Shallow Structure and Stratigraphy of the Liberian Continental Margin[1/]

by

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ABSTRACT

The rifting of Africa from North and South America has affected the structural framework off Liberia in two episodes. As shown by bathymetry, seismic-reflection profiles, magnetic data, and stratigraphy, the southeastern third of the margin is cut by west-southwest-trending fracture zones which we interpret as the extension of the St. Paul's fracture zone. This fracture zone intersects the continental margin off Cape Palmas to give rise to a blockfaulted and slump topography, similar to that in the area where the Romanche fracture zone intersects the African continent off Cape Three Points, Ghana. The fracture zones are covered by a prograded wedge of presumed Tertiary and Cretaceous sedimentary rock off central Liberia. Adjacent to the northwestern third of the Liberian margin, northwest-trending basins filled mainly with Lower Cretaceous paralic sediments occur under the continental shelf; they extend to the upper slope where they are downdropped along a northwest-striking fault zone that separates the shelf deposits from a thick prism of sediment beneath the continental rise. The southeastern third of the margin appears to have formed during the separation of Africa and South America in the Late Jurassic-Early Cretaceous. The rest of the margin seems more strongly influenced by the tensional forces created during the rifting of Africa and North America; volcanic rocks are Late Triassic to Early Jurassic in age, and shelf sedimentation occurred mainly after the continents broke apart.

INTRODUCTION

The rifting of the Americas from Africa should have structurally and stratigraphically modified the continental margins. From the oceanic side, the form of newly created oceanic crust is well described in the pattern of fracture zones, midoceanic rifts, seamount chains, and abyssal plains. Less well described is the response of the continent to the rifting, in part because of a thick prism of postrift sediment deposited over the fractured trailing edge of the continent, as off the eastern United States. Our purpose is to describe the structure pattern of the continental margin off Liberia, formed in response to the separation of Africa and South America, and to compare it with other West African basins. Liberia was chosen because: (1) a vigorous program of geophysical and geologic mapping on land (Behrendt and Wotorson, 1970; White and Leo, 1969) has provided a good foundation to which to tie a marine study, and (2) Liberia is in a strategic area so far as the separation of continents is concerned, south of the part of West Africa associated with the separation of North America and Africa, but northwest of that part of Africa thought to have separated from South America. Further, Liberia fronts on that part of the eastern Atlantic between two major oceanic fracture zones -- the Guinea fracture zone to the northwest, and the St. Paul's fracture zone which appears to intersect the Liberian margin off the eastern end of the country.

Liberia is made up mainly of Precambrian crystalline rocks which have been intruded by diabase (176-192 m.y.) (Grommé and Dalrymple, 1972) and which are overlain near the coast by sedimentary rocks of Cretaceous and Tertiary age. The crystalline rocks are granite, quartzofeldspathic gneiss, granulite, schist, amphibolite, and iron formation (White, in press). The rocks are part of an extensive shield area that covers most of Liberia, Ivory Coast, Sierra Leone, and Guinea. In Liberia, the Precambrian rocks are part of three major age provinces, the Liberian province (@ 2700 m.y.) which occupies the northwestern two-thirds of the country, the Eburnean province (@ 2000 m.y.) which occupies the south-eastern one-third of Liberia, and the Pan African province (@ 550 m.y.) which occupies a narrow northwest-trending coastal belt (Hurley and others, 1971).

During November 1971, a group from the U.S. Geological Survey, the Liberian Geological Survey, and Instituto Geologico y Minero de España ran a geophysical and dredge survey of the Liberian margin (fig. 1) as a part of the National Science Foundation's program for the International Decade of Ocean Exploration.

This paper will concentrate mainly on the shallow structure and stratigraphy offshore, as discerned from continuous seismic-reflection profiles, magnetic data, dredge hauls, and drill holes. J.C. Behrendt and others (in press) have studied the deep crustal structure with particular emphasis on the gravity and magnetic data of the program. Robb and others (in press) have discussed the bathymetry.

Methods

Approximately 5400 km of geophysical profiles were run aboard the chartered 40-m ship UNITEDGEO I, using a 80-140-kilojoule sparker, a proton magnetometer, a 3.5-kilohertz profiler, and a stable platform gravimeter. A satellite navigation system was used to track our position; on the shelf, this was supplemented by sonar doppler. Position accuracy was excellent (less than 1-km error), as checked by water depths and track crossings. We dredged the upper slope and outer shelf at several places with a chain-bag dredge, and two of these attempts brought up pieces of rock (fig. 1).

Most of the details on data collection and reduction have been described by Schlee (1972). For a sound source, we used a single-channel 140-kj sparker, with the towed electrodes 70 m behind the ship. Returning pulses were picked up by a 100-element hydrophone towed 180 m behind the ship. With the exception of two profiles, the survey was run at a 4-second firing rate and a 4-second sweep rate; a 20-76-hz band-pass filter was used on all but one profile. Vertical exaggeration of subsurface reflectors on the profiles is probably around 5:1, if a transmission velocity of 3 km/sec is assumed; we used this velocity realizing that it is a compromise between sound transmission in soft sediment (where velocities are much less) and crystalline rock (where velocities of 4-6 km/sec might be expected).

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D. Bukry, U.S. Geological Survey, examined several dredge samples for nannofossils, and Ruth Todd and G.W. Andrews, also of the Geological Survey, studied dredge samples for the Foraminifera and the diatoms, respectively. Our colleague John C. Hathaway analyzed the samples on the X-ray diffractometer and gave generously of his time in interpretation of the patterns and in photographing the samples.

BATHYMETRY

The character of topography on the continental slope (fig. 1) divides the margin off Liberia into three sectors: a gullied northwest sector, from Cape Mount to Buchanan; a smooth central sector, Buchanan to east of Greenville; and a fractured-eroded southeast sector, east of Greenville to Harper. The northwest and southeast sectors of the margin are narrow, and the slope is topographically rough. The central sector is wider and smoother. More detail on the bathymetry has been given by Robb and others (in press).

The continental slope off Harper has an average slope of about 3°. However, it is cut by a large valley trending southwest, oblique to the trend of the continental slope, whose walls attain slopes of as much as 10° and whose length is 30-40 km. Reflection profiles (next section) indicate a distinct ridge in the subsurface below the southeastern wall of this valley (fig. 2, profile 34). This valley probably formed through rifting of blocks in the vicinity of the continental margin and the St. Paul's fracture zone. The valley shows some similarity to a ridge-and-valley feature described by Fail and others (1970), Arens and others (1970), and Le Pichon and Hayes (1971) off Cape Three Points where the Romanche fracture zone is thought to intersect the continent.

By contrast, off Greenville in the central sector, the surface of the slope is much smoother, with fewer and smaller slump scars and no valleys. It has an average slope of about 1.8°. The smooth regular surface of the upper slope suggests ; depositional outbuilding. The lower part adjacent to the continental slope is steeper and trends east.

The continental slope in the northwest sector has an average slope of about 3°, but it is very rough and is characterized by features that resemble slump and landslide scars and rubble. At least two large submarine valleys cut the slope southeast of Monrovia. The upper slope between Cape Mount and Monrovia is extremely rough, with a large number of small valleys averaging about 170 m deep and spaced at intervals of about 3 km (R.L. McMaster, oral commun., 1972). These valleys are too small to contour with the present density of data.

The surface of the continental shelf if generally flat and featureless, although irregularities in the form of possible rock outcrops (Rancurel, 1965) do occur in a few places, and bands of probable relict strandlines are located along the shelf edge at depths of 80 to 120 m (McMaster and others, 1970). The shelf break is a relatively constant 134 m deep in the northwest sector, is rounded and undefinable in the central sector, and ranges from 100 to 150 m deep in the southeast sector. The shallow parts of the shelf break in the southeast occur at steepened parts of the upper slope which appear to have resulted from slumping.

SEISMIC-REFLECTION PROFILES

Not surprisingly, the seismic-reflection profiles show that the Liberian margin may be divided into three main areas on the basis of structural differences.

Southeastern sector

The seismic profiles taken off the southeastern third of Liberia (fig. 2) show a thin sediment cover on the shelf (points X) and large foundered blocks (presumed to be made of rocks of Jurassic and pre-Cretaceous age) beneath the continental slope. On these profiles oriented normal to the coast, the blocks are 20 km or less across, and their sides tilt at angles that dip from 7° (profile 30) to 20° (profile 34). Like the "basement" beneath the shelf, these blocks lack internal reflectors, and some appear to be downdropped along faults that dip at angles as great as 45°.

In plan view (fig. 7) the long dimension of the blocks is west-southwest, parallel and in a line with the St. Paul's oceanic fracture zone (fig. 9), extended by LePichon and Hayes (1971), Arens and others (1970), and Francheteau and LePichon (1972) into the Cape Palmas area. If Cape Palmas marks such an intersection, our data show a complex structural alignment of foundered blocks along two and possibly three zones. J.C. Behrendt and others (in press) have discussed the geophysical evidence that suggests that lines 22-35 cross three fracture zones off southeastern Liberia.

The blocks have acted as sediment dams for debris carried to the slope, so that small basins of sediment 10-30 km wide and at least 2-3 km thick occur there (fig. 7). The small basins appear to be breached along two broad valleys that cut into the continental slope between long. 9° and 7°W. (profiles 28-29, 32-33, fig. 1). Several hundred meters of sediment in the basins have buried older fault zones that cut an ancestral continental slope (profiles 28-34); this older slope dips at an angle of 13°-45°. Much of the sediment that covers it appears to have slumped there, to judge by the irregular arrangement of internal reflectors. Though slump deposits are most prevalent on the slope and in close association with the blocks, they extend seaward to the rise as thick tongues with an aggregate thickness of a kilometer. The slumped debris dips seaward 1-1/2° or less, and it has been buried by 1/2 km or less of horizontally bedded sediment. Most of these buried slump deposits have their source in the continental slope, but some may have spread laterally (profile 32) because they do not tie in directly with the slumps in the immediate upslope area. The burial of the slump debris clearly points to an earlier phase of mass movement of sediment followed by deposition of hemipelagic silts and turbidites (as exemplified by the evenly spaced reflectors on the profiles).

Off southeastern Liberia, a prominent irregular acoustic basement is evident under the deep ocean floor; it is nearly 1 second (half travel time) below the sea floor, and it deepens below the sea floor toward the upper continental rise where it is lost (fig. 7). Depth estimates from magnetic data suggest greater values along the 4000-m contour which may indicate that acoustic basement is shallower than magnetic basement here. The depth to acoustic basement is similar to that found by Arens and others (1970) off the Ivory Coast and assumed by them to be sediment-oceanic crust interface. The depth value of 1 second is also similar to that found by Emery and others (1970) off eastern North America.

Central sector

Adjacent to the central coast of Liberia, the margin is wider because of a wedge of sediment that obscures tilted crustal blocks beneath the continental slope (fig. 3). The sediment wedge on profile 26 thickens both to northwest along the slope and seaward down it; the wedge ranges from 0.4 second to more than 1 second above the blocks on profile 26, whereas values of a second or more are evident on profiles 18 and 19 (fig. 3). Though faulting and slumping are present, they have caused less displacement and disruption of the sedimentary cover than in other sectors, so that one is impressed by the continuous nature of the deposit as it has extended the margin in a seaward-protruding bulge. The prograded wedge is modified towards the northwest (profile 16) by faulting restricted to the upper continental slope where the buried edge of the shelf block is once again evident (fig. 7).

The foundation supporting the wedge off central Liberia is much broader than the slope-rise transition of the southeastern third (60-80 km vs. 30-60 km). The wider foundation reflects a pattern of long, continuous flat-topped blocks, gradually stepped down toward the southwest and tilted in that direction. The overlying sediment dips at 3°-6°, subparallel to the tilt of the buried blocks. Unlike the basement blocks to the southeast, these blocks show a few reflectors within them, and their flanks dip at angles of 21° to 34°. The blocks are difficult to discern towards the west, so that it becomes impossible to ascertain the maximum thickness of the sediment from these data. The extension of the blocks over to long. 9-1/2°W. does seem likely (profile 22), as indicated by the interruption of reflectors by faults and by the faint suggestion of the edges of blocks.

Profile 21 shows a diapirlike structure beneath the central part of the slope. It is 2-3 km across, and dips of at least 33° can be inferred on the flanks. The fact that there is no strong magnetic anomaly over it suggests that it is not a mafic volcanic plug similar in composition to other intrusions known in the area. Not ruled out is the possibility that the "diapir" is the reflection from the upturned edge of a deeply buried block.

Acoustic basement beneath the continental rise for profiles 16-19 is at about the same depth (1 second or less) as noted for those profiles off Cape Palmas. As with the profiles to the southeast, the reflector deepens landward, and it cannot be traced northwest of profile 16.

Northwest sector

The shelf-slope-rise transition off northwestern Liberia (fig. 4) is marked by step faulting, slumping, and extensive gullying. Faint gently folded reflectors can be traced from beneath the shelf to the slope where they are truncated by a prominent reflector (points Y, fig. 4) that dips seaward at 12° to 23° below the slope. The reflector dips beneath the slope in an irregular, discontinuous steplike manner, and is overlain by 1-3 km of slumped sediment. On profiles 1 and 3, antithetic faults (points Z, fig. 4) are present beneath the lower part of the slope to bound an indistinct grabenlike slump zone which parallels the northwest trend of structural elements of the continental margin (fig. 7). Slump deposits appear to extend beneath the rise, though they are covered by sediment inferred to be turbidites and hemipelagic deposits a few hundred meters or less thick (fig. 4). The extensive slumping under the continental slope leads us to suspect that up to the present time, recurrent faulting along the margin has aided in mass movement of sediment down the slope and in the formation of small surficial slump blocks (e.g., profiles 6 and 13 at points X).

A strong acoustic basement beneath the rise does not appear to be present off northwest Liberia. Several deep reflectors can be seen on profiles 1 to 13, but the deepest strong one is not at a consistent depth from profile to profile, and faint reflectors can be seen beneath it. The relations indicate that we probably have a thick pile of sediment beneath the continental rise thinning seaward, and giving way landward to slump deposits under the slope.

Continental Slope and Rise

The features we have stressed in the preceding three sections are shown in a nearly continuous manner on two profiles taken subparallel to the strike of the slope and rise (fig. 5). A change is obvious from a blockfaulted margin adjacent to southeast Liberia to a more restricted slumped and faulted zone off northwest Liberia. On profile 36, reflectors in the small sediment-filled basins beneath the slope pinch out against the edges of buried blocks. The seaward-thickening apron of sediment off central coastal Liberia (profile 36, fig. 5) shows the change laterally from a prograded slope (with gently dipping reflectors inclined seaward) in the southeast to an irregularly bedded and slumped zone in the northwest. On profile 37, the restricted zone of blockfaulting and gullying under the slope is evident, as are narow zones of slumping a few kilometers wide on the lower slope (profiles 37, 1 and 12). For most of the lower slope, however, reflectors are uniform; the warping of shallow reflectors is an artifact of the recording that arises from velocity changes in sound propagation between the water and sediment, as well illustrated by Allen (1972).

Continental Shelf

The Liberian Shelf (fig. 6) is underlain by shallow basins filled with Cretaceous and Tertiary sedimentary rocks (see Stratigraphy). Prior to drilling, the existence of these basins was inferred on the basis of aeromagnetic data (Behrendt and Wotorson, 1970). Later, seismic-reflection profiles confirmed their existence and allowed us to infer zones of faulting and trends of thickness, and, still later, drilling gave us the age of the sedimentary rocks. Our single-channel reflection profiles (profiles A-A', B-B') on the shelf were limited in what they showed about the structure, but five multichannel reflector profiles (profiles C-C' through G-G'), made available to us by an industry source, reveal much on the deep structure beneath the shelf.

Between the Sierra Leone-Liberia boundary and Monrovia, profiles A-A' and B-B' (fig. 6) show a gently folded sequence under the landward part of the shelf that thins to the northwest toward Cape Mount. Off Monrovia, as much as 5 km of sediment occupies the basin under the shelf in a seaward-thickening wedge. The basin is in about the same location as that shown by Behrendt and Wotorson (1970, fig. 2), though we extend it farther along the coast toward Cape Mount (fig. 7) than they did. A northwest-trending structural high underlies the outer shelf south of Cape Mount, but it disappears west of Monrovia as the basin widens to underlie most of the shelf. The landward boundary of the basin as well as the basin between Monrovia and Buchanan is a pinchout of the strata against the basement. As can be seen in figure 6, some faulting is associated with the margins of the basins, though successively younger units seem to overlap faulted edges. As figure 7 shows, faults bound some of the edges of basins under the continental shelf; one such fault southwest of Monrovia (fig. 7) coincides with a steep magnetic gradient used by Behrendt and Wotorson (1970, fig. 3) to infer the same fault. Within the shelf profiles, three unconformities are apparent, one within a section of nearly flat-lying strata, the second between flat-lying beds above and older warped and faulted strata below, and a third deep unconformity above acoustic basement.

The sedimentary section continues under the shelf as far southeast as Greenville, where the sequence thins to less than 1/2 km. The shelf between Greenville and Harper is apparently veneered by a thin cover of sedimentary rock (fig. 6, profile G-G'), though only crystalline rocks are exposed at the coast.

To summarize, the slope off Cape Palmas is extensively faulted, and a thin cover of sediment veneers crystalline rocks on the shelf. Off central Liberia, west-southwest-trending fault blocks are covered by a prograded wedge of sediment that thickens over the slope. Subsidence coupled with faulting is evident off northwest Liberia, where a sedimentary section beneath the shelf thickens toward shelf edge, there to be fractured and downfaulted along a northwest-trending fault zone beneath the continental slope. Thickest sediment appears to be beneath the lower slope and continental rise.

MAGNETIC INTERPRETATION

The magnetic survey has been dealt with more fully by J.C. Behrendt and others (in press); we have used it in this report where appropriate. Magnetic records f. the northwest area of the survey (fig. 4) show relatively low-amplitude anomalies over the slope. This area might fit some definitions of a "quiet zone", but we interpret the low amplitude as due mainly to deep burial of the magnetic sources under a thick sedimentary section. Profiles 21-31 (fig. 2 and 3) show significantly higher amplitudes, which are probably associated with fracture zones either acting as loci for intrusions or bringing contrasting rocks into juxtaposition. The seaward ends of profiles 32-34 (fig. 2), on the other hand, are magnetically "quiet." Figure 7 shows an area inferred to have more than 4 km of sedimentary rock on the slope on the basis of the magnetic depth estimates following the method of Vacquier and others (1951). The sedimentary section west of Greenville appears to be significantly thicker than that to the southeast. The linear pockets of thicker sections estimated southeast of Greenville are probably associated with the St. Paul's and other fracture zones discussed later.

STRATIGRAPHY

Onshore Stratigraphy

The rocks exposed in two sedimentary basins along coastal Liberia (fig. 9) serve as a guide to the type and age of rocks to be exposed offshore. White (in press) has described five formations younger than the Precambrian crystalline rocks that make up most of Liberia. Paynesville Sandstone (Paleozoic?) is the most widespread sedimentary formation; it unconformably overlies Precambrian crystalline rocks and is intruded by the Monrovia Diabase. The sandstone, a fine-grained well-sorted, crossbedded quartz arenite with layers of mudstone, is projected to be about 1000 m thick, though exposures are limited to only a few meters. The unit contains no known diagnostic fossils, though its position in the stratigraphic sequence and its lithologic similarity to other rocks of early middle Paleozoic age in Sierra Leone led White to infer a comparable age for the Paynesville Sandstone.

The Monrovia Diabase is a collective term for the dikes and sills (radiometric age, 176-192 m.y., Gromme and Dalrymple, 1972) that intrude the Paynesville Sandstone and older crystalline rocks. It is tholeiitic and has labradorite and augite as the essential minerals and magnetite as an accessory. The dikes trend northwest subparallel to the coast and crop out from Greenville to the Sierra Leone border (Behrendt and Wotorson, 1970, fig. 3). These intrusive bodies are probably the source of amygdaloidal basalt flows unconformably overlying the Paynesville Sandstone.

The Farmington River Formation is a massive graywacke with interbedded conglomerate and shale that crops out near Roberts Field, approximately 50 km southeast of Monrovia; shale becomes more abundant and conglomerate becomes less abundant toward the coast. The shale contains spores which have been dated as Early Cretaceous (Aptian-Cenomanian). Some carbonaceous debris and plant fragments are present, not unlike what Spengler and Delteil (1966) found in the sedimentary basin in the Ivory Coast. Pebble counts from the conglomerates in Liberia revealed fragments of Precambrian gneiss and granulite, Paynesville Sandstone, diabase, and amphibolite; lesser amounts of quartzite, chert, and vein quartz are present.

The sparse remains, pollen, and poorly preserved mollusks do not allow one to infer exactly how the Farmington River Formation originated, though a lacustrine or marine setting seems likely.

Unconformably overlying all these older units as a broad blanket is the Edina Sandstone, a flat-lying coarse-grained conglomerate quartzose sandstone exposed in low outcrops as much as 8 m high between Monrovia and Buchanan (White, in press). It is widespread as scattered outcrops over northwest coastal Liberia and is particularly well exposed in and near the mouths of some of the larger rivers. White estimated the thickness of the formation to be a few tens of meters at the most. A few fragments of silicified wood have been found in the Edina Sandstone, but nothing that would permit an age designation. As the Edina is similar to the rocks in Ivory Coast and Sierra Leone, White thought that it is probably Tertiary in age. The bedding, the lack of fossils, and areal distribution of the formation suggest that the Edina is a continental or littoral deposit.

The structural setting for these sedimentary units is in two coastal basins between Monrovia and Buchanan (fig. 7). From a regional Bouguer gravity anomaly map (Behrendt and Wotorson, 1970, fig. 4) and projected dips of the poorly exposed formations, one basin is 20-30 km long and 10-15 km wide, and the other is at least 20 km long and opens out toward the continental shelf.

Offshore Drill Sites

Offshore data from four drill holes and two dredge hauls show the presence of marine Tertiary and Cretaceous sedimentary rocks. Four holes were drilled off Liberia in 1971, all off the northwest part of the shelf between Greenville and Cape Mount (Cortesini and Minner, 1972). The holes (fig. 1) ranged from 1678 to 3172 m deep and bottomed in volcanic rocks of Jurassic age, or sedimentary rocks of Early Cretaceous age, or sandstone inferred to be Paleozoic in age (C.S. Wotorson, personal commun., Nov. 1971).

The oldest sedimentary rocks are limestone, orthoquartzite, and red beds of shale and sandstone; spores from the section indicate a probable Early Devonian age. The sandstone beds may be correlative with the Paynesville and indicate that this part of the Liberian margin subsided sufficiently in the Paleozoic so that at least 1 km (thickness inferred from land) of lower Paleozoi clastic material could be deposited. Similar conditions prevailed in northern Sierra Leone and in the Senegal-Mauritania basin (fig. 9), where Aymè (1965, p. 85) briefly described lower Paleozoic clastic rocks, 1-2 km thick and extending westward an unknown distance towards the West African shelf.

In the offshore holes, the Paleozoic rocks are intruded by diabase dikes and sills and unconformably overlain by basalt and flows. The extrusive and intrusive rocks contrast in density with the overlying sedimentary rocks of Cretaceous age and provide a major reflector for the seismic profiles. Approximately 400 m of basalt was drilled in one hole; another hole bottomed in volcanic rock after having penetrated 470 m into it. Radiometric dates show a Jurassic age for the volcanic rock in one hole and an Early Cretaceous age for the volcanic rock in another hole (C.S. Wotorson, personal commun., Nov. 1971). Thus, the ages are similar though younger than the diabase dated in coastal Liberia.

The Cretaceous rocks cored are mainly shale and sandstone with lesser amounts of siltstone and limestone. On the basis of a sparse collection of spores, pollen, gastropods, and ostracodes, most of the section is Lower Cretaceous (Albian and older stages of the Cretaceous) and ranges in thickness from 450 m to 1940 m; some of the fauna bears similarity to forms in Brazil and Gabon and is unlike the fauna of equivalent age in North America and Europe. As on land, the wide variation in thickness points to the possiblity of basins under the continental shelf, an inference already supported by the seismic-reflection profiles. Further, the sequence tends to become more continental toward the northwest and the southeast; more of a marine section typifies the thicker central part of the shelf basin in between. Some strata contain abundant carbon fragments, which may be interbedded with marine shales. The paucity of fossils and the limited number of those described would appear to indicate a paralic setting of coastal lagoons and bays. A few thin conglomerates contain pebbles of quartz, quartzite, and chert set in a shaly matrix -- a lithology in part similar to that found in the Farmington River Formation but without the pebbles of sandstone, gneiss, and diabase.

A thin sequence (214 m) of Upper Cretaceous sandstone and shale was found at one site where its base is marked by a porous friable sandstone that unconformably overlies older sedimentary rocks.

A thin Cenozoic sequence (160-340 m) of fossiliferous shale, limestone, and sandstone was drilled offshore. Because of the necessity of setting casing to a depth of 100 or 200m below the sea floor, most of the youngest Tertiary and Quaternary rocks were not cored; however, spot bit samples do contain clay of Pliocene-Pleistocene age. Glauconitic sandstone containing shallow-water benthonic Foraminifera of Eocene age were cored near the base of the section. Interlayered glauconitic limestone and claystone, with pellets and a fauna of benthonic Foraminifera, small gastropods, and fish bones suggest a marine shelf environment where coquinas of skeletal debris accumulated and where infauna burrowed the muds to leave abundant fecal pellets.

Dredged rock

The continental slope was dredged successfully in two places, off Cape Palmas and west of Harper (fig. 1) -- at the opposite end of the margin from the drill sites. The dredge samples contain a variety of rocks (table 1). The sites were chosen because profiles 34 and 28 (fig. 2) indicated that older strata might crop out or would be thinly covered on the upper continental slope.

Table 1. Mineralogy of dredged rocks. (Powdered samples of rock were x-rayed and percentages of minerals were determined utilizing a semiautomated technique developed by J.C. Hathaway. Values in parentheses bracket values for kind of layer silicate.)

	Lithologic description	Field designation	Layer silicate	Montmorillonite	Kaolinite	Disordered cristobalite	Quartz	Potash feldspar	Plagioclase	Calcite	Calcic dolomite	Apatite	Other	
	Light-yellowish, gray unfossiliferous claystone	LM2-1,2	73	(66)	(7)		9	3					15	Palygorskite
HAUL 1	Yellowish-gray finely crystalline massive limestone	LM2-3					1			99				
	Yellowish-white soft dull ooze	LM2-4	91*			8							1	Halite
	Mottled gray and white biotite gneiss	LM4-2					33		57				10	Biotite
	Brown calcareous sandy phosphorite	LM4-3	16				1			15		51	17	Aragonite
	Gray sandy poorly sorted phosphorite	LM4-5	20				5		7	8		60		
	Gray pebbly phosphorite and sandy siltstone	LM4-7				31				7		62		
HAUL 2	Dull-brown, aphanitic dolomite	LM4-1	18							1	81			
	Brown sugary Mn-coated dolomite	LM4-4	4						1	2	80	13		
	Yellowish-brown calcareous sandy dolomite	LM4-8	1								81	13	5	Clinoptilolite
	Medium- to light-gray silty claystone	LM4-6	64	(13)	(51)	30	1		2				2	Pyrite
	Light-yellowish white earthy claystone	LM4-9	47	(21)	(26)	47	3	2	1					

* Including some amorphous material.

The dredge haul off Cape Palmas (covering 1200-1800-m isobaths) brought back three rock types: claystone, limestone, and diatom ooze. The claystone is a moderately indurated rock riddled by borers. Texturally, it is a fine fibrous mat of clay minerals with scattered angular grains of quartz and feldspar and trace amounts of glauconite. The limestone is recrystallized as a fine mosaic of interlocking anhedral crystals and contains the faint outlines of rotaliform Foraminifera; anhedral crystals are 1/20-1/40 mm long. None of the forams proved well enough preserved to give an age. The diatom ooze is a porous lightweight punky sediment which, in thin section, is an amorphous mosaic of optically unidentifiable debris. A few diatoms are scattered as stalklike fragments (in cross-section). According to David Bukry (written commun., Jan. 1972) the fossil assemblage is "similar to that of the middle Eocene Sidney Shale"; hence, it suggests that by the early Tertiary, this part of the margin had subsided so that pelagic debris accumulated on an ancestral slope or rise.

The second successful dredge haul, 110 km west-northwest of the first one, covered the upper continental slope from 1250-850 m and retrived nine different types of rock, mostly marine sedimentary rocks of Tertiary age. Details on the petrography of the rocks are given in the appendix. Several angular blocks of a mottled white and gray quartzofeldspathic gneiss were retrieved. This rock consists mainly of quartz, feldspar, and biotite and is similar to sheared quartz chloritic gneiss mapped in the Harper environs (Eric Force, oral commun., Jan. 1973).

Three rocks (table 1) are phosphatic clastics (fig. 8) with similar amounts of carbonate fluorapatite (probably francolite) and variable amounts of layer silicate, disordered cristobalite, quartz, and calcite. Most importantly, two of the phosphorites and phosphatic dolomite contain a similar assemblage of Foraminifera that indicates an early Miocene age (table 2).

	LM4-5 (Phosphorite)	LM4-7 (Phosphorite)	LM4-8 (Sandy dolomite)
Afrobolivina? sp.			x
Anomalina aff. glabrata Cushman			x
Bolivina spp.	x		
Camerina sp.	x	x	x
Carpenteria monticularis Carter			x
Cassidulina sp.	x		
Ceratocancris eshira (de Klasz and Rerat)	x	x	x
Daucina ermaniana Bornemann	x	x	x
Dentalina sp.	x		
Eponides sp.			x
Globigerina spp.	x	x	
Kathina jamaicensis (Cushman and Jarvis)?			x
Lenticulina sp.	x		
Nonion pompilioides (Fichtel and Moll)		x	
Plectofrondicularia? sp.	x		
Pseudononion? sp.	x		
Siphogenerina sp.		x	x
Sphaeroidina bulloides d'Orbigny		x	
Uvigerina aff. peregrina Cushman	x	x	

Table 2. Microfossils of three rocks. (Foraminifera identified by Ruth Todd, U.S. Geological Survey. Foraminiferal assemblage in these rocks is thought to indicate an early Miocene age, possibly with a mixture of Paleocene in LM4-8.)

Three different types of yellowish-brown calcicdolomite were collected — a massive aphanic dolomite (LM4-1; table 1), a finely crystalline dolomite (LM4-4), and a sandy phosphatic dolomite (LM4-8). All are fossiliferous, but only the sandy phosphatic dolomite contains identifiable fauna (table 2), which indicate an age of early Miocene.

The last two rock types are both claystones made up almost entirely of layer silicates and disordered cristobalite. One is a soft laminated gray rock with trace amounts of quartz and glauconite plus scattered coccoliths and a few smaller Foraminifera. The laminations reflect changes in the amounts of blackish-brown opaque inclusions of an unknown composition. David Bukry (written commun., Jan. 1972) examined the laminated claystone and found a coccolith assemblage of the *Heliolithus kleinpellii* Zone, indicative of a middle Paleocene age (57-59 m.y.). The assemblage, plus the lack of pentaliths, led Bukry to infer that the rock formed under marine pelagic conditions.

The other claystone is yellowish gray and massive. It shows a similar matrix of fine detritus with scattered angular quartz, rounded glauconite, rotalid Foraminifera, and coccoliths. None of the fauna permitted an age designation. The subequal amounts of montmorillonite and kaolinite suggest a contribution from a weathered granitic area, such as the West African Shield, and from volcanic ash.

The stratigraphic data give some idea of the ages of sedimentary rocks under the Liberian margin and the conditions under which they formed. Major stratigraphic units, in addition to the Paleozoic rocks, are volcanic rocks of Jurassic age unconformably overlain by thick sparsely fossilferous marine-lagoonal(?) sedimentary rocks of Early Cretaceous age. A thin nonpersistent marine sequence of Late Cretaceous age unconformably overlies older units offshore and is overlain by a thin marine section of Tertiary age -- a sequence that becomes more marine seaward and less so on land. Maximum sedimentation took place during the Early Cretaceous, and it was interrupted toward the close of the Mesozoic and the beginning of the Cenozoic by faulting and folding. A marine transgression occurred during the Tertiary, and subsidence was limited on the shelf.

DISCUSSION

The onshore and offshore stratigraphic information permits some speculation on the ages of reflectors found in the reflection profiles. Off the southeastern third of Liberia (fig. 2), acoustic basement beneath the shelf is probably Precambrian crystalline rocks (X on fig. 2); they appear to extend to the shelf edge, to be dropped downward beneath some parts of the slope, and to be overlapped by younger deposits. Most of the crumpled reflectors beneath the slope and rise in the southeastern area are presumed to be in Cretaceous and Tertiary sediments that have slumped and draped over the foundered blocks of pre-Cretaceous rock. The thickness of these Cretaceous and younger(?) sediments is at least 4-5 km beneath the lower continental rise, thinning gradually seaward and thinning abruptly toward the upper slope. Reversals in the thinning trend landward take place in the form of small sediment basins beneath the continental slope. The increased thickness of layered deposits in some of these "pocket basins" (profile 30, fig. 2) indicates that access to the deep ocean may have been partly blocked, or perhaps the basins have a long history of subsidence and sedimentation, dating back to prerifting time.

Adjacent to both southeast Liberia and northwest Liberia, the slope has been extensively eroded to expose older deposits. As off eastern North America, accelerated erosion of the continental slope may be connected with periodic lowering of sea level during the Pleistocene, which permitted direct delivery of river deposits to the shelf edge, there to move downslope as slumps or turbidity currents.

Beginning with the continental shelf off Greenville and extending to the northwest, pre-Cretaceous rocks are buried by a sedimentary covering of variable thickness (profile 26, fig. 3; fig. 7). The older rocks still extend under the shelf, but they appear downwarped and faulted along the inner shelf. A steepened boundary can be seen on profiles 16, 18, and 19 (X on fig. 3).

Off the central Liberian coast, the thickened prograded wedge of sediments (profiles 16-21) makes it difficult to delineate the depth to pre-Cretaceous rocks. Under the southeastern part of the central area, blocks defining acoustic basement deepen! seaward and westward. The blocks probably are related to a fracture zone in this area. Northwest of profile 21, a strong basement reflector under the slope is apparently obscured by thick sedimentary deposits.

Off northwest Liberia where shelf basins are more extensive, they are truncated at the shelf edge by faulting and downdropped under slump deposits beneath the slope. The steepened reflector (Y on fig. 4) is probably a Late Cretaceous or early Tertiary fault-slump zone formed in response to subsidence at the edge of the crustal block, and as such, it represents the main zone of slippage for shallow crustal layers between theoceanic and continental blocks. Major activity along this zone probably occurred during the late Mesozoic or early Cenozoic. The faulting cuts the gently folded section of what is probably Lower Cretaceous rock and is covered by a few hundred meters at most of Tertiary and Quaternary sediments (age inferred from nearby well data). The strong acoustic basement, which shows up clearly on the multichannel profiles surveyed on the shelf, we infer to be crystalline rock underlying Cretaceous and Tertiary(?) sedimentary rock at a depth equivalent to almost 2 seconds on profile B-B' (fig. 6). In most of the other profiles, the sedimentary section thins to 1 second or less.

At least three unconformities are revealed in well data, and we can see as many as three on the interpreted profiles (fig. 6, profiles D-D', F-F'). Drill data show unconformities between the Lower Cretaceous and older volcanic or sedimentary rocks, between the Lower Cretaceous and Upper Cretaceous rocks, and between the Cretaceous and Tertiary Systems. It is tempting when looking at figure 6, to match surfaces at points X, Y, and Z with unconformities in the drill-hole data. If they are correlative, it would indicate that the Lower Cretaceous section is the thickest unit, that the Upper Cretaceous(?) section wedges, and that the Tertiary sequence is much more extensive than the Cretaceous deposits -- a relation already noted by White (in press, fig. 2) for coastal Liberia.

In summary, the structural fabric of the Liberian margin is that of a fractured blockfaulted zone to the southeast with most sediment beneath the rise; to the northwest, sediment-filled shelf basins are faulted seaward, and at least as much or more sediment is under the rise-lower slope as under the shelf. The basins under the shelf and the sediment prism under the rise trend subparallel to the coast. Now, how does this pattern compare with the Ivory Coast basin to the east and the Senegal basin to the northwest (fig. 9)?

The Ivory Coast basin (Spengler and Delteil, 1966; Arens and others, 1970) trends east, parallel to the coast, and mainly underlies the shelf and slope (fig. 9); it is bordered onshore by a major east-trending coastal fault thought to tie in with the St. Paul's fracture zone near Cape Palmas. South of the coastal fault, more than 5 km of Cretaceous and Tertiary sediments exist in a south-plunging monocline. Maximum thickness of post-Jurassic strata is thought to be under the continental slope and to thin under the Gulf of Guinea. This basin lies between two oceanic fracture zones (fig. 9), the shoreward projection of the St. Paul's fracture zone to the north and the Romanche zone to the south.

Within the Ivory Coast basin, deposits thin and are more clastic to the east -- the presumed source area of some of the clastic materials. In addition, the shield area east and north of the basin appears to have had a complex history of faulting and intrusion (Spengler and Delteil, 1966).

The framework of the margin off Liberia and the Ivory Coast has some features we feel relate to the prerift reconstruction of South America and Africa. On the fit worked out by Bullard, Everett, and Smith (1965), both Cape Palmas and Cape Three Points (near the Ghana-Ivory Coast border) are areas of continental overlap, with an elongate gap in between -- now the site of the Ivory Coast basin. The zone of overlap now constitutes the area of little shelf sedimentation both off Liberia and the Ivory Coast. As such, the zone would appear to have been a positive crustal element as far back as the Mesozoic or even Paleozoic, as indicated by what we have inferred from the seismic-reflection profiles on the shelf adjacent to Cape Palmas (fig. 2), and by the thickness relations outlined by Spengler and Delteil (1966). Hence, the eastern margins of both countries appear to be zones of faulting and intersection of oceanic fracture zones. Westward and seaward, sediments in the Ivory Coast basin thicken, until at the western end of the Ivory Coast, the basin terminates against crystalline basement east of Cape Palmas. Though the Liberian margin also has a fracture zone at its eastern terminus and the sediments thicken seaward and to the northwest, it lacks the continuous border fault and is not the shape of the Ivory Coast basin. Basins beneath the shelf become more extensive to the northwest and thicken in that direction up to the Sierra Leone border, where they die out, and intrusions of unknown age underlie much of that area (White and Leo, 1969, p. 12; C. Thorman, written commun.).

The western terminus of the Liberian margin has several features that lead us to suspect that there may be another oceanic fracture zone obliquely intersecting the coast near the Sierra Leone-Liberia border (fig. 9). Besides the termination of basins beneath the shelf and the presence of intrusives in the Cape Mount area (western Liberia), the whole margin (shelf-slope-rise) changes orientation off Sierra Leone, and there is a noticeable change in the trend of the regional tectonics on land (Behrendt and Wotorson, in press).

In addition to Cape Mount, a basic intrusive body occurs at Freetown, Sierra Leone, on line with the extension of the Guinea fracture zone (Krause, 1964). Radiometric dates and paleomagnetic data (Briden and others, 1971) indicate that the Freetown complex appears to have been emplaced sometime during the Triassic, and thus it overlaps the rifting of the Americas and Africa. The basic composition of these intrusive rocks and their occurrence near the coast leads us to wonder, as have Black and Girod (1970, p. 205-206), whether the intrusive rocks might not be a product of a partial fusion of the upper mantle emplaced during the initial phase of downwarping prior to the actual breakup of Africa and the Americas.

A generalized bathymetric map (Templeton, 1970, fig. 8) shows a deviation in the northwest trend of the slope so that it strikes east for a distance of 100 km southwest of Sherbro Island, southeastern Sierra Leone. The change is similar though less pronounced than the one to the north off Guinea, where the east-trending margin segment is more than 300 km long and is thought to have originated during the creation of the Guinea fracture zone (Krause, 1964). The tectonic trend of foliated crystalline rocks in western Liberia within the Liberian age province is dominantly northeast (Behrendt and Wotorson, in press, pl. 1). Toward the coast, the trend becomes markedly eastward, subparallel to the offshore strike of the slope.

The coincidence of these trends and intrusive rocks may be fortuitous so far as the existence of an oceanic fracture zone off northwest Liberia is concerned. However, if a fracture zone does exist, most of the evidence for it should appear as a fracturing of the southeastern margin of Sierra Leone and as linear magnetic anomalies beneath the rise to the west. An earthquake that occurred in 1957 near the southeastern coast of Sierra Leone (Sherbo Island) is evidence of recent tectonic movement (Sykes and Landisman, 1964, p. 1938).

Though the Liberian margin is situated between places where oceanic fracture zones appear to intersect the African continent (fig. 9), the tectonic framework is different from the Ivory Coast basin, and we think that the difference may relate to the gap in the prerift fit of South America and Africa (Bullard, and others, 1965). In the reconstruction by Bullard and others, the gap is a V-shaped opening to the northwest and extends at least as far north as Guinea. If this gap is the southern end of an ancestral North Atlantic Ocean, it would be logical to expect a margin open to the sea in post-Jurassic time. To judge by the oblique high-angle intersection of the fracture zones with Africa (LePichon and Fox, 1971), the translation of Africa and North America away from each other should have created a seaway far more easily northwest of Cape Palmas than in the Ivory Coast-Ghana area (underside of the West African bulge), where the low angle of fracture zone-continent intersection (fig. 9) resulted in a relatively narrow gulf between South America and Africa as they slid by each other. At the same time, this slow rate of opening between South America and Africa would tend to offer a lateral supply of detritus over a longer time to the elongate basin subsiding in between.

The Senegal basin to the north is an extensive feature, stretching more than 900 km in length from Portuguese Guinea on the south to Mauritania on the north and more than 500 km inland from the coast (fig. 9). It opens towards the west (sea) and contains more than 7 km of Mesozoic and younger sediments. It has been well described by Sougy (1962), Aymè (1965), Spengler and others (1966), Templeton (1970), and Beck (1972). As with the basins to the south, it has formed in response to subsidence at the trailing edge of a continent, but it lies athwart the extension of the Cape Verde fracture zone (LePichon and Fox, 1971). According to Beck (1972, fig. 3), the prism of Cretaceous and Tertiary sediments is built out across a blockfaulted basement of Paleozoic sedimentary rocks (Aymè , 1965, p. 85) and Precambrian slate, quartzite, and granite. Salt domes intrude Cretaceous and younger strata in the southern part of the basin from source beds thought to be of Early Cretaceous age and to be deeper than 5 km (Templeton, 1970, fig. 6).

Much of the earlier history of the proto-Atlantic Ocean is recorded in the foundered part of the crust now deeply buried by younger sediment close to the continents (Beck, 1972, fig. 3). Deep ocean drilling (DSDP project) on Legs 3 and 14 has revealed several unconformities in deep-water sediments of Cretaceous and Tertiary age, and basalt below the sediment, inferred to be of middle Cretaceous age (by the Scientific Staff, 1971; Maxwell and others, 1970), but nothing that could be interpreted as crustal fragments of a shallow Atlantic Ocean.

In contrast to Cape Palmas, Liberia, little disturbance seem to be caused by the intersection of the Cape Verde fracture zone with the Senegal basin. A slight thinning of strata and faulting occurs in the Dakar-Cape Verde area (Templeton, 1970, fig. 8), on line with the extension of the oceanic fracture zone, but these structural-stratigraphic modifications are thought to be due to recurrent movement along a basement hinge line.

Another difference between the Senegalese and Liberian margins is the lack of thick evaporites in offshore Liberian strata. We saw what might be a salt diapir on one section, but the lack of these structures clearly displayed over a wide area, and the absence of evaporites in the well logs, make it doubtful that evaporites formed off Liberia. They did form, however, off northwest and southwest Africa (Emery, 1972) and at several areas around the North Atlantic in Early Cretaceous and Late Jurassic time (Templeton, 1970, fig. 3). The Atlantic apparently was a restricted marine body of water that extended not much farther south than Senegal at that time.

In summary, the Liberian margin appears to have a structural framework intermediate between the open-sided Senegal basin to the northwest and the elongate narrow Ivory Coast basin to the east. Crustal fracturing and subsidence during the separation of Africa and South America seem to have delineated the basin off the Ivory Coast, and to a lesser degree some of the basins off Liberia. The loci of deposition for the Ivory Coast and Liberian margins are mainly the continental shelf and slope, whereas the Senegal basin extends 500 km or more inland, thought it also thickens rapidly over the shelf and slope. For the Senegalese and Liberian margins, the rifting appears to have been attended by intrusion of dikes and subsidence to form basins subparallel to the preexisting structural trends. In the case of Liberia, this trend would be the Pan African province -- a coastal belt of northwest-trending metamorphic rocks whose main episode of metamorphism was 550 m.y. ago. In the case of Senegal, the older trend is the north-striking belt of folded rocks of Paleozoic age, deformed during the Hercynian orogeny (Sougy, 1962).

Spengler and Delteil (1966) have given a fairly complete geologic history of the area bordering Liberia to the east, and doubtless much of it applies to Liberia as well. The oldest sequence connected with the basin development in the Ivory Coast is a sequence of sandstones, conglomerates, and varigated shales as much as 2000 m thick; it contains a few ostracodes and some pollen that indicate a probable lacustrine origin, and it grades in the upper part of the sequence laterally into marine deposits of Aptian-Albian Age (late Early Cretaceous). In Liberia, the probable equivalent sequence lacks the coarse clastic materials, but it is carbonaceous, has the same sparce fauna of ostracodes, contains a few thin limestone beds, and is even thicker (as much as 2690 m). We lack the stratigraphic control to say whether these deposits are a rift filling, as they are thought to be in the Ivory Coast basin. Certainly their limited areal extent in shelf basins in part bounded by faults would be compatible with such a setting. The Ivory Coast basin and the Senegal basin went through a history of marine transgression and regression during the remainder of the Cretaceous to give rise to a fairly thick sequence of marine shale and sandstone (Spengler and Delteil, 1966; Aymé, 1965). Liberia has a far less complete record for this interval, in that Upper Cretaceous rocks show only in one well, where there is 216 m of marine shale, siltstone, and sandstone unconformably above Lower Cretaceous rocks.

The cover of Tertiary rocks is only a few hundred meters thick and poorly sampled offshore, yet the dredged rocks clearly show that the Liberian margin was the site for the accumulation of pelagic deposits at least as far back as the Paleocene when a coccolith marl was deposited. To the east, a transgressive sea covered the Ivory Coast basin, where more than 500 m of foraminiferal glauconite marine clay was deposited (Spengler and Delteil, 1966). In Senegal, the marine transgression gave rise to a widespread marine limestone that unconformably overlies Upper Cretaceous regressive deposits. The limestone is oolitic and glauconitic and contains an abundant fauna of Foraminifera as well as broken debris of gastropods and lamellibranchs (Spengler and others, 1966). The deposits (50-100 m thick) are thought to have formed in a shallow gulf open to the west. A similar though narrower shelf may have existed off Liberia; we can only speculate on its existence because though Tertiary limestone and shale exist there, we know of lower Eocene and younger rocks in only one location (fine- to medium-grained sandstone with abundant benthonic shallow-water Foraminifera). The sandstone off Liberia compares with as much as 490 m of sandy clay and reef limestone with glauconite in the Ivory Coast basin, and with as much as 800 m of fossiliferous limestone and shale with an abundant fauna of benthonic and planktonic Foraminifera in the Senegal basin. This lower Tertiary marine section represents the last major incursion by the sea into Senegal and the Ivory Coast; later deposits are areally restricted or are continental. The one dredge sample of Eocene age brought up off Liberia proved to have been deposited in relatively deep water, as indicated by the abundant marine diatoms and the absence of pennate diatoms (G.W. Andrews, written commun., Dec. 1972).

SUMMARY AND GEOLOGIC HISTORY

Stratigraphy and geophysics indicate that the Liberian margin has had a complex history of volcanism, subsidence, and faulting since the Precambrian. A fragmentary stratigraphic record indicates that the Liberian coastal area subsided enough to provide the site for deposition of marine(?) clastic material and limestone during the early Paleozoic. Both offshore and on land, basic igneous rocks intruded the area during the Jurassic as belts of dikes and sills extending as far southeast as Greenville. Volcanics encountered beneath the shelf tend to be younger than those dated on land, and along the shelf, the youngest volcanic rocks (Lower Cretaceous) are to the southeast. The trends and ages of volcanism seem most clearly connected with rifting of North America and Africa and the tensional strain that attended the opening of the North Atlantic (May, 1971). The basins created after this interval of rifting-volcanism provided the sites for the accumulation of a thick sequence of Lower Cretaceous nonmarine and marine clastic materials, as fluvial, lagoonal, bay, and shelf deposits. Beneath the shelf, this section becomes more continental in origin to the southeast and northwest and more marine to the center. Sedimentation took place from the Late Jurassic through Early Cretaceous; it covered a more restricted interval in time to the southeast because the preceding period of volcanism affected the shelf for a longer part of the Cretaceous and shifted the loci of deposition to the slope (off central Liberia) and the continental rise. Subsequent faulting in the Late Cretaceous or early Tertiary truncated shelf basins to the southwest and downdropped them beneath the slope and rise. Limited subsidence and unrestricted marine conditions marked the Liberian shelf during much of the Tertiary. In the early Miocene, a combination of upwelling, biological productivity, and sea-water chemistry helped to form marine apatite, in part through replacement of carbonate deposits.

APPENDIX

Petrology of some of the dredged rocks

Several rocks obtained offshore shed information on conditions of deposition during the Tertiary and are of possible economic significance; hence, a more detailed description and genesis are given here than were presented in the main body of the paper. The rocks are all from th second dredge haul (table 1) due west of Harper.

The phosphatic rocks (LM4-3,5,7) contain sufficiently large amounts of fluorapatite to be of economic interest. But for the phosphate content, the first of these rocks would be a foraminiferal calcarenite. It is a brown bioclastic rock in which the framework is mainly unreplaced rotalid and globigerinid Foraminifera (80 per cent) and pellets (20 per cent). A phosphatic groundmass of layer silicate and apatite binds together the fairly well sorted assemblage of microfossils. Pellets are well rounded, as much as 0.5 mm long, and made of a finely crystalline mixture of apatite, calcite, and opaque impurities. The other two rocks are conglomerate and dark-gray phosphatic sandstone. The sandstone is medium- to coarse-grained fossil fragments and sporbo set in a matrix of finely divided bioclastic debris, clay minerals, and apatite (fig. 8). The poorly sorted mixture contains an abundant fauna of planktonic and benthonic Foraminifera (table 2), though the tests are corroded and stained. Phosphate pellets are as much as 4 mm long, concentric and massive, nucleated and nonnucleated. The conglomerate is intercalated with thin greenish-gray sandy siltstone. Compositionally, the conglomerate is similar to the sandstone except that it contains large gray (light inside, dark outside) rounded to subrounded aphanic phosphate pebbles as much as 16 mm long in a loosely packed framework with well-sorted foraminiferal sand. Foraminifera make up approximately 4/5 of the interstitial debris; broken fragments of larger fossils make up the remaining 1/5. Most of the debris has been replaced by apatite, and some is silicified. A finely crystalline mixture of apatite and disordered cristobalite binds the rock together.

The Liberian phosphorites show similarities to other phosphorites elsewhere; from other studies, we can gain some insight as to the conditions of deposition. The tectonic situation along the "hinge line," or border zone of a subsiding continental edge is the same setting noted by McKelvey and others (1959) for the Phosphoria Formation. Off Liberia, however, the apatite is mainly associated with carbonate, whereas in the western United States, Permian deposits are associated with chert and carbonatic mudstone.

To judge by the marine fauna and the sorting of the debris, the deposits accumulated on an open shelf, not unlike what Gibson (1967) inferred for the Pungo River Formation (Miocene) of North Carolina. We are impressed by the widespread distribution of phosphatized Miocene deposits in the Atlantic (southeast United States, northwest Africa, Liberia, and South Africa) and, like Summerhayes (1970), wonder whether there was a peculiar pattern of paleocirculation that facilitated phosphatization in such widely scattered areas over a limited time span. We do not find the volcanic debris or large amounts of glauconite noted by other workers, but we do see the evidence of reworking and sorting of pellets and bioclastic debris noted by D'Anglejan (1967), Baturin (1971), Gibson (1967), and Summerhayes (1970). We cannot say whether or not the phosphorites accumulated in a regime marked by slow sedimentation, but certainly good sorting and lack of much terrigenous debris seems to indicate that the phosphorite accumulated in an offshore area where currents were active.

The actual way in which the pellets (sporbo) formed is not understood. They could have started out as soft gel-like blobs of apatite similar to those described by Baturin (1971) off southwest Africa and Chile, that grew in the sediment in response to relatively high concentrations of dissolved phosphorous and calcium in the interstitial waters. The situation Baturin described was not exactly the same as that in Liberia because the soft nodules he described formed in a diatom ooze, whereas the pellets we described are associated with carbonate. Some movement during phosphatization with multiple accretion of phosphate in the Liberian deposits is indicated by the presence of incomplete overlapping rims on some pellets. Other pellets have a few concentric layers near the outer edge or are built around bone fragments or other pieces of organic debris. Clearly the presence of organic debris in association with $CaCO_3$ seems an aid in forming the pellets.

As off South Africa (Parker and Siesser, 1972) and northwest Africa (Summerhayes, 1970), phosphate mineralization has affected the matrix and fossils. The conversion is selective in that the matrix may be phosphatized (still retaining scattered grains of carbonate and opaque impurities) but not the Foraminifera; this degree of phosphatization is similar to what Parker and Siesser (1972) describe on the Agulhas Bank, except that our samples do contain structureless phosphatic pellets and theirs do not. As we have already described, many of the chambered tests are replaced by apatite, possibly through contact with sea water or interstitial waters concentrated in dissolved phosphate. Such transformations have been accomplished in the laboratory at fairly low PO_4^{-3} concentrations by Ames (1959).

Though varied in texture, the dolomites (LM4-1,4,8) do show some similarity to the phosphorite in age and mineralogy (tables 1 and 2). The dull aphanic dolomite (LM4-1) is worm bored, coated by a brownish-black iron oxide, and breaks with the conchoidal fracture. In thin sections, it is a finely crystalline mosaic with scattered grains of glauconite and a few recrystallized Foraminifera tests. Faint brown oval outlines of pellets(?) 0.2-0.4 mm long are scattered through the dolomite and contribute to the general impression that the rock was originally a wackestone (Dunham, 1962, p. 117).

The second type (LM4-4), a finely crystalline dolomite, differs from the first type in that the dolomite is coarser (1/20-1/100 mm in diameter) and the apatite occurs as discontinuous patches and fillings in between the dolomite crystals. The coarser crystallinity of the dolomite and phosphate gives the rock a powdery dull cast and blocky fracture. Dolomite rhombs as much as 1/20 mm long line some vugs in the rock, though most of the crystals are irregularly shaped. Scattered detrital silicate grains and recrystallized fragments of fossils testify to the former clastic nature of the rock.

The third type of dolomite (LM4-8) is likewise phosphatic but consisting of an abundant matrix of coarsely crystalline dolomite rhombs (1/5-1/10 mm) that surrounds scattered sporbo, phosphatized Foraminifera tests, shell fragments, and a few angular quartz grains. As can be seen from table 2, the rock contains an abundant planktonic fauna, mostly indicative of a pelagic realm well away from the coast. Like the phosphorites, this dolomite shows two intervals of phosphatization, the first connected with formation of the rounded phosphate pellets, and the second, a phase of replacement of carbonate debris.

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LIST OF ILLUSTRATIONS

Figure 4 Interpreted seismic-reflection profiles for the northwestern sector of the Liberian continental margin. Notice the buried discordant reflectors beneath the slope (points Y), the slump(?) scars (points X), antithetic faults (points Z), and the gullying of the slope. Above each profile is the total magnetic intensity with the International Geomagnetic Reference Field (IGRF) removed. Data used to plot magnetic profiles were sampled at 2.5-km intervals from original more closely spaced observations; hence, the profile is overly smooth above shallower magnetic basement of the continental shelf.

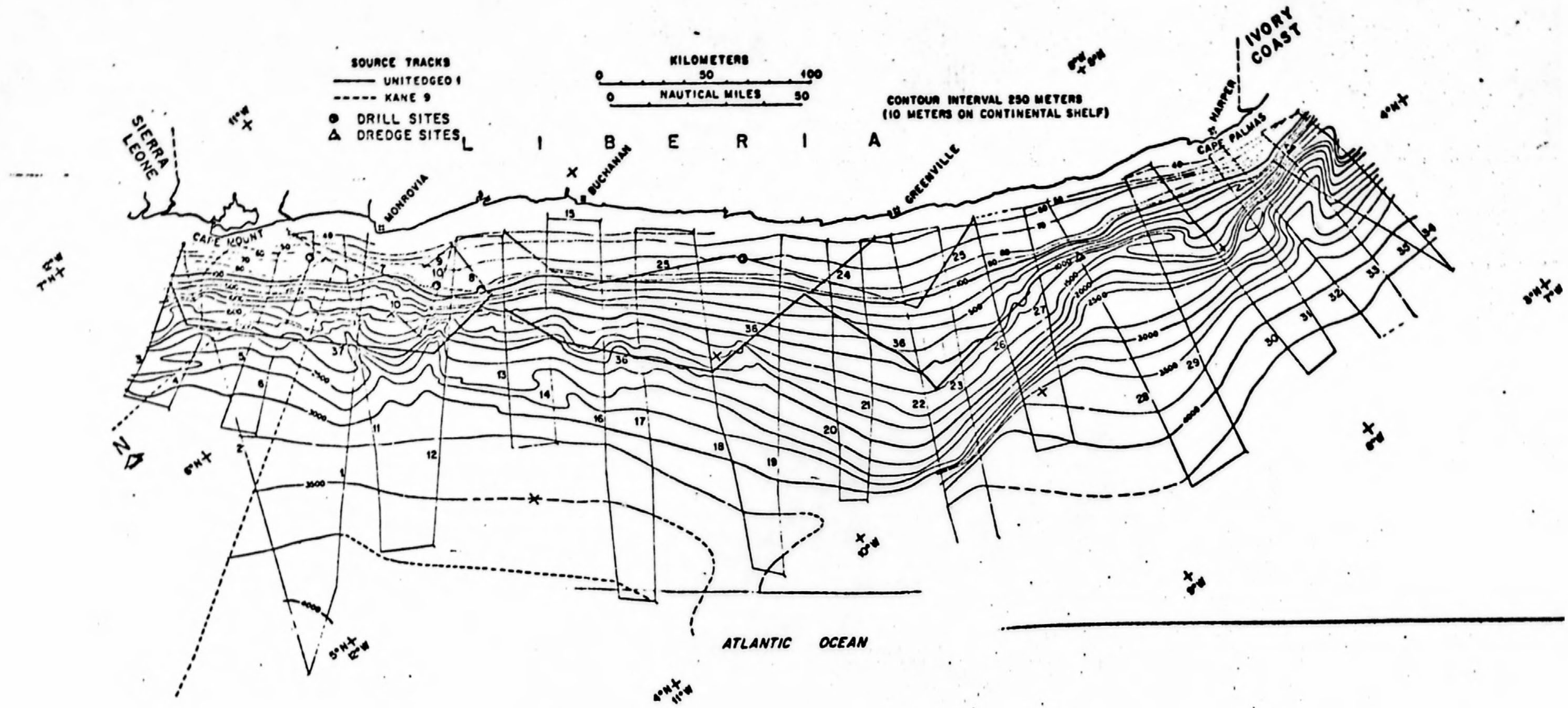
Figure 5 Interpreted seismic-reflection profiles taken along the Liberian slope and rise. The right-hand side of the top profile is continuous with the left-hand side of the middle profile. Notice the broad tilted buried block at the southeastern end of profile 36. Reflectors are more even along the central and northwestern part of profile 36, though even here marked discordancies (points X) suggest the edge of a buried block.

Figure 6 Interpreted seismic-reflection profiles taken on the Liberian continental shelf. Profiles C, D, E, F, and G are interpretations of profiles given to us from an industry source; inset map shows the location of shelf profiles. Notice faulting of acoustic basement (profiles B, C, D, and F) and the discordancy of major reflectors in the shelf basins (points X, Y, and Z). The discussion section suggests possible ages of the reflectors based on drill-hole findings.

Figure 7 Schematic map of the structural-stratigraphic framework of the Liberian margin based on bathymetry, reflection profiles, and magnetic surveys. General east-west alinement of elements off southeastern Liberia is probably the result of the intersection of the St. Paul's fracture zone plus auxiliary zones with the margin. The northwest alinement of structural elements off the remainder of Liberia is parallel to the Pan African trend and to diabase belts emplaced during the rifting of North America and Africa.

Figure 8 Photomicrographs of phosphorites (plane-polarized light); dark-gray phosphatic sandstone. A, Partly phosphatized Foraminifera test and elongate phosphate pellets set in a matrix of disordered cristobalite (field number LM 4-7). B, Massive phosphorite pellet (upper left), carbonate fossil fragments, and sporbo (oval concentric grains in center) surrounded by a matrix of angular quartz, feldspar, and layer silicate (field number LM 4-5).

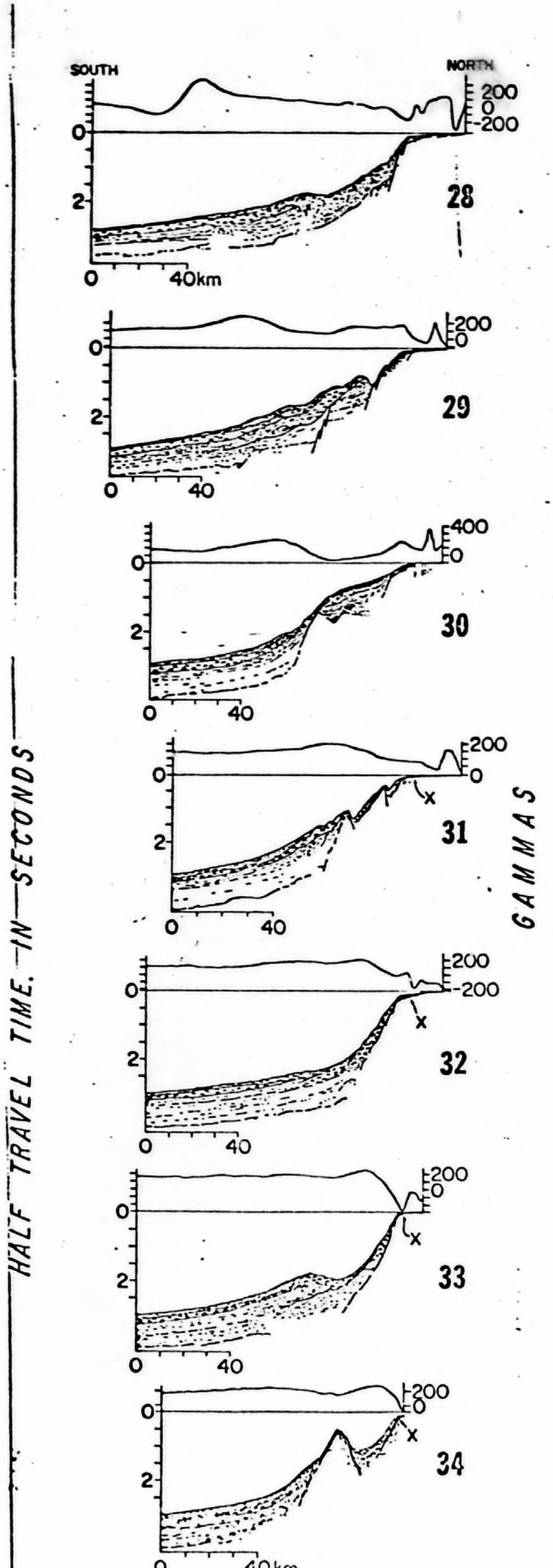
Figure 9 Map of West African coastal basins. Vertically lined area marks the edges of the West African Shield.



SOURCE TRACKS
UNITEDGEO 1
KANE 9
DRILL SITES
DREDGE SITES
KILOMETERS
0 50 100
NAUTICAL MILES
0 50
CONTOUR INTERVAL 250 METERS
(10 METERS ON CONTINENTAL SHELF)
SIERRA LEONE
L I B E R I A
IVORY COAST
CAPE MOUNT
MONROVIA
BUCHANAN
GREENVILLE
HARPER
CAPE PALMAS
ATLANTIC OCEAN
N

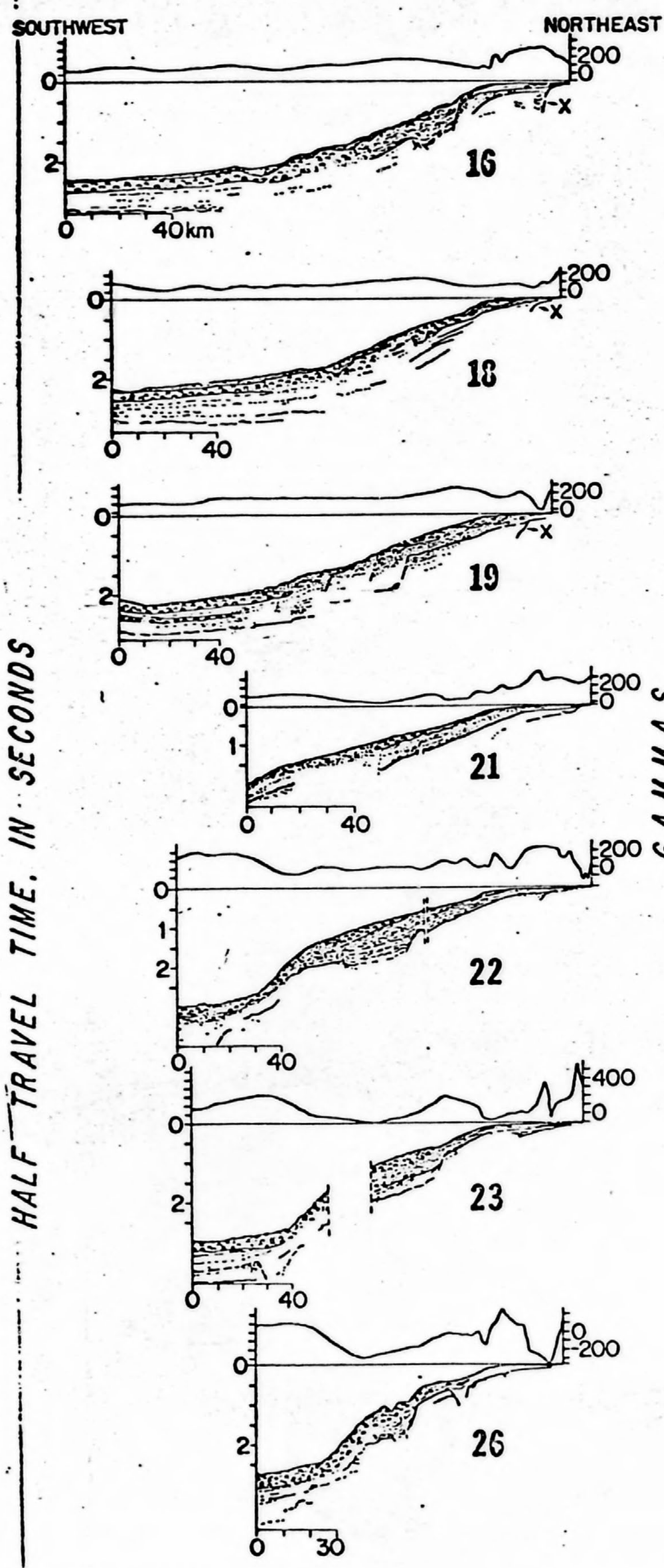
Figure 1

Fig. I



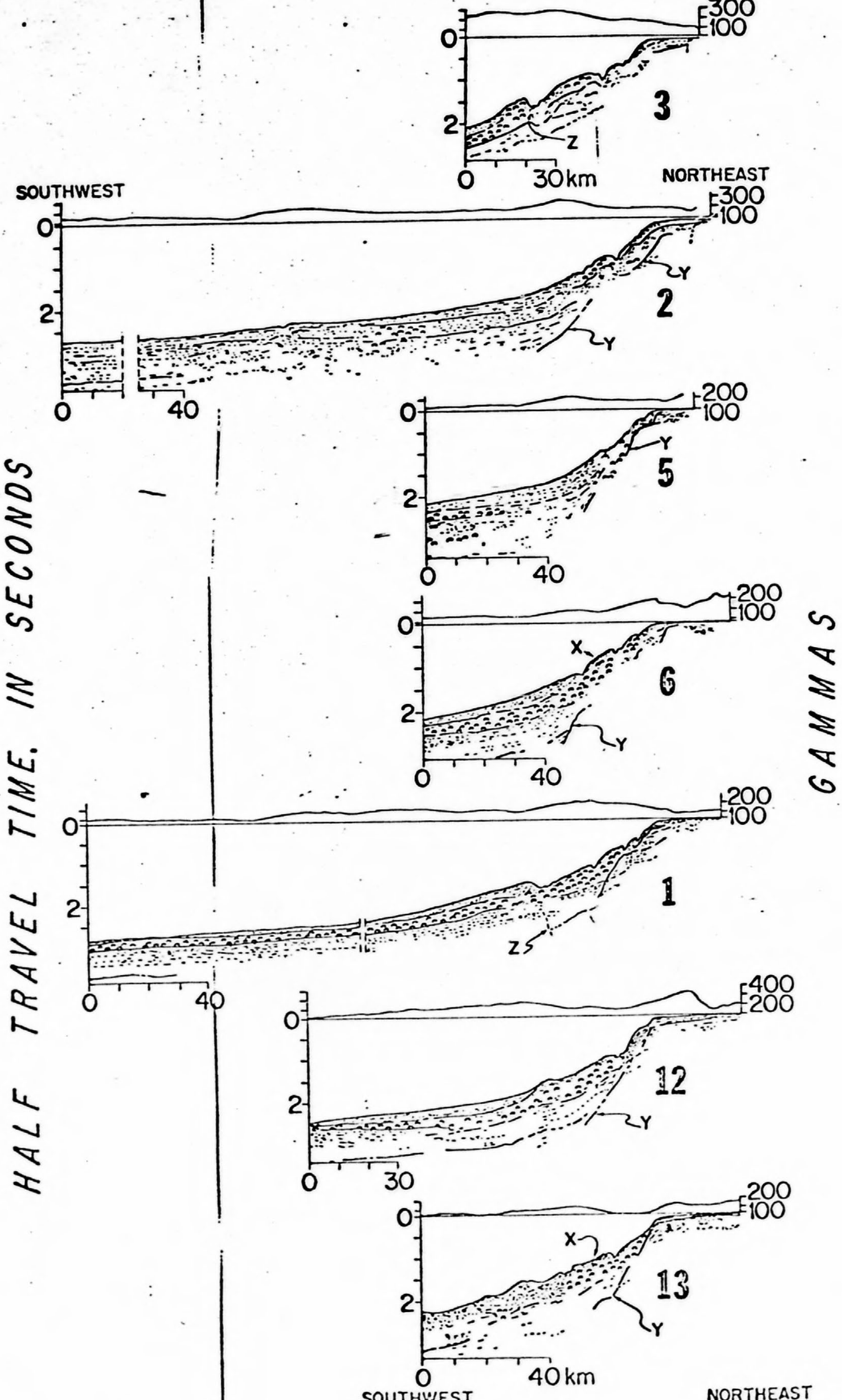
VERTICAL EXAGGERATION OF TOPOGRAPHY
ABOUT x9; SUBSURFACE REFLECTORS x5 OR LESS

Fig. 5

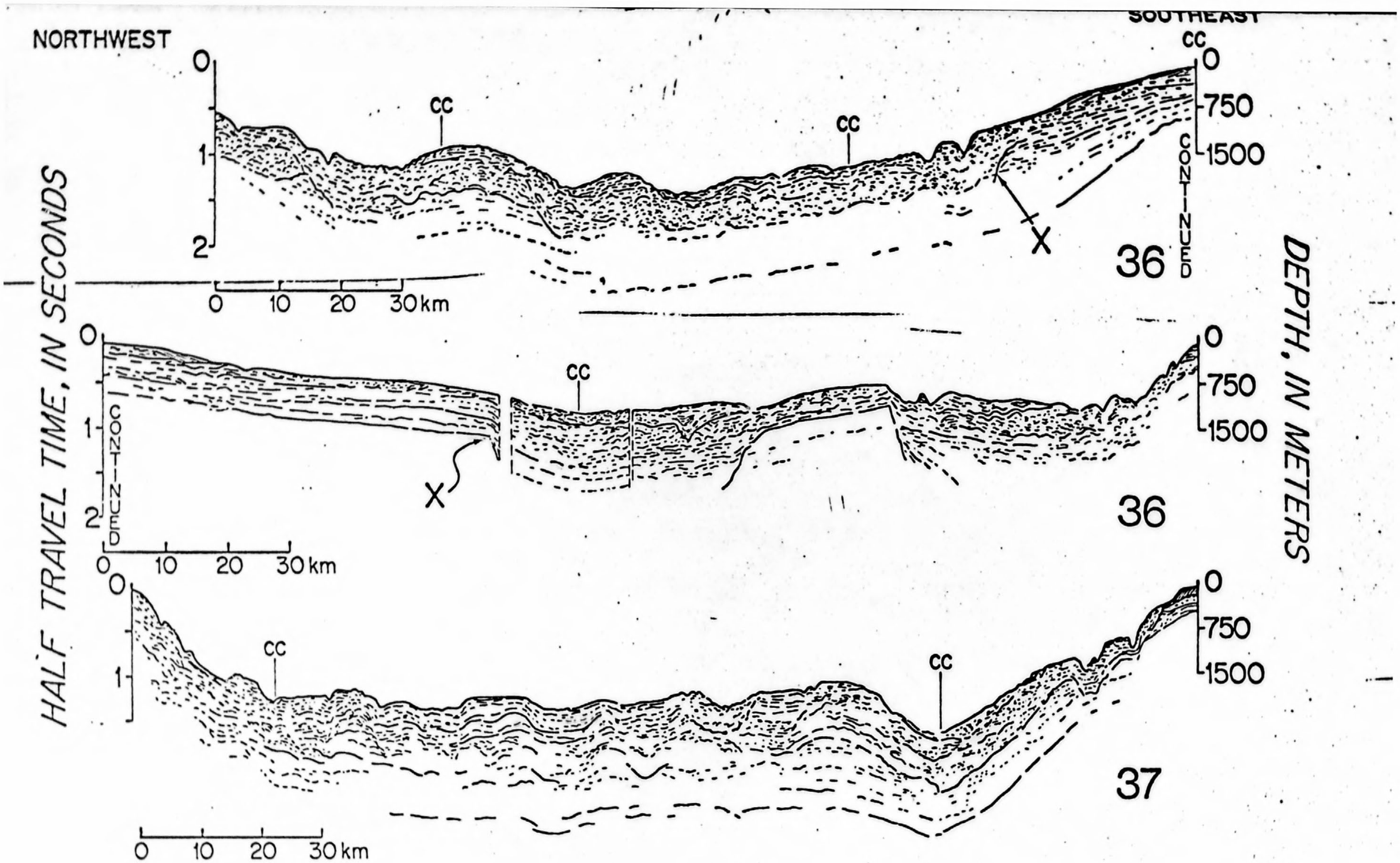


VERTICAL EXAGGERATION OF TOPOGRAPHY ABOUT ×9; SUB-SURFACE REFLECTORS ×5 OR LESS

Fig. 4



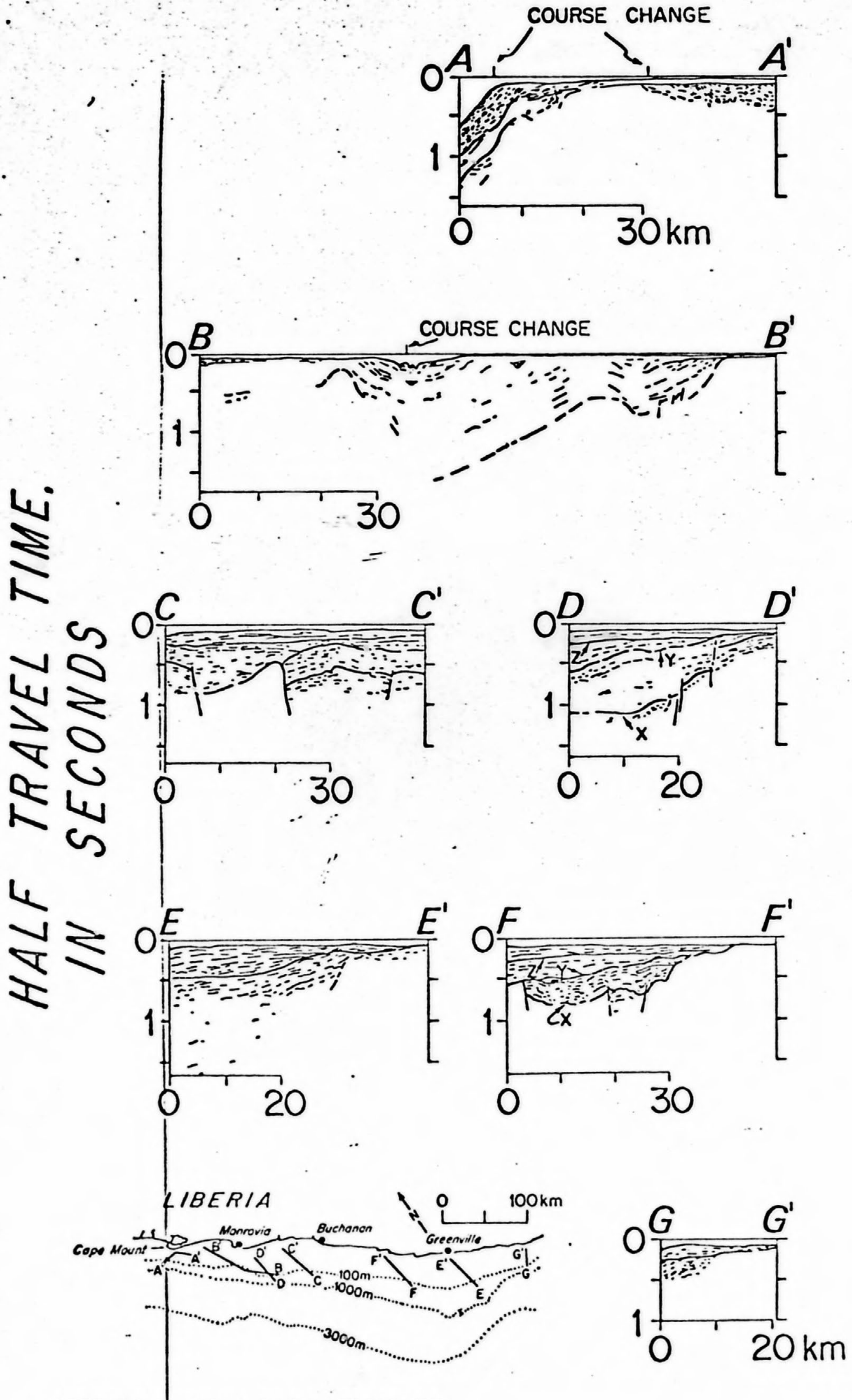
VERTICAL EXAGGERATION OF



VERTICAL EXAGGERATION OF
TOPOGRAPHY ABOUT x9; SUB-
SURFACE REFLECTORS x5 OR LESS

Fig. 5

Fig. 6



VERTICAL EXAGGERATION OF TOPOGRAPHY ABOUT x10; SUB-SURFACE REFECTORS x5 OR LESS

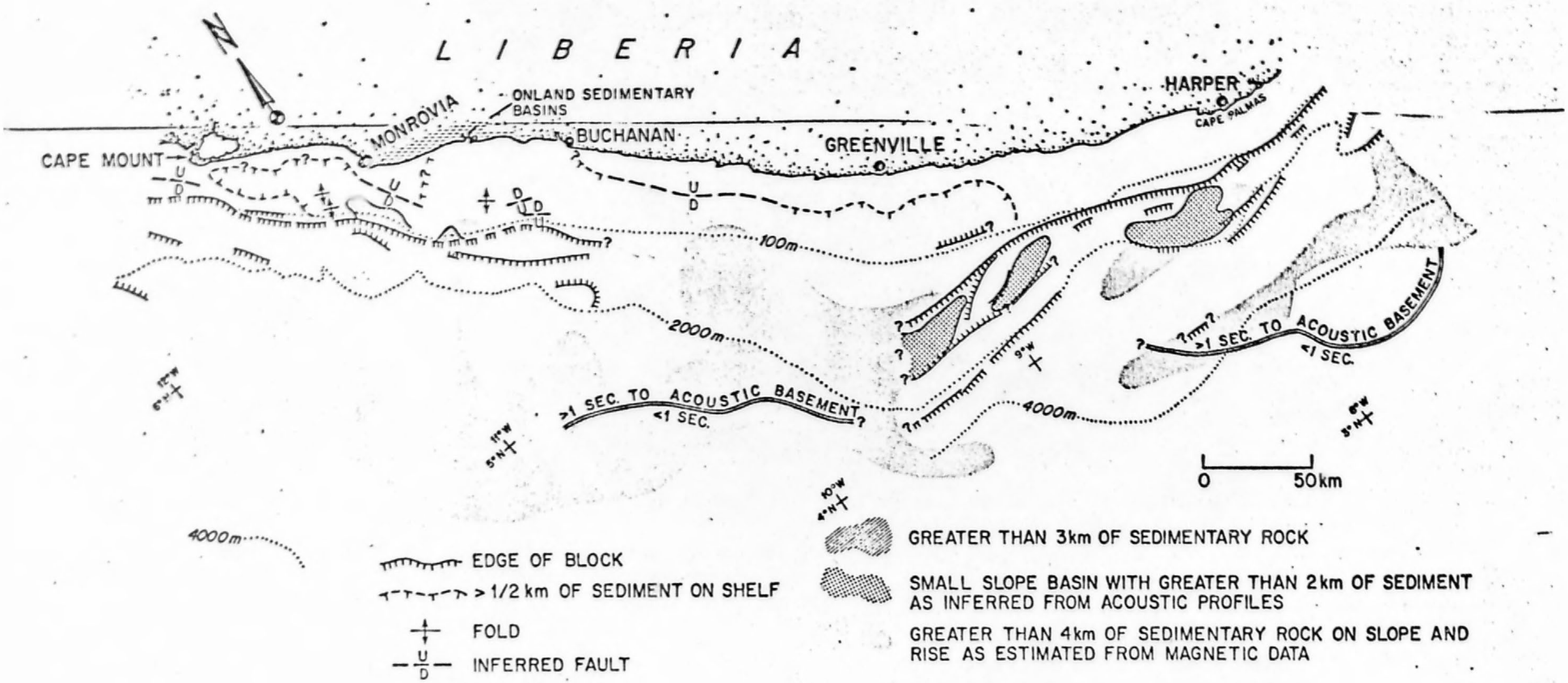
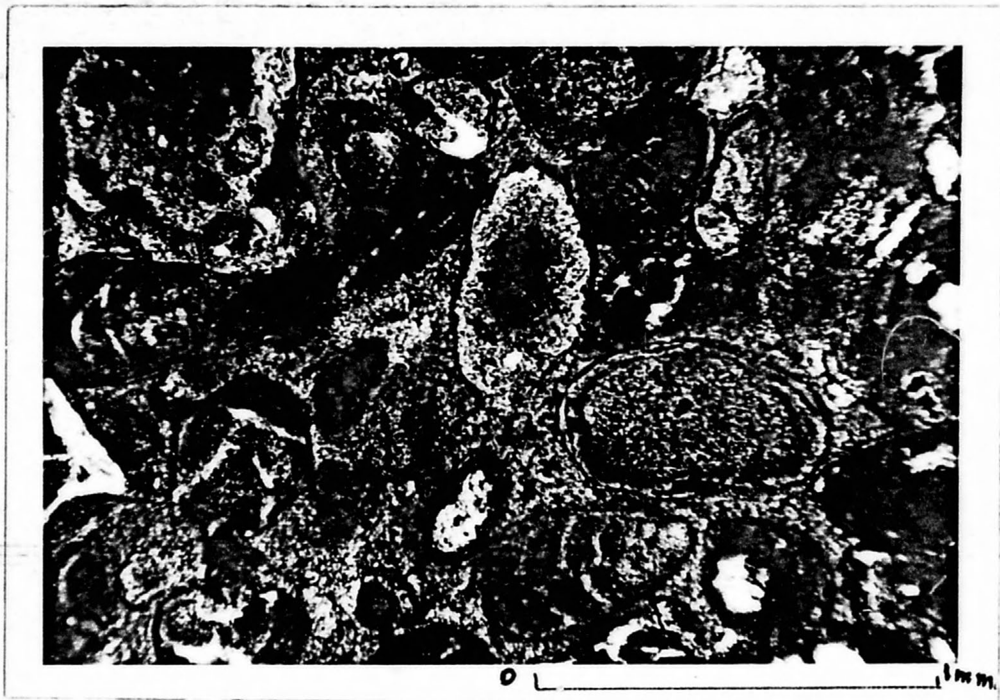

LIBERIA
ONLAND SEDIMENTARY BASINS
MONROVIA
BUCHANAN
GREENVILLE
HARPER
CAPE PALMAS
CAPE MOUNT
100m
2000m
4000m
>1 SEC. TO ACOUSTIC BASEMENT
<1 SEC.
0 50km
4000m
EDGE OF BLOCK
> 1/2 km OF SEDIMENT ON SHELF
FOLD
INFERRED FAULT
GREATER THAN 3km OF SEDIMENTARY ROCK
SMALL SLOPE BASIN WITH GREATER THAN 2km OF SEDIMENT AS INFERRED FROM ACOUSTIC PROFILES
GREATER THAN 4km OF SEDIMENTARY ROCK ON SLOPE AND RISE AS ESTIMATED FROM MAGNETIC DATA

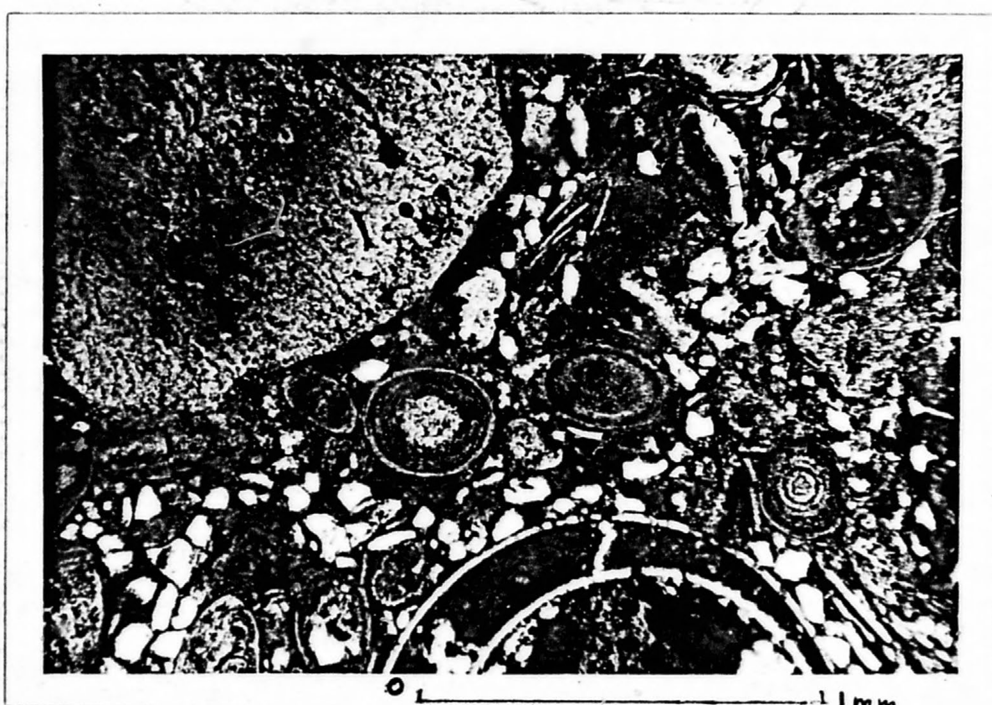
Figure 7

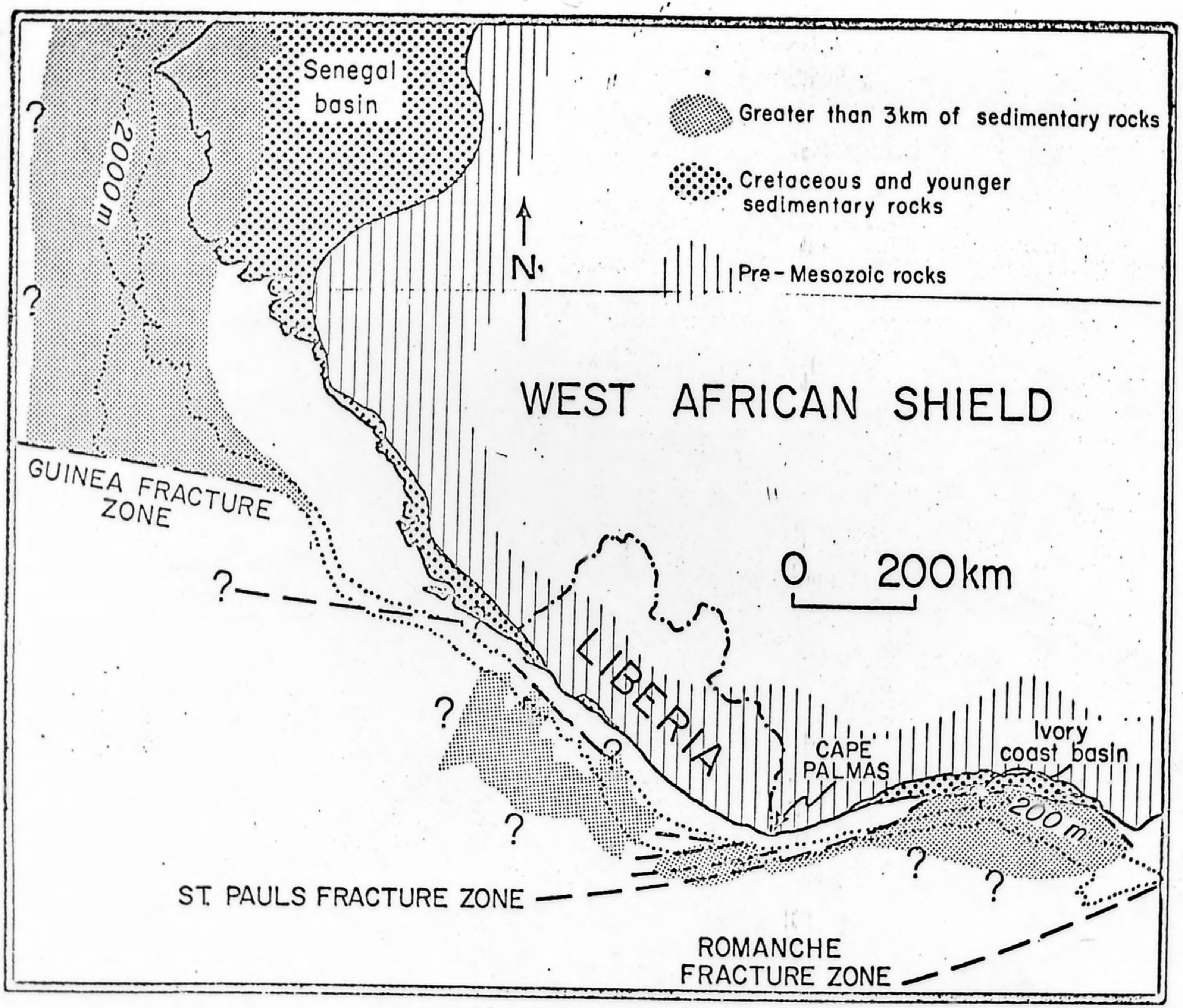
Figure 8

A



B





Senegal basin
2000m
Greater than 3km of sedimentary rocks
Cretaceous and younger sedimentary rocks
Pre-Mesozoic rocks
N
WEST AFRICAN SHIELD
GUINEA FRACTURE ZONE
0 200km
LIBERIA
CAPE PALMAS
Ivory coast basin
200 m
ST. PAULS FRACTURE ZONE
ROMANCHE FRACTURE ZONE

Fig. 9