Art. N° 342
Contribution COB N° 388

Submarine Niger Delta: Structural Framework+

by

JEAN MASCLE ++

ABSTRACT

– Numerous data obtained during recent marine geophysical surveys have been compiled together in order to present the structural framework of Niger Delta and adjacent areas. Seismic reflection results show that the delta slope is characterized by intense diapiric deformations and that the overall structure of the delta is fairly comparable to the structures of the Gulf Coast province margin or of Angolan margin. Seismics as well as gravity and magnetic measurements indicate the existence in the vicinity of the Niger delta of two oceanic trends apparently related to an early phase of opening of the South Atlantic. Both trends can tentatively be correlated on land with the major structures known in the southern and northern Benue trough. A comparion between the whole area (Niger Delta and Benue trough) and another intracratonic chain — the Pyrenees mountains — is briefly discussed. –

INTRODUCTION

THE Niger delta, the most important Cenozoïc deltaïc construction in the South Atlantic, lies in the Gulf of Guinea to the southwest of a relatively narrow (∽ 300 km wide), long (∽ 1000 km long) and quasi-linear Cretaceous sedimentary depression of the African craton known as the Benue trough (figure 1) (Cratchley and Jones 1965; Reyment 1965).

Although there has been considerable debate concerning the origin of this intracontinental trough, alternatively interpreted as a simple continental graben (Farrington 1952), a Ridge-Ridge-Fault triple-junction (McKenzie and Morgan 1969; Grant 1971) or the failed arm of a Cretaceous active Ridge-Ridge-Ridge triple junction (Burke and Whiteman 1973; Burke *et al.* 1971 1972), it is generally agreed that the present-day Niger delta itself is built on oceanic crust. Supporting arguments come from the precontinental drift reconstruction (Carey 1959; Stoneley 1966) (which indicated an important overlap of northeastern Brazil on the present Niger delta) and from a series of geological and geophysical observations such as the presence beneath the Niger delta of a series of linear, subdued and alternatively positive and negative magnetic anomalies interpreted as seafloor spreading lineations (Burke *et al.* 1971).

Although several papers have dealt with the geology and structures of both areas (Niger delta and Benue trough), including those of Cratchley and Jones (1965), Frankl and Cordry (1967), Short and Stauble (1967), Hospers (1965-1971), Reyment (1965-1972) little is known of the submarine geology of the Niger delta, with exceptions of some data concerning the continental shelf morphology, sedimentation and possible Cenozoïc structural evolution (Allen 1964, 1965; Burke 1972; Merki 1972) and some isolated seismic lines obtained across the delta continental margin (Mascle *et al.* 1973; Delteil *et al.* 1974; Emery *et al.* in press).

In the past few years, in addition to numerous but up to now confidential oil industry results, several marine geophysical surveys, including continuous seismic profiling, magnetic, gravity and bathymetric measurements as well as unreversed oblique reflection-refraction profiles, were made in this area especially by American and French Institutions. Among them Géoguinée cruise (1969, CEPM), Walda cruise (1971, CNEXO-COB), Benin cruise (1971, IPG-CEPM), Vema and R. Conrad cruise and Atlantis II IDOE continental margin cruise (respectively Lamont Doherty Geological Observatory and Woods Hole Oceanographic Institution).

I have used the available data with the already published results in several composite maps (figures 3, 5, 7, 12, 13, 15). These maps are the support of the description of the overall geology and structure of the area. The relationship of the Niger delta with the Benue trough and the adjacent deep oceanic seafloor is also discussed.

Bathymetry

Sounding track lines indicated on figure 2 have been used together with additional data obtained from the general bathymetric chart of the oceans (GEBCO) plotting sheets to contour the bathymetric map of figure 3. The interpretation between sounding data has been made on the basis of the U.S. geodetic chart H. B. 2202.

On the map of figure 3 the large advance of the continental shelf in the delta area is obvious. Two relatively well developed submarine fans, West and South of the delta, separated by a complex area of continental slope (Southwest of Cape Formoso) are the important features of the delta submarine topography. The morphology

+ Contribution no. 388 of the Departement Scientifique, Centre Oceanologique de Bretagne.
++ Centre National de la Recherche Scientifique presently at COB, B. P. 377, 29273 Brest, France.

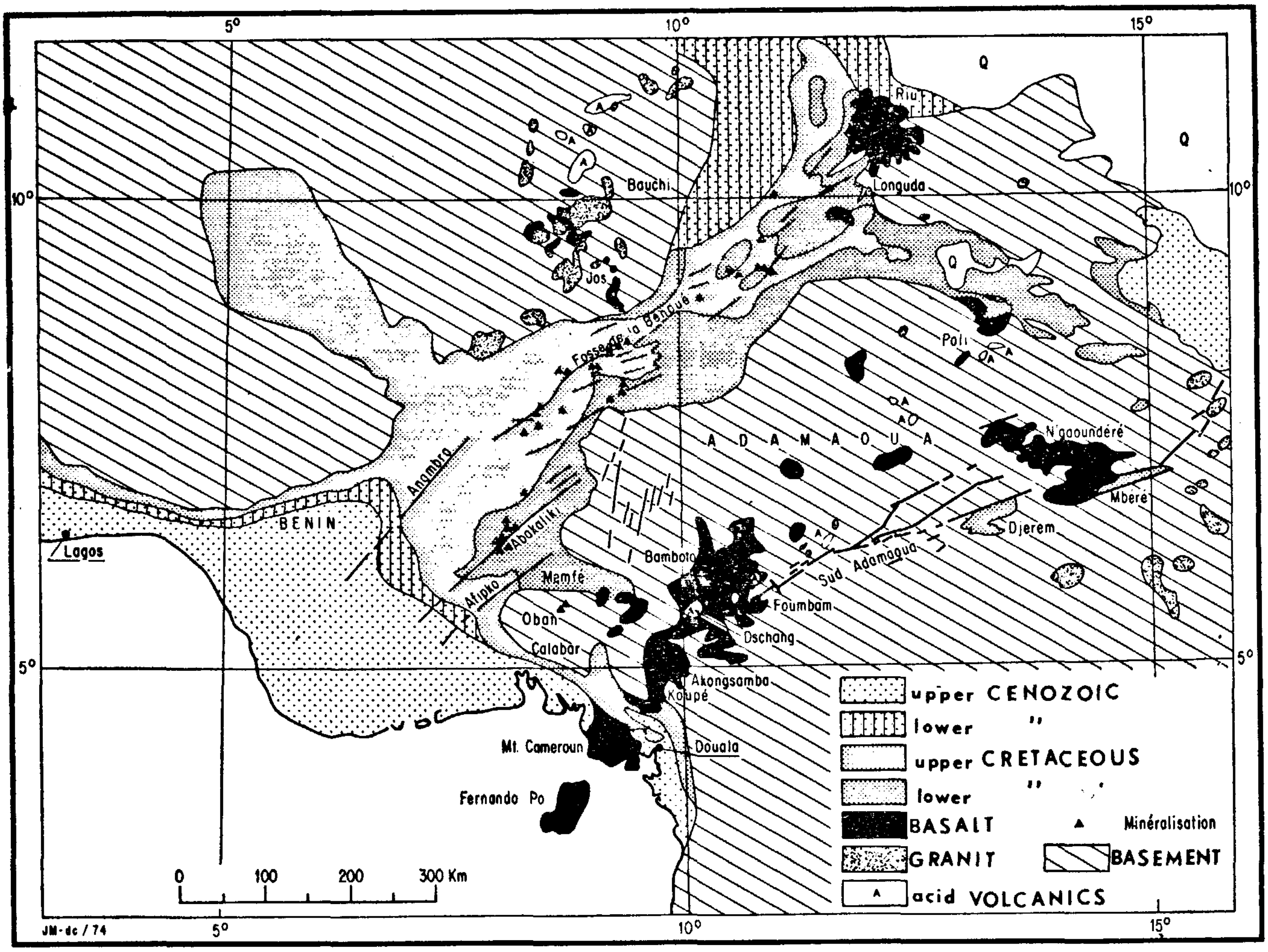

Figure 1. Schematic geological map of Niger delta and adjacent areas simplified from geological map of Africa (ASGA-UNESCO, 1963) and Le Marechal and Vincent (1972). Note the general southwesterly trend of the Benue trough, of the Adamawa massif and of the south Adamawa Cretaceous basins and mylonitic zones (Le Marechal and Vincent 1972).

of the continental shelf (75 km-wide south of the Calabar area but only 30 km wide south of Lagos) was studied in detail by Allen (1964, 1965). He describes small topographic features including terraces, small rises and ridges, shallow valleys which he relates to the late Quaternary geological history. Others, but less frequent, features are linear and smooth escarpments and pinacle-like structures, particlarly Southwest of Cape Formoso. Numerous submarine canyons cut across the continental slope. Burke (1972) has proposed that the submarine fans were fed by the three most important of them, the Avon, Mahin and Calabar canyons.

Two major scarps characterize the continental slope (figure 9). The upper one near the 1000 m isobath is fairly smooth; a lower one, more abrupt and accidented by numerous second-order topographic features, faces the continental rise in a manner similar to the Sigsbee scarp at the base of the Gulf Coast margin (Emery 1969) or the Angolan escarpment (Emery *et al.* in press) bordering the Angolan margin. All along the slope, but particularly southwest of Cape Formoso, there are frequent dome-shaped features, 200 m high, on the average (but reaching locally 400 m) with a basal width of about 10 km.

The surface of the continental rise, although much more subdued, is locally incised by deep sea channels probably related to the main submarine canyons as has been shown to be the case for the deep submarine Congo canyon (Heezen *et al.* 1964; Shepard and Ewing 1973). Southwest of the delta there are several seamounts rising from the abyssal plain. They seem to line up along a southwesterly trend which is slightly different from the Gulf of Guinea volcanic island trend as previously given by Merki (1972). One of these, 400 m high above the surrounding sea floor, was discovered during one of the recent cruises (Atlantis II, leg 87).

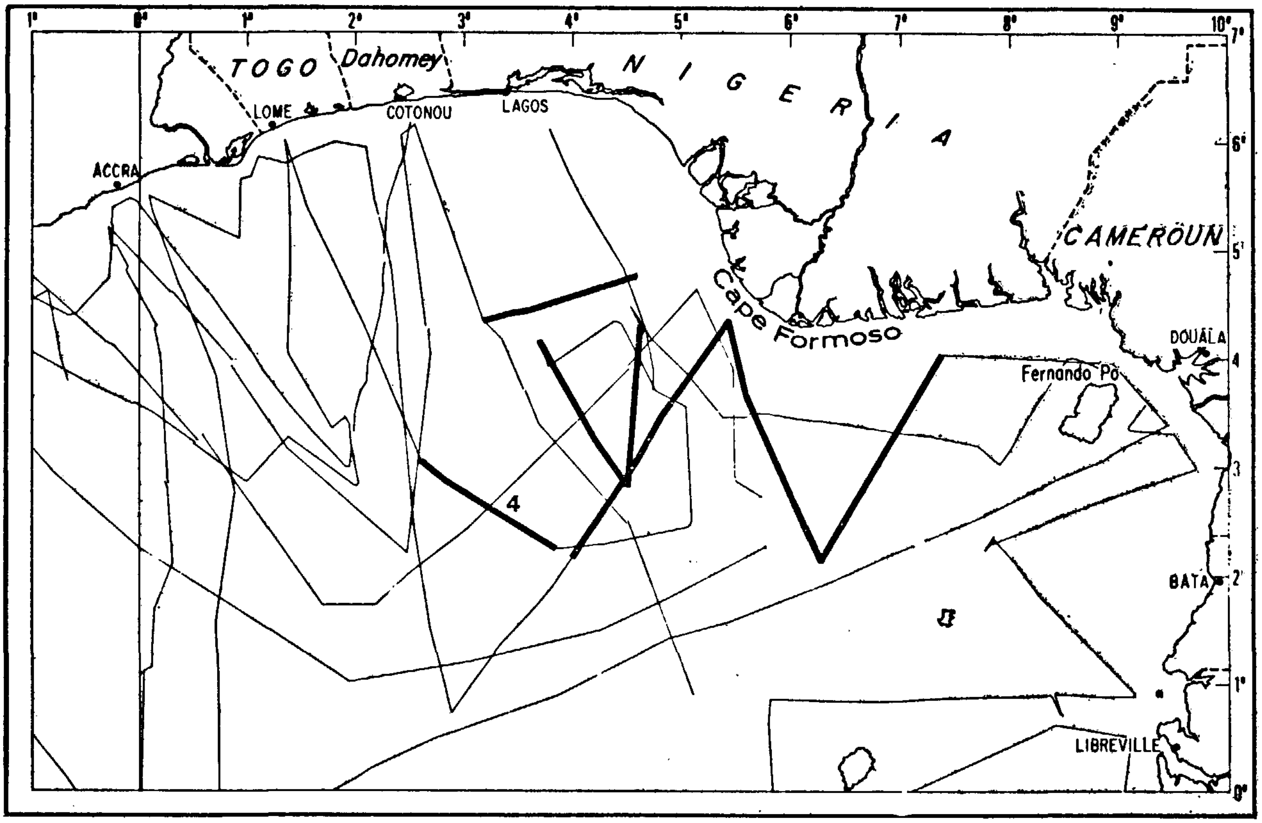

Figure 2. Index map of the area surveyed. Heavy lines show seismic reflection profiles illustrated in this paper. Number 4 indicates the profile of figure 4.

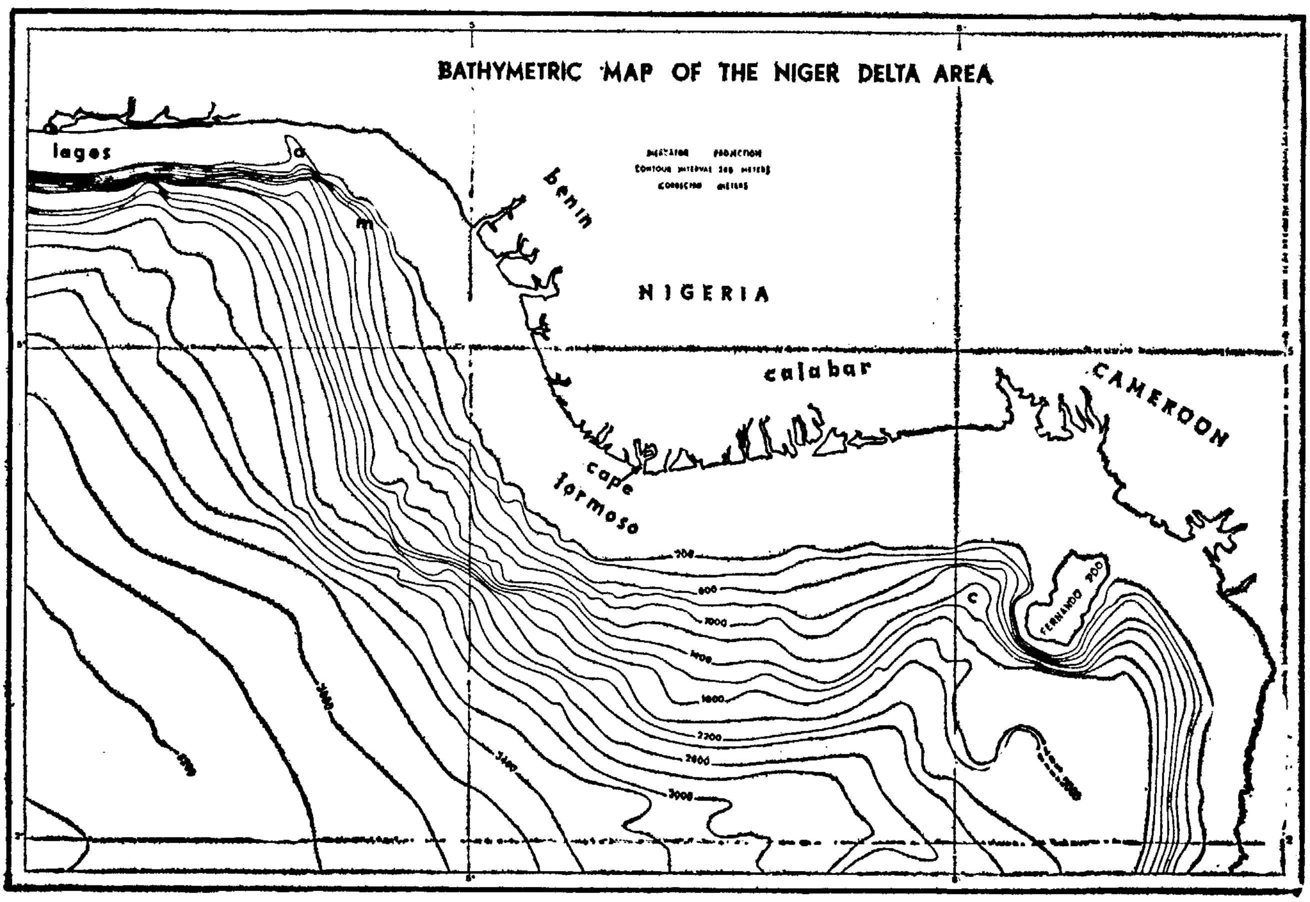

Figure 3. Bathymetric map of the Niger delta compiled from data along the profiles of figure 2 and from the Gebco plotting sheets. Depths are corrected meters according to Matthews' tables (1939), A, B, C indicate the position of the three main canyons (Avon, Mahin and Calabar canyons) mapped on the upper slope by Allen (1965).

Seismic reflection results

The results of the geophysical surveys made on the Nigerian continental margin have been partially published elsewhere by Mascle *et al.* (1973), Delteil *et al.* (1974), Emery *et al.* (in press). I shall describe here unpublished seismic reflection profiles which illustrate two prominent characteristics of the submarine Niger delta geology: the intense diapiric phenomenon which affects the entire continental slope and the prolongation, beneath the delta, of two extinct oceanic fracture zone (fossil transform faults).

Except on the continental slope where the sedimentary thickness is far too great, the sedimentary cover is seen to lie on a strong reflector with a rough and buried topography which strongly diffracts the seismic waves. Locally the acoustic basement protrudes within the sedimentary layer (figure 4) and may give rise to important seamounts (Uchupi and Emery 1974). Refraction as well as magnetic data (see later) strongly suggest that this generally deeply buried surface represents the top of the oceanic basement (layer 2) or is close to it. The acoustic basement map (figure 5) indicates a progressive deepening of the basement towards the East in the direction of the Niger delta, while the depth south of Togo averages 8 sec. Such a deepening cannot be explained only by thermal subsidence away from the mid-oceanic crest (see for example Sclater and Detrick 1973), and it seems probable that there is a local lithosphere flexuration under the load of the Niger delta (see for example Walcott 1972). Figure 5 also shows that the basement relief follows a general Southwest-Northeast direction. One of these basement features between 2° and 4° E (see also figure 6) is a large linear basement ridge, piercing locally the sedimentary cover (at long. 2° 30' E, lat. 2° N). The oceanic basement shows a vertical offset along this ridge. This feature, which was discovered during the Walda "Jean Charcot" cruise, has been named the "Charcot Fracture zone" (Delteil *et al.* 1974). It reaches the southwestern base of the Niger delta continental slope. The Charcot fracture zone displays several characteristics typical of transform fault fossil prolongation; these include its apparent linearity as tested on 5 sections over a length of 300 km), the large vertical offset of basement level between its northern and southern sides, the basement trough along its northern wall and finally the association with sharp free air gravity and magnetic anomalies (figs. 12 and 13). Mascle and Sibuet (1974) related this trend to the kinematics of the early south Atlantic opening phases. Their interpretation supports the oceanic nature of the submarine delta crust. A second structural direction, marked by a broad and subdued basement rise is present beneath the abyssal plain south

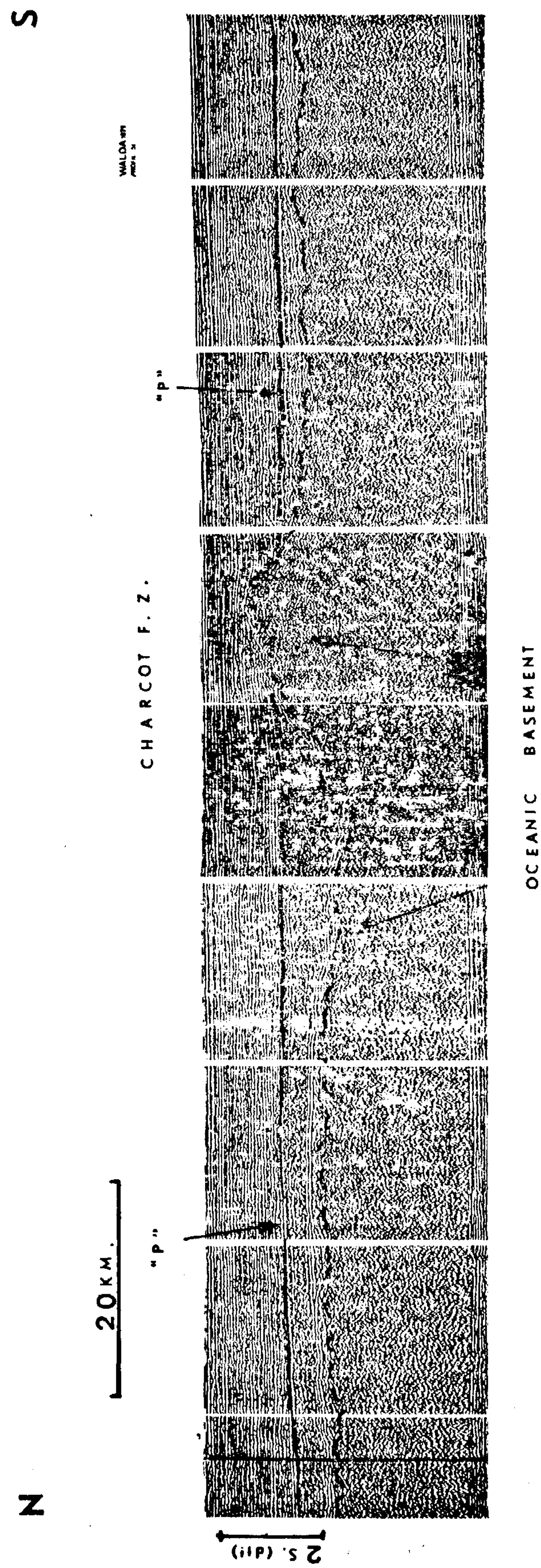

Figure 4. Profile Walda nº 51 using Flexotir as seismic source. The "p" horizons discussed in the text separate the two main sedimentary units, acoustically different and resting on the oceanic basement. Note the difference in basement level between north and south of the Charcot fracture zone. Note also that South of the accident the upper unit rests almost directly on the basement.

J. Min. Geol. 13 (1): 12-28 (1976)

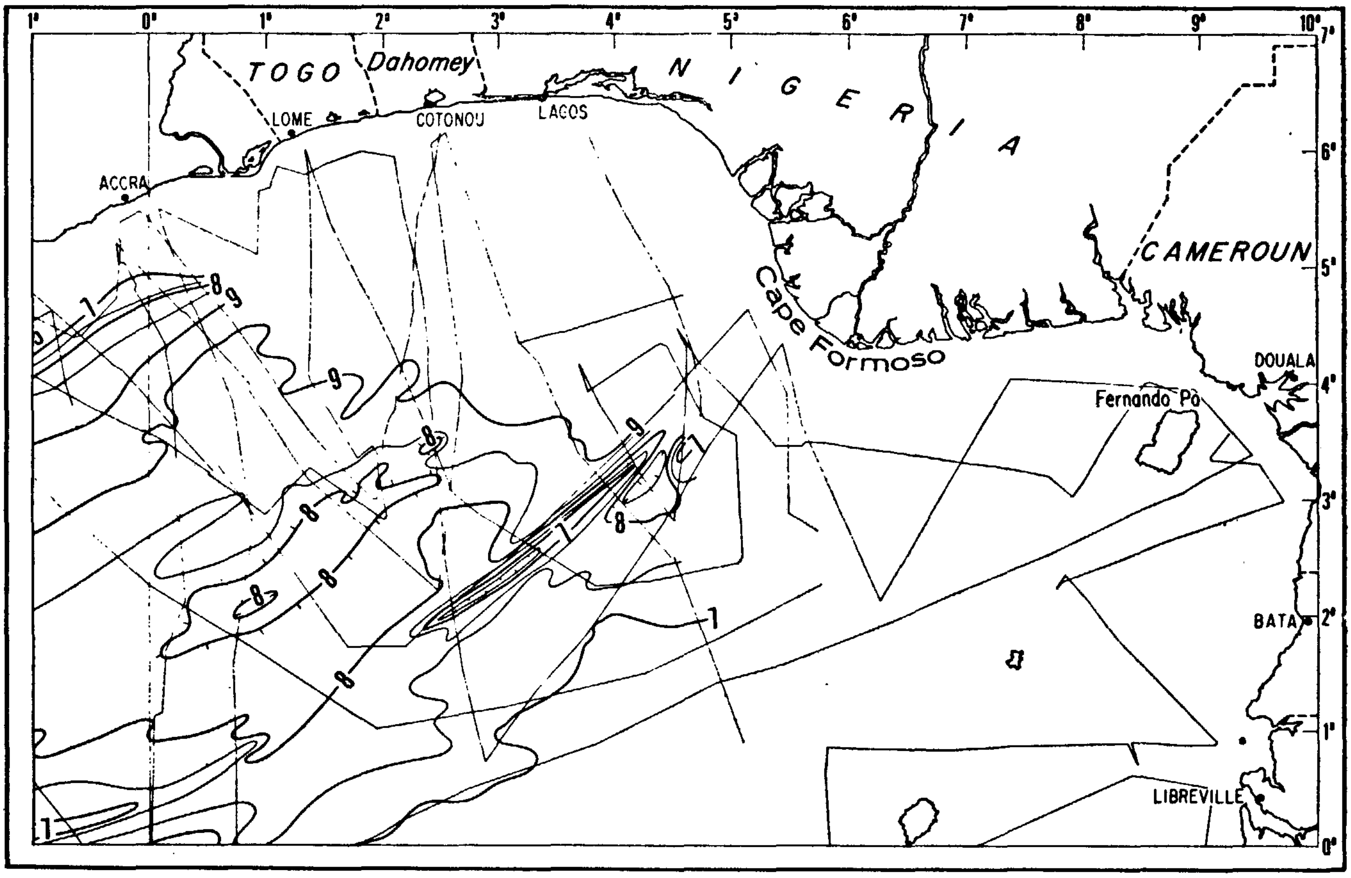

Figure 5. Map of the depth to the acoustic basement (probable oceanic basement). Values are in seconds of two way travel time from the sea surface.

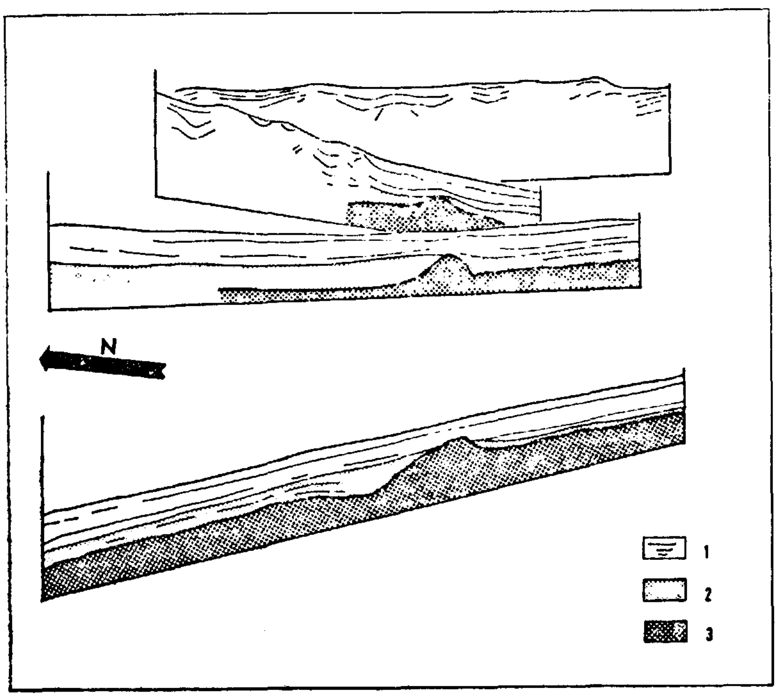

Figure 6. Interpretation of four Walda profiles across the Charcot Fracture zone prolongation and its intersection with the delta continental margin. 1, 2, 3 successively the upper and lower sedimentary units and the acoustical basement.

of Togo and has been tentatively related by Mascle and Sibuet to the Chain Fracture zone. Large free air and magnetic anomalies are also associated with it, as shown by Mascle and Renard (1973). The Chain Fracture Zone prolongation's trend has been shown by Mascle and Sibuet (1974) to follow the early opening flow line. However it cannot be traced east of long. 3° E because of the large thickness (exceeding 4 sec.) of the sedimentary cover. If the kinematic analysis of Mascle and Sibuet is correct, its buried extension should extend to the Okitipupa Ridge described by Adegoke (1969) in Southern Nigeria, in prolongation with the northern limit of the Niger delta or the Benin hinge line (Murat 1972). South of the Charcot Fracture Zone, the basement depth averages 7 sec. The isochrones appear to follow the same general southwesterly trend, suggesting that several other fracture zones may be present but the lack of data prevents us from making any conclusions.

In the deep areas of the eastern gulf of Guinea (approximately between long. 1°W and 3°E and lat. 1° and 4° N) the sedimentary layer on top of the oceanic basement, varies in thickness from 4 sec. (and more locally) to 1.5 sec. north of the Charcot Fracture Zone, and from 3 sec. to 0.5 south of it (fig. 7). The isopachs trend reflects the overall basement trend, which indicates that major factors governing sediment distribution are the age of the oceanic crust and the damming effect of the fracture ridges as well as the proximity of the sedimentary supplies.

Two main sedimentary units, separated by a thin series of strong reflectors (the "p" horizons of figure 4) can be distinguished throughout most of the area. The upper unit is formed of acoustically well-stratified and relatively continuous reflectors. Its thickness is fairly uniform (∽ 2sec.) except near the northern and eastern continental margins where it seems to increase. A lower unit, highly diffractive, seems to have filled the underlying basement depressions; as a consequence, the thickness of this sequence is variable (from O to 2.2 sec.). It generally thickens towards the margin north of the Charcot Fracture Zone while it is almost absent south of it where the upper series rests directly over the oceanic crust (figs. 4 and 6). Except for a few local and minor deformations, presumably due to sediment ponding, both series appear, in deep areas, to be almost undeformed.

In the absence of any direct sampling, the dating of acoustical reflectors remains uncertain. Factors such as their wide regional extension, the presumed age of the underlying oceanic crust and their similarity with deep seismic horizons off Liberia and Ivory Coast, have tentatively led Mascle (1975) to believe that the lower unit could correspond to relatively coarse and clastic deposits of Cretaceous age contemporaneous with the early South Atlantic opening phase when both continents, South America and Africa, were close to one another in the area of the present Gulf of Guinea. In this interpretation, the relatively well-stratified and uniformly thick upper unit would then be made of more homogeneous Cenozoïc sediments. If such an hypothesis is correct, special attention should be paid to the strong and widespread "p" reflectors, which could result from a rather sudden change in the sedimentary conditions.

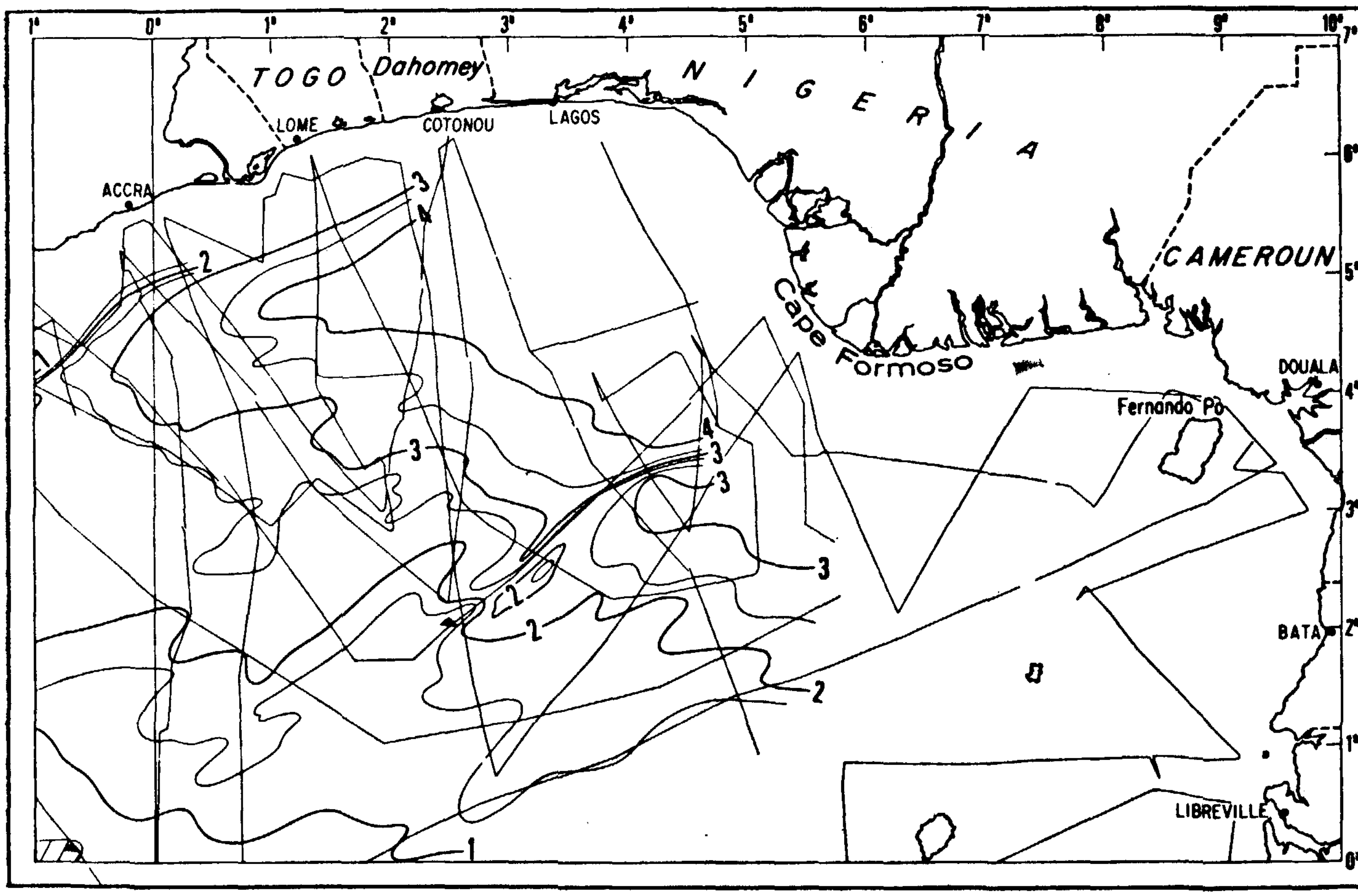

Figure 7. Map of the sedimentary cover above the acoustic basement. Black triangle indicates basement seamount. Values are in second of two-way travel time.

Mascle (1975) following Le Pichon and Hayes (1971) and Francheteau and Le Pichon (1972) assumed that, at this time in Upper Cretaceous, the opening of the South Atlantic had reached the open ocean stage as the pole of early opening shifted to a more northerly position. This resulted in ruptures of the equatorial fracture zones and especially the Romanche fracture zone, structural dams to the north and of the Walvis Ridge-Rio Grande Rise dam to the south and could have allowed deep water to flow across the equatorial Atlantic from the South Atlantic-Antarctic oceans to the North Atlantic. The sedimentary conditions were consequently drastically changed. It is important to remark that the first evidence of faunal exchange between the North and South Atlantic ocean dates from the Upper Cretaceous-Upper Paleocene times (Danian) according to Reyment (1970). In this respect note that Lower Cretaceous sapropelic shales, interbedded with siltstones, have been recently drilled at the base of DSDP site 361 in Cape Basin (Bolli *et al.*, in press). They have been correlated with horizon "A II" of Emery *et al.* (1975) tentatively identified along the entire South Atlantic African margin (Emery *et al.*, in press) including the Gulf of Guinea, where horizon "A II" can be correlated with "p" horizons. A lower Cretaceous age seems somewhat too old for the "p" horizons but it should be specified that, north of Walvis Ridge, restricted conditions persisted until Santonian times as shown by DSDP site 364 on the Angolan continental margin. Thus it appears that the change from restricted to open sea conditions is not necessarily contemporaneous throughout the whole South Atlantic, but could be of Upper Cretaceous age (Santonian) north of Walvis Ridge while it is Lower Cretaceous south of it.

The major characteristics of the sedimentary cover of the offshore delta are the huge Cenozoïc sediments thickness proven by numerous wells drilled offshore and onshore (Fränkl and Cordry 1967) and its intense deformation by numerous diapiric structures. The occurrence of diapirs along the delta's slope was first reported by Stoneley (1966), then by Hospers (1971) and Burke (1972) on the basis of unpublished oil industry surveys. Merki (1972) illustrated the presence of pseudo-diapiric structures on the continental shelf while Mascle *et al.* (1973) soon followed by Delteil *et al.* (1974) and Emery *et al.* (in press) published examples of diapiric structures recorded along the continental slope. As shown on figures 8 and 9, the diapiric structures, although present everywhere along the slope, are most numerous in two areas of the continental slope. The first one, containing large and buried structures, corresponds to the upper topographic escarpment in the second which corres-

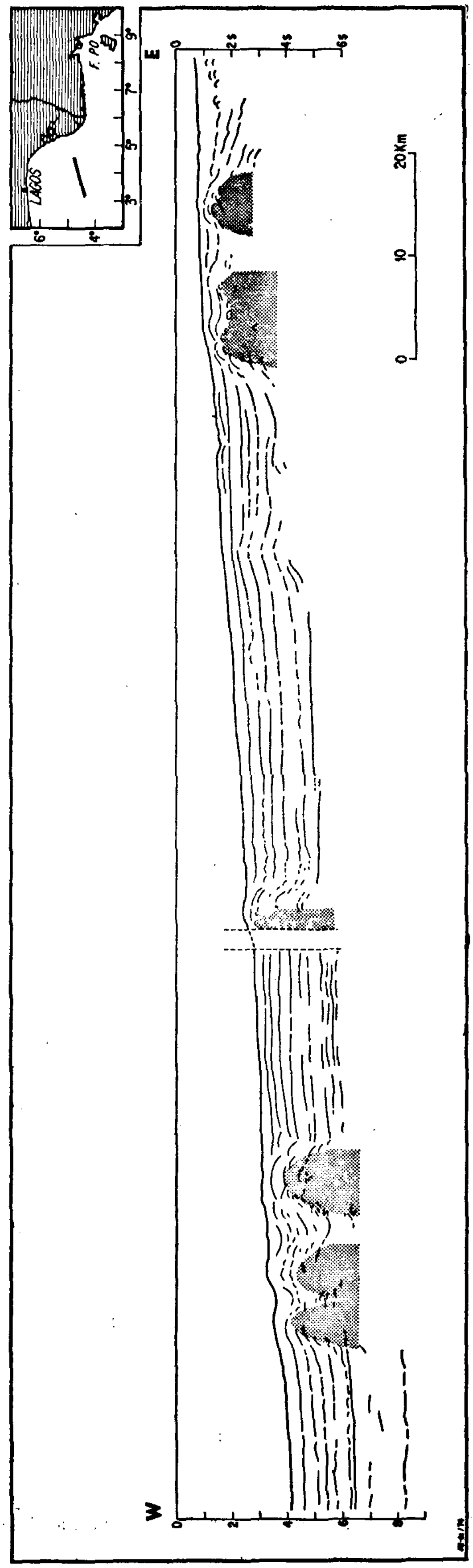

Figure 8. Schematic interpretation of Benin profile (using Flexichoc as a seismic source). Note the presence of diapir-like structures characterizing mainly the upper end of the lower part of the slope. A large sedimentary basin lies between both zones. On the rise, the sediment thickness reaches up to 4 sec. and sediments are sub-horizontal.

ponds to the lower escarpment, the diapiric structures appear to be almost coalescent. A 75 km-wide undeformed basin lies between these two sectors. Profile A (figure 8), southwest of Cape Formoso where we note the presence of a more complex topography, exhibits a different structure: diapirs are distributed equally over the whole length of the slope. This profile is very close to a profile published by Mascle *et al.* (1973) (see their figure 6) showing the same phenomenon and also showing the presence, at depth, of a basement ridge related to the Charcot fracture zone prolongation according to them. Diapiric activity may have been increased by the presence of the basement ridge acting as a dam to deep sedimentary flowage.

The nature of the diapirs remains difficult to specify in the absence of drilling result. Basing their conclusions on the oil industry offshore results reported by Merki (1972), Burke (1972) and Beck (1972), Delteil *et al.* (1974) favored a clay-shale origin for the deformations. The Akata formation (an undercompacted shale formation) present beneath the delta, is considered to be responsible for the continental shelf diapir features and the growth faults network (Merki, 1972). It is also argued that there is no known evaporitic formations in Nigeria. Without challenging the existence of mud diapirs, which are by the way often closely associated with deep salt diapirs (see for example Musgrave and Hicks 1968). Mascle *et al.* (1973) proposed instead that the large continental slope diapirs were made up of evaporites.

This hypothesis is supported by the deep origin of lower slope diapirs (see figure 6 of Mascle *et al.* 1973), which appear to originate from the lower sedimentary unit previously discussed and tentatively dated Cretaceous age. In addition, the large size of the diapirs are more in favour of an evaporitic rather than a mud origin. The presence of a marginal evaporitic basin there would not be surprising in view of the existence of such basins just south of it, on the African continental margin. There is furthermore a close similarity between

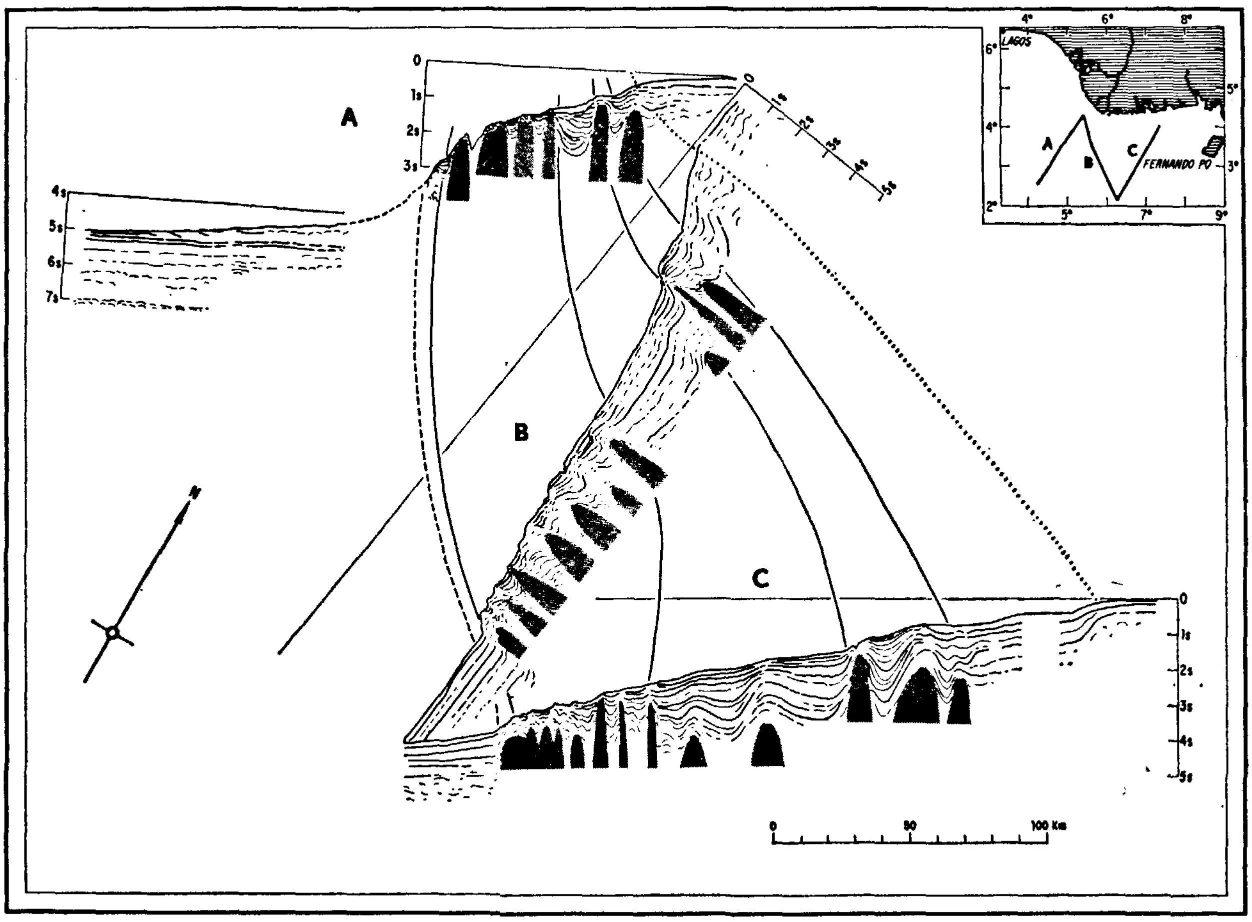

Figure 9. Three interpretations of seismic profiles recorded (using an air-gun seismic source) during leg 67 of Atlantis II. Note that on profiles B and C the general arrangement is similar to the one of Benin profile (figure 8) including two diapiric belts and a large sedimentary basin. Profile A displays a different structure and shows a highly diapiric perturbed slope. On the rise sediment penetration reaches only 2. 5 sec. mostly because of the use of a less performant seismic system.

the overall structure of the delta and the overall structures of the Angolan continental margin or of the Northern Gulf of Mexico margin. In these two areas the evaporitic nature of the diapirs is proven. The southern Cameroon to Angola submarine evaporitic basin is now well mapped (Leyden *et al.* 1972; Pautot *et al.* 1973; Beck and Lehner 1974; Emery *et al.* in press) and its probable Albo-Aptian age has been just recently partly confirmed by DSDP drillhole 364 (Bolli *et al.* in press) which has recovered high salinity sediments of Aptian age just on the top of a series of strong reflectors inferred to mark the transition to the evaporites.

Many bathymetric features of the Gulf coast basin, such as the presence of a lower slope scarp, of broad sedimentary ridges and troughs and of crestal grabens over diapirs (Lehner 1969) are found in the Niger delta continental margin. In the Gulf Coast continental margin, the diapiric structures and the Sigsbee scarp have been proven by drilling to be due to salt flowage (Lehner 1969; Emery 1969; Antoine and Bryant 1969); Burke *et al.* 1969). In fact the overall structure of the margin has been directly related to the deep flowage of an Upper Jurassic salt formation under the excessive load of a prograding clastic wedge. Lehner (1969) even believes that the growth fault network of the Gulf Coast province may have the same deep origin. A comparable explanation would explain the strikingly similar general structure of the Niger delta. Moreover Nwachukwu (1972) has proposed that tectonic evolution of the southern Benue trough may have created favourable conditions for the deposition of evaporites. These evaporitic sequences may be present at depth in Southern Nigeria, although there is still no drillhole evidence.

Figure 10 is a hypothetical general section of the Niger delta taking into account all available published data which assume the existence of deep evaporitic sequences. It takes account of the large diachronism phenomenon known in the Niger delta (Frankl and Cordry 1967) and suggests that shale diapirs are related to the Akata formation through the growth fault system

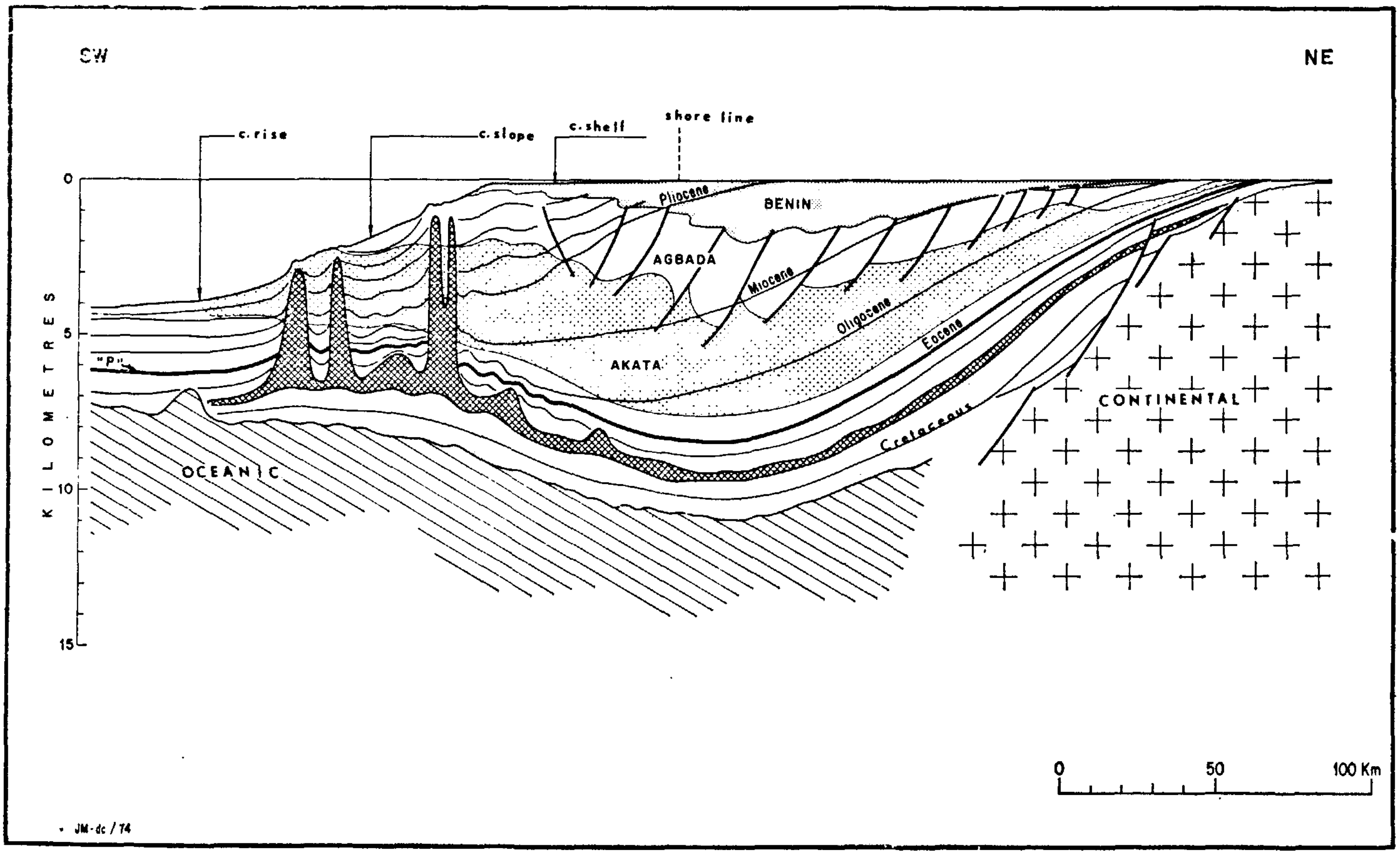

Figure 10. Hypothetic Niger delta schematic cross section. The structures of the continental slope and rise has been constructed using seismic reflection profiles, while a schematic deep section of the continental shelf and subaerial delta is modified from Merki (1972). Total thickness has been deduced from gravity models (Hospers 1971; Walcott 1972) and from refraction data. The possibility of a deep Cretaceous evaporitic layer has been retained as an hypothesis. A normal faulting of the continental basement and Lower Cretaceous strata (hinge line) may explain the absence of evaporitic outcrops. Note also the strong diachronism phenomenon affecting the Cenozoic deposits.

originally proposed by Merki (1972). The total sediment thickness as well as the oceanic basement depth have been estimated on the basis of refraction, gravity and magnetic data that will now be discussed.

Oblique reflection – refraction profiles
Twelve expendable sonobuoys oblique refraction-reflection profiles were shot in the vicinity of the submarine Niger delta and adjacent areas during leg 67 of the R. V. Atlantis II (1973). Their detailed results have been published elsewhere together with more than 200 other unreversed profiles collected along the Atlantic African margin (Hoskins *et al.* 1974). Additional information comes from refraction measurements recorded in 1970 by the Lamont-Doherty Geological Observatory (Leyden, personal communication). I shall discuss here their geological interpretation.

Table 1 lists the results of the Atlantis II profiles. Their locations are plotted in figure 11. An inspection of Table 1 shows that, except for sonobuoys shot over the delta continental margin itself and for sonobuoy 125, high refraction velocities have always been recorded. They vary between 4.29 km/sec (buoy 116) to 6.07 km/sec. (buoy 124) with an average value of 5.5 km/sec Within the South Atlantic and more specifically along the African margin (Goslin *et al.* 1974; Goslin and Sibuet 1975; Emery *et al.* 1975) velocities attributed to oceanic basement (layer 2) vary between 4.0 and 6.3 km/sec. Such a wide range has been interpreted to be the result of petrographical variation by comparison with measured compressional wave velocities (Peterson *et al.* 1973; Fox *et al.* 1973). The so-called oceanic basement may be represented either by basalts, dolerites or metabasalts. In any case, these velocities are compatible with the existence of an oceanic basement under the whole of the Gulf of Guinea. This conclusion is reinforced by an ocean-like pattern of magnetic anomalies and by the implication of preopening South Atlantic reconstruction (Bullard *et al.* 1965).

Sonobuoys 114 to 118 show a progressively more complex velocity structure together with a thickening of the sedimentary cover towards the Cameroon continental margin. Relatively thin unconsolidated sediments were detected by buoys 114-115 and this result is con-

TABLE 1. TABLE SHOWING ATLANTIS II PROFILES

Sonobuoy No	*V0*	*H0*	*V1*	*H1*	*V2*	*H2*	*V3*	*H3*	*V4*	*H4*	*V5*	*H5*	
114	1.50	4.64	1.95	0.88	5.29 +								
115	1.50	3.91	183	0.44	207	0.80	5.60 +						
116	1.49	3.01	1.64	0.43	2.39	4.95	4.29 +						
117	1.49	2.45	1.45	0.49	1.95	0.95	3.21	0.82	5.62 +				
118	1.54	0.4	1.60	0.21	1.81 +	0.49	2.28 +	0.29	2.65 +	0.68	2.28 +	1.80	5.62 +
119	1.49	1.99	1.51	0.22	2.09	0.68	2.40	0.10	2.65 +				
120	1.49	1.96	1.45	0.49	2.19	0.58	2.68 +	1.00	3.59 +				
122	1.54	0.7	1.70	0.28	1.84 +	0.70	2.16 +	2.00	3.21 +				
124	1.50	4.33	1.99	1.25	2.99 +	1.17	6.07 +						
125	1.50	4.06	1.56	0.70	2.30	2.28	3.26	1.35					
126	1.50	4.02	2.00	1.47	2.53	0.73	3.00	1.40	3.46 +	1.80	5.39 +		
127	1.50	3.17	1.64	0.63	3.07	1.67	3.24 +	2.40	4.03 +	0.6	5.65 +		

Note: V: velocities, V+ when determined from refraction — km/sec.
H: thicknesses of layer in km.

firmed by seismic reflection (Emery *et al.*, in press). In contrast a thickening, mainly due to low velocity sediments and probably related to the proximity of the Niger delta, can be observed at sonobuoys 116 and 117. Sonobuoy 118 exhibits a more complex velocity structure. Velocities such as 2.20 and 3.20 km/sec have been recorded elsewhere on the Cameroon continental shelf (Leyden *et al.* 1971) and have been interpreted as indicative of the presence of Cenozoic and Mesozoic sediments resting on a pre-Aptian arkosic or evaporitic layer characterized by a 4.8 km/sec. velocity. The absence of such a velocity at sonobuoy 118 may indicate the absence of pre-Aptian deposits and thus confirm the closing of the marginal evaporitic basin south of Douala as proposed by Leyden *et al.* (1972), Pautot *et al.* (1974), Beck and Lehner (1974) and Emery *et al.* (in press) on the basis of seismic reflection data. Sonobuoys 124 to 127 (figure 11) show the presence, over the oceanic basement, of relatively high velocities layers (2.99 to 4.03 km/sec.) thickening towards the direction of the Togo-Dahomey continental margin. Seismic reflection profiles (Delteil *et al.* 1974; Mascle 1975; Emery *et al.*, in press) also indicate the presence, in this sector, of a deep acoustically poorly stratified sedimentary unit, thickening in direction of the continental margin, covered by a well-stratified unit and resting directly on the oceanic basement. The acoustic reflectors have been tentatively attributed to relatively coarse clastic deposits of Cretaceous age. The 2.99 to 4.03 km/sec. velocities may well correspond to these deposits. This interpretation is in agreement with refraction measurements obtained elsewhere along the South Atlantic African margin (Leyden *et al.* 1972; Emery *et al.* 1975), which commonly indicate velocities ranging between 3.0 and 3.8 km/sec. for Mesozoic sediments.

Sonobuoys 119, 120, 122 reveal a different velocity structure. Relatively low velocities (between 1.84 and 2.68 km/sec) seem to characterize thick layers (2.0 km at sonobuoy 122) while no typical oceanic basement velocity is recorded. This fact is most probably due to the great thickness of unconsolidated sediments known

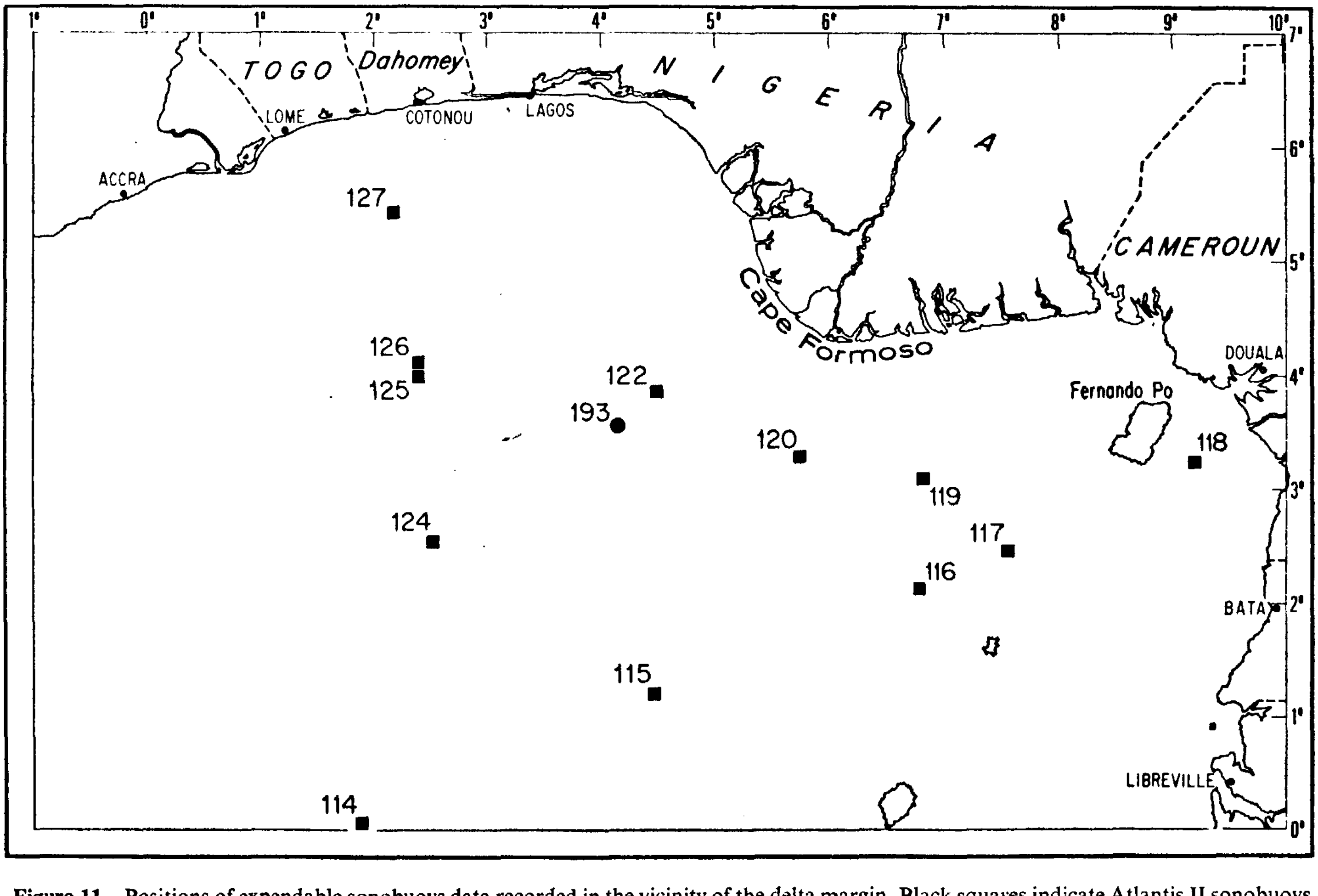

Figure 11. Positions of expendable sonobuoys data recorded in the vicinity of the delta margin. Black squares indicate Atlantis II sonobuoys results (Hoskins *et al.* 1974) while the black circle shows the position of a Lamont-Doherty Geological Observatory result (R Leyden, personal communication).

on the Tertiary and present-day Niger delta (Short and Stauble 1967; Hospers 1971; Merki 1972; Mascle 1975) masking the underlying strata. The presence of velocities such as 3.59 km/sec. (sonobuoy 120) and 3.21 km/sec. (sonobuoy 122) may indicate that the slope of the Tertiary Niger delta is underlined by consolidated Cretaceous and Paleocene sediments. Such a possibility does not preclude the existence, at depth, of an evaporitic layer responsible for the numerous diapiric structures that we previously described along the delta slope.

A refraction line shot by the Lamont-Doherty Geological Observatory (sonobuoy 193) indicate the presence of a high velocity horizon (5.05 km/sec.) under a relatively thin sedimentary cover (about 1 km) southwest of the delta; the shallow basement there may correspond to the prolongation of the "Charcot" fracture zone which is marked by several important basement rises.

Magnetics

Very few magnetic results obtained in the Niger delta area have been published up to now. Figure 12 includes data published by Ahrens *et al.* (1971) Mascle *et al.* (1973), Delteil *et al.* (1975) and Emery *et al.* (in press). In addition to those shipboard data, extensive aeromagnetic surveys have been conducted over the Niger delta oil province. Being confidential they obviously cannot be taken into account here, although Burke *et al.* (1972) mention that they show the existence, beneath the northeastern part of the delta, of a series of six subdued magnetic anomalies alternatively negative and positive which they consider to be an indication of a Ridge-Ridge-Ridge junction beneath the Niger delta which was active in Lower Cretaceous times.

Seawards of the coastline, the main characteristics of the magnetic anomaly profiles are the generally very low amplitude anomaly pattern over most of the area and the presence of sharp positive and negative southwesterly trending anomalies particularly evident south of Togo-Dahomey and Southwest of the delta (fig. 12).

As the Niger delta region lies in low magnetic latitude, it is difficult to decide whether such a smooth magnetic pattern results from the absence of northerly trending

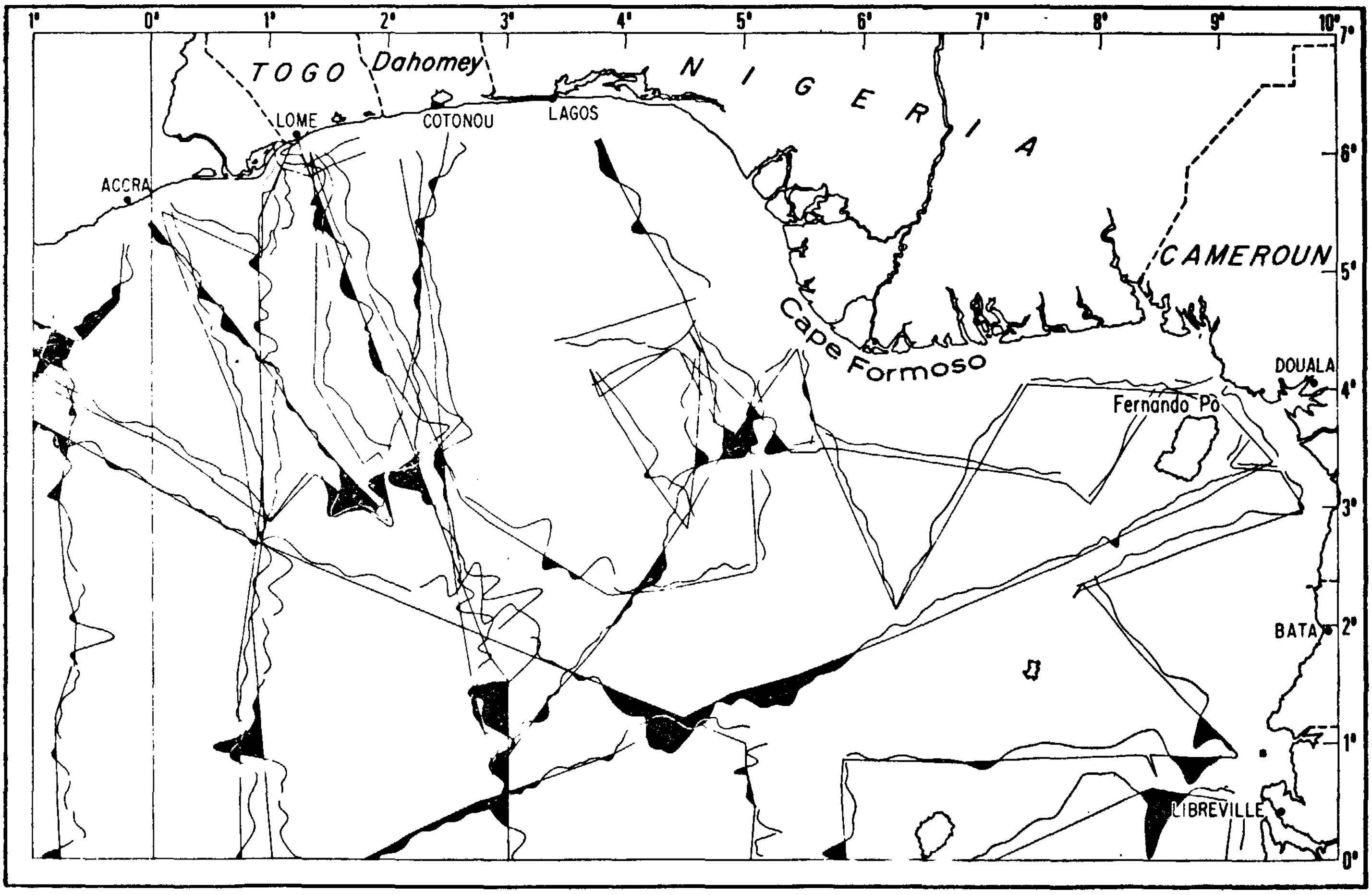

Figure 12. Magnetic anomalies plotted along the ship's tracks. Black areas indicate negative anomalies. Note the generally subdued magnetic pattern in contrast to the sharp southwest-northeast trending anomalies South of Togo-Dahomey and Southwest of the Niger delta.

magnetic bodies or whether it is due to the presence of a magnetic smooth zone. Such magnetic smooth zones tentatively correlated with a constant magnetic polarity period during Upper Cretaceous times have been first defined by Mascle and Philips (1972) and recently mapped with more precision seaward of Angola and Gabon by Emery *et al.* (in press). Another explanation could be that the great thickness of sediments has led to burial metamorphism (Taylor *et al.* 1969) and subsequent demagnetization.

The coincidence between easterly trending accidents such as the equatorial fracture zones and sharp magnetic anomalies has been established in the South Atlantic by Van Andel *et al.* (1973), Emery *et al.* (1975), Mascle and Renard (1973) and Cochran (1973). This observation has been diversely interpreted. Malahoff and Woollard (1972) proposed that highly magnetized bodies are intruded along fracture zone; Van Andel *et al.* (1973) and Cochran (1973) favoured the presence of magnetized intrusions within the fracture zone trough. Rea (1972) prefers to explain the magnetic anomalies associated with a fracture zone by the orientation of the fracture with respect to the earth magnetic field as suggested by Schouten (1971). An alternative explanation has recently been suggested by Emery *et al.* (in press): considering the good resemblance between observed magnetic profiles and simulated synthetic magnetic anomalies, computed using different configuration of simple two-dimensional models, these authors simply propose that the North-South juxtaposition (due to the offset along the fracture zone) of positive and negative magnetic bodies could account for the magnetic pattern over a fracture zone.

These hypotheses seem confirmed by the good correspondance which is seen between magnetic trend, as shown on figure 15 and basement configuration.

Gravity

Figure 13 is a free-air gravity anomaly map of the area seawards of the continental shelf based on data obtained during Walda and Atlantis II cruises only. The map was continued on land using the Bouguer anomalies map of Hospers (1965). The most striking features are the Niger delta minimum (-40 mgal) centered on the subaerial delta, and the Ekenié high (+ 40 mgal) in the area of Cape Formoso. Hospers (1971) explains the delta minimum by factors such as a density contrast, an uncompensated downwarp of the crust or a low average density, while the Ekenie high could be due to either a local loss of the isostatic equilibrium or to the presence, at depth, of a basement rise.

At sea, the prominent features of the free-air anomaly map is the presence of a belt of positive anomalies along the shelf and the upper slope, flanked on the seaward

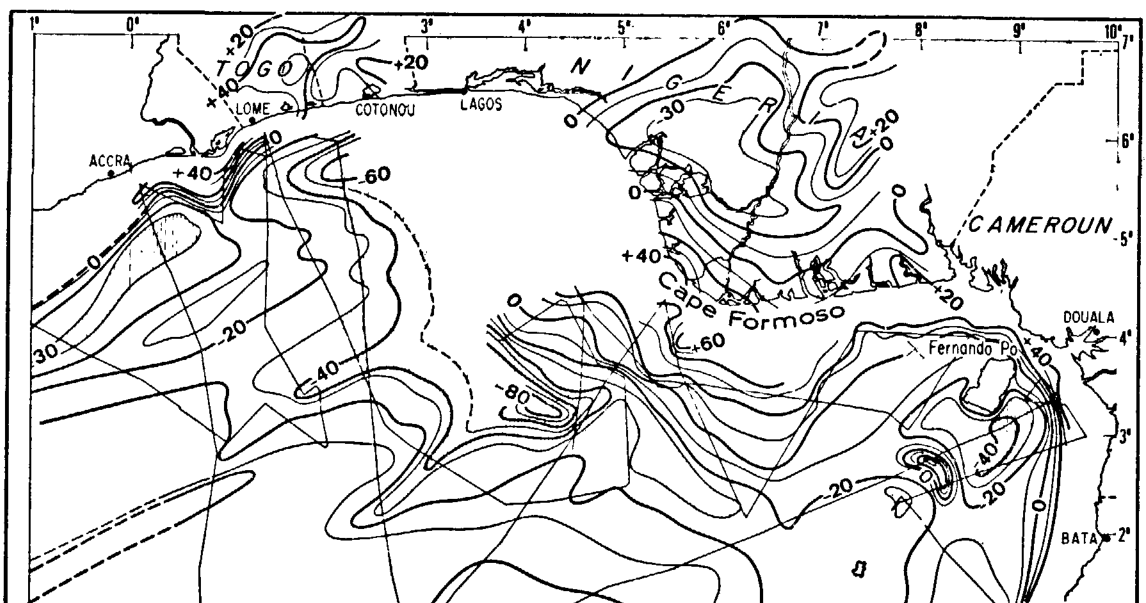

Figure 13. Gravity anomaly map (contour interval 10 mgal). Free air anomalies in ocean and Bouguer anomalies on land (from Hospers 1965 and 1971). Areas with anomalies smaller than – 30mgals are dashed.

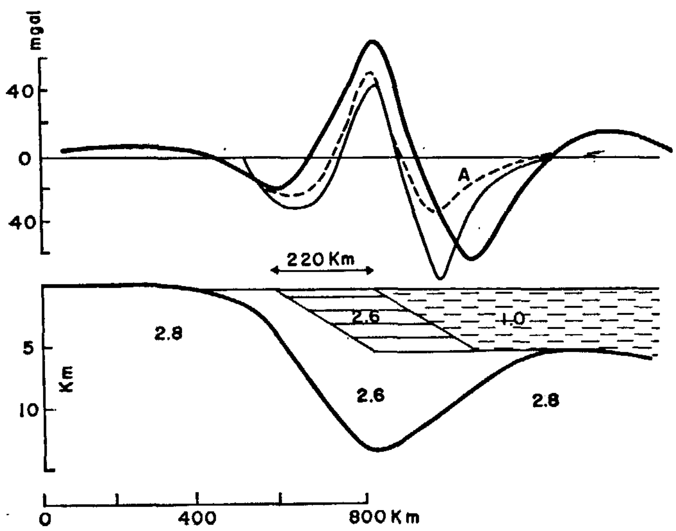

Figure 14. Niger delta flexural model and calculated free-air gravity anomalies (modified from Walcott 1972). Two gravity curves constructed (from figure 13) across the whole area have been superimposed and are in good accordance with the inferred curve, showing thus that, as a first approximation, the Walcott's model for the Niger delta is acceptable.

side by a series of lows reaching locally - 80 mgals, distributed in a way similar to the one described by Cochran (1973) for the Amazon cone. Southwesterly trending anomalies characterize the western continental rise of the delta. These apparently disrupt, southwest of Cape Formoso, the regular pattern of quasi-concentric slope anomalies.

Association between fracture zones and free air anomalies have been shown by Cochran (1973) to exist in the equatorial Atlantic and the Guiana Basin. This author has been able to trace the Saint Paul, Romanche and Chain fracture zones on the basis of linear positive free air anomalies flanked to the north or to the south by lows corresponding to sedimentary filled troughs.

In the vicinity of the Niger delta, a first SW-NE trend of anomalies (corresponding to a low of - 40 mgals) has been associated in the same way with the Chain Fracture zone prolongation (Mascle and Renard 1973) while a second trend (reaching the base of the delta southwest of Cape Formoso) is easily correlated with the Charcot fracture zone marked by a SW-NE

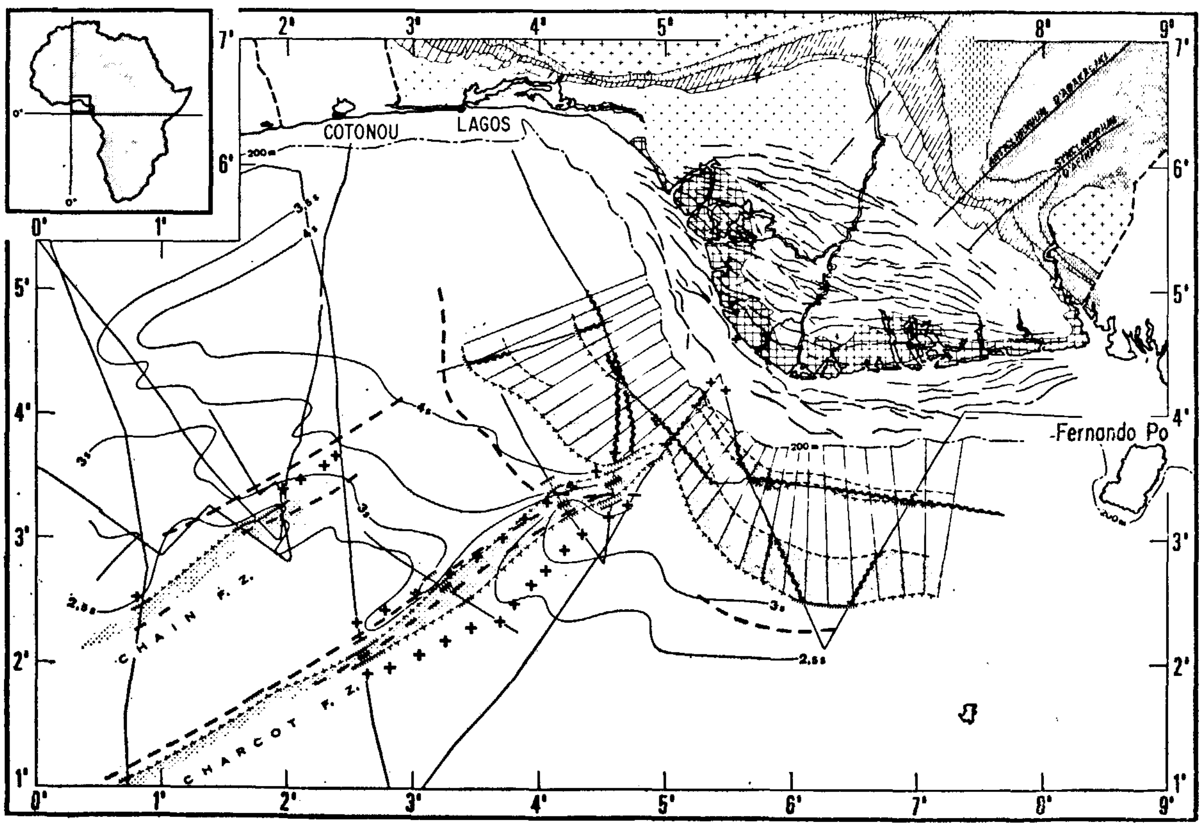

Figure 15. Schematic structural map of Niger delta and adjacent areas. Cenozoic growth fault pattern on land after Merki (1972) and simplified geology from Short and Stauble (1967).
The continental slope is hatched, probable diapiric zones dotted, except along control line where they have been underlined. In deep areas, the fracture zone trends are underlined by basement rises (dotted) and locally expressed by crests. Sedimentary isochrons have been indicated. White crosses and dashes show positive and negative magnetic trends, while black crosses and dashes indicate main positive and negative gravity anomalies.

basement ridge (Delteil *et al.* 1974; Mascle 1975). The gravity pattern over Equatorial fracture zone has been interpreted by Cochran (1973) as due to an additional mass of ultrabasic rocks under the fractures ridges and troughs. However, an alternative explanation takes into account the difference in age, and hence in density structure, of the oceanic crust and lithosphere on both sides of fracture zone (Sibuet *et al.* 1974). Recently Sibuet *et al.* (1975) have successfully tested such an hypothesis on the Equatorial fracture zones.

A general relationship has been proposed between gravity anomaly patterns over continental margins and a flexuration of the lithosphere due to loading by large sedimentary accumulations (e.g. Walcott 1972). One of the examples tested by Walcott was the Niger delta. The Walcott's model has been redrawn on figure 14, on which we have superimposed two gravity anomaly curves constructed from figure 13. Both curves fit fairly well with the theoretical curve computed by Walcott (1972) which sugests a sedimentary thickness under the shelf, of the order of 12 km. This value is somewhat more important than the one proposed by Hospers (1971), 8 km, which is computed with an average density of 2.3 or 2.4 g/cm^3, while Walcott's computation was made using a 2.6 g/cm^3 density. This value is however more in accordance with the maximum thickness of Cenozoic sediment indicated by Merki (1972): 9000 to 12000 meters on the basis of wells or by Frankl and Cordry (1967): 11-12 km on the basis of aeromagnetic data.

CONCLUSIONS AND DISCUSSION

Using those results together with previously published data, particularly those of Merki (1972) I have constructed on figure 15, a structural sketch of the Niger delta and adjacent areas. The following remarks can be made in connection with this map.

(1) The general morphology of the Slope is controlled by the flowage of a probable deep evaporitic layer as in Gulf Coast province margin or along the western African margin between Cameroon and Angola.

(2) Two different sets of linear structures having the same southwesterly trend exist in the deep area.

They are associated with free air gravity and magnetic anomalies. It is argued that they correspond to extinct oceanic fracture zones. They appear to have controlled the sediment distribution. They can be followed up to the vicinity of the delta slope. This is particularly clear for the Charcot Fracture zone, which disrupts the entire delta continental slope and along which an increase in diapiric activity can be detected. The Ekenie gravity high of Hospers (1965; 1971), in the Cape Formoso area, lies in its prolongation and may be explained by the presence, at depth, of a basement rise. The extension of the fracture zones under the delta supports the oceanic nature of the present-day Niger delta underlying crust.

(3) A striking correspondence exists between the trend of both fracture zones and land structural trends known in Nigeria. In particular the Chain fracture zone prolongation lies along the Benin hinge line and similarly the Charcot fracture prolongations lies in the sector of the Abakaliki anticlinorium and Afikpo area southwest of the Benue trough (Figures 1 and 5). The Abakaliki area corresponds to the southwestern extremity of the so-called Cretaceous Benue folded belt (Murat 1972). This long (∽ 1000 km) and narrow (150 km) intra-continental folded zone borders to the north an important and regional basement uplift the Adamaou massif bounded to the south by mylonitic zones and small Cretaceous basins (Le Maréchal and Vincent 1971) (figure 1). The geological history of the Benue trough could be summarized in two main tectonic phases: a subsiding Lower Cretaceous distension phase along a NE-SW direction and an Upper Cretaceous compressive episode (Cratchley and Jones 1965; Murat 1972; Burke *et al.* 1971). It should be noted that the geological history of the Benue trough has been diversely interpreted and that one of the explanations takes account of a possible Lower Cretaceous oceanic opening and posterior closing of this area in relation with an active Cretaceous triple junction (RRR type) (Burke *et al.* 1971; Burke and Whiteman 1973; Burke and Dewey 1974). Supports for such a geological history mainly come from the peculiar gravity pattern of the Benue trough (Cratchley and Jones 1965), from the presence of linear magnetic anomalies beneath the delta, and from the presence of volcanics and mineralizations (see figure 1) in the Benue area (Burke *et al.* 1971).

Our data cannot confirm such an hypothesis. However the continuity of oceanic trends related to the early opening phase of South Atlantic (Mascle and Sibute 1974) does not fit well with the existence of an RRR triple junction, which should have disrupted the early oceanic trends in the vicinity of the persent Niger delta, unless both oceanic features were on the same side of the active Benue ridge or unless the Benue opening was very small. It is tempting to compare the Niger delta-Benue trough folded belt-Adamawa uplift system to another well-known intracontinental system, lying partially along the oceanic domain, the Pyrenees mountains-Bay of Biscay system. Although the geological history of this last area is still controversial, its complex tectonic history includes a Lower Cretaceous distension phase and an Upper Cretaceous to Eocene compressive phase related to a possible triple junction west of the Bay of Biscay, with a very limited amount of shortening or opening (Le Pichon *et al.* 1971; Boillot *et al.* 1971; Choukroune *et al.* 1973; Mattauer 1968; Williams 1975). This may suggest that the tectonic history of Southern Nigeria has been, in some respect, comparable to the Bay of Biscay-Pyrenees Mountains geological evolution including the possibility of a triple junction. However still little is known of the geology of Nigeria, except for the post-tectonic Niger delta construction and more field geology studies are needed to test such an hypothesis.

ACKNOWLEDGMENTS

This study is based on data collected by the R. V. "Jean Charcot" during the Géoguinée cruise (CEPM, 1968), Walda cruise (CNEXO-COB, 1971), Benin cruise (IPG-CEPM, 1971) and by the R.V. Atlantis II (Woods Hole Oceanographic Institution, IDOE program, 1973). Additional data were kindly provided by D. Hayes and R. Leyden (Lamont-Doherty Geological Observatory). I thank J. R. Delteil, K. O. Emery, L. Montadert, G. Pautot, V. Renard and R. Schlish for the use of data and for helpful discussions. An early draft of the manuscript was critically read and improved by X. Le Pichon.

REFERENCES

ADEGOKE, O.S. (1969). Eocene stratigraphy of Southern Nigeria. *Bur. Rech. Geol. Min. Memoires*, **69**, p. 23-48.

ALLEN, J.R.L. (1964). The Nigerian continental margin: Bottom sediments, submarine morphology and geological evolution. *Marine Geol.* **1**, p. 289-332.

ALLEN, J.R.L. (1965). Late quaternary Niger delta, and adjacent areas: sedimentary environments and lithofacies. *Amer. Assoc. Petroleum Geologists Bull.*, **49**, p. 547-600.

AMERY, G,B. (1969). Structure of Sigbsee scarp, Gulf of Mexico *Amer. Assoc. Petroleum Geologists Bull.*, **53**, p. 2480-2482.

ANTOINE, J.W. & BRYANT, W.R. (1969). Distribution of salt and salt structures in Gulf of Mexico. *Amer. Assoc. Petroleum Geologists Bull.*, **53**, p. 2543-2550.

ARENS, G., DELTEIL, J.R., VALERY, P., DAMOTTE, B., MONTADERT, L. & PATRIAT, L. (1971). The continental margin off Ivory Coast and Ghana, *In: The Geology of the east Atlantic continental margin*, Delany F. M. (Editor) 4, Africa: Great Britain Inst. Geol. Sci. Report 70/16, p. 61-78.

BECK, R.H. (1972). The oceans, the new frontier in exploration. *APEA Journal*, **12**, p. 1-21.

BECK, R.H., & LEHNER, P. (1974). Oceans, new frontier in exploration *Amer. Assoc. Petrol. Geologists Bull.*, **58**, p. 376-395.

BOILLOT, G., DUPEUBLE, P.A., LAMBOY, M., D'OZOUVILL E, L., SIBUET, J.C. (1971). Structure et histoire geologique de la marge continentale au nord de l'Espagne. *In: Histoire structurale du golfe de Gascogne*. Technip. Paris, v. 6-1. a v. 6-52.

BOLLI, H.M., RYAN, W.B.F. *et al.*, Deep Sea Drilling Project preliminary results of leg 39, *Geotimes* (in press).

BULLARD, E., EVERETT, J.E. and SMITH, A.G. (1965). The fit of the continents around the Atlantic. *In: Symposium on continental drift: Roy. Soc. London Philos. Trans.*, **258**, p. 41-51.

BURK, C.A., EWING, M., WORZEL, J.L., BEALL, J.R., BERGGREN, W.A., BUKRY, FISHER, A.G. and PESSAGNO, E.A. (1973). Deep-Sea Drilling into the Challenger knoll central gulf of Mexico. *Amer. Assoc. Petroleum Geologists Bull.*, **57**, p. 1338-1347.

BURKE, K. (1972). Longshore drift submarine canyons and submarine fans in development of Niger Delta. *Amer. Assoc. Petroleum Geologists Bull.*, **56**, p. 1975-1983.

BURKE, K. and WHITEMAN, A.J. (1973). Uplift, rifting and the break-up of Africa. *In:* Tarling T.H. et Runcorn (Eds.), *Implications of continental drift to earth sciences*. Academic Press, London and New York, **2**, p. 735-755.

BURKE, K. and DEWEY, J.F. (1974). Two plates in Africa during the Cretaceous. *Nature.*, **249**, p. 313-316.

BURKE, K., DESSAUVAGIE, T.F.J. and WHITEMAN, A.J. (1971). Opening of the Gulf of Guinea and geological history of the Benue depression and Niger delta. *Nature Phys. Sci.* **233**, p. 51-55.

BURKE, K., DESSAUVAGIE, T.F.J. & WHITEMAN, A.J. (1972). Geological history of the Benue Valley and adjacent areas. *In:* Dessauvagie, T.F.J. & Whiteman, A.J. (Eds.), *African Geology*, (Ibadan, 1970), p. 187-206.

CHOUKROUNE, P., LE PICHON, X., SEGURET, M., SIBUET, J.C. (1973). Bay of Biscay and Pyrenees. *Earth and Planet. Sciences Letters*, **18**, p. 409-448.

COCHRAN, J.R. (1973). Gravity and magnetic investigations in the Guiana basin, Western Equatorial Atlantic. *Geol. Soc. America Bull.*, **84**, p. 3249-3268.

CRATCHLEY, C.R. & JONES, G.P. (1965). An interpretation of the geology and gravity anomalies of the Benue valley, Nigeria, *Overseas Geol. Surv. Geol. Div. London*, no. 1, p. 1-26.

DELTEIL, J.R., VALERY, L., MONTADERT, C., FONDEUR, PATRIAT, P. & MASCLE, J. (1974). The continental margin in the northern, part of the Gulf of Guinea. *In:* C. A. Burk and C. L. Drake eds., *Geology of Continental Margins*.

EMERY, K.O., UCHUPI, E., BOWIN, C.O., PHILLIPS, J. & SIMPSON, E.S.W. (1975). The continental Margin of Western Africa,: Cap St-Francis (South Africa) to Walvis Ridge (South West Africa). *Amer. Assoc. Petroleum Geologists, Bull.* **59**, p. 3-59,

EMERY, K.O., UCHUPI, E., BOWIN, C.O., PHILLIPS, J. & MASCLE, J. (in press) The continental margin of western Africa: Angola to Sierra Leone. *Amer. Assoc. Petroleum Geologists Bull.*

FARRINGTON, J.L. (1952). A preliminary description of the Nigerian Lead-zinc field. *Econ. Geol.*, **49**, p. 583-608.

FOX, P.J., SCHREIBER, E. & PETERSON, J.J. (1973). The geology of the oceanic crust: compressional wave velocities of oceanic rocks. *Journ. Geophys. Res.* **78**, p. 5155-5172.

FRANCHETEAU, J. & LE PICHON, X. (1972). Marginal fractures zones as structural framework of continental margins in the South Atlantic ocean. *Amer. Assoc. Petroleum Geologists Bull.*, **56**, p. 891-967.

FRANKL, E.J. & CORDRY, E.A. (1967). The Niger Delta oil province: recent developments onshore and offshore. *Proc. 7th World Petroleum Congress, Mexico*, **2**, p. 195-209.

GOSLIN, J., MASCLE, J., SIBUET, J.C. & HOSLINS, H. (1974). Geological study of the Easternmost Walvis Ridge, South Atlantic: Morpology and shallow structure. *Geol. Soc. Amer. Bull.*, **85**, p. 619-632.

GOSLIN, J. & SIBUET, J.C. (1974). Geophysical study of the easternmost Walvis Ridge, South Atlantic: Deep structures. *Geol. Soc. Amer. Bull.* (in press).

GRANT, N.K. (1971). South Atlantic, Benue trough and Gulf of Guinea Cretaceous triple junction. *Geol. Soc. Amer. Bull* **82**, p. 2295-2298.

HEEZEN, B.C., MENZIES, R.J., SCHNEIDER, E.D., EWING, W.M. & GRANELLI, N.C.L. (1964). Congo submarine canyon. *Amer. Assoc. Petroleum Geologists Bull.*, **48**, p. 1126-1149.

HOSKINS, H., ROGERS, C.U. & WOO, A.O. (1974). Data report of oblique reflection — refraction radio-sonobuoy profiles on the African Atlantic continental margin (R/V Atlantis II cruises 67 and 75). *Woods Hole Oceanographic Institution, Ref. no.* 74-34., 40 p.

HOSPERS, J. (1965). Gravity field and structure of the Niger Delta, Nigeria, West Africa. *Geol. Soc. America Bull.*, **76**, p. 407-422.

HOSPERS, J. (1971). The geology of the Niger delta area, *In:* F. M. Delany, Ed., *The geology of the East Atlantic continental margin:* ICSU/SCOR Working Party 31 Symposium. Cambridge 1970, Inst. of Geol. Sciences, Rept. no. 70/16, p. 121-142.

LEHNER, P. (1969). Salt tectonics and Pleistocene stratigraphy on continental slope of northern gulf of Mexico. *Am. Assoc. Petroleum Geologists Bull.*, **53**, p. 2431-2479.

LE MARECHAL, A. & VINCENT, P.M. (1972). Le fosse cretace du sud Adamaoua, Cameroun: *In:* Dessauvagie T.F. and Whiteman, A.J. (Eds.) *African Geology*, p. 227-249.

LE PICHON, X. & HAYES, D.E. (1974). Marginal offsets fracture zones and the early opening of the South Atlantic. *Journ. Geophys. Research*, **76**, p. 6283-6293

LE PICHON, X., BONNIN, J., FRANCHETEAU, J. & SIBUET, J.C. (1971). Une hypothese d'evolution tectonique du Golfe de Gascogne. *In: Histoire Structurale du Golfe de Gascogne.* Editions Technip, Paris, 22, VI. 11-1 to *Vs.* 11-44.

LEYDEN, R., BRYAN, G. & EWING, M. (1972). Geophysical reconnaissance on African Shelf: 2 Margin sediments from the Gulf of Guinea to the Walvis Ridge. *Amer. Assoc. Petroleum Geologists Bull.*, **56**, p. 682-693

MALAHOFF, A. & WOOLARD, G.P. (1970) Geophysical studies of the Hawaiian Ridge and Murray fracture zone in the Sea, v. 4, pt. II, *New concepts in sea floor evolution,* Wiley Intersciences, N.Y., p. 73-131.

MASCLE, J. (1975). Geologie sous-marine du Golfe de Guinea Sciences dissertation thesis. Univ. Paris 385 p

MASCLE, J. & PHILLIPS, J.D. (1972). Magnetic smooth zones in the south Atlantic. *Nature*, **240**, p. 80-84.

MASCLE, J. & V. RENARD, (1973). Eastward extension of the Chain fracture zone: EOS. *Trans. Amer. Geophys. Union*, **54**, p. 477.

MASCLE, J. & SIBUET, J.C. (1974). New pole for the early opening of the South Atlantic. *Nature*, **252**, p. 464-465.

MASCLE, J., BORNHOLD, B.P. and RENARD, V. (1973). Diapiric structures off Niger Delta. *Amer. Assoc. Petroleum Geologists Bull.*, **57**, p. 2672-2678.

MATTAUER, M. (1968). Les traits structuraux essentiels de la chaine pyreneene. *Rev. Geogr. Phys. et Geol. Dyn.*, **10**, p. 3-11.

MERKI, P. (1972). Structural geology of the Cenozoic Niger Delta. *In:* Dessauvagie, F.F.J. & Whiteman, A.J. (Eds), *African Geology*, p. 636-646.

MURAT, R.C. (1972). Stratigraphy and paleogeography of the Cretaceous and lower Tertiary in southern Nigeria. *In:* Dessauvagie T.F.J. & Whiteman A.J. (Eds.), *African Geology*, p 251-265

MUSGRAVE, A.W. & HICKS, W.G. (1968). Outlining shale masses by geophysical methods. *In:* J. Braunstein & G. D. O'Brien, Eds., *Diapirism and Diapirs. AAPG Mem.* 8, p. 122-136.

NWACHUKWU, S.O. (1972). The tectonic evolution of the southern portion of the Benue trough, Nigeria, *Geol. Mag.*, **109**, p. 411-196.

PAUTOT, G., RENARD, V., DANIEL, J. & DUPONT, J. (1973). Morphology, limits, origin and age of the salt layer along South Atlantic African margin. *Amer. Assoc. Petroleum geologists Bull.*, **57**, p. 1658-1671.

PETERSON, J.J., FOX, P.J. and SCHREIBER, E. (1974). Newfoundland ophiolites and the geology of the oceanic layer. *Nature*, **247**, 194-196

REA, D.K. (1972). Magnetic anomalies along fracture zones. *Nature, Phys. Science*, **236**, p. 58-59.

REYMENT, R.A. (1965). *Aspects of the geology of Nigeria.* Ibadan University Press, 145 p

REYMENT, R.A. (1970). Ammonite biostratigraphy, continental drift and oscillating transgressions *Nature*, **224**, p. 137-140.

REYMENT, R.A. (1972). Cretaceous (Albian-Turonian) geology of the South Atlantic. *In:* Dessauvagie, T.F.J. & Whiteman, A.J. (Eds.): *African Geology*, p. 505-512.

SCLATER, J.G. & DETRICK, R. (1973). Elevations of mid-ocean ridges and the basement age of the JOIDES sites, *Geol. Soc. America Bull.*, **84**, 1547-1554.

SCHOUTEN, J.A. (1971). A fundamental analysis of magnetic anomalies over oceanic ridges. *Marine Geophys. Research*, **1**, p. 111-144.

SHEPARD, F.P. & EMERY, K.O. (1973). Congo submarine canyon and fan valley. *Amer. Assoc. Petroleum Geologists Bull.*, **57**, p. 1679-1691.

SHORT, K.C. & STAUBLE, A.J. (1967). Outline of geology of Niger Delta. *Amer. Assoc. Petroleum Geologist Bull.*, **51**, p. 761-779.

SIBUET, J.C., LE PICHON, X. & GOSLIN, J. (1974). Thickness of the lithosphere deduced from gravity edge effect across the Mendocino fault. *Nature*, **252**, p. 676-678.

SIBUET, J.C., MASCLE, J. & VEYRAT-PEINEY, B. (1975). Equatorial fracture zones and the opening of the South Atlantic. *EOS*, **56**, p. 452.

STONELEY, R. (1966). The Niger delta region in the light of the continental drift. *Geol. Mag.* **103**, p. 385-397.

UCHUPI, E. & EMERY, K.O. (1974). Seismic reflection, magnetic, and gravity profiles of the eastern Atlantic continental margin and adjacent deep-sea floor. II. Congo canyon (Republic of Zaire) to Lisbon (Portugal). *Woods Hole Oceanog. Inst., Ref. no.* 74-19, 14 sheets.

VAN ANDEL, T.J.H., REA, D.K., VON HERZEN, R.P. & HOSKINS, H. (1973). Ascension fracture zone, Ascension Island, and the mid-Atlantic ridge. *Geol. Soc. America Bull.*, **84**, p. 1527-1546.

WALCOTT, R.I. (1972). Gravity, flexure and the growth of sedimentary basins at a continental edge. *Geol. Soc. America Bull.* **83**, p. 1845-1848.

WILLIAMS, C.A. (1975). Sea floor spreading in the bay of Biscay and its relationship to the north Atlantic. *Earth Planet. Sci. Letters*, **24**, 440-456.

CAREY, S.W. (1958). *Continental drift, a Symposium.* Hobart, p. 177-355.

TAYLOR, P.T., ZIETZ, & DENNIS, L. (1968). Geologic implications of aeromagnetic data for the eastern continental margin of the U.S. *Geophysics*, **33**, p. 755-780.