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Morphology, Limits, Origin, and Age of Salt Layer along South Atlantic African Margin[1]

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Abstract—The west African continental margin between Abidjan (Ivory Coast) and Walvis Bay (Southwest Africa) was surveyed in 1971 by the R/V *Jean Charcot*. Fifty-eight seismic-reflection (flexotir source), bathymetric (3.5 and 12 kc), gravimetric, and magnetic profiles were obtained. The seaward limit of an evaporitic zone outlined during the survey is at the boundary between continental slope and continental rise. Variation of depth of this limit as a function of latitude shows the presence of a large offset at 11°S which seems to be related to an east-east-southeast line of magnetic seamounts cutting into the continental slope. The Annobon-Cameroun volcanic axis separates the salt zones of the Nigerian basin and Congo-Angola basin. The northern limit of salt deposition in the Congo-Angola basin is marked near 1°N by a strong southwest-northeast magnetic trend. On the south it extends to near 14°S. The Walvis Ridge, located farther south, does not seem to have an effect on evaporite deposition.—

Introduction

In 1971, the R/V *Jean Charcot* made a reconnaissance survey (cruise Walda) of the west African continental margin from Walvis Bay to Abidjan. Two main objectives were pursued: (1) mapping the seaward extension of the salt structures known on land; and (2) investigation of possible landward extensions of ocean fracture zones. This paper deals only with the first objective.

Fifty-eight profiles were obtained from Abidjan to Walvis Bay across the African margin. Seismic reflections (flexotir seismic source), bathymetry (3.5 and 12 kc), gravity (Graf-Askania), and magnetics (Geometrics) were recorded continuously along the profiles. Thirty-five refraction profiles were made using sonobuoys (Fig. 1).

A first paper (Mascle *et al.*, 1973) has reported diapiric structures found off the Niger delta. This paper will deal mostly with the salt zone south of the Annobon-Cameroun volcanic axis. Gravity, magnetics, seismic-refraction data, and other results of the Walda cruise will be presented in subsequent papers.

Land Sedimentary Basins

Between Abidjan (Ivory Coast) and Mocamedes (Angola) the African cratonic block is bordered by a succession of coastal sedimentary basins. The extension and stratigraphy of this sedimentary zone are well described in various publications including "Salt Basins around Africa" (Inst. Petroleum, London, 1965), "Bassins sedimentaires du littoral africain" (Reyre, 1966), and "The geology of the east Atlantic continental margin" (Delaney, 1971).

The generally narrow (5–20 km) coastal zone locally broadens and contains basins that are exceptionally 100–500 km wide. The basins (Fig. 1) appear to be essentially continuous from north Gabon to south Angola through the basins of Gabon, Congo, Cuanza, and Mocamedes (Reyre, 1966).

Sedimentary units in these coastal basins commonly are discordant over the old African basement. The section is essentially Cretaceous and Tertiary. It can be divided into three main lithostratigraphic units (Reyre, 1966): a lower unit with continental or lacustrine affinities best developed in the northern part; a middle unit with evaporitic facies; and an upper unit predominantly of marine and littoral origin that is thickest in the southern part. The lower unit lies on basement and is Neocomian to Aptian in age (140–110 m.y.). The evaporitic deposits of the middle unit accumulated during Aptian and part of Albian time. In the Aptian salt sequence, halite, carnallite, some anhydrite, and many potassic or magnesitic salt

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interbeds (Reyre, 1966) are found. The upper unit is late Albian.

Thickness and stratigraphic position of the evaporitic series differ from place to place. In Gabon, for example, 2,000 m of salt was drilled in the central basin domes and 1,000 m in other areas. In Angola, the evaporitic series is more varied having sequences that include evaporites, marine series with evaporites, and lacustrine deposits. The thickness is everywhere more than 1,000 m.

Salt tectonism seems to start when the sedimentary overload is more than 600 m (Nettleton, 1934). In the lower Congo, for example, a salt layer is well developed but deformations are few because the overburden is thin, or perhaps because the limits of the evaporitic basin are close. Salt presence is marked by salt migration and consequent creation of anticlinal structures and domes.

In general, the salt layer thins or even disappears in the intermediate synclines which commonly are the sites of collapsed structures. In northern Gabon near the Annobon-Cameroun volcanic axis, and in southern Angola in the region of Mocamedes, the evaporitic series thins and contains only gypsum and anhydrite. Both are denser than halite and therefore less subject to deformation.

The present depth of the salt deposits, about 3 km in the Cuanza basin, indicates that a major change, most probably linked to the opening of the South Atlantic, has taken place. A continental flexure (Bourcart, 1950) has produced since the Cretaceous an inland progression of the ocean of more than 150 km, involving a downward vertical movement of 3 km over a zone 300–600 km long (Reyre, 1966).

Continental Margin Off West Africa

Between the Annobon-Cameroun volcanic axis and the Walvis-southern Angola ridge, extension of diapiric structures over the shelf has been brought to light previously by workers such as Belmonte *et al.* (1965) in Gabon.

Baumgartner and van Andel (1971) discovered basement highs and diapirs over the shelf and continental slope off Angola. They interpreted these highs as extensions of the Cuanza basin highs and suggested that the diapiric evolution of the continental margin is analogous to that of the Cuanza basin. In the same region, Von Herzen *et al.* (1972) showed two seismic profiles and heat-flow measurements in good relation with the presence of salt structures.

Leyden *et al.* (1972) presented a series of seismic reflection and refraction profiles over the Angola shelf. Structures outlined and seismic velocities suggest the presence of a salt layer. The seaward limit of this layer corresponds to a sudden break of topographic slope.

Mascle *et al.* (1973) showed that diapiric structures exist over the Nigerian continental slope, although no such structures exist on land. According to these authors, the salt zone is interrupted but not limited by the Annobon-Cameroun volcanic axis.

The *Charcot* data provide additional information about the characteristics of diapiric structures off west Africa, their geographic extension and their relation to the general structural framework.

Diapiric Structures

Evaporitic layers (Braunstein and O'Brien, 1968) are easily recognized on seismic reflection profiles by their undulating structures and their subhorizontal floor (Fig. 2).

Three principal structural types can be outlined (Fig. 3): (1) salt anticlines or undulations of the roof with little or no deformation of the bottom of the salt layer (Fig. 3A); (2) diapirs or salt intrusions (Fig. 3B) caused by the flow of the salt layer, its local concentration, and its piercing of the overlying beds with or without deformation of the surface topography; and (3) salt-injected faults (Fig. 3C) caused by the upward migration of salt along preexisting or induced faults.

In Figure 3, the floor and roof of the salt layer are indicated. Thickness of the salt layer and resulting structures was estimated using a sound velocity of 4 km/sec for the evaporites.

Salt thickness, in the diapir zone measured with the roof of the adjoining syncline as a base line, averages 2–3 km. In a few places, it reaches 4–5 km, but the salt layer in the neighboring syncline has disappeared almost completely. Widths of these domes, measured between neighboring synclinal axes, range from 4 to 10 km. As in domes on land, thickness-to-width ratios are between 2 and 3, and in very few places are 1. For example in Figure 3B, the width is 8 km and the height 3.8 km with a ratio of 2.1. In the undulation zone, thickness averages 2–3 km, with a slight decrease toward the northern and southern limits of the basin. The height-to-width ratio is more than 4, and width of the same order as for diapirs. For example, in Figure 3A the width is 3–4 km, the height 0.4 km and the ratio 7.5–10.

In a process of continuous evolution from undulation to domes, the wavelength of the undulations is preserved, as shown by Trusheim (1960) in northern Germany. This wavelength depends on the characteristics of the sediments but does not change as undulations change into diapirs and domes. In the present case, the typical wavelength observed for undulations is 4.5 km, but for diapirs or domes it is 9 km. This can be explained either by differences in the characteristics of the salt layers off west Africa and in north Germany, or by the fact that large diapirs include two successive undulations, thus doubling the wavelength.

Thickness of the beds overlying the evaporitic undulations, estimated with a sound velocity of 2 km/sec, averages 1 km, with a minimum of 700 m and a maximum of 1,800 m. These thicknesses agree with the value of 600 m given by Nettleton (1934) as the minimum thickness necessary to start diapirism.

Geographic Extension of Salt Layer

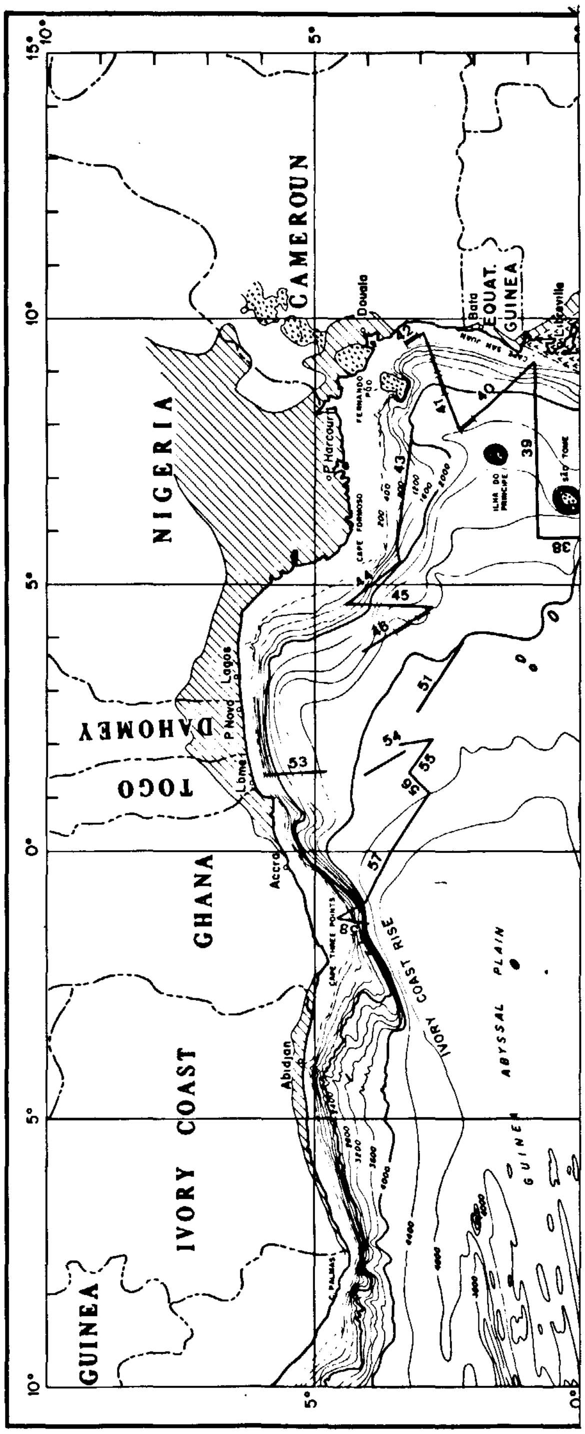
Three types of salt structures described in the preceding section (Fig. 3) have been reported along our profiles. Their distribution in the coastal basins is shown in Figure 4. We describe here the extension of the salt layer from south to north with greater emphasis on the northern and southern limits.

ESE-WNW seismic profile 16 (Figs. 1, 5, 6) at the latitude of Mocamedes (15°S) does not show any diapiric structures. The first diapirs appear on profiles 18 and 19 (Figs. 1, 5, 7) at 13° 30′S lat., 70 km from the Angolan coast between Benguela and Mocamedes (Fig. 8). The westward limit keeps a north-south direction as far as 11°S lat., although the coastline bends between Benguela and Luanda. Between 10° 30′S and 11°S, a sudden change toward the west (Fig. 4) corresponds to what Von Herzen *et al.* (1972) considered as the southern limit of the salt layers (they had no other data from the south).

At the latitude of Luanda, the salt zone reaches its largest width of 300 km (Fig. 9).

Farther north, the western limit of the salt layer is subparallel with the coastline, becoming gradually closer to it. South of the Congo delta at 5° 30′S, the limit is 120 km away from the coastline and matches the limit proposed by Leyden *et al.* (1972).

The northern limit is more difficult to determine because the continental slope is steeper, and structures are less numerous. Two diapir-like structures appear on profile 39 (Fig. 1), one accompanied by a large negative magnetic



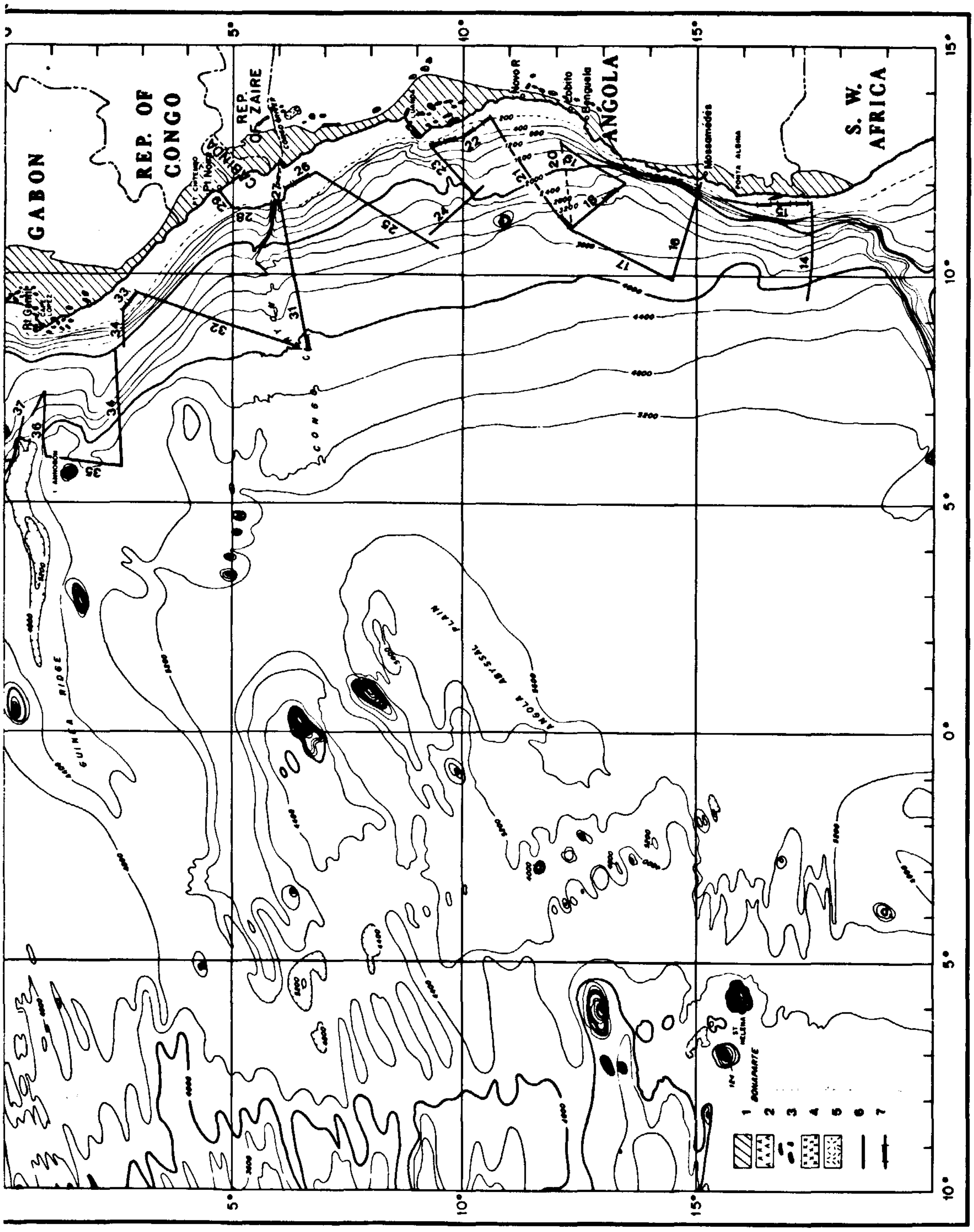


FIG. 1—Outline of African coast sedimentary basins between Angola and Ivory Coast and track of R/V *Jean Charcot* Walda cruise: *1*, sedimentary basins; *2*, northern limit of evaporitic facies (from Reyre, 1966); *3*, salt domes; *4*, Annobon-Cameroun volcanic axis; *5*, post-tectonic acidic intrusions; *6*, seismic reflection profiles; *7*, sonobuoy locations.

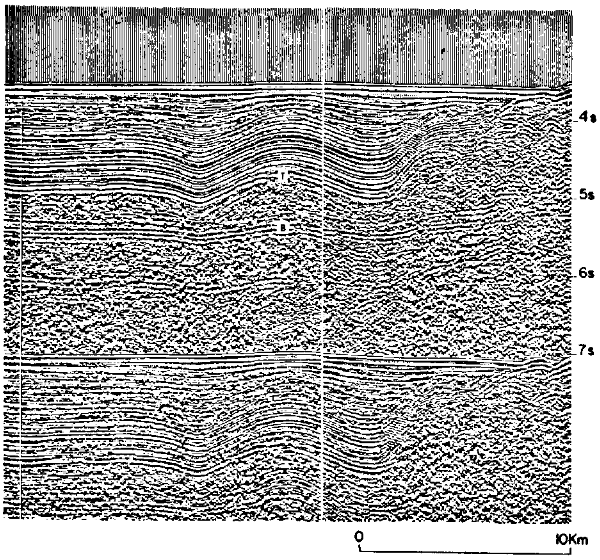


FIG. 2—Undulate structures from western Mediterranean Sea: *T*, roof of salt layer; *B*, floor of salt layer.

anomaly. The same magnetic anomaly appears on profile 40 (Fig. 1) but with no visible diapiric structures. The cause of that anomaly thus is probably not related to the structures of profile 39. We suggest that the undulating structures of the slope on profile 39 are salt structures. Similar structures seem to exist also on the adjoining shelf. On profile 40, no undulations are visible on the slope, which is quite abrupt there. Only some features on the continental shelf are visible. On profiles 41 and 42 (Fig. 1) between Cameroun and Fernando Po, no structures can be seen.

In conclusion, the northern limit of the salt zone seems to reach 1°N lat. over the continental margin. This limit is slightly farther north than the narrowing of the evaporitic zone south of Douala as presented by Reyre (1966).

In general, diapiric structures are displayed clearly in seismic profiles over the continental slope, with the most characteristic ones between 1,300 and 1,800 m. On the shelf and at the top of the slope, multiple echoes (reverberations) make the identification of diapirs more ambiguous. No typical diapiric structures are visible in water shallower than 1,000 m according to Von Herzen *et al.* (1972). However, from our profiles, evaporites from the continental slope reach the littoral of Gabon and extend into the coastal basin of Cuanza. We believe, therefore, that the evaporitic layer is continuous although not always easily recognized between the coastal basins and the lower continental slope from 1°N to 14°S.

Salt anticlines and undulations are present in the eastern part of the coastal basins (Gabon, Congo, and Cuanza). A zone of injected faults lies along the littoral or the shelf. They seem to correspond to horst-type basement highs (Cabo Lebo, Lambarene, *etc.*).

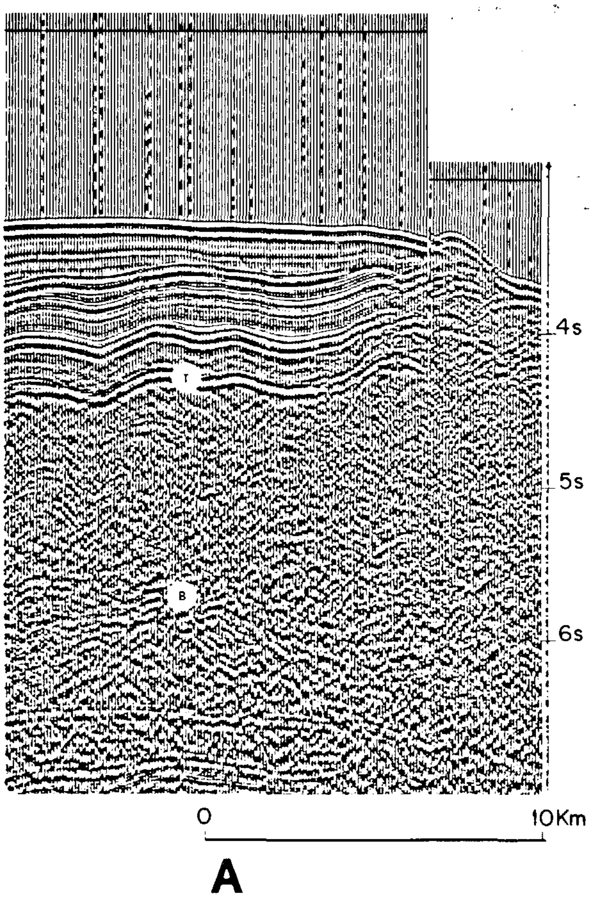
In the Gulf of Guinea, northwest of the Annobon-Cameroun volcanic axis, no evaporites are reported in coastal basins (McCurry, 1971). Our profiles 43–45 (Fig. 1), however, show diapirs with characteristics similar to the ones described in this paper (Figs. 5, 10). The salt zone therefore is probably not limited by the Annobon-Cameroun axis. The problem of the continuity of the salt zone from the Gulf of Guinea to the south equatorial zone is discussed by Mascle *et al.* (1973). Here again (profile 45), the deepest limit of the salt zone corresponds to a sudden change in bathymetry near 3,100 m. The salt-zone limit in Figure 4 was traced by using a similar break of slope on other profiles as a criterion. On the east, diapirs are found along profile 43, and the limit of the salt zone is quite near the Annobon-Cameroun axis.

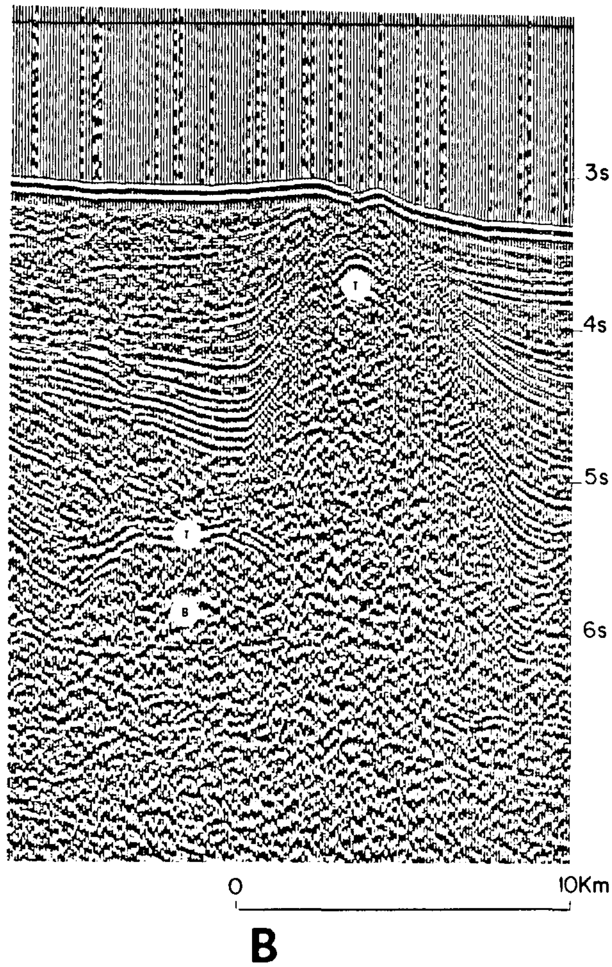
Relation of Salt Limit with Bathymetry

In general, there seems to be a relation between the seaward limit of the salt zone and a break of topographic slope (Fig. 11). The depth of this break ranges from 2,250 to 4,000 m. This break is the only one observed on the profiles and seems to correspond to the transition from the continental slope to the continental rise.

Figure 12 shows the depth of the westward extension of the salt zone as a function of latitude. From Mocamedes (15°S) to 11°S, the depth is less than 3,000 m. At 11°S a sudden deepening of more than 1,000 m parallels the change of direction of the limit. Toward the north, the limit becomes shallower as far as 1° N, where the salt disappears suddenly. The deepest limit on profile 32 is at the latitude of the Congo delta.

We shall examine in greater detail some of the western limits of the salt zone. On profile 18 (Fig. 7), the southernmost one showing diapiric structures, the contact between the continental slope and the continental rise is marked by a basement high (A). On our profiles 10–21, on *Circe* 8 (Baumgartner and van Andel, 1971), there is also a basement high associated with magnetic anomalies. At the latitude of the east-west swing (11°S) of the salt limit along *Chain* 99/4 profile, the basement high emerges





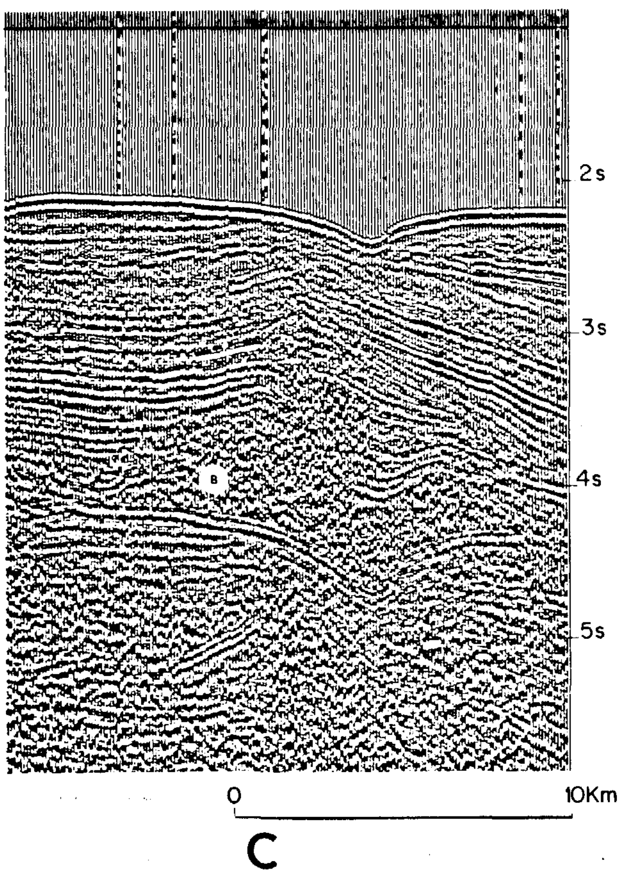


FIG. 3—Three types of salt structures: *A*, salt anticlines (*X* on Fig. 5); *B*, diapirs (*U* on Fig. 5); *C*, salt-injected fault (*V* on Fig. 5); with *T*, roof of salt layer, *B*, floor of salt layer.

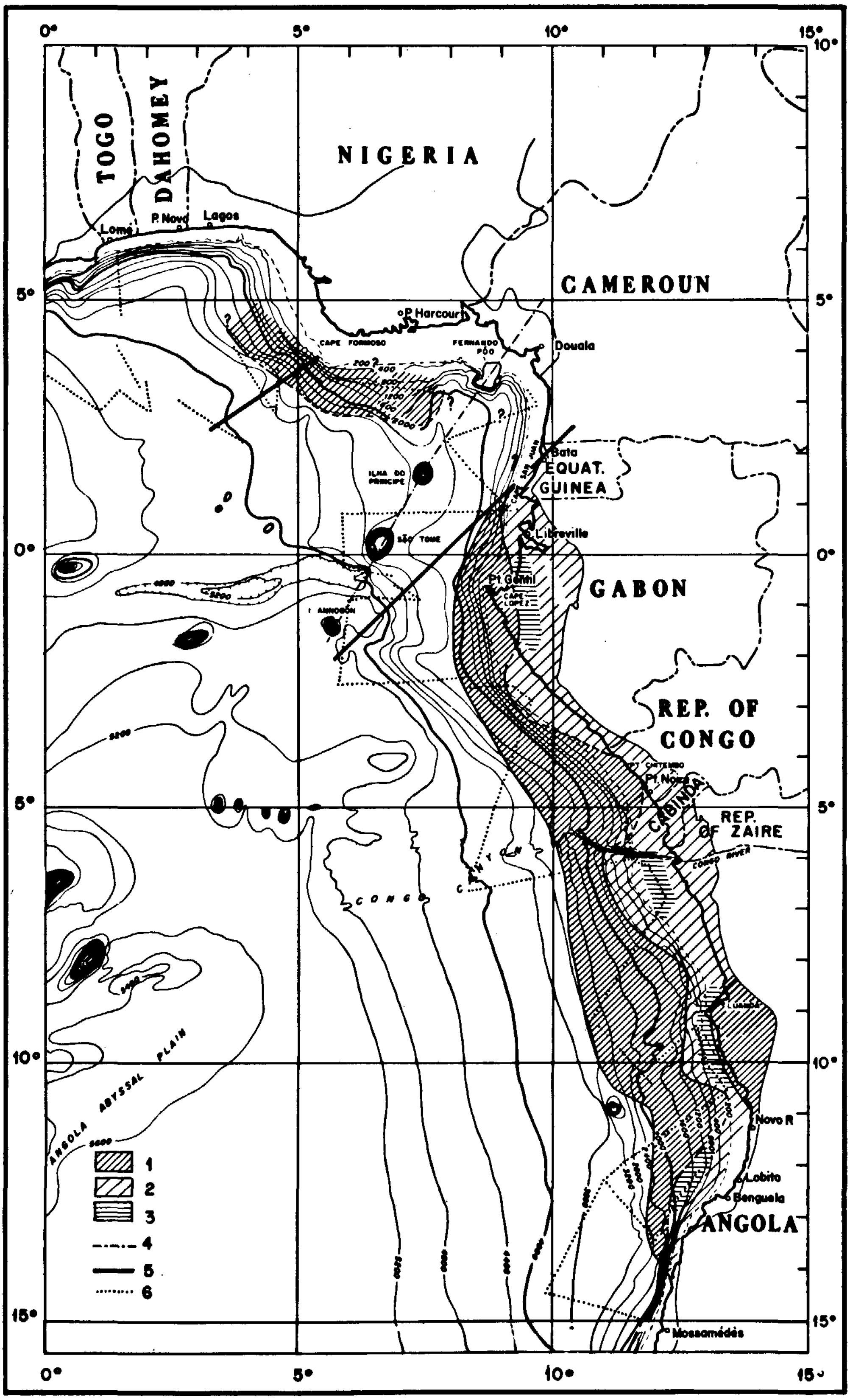


FIG. 4—Geographic extension of salt layer: *1*, zone of diapirs; *2*, zone of undulations; *3*, zone of salt-injected faults; *4*, Annobon-Cameroun volcanic axis; *5*, structural trends after our profiles; *6*, seismic reflection profiles.

from the abyssal plain and does not seem to form the limit of the salt zone.

North of 11°S, from profile 25 (Fig. 9), the contact between the continental slope and the continental rise clearly limits the diapiric zone on the west. It is not accompanied by any intrusive or basement high. No magnetic anomaly is present. The same can be observed on *Chain* profiles 99/3 and *Circe* 9 (Baumgartner and van Andel, 1971; Von Herzen *et al.*, 1972; Leyden *et al.*, 1972).

Magnetic Data

Magnetic anomalies might reveal whether evaporites have been deposited on a continental basement that later subsided, or on the oceanic basement of the initial rift.

Only the main characteristics of the magnetic anomalies (Dickson *et al.*, 1968) are discussed herein. Detailed magnetic and other geophysical profiles will be presented in a later study (Renard *et al.*, in prep.).

From Van Andel and Moore (1970), Mascle and Phillips (1972), and from our profiles, there is no clear relation between the salt limit and a change in the magnetic anomalies. The anomalies found at the foot of the continental slope (Figs. 7, 8, 10) seem to be related to oceanic basement highs shown on Figure 13. Profile 25 (Fig. 9), where no basement high is present, shows no anomalies at the foot of the continental slope. On the Angola continental slope, anomalies have large amplitudes and high frequencies of oceanic character, but with no apparent linear trends, and they probably are related to intrusions.

Between the Congo and the Annobon-Cameroun axis, the low amplitude and frequency of magnetic anomalies on the rise are probably due to the absence of shallow magnetic sources.

Two main magnetic trends extend from ocean depth to the shelf. One intersects the Nigerian salt zone (Fig. 4). The other borders the Annobon-São Tomé line on the southeast and seems to limit the Gabon-Angola salt zone on the north. Because they cut the shelf around Bata, their relation to fracture zones is probable (Burke, 1969).

Discussion

From the relation between seismic reflectors and bathymetry, the western limit of the salt zone is near the slope change at the contact of the continental rise and slope. From seismic reflection data, no basement ridge is apparent.

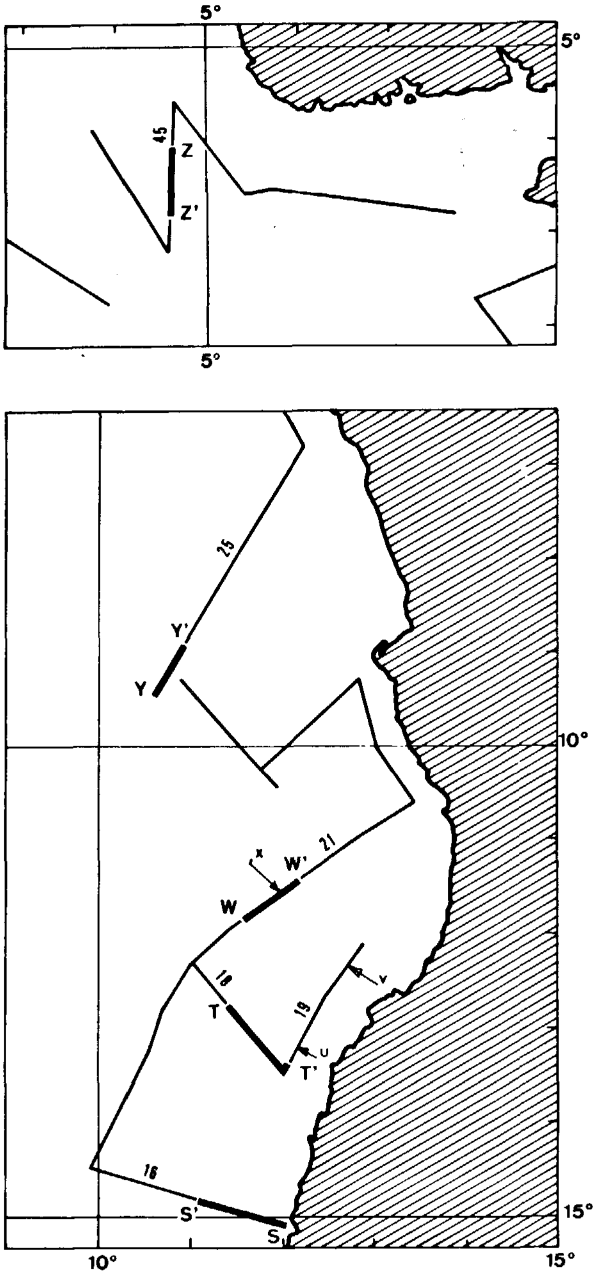


FIG. 5—Position of seismic sections mentioned in text and shown as figures.

Oceanic basement highs, 10–20 mi seaward, accompanied by strong magnetic anomalies outlined on Figures 7 and 10, are followed by a plunging of the oceanic basement toward the foot of the continental rise with a thickening of the sedimentary section. However, profile 25 (Fig. 9) does not show such a basement high nor any magnetic anomaly, whereas the *Circe* 9 profile exhibits a strong magnetic anomaly with no apparent basement high (Baumgartner and van Andel, 1971).

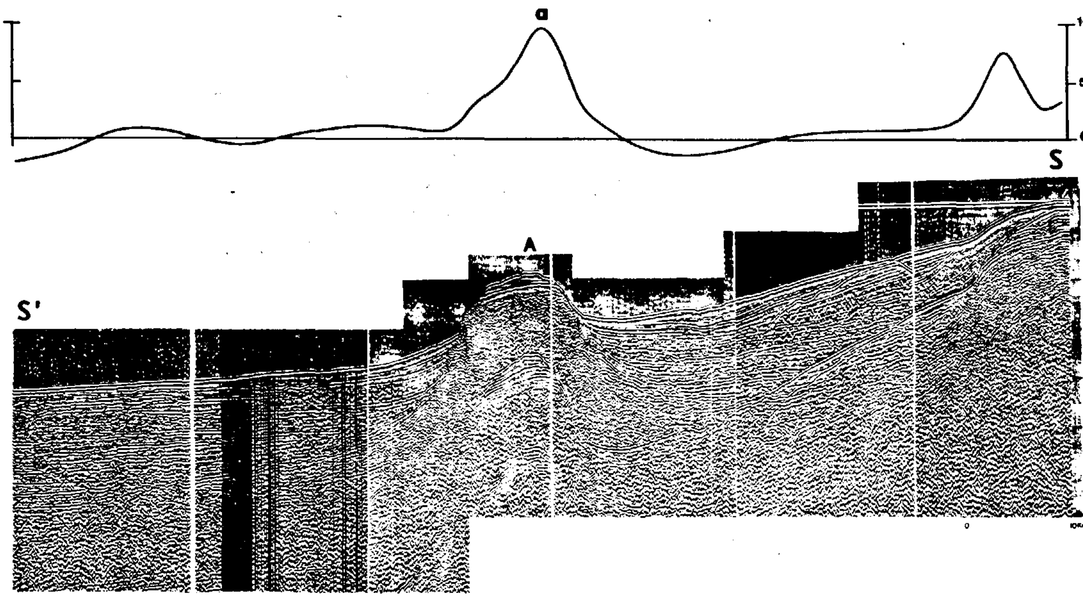


FIG. 6—S-S' section of Walda profile 16 (Fig. 5) showing seamount (*A*) which is highly magnetic and has no visible salt structure.

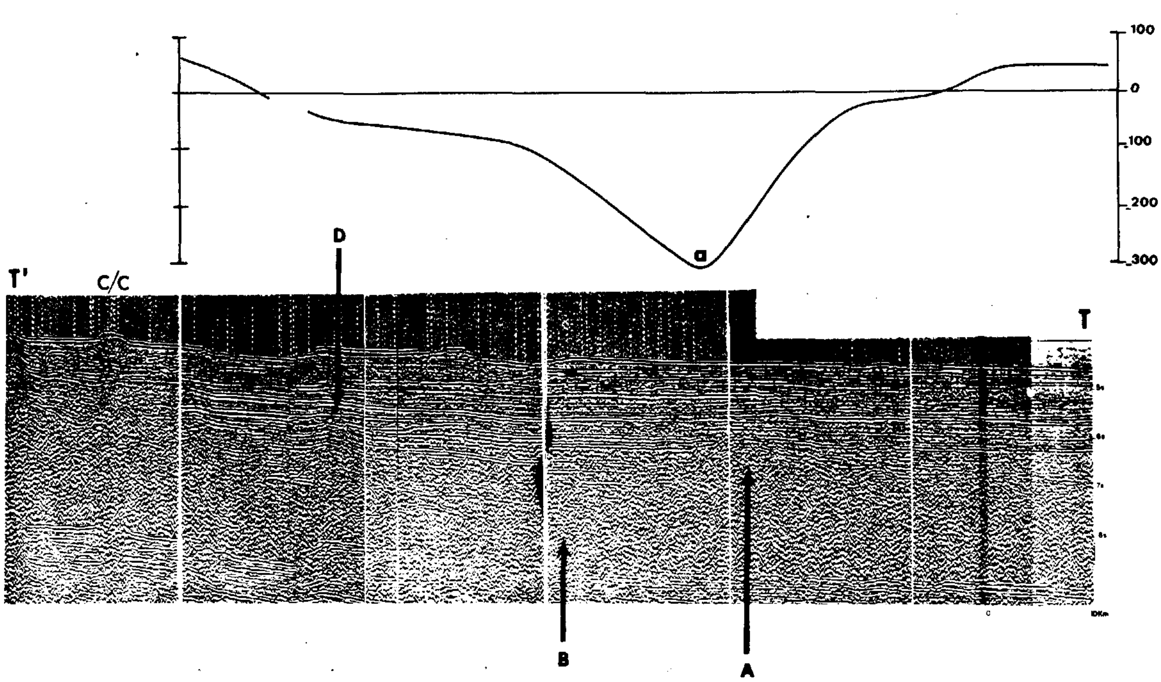


FIG. 7—T-T' section of Walda profile 18 (Fig. 5) showing southernmost diapiric structures. Rise of oceanic basement (*A*) marked by negative magnetic anomaly (*a*) of 300 γ is followed by its deepening under 3.5 sec of sediments (*B*). *D* is diapiric feature.

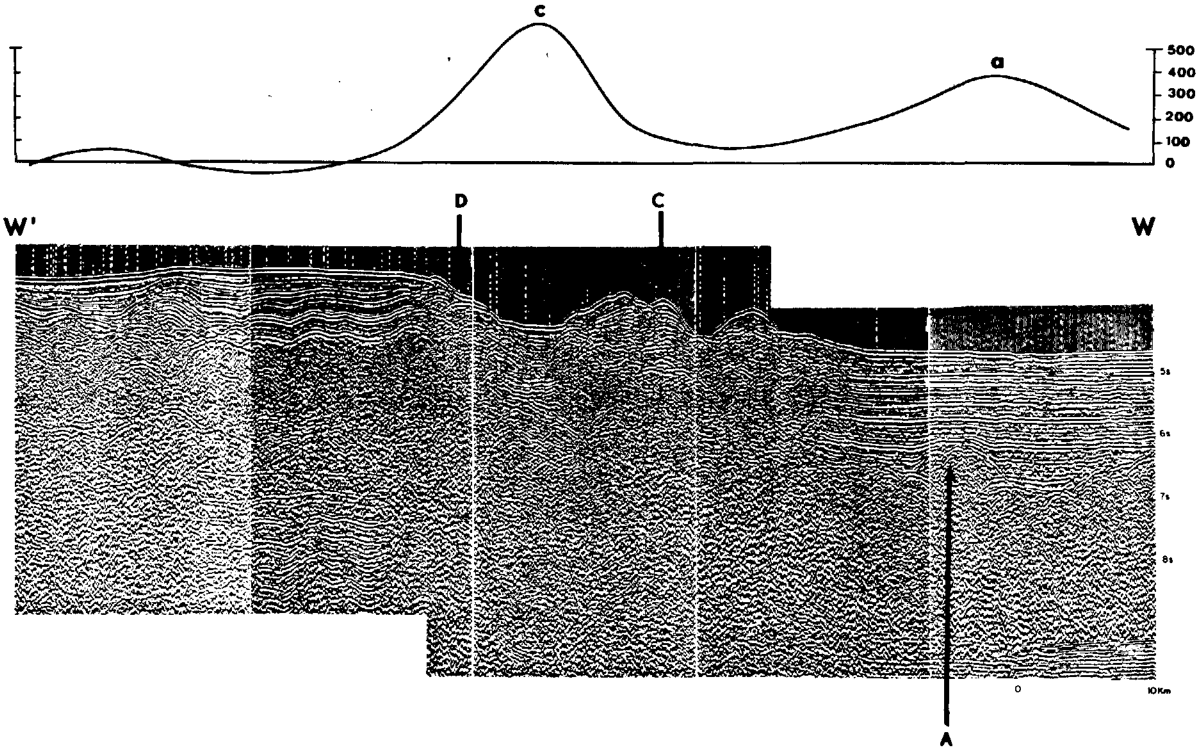


FIG. 8—W-W′ section of profile 21 (Fig. 5) showing presence of hills (*C*) between diapirs (*D*) and abyssal plain. Strong magnetic anomaly seems to be related to passage from these hills to diapirs. Slight oceanic basement rise (*A*) is west of these hills in abyssal plain accompanied by magnetic anomaly (*a*).

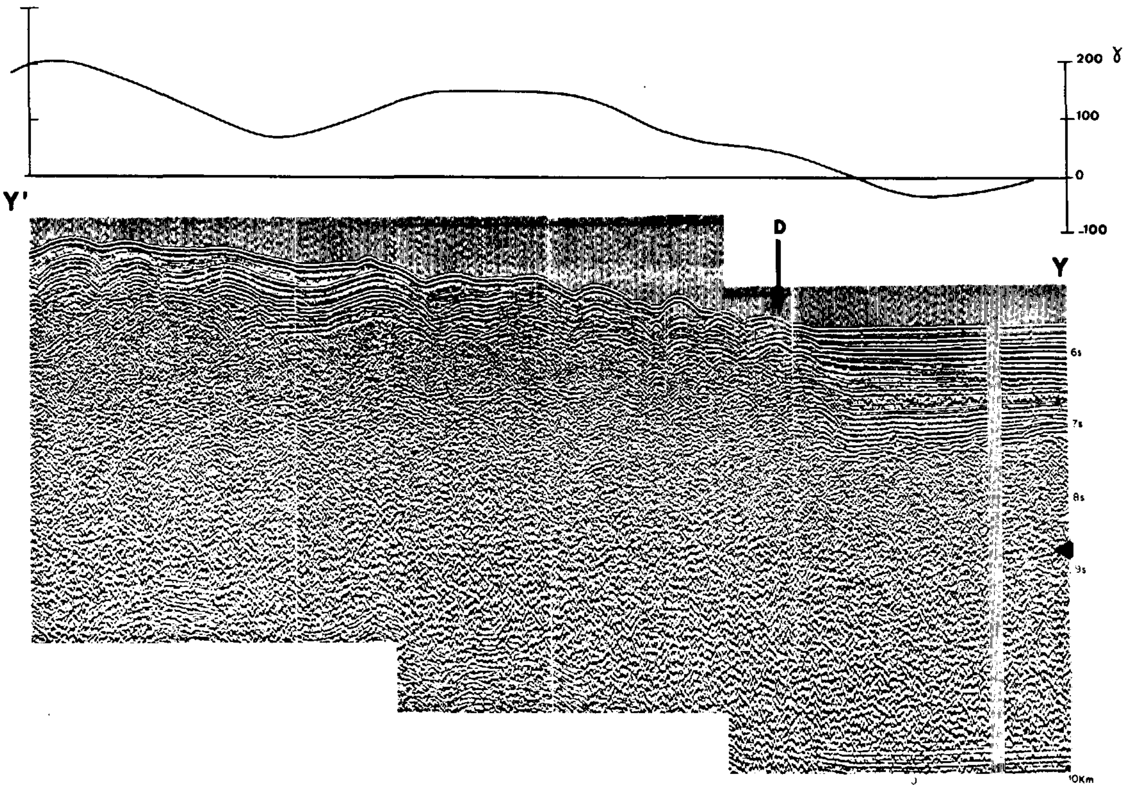


FIG. 9—Y-Y′ section of Walda profile 25 (Fig. 5) showing contact between diapiric structures (*D*) and abyssal plain. As opposed to other profiles, oceanic basement is rather smooth with no magnetic anomalies.

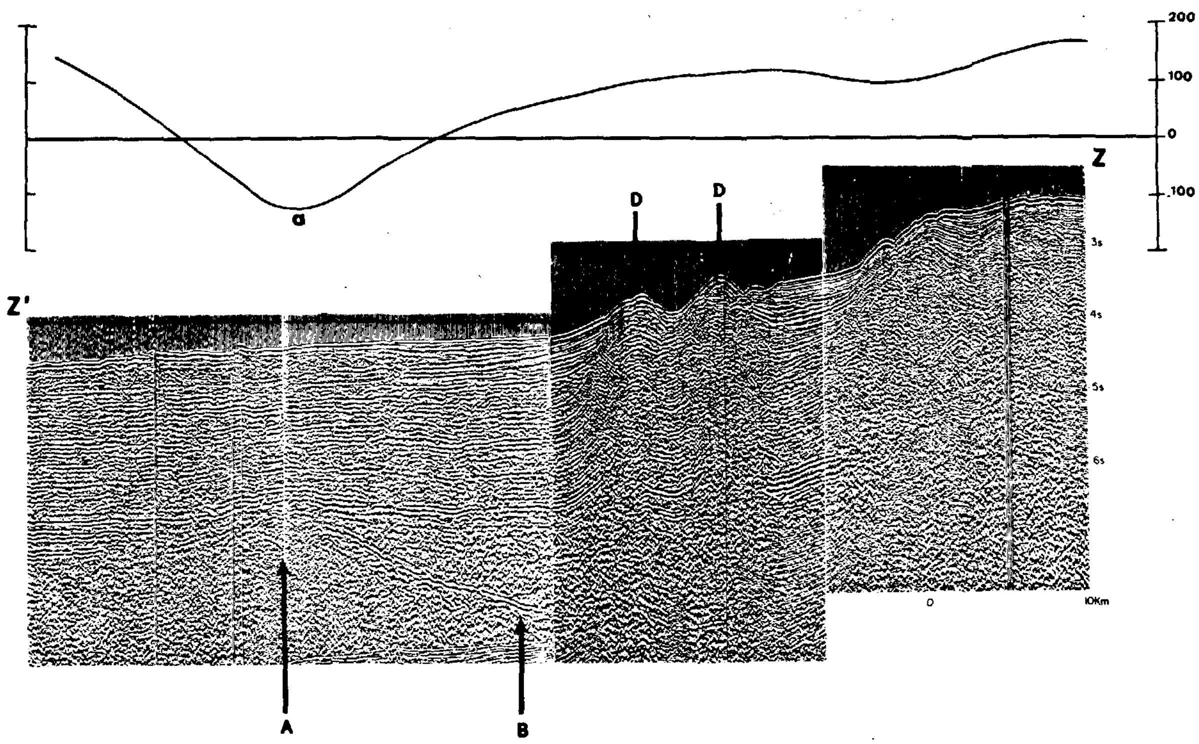


FIG. 10—Z-Z′ section of Walda profile 45 showing southern limit of diapiric structures in Gulf of Guinea (Fig. 5). Limit corresponds to change of slope at bottom of continental slope. Rise in oceanic basement (*A*) marked by negative magnetic anomaly (*a*) is followed by its deepening (*B*) under 4 sec of sediments at base of continental slope.

Other magnetic anomalies seem to relate to the 11°S-seamount trend and to intrusions along the continental margin. This seamount trend offsets the salt limit (Fig. 13) and acted as a sedimentary barrier between deposition north and south of 11°S. This east–east-southeast trend seems to continue inland along the Nova Redondo–Nova Lisboa direction, where many acidic ring intrusions, kimberlites, and carbonatites are present. These intrusions were emplaced between Wealdian and Albian time (UNESCO-ASGA, 1963).

The positive isostatic gravimetric trend A, outlined by Rabinowitz (1972) north of 13.5°S lat., and associated with the scarp between the continental rise and the abyssal plain, is in good parallelism with the salt limit. On our profiles 25, 18, and 19, however, no gravimetric high is observed above the salt limit.

From these data, no clearly apparent barrier limits the salt westward.

Analogy between the Gabon-Angola and Niger salt zones also indicates the presence of oceanic layer under the salt. Indeed, the Niger salt zone is a post-opening feature, as can be seen from a pre-opening fit of the continents (Bullard *et al.*, 1965; Smith and Hallam, 1970), and therefore salt lies over an oceanic basement as in the Red Sea (Pautot *et al.*, 1970; Allan and Morelli, 1970; Lowell and Genik, 1972).

The salt deposition along the African continental slope probably is related to the opening of the South Atlantic Ocean. Francheteau and Le Pichon (1972) constructed a model of the principal features of the opening. Transform directions linked to the first opening phase match quite satisfactorily with the structure of the African continental margin. However, the details of the paths and speeds of early relative motion between Africa and South America are not known precisely.

Coastal basins would have been created by the subsidence of the newly created oceanic basin (Bott, 1971). Subsidence could be linked to thermal evolution of the lithospheric plate under the oceanic crust. Cooling of this crust would increase density and thus create subsidence (Sheridan, 1969; Sleep, 1971).

If one examines the rotation pole postulated by Francheteau and Le Pichon (1972), one finds that the South American margin zones homologous to the west African salt zone limits are south of the Santos area (Brazil) and north of Salvador (Brazil). The homologous zone of the northern limit of the Niger delta salt zone is the Natal region south of the Fernando de Noronha Archipelago.

The salt is not older than Early Cretaceous if a constant spreading velocity is used. Maxwell *et al.* (1970) reported results from *Glomar Challenger* drillings that indicate opening rates compatible with an Early Cretaceous (Valanginian, 130 m.y.) separation of Africa from South America. Thickness uniformity of the salt layer across the continental rise, however, suggests that a period of relative stability existed after an initial phase of opening. If this is true, the salt could be older.

Conclusion

The equatorial and south equatorial African salt zone is continuous from coastal basins to the continental rise.

The salt zone exhibits different types of structures (undulations, diapirs, or injected faults) but seems to be continuous from Gabon to south Angola. Its western limit corresponds to the transition from continental rise to abyssal plain except at 11°S, where it is offset to the east along a zone of seamounts trending east–east-southeast. Its northern limit is near 1°N, and is marked by a strong southwest-northeast magnetic trend cutting the shelf in the vicinity of Bata (equatorial Guinea). Its southern limit is near 14°S, well north of the Walvis Ridge which apparently is not related to the salt zone.

Offshore of Nigeria, another salt zone with similar characteristics is present. This zone is separated from the southern occurrence by the Annobon-Cameroun axis. The two zones do not seem ever to have been continuous.

The origin of the salt zone relates to the opening of the South Atlantic (Le Pichon and Hayes, 1971) and the evolution of the continental margin (Summerhayes *et al.*, 1971). It probably has been deposited in place. The age of the salt is probably Mesozoic.

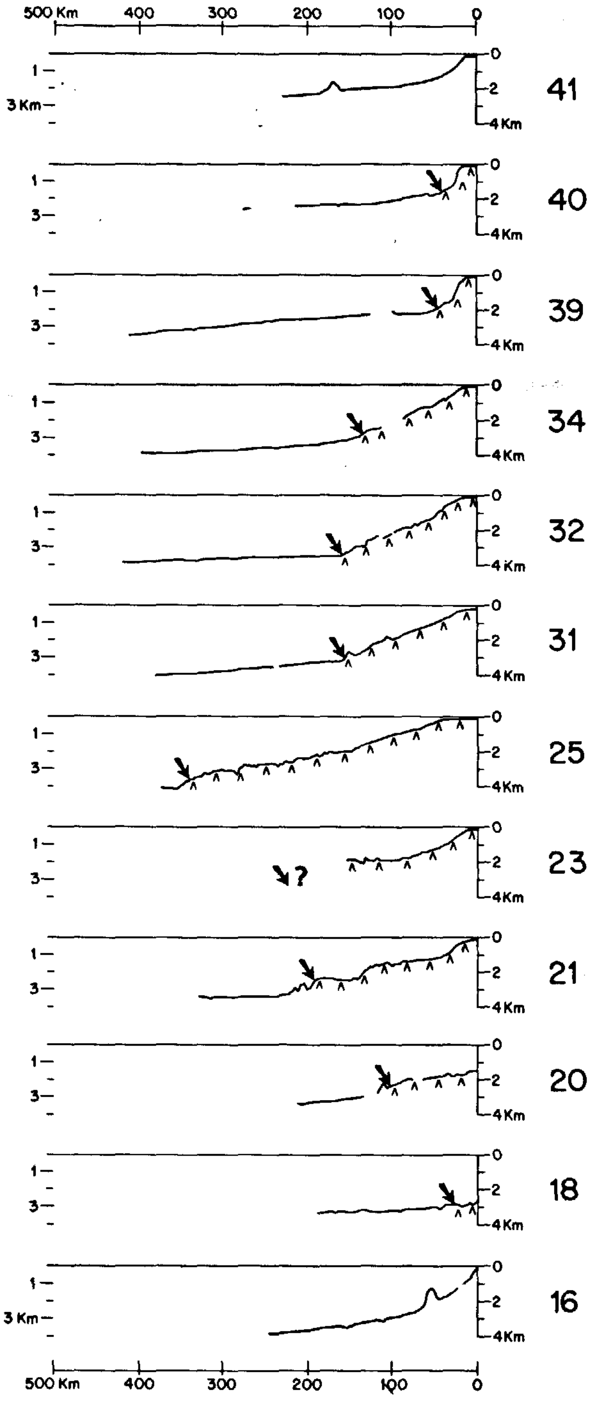


Fig. 11—Arrow marks western limit of diapiric structures along bathymetric profiles. Profiles have been projected perpendicular to track and numbered (see Fig. 1).

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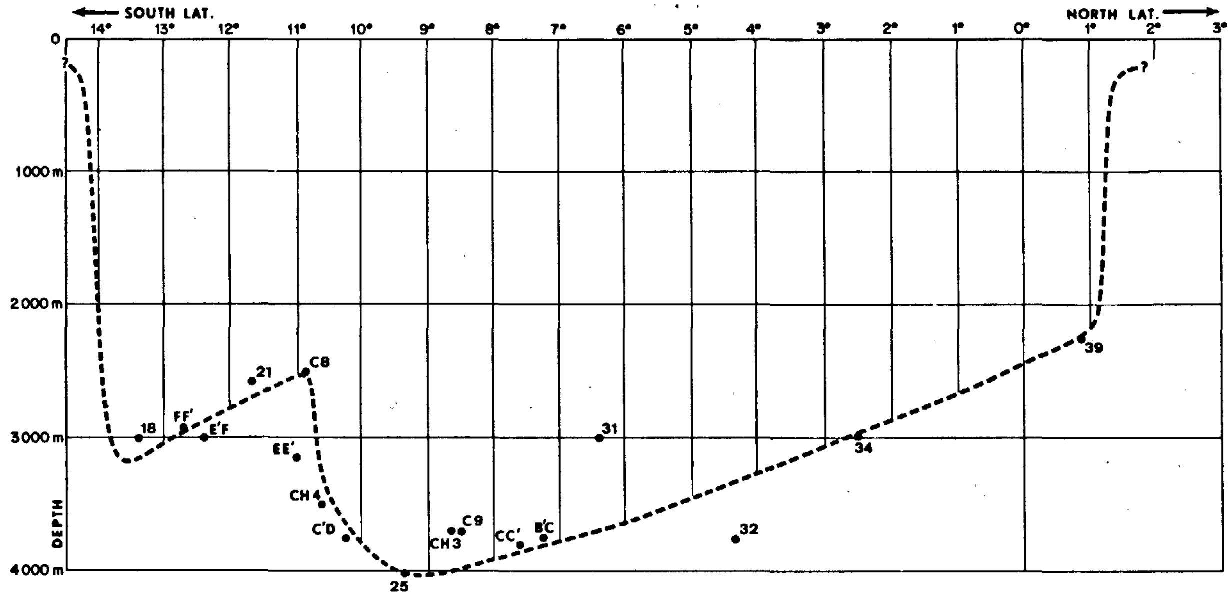

FIG. 12—Water depth of western extension of diapiric structures as function of latitude: 18, *etc.* . . . , Walda profiles; B'-C, C-C', E-E', E'-F, F-F', *Vema* and *Conrad* profiles (Leyden *et al.*, 1972); CH 3, CH 4, *Chain* profiles 99/3, and 99/4 (Von Herzen *et al.*, 1972); C 8, C 9, *Circe* profiles 8, 9 (Baumgartner *et al.*, 1971).

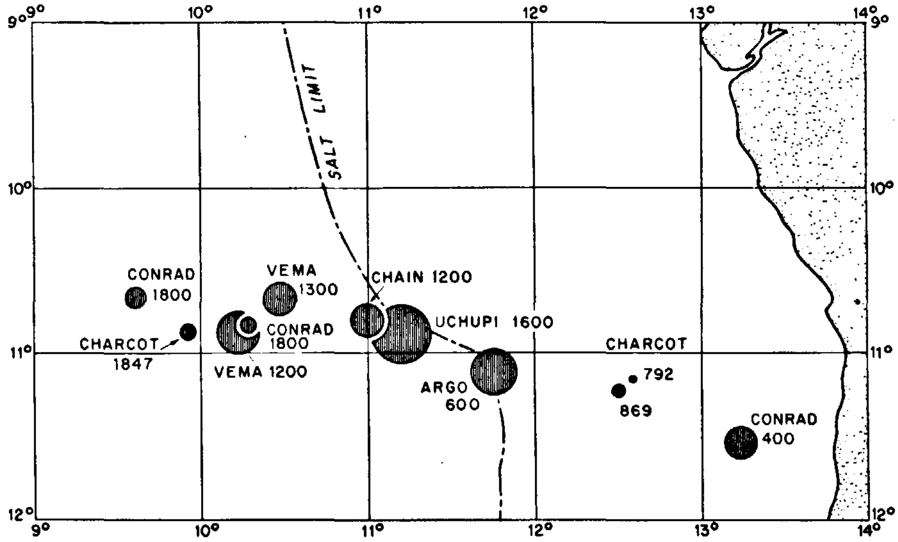

FIG. 13—Salt limit and east-west alignment of seamounts at 11°S. Radius of circle is proportional to relative elevation of seamount above mean surrounding topography. Numbers give approximate depths of seamounts in fathoms.

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