

Reconstruction of the early South Atlantic (135-120 m. y. B. P.) spreading direction proposed in this paper differs from the model suggested by Francheteau and LePichon (1972). According to them, the trends of equatorial Atlantic fracture zones extrapolated into the West African margin along Ghana and the Ivory Coast, can be fitted to small circles about a pole at 21.5°N, 14.0°W. Rotation about this pole would have occurred between 140 m. y. B. P. and 80 m. y. B. P. According to this paper the initial spreading of the South Atlantic occurred about a pole at 5°N, 26°W between 135 m. y. and 120 m. y. B. P. This apparent conflict between the early spreading directions in the equatorial South Atlantic and the area further south described in this paper, may have arisen from jumps of the Mid-Atlantic Ridge spreading centers during the major reorientation at 120 m. y. B. P. Rotation of the present zone of epicenters along the Mid-Atlantic Ridge crest (McKenzie and Sclater, 1971, Figure 40) back to the Bullard fit of South America against Africa (Bullard and others, 1965) shows deviations from the initial rift along most of its length. Present epicenters lying between the equatorial fracture zones and the Walvis Ridge are placed within South America between 13°S and 20°S (with respect to South America) by this rotation. The tectonic hypothesis of Figure 15 suggests a westward spreading jump in these latitudes during the 120 m. y. reorientation and breaks through older crust of the South American plate by the spreading centers. Thus the positions of present rotated epicenters deviate to the west of the initial rift between 13° and 20°S. A similar rotation of the present equatorial epicenters (McKenzie and Sclater, 1971) places them within Africa near 10°W (with respect to Africa), particularly where the Romanche and Chain fracture zones are projected into the continent by Francheteau and LePichon (1972). The eastward deviation of the epicenters from the initial rift near the Romanche and Chain Fracture Zone projections, suggests that during the 120 m. y. reorientation, the spreading centers may have jumped to the east, and that these fractures broke through the older sea floor lineations produced by opening parallel to the Pan-African zones of weakness. This is supported by the abrupt change in direction at the eastern end of the Romanche Fracture Zone trend where it parallels the continental margin along a steep escarpment called the Ivory Coast-Ghana Ridge (Arens, and others, 1971). The Ivory Coast-Ghana Ridge emerges from the continental margin near Accra where the Buem-Togo Thrust zone intersects the margin (Grant, 1969). This thrust zone is of Pan-African age and generally parallels the Pan-African offsets of the continental margin to the south. The eastern terminus of the Ivory Coast-Ghana Ridge has the same strike as that of the onshore Buem-Togo Thrust Zone and may be a structural remnant of the initial opening between South America and Africa whose direction of spreading was controlled by the Pan-African structures.

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