UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROJECT REPORT
West African States (ECOWAS) Region Investigation
(IR)WA-5

ASSESSMENT OF THE PETROLEUM, COAL, AND GEOTHERMAL RESOURCES OF THE ECONOMIC COMMUNITY OF WEST AFRICAN STATES (ECOWAS) REGION

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Open-File Report 82-714

1982

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ILLUSTRATIONS

ABSTRACT

Approximately 85 percent of the land area of the ECOWAS (Economic Community of West African States) region is covered by basement rocks (igneous and highly metamorphosed rocks) or relatively thin layers of Paleozoic, Upper Precambrian, and "Continental Intercalaire" sedimentary rocks. These areas have little or no petroleum potential.

Areas of the ECOWAS region that have potential for petroleum production or potential for increased petroleum production include the narrow belt of sedimentary rocks that stretches along the continental margin from Mauritania to Nigeria and the Niger Delta and the Benue depression. The Senegal Basin, located on the continental margin of Mauritania, Senegal, Gambia, Guinea Bissau, and Guinea, has been intensely explored by the oil industry and most of the larger structures onshore and on the shelf probably have been tested by drilling with little or no resulting commercial production. Unless basic ideas pertaining to the petroleum geology of the Senegal Basin are revised, future discoveries are expected to be limited to small fields overlooked by industry at a time when petroleum prices were low. On the continental shelf of Sierra Leone and the continental shelf of northeast and central Liberia, the sedimentary rocks are relatively thin, and industry has shown little interest in the area. On the continental rise of these countries, however, the sedimentary section, deposited in a complex fault-block system, increases in thickness. A renewal of industry interest in this deep-water area will probably follow further development of deep-water production technology. A recent oil discovery on the continental slope off the Ivory Coast is expected to spur further exploration offshore of southeastern Liberia, Ivory Coast, Ghana, Togo, and Benin. This relatively unexplored area in the Gulf of Guinea has good possibilities for the discovery of giant oil fields.

Nigeria's oil development from the Niger Delta may have peaked, as 13 of 14 giant oil fields were discovered prior to 1969 and the greatest number of fields were discovered in the period 1965 through 1967. Like delta regions in other parts of the world, individual oil fields of the Niger Delta are small to medium by world standards and future discoveries, therefore, are likely to reflect this reality. The natural gas resources of the Niger Delta, unlike its oil resources, are comparatively underdeveloped.

Parts of the Benue depression in Nigeria and Niger could contain significant deposits of petroleum. The lower Benue depression, immediately north of the Niger Delta, has been extensively explored by drilling. Except for noncommercial discoveries of oil and gas and traces of oil and gas on the ground surface, the results of exploration in the lower Benue depression were negative. However, in the Lake Chad area of Chad and in southern Chad near the Central African Republic boundary, oil and gas discoveries were made just prior to the cessation of all drilling and exploration activity in early 1979. It is rumored that these discoveries may be large although little information is available. The relation between the two areas in Chad and their overall relation to the Benue depression is poorly understood; however, the possibility of thick sedimentary sections containing Cretaceous marine source rock and Tertiary reservoir beds--all contained within grabens in a highly faulted failed-arm system subjected to high heat flow--is attractive.

Of the ECOWAS countries, only Nigeria and Niger produce coal commercially. Nigeria produces subbituminous coal from Paleocene-Maestrichtian and Maestrichtian (Late Cretaceous) age rocks of the Niger Delta region; reserves are estimated, on the basis of extensive drilling, to be 350 million tons (standard coal equivalent). In addition, lignite deposits of the Niger Delta appear to be large but have not been developed. Niger produces small amounts of coal used locally by uranium mine and mill operations from Carboniferous age rocks of the Niger Basin.

In Senegal and Benin, coal has been penetrated in wells or boreholes. In Senegal, at least 33 oil and water wells have penetrated lignite beds that range from a few centimeters to more than 70 m in thickness and that are at depths ranging from about 55 to more than 647 m. The lignite in the Senegal Basin is in strata of Maestrichtian (Late Cretaceous) age. In Benin, medium-quality lignite in thin beds (0.5-1 m) was penetrated at depths from 60 to 100 m. Peat, which is not classified as coal, occurs in the deltas, lower river areas, and lower basin areas of the Senegal, Sine Saloum, Caasamance, and Gambia Rivers.

Despite the relatively small quantities of coal discovered to date, the age and lithology of the strata containing these coals suggest that other areas are worthy of further exploration. Carboniferous age rocks are present in the Taoudeni and Bove Basins and in the northern parts of the Niger and Chad Basin. In the Taoudeni Basin especially, Carboniferous rocks crop out in and underlie extensive areas. However, the middle and Upper Carboniferous rocks in the Taoudeni Basin are continentally derived red sandstones, whereas, the Carboniferous strata that contain subbituminous coal in the Niger Basin are sandstones and shales that reflect deposition in a lagoonal environment. The Paleocene-Maestrichtian and Maestrichtian subbituminous coals and Eocene lignite of the Niger Delta are associated with deltas built across the lower reaches of the Benue Trough. Although these particular deltas do not extend up the Benue depression, deltas of similar age may have been built in the lower reaches of the Bida Basin and Yola Trough and could contain coal deposits. During the Maestrichtian transgression, marine sedimentation reached the Chad syncline, and Upper Cretaceous and Paleocene rocks in this area contain lagoonal and lacustrine deposits. However, the overlying Tertiary beds of the "Continental Terminal" are thick; thus, potential coal deposits in the area may be difficult to exploit. The Maestrichtian lignites penetrated in Benin probably represent a northwest subsurface continuation of lithologies similar to those in the Niger Delta. The discoveries of large quantities of Maestrichtian to Pleistocene age lignite in the subsurface of the Senegal Basin suggests the need for further subsurface investigations in coastal Mauritania, Senegal, Gambia, Guinea Bissau, Guinea, and Sierre Leone.

Published literature contains limited data on heat-flow values in the ECOWAS region. However, the few values available and the regional geology indicate that the development of geothermal resources, in general, would be uneconomical. Exceptions may include a geopressured zone in the Niger Delta and areas of recent tectonic activity in the Benue Trough and Cameroon. Development of the latter areas under present economic conditions is not feasible.

PART I--PETROLEUM RESOURCES

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INTRODUCTION

The purpose of this report is to summarize the petroleum resources of the Economic Community of West African States (ECOWAS). The member states are Nigeria, Niger, Mali, Upper Volta, and all the coastal nations between and inclusive of Nigeria and Mauritania. The author has attempted, throughout the report, to summarize the hydrocarbon potential within the geologic framework of the region.

Economic oil and gas deposits are usually consequences of three processes: thermal conversion to oil and gas of biotic residues contained in source rocks (usually shales) having a high organic carbon content; migration of the oil and gas through permeable reservoir rocks; and their accumulation in structural or stratigraphic traps that are sealed by impermeable rock layers which impede the escape of liquids and gases. Because large accumulations of source rock are associated only with sedimentary rocks, oil and gas deposits are limited to sedimentary basins or the borders of these basins. Relative favorability of the geologic conditions and processes that have affected the sedimentary rocks deposited in a particular basin will have determined the amount, if any, of oil and gas generated and subsequently trapped. Because basin boundaries transcend political boundaries in the ECOWAS region, it is desirable to present a discussion of hydrocarbon potential based upon basinal analysis rather than to present a country-by-country analysis.

The ECOWAS region can be divided into 13 sedimentary basins on the basis of analysis of the geologic framework of Africa. These 13 basins can be further grouped into 8 categories on the basis of similarities in stratigraphy, geologic history, and probable hydrocarbon potential. For example, all the basins in which the primary objective of petroleum exploration is the Paleozoic section can be grouped into a single category for discussion purposes. Both these subdivisions are shown in figure 1.

The information contained herein was gathered entirely from published literature and from the reports of Petroconsultants (written commun., 1976; 1981). The author's aim is not to present new ideas or concepts but to summarize the available data as a preliminary step to facilitate group discussion and to aide in further analysis.

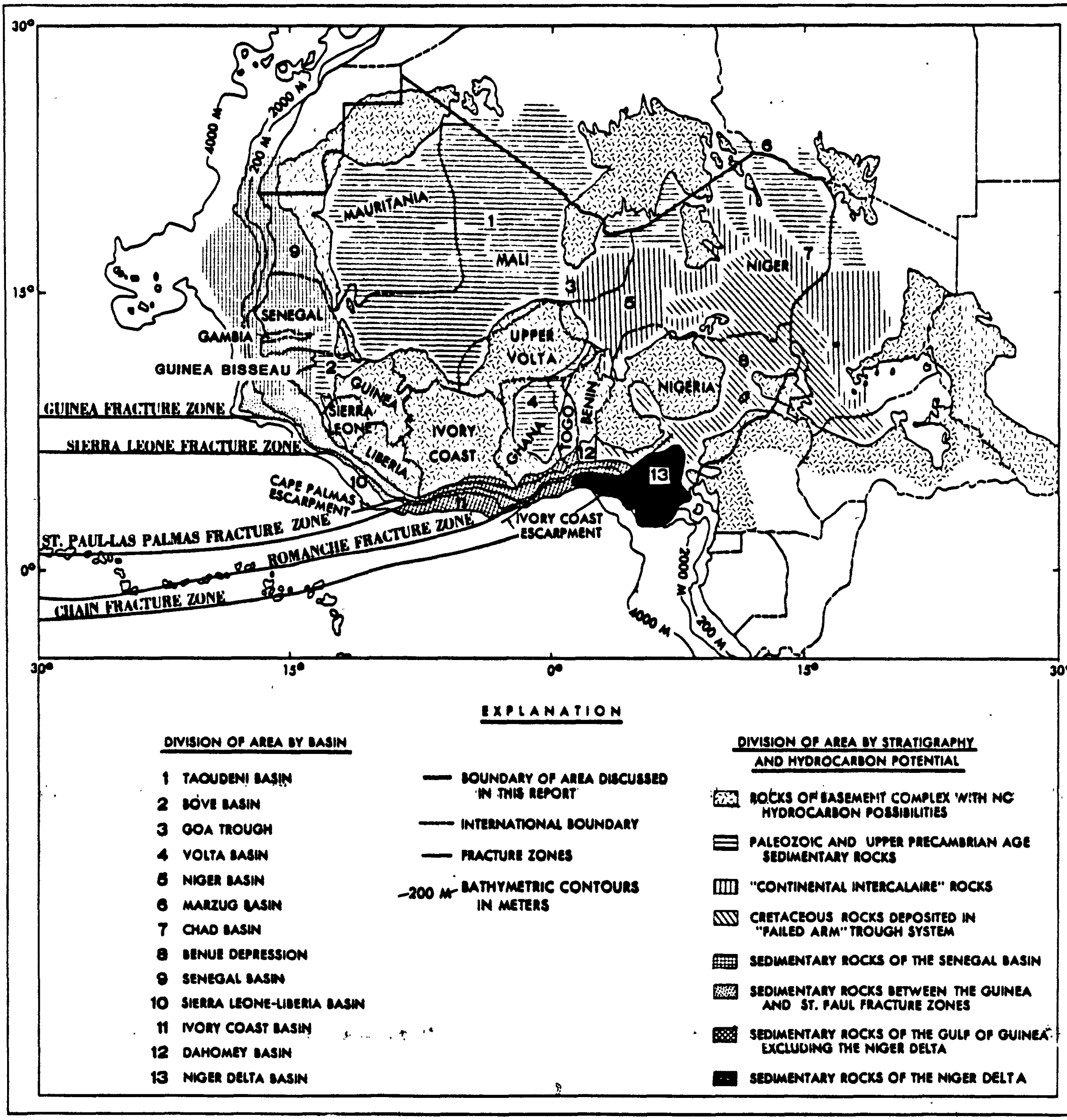


Figure 1. Map of ECOWAS region showing division of region by basin (numbers) and division by stratigraphic similarity (patterns).

GEOLOGIC HISTORY

Geologic events that are important to an analysis of the hydrocarbon potential of the ECOWAS region span much of geologic history from Precambrian through Tertiary time. Continental West Africa consists essentially of a Precambrian granitized craton (age of 2,700 to 1,600 m.y.) covered by a thin sedimentary cover; the oldest sedimentary rocks are as old as 1,000 m.y. (Dillon and Sougy, 1974). The granitized rocks of the craton are referred to as basement rocks.

The oldest sedimentary rocks reflect deposition during upper Precambrian and most of Paleozoic time when Africa, North America, and South America formed a single large continental area. Important to petroleum exploration is the Gothlandian (Silurian) Shale; much of the oil and gas discovered in Paleozoic and Triassic reservoirs of Algeria was thermally generated from this rock unit. Black shales of similar age are known to extend into the Taoudeni, Bove, and Volta Basins and into the northern parts of the Niger and Chad Basins.

Following Paleozoic deposition, a major deposional hiatus is reflected by an unconformity that occurred over much of the ECOWAS region. In places, Cretaceous sedimentary rocks directly overlie rocks of the basement complex, and in other places they overlie Paleozoic sedimentary rocks. Some thin units of Permo-Triassic sedimentary rocks are recognized.

Processes associated with this unconformity probably explain the apparent absence of Paleozoic hydrocarbon deposits in the ECOWAS region in contrast to the large deposits contained in Paleozoic rocks to the north in Algeria. In the Hassi Messaoud and Hassi R'mel fields of Algeria, thick deposits of Jurassic-Triassic salt and anhydrites overlie thin Triassic sandstones and the Paleozoic section. These salt and anhydrite deposits are absent in the ECOWAS region. The Paleozoic section in the ECOWAS region, therefore, was not adequately sealed throughout much of its post-depositional history--especially during critical periods of possible hydrocarbon generation.

The depositional hiatus or erosional event mentioned above was probably related to the opening of the North Atlantic during Triassic time. During Late Triassic-Early Jurassic time, North America and northwest Africa were separated by a narrow shallow Atlantic sea. The area now represented by the Senegal Basin was part of this early Atlantic sea. Its earliest sedimentary fill consists of a thick section of evaporites that has been age dated as Triassic to Liassic (Templeton, 1970, p. 52). The evaporite section is overlain by carbonate rocks of Jurassic age laid down on a shelf margin carbonate platform. Sediment deposition was controlled by basement subsidence owing to tensional stresses and cooling of the crust. The evaporitic basin off Mauritania and Senegal has its counterpart off the coast of North America.

In Early Cretaceous time separation of Africa and South America was initiated by opening of the South Atlantic. Opening occurred about a triple-junction rift-ridge system under the present Niger Delta (Burke and others, 1970). One arm of the triple-junction system is believed to have extended into Africa along a zone of weakness between the West African and Congo Cratons (fig. 2). Although Africa started to split along this arm, movement later stopped. The trough system formed by this incomplete continental splitting is referred to as a "failed-arm" system or Benue depression. The trough was filled by over 3 km of Albian to Coniacian sediments consisting of shallow-

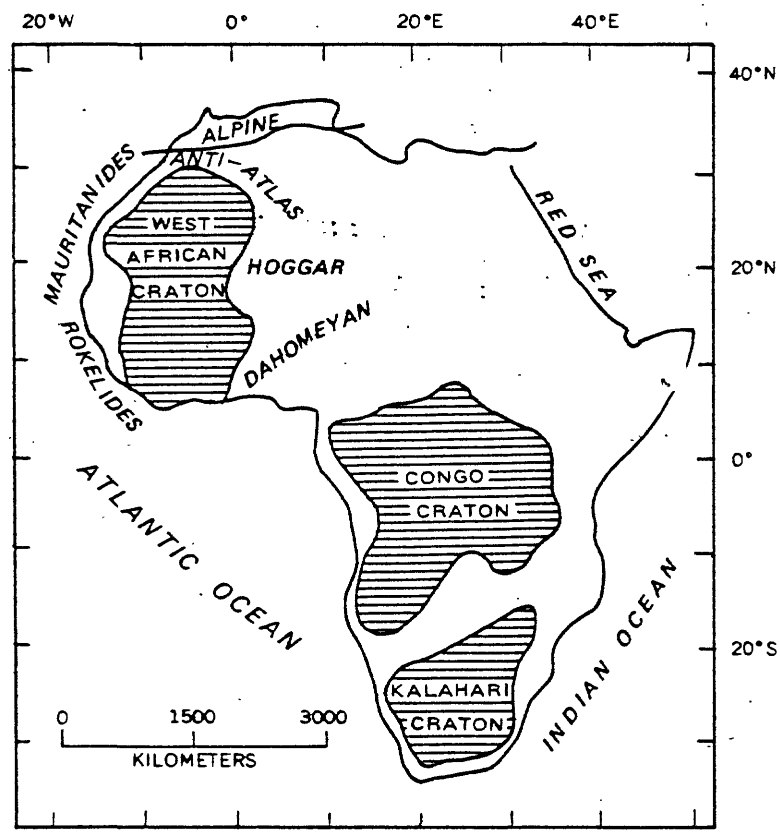


Figure 2. Cratons of Africa, and approximate locations of orogenic zones of West Africa. From Dillon and Sougy (1974).

and deep-water marine shales with limestones and sandstones deposited at the margins of a marine embayment. Cretaceous age marine shales in this section may have been the source rock for the oil recently discovered in Chad. High heat flow rates possibly associated with the early history of the Benue depression could have generated significant amounts of hydrocarbons.

During opening of the Gulf of Guinea, fracture zones determined the shape of basins in the area. Major fracture zones, or transform faults that extend from the Mid-Atlantic Ridge, intersect the continental margin and determine its trend (fig. 1). The thick sedimentary wedges on the Continental Slope and Rise in the Ivory Coast and Dahomey Basins are probably related to the location of the fracture zones. According to Emery and others (1974), the basement lows between fracture zones acted as conduits to funnel sediment westward whereas the ridges acted as dams to southerly sediment transport. The discovery of a new oil field--possibly of giant size--off Ivory Coast on the Continental Slope was recently reported (Oil and Gas Journal, 1981). This new discovery will probably spur deep water exploration activity for oil and gas in the Gulf of Guinea.

The rocks that contain large deposits of oil and gas in Nigeria were deposited during Tertiary time (fig. 1). The Tertiary history of the Niger Delta began in Paleocene time when the formation of Cretaceous prodeltas in the lower part of the Benue depression was terminated by a major marine transgression. Subsequently, the bulk of Eocene to Holocene sedimentary rocks that comprise the thick sedimentary wedge from which oil and gas are presently produced was deposited during a major regression. Large volumes of deltaic sediments prograded across the continental margin and at their seaward extent were deposited directly on oceanic crust as the margin subsided. The Tertiary section in the Niger Delta is over 8 km thick.

TAODENI BASIN

Geologic setting

The Taoudeni Basin (fig. 3) is essentially a Paleozoic basin, bounded to the northwest and east by Precambrian basement rocks of the Reguibat massif and Adrar des Iforas, respectively. To the southwest the basin is limited by Precambrian and Paleozoic rocks of the Mauritanides fold belt and to the south and southeast by basement rocks of the Leo uplift. To the north, the basin is connected with the Algerian basin complex through the Tannezrouft saddle, to the east with the Niger Basin through the strait of Gao, and to the south with the Bove Basin. Including its exposed rims it covers about 975,000 km^2, approximately half of this area being in Mauritania and the other half in Mali. In central Mauritania, sedimentary rocks are greater than 3 km thick (Association of African Geological Surveys, 1968); although, in general, the sedimentary rocks are less than 2 km in most parts of the basin (fig. 3). The central part of the Taoudeni Basin is masked by thin continental formations of Cretaceous, Tertiary, and Recent age.

In Precambrian time the basement surface in West Africa was peneplaned during the course of long continental evolution. Later, this continental paleosurface, characterized by scattered aeolian pebbles (Bongrand and others, 1961), was covered by upper Precambrian through Upper Carboniferous sedimentary rocks. In the Taoudeni Basin, although much faulting occurs (Houghton, 1963), the beds are generally unfolded or gently folded and generally consist of epicontinental marine or continental types of rocks with unconformities and some discordances resulting from minor adjustments of the West African craton (Dillon and Sougy, 1974). The stratigraphy along the northwest margin of the Taoudeni Basin was established by Trompette (1969a, 1969b, 1970).

Stratigraphy

According to Dillon and Sougy (1974), the upper Precambrian and Paleozoic sedimentary rocks in the Taoudeni Basin can be divided into 3 series (fig. 4) as follows: Upper Precambrian rocks (1,000-650 m.y.), upper Precambrian and lower Paleozoic rocks (650-440 m.y.), and upper Ordovician to Carboniferous rocks (440-270 m.y.).

Upper Precambrian rocks (1,000-650 m.y.)--This series of rocks was deposited prior to the Pan-African orogeny which mobilized the margins of the West African craton (500-650 m.y.). They consist of a series of sandstone and shale beds some containing thick stromatolitic limestones. At least three groups, separated by discontinuities can be recognized (Dillon and Sougy, 1974). Most of the rocks of this series were deposited in either continental or shallow marine environments (Dillon and Sougy, 1974). Stromatolite reefs may have been deposited in warm, calm, shallow water (Trompette, 1969b).

Upper Precambrian and Lower Paleozoic rocks (650-440 m.y.)--The lowest beds in this series lie above a surface of glacial erosion and consist of glacial conglomerates. These beds are overlain by shales, including limestones, probably deposited during a transgression following glaciation (Dillon and Sougy, 1974). A red bed section lies above the shale and is succeeded by sandstone. Late Precambrian and Early Cambrian deposition that straddled the glacial event is

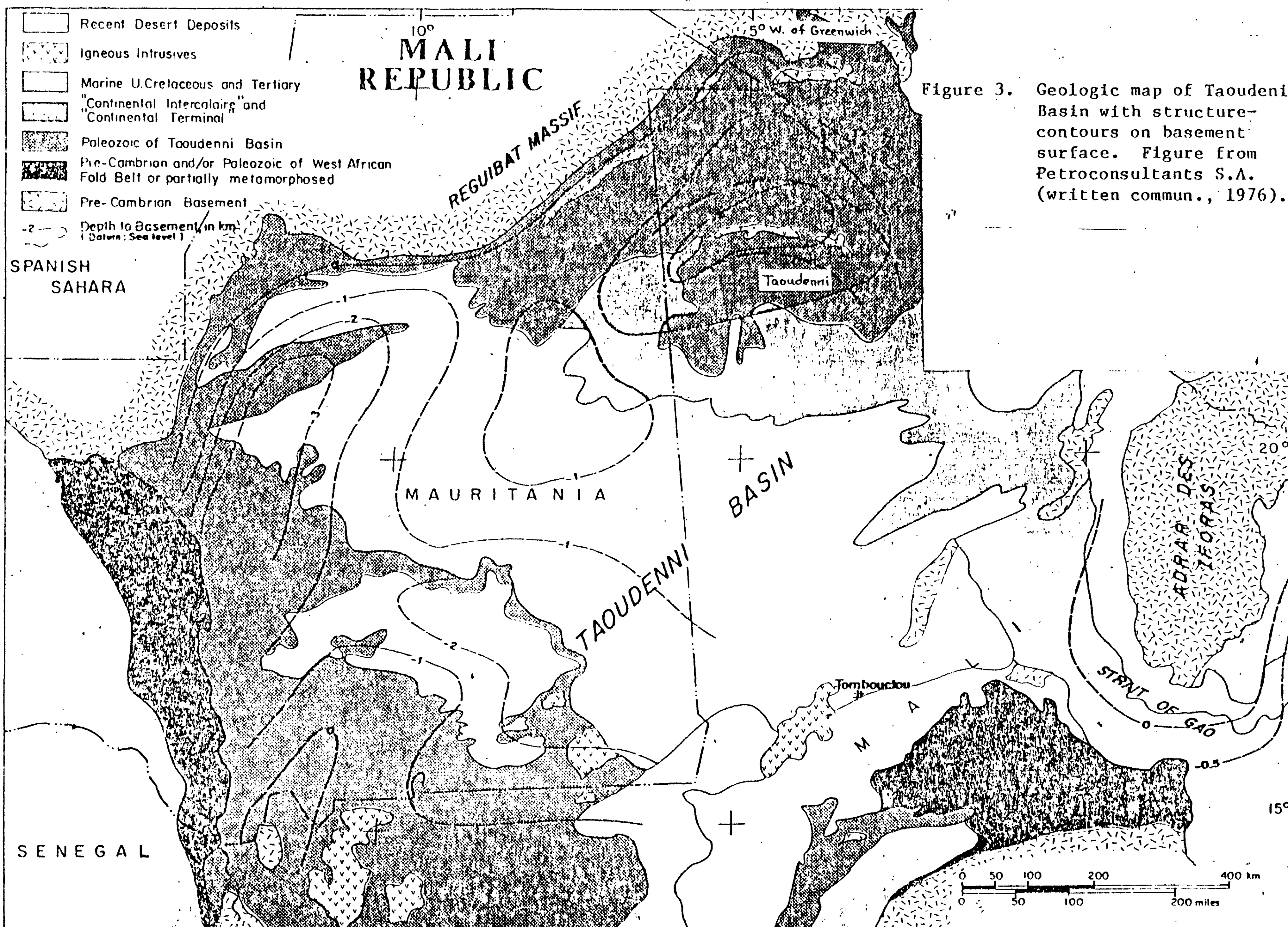


Figure 3. Geologic map of Taoudeni Basin with structure-contours on basement surface. Figure from Petroconsultants S.A. (written commun., 1976).

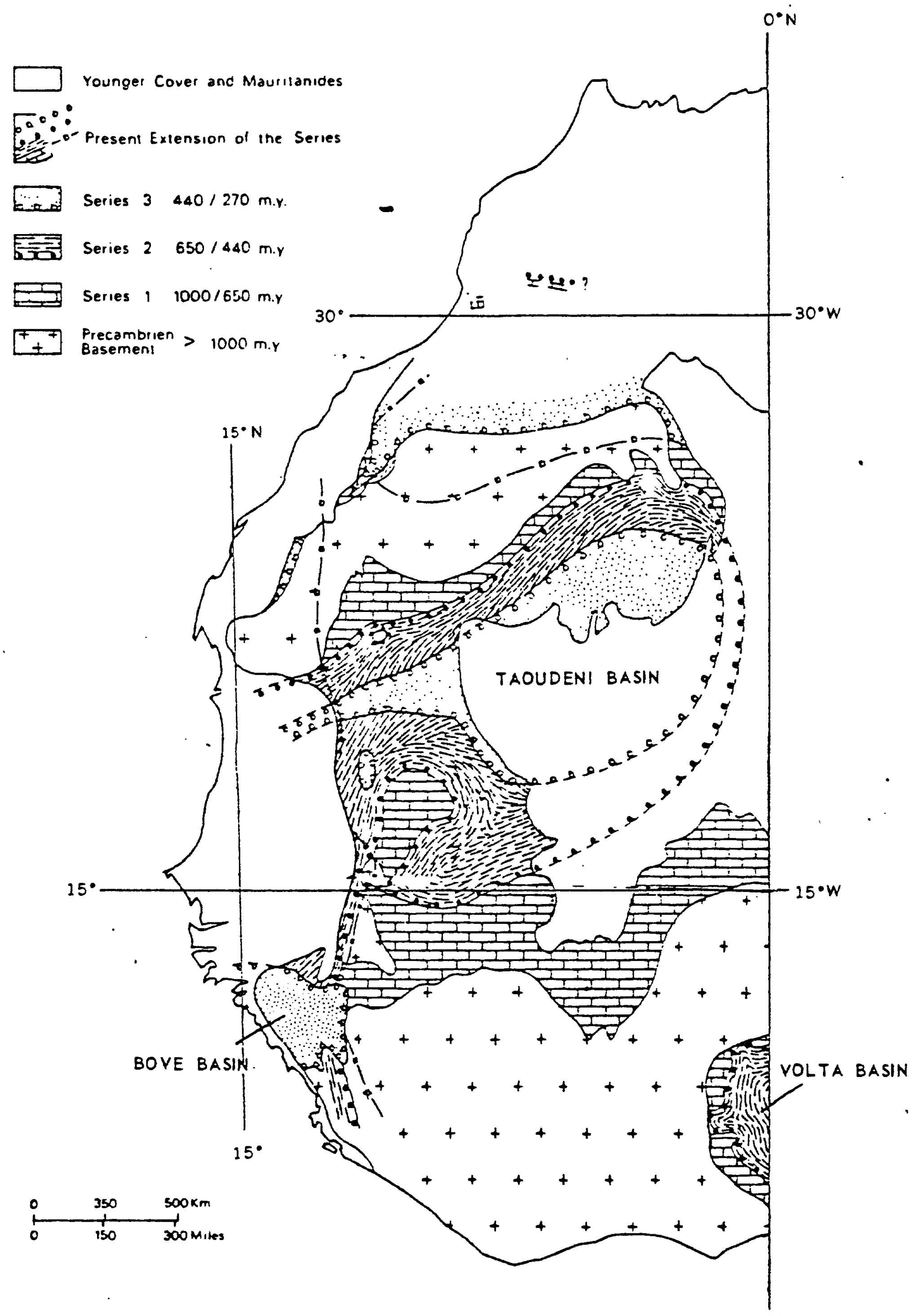


Figure 4. Zones of outcrop and probable extensions of upper Precambrian and Paleozoic sedimentary series in Africa west of Greenwich. Figure modified from Dillon and Sougy (1974).

sometimes called "Infracambrian." The lower Cambrian section contains tillite of possible marine origin and massive beach-type sandstone.

Upper Ordovician to Carboniferous rocks (440-270 m.y.)--Basal sedimentary rocks in this series are glacial tillites derived in the Ordovician with cross-bedded sandstones. During the Silurian (Gothlandian), a graptolitic, black shale with a high organic content was deposited in the basins of West Africa (Kilian, 1926; Menchekoff, 1930; Remack-Petitot, 1960). According to Dillon and Sougy (1974), the slaty pyritiferous, graptolitic black shale in the Bove Basin generally amounts to 45-100 m; over 150 m has been cored in the Casamance area of southern Senegal. The Silurian apparently represents a time of transgression. (Lecorche and Sougy, 1969). Devonian through Carboniferous rocks (up to 500 m thick) consist of sandstones, siltstones, shales, and limestones overlain by continental Carboniferous deposits represented by red beds and freshwater limestones. Carboniferous deposits signal the beginning of a major regression that affected all of the West African craton. Post-Paleozoic formations consist of a thin veneer of continental sands and shales unconformably covering much of the Paleozoic sequence in the central part of the Taoudeni Basin and are overlain by Holocene desert deposits. Thin shallow marine Upper Cretaceous and lower Tertiary deposits occur along the western part of the basin and in the Gao Strait.

Source and reservoir rocks

Potential source rocks are the graptolitic black shales of Silurian age. According to Petroconsultants (written commun., 1976), however, "source rock analyses on surface samples were disappointing." This may be due to the altered nature of the surface samples tested. No reported seeps of oil or tars are contained in the literature.

Potential reservoir rocks include Lower Cambrian (Infracambrian) carbonate rocks (reefs) and sandstones and sandstones and carbonate rocks of Cambrian through Devonian age.

Petroleum potential

Two exploratory wells were drilled in the Taoudeni Basin, both prior to 1975. One well was drilled to a depth of 2,912 m and bottomed in Infracambrian deposits; the other bottomed in Upper Precambrian deposits at 3,488 m. A show of gas may have been found in one (Brown, 1981). Apparently the results from these wells were discouraging as further drilling was discontinued. Results from the drilling are not available. Without further details on results of analysis, it is difficult to condemn the source and reservoir rock potential of an entire basin as large as the Taoudeni on the basis of two wells. Porosities and permeabilities of sandstones and carbonates can vary from site to site depending upon the environment of deposition and the effects of secondary processes. If, although unlikely, source rocks throughout the section were found to be highly over mature (relative to both oil and gas), then the possibilities of finding significant hydrocarbon deposits would be greatly reduced.

A remote possibility exists for finding small gas deposits in the Mauritanides (fig. 3) folded belt (Brown, 1981). It has been described as a Precambrian and Paleozoic overthrust belt similar to the Appalachian fold belt in eastern United States (Sougy and Pouit, 1968).

BOVÉ BASIN

Geologic setting

The Bové or Bafata Basin is a southward continuation of the Taoudeni Basin and basically represents a Paleozoic synclinorium (fig. 5). Sedimentary rocks of Paleozoic age crop out in Guinea and Guinea Bissau. Its extension in the subsurface has been recognized in wells and in core holes drilled in the northwestern corner of Guinea Bissau and southernmost Senegal where Paleozoic rocks are unconformably overlain by thick Mesozoic and Tertiary sedimentary rocks of the coastal basin of Senegal. Paleozoic formations may also extend offshore as far as the shelf edge where they may be up to 3,000 m thick. This assumption is based on the results of seismic refraction surveys.

Stratigraphy

The stratigraphy and rock formations outlined for the Taoudeni Basin are similar to those in the Bove Basin. According to Dillon and Sougy (1974), stratigraphic relationships suggest that the Bove Basin did not begin to form until Late Ordovician time; hence, the basal sedimentary rocks of the Bove Basin, may be Ordovician in age.

In general, Ordovician sedimentary rocks become more nonmarine south from the Taoudeni Basin to the Bové Basin (Destombes and others, 1969). The Bové Basin, unlike most areas to the north, apparently received an influx of coarser clastics in Early and Middle Devonian with deposition of finer clastics in Late Devonian (Dillon and Sougy, 1974). At the end of Devonian time, the Bove Basin apparently was uplifted during the Hercynian orogeny as indicated by the absence of Carboniferous formations (Carrington da Costa, 1951). Paleozoic formations in the Bove Basin are pierced by frequent dikes and sills of dolerite and gabbro.

Source and reservoir rocks

As in the Taoudeni Basin, potential source rocks are Silurian (Gothlandian) and Devonian shales. Lower and Middle Devonian sandstones may be coarser than age equivalent sandstones in the Taoudeni Basin and could have reservoir potential. Ordovician or Cambrian(?) dolomitic limestones and Ordovician sandstones also may contain beds with reservoir potential. The Ordovician(?) section in the Bové Basin, although mainly of continental origin, contains 1,000 m of white sandstone which is siliceous, calcareous, or sometimes cemented by salt (Dillon and Sougy, 1974, p. 328). Reservoir beds in Devonian strata could be sealed by Cretaceous shales that unconformably overlie the Devonian section.

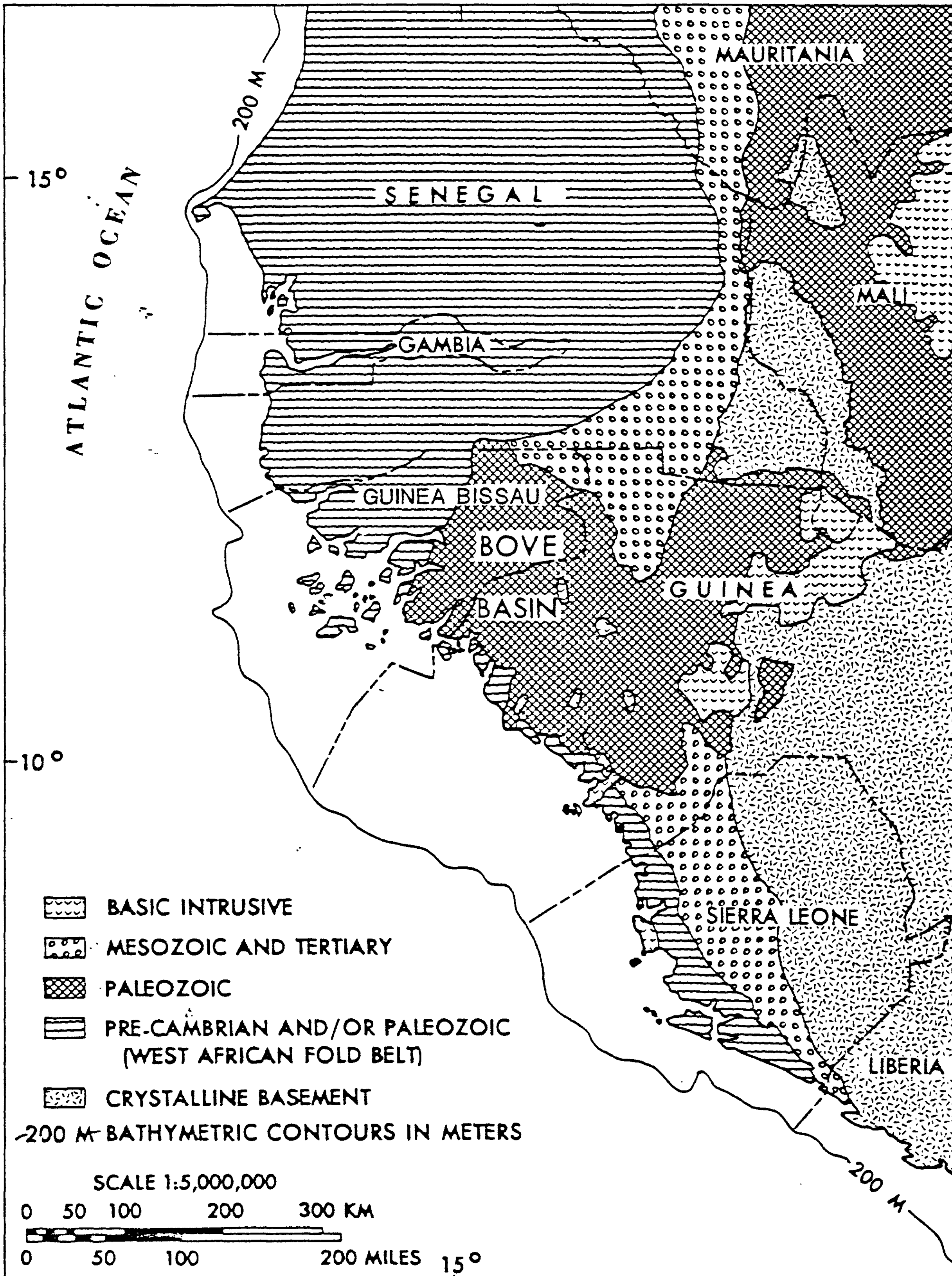


Figure 5. Geologic map of Bové Basin and adjacent areas. Figure modified from Petroconsultants S.A.

Petroleum potential

Shows of hydrocarbons in Guinea are rare although bituminous impregnations in water wells near Conakry, Guinea, as well as on contacts of igneous intrusives and Gothlandian shales have been reported (Petroconsultants, written communication, 1976). With the exception of 4 exploratory wells drilled in the northwest corner of Guinea Bissau, the Palezoic Bove Basin has not been explored by deep drilling. These four wells, two or three of which penetrated a small section of Paleozoic rocks, were probably drilled to test the Mesozoic and Tertiary sections rather than the Paleozoic section.

Because of the negative results obtained so far in the Bové Basin and the Taoudeni Basin to the north, the Bove Basin would appear to have little hydrocarbon potential. Industry has shown little interest in the area probably owing to their analysis of drilling results. Maturation analysis of Devonian and Silurian (Gothlandian) shales, most likely already done by industry, would be a helpful basis for making a better evaluation.

VOLTA BASIN

Geologic setting

The Volta Basin (fig. 6) represents a sedimentary series of stable shelf deposits of a late Precambrian geosynclinal system, which prior to the break-up of the African and South American continents in pre-Cretaceous or Early Cretaceous time, probably extended across present day northwestern Africa and Ghana into Brazil. The unmetamorphosed and gently folded Paleozoic basin fill crops out throughout central and eastern Ghana, northern Togo, and Benin, the southeastern corner of Upper Volta, and in Niger. These rocks probably extend in the subsurface further into Niger beneath Cretaceous and Tertiary cover. The Volta Basin covers an area of some 125,000 km^2.

In the eastern part of the basin, slightly metamorphosed rocks of the Precambrian or Paleozoic West African fold belt are recognized (fig. 6). According to Dillon and Sougy (1974), this belt was formed during the Pan-African (650 m.y.) orogeny and involved thrusting toward the west at the western boundary of the West African Craton. According to magnetic interpretations the thickness of basin fill exceeds 5,000 m with its deepest part running parallel to the eastern mobile belt (Petroconsultants, written commun., 1976). However, at the margins of the basin, where Furon (1968) established a stratigraphic sequence, the sedimentary section is relatively thin. Throughout most of the basin gently folded beds dip eastward toward the center of the basin. Magnetic surveys indicate a number of southwest-northeast striking basement highs.

Stratigraphy

Furon (1968) established the following stratigraphic sequence for the Paleozoic sequence:

Upper Voltaian - Thickness about 325 m. Coarse crossbedded sandstone (200 m) grading down section into fine grained sandstone (125 m).

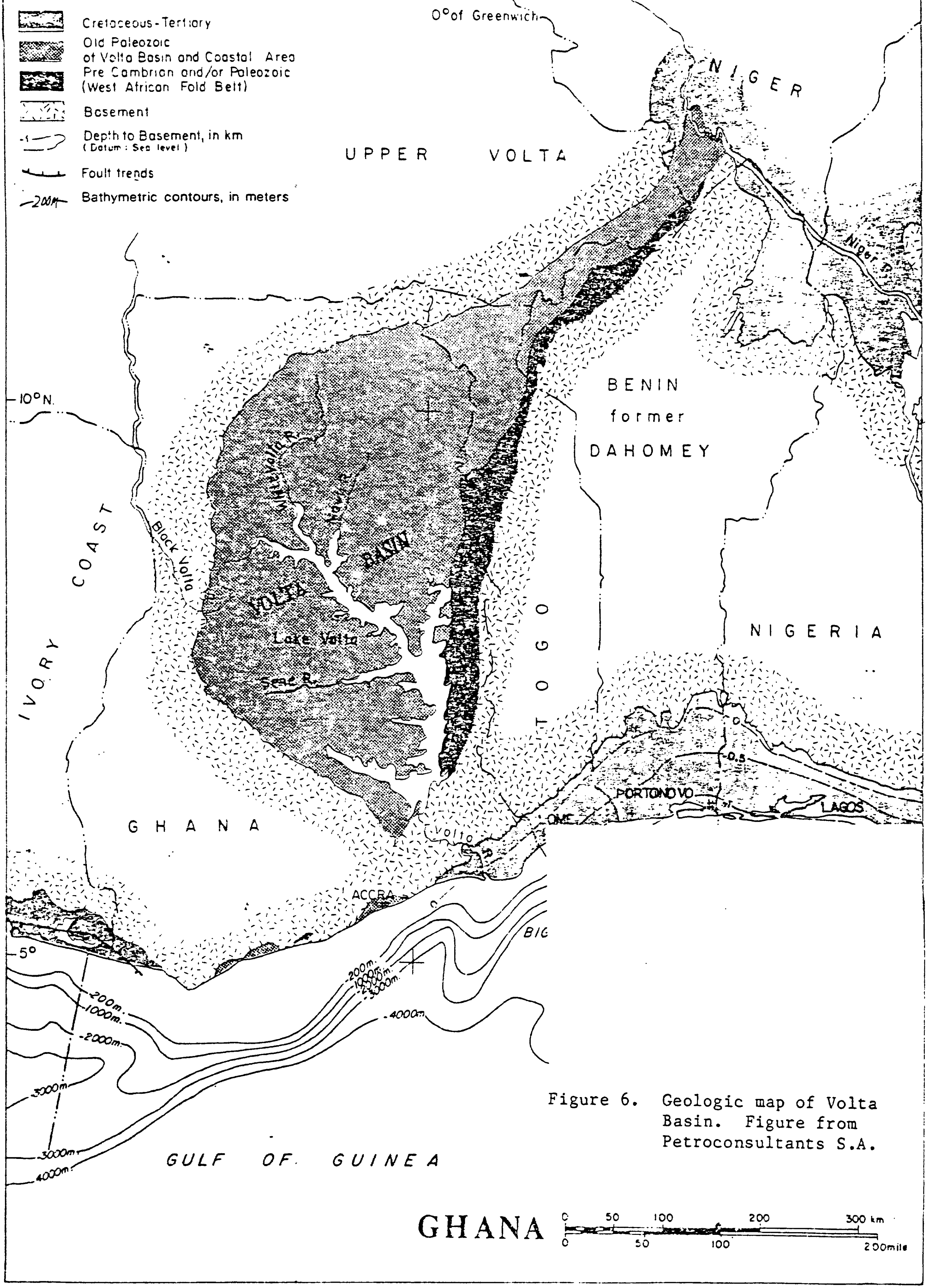


Figure 6. Geologic map of Volta Basin. Figure from Petroconsultants S.A.

Lower Voltaian - Thickness about 460 m.

Obosum Formation: (150 m) Sandstones, conglomerates and shales with intercalated tillites. Could correspond to Cambro-Ordovician.

Oti Formation: (250 m) Arkosic sandstones, shales, siliceous shales and cherts, intercalations of thick lenses of stromatolite limestone.

Basal Sandstone: (60 m) Coarse pebble-to-boulder sandstone of probable fluvial, glacial origin.

Petroleum Potential

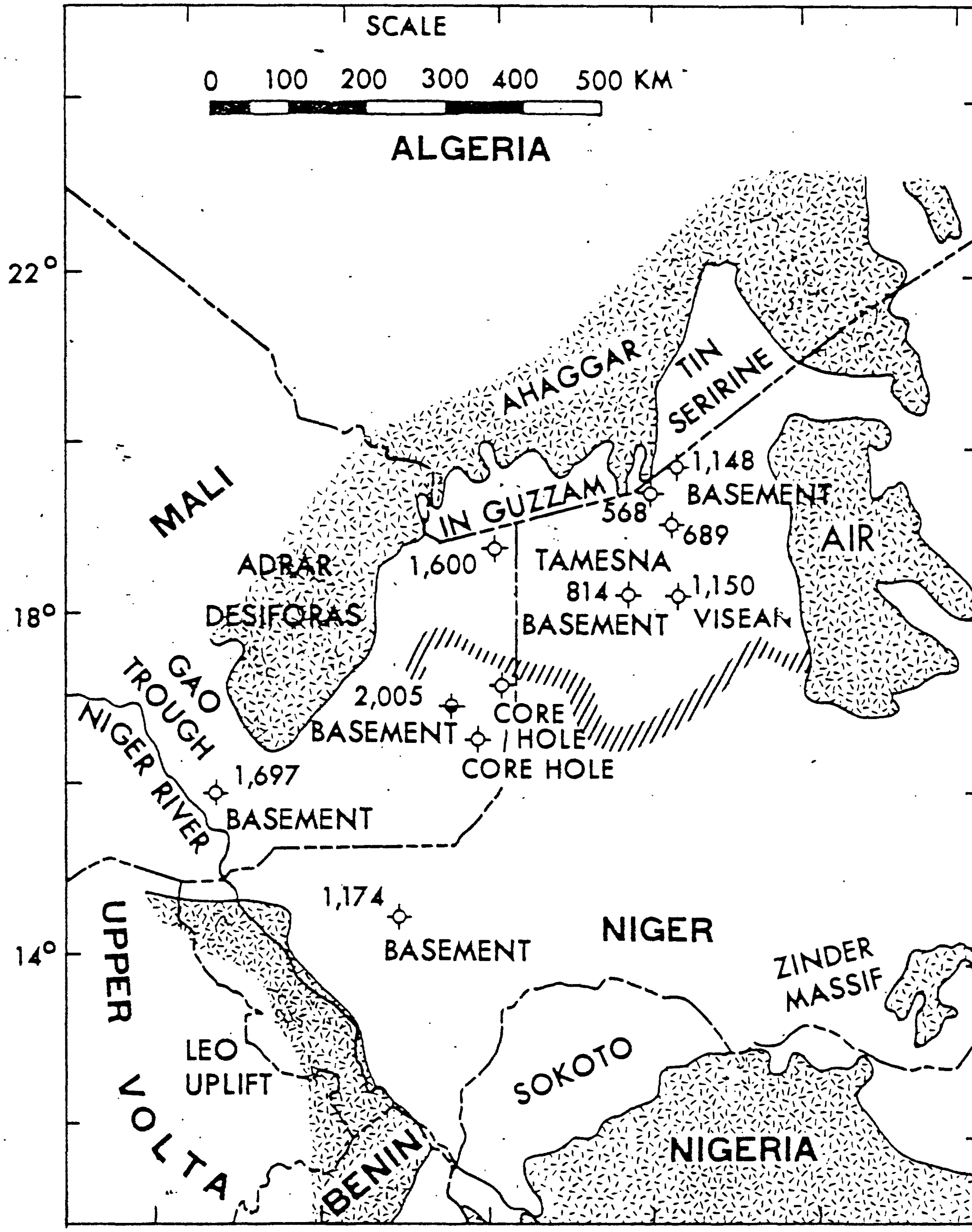
According to Petroconsultants (written commun., 1976), saltwater associated with oil impregnated sediments as well as viscous bitumen is reported from some water wells in the Volta Basin. The same author shows 11 stratigraphic tests and one deep exploratory well scattered throughout the basin in Ghana; all are reported as dry holes. The stratigraphic test wells varied in depth from 22 m to 795 m and averaged about 500 m. The deeper exploratory well was drilled to a depth of 1,200 m. The northernmost stratigraphic test, located in Ghana near the Upper Volta border, penetrated bitumen (asphalt?) between 450 and 760 m. A well, located near the center of the basin, penetrated pockets filled with bitumen in Upper Voltaian (Devonian) siltstone. the bitumen impregnated rock was penetrated at 585 m. Gas was detected in the same well.

The author was unable to find any detailed analysis of reservoir and source rock properties of the Paleozoic sequence in the Volta Basin. Until these data are made available, especially maturation properties of source rock, it will be difficult to assess the hydrocarbon potential of the basin. The Volta Basin, apparently, has a thicker Paleozoic section than either the Taoudeni or Bove Basins. It, therefore, has better hydrocarbon potential.

NIGER BASIN

Geologic setting

The Niger or Illemmeden Basin (also known as the Sokoto Basin in northwestern Nigeria) covers approximately 220,000 km^2 chiefly in western Niger and eastern Mali (fig. 7). The basin also extends into southern Algeria, the northwest corner of Nigeria and northern Benin (formally Dahomey). The basin is limited on the west by basement outcrops of the Adrar des Iforas and Leo uplift. To the north, it is limited by basement outcrops of the Ahaggar or Hoggar which form part of the central Saharan massif; to the south by crystalline and metamorphic rocks of northern Nigeria and the Upper Volta Arch. The Niger Basin is separated from the Chad Basin to the east by a subsurface ridge extending from outcrops of basement rocks in the Zinder region to outcrops of basement rocks of the Air complex. The Niger Basin is connected to the Taoudeni Basin to the west via the Gao trough or strait. In the northern part of the Niger Basin, where past exploration has been concentrated and more detailed subsurface data exists, the sub-basins called In Guezzam, Tin Seririne, and Tamesna (or Talak) are recognized (fig. 7).



EXPLANATION

WELL SYMBOLS		OTHER SYMBOLS
	DRY	---- INTERNATIONAL BOUNDARIES
	SHOW OF OIL	BASEMENT ROCKS
2,005	TOTAL DEPTH IN METERS	SOUTHERN LIMIT OF PALEOZOIC UNDER MESOZOIC COVER
BASEMENT	BOTTOM HOLE FORMATION	

Figure 7. Map of Niger Basin showing selected wells and names of sub-basins in the area.

Stratigraphy

Except in the north, the subsurface of the Niger Basin has been relatively unexplored. The basin contains Paleozoic, Mesozoic, and Cenozoic sedimentary rocks; but, except for outcrop areas in the In Guezzam and Tin Seririne areas, Paleozoic rocks are thought to feather out beneath the Mesozoic section in northern Niger. The suspected southern limit of Paleozoic rocks beneath Mesozoic cover is shown in Figure 7. The results from 5 wells, which penetrated basement in the northern and eastern parts of the basin, suggest that the entire sedimentary section is only about 2,000 m thick. The deepest well, drilled to a depth of 2,005 m, penetrated basement rocks unconformably overlain by Mesozoic rocks.

A north-south section across the Tin Seririne basin from basement outcrops of Ahaggar to south of the suspected pinchout of Paleozoic rocks is shown in Figure 8. The Paleozoic section is represented by rocks of Cambro-Ordovician through Carboniferous age. This section is unconformably overlain by rocks of Cretaceous age. However, thin Permian-Triassic age rocks crop out on the southwestern flank of the Air massif. The southern part of the basin is marked by thin Cenozoic deposits. Following is a brief summary of the stratigraphy of the Niger basin based on the report of Petroconsultants (written commun., 1976).

Cambro-Ordovician: (0-400 m in Tin Seririne area). Rocks consist of conglomerate and sandstone possibly deposited in a marine environment. The section appears to be water flushed.

Silurian-Devonian: (0-700 m) These rocks are not known in outcrop or subsurface except in the Niger Basin between Adrar des Iforas and Air. Silurian rocks are predominantly argillaceous with intercalations of limestone and sandstone of marine and glacial origin. The Silurian section is overlain by basal conglomerate and sandstone of chiefly marine and lagoonal origin. The Silurian section contains "Gothlandian" shales which are considered source rocks for oil in Algeria. In the northern part of Niger Basin the Silurian-Devonian section has been water flushed.

Carboniferous: (0-1,000 m) In the Tin Seririne area, this section consists of continental red beds at the base overlain chiefly by sandstones and siltstones with thin limestones of marine and nonmarine origin.

Perma-Triassic: (200-400 m) Section consists of variegated and crossbedded arkoses, sandstones, and mudstones of continental desert type origin.

"Continental Intercalaire": (0-2,000 m) Rocks younger than last dated Paleozoic and older than marine Cretaceous are termed "Continental Intercalaire" and consist mainly of continental red bed facies (0-2,000 m).

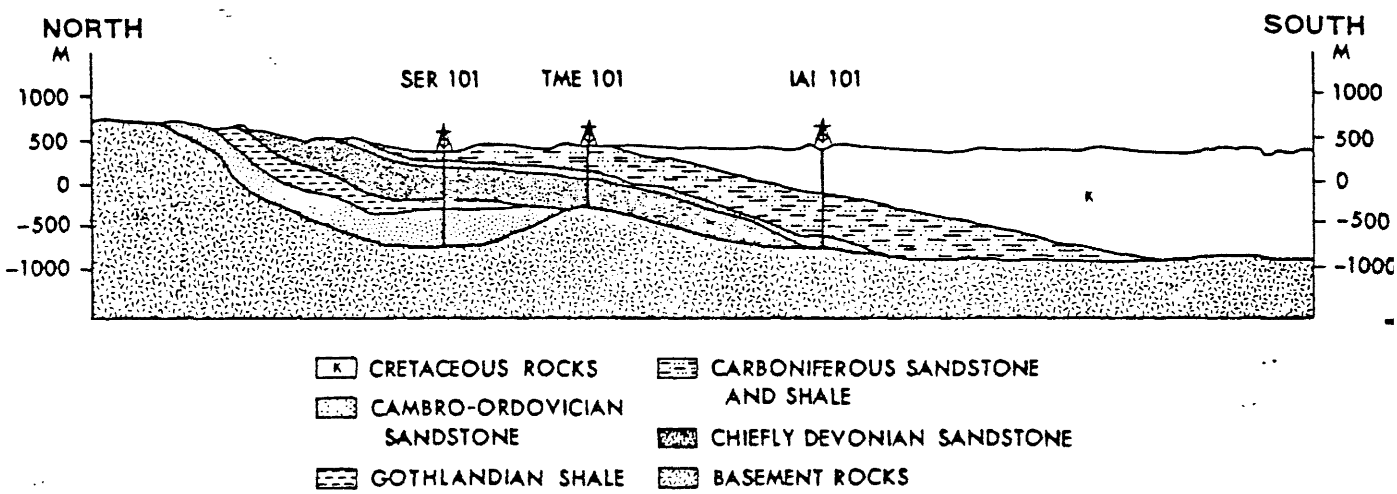


Figure 8. Cross section of northern part of Niger Basin (Tin Seririne area). Note that erosion has truncated south-dipping beds. Figure modified from Petroconsultants S.A. (written commun., 1976)

Middle and Upper Cretaceous and Younger:	(500 m in west and 1,000 m in east) During this time alternating marine and nonmarine conditions prevailed. Upper Senonian rocks contain bitumen and sands rich in carbonaceous matter. The thin section, however, precludes possibility of maturation.

Petroleum Potential

Paleozoic section.— Although hydrocarbons have been found in equivalent age rocks with similar lithologies in Algeria, the possibility of discoveries in the Niger basin are extremely low. As shown in Figure 8, Paleozoic rocks exposed in the Tin Seririne and In Guezzam areas dip steeply to the south and pinchout. Most likely, any oil generated within the section would have migrated north and subsequently leaked out of the formation. Water flushing of Cambrian-Devonian strata would have destroyed possible oil deposits. In addition, 6 exploratory wells have penetrated the Paleozoic section without any reports of oil or gas shows. It may be that Paleozoic rocks are preserved in faulted troughs or small basins in other areas of the Niger Basin. If adequately sealed, they could have the potential of containing oil and gas deposits.

Cretaceous section.--Prospects for the "Continental Intercalaire" are also considered highly speculative because of the absence of potential source rock. Although the Middle and Upper Cretaceous sections appear to have the potential for containing source rock, these sections are thin and, therefore, probably not thermally mature with respect to the generation of oil and gas. As is discussed in a later section (Benue depression, this report), however, the Cretaceous section may prove to be thicker in the eastern Niger Basin than previous thought. It is possible that tectonic activity associated with formation of the Benue Depression extends as far east as the Niger Basin. If this hypothesis proves correct, then a thick Cretaceous section may exist in parts of the eastern Niger Basin. A thicker Cretaceous section coupled with high heat flow resulting from a "failed-arm trough" system could make Cretaceous prospects in the eastern Niger Basin more attractive.

CHAD BASIN

The Chad Basin covers eastern Niger and Chad and extends south into Nigeria, Cameroon, and Central African Republic (fig. 9). Exploration drilling and geophysical surveys have revealed that much of the Chad Basin is underlain by a complex system of basins or troughs related to a "failed-arm" system (fig. 10). Recent oil and gas discoveries in the Lake Chad area and southern Chad are related to this trough system and will be discussed in another section (Benue depression, this report).

In the northern part of the Chad Basin, exploration has been concentrated in Paleozoic rocks. There, the Marzug Basin of southwestern Libya and Algeria extends into northeast Niger and Chad near the Tibesti massif (fig. 9).

Paleozoic rocks in this area wedge out along a sinuous line between 17° and 20° North Latitude. The discovery of large oil and gas deposits in Algeria, in the early sixties, led to the drilling of wildcat wells in northeastern Niger.

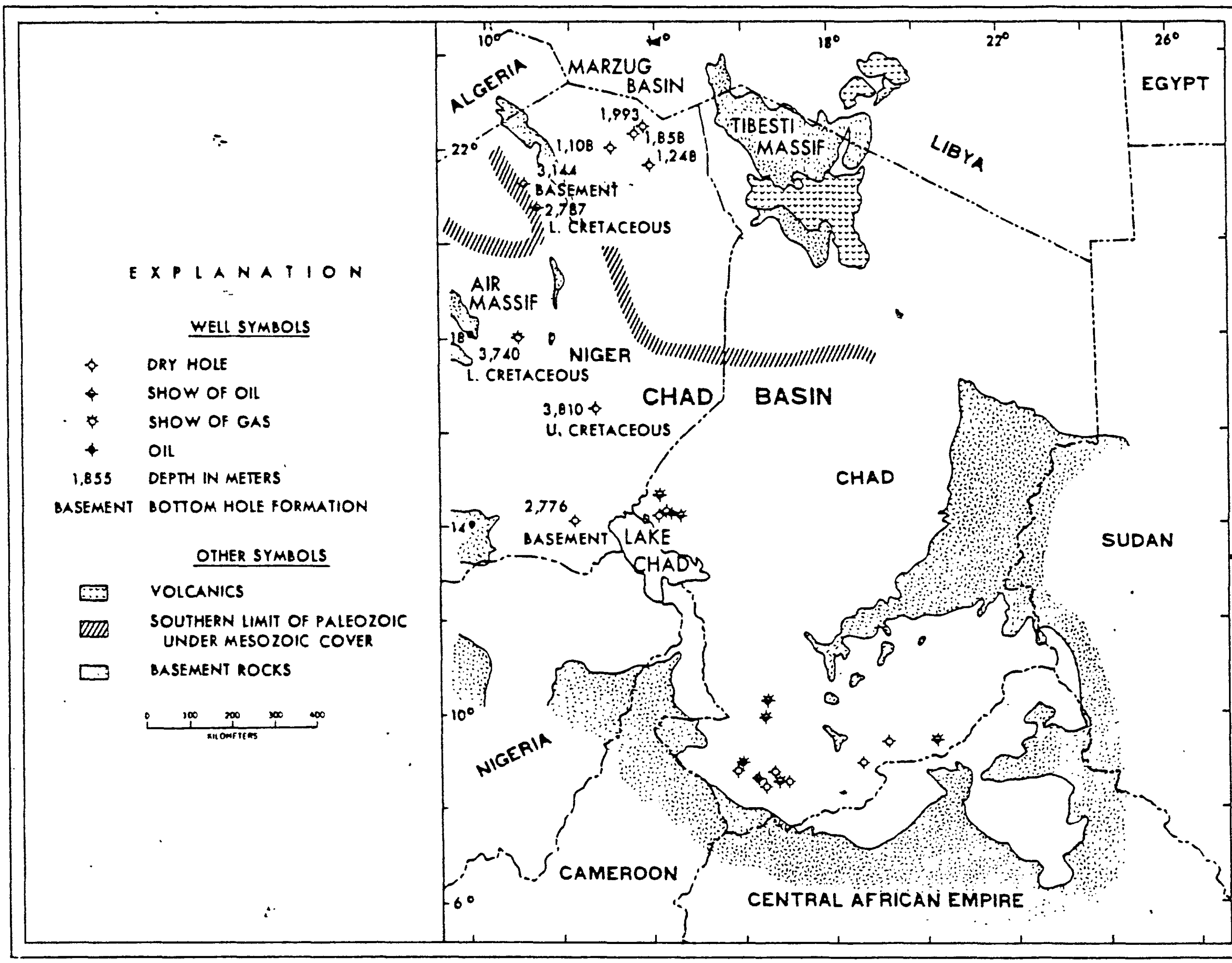


Figure 9. Map of Chad Basin showing selected wells.

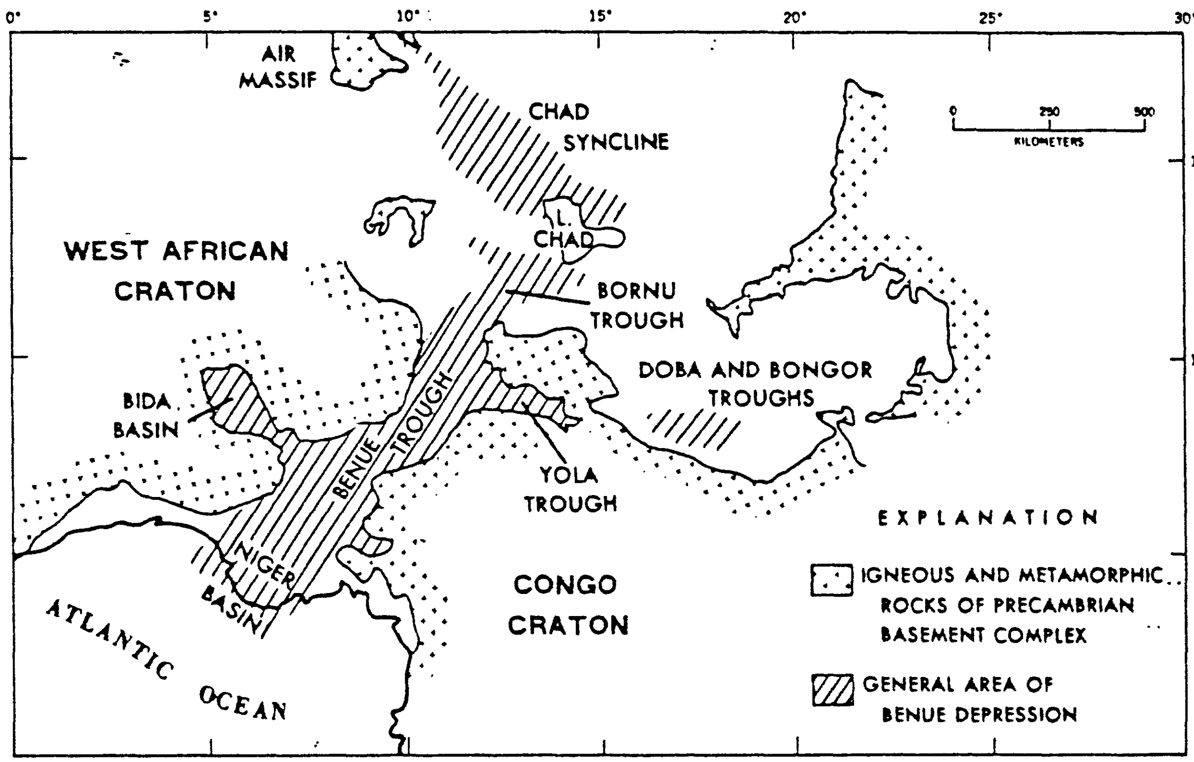


Figure 10. Map showing general area of Benue depression and associated basins and troughs.

The stratigraphy, formation thicknesses, and geological history are similar to that described for the Niger Basin. The Paleozoic section is thin and the lowermost part of the Mesozoic section probably consists of a red bed facies of the "Continental Intercalaire." Six wells have been drilled; five have been reported as dry and a show of oil reported from the sixth (Petroconsultants, written commun., 1976).

On the basis of drilling and by analogy with the Niger Basin, the probability of finding commercial quantities of hydrocarbons in the northern Chad Basin must be considered low.

BENUE DEPRESSION

Geologic setting

The term Benue depression (fig. 10) is used in this report to refer to the basin and trough system between the West African and Congo Cratons that formed in Early Cretaceous time when separation of Africa and South America was initiated by opening of the South Atlantic. Exploration of this "failed-arm" system is in the early stages, and its subsurface extent, especially in northern Nigeria, Niger, and Chad, is not fully known. Based on structural contours shown on the Tectonic Map of Africa (Association of African Geological Surveys, 1968), the Cretaceous trough system appears to extend northeast from the Benue Trough, where the geology is relatively well understood, to the vicinity of Lake Chad. The Chad syncline (Termit trough) which extends northwest from Lake Chad to the Air Massif, and the Doba and Bongor troughs, in southern Chad, may be part of this system. In addition, a general thickening of sediments from the Chad-Niger border into the Niger basin suggests that the trough system may extend as far west as the Niger Basin.

Although large discoveries of oil and gas have been made in the Niger Delta Basin, these discoveries are only indirectly related to the opening of the South Altantic. The great thickness of sediments that produce oil and gas in the Niger Delta Basin was deposited between Eocene and Holocene time (Weber and Daukoru, 1975) and will be discussed in a later section of this report.

Evolution of the Benue depression (fig. 11) began in Early Cretaceous time (Aptian and Albian) when the Gulf of Guinea opened about a triple-junction rift-ridge system under the present Niger Delta. Opening along the Benue arm later stopped and it became what is known as a failed-arm system. Opening followed existing lines of weakness close to the edges of the West African and Congo cratons (Burke and others, 1970). The Benue-Abakoliki Trough was flanked by the Anambra Platform on the northwest and the Ikpe Platform/Oban Massif on the east-southeast (fig. 12). The trough was filled by more than 3 km of sediments of Albian to Coniacian age (Weber and Daukoru, 1975). During the Santonian, the Benue-Abakoliki Trough was uplifted to form the Abakoliki High/ Benue folded belt, and the Anambra Platform was downwarped to form the Anambra Basin (Murat, 1970). Burke and others (1972), attribute the folded belt to Late Santonian folding resulting from misfit motion within the African plate due to faster spreading opposite the bulge of Africa than in the south Atlantic. This partial Santonian closing episode may have produced long linear folds subparallel to the main trough margins in contrast to the unfolded gently dipping Cretaceous rocks of the Bida Basin. Those of the Yola Basin are folded subparallel to the local trough axis (Burke and others, 1970).

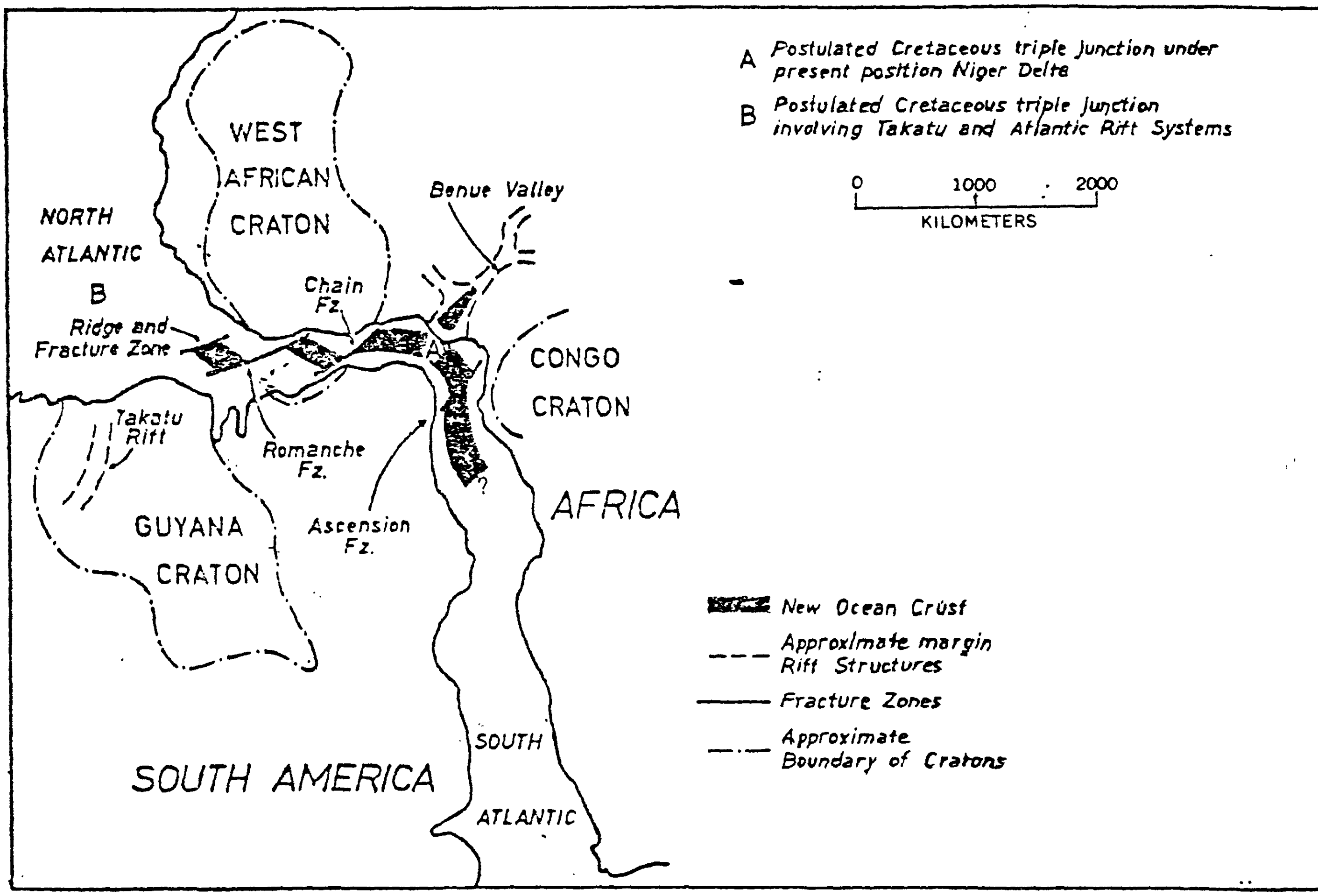


Figure 11. Sketch map showing the Gulf of Guinea in the Early Cretaceous. The Atlantic is shown as opening about triple junctions situated under the Niger delta and north of the Takatu rift. Figure based on Hurley and Rand (1969) and modified from Burke and others (1970).

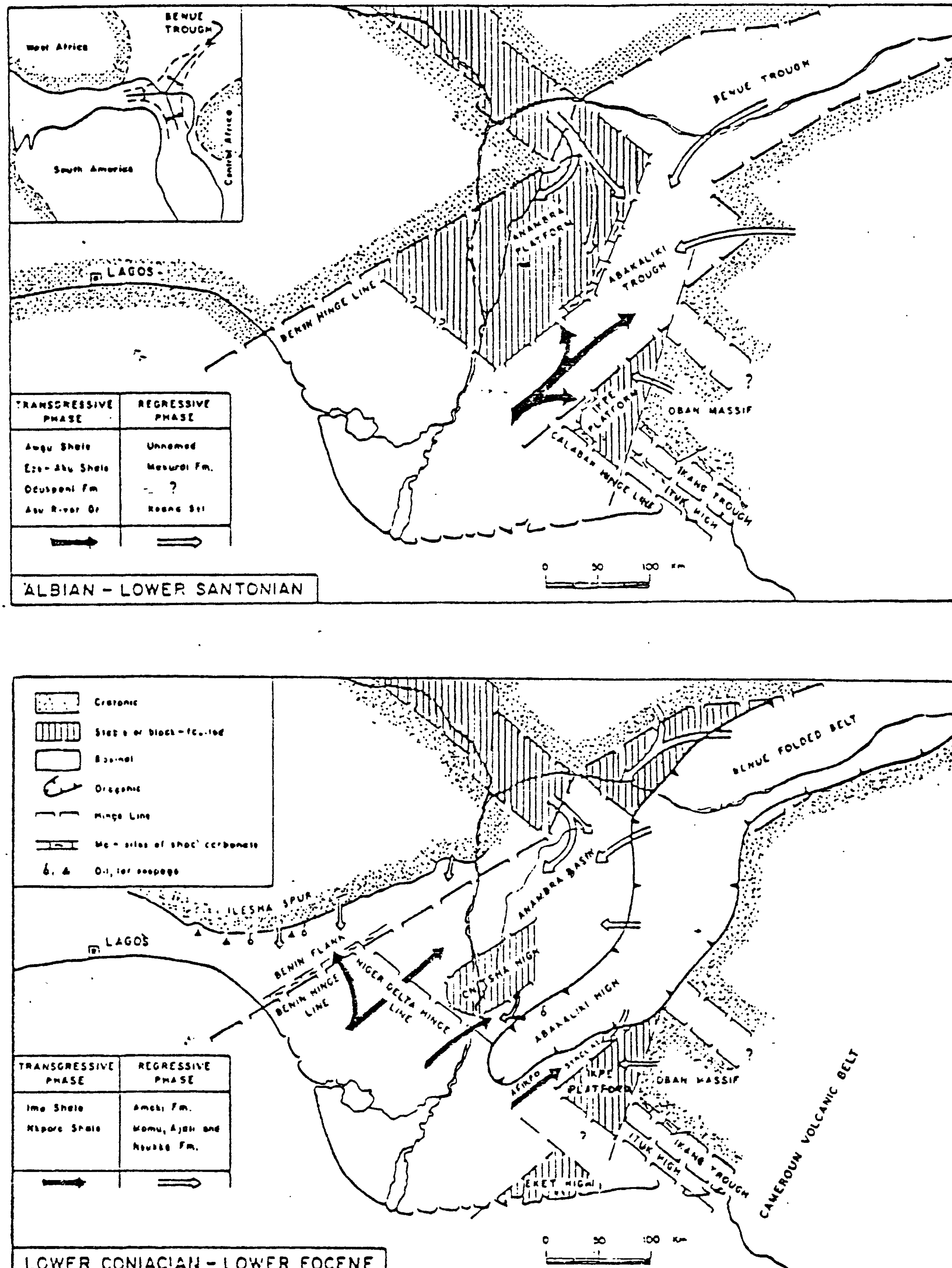


Figure 12. Evolution of the Benue depression. Figure from Weber and Daukoru (1975).

Existing from the Campanian to the Paleocene were the large Anambra Basin and two smaller basins--the Ofikso Syncline and the Ikang Trough. Within the Anambra Basin was the Onitsha High, possibly formed by block faulting and tilting (Weber and Daukoru, 1975). Late Cretaceous delta systems advanced down the Benue Trough resulting in the formation of the Bima and Gombe-Coal Measures deltas (fig. 13). By Eocene times delta systems had started to develop down the continental slope and had spread onto oceanic crust (Burke and others, 1970).

Stratigraphy

The stratigraphy is summarized chiefly from Burke and others (1970) who relied on the earlier works of Cratchley and Jones (1965), Wright (1968), and Reyment (1969). Precise stratigraphic data is available only for the lower Benue area (fig. 13) where numerous wells have been drilled in Nigeria.

Six transgressive and regressive phases have been recognized in the lower Benue; not all are recognized in the middle and upper parts of the depression. From Albian to Santonian times continuous deposition representing a variety of environments occurred. These included marine shales (deep and shallow water) with limestones and sandstones deposited at the margins of a marine embayment at the southern end of the depression. Sandstones were derived mainly from flank areas up the valley and laid down during regressive phases. In Turonian times, thick marine shales with limestone at their base were deposited. The Turonian transgression was widespread and extended over the Zambuk ridge (fig. 13) into the Chad Basin (Burke and others, 1970, p. 196). the Albian-Santonian section is separated from the overlying section by an unconformity believed to be associated with partial closing and folding of the failed-arm system.

Above the unconformity, sandstones and coarse clastics represent erosion of the uplifted flanks of the depression. New major depocenters developed in the Anambra Basin, the Afikpo Syncline and the Dahomey (Benin) Basin. During a Maestrichtian transgression marine sedimentation reached the Chad Basin (Carter and others, 1963). Shale and limestone deposited in the lower Benue represent a Lower Paleocene transgression. Since then thin continental sediments were laid down in most of the depression north of the Niger Delta.

Petroleum potential

Initial oil and gas exploration in Nigeria was concentrated in marine Cretaceous rocks in the lower Benue depression where traces of oil and gas occur at the surface. This early exploration phase, however, proved unsuccessful. Petroconsultants (written commun. 1976) reports that as a result of drilling in 1967, gas was tested in post Turonian rocks and that oil was discovered in rocks of unspecified Cretaceous age. No development drilling has been reported on these discoveries. More than 20 wells were drilled into the Cretaceous section.

In the lower Benue depression, Cretaceous possibilities for structural and stratigraphic traps exist in the Anambra Basin, where marine Cretaceous rocks are over 9 km thick, and in the Abakaliki Basin. In the latter basin,

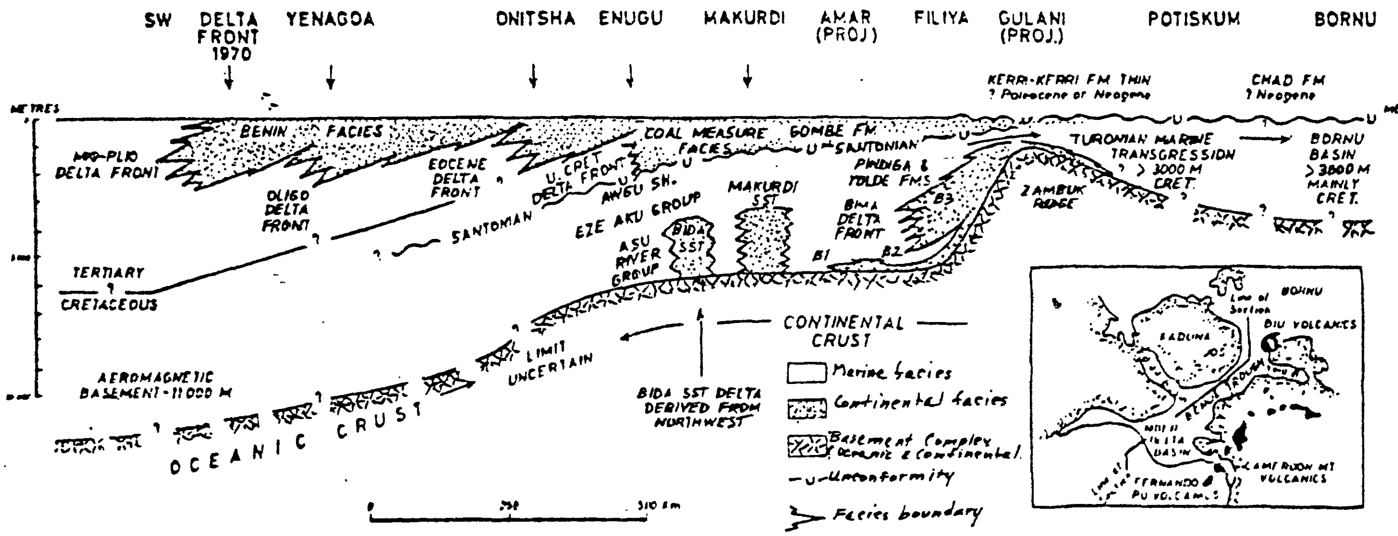


Figure 13. Reconstructed section of the Benue depression and Niger Delta systems. Figure from Burke and others (1970).

Cretaceous rocks were folded beneath a Santonian unconformity. In the Anambra Basin, Cretaceous delta complexes with growth faults as well as tectonic structures may be accessible. Stratigraphic traps could involve changes from limestone to shale facies. Coal measures (fig. 13) may be an important gas source.

More intriguing than the possibility of discoveries in the lower Benue depression, however, is the possibility of significant discoveries in the Bornu trough-Chad syncline and the Doba-Bongor areas in the Chad Basin (fig. 10). The relationship of these areas with each other and their relationship to the overall Benue depression is still unknown. In the Bornu Basin, preliminary geophysical data indicate that the Mesozoic-Tertiary section is over 3,000 m thick. In southern Chad, the en echelon Doba and Bongor trough system contains more than 4-5,000 m of sedimentary rocks. Prior to the cessation, early 1979, of all drilling and exploration activity in Chad, oil and gas discoveries were made in Chad north of Lake Chad and in the Doba-Bongor trough system. It is rumored that these discoveries may be large although little information is available. According to Petroconsultants (written commun. 1976), sandstone of the "Continental Terminal" is thought to be the reservoir, which is located in favorable structural position over Cretaceous rocks in a marked graben system.

In the Chad Basin the "Continental Intercalaire" (Early Cretaceous and older) consists mainly of red beds and fluvial and deltaic deposits. Upper Cretaceous and Paleocene rocks (thought to be thin) are predominantly shallow marine to lagoonal and lacustrine deposits, grading upwards into the Tertiary beds of the "Continental Terminal." The petroleum prospects of these rocks, in the past, have been considered low because most of the section was considered to consist chiefly of continental facies barren of potential source rocks.

If this area, however, proves to be part of the Benue failed-arm system, deep fault-related troughs linked to tensional tectonics may underlie the area. These troughs could contain thick marine/lagoonal Upper Cretaceous rocks with both source and reservoir rocks sealed by Cenozoic sediments and possible reservoir sandstones in the underlying "Continental Intercalaire" as well as in the overlying "Continental Terminal." In Cretaceous time these rocks may have experienced high temperatures associated with an increased geothermal gradient related to failed arm tectonics. These higher than normal temperatures could have generated large quantities of oil and gas in marine, lacustrine, and lagoonal source rocks.

SENEGAL BASIN

Geological setting

The Senegal Basin with its extension into Mauritania to the north and Guinea Bissau to the south covers an area of some 340,000 km^2 (fig. 14). Throughout much of its history (Cretaceous-Cenozoic) it was an open coastal basin, in essence homoclinal and controlled by basement subsidence caused by tensional stress, thermal cooling, and sediment loading. Its sedimentary fill of sandstone, siltstone, shale, carbonate rock, and evaporites exceeds 7 km in thickness (fig. 14) and ranges in age from Triassic to Miocene, covered

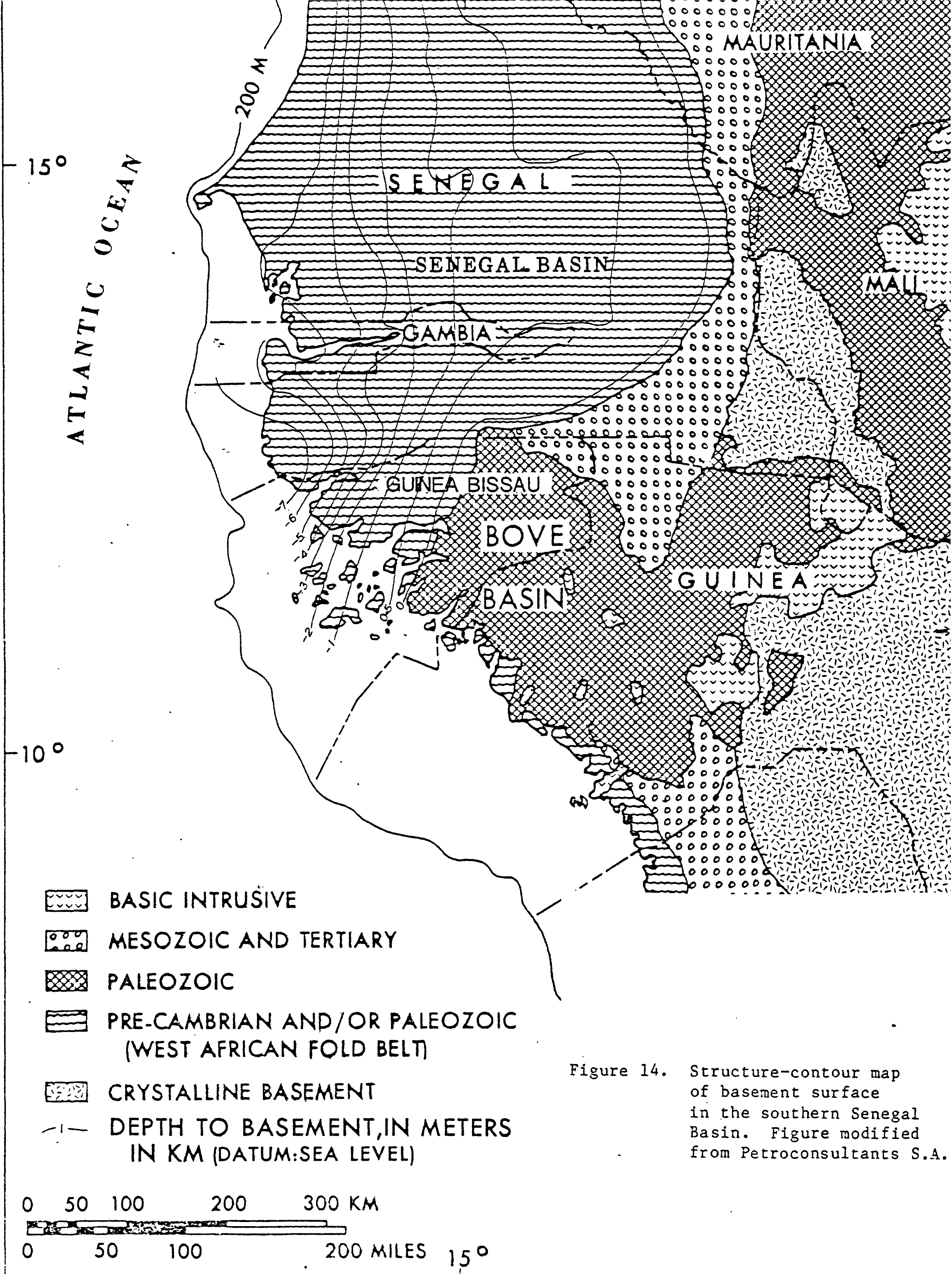


Figure 14. Structure-contour map of basement surface in the southern Senegal Basin. Figure modified from Petroconsultants S.A.

by a thin Miocene-Pliocene veneer of continental sands. Salt diapirs are present in the basin. Sedimentary rocks are continental in the east and become thicker and more marine to the west (Castelin, 1965).

The Senegal Basin represents a typical Atlantic type marginal basin and its petroleum potential has been compared to basins of a similar type offshore of eastern United States (Mattick and others, 1978). The oldest sedimentary rocks penetrated in the Senegal Basin consist of salt which has been age dated as Triassic to Liassic (Templeton, 1970, p. 52). In comparison, the oldest sedimentary rocks penetrated offshore of eastern United States also consist of salt of probable Triassic age. In Georges Bank Basin (offshore of northern United States), this salt unconformably overlies metamorphic rocks of Paleozoic age (Amato and Simonis, 1980). Rona (1969) has drawn the logical conclusion that these areas were part of a restricted Atlantic sea such as is shown in Figure 15 during Jurassic times. This early Atlantic sea resulted from a late Paleozoic or early Mesozoic break up between Africa and North America.

Magnetic data together with the fact that no evidence has been published for the existence of salt domes offshore of Guinea, Sierra Leone, or Liberia, led Templeton (1970) to conclude that the postulated Triassic-Jurassic evaporitic sea did not extend south beyond the continental shelf in the area of the Bijagos Archipelago in Guinea Bissau (fig. 16). The southern limit of the Senegal Basin, therefore, is thought to be the Bijagos Archipelago.

South of the Bijagos Archipelago the thickness of sedimentary rocks rapidly diminishes to less than 4,000 m (Sheridan and others, 1969). According to Behrendt and Wotorson (1970), aeromagnetic studies off Liberia indicate that the sedimentary section there on the Continental Shelf is relatively thin. In addition, the seismic reflection studies of Schlee and others (1974) found no evidence of pre-Cretaceous sedimentary rocks in the Liberian coastal and offshore areas. The Senegal Basin, therefore, probably marks the southern limit of Triassic-Jurassic sedimentary rocks.

Stratigraphy

The stratigraphic sequence of the basin fill as summarized by Templeton (1970), Castelain (1965), and Petroconsultants (written commun. 1976) is as follows (see also Figure 17):

Triassic-Jurassic: Triassic-Jurassic sediments are probably represented by evaporites which were deposited in a small, shallow early Atlantic basin. Salt was penetrated in wells on the Continental Shelf offshore of Senegal near Guinea Bissau. Salt basins both north and south of Dakar in the deepest parts of the basin are postulated (fig. 17). Piercement of some salt domes stopped at the end of Cretaceous and positive buoyancy caused thinning and folding of overlying Tertiary beds (Templeton, 1970).

Upper Jurassic: (>760 m) This section penetrated onshore near Dakar, consists of dolomitic limestones, at places oolitic, probably deposited on a carbonate platform.

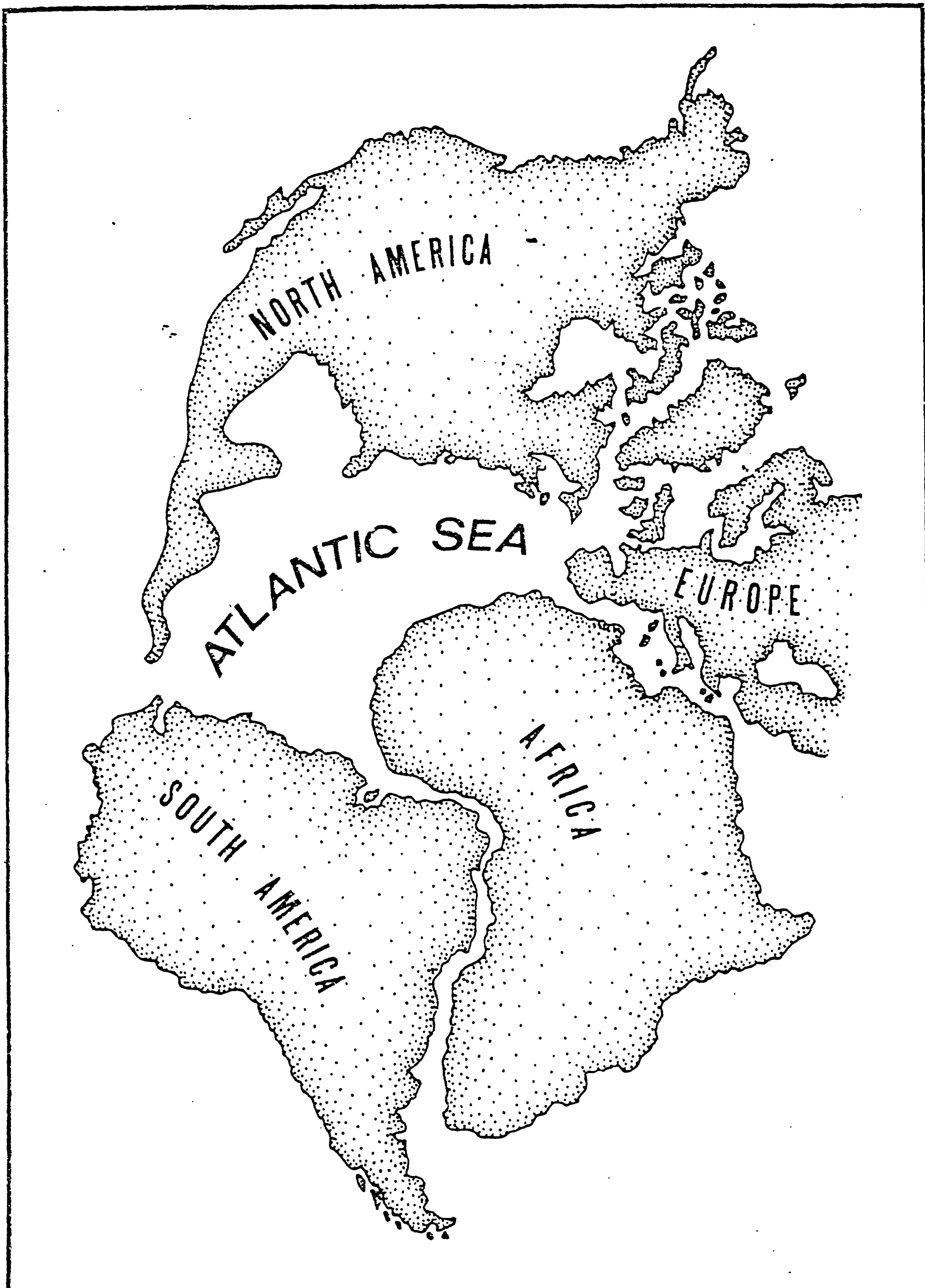


Figure 15. Interpreted sketch of the Atlantic during Jurassic time. Figure from Rona (1970).

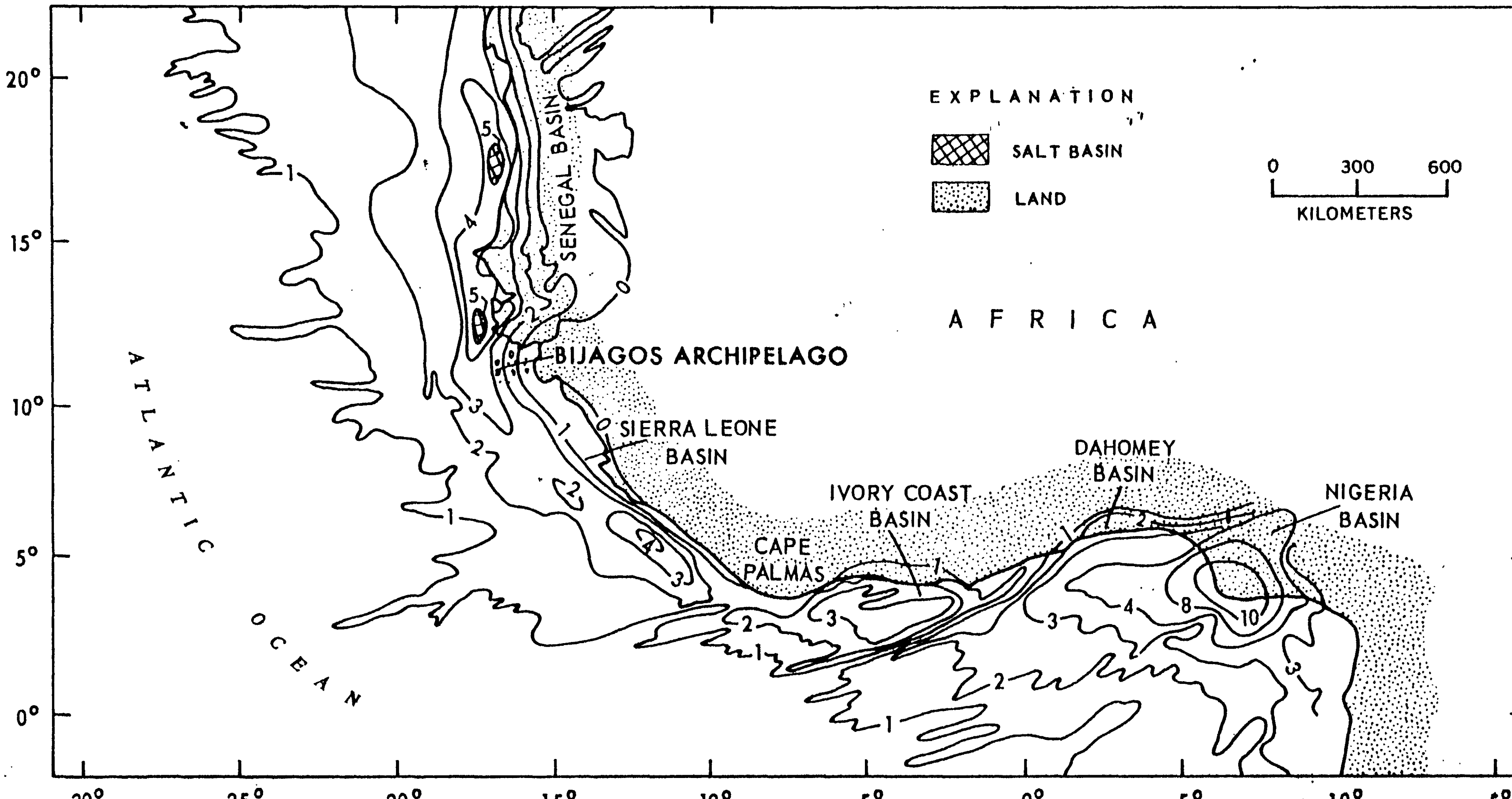


Figure 16. Isopach map of total sediment thickness in seconds of reflection time. Figure modified from Emery and others (1974) and Uchupi and others (1975).

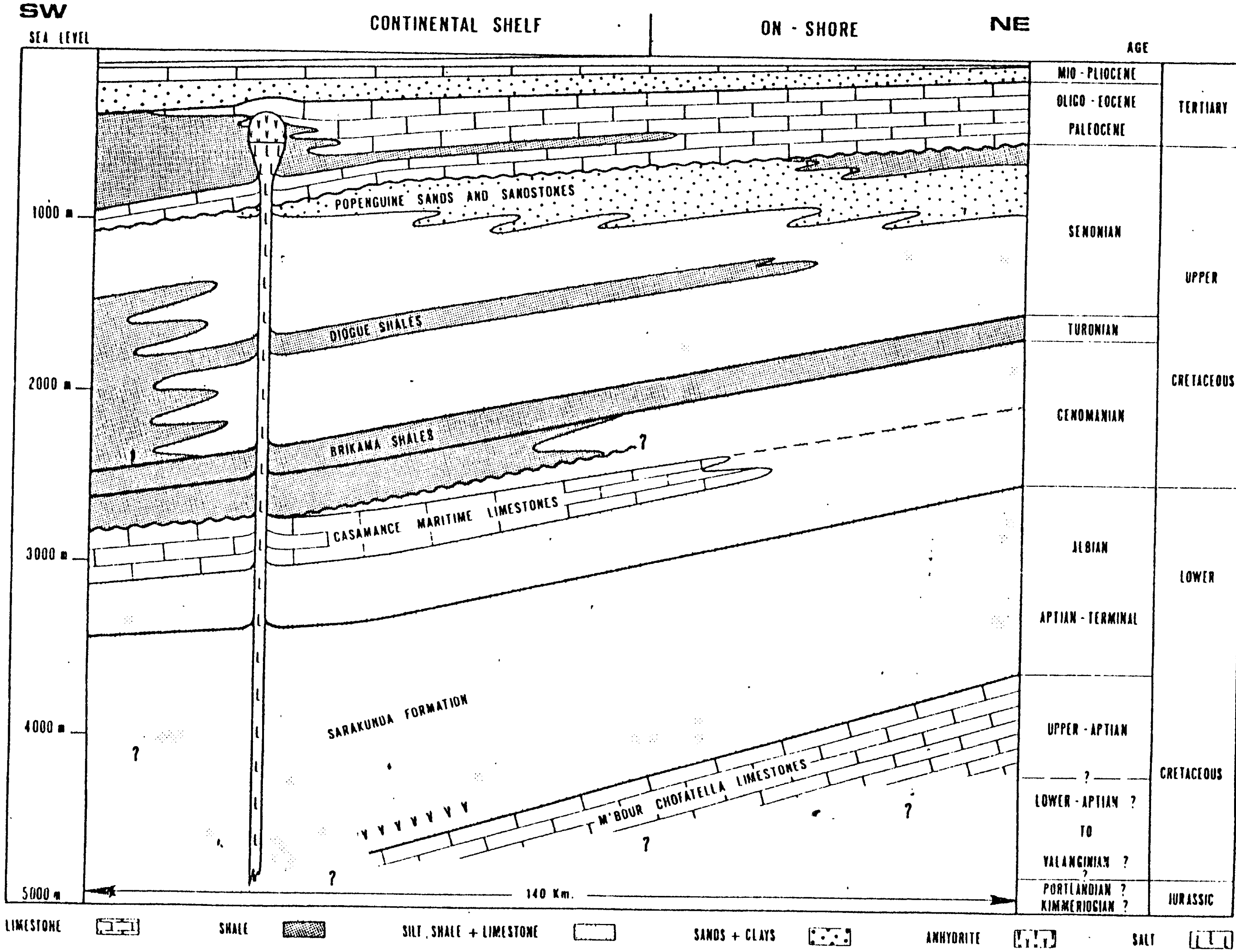


Figure 17. Generalized geological section of the southern part of the Senegal Basin. Vertical exaggeration 25:1. Figure from Templeton (1970).

Valanginian-Aptian:	(>1,700 m) Near Dakar (center of basin), this section consists of neritic (shelf) limestone referred to as the M'Bour Chofattella Limestone (fig. 17). It grades to shale and sandstone and near the rim of the basin grades into reddish shale and silt of continental origin.
Aptian-Cenomanian:	(up to 1,500 m) The basically neritic to continental Sarakunda Formation consisting of poorly differentiated alternations of silt, shale, and limestone with occasional anhydrite bands or nodules. This sequence is missing in places at shoreward margin of basin.
Cenomanian-Turonian:	(>1,000 m in south) Section consists mainly of shale with sandy interbeds grading rim-ward to dirty massive sandstone. Turonian pelagic (deep sea) Brikama Shale (fig. 17) marks an (Atlantic-wide) Upper Cretaceous transgression. This section could contain good source rocks where deeply buried or subjected to high temperatures.
Upper Cenomanian-lower Senanian:	(up to 950 m) Poorly sorted silts, shales, marls, and limestones which grade westward from a littoral and lagoonal facies to a pelagic shale facies at shelf margin. Diogue Shales (fig. 17) represent a transgression. Popenguine sandstones represent a major regression during Maestrichtian time.
Tertiary:	(up to 1,050 m) Following uplift and erosion, Paleocene limestone was deposited. It is overlain, onshore, by neritic Eocene and Oligocene limestones grading offshore to shales. Miocene deposition is represented by clay, sand, gravel, and limestone beds overlain by a thin veneer of continental Mio-Pliocene sediments.

Past exploration activity

Although Senegal was reported to have produced small amounts of oil in the early 1960's (Moody and Parson, 1963), no production was reported for 1979 (Auldridge, 1979). The French companies, Bureau de Recherches de Petrole (BRP) and Societe Africaine des Petroles (SAP), started exploration in 1952 and were following by British Petroleum in 1960, then by Capagnie Francaise des Petroles (CEP) in 1976, and finally by Shell Oil Company which relinquished their concession in 1977 (Philip Woodside, U.S.G.S., written commun. 1981). The onshore area, near Dakar has been extensively covered by geophysical surveys. The entire shelf area north of Gambia has been explored using a dense seismic reflection grid. Although not reported in the literature, the offshore area of Gambia probably also has been explored using a dense seismic network.

Seven wells have been drilled in the Senegal Basin offshore Mauritania. Two wells were in deep water—one in 588 m of water was drilled to a depth of 4,105 m and bottomed in Albian rocks, the other in over 1,000 m of water was drilled to a total depth of 5,015 m. According to Petroconsultants (written commun., 1976), there may have been a marked absence of potential reservoirs in much of the penetrated section. Thirty-six wells were drilled in the area of the Dakar Penninsula in the late fifties and early sixties resulting in a number of oil and gas shows in Maestrichtian sandstones. This early work apparently also resulted in some early production of oil. The same authors show 15 dry holes drilled north, south, and east of the penninsula; at least three of these wells are drilled to basement. Offshore of Dakar, on the shelf, 6 exploratory wells were drilled and abandoned prior to 1970—the deepest of these was drilled to 4,271 m. The results of these offshore tests were not disclosed but it is suspected that Jurassic reefs were targets. In Gambia two wells have been drilled onshore near the coast. In the deeper of the wells (the Brikama-1 well), gas shows were reported from the Albian-Cenomanian and Aptian sections (Petroconsultants, written commun. 1976). On the slope offshore of Gambia, the Jammah-1 well was completed to 3,020 m and reported as dry (Petroconsultants, written commun. 1976). In Senegal, south of Gambia at least 15 deep wells and other shallow wells were drilled on the shelf and coastal plain and 1 on the slope. In Guinea Bissau, 4 wells have been drilled on the shelf and 1 on the slope. Petroconsultants (written commun., 1976) reports that most of the wells drilled south of Gambia were dry except on the shelf near the Senegal-Guinea Bissau boundary where reserves of heavy oil were found.

The heavy oil deposits penetrated on the Senegal shelf are at depths of less than 1,000 m in Oligocene age rocks above shallow piercement type salt domes. Estimates vary as to the amount of heavy oil discovered. Philip Woodside (U.S.G.S., written commun., 1981) reports an estimated 100 billion barrels of oil in place, whereas, Petroconsultants (written commun., 1976) reports 1 billion barrels without specifying whether this refers to in-place oil or potentially recoverable oil. A feasibility study involving the applicability of stimulation methods, is being prepared by foreign contractors; the project is being sponsored by the World Bank.

Petroleum potential

Major exploration activity for oil and gas in the Senegal Basin ceased in about 1977 following completion of the Cayor-1 well located offshore of northern Senegal near the shelf edge. This culminated at least 25 years of intense exploration during which over 83 wells were drilled. Except for the production of small amounts of oil from the Dakar Pennisula in the early 1960's and the discovery offshore of heavy oil deposits above salt intrusions, no significant discoveries of oil or gas have been made.

Based on the intensity of past exploration efforts, we can assume that most of the large structures, at least those that can be found by seismic reflection methods, have been tested--expecially in the area of the Dakar Penninsula where much of the drilling was concentrated and where numerous oil and gas shows were reported. These shows and heavy oil discoveries indicate that source rocks capable of producing petroleum exist within the basin and, perhaps, small discoveries will be made in the future.

We can only speculate as to the reasons for the apparent absence of major producible hydrocarbon accumulations in the Senegal Basin. The literature does not contain descriptions of major structures in the basin. Scarcity of major structures in an Atlantic type marginal basin is consistent with results obtained from seismic reflection surveys in other parts of the world such as offshore eastern United States and the Nova Scotia shelf offshore of Canada (Mattick, 1978). Except during their early history, when vertical block faulting and the formation of horst and graben structures is prevalent, the predominant structural style of Atlantic type margins involves gentle, seaward dipping beds. Because the basins on these margins are formed by tensional, rather than compressional forces, and by simple basement subsidence, significant folding of strata does not occur. Structures in the younger part of the section (in this case post-Upper Jurassic) will probably be limited to piercement type structures such as might be caused by salt, shale, or volcanic intrusions. Growth faults near the shelf margin are also common features of Atlantic type margins.

Another factor that must be considered is the thermal maturation of source rock. Although detailed geochemical analysis of subsurface samples from the Senegal Basin are not available, we can speculate on the maturity of the sediments based on data available from other Atlantic type margins. In offshore basins of eastern United States, peak thermal maturation with respect to oil does not occur above depths of about 4.5 km (Mattick, 1980)—the approximate depth of the deepest wells drilled on the area offshore of Senegal. In this respect, Atlantic type margins are considered to be cold margins. Discoveries of oil in Senegal are limited to the Dakar Peninsulas, where Tertiary volcanic activity has been reported, and to areas of salt intrusion. Both of these mechanisms, volcanic activity and salt intrusion, involve local generation of heat and local rise of the geothermal gradient. The above discussion suggests that oil generation in the Senegal Basin may be a local rather than widespread phenomenon.

Significant quantities of hydrocarbons may have been generated in the deeper parts (Jurassic) of the sedimentary section where they have been subjected to higher temperatures. This part of the sedimentary section, probably contains mainly continentally derived organic matter and, therefore, would be more likely to generate gas than oil. However; shale beds that reflect lacustrine deposition could be good source rocks for oil.

In deep-water areas traps may occur above horst structures with associated drape-over of clastic rocks, in backreef, reef, and forereef facies associated with a Jurassic carbonate platform, and in Cretaceous turbidites. The deep water areas (>200 m water depth) of the Senegal Basin are relatively unexplored; sparce drilling, however, indicates a lack of reservoir rock.

GUINEA TO ST. PAUL FRACTURE ZONE

Geological setting

Between the Guinea and St. Paul fracture zones (fig. 1), the Continental Shelf and associated bathymetric contours generally trend in a northwest direction; but, where the Guinea fracture zone intersects the continental margin, the general trend is interrupted and the 200 m bathymetric contour trends in an east-west direction. A similar, but more subdued change in trend, is seen where the Sierra Leone and St. Paul fracture zones intersect the margin. These fracture zones extend westward to the Mid-Atlantic Ridge and their pattern with respect to the coast is due to control by sea-floor spreading. Along the fracture zones, topographic relief on the basement surface is expressed by valleys and ridges and they have acted either as loci for intrusions or as a mechanism for juxtaposing contrasting rocks. Along the Guinea fracture zone, the contact between oceanic and continental-type basement rocks are offset by about 300 km (fig. 18). Much of the area seems to have been influenced by tensional forces created in Late Triassic-Early Jurassic time during rifting of Africa and North America. However, in the area off eastern Liberia, the margin appears to have formed during Late Jurassic-Early Cretaceous time during separation of Africa and South American (Schlee and others, 1974).

The change in geology from the Senegal Basin to the area offshore of Guinea is shown in Figure 19. In the Senegal Basin, the outer shelf and slope are underlain by a thick section of Cretaceous-Jurassic rocks that represent a Mesozoic carbonate platform. Salt domes probably originated from an evaporite layer at the base of the Mesozoic carbonate sequence at 8-10 km below sea level (Lehner and De Ruiter, 1976). It is not known whether Paleozoic sediments underlie the thick Mesozoic sequence near the Mesozoic shelf edge. In contrast, offshore of Guinea, a much thinner Mesozoic section, represented chiefly by rocks of Cretaceous age, overlies more than 2 km of Paleozoic sedimentary rocks.

There is little detailed information contained in the literature on the sedimentary and structural aspects of the shelf, slope, and rise offshore of Sierra Leone and Liberia. The Continental Shelf in the area narrows from more than 140 km wide in nothern Sierra Leone to an average width of 35 km off Liberia (fig. 1). In general, the Cretaceous-Tertiary section on the Continental Shelf is thin. A single seismic refraction profile recorded on the shelf of Sierra Leone by Sheridan and others (1969) shows a seaward thickening wedge of Cretaceous sedimentary rocks that reaches a maximum thickness of about 2 km at the shelf edge. Based on 6 seismic reflection profiles, Schlee and others (1974) show the Cretaceous-Tertiary section on most of the shelf off northwestern Liberia to be less than 1/2 km thick. A much thicker sedimentary section underlies the lower slope and rise.

The shallow penetration seismic reflection surveys by McMaster and others, (1970) and Schlee and others, (1974) suggest a complex fault-block structure with sediment thicknesses increasing to over 4 km on the slope and rise (figs. 20 and 21). Off Monrovia, as much as 5 km of sedimentary rock may occupy a fault controlled basin under the shelf with thicknesses of sedimentary rock increasing seaward (Schlee and others, 1974). The small fault-controlled basins trend both parallel to the shelf and oblique to the shelf margin.

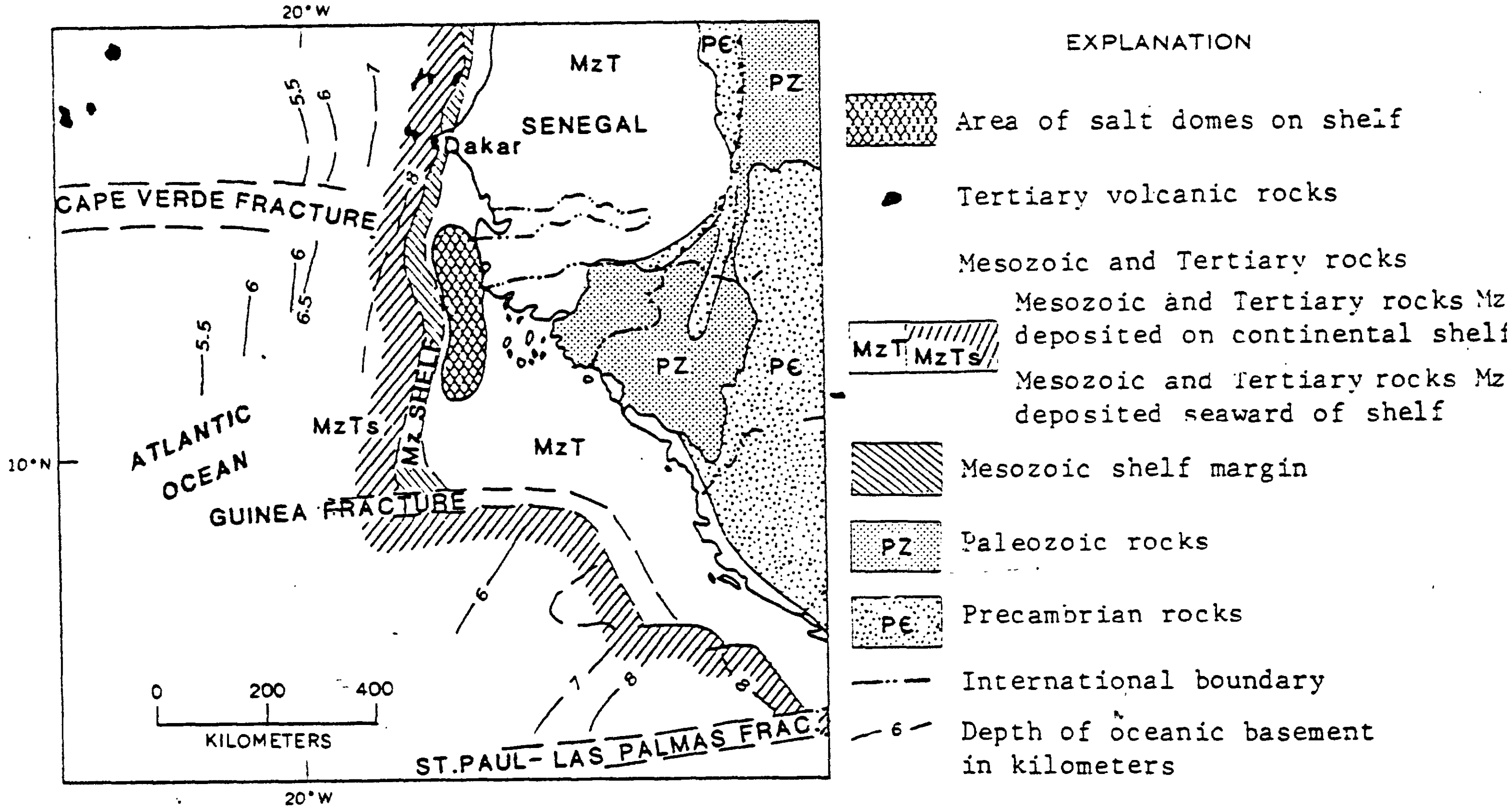


Figure 18. Schematic diagram of tectonic features in southern Senegal Basin, Africa. Modified from Lehner and De Ruiter (1976).

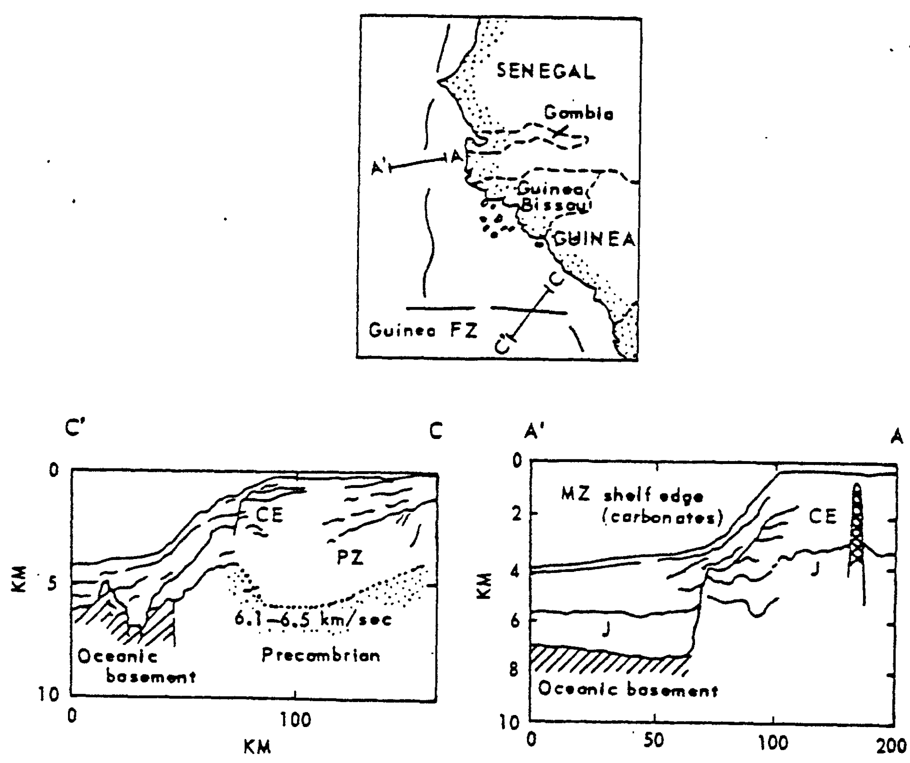


Figure 19. -- Schematic sections representing seismic profiles across Senegal Basin. Modified from Lehner and De Ruiter (1976).

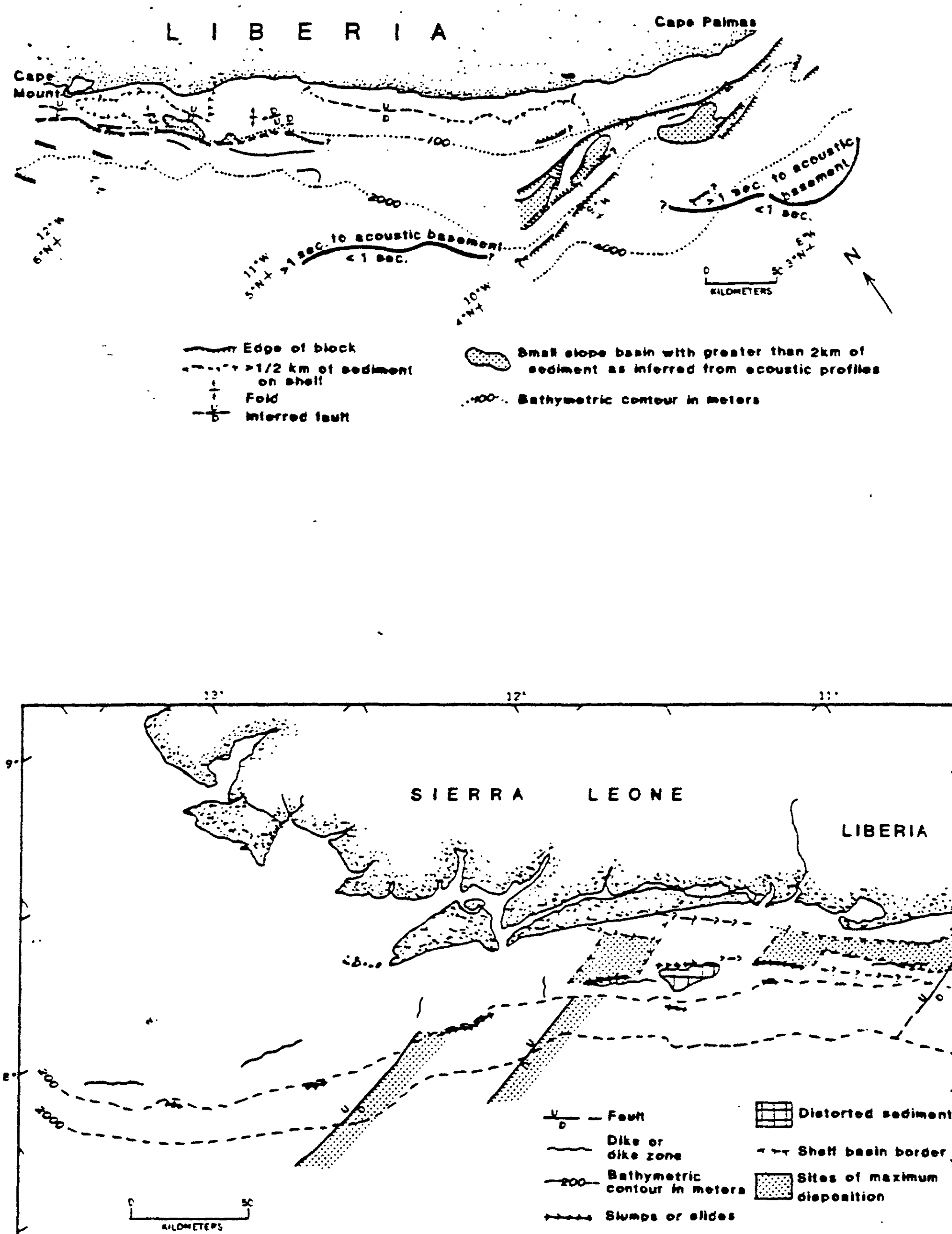


Figure 20. Schematic maps of structural-stratigraphic framework of the continental margins of Liberia (above) and Sierra Leone (below). The former is modified from Schlee and others (1974) and the latter is modified from McMaster and others (1970).

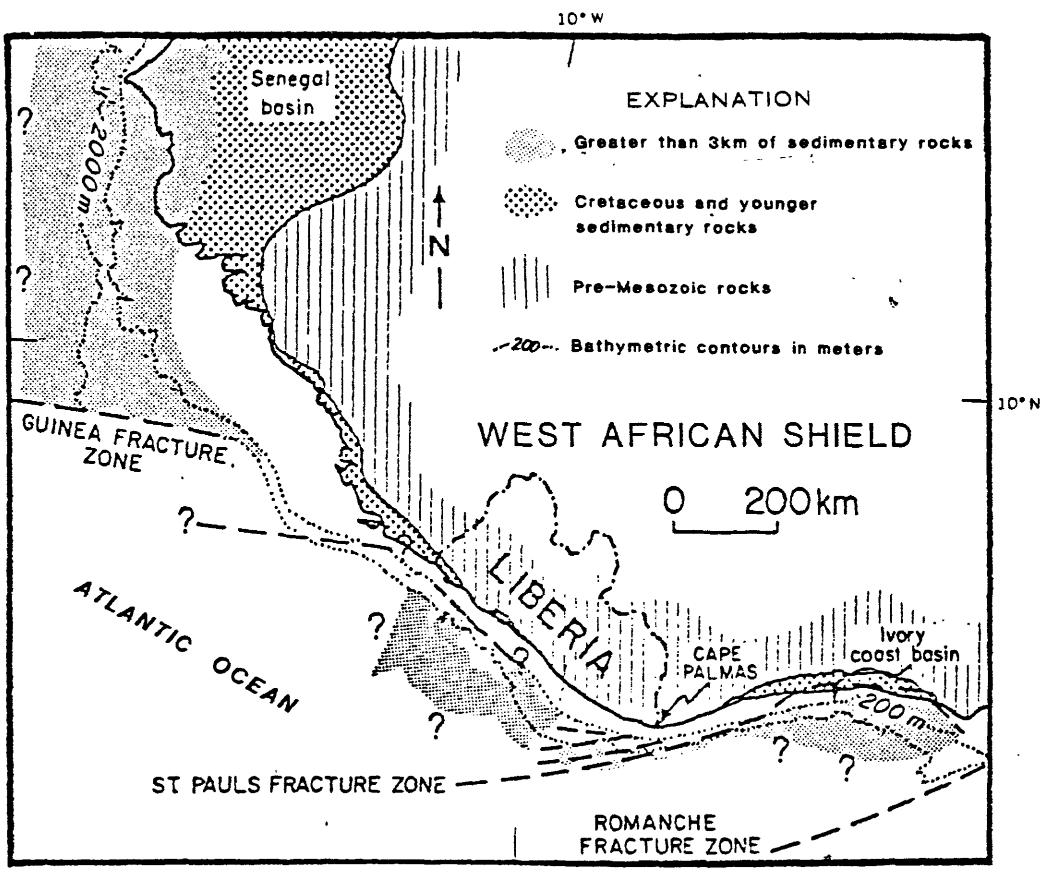


Figure 21. Shallow structure and stratigraphy of the Liberian continental margin. From Schlee and others (1974).

Stratigraphy

Four exploratory wells were drilled on the shelf off Liberia in 1971—three off Monorovia and another 150 km southeast (Cortesini and Minner, 1972). The holes ranged from 1,678 to 3,172 m deep and bottomed in volcanic rocks of Jurassic age, or sedimentary rocks of Early Cretaceous age, or sandstone inferred to be of Paleozoic age (Schlee and others, 1974).

The oldest sedimentary rocks penetrated consist of limestone, orthquartzite, and redbeds of shale and sandstone and are of Early Devonian age based on spore analysis. Onshore lower Paleozoic clastic rocks reach a thickness of 2 km (Ayme, 1965). The work of Sheridan and others (1969) and Lehner and DeRuiter (1976) indicates that Paleozoic rocks do not extend much further seaward than the shelf-slope break. This fits well with the idea of continental breakup during Mesozoic time. The Paleozoic rocks are intruded by dikes and sills, and are overlain by basalt flows of Early Cretaceous and Jurassic age. The flows are more than 470 m thick. The Cretaceous section, most of which is Lower Cretaceous (Albian and older), consists mainly of shale and sandstone and ranges in thickness from 450 to 1,940 m where penetrated in wells. Some beds contain abundant carbon fragments interbedded with marine shales and the fossils indicate a lagoon or bay environment of deposition. Thin (214 m) Upper Cretaceous sandstone and shale unconformably overlie the older rocks at one well site. The Cenozoic section ranges from 160-340 m where drilled and consists of shale, limestone, and sandstone.

Past exploration

Petroconsultants (written commun., 1981) has summarized exploration offshore of Sierra Leone and Liberia. Off Sierra Leone, no wells have been drilled as of January 1981 and a 2,500 km seismic reflection survey represents industry's recent exploration efforts. In Liberia, no petroleum rights are known to be currently held--the last offshore rights were relinquished in 1979 or early 1980. Four wells (discussed previously in this report) were drilled and all were reported as dry. The last seismic survey completed by industry offshore of Liberia was in 1972.

Petroleum potential

No hydrocarbon shows of any kind have been reported from either Sierra Leone or Liberia and industry has shown little interest in the area. Recent deep-water discoveries offshore of nearby Ivory Coast, however, could renew industry interest.

Prospects for finding hydrocarbon accumulations on the Continental Shelf are poor. The width of the shelf averages about 35 km in the southeast part of the area and the Mesozoic section is thin (generally <2 km)—probably too thin for thermal maturation with respect to petroleum to have occurred. Possible high heat flow rates in Early Cretaceous time, however, could have resulted in the maturation of Lower Cretaceous marine shale where deposited within small block faulted basins. the Paleozoic section, probably limited by the shelf-slope break, appears to have little potential as proved by exploration to the north in the Taoudeni Basin and to the east in the Volta Basin.

Prospects for deep-water areas, where the Cretaceous-Tertiary section is more than 4 km thick, could be better than those of the shelf. Here, sediments were probably deposited directly on oceanic crust. These sedimentary rocks, however, may consist mainly of fine-grained clastics and lack reservoir potential. This is in contrast to similar age sediments deposited off the Ivory Coast. Off the Ivory Coast, fracture zones probably acted as a funneling mechanism whereby coarse-grained sediments were deposited on the slope and rise during Cretaceous and Tertiary time.

The supposition that fine-grained, rather than coarse-grained, rocks underlie deep water areas is somewhat supported by geological evidence. The Farmington River Formation of Early Cretaceous age crops out onshore in Liberia and consists of massive graywacke with coarse clastics and conglomerates. Where penetrated on the shelf, however, similar age rocks consist of a finer-grained marine facies. If, however, sediments moved down slope along the axis of submarine canyons located on the slope, coarse-grained sediments may have bypassed the shelf and been deposited directly on the rise during Cretaceous time.

Traps on the shelf and in deep water areas could be associated with Lower and Upper Cretaceous clastics draped over tilted fault blocks with interbedded or overlying marine shales acting as the source material. Paleozoic reservoirs (on the shelf) and Lower Cretaceous clastics preserved in tilted blocks with source rock in and sealed by overlying Cretaceous or Tertiary shales are potential traps.

GULF OF GUINEA (EXCLUDING NIGER DELTA)

All current oil and gas production of the ECOWAS region considered in this report is from the Gulf of Guinea (fig. 1). However, with the exception of the Niger Delta, which will be discussed in the following section of this report, the amount of petroleum produced to date (Oct. 1981), is relatively small. Ghana's Saltpond field with proved reserves of 7 million barrels of oil, started production in late 1978 and it produced about 3,500 barrels of oil per day in 1979 (Auldridge, 1979). The Seme oil field, offshore of Benin, is still in the development stage. Production from the Belier field, offshore Ivory Coast, began in mid-1979 and is presently about 3,000 barrels of oil per day. Total production, therefore, from the Gulf of Guinea excluding the Niger Delta is about 6,500 barrels per day.

Benin's Seme field is a typical example of a marginal oil field which--as a result of rapidly increasing oil prices--became commericial (Glenne, 1981). The field was discovered in 1968 but was not profitable to develop at that time. The production of heavy crude oil (22° gravity) is expected to begin by the end of 1982 (Glenne, 1981).

Ivory Coast's Belier field was discovered in 1975--like Seme field, the rising crude oil prices have played a major part in bringing it into production (Oil and Gas Journal, 1981). Belier field was discovered in 1975 and was put on production in 1980. Present production of about 3,000 barrels of 33°-gravity crude is expected to rise to about 10,000 barrels per day (Oil and Gas Journal, 1981).

The most recent discovery (April 1980) is Ivory Coast's Espoir field. The initial discovery was 21 km offshore in about 360 m of water (on the Continental Slope). On initial test, oil flowed from the discovery well at a rate of 2,900 to 4,915 barrels of oil per day between depths of 2,008 and 2,152 m. A stepout well, located in about 485 m of water and about 4 km southeast of the discovery well, was reported to have penetrated oil-bearing sands which appeared to be equivalent to some of those penetrated in the discovery well (Oil and Gas Journal, 1981). The discovery well is believed capable of producing 20,000 barrels of oil per day and the field could have producible reserves of 500 million barrels (Oil and Gas Journal, 1981). Water depths above the field range from about 250 to 730 m.

Geologic setting

In the area between the St. Paul fracture zone and the Niger Delta are the Ivory Coast or Tano Basin, with its onshore extension called the Abijan Basin, and the Dahomey or Keta Basin (figs. 1 and 16). In the offshore, the Ivory Coast Basin extends from southeast Liberia to south-central Ghana and is bounded to the west by the St. Paul fracture zone or the Cape Palmas Escarpment and to the east by the Romanche fracture zone or the Ivory Coast Escarpment (fig. 1). The Dahomey Basin extends south-southwest from the Ghana, Togo, Benin, and Nigeria coastal plain where Tertiary-Cretaceous sedimentary rocks are exposed.

Fracture zones and faults have determined the shape of the basins in the area. The Chain, Romanche, and St. Paul fracture zones, transform faults that extend to the Mid-Atlantic Ridge, intersect the continental margin and determine its trend (fig. 1). The thick sedimentary wedges of the Ivory Coast and the Dahomey Basins are limited to the north by major faults (figs. 22 and 23). North of the major fault in the Ivory Coast the sedimentary rocks are thin and cover Precambrian basement rocks (Arens and others, 1970); south of the fault, which has throw in excess of 5 km, (Delteil and de Spengler, 1966) the Cretaceous section on the slope and rise probably exceeds 8 km in thickness (fig. 22). South of the major fault offshore of Benin (formerly Dahomey), the sedimentary wedge may exceed 4 km in thickness in the Dahomey Basin (fig. 23).

Between the Ivory Coast and Dahomey Basins, in the deep waters off Ghana, a major structural feature is represented by the Takoradi high, a subsided shoulder of the Precambrian continental platform of Ghana. This feature is limited to the south by the west-southwest trending Ivory Coast Escarpment (possibly connected with the Romanche fracture zone) and toward the northeast by the Accra fault which crosses Precambrian basement outcrops near the Togo-Ghana boundary (fig. 24).

Seismic reflection surveys indicate that no noticeable structural deformation occurs in the shallow sedimentary section in the Gulf of Guinea. From this fact, Arens and others (1970) concluded that no diapiric phenomena exist and, consequently, no salt formations such as are known in the Senegal Basin.

Stratigraphy

Pre-Mesozoic--Devonian formations consisting of, fossiliferous sandstones and shales crop out in small separated remnants in coastal areas of Ghana. In outcrops near Takoradi, pre-Mesozoic rocks consist chiefly of sandstone (300 m) with some pyritic and bituminous shales. Oil bearing, pre-Mesozoic rocks, up to 540 m thick, have been penetrated in exploration wells off Ghana and Togo. Here the section consists of sands and shales and some limestones of probable Devonian age. Pre-Mesozoic rocks are probably limited to the Continental Shelf in the

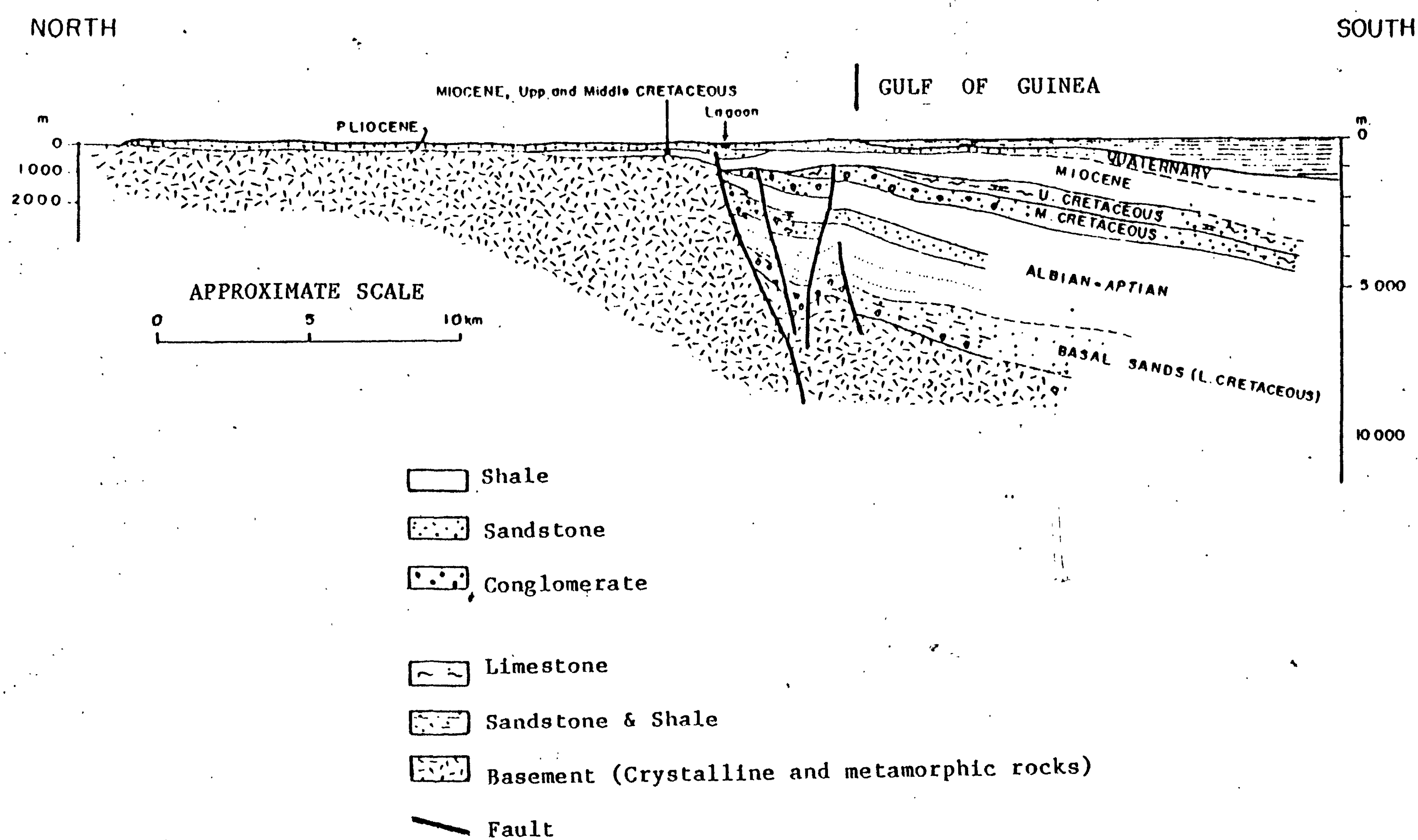


Figure 22. Schematic cross section of the Ivory Coast Basin. Modified from Petroconsultants S.A. (written commun., 1976).

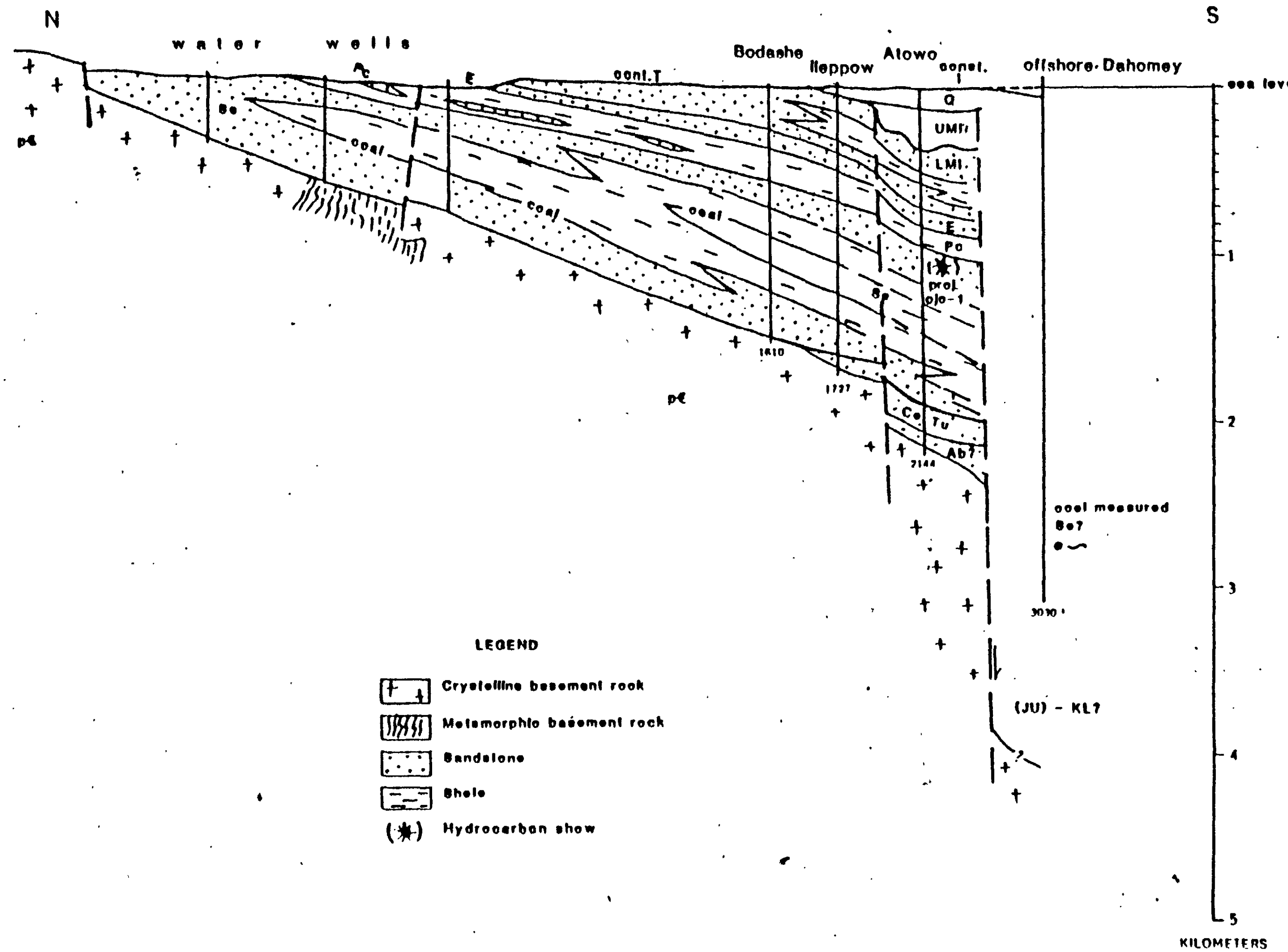


Figure 23. Schematic cross section of the eastern part of the Dahomey Basin. Figure modified from Petroconsultants S. A. (witten commun.,1976). Vertical scale is 1/25 of horizontal scale.

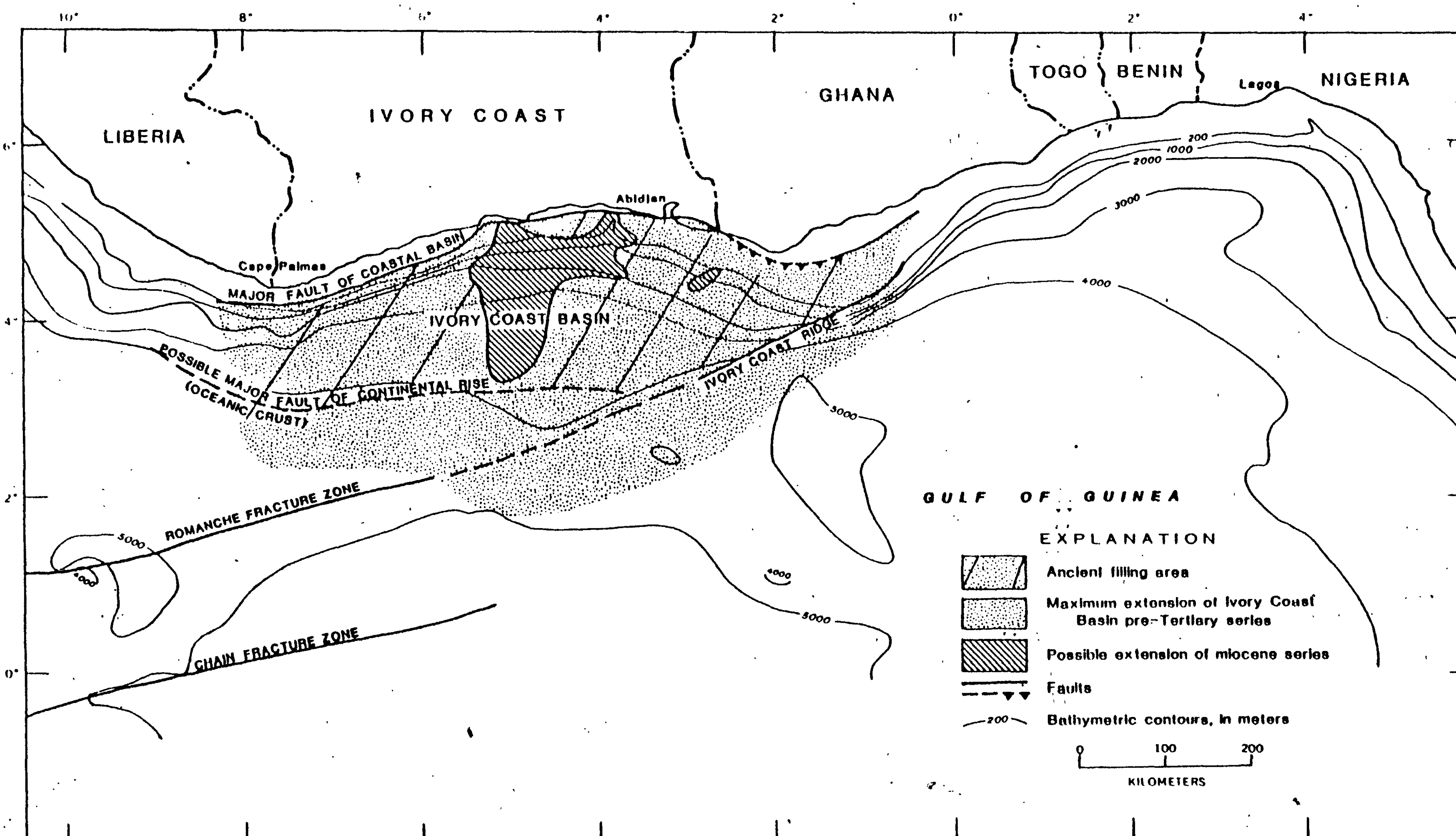


Figure 24. Interpretative paleogeographic sketch map sketch of the Ivory Coast Basin. Figure modified from Arens and others (1970).

Dahomey Basin; rocks of similar age have not been reported in the Ivory Coast area. The pre-Mesozoic section is overlain unconformably by Mesozoic age rocks that represent deposition following continental breakup.

In general, following continental breakup, the entire sedimentary section represents continued subsidence through the Tertiary. The influence of the major fracture zones is important because of their sediment-damming effect (Arens and others, 1970). According to Emery and others (1974), the grabens (basement lows between translation zones) acted as conduits to funnel sediment westward; whereas, the horsts (ridges) acted as dams to southerly sediment transport. This resulted in two major depocenters separated by the Ivory Coast escarpment.

Basal Mesozoic--Grabens, formed during early stages of continental breakup, received substantial amounts of continental or lacustrine sediments. The graben-fill consists of coarse-grained clastics with conglomerates, and coarse-grained sandstones alternating with variegated shales (Reyre, 1966; Delteil and de Spengler, 1966). This section is reported to be over 2,000 m thick in the eastern part of the Ivory Coast Basin and at least 472 m thick in the western part of the basin (Arens and others, 1970). The microfauna indicate a Late Jurassic to Early Cretaceous age (Arens and others, 1970). Furon (1960) and Reyre (1966) suggest that it is possible to postulate an earlier date of sedimentation but this seems unlikely. According to Arens and others, (1970) this basal series of sedimentary rocks may continue down the slope and rise to a major fault on the Continental Rise (fig. 24).

Lower Cretaceous--Lower Cretaceous sedimentary rocks (Albian-Aptian) overlie the basal series with marked unconformity and represent sediments deposited after the ocean opened. In the eastern region of the Ivory Coast Basin, the Lower Cretaceous section is represented by coarse detrital sedimentation (Delteil and de Spengler, 1966; Arens and others, 1970). In the central part of the Ivory Coast Basin, south of the major fault that extends along the shelf-slope break (fig. 22), the lower part of the section consists of black laminated shales with more or less abundant intercalations of sands. The upper part is composed mainly of coarse-grained sandstone, grey shales, and black laminated shales. The Lower Cretaceous section is over 2,500 m thick and appears to be organic-rich (Petroconsultants, written commun., 1976). The Lower Cretaceous section probably contains source rock that generated much of the oil and gas found in the Ivory Coast and Dahomey Basins.

Upper Cretaceous--The Upper Cretaceous section is as much as 1,000 m thick. In the center of the Ivory Coast Basin, Cenomanian deposition is represented by fluviatile conglomerates and sandstones, and Senonian through Turonian deposition is represented by clastic rocks containing gravel. Toward the western extremity of the Ivory Coast Basin, the Senonian through Turonian section consists of mainly shale, and in the east, of beach deposits.

Tertiary--Paleocene deposits unconformably overlie Upper Cretaceous deposits in the Ivory Coast Basin. The Tertiary section there is about 1,700 m thick. Oligocene age deposits are missing in places where a disconformity separates Eocene from Miocene age rocks. The basal 1,000 m of the Tertiary section consists mainly of glauconitic shales and glauconitic fine clastics with thin interbeds of limestones deposited in a near-shore environment. The upper part of the section consists predominantly of claystone overlain by 50 to 100 m of coarse-grained sand of Pliocene age.

Petroleum potential

Shows--Shows of oil and gas are common throughout the Gulf of Guinea both onshore and offshore. Numberous shows of oil and gas have been reported from wells drilled on the coastal plain and Continental Shelf of Ivory Coast, Ghana, Togo, Benin, and Nigeria (Petroconsultants, written commun., 1976). The small commercial discoveries--Ivory Coast's Belier field, Ghana's Saltpond field, and Benin's Seme field--have been discussed previously, as has the possible major discovery off Ivory Coast, Espoir field. Other significant shows include the Lome-1 well off Togo, and the Tano and Cape Three Points wellls off Ghana. At the Lome-1 well, 40 barrels of oil flowed over a 6 hour period (Petroconsultants, written commun., 1976). At the Tano and Three Points sites significant amounts of natural gas flowed before the wells were shut-in (Phillip Woodside, U.S.G.S., written commun.,). Other evidence of oil includes the asphalt ponds of western Ghana and the tar sands in eastern Ivory Coast. In addition, surface seeps are common all along the coastal areas of Ivory Coast, Ghana, and Togo. In some shallow wells drilled by the Nigerian Bitumen Corporation (1907-1914), oil still stands at the surface.

Previous exploration--According to maps of Petroconsultants (written commun., 1976; 1981), 90 deep exploratory and stepout wells have been drilled on the continental margin of Ivory Coast, Ghana, Togo, and Benin--20 onshore, 68 on the offshore shelf, and 2 on the offshore slope. Throughout Ivory Coast and Ghana, 55 wells are spaced somewhat regularly along the entire shelf area; whereas on the shelf off Benin, 11 wells were drilled on the Seme field. On the one hand, these statistics suggest that on the Continental Shelf there is a low probability of making large new discoveries. On the other hand, they highlight the fact that the slope and rise areas, where the sedimentary section reaches its maximum thickness, are relatively unexplored by drilling.

Source rocks--The numerous shows of oil and gas indicate that hydrocarbons have been generated in the area. A large part of these hydrocarbons probably was generated in Lower Cretaceous organic-rich shales. The oil seeps and standing oil in shallow wells drilled on outcrops of Cretaceous rocks are evidence that the source rocks are of Cretaceous rather than Tertiary age. In addition, some amounts of oil may have been generated from Devonian shales. In the Lome-2 well (fig. 25), and in Signal 10-1 well (Saltpond field), oil occurs in Devonian age sandstone. From the Signal 10-1 well, crude of 40° API was produced at the rate of 1,300 barrels per day from Cretaceous sandstone and crude of 37° API was produced at the rate of 2,300 barrels per day from Devonian sandstone. The difference in API values could be indicative of generation from different source rocks.

Traps--On the Continental Shelf, traps are likely to be associated with tilted fault blocks that have affected basement and overlying Paleozoic and Lower Cretaceous sedimentary rocks (fig. 26). Reservoirs are likely to be found in Paleozoic sandstone sealed by overlying Lower Cretaceous shales and in basal Mesozoic coarse-grained, continentally derived sandstone and conglomerate.

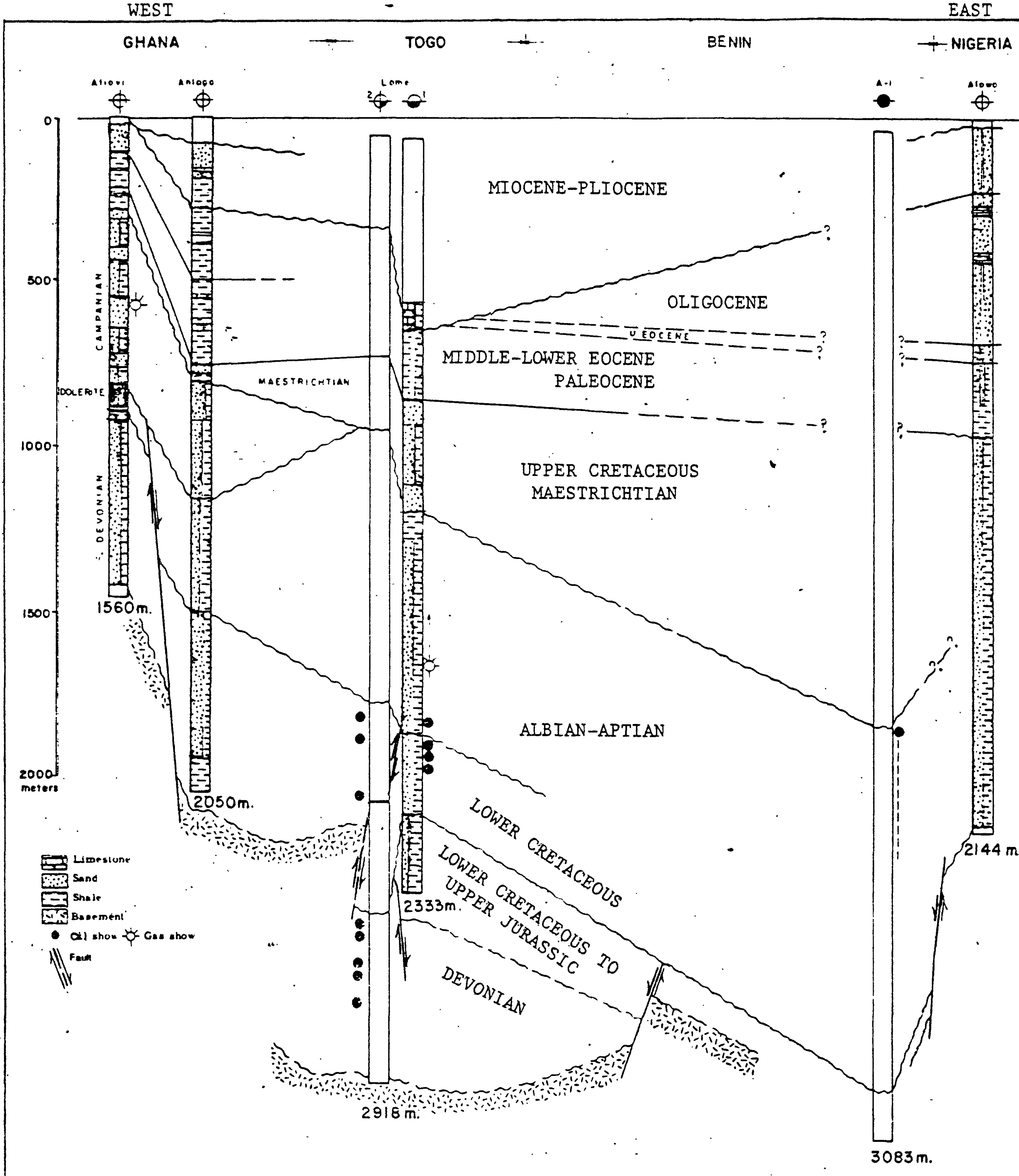


Figure 25. Stratigraphic cross section of the Dahomey Basin. Figure modified from Petroconsultants S.A. (written commun., 1976).

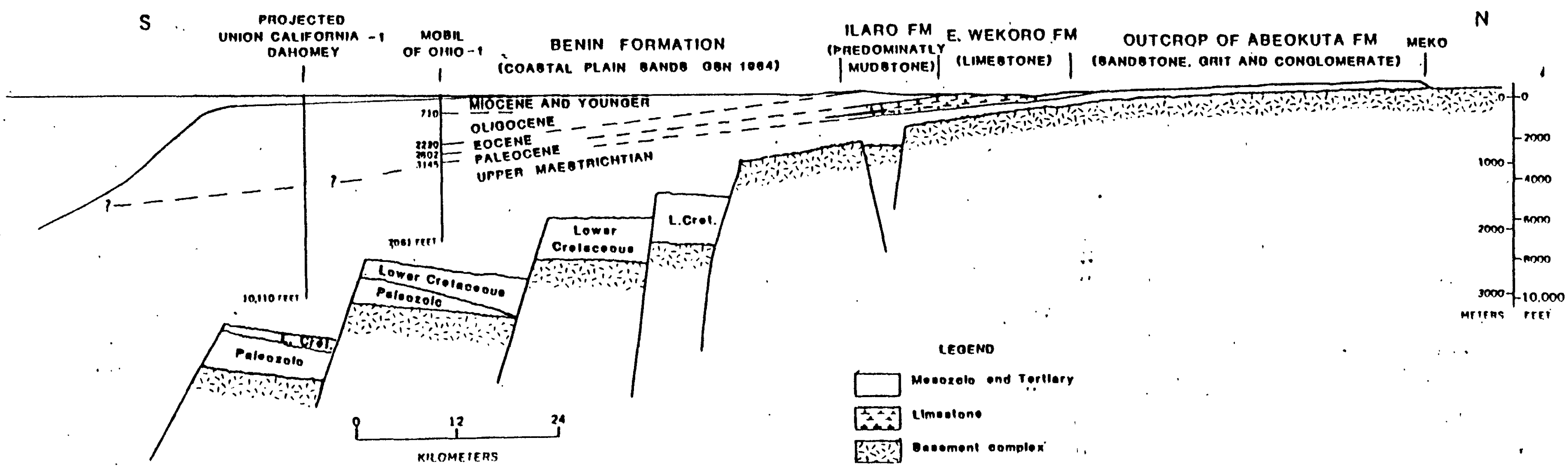


Figure 26. Schematic section across the eastern part of the Dahomey Basin. Modified from Petroconsultants S.A. (written commun., 1976.)

Other traps could include Upper Cretaceous and Tertiary sand/shale sequences draped over such fault blocks. In the latter case, the source rocks would probably be Lower Cretaceous shales. Paleozoic sedimentary rocks are expected to be absent in the Ivory Coast Basin.

In deep-water areas, a great variety of depositional environments ranging from continental graben fill to abyssal plain deposits are likely to be represented. Graben fill, consisting of good quality reservoir rock, and shallow marine deposits probably represent deposition in an early stage prior to extensive continental separation. Source rocks, deposited during periods of stagnant marine sedimentation, could alternate with high-quality reservoir rocks. Block faulting of basement probably continues far out onto the rise--at least to the possible major fault of the Continental Rise (fig. 24).

NIGER DELTA

Geologic setting

The Niger Delta, located chiefly onshore and offshore of Nigeria, covers approximately 105,000 km^2 (figs. 1 and 16). Oil production from the delta has made Nigeria one the ten largest oil producing countries of the world, and knowledge of Niger Delta geology has reached an advanced stage as a result of exploration for oil and gas. The early evolution of the Niger Delta during Cretaceous time was presented in a previous section of this report (Benue depression). Although initial oil and gas exploration in Nigeria was concentrated in the Cretaceous section of the Benue depression, all significant production of oil and gas has been from the Tertiary deltaic section.

The Cenozoic history of the delta began in Paleocene time when the formation of Cretaceous protodeltas was terminated by a major marine transgression. The sea transgressed the whole of southern Nigeria and deposited neritic to bathyal shales, with time equivalent arenaceous deposits in eastern Nigeria, in an embayment with an axis roughly conincliding with the modern lower Niger River. Subsequently, the bulk of Eocene to Holocene sedimentary rocks that comprise the thick sedimentary wedge from which oil and gas are presently produced was deposited during a major regression. Large volumes of deltaic sediments prograded across the continental margin and at their seaward extent may have been deposited directly on oceanic crust as the margin subsided (fig. 27). Avbovbo and Ogbe (1978) estimate that approximately 8.5 km of Tertiary sediments were deposited in the Niger Delta Basin. From a petroleum exploration viewpoint, the geology of the Niger Delta has many similarities with the Mississippi Delta of the United States Gulf Coast (Girard, 1979).

Stratigraphy and reservoir rocks

The works of Short and Stauble (1967) and Frankel and Cordry (1967) (later summarized by Girard, 1979) were used extensively by the author to compile the stratigraphy of the Niger Delta. This discussion is limited to the Eocene through Holocene sections that form the thick wedge of sedimentary rocks from which oil and natural gas are produced in the Niger Delta. Rocks of these ages can be divided into three diachronous (time transgressive) rock-stratigraphic formations: Akata, Agbada, and Benin Formations (fig. 28).

The basal unit, the Akata Formation of Eocene to Holocene age, is composed primarily of shallow-water marine shale deposited in front of the advancing deltas. It contains some sandstone and siltstone beds that reflect deposition in deeper water environments (Weber and Daukoru, 1975). Little is known about the distribution and frequency of occurrence of these sandstone beds because they lie below thick sections of shale, generally abnormally pressured. These relatively unexplored sandstone beds, which may contain hydrocarbons, could be the targets of future exploration (Girard, 1979). The Akata Formation underlies the whole of the Niger Delta. It is penetrated in most onshore fields between depths of 4 and 6 km and in most of the offshore fields between depths of 1 and 3 km. For economic purposes, the top of the Akata Formation represents "basement," with the possible exception of isolated deep-water sandstones mentioned above (Girard, 1979).

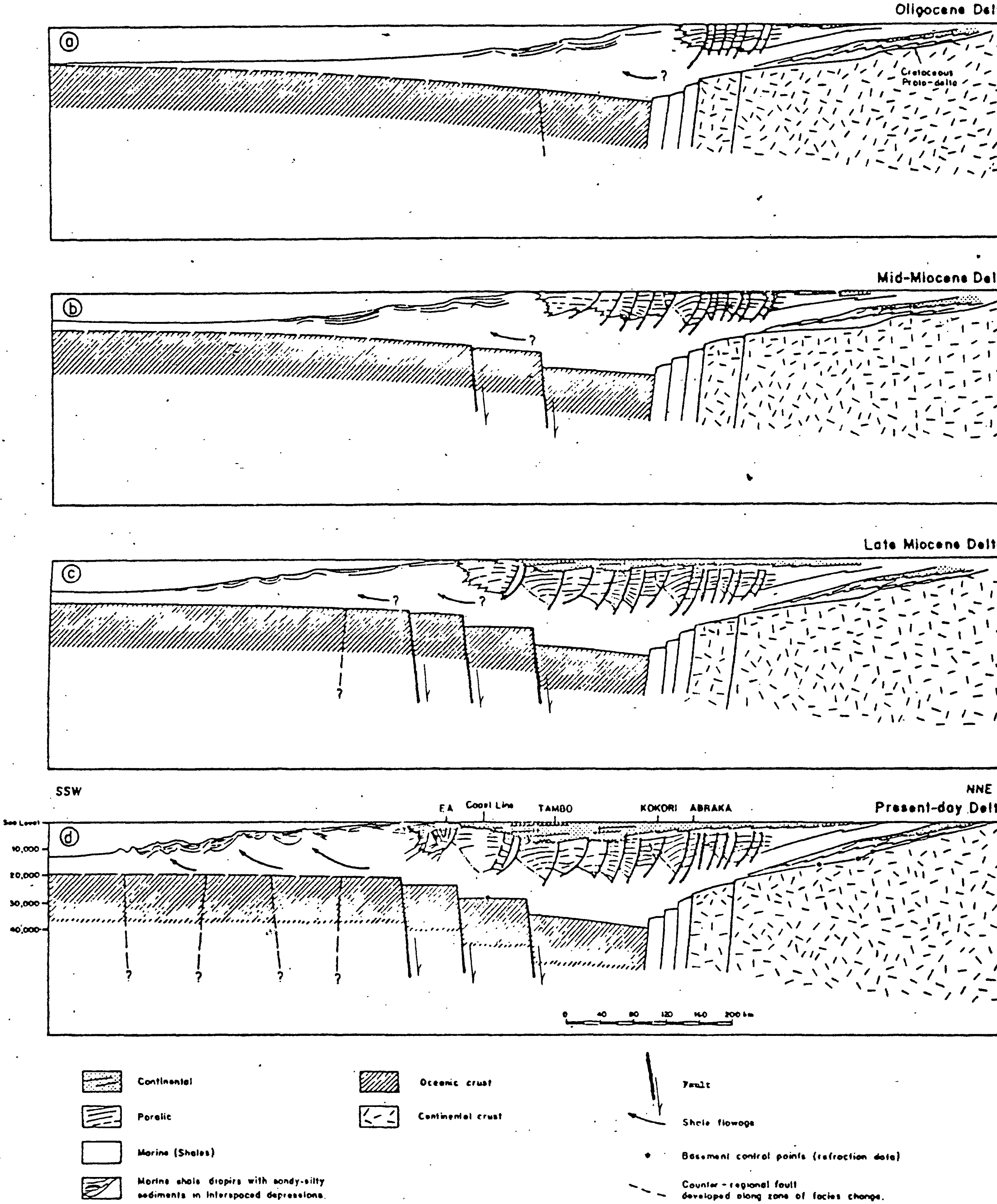


Figure 27. Schematic diagram showing evolution of the Niger Delta. Figure modified from Evamy and others (1978).

The Akata Formation is overlain by the Agbada Formation, which contains the principle reservoir rocks of the Niger Delta. The Agbada Formation is more than 3 km thick in the central part of the delta and ranges in age from Eocene far inland to Plio-Pleistocene offshore. The Agbada Formation, built from numerous deltaic offlap cyclic sequences of marine and fluvial deposits, is present throughout the Niger Delta subsurface (fig. 28). Each depositional cycle ranges in thickness from 10 to 100 m and, in ascending order, generally consists of a thin fossiliferous transgressive marine sandstone and an offlap sequence of marine shale and laminated fluviomarine sedimentary rock (Weber, 1971). This cyclic sequence of reservoir rock deposition explains the multi-reservoirs of most of the Nigerian oil and gas fields. In general, the upper part of the Agbada section is intercalated sandstone (about 75 percent) and shales (about 25 percent). The lower part of the section, which probably accounts for the bulk of the hydrocarbon reserves, is about 50 percent sandstone and 50 percent shale. The sandstones, which make up the reservoir rocks, are very coarse to very fine grained, slightly consolidated, feldspathic, fairly clean, and locally calcareous, glauconitic, and shelly. Sorting generally is poor. The shales are medium to dark gray, fairly hard and silty, and contain mainly kaolinite (75 percent) and small amounts of mixed layers of illite and montmorillonite (Avbovbo and Ogbe, 1978). These intercalated shales make up the vertical seals in the fields of the Niger Delta. In fact, the production takes place where it does because these transgressive shales act as vertical seals to the migration of hydrocarbons—the shalier than normal intervals are productive, and the sandier than normal intervals are nonproductive (Dailly, 1976).

Most of the reservoir rocks of the Nigerian fields are in the Agbada Formation and are of excellent quality; porosity is between 28 and 32 percent and permeability in the darcys (Habarta, 1970). The offshore Okan field has permeability as high as 5 darcys. The reservoir rock quality and geometry is strongly dependent on the depositional environment. For example, the pre-Miocene reservoir rocks were deposited as widespread continuous sands, point bars, and channel sands, whereas the Miocene to Holocene reservoir rocks were probably deposited as barrier bar sands less than 10 m thick (Weber and Daukoru, 1975; Weber, 1971).

The uppermost unit, the Benin Formation, contains mostly freshwater-bearing, massive, continental, coarse-to-fine-grained sands and gravels deposited in an upper deltaic-plain environment with only local shale interbeddings. The Benin Formation is as much as 2,000 m thick. The sands and gravels of the Benin Formation may represent point-bar deposits, braided streams, channel fills, or natural levees, whereas the shales may be interpreted as backswamp deposits and oxbow fills. In the subsurface, the Benin Formation is Oligocene in the north and Holocene near the coastline. Although the Benin Formation contains continentally derived sediments, it is generally freshwater bearing, highly porous, and has few seals. A small quantity of hydrocarbons are produced both onshore and offshore from this formation.

Petroleum traps

Hydrocarbon production in the Niger Delta area has been from lower Turonian through probably, Pleistocene-age rocks. However, virtually all current Nigerian production comes from Tertiary-age rocks Girard, (1979). Seventy-seven percent of the proven oil reserves has been discovered in a narrow arcuate trend that cuts across the depositional and structural trends of the delta from the offshore northwestern flank of the Niger Delta to its offshore southwestern flank (fig. 29) (Avbovbo and Ogbe, 1978). The fields located in the prolific arcuate trend produce from rocks of Miocene to Pliocene age. Within each circular-shaped area (fig. 29), the age of the rocks from which hydrocarbons are produced decreases in a seaward direction.

The productive trends, are delineated by large regional growth faults, or a series of closely spaced en echelon growth faults (Girard, 1979). The throw on the major faults is probably greater than 800 m. The fault trends parallel paleoshorelines and, because growth faults are syndepositional, the age of faulting decreases seaward.

Most hydrocarbon traps in the Niger Delta consist of "rollover structures" on the downthrown block of regional growth faults. The term rollover structure refers to the closure formed by the reversal of dip of strata on the downthrown block of some faults. In cross section perpendicular to the fault, the strata appear to "roll" into the fault thereby forming a dome-shaped structure. The fault generally does not provide the updip lateral seal but only the mechanism for trapping (Girard, 1979). The productive rollover structures in Nigeria average about 7 km in length and 4 km in width (Owen, 1975). Many "pure" fault traps are also present on both upthrown and downthrown fault blocks (Girard, 1979). These consist of growth faults and antithetic faults in which the fault does provide the lateral seal.

The existence of a small number of structures associated with shale diapirs has been noted on the Continental Slope off the Niger Delta (Mascle and others, 1973) and in the proximal part of the eastern Continental Shelf area (Evamy and others, 1978). Some oil is produced from diapiric shale or shale ridge-related traps near the coastline and in the offshore (Habarta, 1970; Merki, 1972). In addition, a few offshore fields produce from unconformity truncation traps (Avbovbo and Ogbe, 1978).

In general, from an updip position in the delta toward the Continental Slope, the intensity of structural deformation and trap complexity increases, i.e., simple rollover traps, to complex, highly faulted anticlines, to faulted shale diapirs and shale ridges with associated unconformities (Girard, 1979).

Source rocks

Despite the fact that substantial amounts of oil and gas have been generated in the Niger Delta, Evamy and others (1978) concluded that shales in the area from a wide variety of depositional environments, ranging from fully marine to paralic, contain relatively small amounts of organic material of the humic and mixed types, which are precursors for gas and light oil, respectively. Unpublished research by K. deGroot, K. Reiman, and T. T. Hartog (Evamy and others, 1978) showed that the Nigerian crudes originated from source rocks containing land-plant matter. The most effective source rocks are believed to be marine shales of the Akata Formation and the shales intercalated with the paralic sandstones of the Agbada Formation. In terms of shale volume, the Akata and the lower part of the Agbada Formations are more important in the generating of hydrocarbons (Girard, 1979). However, Evamy and others (1978) suggested that any oil generated in the Akata Formation had only a remote chance of finding its way into the overlying

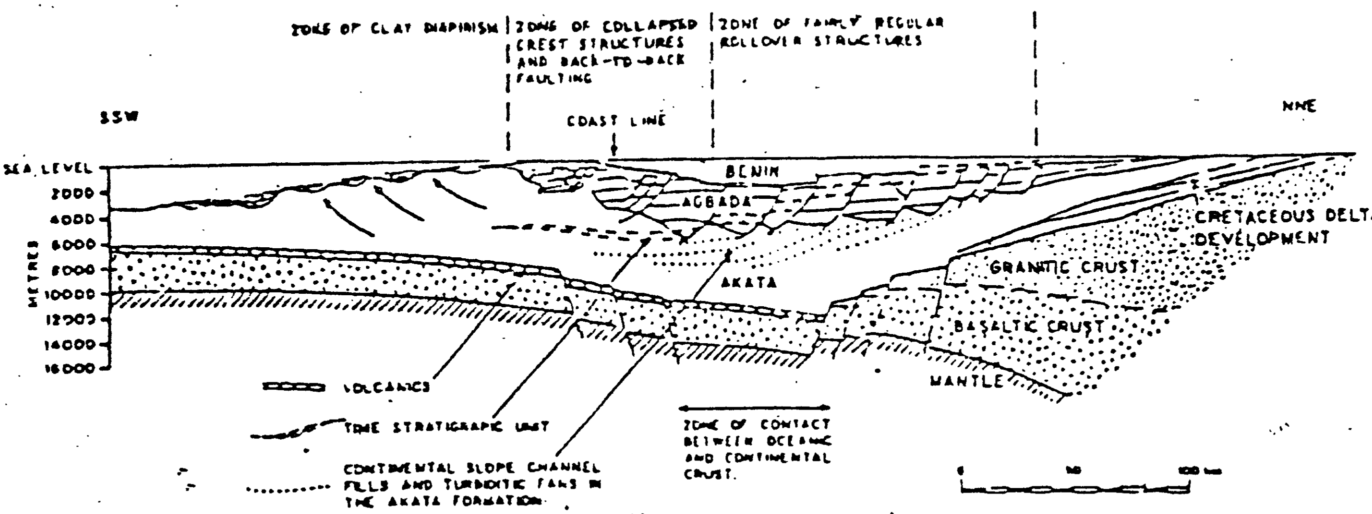


Figure 28. Schematic dip section of the Niger Delta. Figure from Frankle and Cordry (1976).

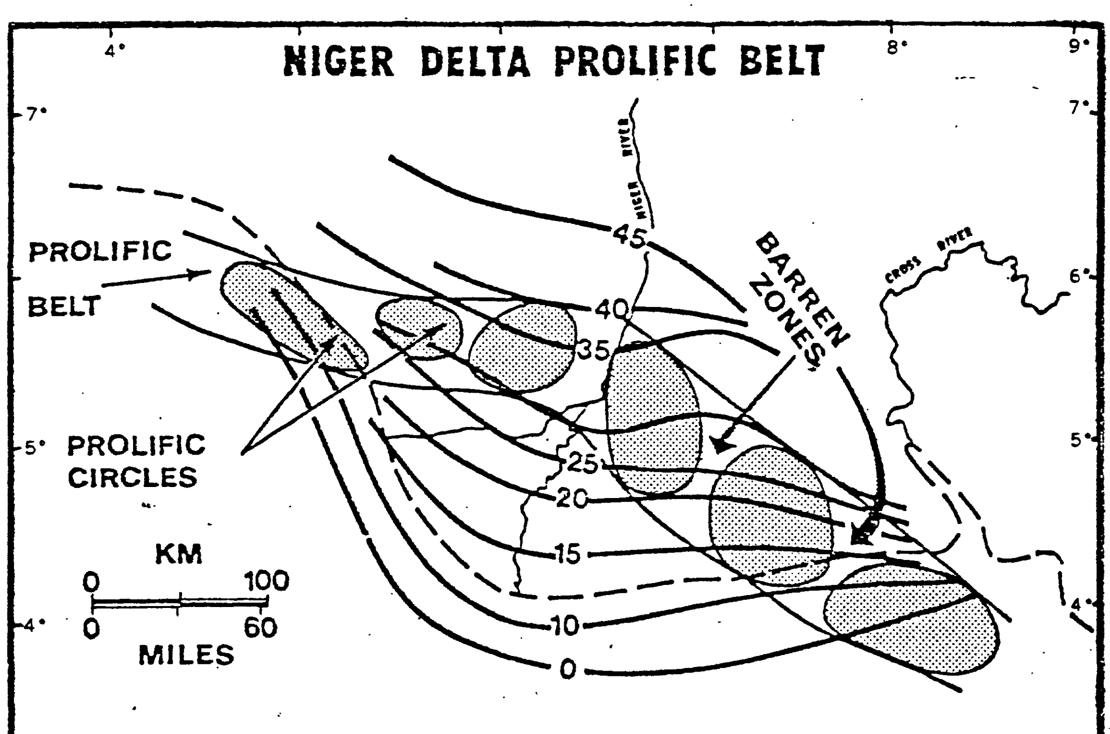


Figure 29. Successive stages of Niger Delta growth and location of the prolific belt. Contours are in millions of years before present. Figure from Dailly (1976).

Agbada reservoirs because the faults at depth, within the Akata shales, are not effective migration paths.

Unpublished Shell research suggests that 240° F and 300° F represent the highest temperatures of the oil-generating zone and gas-generating zone, respectively, for Tertiary provinces (Evamy and others, 1978). Over a large part of the area west of the Niger and Nun Rivers, the top of the oil-generating zone lies well above the continuous shales of the Akata Formation, within the paralic and paralic-to-marine sequences of the Agbada Formation. In the east, however, the oil-generating zone generally lies entirely within the continuous marine shales of the Akata Formation. This is because the Agbada Formation is generally thinner over the eastern part of the delta.

By tracing the oil-generating zone through geologic time, Evamy and others (1978) found that the boundary between the paralic sequence and the continuous marine shales reached a level of oil maturity much later in the east than in the west. In the east, even at present, the fact that the Agbada formation is only locally within the oil-generating zone implies that the eastern oil was derived not only late but also from source rocks mainly in the continuous marine shales. Evamy and others (1978) concluded that primary migration took place at a very late stage, certainly after most of the sedimentation and trap formation, and that the origin and migration of the oils in the west were earlier than the very late origin and migration of the east.

Production and reserves

Estimates of the oil and gas resources of Nigeria have been made by the U.S. Department of Energy and the U.S. Geological Survey (1979). Excerpts from a summary of this report follow.

Nigeria produced as much as 2.4 million barrels of oil per day during the first part of 1979. Total natural gas production in 1977 was an estimated 757 billion ft^3 of which approximately 739 billion ft^3 were flared or not marketed.

Estimates of ultimately recoverable oil resources range from 20.5 to 41.5 billion barrels. Through 1977, 6.1 billion barrels had been produced; thus, the remaining recoverable oil ranges from 14.4 to 35.4 billion barrels. About 18.7 billion barrels have been discovered; about 8.4 billion barrels remain to be discovered.

Nigeria's exploration began early in this century, although the modern exploration phase began in 1955. Exploration and development may have peaked quickly, as 13 of 14 known, probable and possible giant oil fields were discovered prior to 1969, and the greatest number of fields were discovered in the period 1965 through 1967.

Of the known producing fields, more than two-thirds have or had sustainable peak production rates (production for three successive years at a specified rate) of less than 5 million barrels of oil per year; nearly one-half of the fields produced less than 3 million barrels per year. Only 16 fields have produced at peak rates ranging from 15 to 45 million barrels per year. In essence, most of Nigeria's oil fields are small to medium size fields by world standards. Future oil discoveries are likely to reflect this trend, even though several more giants may be found.

Proved reserves of natural gas as of January 1, 1977, were 51.42 trillion ft^3. The natural gas resources of Nigeria, unlike the oil resources, are comparatively underdeveloped. The U.S. Department of Energy and the U.S. Geological Survey (1979) estimate that the amount of undiscovered recoverable natural gas is 26 to 130 trillion ft^3.

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Part II - COAL RESOURCES

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INTRODUCTION

Part II of this report treats producing and reported coal deposits in the ECOWAS region. The report also outlines areas of the region that contain rocks similar (with respect to age and depositional environment) to those from which coal has been reported.

COAL OCCURRENCES BY INDIVIDUAL COUNTRIES

Benin

Most of Benin is underlain by igneous and metamorphic rocks that are not prospective for coal. At the northern tip of the country a strip of land about 25 km (15 mi) wide along the Niger River contains continental deposits of sandstone and gravel of late Tertiary to Holocene age. The northeastern part of the country is underlain by rocks of Upper Cretaceous age. The southern part of the country is covered by a narrow strip of sedimentary rocks ranging in age from Late Cretaceous through Eocene to Holocene.

Feyes and Fabre (1966, p. 48) reported that strata of Late Cretaceous-Tertiary (Maestrictean-Paleocene) age continue from Nigeria into Benin where they appear to occupy an area of about 3600 km^2 (1400 mi^2). Any coal deposits in Benin therefore, are probably subsurface continuations of those in Nigeria. In Benin, lignite has been penetrated in boreholes but has not been found in outcrop. The lignites are reported (Feyes, and Fabre, 1966) to be of medium quality, to range in thickness from 0.4 m to 1 m (1-3 ft), and to lie at depths of 60 to 100 m (180-300 ft). Analyses of these lignites are not available. The source of the report by Feyes and Fabre is the Record office of the Benin Geological Survey.

Ghana

The Republic of Ghana has an area of approximately 240,000 km^2 (92,000 mi^2). Almost the entire area is covered by Archaean gneiss, schist, graywacke, and quartzite and Paleozoic quartzite, shale, arkose, and mudstone. Tertiary to Holocene continental and lagoonal deposits of clay, sand, and gravel and Cretaceous age marine deposits occupy a small area along the coast. These rocks are not known nor believed to contain or to be potentially prospective for coal.

Guinea

Rock units in The Republic of Guinea consist mainly by Precambrian schist, quartzite, and dolerite and Cambrian, Ordovician and Silurian sandstone, quartzite and conglomerate. Sedimentary rocks of Quaternary age form a coastal band ranging in width from 10 to 40 km (6-25 mi). These rocks are not known to or believed to contain any commercial coal beds.

Guinea Bissau

Approximately one-half of Guinea Bissau (the area southeast of the Rio Geba and east of 15° longitude) is underlain by rocks of late Precambrian age and schists, pellites and calcareous rocks of Cambrian, Ordovician and Silurian age. Alluvium of Quaternary age occurs in a narrow strip along the coast. North of the Rio Geba to Senegal, the Rio Mansoa and Rio Cacheu basins are covered by Quaternary alluvium and Pliocene sedimentary rocks. However, strata of Cretaceous age, similar to those that are known to contain lignite in Senegal, probably extend in the subsurface into the Guinea Bissau area along the coast.

Ivory Coast

The Republic of Ivory Coast has an area of approximately 324,000 km^2 (125,000 mi^2). Precambrian schists, quartzites, and volcanic rocks and Cambrian volcanic and intrusive rocks--all known to contain no coal--crop out over 80 percent of the area. A coastal belt of sedimentary rocks that comprises the remaining 20 percent of the area contains Pliocene and Quaternary marine lagoonal and continental river deposits and Cretaceous sandstone and shale, none of which are likely to contain significant deposits of coal.

Liberia

The Republic of Liberia is covered almost entirely by schists, gneisses, quartzites and dolerites. Along the coast are deposits of lacustrine and beach sands and a thin veneer of fluvial silt and sand of Quaternary age. Further inland is a small area of about 400 km^2 (150 mi^2) of conglomerate, sandstone, and shale of the Farmington River Formation of Cretaceous age. Some granular coal that has been found in the Harper quadrangle (along the southeastern coast) is generally believed to be disintegrated coal lost from passing freighters. None of the basement rocks nor sediments found in Liberia are likely to contain significant amounts of coal.

Mali

The western part of Mali is largely underlain by rocks of Cambrian and/or Cambrian and Silurian ages that are, in part, covered by Quaternary age rocks containing scattered sand dunes. The rocks of Quaternary age continue to the north as far as the 20th Parallel and east to the west side of the bend of the upper Niger Basin. Within the bend of the Niger River are rocks of Cambrian age which form a north-northeast-trending core flanked on both sides by younger rocks of Jurassic, Cretaceous, and Tertiary ages.

No surface or subsurface occurrences of coal have been reported in Mali. However, the Gao area (northeast side of the Big Bend of the Niger River) is indicated by Feyes and Fabre (1966) to be an area of potentially coal bearing rocks. All these areas should be investigated for coal prospects. In addition, possible coal-bearing Jurassic and Cretaceous undifferentiated rocks crop out over large areas of Mali (Bureau de Recherche Geologiques et Minieres, 1968a). Strata believed to be correlative to Maestrichtian age rocks occur in the subsurface in an area of about 10,000 km^2 (4,000 mi^2) near the Mauritania-Mali boundary.

Mauritania

Coal has not been reported at the surface in Mauritania. However, strata of Maestrichtian (Late Cretaceous) and Carboniferous ages that contain lignite and or subbituminous coal in nearby countries of Africa underlie areas of Mauritania and should be evaluated as to prospective coal deposits. More than 1100 km^2 (420 mi^2) of Maestrichtian rocks occur in a strip ranging in width from 10 to 35 km (6-22 mi) that extends for some 60 to 85 km (40-50 mi) from Senegal north to the Western Sahara-Mauritania border. Lignite has been penetrated by drill holes in widespread areas onshore in Senegal.

Another area of Mauritania that may contain lignite is the Taoudeni Basin. Although lignite has not been reported, data from oil and gas wells indicate that an extensive area (2000 km^2 (800 mi^2)) along the Mauritania-Mali border is underlain by rocks of Maestrichtian age. Strata of this age contain lignite in Senegal and coal is produced from equivalent age rocks rocks in Nigeria. The Taoudeni Basin has a relatively thick cover of Quaternary desert deposits that make conventional field methods of exploration difficult.

Approximately (1400 km^2 (540 mi^2) of Mauritania is underlain by rocks of Carboniferous age. Coal is produced from strata of this age in Niger at d'Añon Araren near d'Agades west of the Air Massiff.

Niger

Coal occurs in Carboniferous strata in the Niger Basin about 30 km (19 mi) north of Agades on the west edge of Air Massif. Apparently, small amounts of coal have been produced and used for generating power in local uranium mine and mill facilities. Information as to production rates, type of coal mined, and the reserves of the area are not available. Prospect holes drilled in 1964 penetrated 60 to 150 m (200-490 ft) of strata containing siltstone, sandstone, and coal beds. According to Feyes and Fabre (1966, p. 53) two coal beds 1.3 m (3 ft) and 0.75 (2 ft) thick were penetrated. The coal is not cokeable and has a high ash content.

The Geologic Map of the Republic of Niger (Greigert and Pougnet, 1965) shows an area of more than 4,800 km^2 (1,850 mi^2) that contains rocks of the Agades Formation of Upper Carboniferous age. Analysis of data from wells drilled for oil and gas in these areas could provide useful information pertaining to possible existence of coal deposits. Five wells were drilled by CEP in the area of the Bishop-Taiga concession. The westernmost wells probably penetrated much of the Carboniferous section. Examination of electric and cuttings logs from these wells might reveal much information as to coal prospects of these rocks.

The tributary areas of the Niger River, notably the Tadiss, Dallal, Maouri and the Tarka Rivers; are underlain by about 4,160 km^2 (1600 mi^2) of Upper Senomian age (Late Cretaceous) rocks that may contain lignite beds and which probably warrant exploration.

Nigeria

Deposits of lignite of Tertiary age and subbituminous coal of Cretaceous age occur in southern Nigeria; bituminous coking coal has also been reported. Coal production reached a peak of 341,000 metric tons in 1972 but has declined yearly to an estimated 172,000 metric tons in 1979. (Jolly, 1981b). In 1976, two of four mines scheduled for mechanization were equipped for long-wall mining. The country has the production capability to export coal and to generate considerable electrical power from coal. Plans have been made in the Urat area to produce coke for a proposed steel plant.

Lignite reserves of 71 million metric tons were indicated for an area near Benin City, but no commercial production of lignite has been recorded (Jolly, 1981a). Subbituminous coal reserves have been estimated at 144 million metric tons in the Enugu area, and reserves of coal with coking qualities are in excess of 100 million metric tons in the area near Lafia (Jolly, 1981a). Because of more recent development, calculated resources now are probably much greater.

Subbituminous coal occurs in two stratigraphic sequences. The lower sequence consists of a section of sandstone and shale containing at least five coal beds of Late Cretaceous age. The stratigraphic section containing the coal beds is about 390 m (1,300 ft) thick and was deposited during Campanian-Maestrichtian time. The five coal beds are lenticular and have been mined along the crescent-shaped Enugu escarpment. The thickest coal bed ranges from 1.2-1.8 m (4-6 ft) in thickness and is currently being mined in six areas.

The upper stratigraphic sequence is about 330 m (1100 ft) thick and consists of sandstone and sandy, calcareous shale with thin coal beds. Coal measures in the upper sequence are probably of late Maestrichtian to early Paleocene age.

The lignite resources of Nigeria appear to be large but have not been developed. Lignite deposits are present in rocks of Tertiary age west of the Niger River and east of Benin City and Warri. At Obomkpa, three major beds occur (de Swardt, 1960). Two of these beds have been drilled over a large area and the lower bed, of good quality, has an average thickness of about 2.4 m (7.9 ft). Other promising deposits are at Ogwaski-Asaba near the Niger River where two beds averaging 5.2 m (17 ft) and 2.4 m (8 ft) are separated by about 3.6 m (12 ft) of shale.

East of the Niger River other beds of lignite occur (de Swardt, 1960, p. 8) with bed thicknesses up to 2 m (6 ft). In the Mbala stream area and the headwater area of the Nemagadi River, boreholes drilled in 1910 supposedly penetrated lignite thicknesses up to 6 m (20 ft) but further work in these areas did not confirm such bed thicknesses.

Senegal

There are no surface occurrences of coal in Senegal. However evidence of lignite has been reported from boreholes drilled doubtless for stratigraphic information by the major oil companies in connection with their search for oil and gas during the period 1952-1977. Lignite was also penetrated in wells drilled for water. According to Bliss (1981), considerable drilling and research has been done toward furthering an understanding of the lignite resources of the county. In all, 33 drill holes found traces of lignite. In 24 of these holes the lignite generally ranged in thickness from 1 m (3 ft) to 2 m (6 ft). In four areas (location not known) the drill holes penetrated coal of as much as 4 m (13 ft), 14 m (46 ft), 10 m (33 ft), 4 m (13 ft), 32 m (105 ft), 71 m (230 ft) and 10 m (33 ft) thickness. The lignite was reported at depths ranging from 55 m (180 ft) to 647 m (2,120 ft) with an average depth of about 300 m (1,000 ft).

In one of the drill holes notably Kb 1 (no accurate location available), more than 105 million metric tons per km^2 (300 million short tons per km^2) have been estimated for 3 coal beds of 4 m (13 ft), 32 m (105 ft) and 71 m (230 ft). Presently no analyses of these lignite beds are available.

The lignite discussed above is found in rocks of the Maestrichtian (Late Cretaceous) age. Although these rocks apparently do not crop out in Senegal, they are extensive, doubtless underlying Gambia to the south and, perhaps, Mauritania to the north. They may also extend into Mali and Guinea Bissau.

Although not classed as coal, peat is closely related to lignite and should be mentioned because it can be used as a fuel. The delta and lower river areas and the lower basin areas (upstream of the Senegal, Sine-Saloum and Casamance Rivers) contain peat deposits. The lower Gambia River area would appear to have minor peat deposits. It is reported that the peat deposits of Senegal are as much as 2 m (6 ft) thick, have high clay and silt contents, and have low organic-matter content.

Sierra Leone

A deposit of lignite represents the only known coal in Sierra Leone. The lignite occurs in rocks of the Bullom Group of Pleistocene age in the Rokel Estuary. Onshore the thickness of the Bullom Group is variable but appears to attain about 120 m (390 ft) east of Freetown (Strasser-King, 1979, p. 337). Offshore rocks of the Bullom Group may be much thicker.

The occurrence of lignite in outcrop north of Newton was first reported in 1928 by the Geological Survey. The areas of Madanke, Matoli, Rosenda and Kenta Creeks were examined and sampled in 1929 and 1934. In 1944 further examination and bulk sampling was completed. Analyses of the lignite indicated a sufficient quality to justify further investigation and drilling was recommended.

Twelve holes were drilled and three penetrated lignite. The drilling indicated that the lignite beds were not of persistent thickness nor continuous. The area in the vicinity of Konka Creek near Matam and Maplete is estimated to contain approximately 1.25 million tons (1.13 million metric tons). The thickness of the lignite beds averages 1.1 m (3.5 ft). Maximum overburden is 30 m (100 ft) and the average is 12 m (40 ft). Trial workings were set up in the Yema area and two large samples gave the following results:

		Sample No. 1		Sample No. 2	
		Air-dried	Calculated on moisture-free basis	Air-dried	Calculated on moisture-free basis
Proximate Analysis					
Moisture	percent	15.0	---	7.1	---
Volatile matter less moisture	"	42.7	50.2	44.2	47.5
"Fixed carbon"	"	32.0	37.6	34.6	37.3
Ash	"	10.3	12.2	14.1	15.2
Sulphur		4.0	4.7	4.5	4.9
Calorific value	cal. gm	4,300	---	4,500	---
		7,740	9,100	8,100	8,700

Forms of Sulphur in Dry Lignites

	Sample No. 1	Sample No. 2
	Percent	Percent
Sulphate sulphur	1.3	1.3
Pyritic sulphur	0.5	0.4
Organic sulphur	2.9	3.2
Total sulphur	4.7	4.9

		Sample No. 1		Sample No. 2	
		As received	Air-dried	As received	Air-dried
Crude tar	gal/ton	12.2	15.9	7.43	14.7
Coke	cwt/ton	7.45	9.7	5.25	10.4
Gas	cu ft/ton	4,600	6,058	3,140	6,207

The Bullom Series of Pleistocene age as described by Pollette (1952, p. 12-13) consists of gravel, grit, sand and clay of lacustrine, esturarian, deltaic and marine origin which form a narrow belt along the entire coast of Sierra Leone. These rocks overlie rocks of the basement complex.

A narrow strip along the western coast of Sierra Leone is occupied (Marel, 1976, p. 17-18) by marine and estuarine sediments. They consist of mottled red and white clay overlain by coarse sand and are exposed in cliffs along the sea. The maximum known thickness is about 110 m (350 ft) in boreholes drilled on the eastern side of Freetown. These sediments may be much thicker elsewhere.

Togo

The Republic of Togo covers an area of approximately 57,000 km^2 (22,000 mi^2). Crystalline rocks crop out over most of the country. Sedimentary rocks of Quaternary, Pliocene, and Eocene age extend from Dahomey west along the coast for about 200 km (120 mi). These sedimentary rocks have little or no potential for commercial quantities of coal.

Upper Volta

The Republic of Upper Volta covers an area of approximately 274,000 km^2 (106,000 mi^2) in the savannah region of Africa. Crystalline rocks and Cambrian and Silurian age sandstone, conglomerate and calcareous rocks extend over almost the entire area. None of these rocks are believed to contain potential economic coal deposits.

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PART III--GEOTHERMAL RESOURCES

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INTRODUCTION

For the upper 10 km of Earth, regions of normal heat flow have a worldwide average of 1.47 heat flow units (HFU), where 1 HFU = 1 calorie x $10^{-6}/cm^2/s$ or 41.8 milliwatts/m^2, and geothermal gradients of 2° to 4°C/100 m (Muffler, 1975a and 1975b). Geothermal resource development in regions with average or lower than average heat flows and geothermal gradients is presently considered uneconomical due to the high drilling and support technology costs (Muffler, 1975b). A limited number of heat flow measurements from northwest Africa indicate that this region, in general, is an area of average or lower than average heat flow. This generalization is confirmed somewhat by an analysis of worldwide tectonism and seismicity.

World heat flow data (Grim, 1976) indicate that regions of high heat flow, on a global scale, reflect active tectonic features. The high heat flow and geothermal gradients observed in areas of recent tectonic activity suggest that some of these regions are favorable for exploitation of geothermal resources. Conversely, tectonically stable Precambrian shield masses displaying no recent volcanism, such as northwest Africa, are noted by Combs and Muffler (1973) as being particularly unfavorable geothermal resource areas possessing heat flow values lower than the world average. Worldwide seismic behavior also correlates, on a global scale, with recent tectonic activity. Tarr's (1974) "World Seismicity Map" shows a pattern of seismic activity associated with tectonically active regions, while shield areas are seismically inactive.

Areas in this report are discussed using either heat flow values or geothermal gradients or both, depending on the available data. Economically attractive geothermal areas exhibit gradients at intermediate depths (<3 km) greater than 7°C/100 m (Combs and Muffler, 1973). While geothermal gradients will define the areal extent of geothermal anomalies, heat flow measurements have several advantages: In areas of lithologic heterogeneity heat flow measurements are preferred to thermal gradient measurements. In such areas, thermal conductivity generally increases with depth and linear extrapolation of shallow gradients to depth may for this reason lead to estimates with errors on the high side. In addition, convection will produce high gradients above a convection cell and low gradients within. Where pore spaces in the rocks allow the convection of water, extrapolation of near surface gradients measured above the conventive zone will suggest erroneously high temperatures at depth (Combs and Muffler, 1973).

GEOTHERMAL RESOURCES BY INDIVIDUAL COUNTRIES

Ghana

Beck and Mustonen (1972) made preliminary heat flow measurements from four bore holes with depths of measurements ranging from 300 to 500 m. Due to a lack of rock samples for thermal conductivity experiments, an upper limit on heat flow values was set by examining the thermal gradients in the boreholes. Below depths of 100 m the characteristic gradients were 1.8° C/100 m for siltstones and mudstones, and 0.8° C/100 m for sandstones. Beck and Mustonen (1972) calculated the upper limit for heat flow in Ghana to be 1.44 HFU based on the conductivity of pure sandstone and fresh quartzite. Three sandstone samples available for thermal conductivity studies suggest a heat flow of 1.1 HFU, though they note these samples may be unrepresentative of the area. They conclude that while 1.44 HFU represents the upper limit for heat flow values, the correct value is within 20% of 1 HFU. This is consistant with oceanic values measured off the western coast of Africa and with values measured in a sedimentary basin close to the Canadian Precambrian Shield, indicating regionally poor geothermal resource potential.

Niger Republic

Poor geothermal resource potential is also indicated by heat flow studies by Chapman and Pollack (1974) in the Niger Republic. Very low heat flow values of 0.42 and 0.51 HFU were measured for two sites 85 km apart in the western part of the Niger Republic. Both sites were located in Precambrian terrain on the eastern edge of the West African craton, with rock ages ranging from 2,487 to 1,206 m.y. and average thermal gradients of 0.81 and 0.57°C/100 m. These thermal gradients equate to heat flow values that are considerably lower than the worldwide average of 0.96 HFU for shield areas. Chapman and Pollack (1974) conclude that Precambrian crust and underlying upper mantle of western Niger probably comprise one of the coldest regions of Earth. Models using the average shield heat flow imply a lithospheric thickness of approximately 175 km for typical shields, a value supported through seismic investigations. Chapman and Pollack (1974) suggest the heat flow values of the West African Shield arise from a lithospheric thickness extending to depths of over 400 km with a very thin or absent athenosphere.

Liberia

Heat flow studies by Sass and Behrendt (1980) show that the Liberian Precambrian Shield has some of the highest observed values from Precambrian areas older than 2,000 m.y. However, corrected values average 0.96 HFU. This corresponds to the world average for Precambrian shield areas, though higher than those found by Chapman and Pollack (1974) for the Niger Republic, and comparable to those found by Beck and Mustonen (1972) for Ghana. Geothermal gradients, measured from five wells at depths from 78 to 229m (average interval length of 33 m/ measurement), were found to range from 0.71 to 1.43°C/100 m. Sass and Behrendt (1980) note also that the average heat flow offshore to the south and west in the Guinea and Sierra Leone Basins, approximately 1.39 HFU, is higher than that found in oceanic crust of comparable age (>80 m.y.) and that noted by Beck and Mustonen (1972) off the western coast of Africa. They attribute these higher values to possibly renewed tectonic activity beneath those basins. However, they conclude that the thermal effects of this presumed tectonic activity do not extend inland to the Liberian Shield and suggest that large lateral thermal gradients exist between the equatorial Atlantic and the West African Shield. The heat flow values found, though comparable with normal Precambrian shield values, suggest a poor geothermal resource development potential for Liberia.

Nigeria

Geothermal studies were made in southern Nigeria by Nwachuhwa (1975, 1976) and Avbovbo (1978). Sedimentary rocks in the Southern Nigeria Basin range in age from Cretaceous to Holocene, with sedimentary rock thickness estimated at greater than 9 km in the delta region, primarily composed of deltaic sandstone and shale sequences reflecting rapid sedimentation. Nwachuhwa (1975), using data generally logged from wells deeper than 3 km, measured thermal gradients ranging from 1.3 to 1.8°C/100 m in thick Tertiary sedimentary rocks to 5.5°C/100 m in the north where Cretaceous sedimentary rocks are exposed. The thermal gradients in the north, higher than the world average of 2-4°C/100 m; suggest a marginally potential geothermal resource area. The lower gradient values are found at the center of the delta region (the area of maximum sedimentary rock thickness); these increase both northward and seaward. Avbovbo (1978) found similar geothermal gradients for southern Nigeria. Gradients were found to increase to the northeast, with the highest of 5.5°C/100 m occurring along the Agwu-Enuga-Nsukka axis associated with outcrops of coal-bearing Cretaceous rocks of the Anambra Basin. Intermediate gradients of 2.9-4.7°C/100 m were measured along the Calabar-Onitshua-Benin City axis extending into the coastal region south of Okitipupa and Lagos, roughly coinciding with the Tertiary/Holocene sedimentary rock boundary of the Niger delta. Lower gradients of 2.2 to 2.6°C/100 m were found in the Warri-Port Harcourt area where Tertiary sedimentation is at a maximum. Avbovbo (1978) notes that offshore areas of the Niger delta have gradients of 4.7°C/100 m on the northwestern flank, 4.0°C/100 m on the eastern flank and 3.3°C/100 m along the nose of the delta where sedimentary rocks are thickest. The higher gradient values for the Anambra basin again suggest marginally potential geothermal resources. Verheijen and Ajakaiye (1979) made heat flow measurements in the center of the Nigerian Ririwai Ring Complex and found an average heat flow of 0.92 HFU, about equal to the world average for Precambrian shield masses. An average geothermal gradient of 2.6°C/100 m was measured from two boreholes with depths of 70 and 160 m. The ring complexes extend from north of the Niger Republic south to near the Benue Valley in Nigeria, forming a series of massifs which decrease in age from north to south and differ in age by about 300 m.y. This suggests movement of the African plate relative to a mantle plume with associated upwards convection of mantle material. Heat flow measured inside the complex was found to be equivalent to or less than heat flow outside the complex, suggesting thermal activity existing at the time of formation (175 m.y.) has ceased. Young basalt flows (2 m.y.) cropout at several locations indicating recent thermal activity but apparently do not affect regional geothermal gradients.

In general geothermal gradients of the Niger Delta region suggest the area has at best only a marginal potential for the development of hydrothermal and hot dry rock geothermal development. However, the Niger Delta region shows some potential for development of geothermal resources in geopressured zones. Nwachukwa (1975) notes a close correlation between the 100°C isothermal contour and the depth to the top of a geopressure zone similar to that described by Jones (1972) for the Gulf Coast of the United States. Jones (1972) describes an environment of rapid sedimentation allowing water to be trapped in loosely compacted sediments which are sealed by later sedimentary processes. As the overburden increases from later sedimentation, pressures within the sealed zone increase, approaching lithospheric pressure. The diagenesis and dewatering of clay minerals, releasing water which remains trapped beneath the seal, cause a corresponding rise in temperature with the increased pressure. Any above average heat flow will accelerate this process. Although geopressured zones of the Niger Delta region may provide geothermal resources in the future, the necessary technology and cost-benefit ratio probably will not be available for at least 50 years.

Benue trough/Cameroon

Further evidence for migration of the African Plate over a hot zone in the athenosphere, suggested by Verheijen and Ajakaiye (1979) above, may be seen in the Benue trough/Cameroon region (Fitton, 1980). The Benue trough splits at the northeastern end into two branches. The northern branch extends into the Chad Basin forming the Chad rift, while the eastern branch forms the Yola rift which extends as far east as the Sudan border (fig. 10). The southwestern part extends to the Atlantic ocean. Fitton (1980) describes the Benue trough as a failed arm of a Cretaceous RRR triple junction. The other two arms subsequently formed the South Atlantic through the upwelling of a deep mantle plume, which ultimately caused the rifting of the Benue trough.

Fitton (1980) also describes the Cameroon line as a chain of Tertiary to Holocene volcanoes stretching from the Atlantic north to the mountains of the Cameroon Republic. There it splits into two branches, one running northward into northeastern Nigeria and the other eastward into eastern Cameroon. Fitton (1980) notes that as the volcanic activity does not seem to be controlled by pre-existing basement features, it is considered a product of mantle processes unmodified by the overlying crust. While no heat flow or geothermal gradient data were found available, Muffler (1975a and 1975b) notes that volcanic activity and the associated igneous intrusions occurring along rift valleys, such as is seen in East Africa, favor the development of hydrothermal and hot dry rock geothermal systems which suggests this region deserves further investigation.

In summary, West Africa is essentially a Precambrian craton or shield area (fig. 2) consisting of granitized rocks radiometrically age dated at 2.700 to 1,600 m.y. (Dillon and Sougy, 1974). Precambrian shields characteristically exhibit low heat flow values, 0.72 to 1.20 HFU, with an average of 0.96 HFU. While data were not available for every country in the ECOWAS region, what information is available suggests that heat flow value for the ECOWAS region are average or lower than average in comparison to other Precambrian shield areas. Development of geothermal resources, therefore, is presently considered uneconomical. Exceptions may include a geopressured zone in the Niger Delta and areas of recent tectonic activity in the Benue Trough and Cameroon.

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SUMMARY

Petroleum resources

The Economic Community of West African States (ECOWAS) region can be divided into 13 basins or geographic areas based on an analysis of the geologic framework of Africa. These 13 basins can be grouped into 8 categories based on similarities of stratigraphy and suspected hydrocarbon potential. Figure 1 shows the areal extent of both divisions. A brief summary of the hydrocarbon potential of each of the 8 stratigraphic categories follows.

Rocks of the basement complex--The basement complex (fig. 1) consists of crystalline or highly metamorphosed sedimentary rocks of Precambrian age and younger volcanic rocks. These rocks have little or no permeability and any hydrocarbons that they may have contained were destroyed long ago by high temperature thermal alteration.

Paleozoic and upper Precambrian sedimentary rocks-In the Taoudeni, Bove, and Volta Basins and in the northern parts of the Niger and Chad Basins (fig. 1), the only sedimentary rock formations that have the potential for containing petroleum are of Paleozoic and upper Precambrian age. In the Niger and Chad Basins and to a much lesser extent in the remaining basins, the Paleozoic and upper Precambrian sedimentary rocks have been explored by drilling. With the exception of a few minor shows of oil and gas the results have been negative.

Exploration of the Taoudeni, Niger, and Chad Basins probably was spurred by large hydrocarbon discoveries to the north in Algeria. Much of the oil produced from Paleozoic and Triassic reservoirs in Algeria is believed to have been thermally generated from Gothlandian (Silurian) and Devonian shales. Black shales of similar age are known to extend into the Paleozoic basins of the ECOWAS region. Here, however, the Paleozoic section is generally thinner than in northern Africa. Of even more importance than the thickness of the section, is the fact that unlike the Paleozoic section in Algeria, the Paleozoic section in the ECOWAS region may not have been adequately sealed throughout much of its post-depositional history.

In the Hassi Messaoud and Hassi R'Mel fields of Algeria, thick deposits of Jurassic-Triassic salt and anhydrites overlie thin Triassic sandstones and the Paleozoic section. In contrast, in the Taoudeni, Bove, and Volta Basins, the Paleozoic section is either exposed at the surface or covered by a thin veneer of chiefly continental sandstones of Cretaceous to Holocene age. In the northern part of the Niger and Chad Basins, the Paleozoic section is covered by red-bed facies of the "Continental Intercalaire"--chiefly nonmarine deposits of Cretaceous age.

The Volta Basin, with a relatively thick Paleozoic section, may have some prospects. Well data pertaining to source rock maturation and reservoir characteristics would be necessary to evaluate prospects of the Paleozoic and upper Precambrian section.

"Continental Intercalaire" rocks--Over much of the Niger and Chad Basins rocks of the "Continental Intercalaire" unconformably overlie the basement surface (fig. 1). "Continental Intercalaire" refers to rocks younger than last dated Paleozoic sedimentary rocks and older than overlying marine Cretaceous deposits. In the Niger and Chad Basins this section consists chiefly of

Cretaceous age nonmarine red-bed facies, 0 to 2,000 m thick and is overlain by 500 to 1,000 m of middle and Upper Cretaceous sandstones and shales that reflect deposition under alternating marine and nonmarine conditions.

Propects for finding significant quantities of petroleum in rocks of the "Continental Intercalaire" are probably poor because of the absence of potential source rock--the section probably represents deposition in a highly oxidizing environment in which organic matter was not preserved. Marine deposits in the overlying Cretaceous section, in general, were not buried deep enough to reach high temperatures sufficient for thermal generation of oil and gas.

Benue depression--Cretaceous sedimentary rocks in the Benue depression (fig. 1) represent deposition in a "failed-arm" trough system initiated by opening of the South Atlantic Ocean. The trough was filled by more than 3 km of sediments of Albian to Coniacian age. This section contains shallow-and deep-water marine shales with limestones and sandstones deposited at the margins of a marine embayment.

Many parts of this relatively poorly understood trough system could contain significant deposits of petroleum. The lower Benue depression, immediately north of the Niger Delta, has been extensively explored by drilling. Except for non-commerical discoveries of oil and gas and traces of oil and gas on the ground surface, the results of exploration in the lower Benue depression were negative. However, in the Lake Chad area of Chad and in southern Chad near the Central African Republic boundary, oil and gas discoveries were made just prior to the cessation of all drilling and exploration activity in early 1979. It is rumored that these discoveries may be large although little information is available. The relationship of the two areas in Chad and their overall relation to the Benue depression is poorly understood; but, the possibility of thick sedimentary sections containing Cretaceous marine source rock and Tertiary reservoir beds--all contained within grabens in a highly faulted failed-arm system subjected to high heat flow--is attractive.

Senegal Basin-- The Senegal Basin (fig. 1) is related to the opening of the North Atlantic Ocean and contains in excess of 7 km of sedimentary rock. The sedimentary fill consists of sandstones, siltstones, shales, carbonate rocks, and evaporites chiefly of Triassic to Miocene age. The basin represents a typical Atlantic-type marginal basin. In general, analogous type basins off the coast of North America have proved to be poor prospects for discoveries of oil and gas.

Intense exploration since 1953 of the onshore and Continental Shelf has resulted in the drilling of more than 80 wells. Except for the production of small amounts of oil from the Dakar Penninsula in the early 1960's and the discovery, on the shelf, of shallow heavy-oil deposits above salt intrusions, no significant discoveries of oil and gas have been made. Locally high heat flow rates, related to Tertiary volcanic activity in the Dakar Penninsula area and to salt intrusion in the area of heavy oil discovery, may have generated hydrocarbons in an otherwise "cold" basin. Based on the number of wells drilled, we can assume that nearly all of the large structures, onshore and on the shelf, have been tested and that any future discoveries in these areas will be small unless new data revises our basic ideas.

Deep-water areas of the Continental Slope and upper Continental Rise are still relatively unexplored by drilling. Petroleum targets in these areas will probably be Cretaceous turbidites and backreef, reef, and forereef facies associated with a Jurassic carbonate platform. Results are difficult to predict; but, the results so far of sparse drilling in the deep water areas indicates a lack of permeable reservoir rock.

Guinea fracture zone to St. Paul fracture zone (Sierra Leone to Liberia)--In the area between the Guinea and St. Paul Fracture Zones, the Continental Shelf narrows from over 140 km wide in northern Sierra Leone to an average width of 35 km off Liberia (fig. 1). The thickness of Cretaceous sedimentary rocks on the shelf range from an average of 2 km off Sierra Leone to less than 1/2 km off Liberia. A much thicker sedimentary section underlies the lower slope and rise, however.

No hydrocarbon shows of any kind have been reported from the Continental Shelf off Sierra Leone and Liberia, and industry has shown little interest in the area--probably because of the thin sedimentary section. Four wells drilled in 1971 off Liberia were located in an area of the shelf where thick sedimentary rocks occupy a small fault controlled basin.

Seismic reflection surveys indicate that on the slope and rise the sedimentary section increases to more than 4 km in thickness and was deposited in a complex fault-block system. Small, fault-controlled basins trend both parallel to the shelf and oblique to the shelf margin. Geologic evidence, however, indicates that these basins contain mainly fine-grained clastic rocks and may lack reservoir potential. This is in contrast to similar age sediments with good reservoir properties deposited in deep-water environments off nearby Ivory Coast. The recent deep-water discoveries off Ivory Coast will probably renew industry interest in the area.

Gulf of Guinea (excluding Niger Delta)--This area includes the Ivory Coast and Dahomey Basins (fig. 1). A Tertiary-Cretaceous section, more than 8 km thick, is bounded to the north and to the south by major faults at the shelf edge and on the rise. Seismic data indicate that the area is extensively faulted and that tilted fault block structures are common throughout the area. East-west trending fracture zones, that intersect the continental margin and control its trend, have probably acted as funneling mechanisms whereby coarse-grained sediments were deposited in a slope-rise trough during Cretaceous and and Tertiary time.

A recent discovery, Ivory Coast's Espoir field, will probably spur deep water exploration in the area. The discovery well is reported to be capable of producing 20,000 barrels of oil per day and the field could have producible reserves of 500 million barrels of oil (Oil and Gas Journal, 1981). It is rumored, however, that the distribution of reservoir rock (chiefly uncompacted sands) is irregular. This rumor does not conflict with geologic data. An analogous area might be offshore southern California (U.S.A.) where a similar depositional environment has resulted in a very irregular distribution of reservoir sandstones. Water depths at the field location range from about 250 to 730 m.

In deep-water areas, extensive block faulting of basement probably continues far out onto the rise; traps are likely to be associated with tilted fault blocks which have affected basement and Lower Cretaceous sedimentary rocks. Likely source rocks would be Lower Cretaceous shales deposited during periods of stagnant marine sedimentation and younger shales associated with abyssal plain deposits. Good quality reservoir rocks associated with graben fill of coarse-grained sedimentary rock funneled seaward between fracture zones can be expected.

Niger Delta--In the Niger Delta oil and gas production is from a Tertiary delta system that prograded across the continental margin in the lower Benue depression (fig. 1). The thickness of Tertiary sedimentary rocks probably exceeds 8 km. From a petroleum exploration veiwpoint, the geology of the Niger Delta has many similarities with the Mississippi Delta of the United States Gulf Coast. Knowledge of the Niger Delta area has reached an advanced stage as a result of over 30 years of intensive exploration for oil and gas.

In 1977 the proved reserves of Nigeria (Niger Delta) were 12.6 billion barrels of oil and 51.42 trillion ft^3 of natural gas. The U.S. Department of Energy and the U.S. Geological Survey (1979) estimate (mean value estimation) that 8.4 billion barrels of recoverable oil and 65 trillion ft^3 of recoverable natural gas remain to be discovered.

Nigeria's oil development from the Niger Delta may have peaked, as 13 of 14 giant oil fields were discovered prior to 1969 and the greatest number of fields were discovered in the period 1965 through 1967. Like delta regions in other parts of the world, individual oil fields in Nigeria are small to medium by world standards and future oil discoveries are likely to reflect this reality.

The natural gas resources of Nigeria, unlike its oil resources, are comparatively underdeveloped. Total natural gas production in 1977 was an estimated 757 billion ft^3 of which approximately 739 billion ft^3 were flared or not marketed.

Coal resources

Of the ECOWAS countries, only Nigeria and Niger produce coal commercially. Nigeria produces subbituminous coal from Paleocene-Maestrichtian and Maestrichtian (Late Cretaceous) age rocks of the Niger Delta region (fig. 13); reserves are estimated, on the basis of extensive drilling, to be 350 million tons (standard coal equivalent). Niger produces coal from Carboniferous age rocks of the Niger Basin west of the Air Massif (fig. 7). Apparently, small amounts of coal are produced and used locally by uranium mine and mill operations.

The lignite deposits of the Niger Delta appear to be large but have not been developed. The lignite occurs in strata of Eocene age. In coastal Sierra Leone, exploratory workings were established in the 1940's to investigate Pleistocene lignite discovered in marine and estuarine sediments; operations apparently were discontinued after initial tests.

In Senegal and Benin, coal has been penetrated in wells or boreholes. In Senegal, at least 33 oil and water wells have penetrated lignite beds that range from a few centimeters to more than 70 m in thickness and at depths ranging from about 55 to more than 647 m. The lignite in the Senegal Basin is in strata of Maestrichtian (Late Cretaceous) age. In Benin, medium quality lignite in thin beds (0.5-1 m) was penetrated at depths from 60 to 100 m.

Peat, although not classified as coal, occurs in the deltas, lower river areas, and lower basin areas of the Senegal, Sine Saloum, Caasamance, and Gambia rivers. The age of these deposits are not reported. Granular coal found along the coast of Liberia is generally believed to be disintegrated coal lost from passing freighters.

The coal discoveries can be summarized as follows: the Carboniferous section in the Niger Basin; the Paleocene-Maestrichtian, Maestrichtian, and Eocene sections in the Niger Delta and Benin; the Maestrichtian section in the Senegal Basin; and the Pleistocene section in Sierra Leone. The only proved commercial deposits are the Paleocene-Maestrichtian and Maestrichtian subbituminous coal beds of the Niger Delta. Some of the lignite deposits of the Niger Delta and Senegal Basin, however, may be exploitable in the future.

Despite the relatively small quantities of coal discovered to date, the age and lithology of the strata containing these coals suggest that other areas are worthy of further exploration. Carboniferous age rocks are present in the Taoudeni and Bove Basins and in the northern parts of the Niger and Chad Basins (fig. 1 and 4). In the Taoudeni Basin especially, Carboniferous rocks crop out over and underlie extensive areas (fig. 4). However, the Middle and Upper Carboniferous rocks in the Taoudeni Basin are described as continentally derived red sandstones (Dillon and Sougy, 1974); whereas, the Carboniferous strata that contain subbittuminous coal in the Niger Basin are sandstones and shales that reflect deposition in a lagoonal environment (Petroconsultants, written communication, 1976). The Paleocene-Maestrichtian and Maestrichtian subbituminous coals and Eocene lignite of the Niger Delta are associated with deltas built across the lower reaches of the Benue Trough (fig. 13). Although these particular deltas do not extend up the Benue depression, deltas of similar age may have developed in the lower reaches of the Bida Basin and Yola Trough (fig. 10). During the Maestrichtian transgression, marine sedimentation reached the Chad syncline (fig. 10) and Upper Cretaceous and Paleocene rocks in this area contain lagoonal and lacustrine deposits. However, the overlying Tertiary beds of the "Continental Terminal" are thick; thus potential coal deposits in the area may be difficult to exploit. The Maestrichtian lignites penetrated in Benin probably represent a northwest subsurface continuation of lithologies similar to the Niger Delta. The subsurface discoveries of large quantities of Maestrichtian to Pleistocene age lignite in the subsurface of the Senegal Basin suggests the need for further subsurface investigations in coastal Mauritania, Senegal, Gambia, Guinea Bissau, Guinea, and Sierra Leone (fig. 1).

Geothermal resources

Published literature contains limited data on heat-flow values in the ECOWAS region. It is inferred, however, from the few values available and the regional geology that the development of geothermal resources, in general, would be uneconomical. Exceptions may include a geopressured zone in the Niger Delta and areas of recent tectonic activity in the Benue Trough and Cameroon. Development of the latter areas under present economic conditions is not feasible.