Geology and Total Petroleum Systems of the Gulf of Guinea Province of West Africa

U.S. Geological Survey Bulletin 2207-C

U.S. Department of the Interior
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By Michael E. Brownfield and Ronald R. Charpentier

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Foreword

This report was prepared as part of the World Energy Project of the U.S. Geological Survey. The purpose of the World Energy Project is to assess the quantities of oil, gas, and natural gas liquids that have the potential to be added to reserves within the next 30 years. These volumes either reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit (variable, but must be at least 1 million barrels of oil equivalent) or occur as reserve growth of fields already discovered.

For this project, the world was divided into 8 regions and 937 geologic provinces, which were then ranked according to the discovered oil and gas volumes within each (Klett and others, 1997). Of these, 76 “priority” provinces (exclusive of the U.S. and chosen for their high ranking) and 26 “boutique” provinces (exclusive of the U.S. and chosen for their anticipated petroleum richness or special regional economic importance) were selected for appraisal of oil and gas resources. The petroleum geology of these priority and boutique provinces is described in this series of reports.

A geologic province is a region that characteristically has dimensions of hundreds of kilometers and that encompasses a natural geologic entity (for example, sedimentary basin, thrust belt, accreted terrain) or some combination of contiguous geologic entities. Province boundaries were drawn as logically as possible along natural geologic boundaries, although in some provinces their location is based on other factors, such as a specific bathymetric depth in open oceans.

The total petroleum system constitutes the basic geologic unit of the oil and gas assessment. The total petroleum system includes all genetically related petroleum that occurs in shows and accumulations (discovered and undiscovered) that (1) has been generated by a pod or by closely related pods of mature source rock, and (2) exists within a limited mappable geologic space, along with the other essential mappable geologic elements (reservoir, seal, and overburden rocks) that control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum. The minimum petroleum system is that part of a total petroleum system encompassing shows and discovered accumulations along with the geologic space in which the various essential elements have been proved by these discoveries.

An assessment unit is a mappable part of a total petroleum system in which discovered and undiscovered fields constitute a single, relatively homogeneous population such that the chosen methodology of resource assessment based on estimation of the number and sizes of undiscovered fields is applicable.

A total petroleum system may equate to a single assessment unit, or if necessary may be subdivided into two or more assessment units such that each unit is sufficiently homogeneous in terms of geology, exploration considerations, and risk to assess individually.

A graphical depiction of the elements of a total petroleum system, in the form of an events chart, shows the times of (1) deposition of essential rock units; (2) trap formation; (3) generation, migration, and accumulation of hydrocarbons; and (4) preservation of hydrocarbons.

A numeric code identifies each region, province, total petroleum system, and assessment unit; these codes are uniform throughout the project and throughout all publications of the project. The code used in this study is as follows:

Unit	Name	Code
Region	Sub-Saharan Africa	**7**
Province	Gulf of Guinea	7**183**
Total petroleum system	Cretaceous Composite	7183**01**
Assessment unit	Coastal Plain and Offshore	718301**01**

The codes for the regions and provinces are listed in Klett and others (1997).

Oil and gas volumes quoted in this report are derived from Petroconsultants, Inc., 1996 Petroleum Exploration and Production database (Petroconsultants, 1996) and other area reports from Petroconsultants, Inc., unless otherwise noted.

Figures in this report that show boundaries of the total petroleum system and assessment unit were compiled using geographic information system (GIS) software. Political boundaries and cartographic representations were taken, with permission, from Environmental Systems Research Institute's ArcWorld 1:3 million digital coverage (1992), have no political significance, and are displayed for general reference only. Oil and gas field centerpoints, shown in these figures, are reproduced, with permission, from Petroconsultants (1996).

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Abstract

The Gulf of Guinea Province as defined by the U.S. Geological Survey (USGS) consists of the coastal and offshore areas of Côte d'Ivoire, Ghana, Togo, and Benin, and the western part of the coast of Nigeria, from the Liberian border east to the west edge of the Niger Delta. The province includes the Ivory Coast, Tano, Central, Saltpond, Keta, and Benin Basins and the Dahomey Embayment. The area has had relatively little hydrocarbon exploration since 1968, with only 33 small to moderate-sized oil and gas fields having been discovered prior to the USGS assessment. Most discoveries to 1995 have been located in water depths less than 500 m. Since 1995, only eight new offshore discoveries have been made, with four of the discoveries in the deep-water area of the province.

Although as many as five total petroleum systems exist in the Gulf of Guinea Province, only one, the Cretaceous Composite Total Petroleum System, and its assessment unit, the Coastal Plain and Offshore Assessment Unit, had sufficient data to allow assessment. The province shows two important differences compared to the passive-margin basins south of the Niger Delta: (1) the influence of transform tectonics, and (2) the absence of evaporites and salt deformation. The province also lacks long-lived, large deltaic systems that typically result in rapid source rock burial and abundant high-quality hydrocarbon reservoirs.

The USGS assessed the potential for undiscovered conventional oil and gas resources in the Gulf of Guinea Province as part of its World Petroleum Assessment 2000, estimating a mean of 1,004 million barrels of conventional undiscovered oil, 10,071 billion cubic feet of gas, and 282 million barrels of natural gas liquids. Most of the hydrocarbon potential is postulated to be in the offshore, deeper waters of the province. Gas resources may be large, as well as accessible, in areas where the zone of hydrocarbon generation is relatively shallow.

Introduction

The U.S. Geological Survey (USGS) assessed the potential for undiscovered oil and gas resources in the Gulf of Guinea Province (7183) as part of its World Petroleum Assessment 2000 (U.S. Geological Survey World Energy Assessment Team, 2000). The province extends from the Niger Delta west to Liberia, and includes the coastal and offshore areas of Côte d'Ivoire, Ghana, Togo, Benin, and westernmost Nigeria (fig. 1). At least five total petroleum systems have been identified in the province, but existing exploration and production data in the province are mostly limited to the Cretaceous rocks. Therefore, only the Cretaceous Composite Total Petroleum System (TPS) with its contained Coastal Plain and Offshore Assessment Unit (AU) was assessed in this study (fig. 2). Also owing to limited drilling and production data, the total petroleum system and assessment unit boundaries can only be approximately delineated and so are subject to future revisions.

This report documents and supplements the oil and gas assessment reported in USGS World Petroleum Assessment 2000—Description and results (U.S. Geological Survey World Energy Assessment Team, 2000) by providing additional geologic detail concerning the total petroleum systems and assessment units and a more detailed rationale for the quantitative assessment input. Since the Gulf of Guinea assessment in 1999, three major volumes (Cameron and others, 1999; Mello and Katz, 2000; Arthur and others, 2003) on the petroleum geology of west Africa have been published, signifying increased interest and exploration activity in the region.

Geology of the Gulf of Guinea Province

The Gulf of Guinea Province includes the Ivory Coast, Tano, Saltpond, Central, Keta, and Benin Basins and the Dahomey Embayment in the northwestern part of the Gulf of Guinea (figs. 3, 4). These basins share common structural and stratigraphic characteristics, in that they are wrench-modified basins (Clifford, 1986) and contain rocks ranging in age from Ordovician to Holocene (Kjemperud and others, 1992); they were therefore grouped together as one province. The eastern boundary is the Niger Delta Province (Klett and others, 1997), and the western boundary is the West African Coastal Province (fig. 4).

The Gulf of Guinea formed at the culmination of Late Jurassic to Early Cretaceous tectonism that was characterized by both block and transform faulting superimposed across an extensive Paleozoic basin during breakup of the African, North American, and South American paleocontinents (figs. 5, 6).

Figure 1. Gulf of Guinea Province (7183) in west-central Africa and locations of oil and gas field centerpoints (Petroconsultants, 1996).

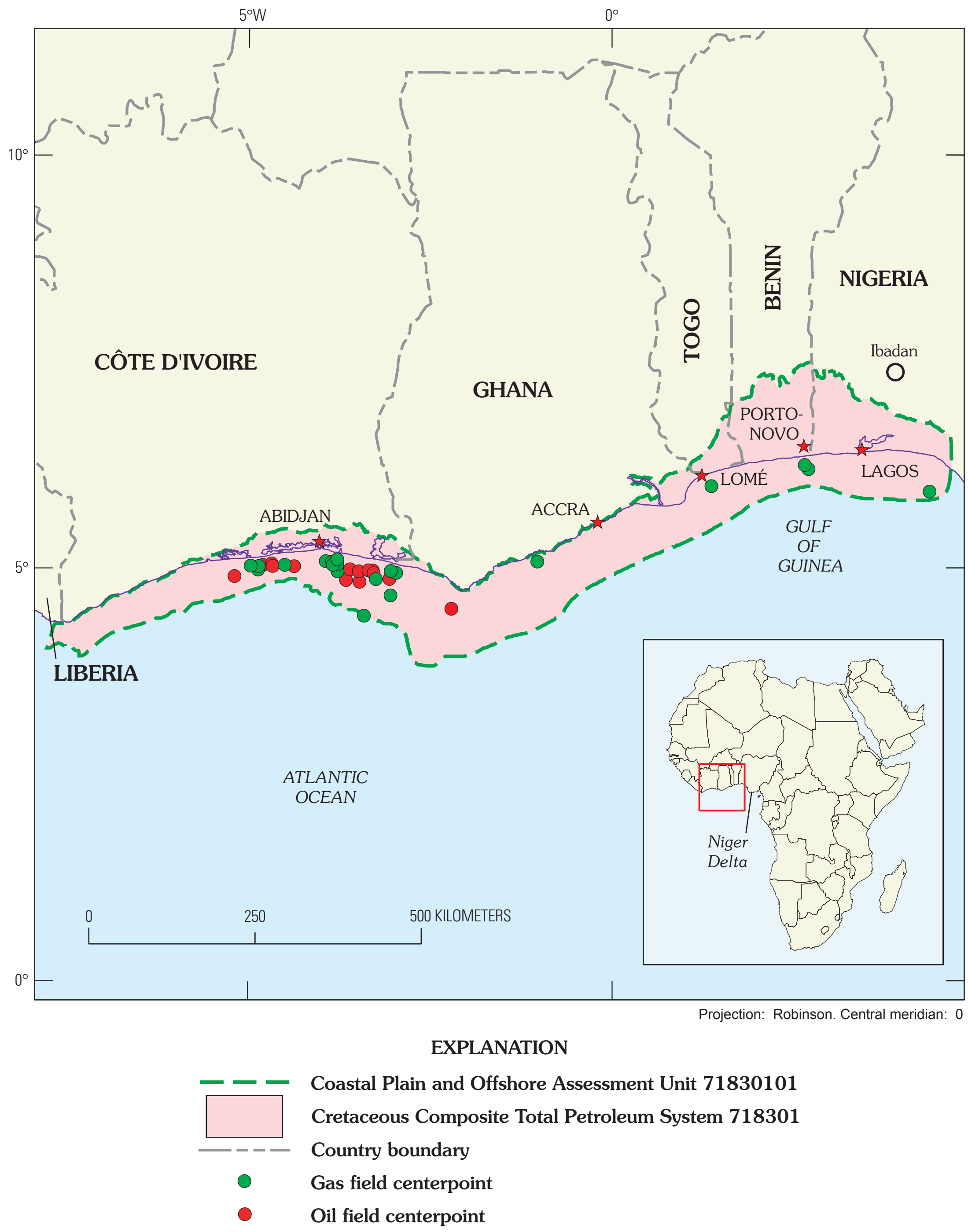


Figure 2. Gulf of Guinea Province showing area of Cretaceous Composite Total Petroleum System and Coastal Plain and Offshore Assessment Unit, and oil and gas field centerpoints (Petroconsultants, 1996).

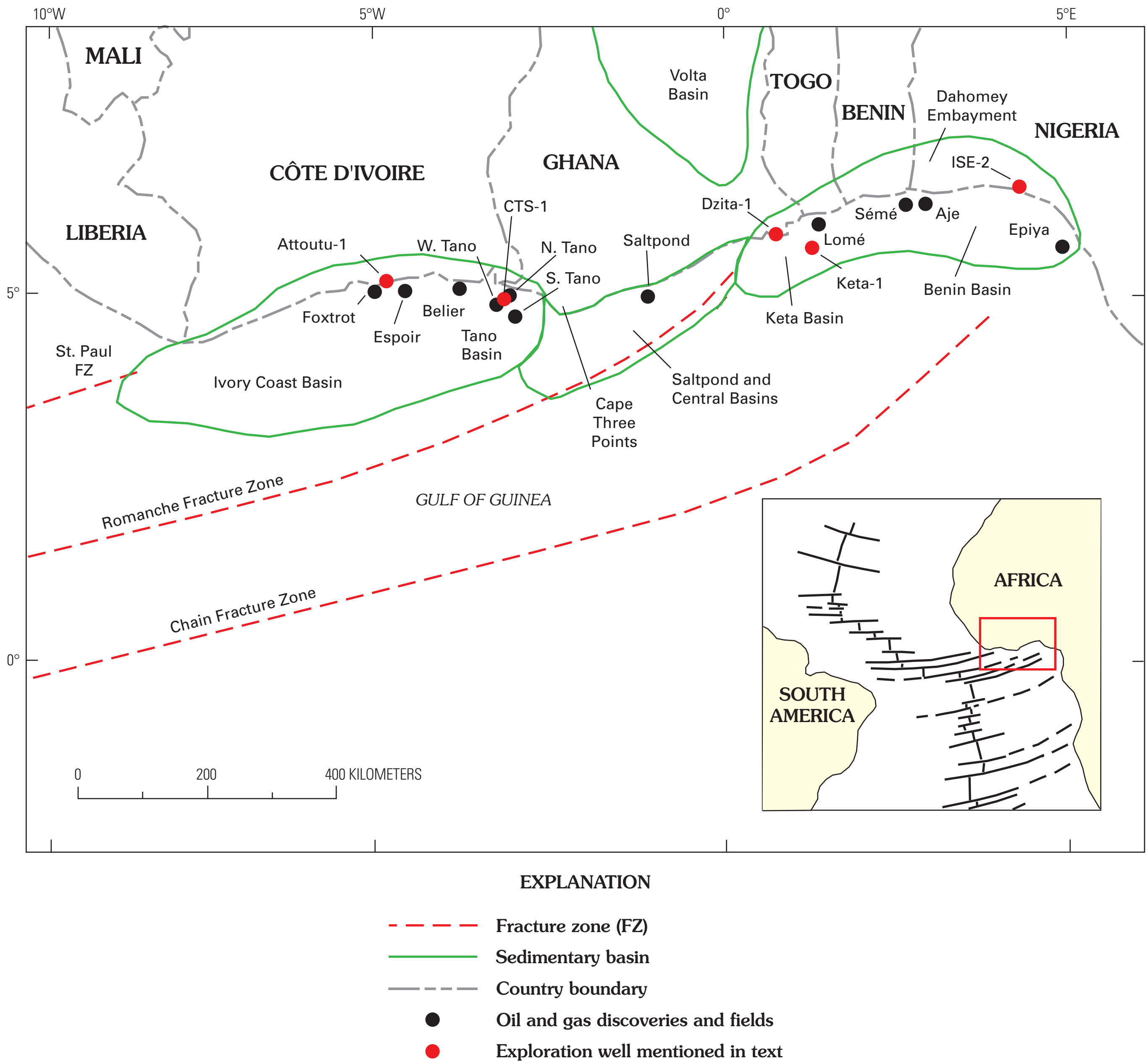


Figure 3. Major features of the Gulf of Guinea Province, west Africa: Benin, Central, Ivory Coast, Keta, Saltpond, Tano, and Volta Basins, Cape Three Points, major fracture zones, and approximate locations of exploration wells and of the oil and gas discoveries and fields mentioned in the text. Mid-Atlantic Ridge and fracture zones shown in index map. Modified from Kjemperud and others (1992).

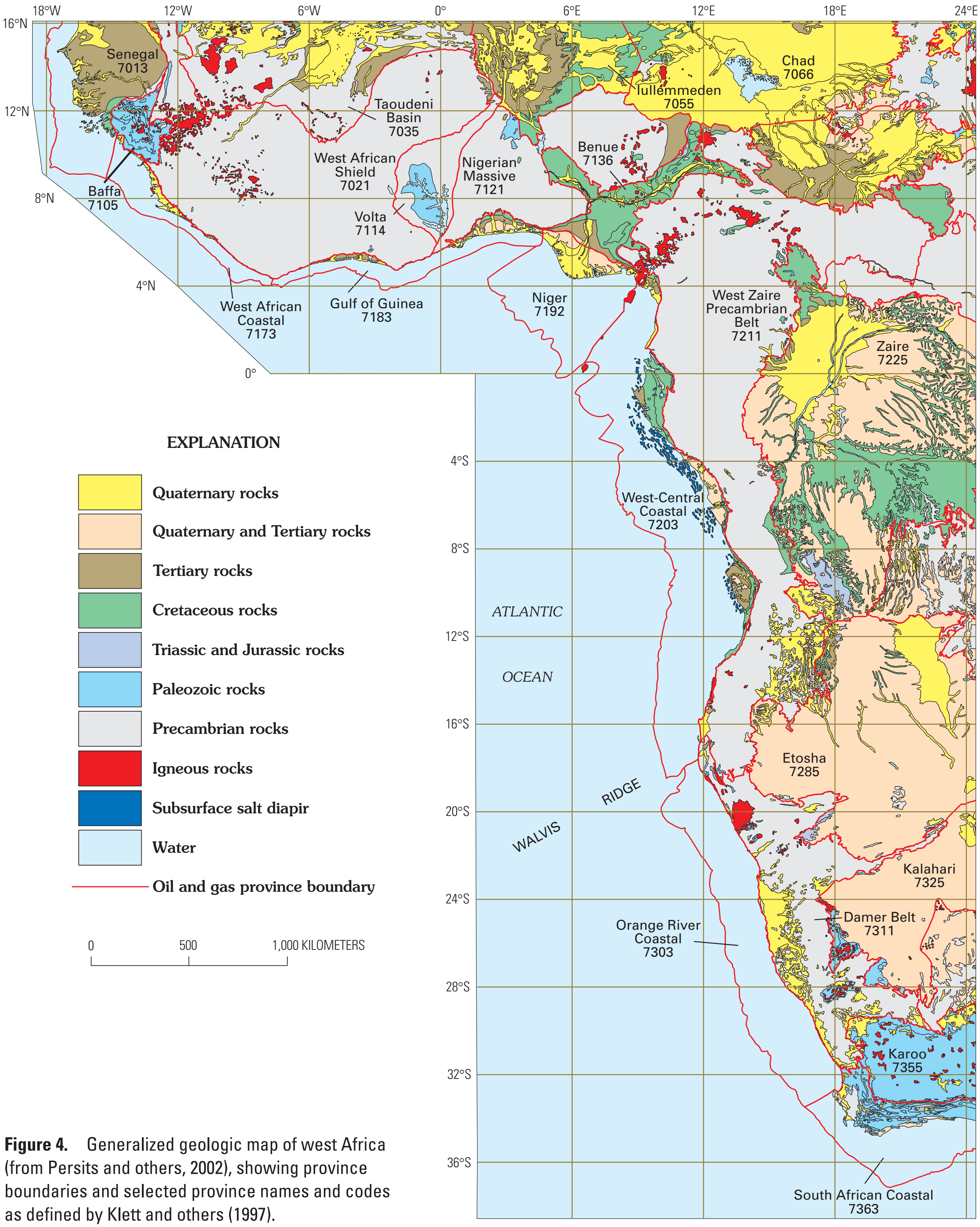


Figure 4. Generalized geologic map of west Africa (from Persits and others, 2002), showing province boundaries and selected province names and codes as defined by Klett and others (1997).

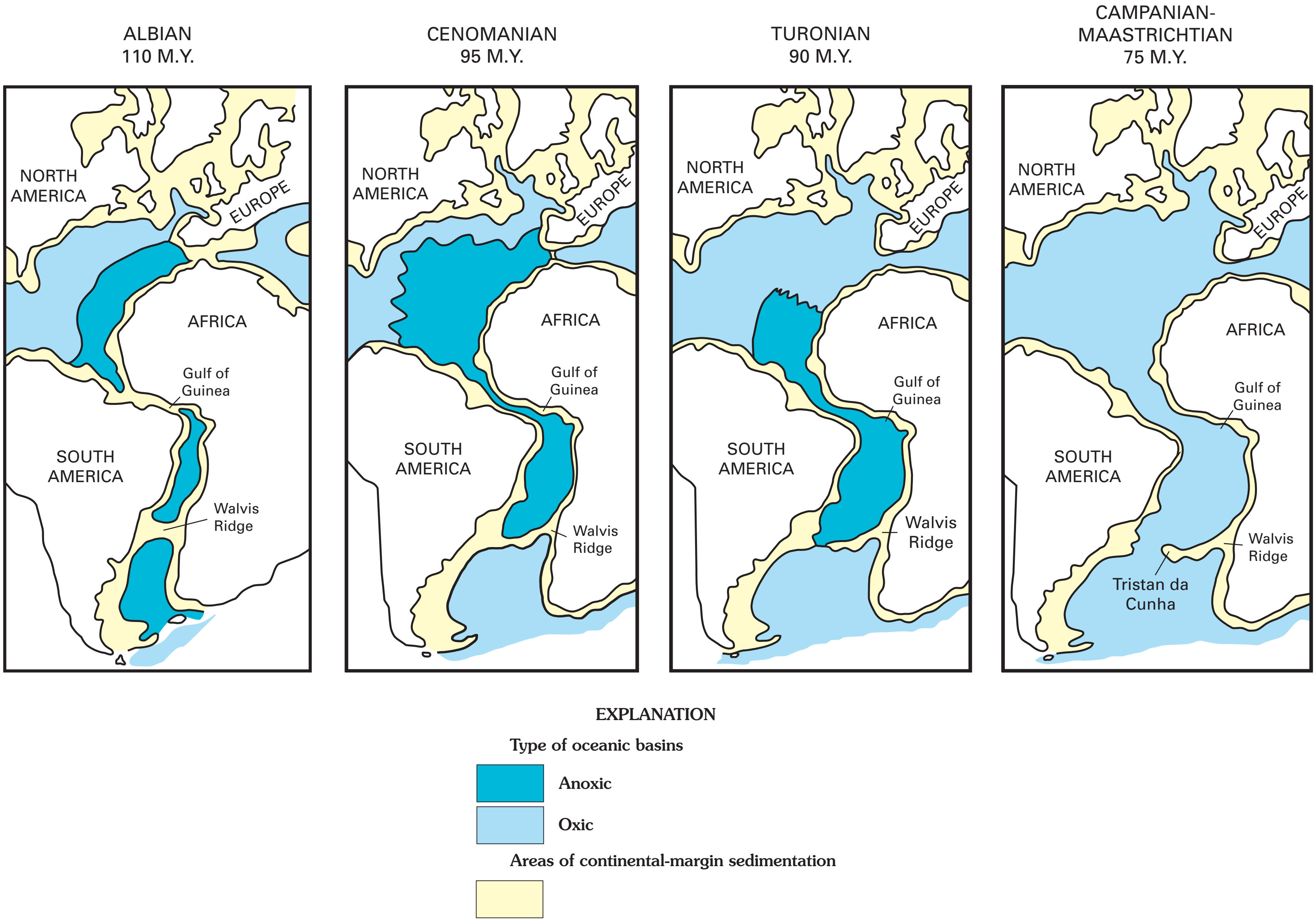


Figure 5. Paleogeographic stages in the separation of Africa and South America during the Cretaceous. Modified from Tissot and others (1980).

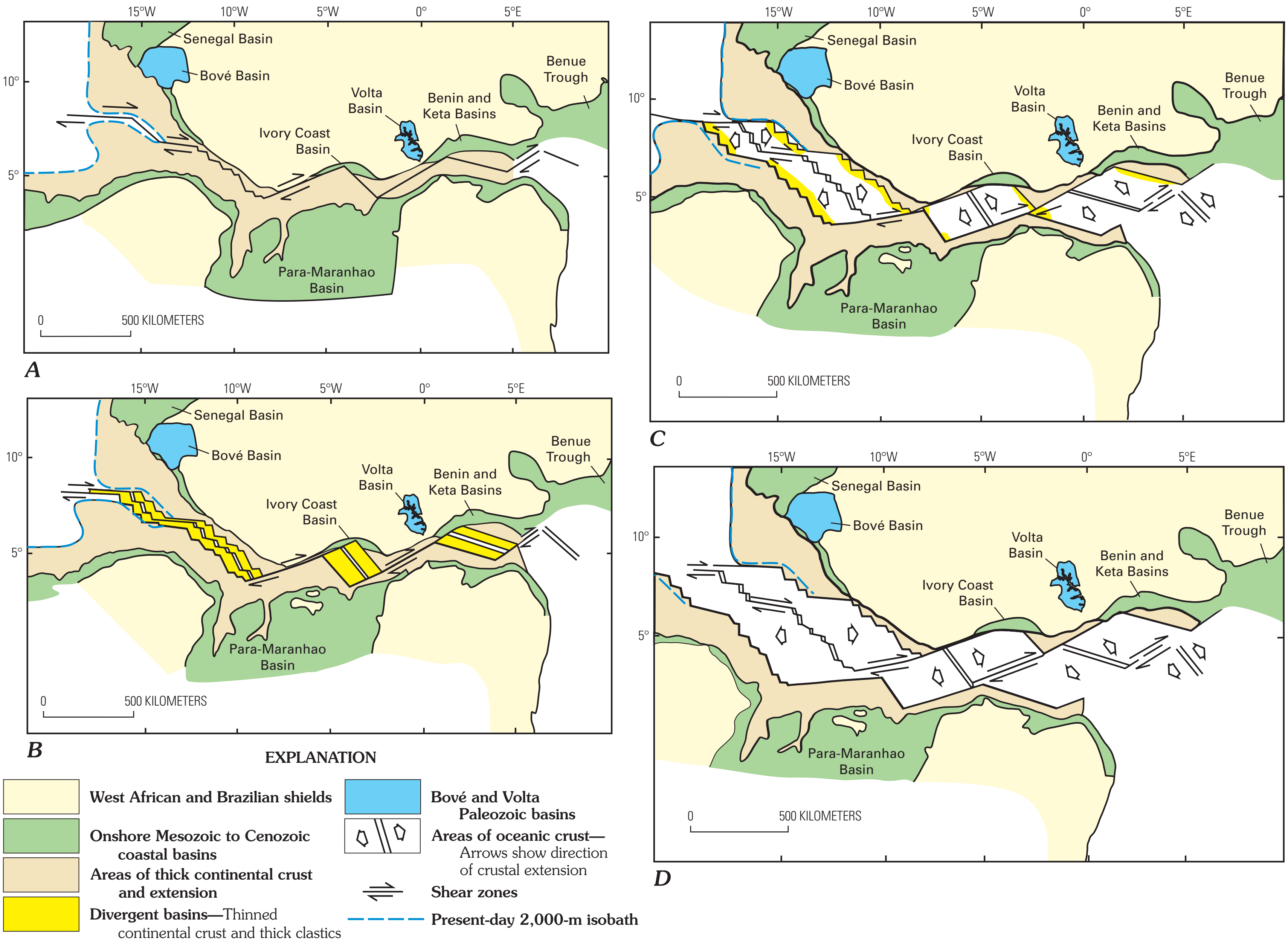


Figure 6. Schematic Cretaceous stages in the Mesozoic breakup of Africa and South America and the tectonic evolution of the Equatorial Atlantic, and showing the approximate location of the Bové, Benin, Ivory Coast, Keta, Senegal, and Volta Basins and the Benue Trough of Africa and the Para-Maranhao Basin of Brazil. *A*, Hauterivian, 125 Ma; *B*, early Albian, 110 Ma; *C*, late Albian, 100 Ma; *D*, Santonian, 85 Ma. Modified from Mascle and others (1988).

Thus, the province has undergone a complex history, which we divide into pre-transform (late Proterozoic to Late Jurassic), syn-transform (Late Jurassic to Early Cretaceous), and post-transform (Late Cretaceous to Holocene) stages of basin development. These three stages are referred to as the pre-rift (or intracratonic), syn-rift (or rift), and post-rift (or drift) stages by Dumestre (1985), Kjemperud and others (1992), Tucker (1992), and Chierici (1996). The structural basins within the province are aligned generally east-west, with boundaries delimited by an east-west transform fault system (fig. 3) and north-south structural arches.

The initial phase of the post-Hercynian opening of the north Atlantic and the splitting of North America from Eurasia and Africa began during Late Permian–Early Triassic time (Lehner and De Ritter, 1977; Ziegler, 1988; Lambiase, 1989; Uchupi and others, 1976). The final breakup of Africa and South America began in the Late Jurassic in the southernmost part of the south Atlantic and prograded northward during Neocomian time (Binks and Fairhead, 1992; Guiraud and Maurin, 1992). The area now occupied by the Gulf of Guinea opened last, forming a continuous anoxic seaway in the late Albian to Turonian (Tissot and others, 1980). A continuous oxic Atlantic Ocean (fig. 5) existed by the end of the Santonian (Blarez and Mascle, 1988). The presence of Aptian evaporites and clastics in the West-Central Coastal Province to the south (fig. 4) provides evidence that rift-basin sedimentation occurred during the Early Cretaceous, associated with the breakup of Africa and South America.

The early tectonic history of the Gulf of Guinea Province is different from that of the West-Central Coastal Province (fig. 3) or "Aptian salt basin" (Blarez and Mascle, 1988; Mascle and others, 1988; Basile and others, 1993; MacGregor and others, 2003; Brownfield and Charpentier, 2006). In the evolution of the "Aptian salt basin," the rifting stage was dominated by extensional or block faulting, forming grabens that filled with lacustrine and fluvial sediments; this was followed by deposition of regional evaporates, and subsequent halokinesis (McHargue, 1990; Teisserenc and Villemin, 1990). The Gulf of Guinea Province shows two important geological differences compared to the passive-margin basins south of the Niger Delta: (1) the influence of transform tectonics, and (2) the absence of evaporites and halokinesis. Middle Jurassic volcanic rocks occur in the Gulf of Guinea Province, indicating that tectonism started no later than the Middle Jurassic (Dumestre, 1985; Kjemperud and others, 1992).

Transform faulting was initiated between the African and South American continental plates in Early Cretaceous time (Hauterivian, fig. 6*A*). The thick continental crust of the African and South American platform started to break up, forming divergent basins or pull-apart grabens separated by transform faults (Blarez and Mascle, 1988) in early Albian time (fig. 6*B*). Thick continental clastics, consisting of fluvial and possibly lacustrine facies, were deposited in the divergent basins. In the Dahomey Embayment (figs. 3, 7), source-rock samples have chemical and geologic characteristics similar to Lower Cretaceous lacustrine source rocks in the Congo Basin (Haack and others, 2000). Such rocks may also be present in the Benue Trough and in the Keta and Ivory Coast Basins (figs. 3, 6). Transform tectonism was active between the African and South American plates until middle to late Albian time, when the first oceanic crust was formed (fig. 6*C*) and the last connection between the two continents was breached (Blarez and Mascle, 1988). The end of syn-transform tectonism and sedimentation in the Gulf of Guinea Province coincides with this phase. A major Albian–lower Cenomanian unconformity was a direct consequence of the final separation of the continental margins (Blarez and Mascle, 1988; Chierici, 1996; MacGregor and others, 2003). By Santonian time (fig. 6*D*), continued crustal extension resulted in the formation of major oceanic crust, and the marginal basins and offshore platform of the province were subjected to an increase in clastic deposition and thermal subsidence, resulting in development of several Late Cretaceous and Tertiary unconformities.

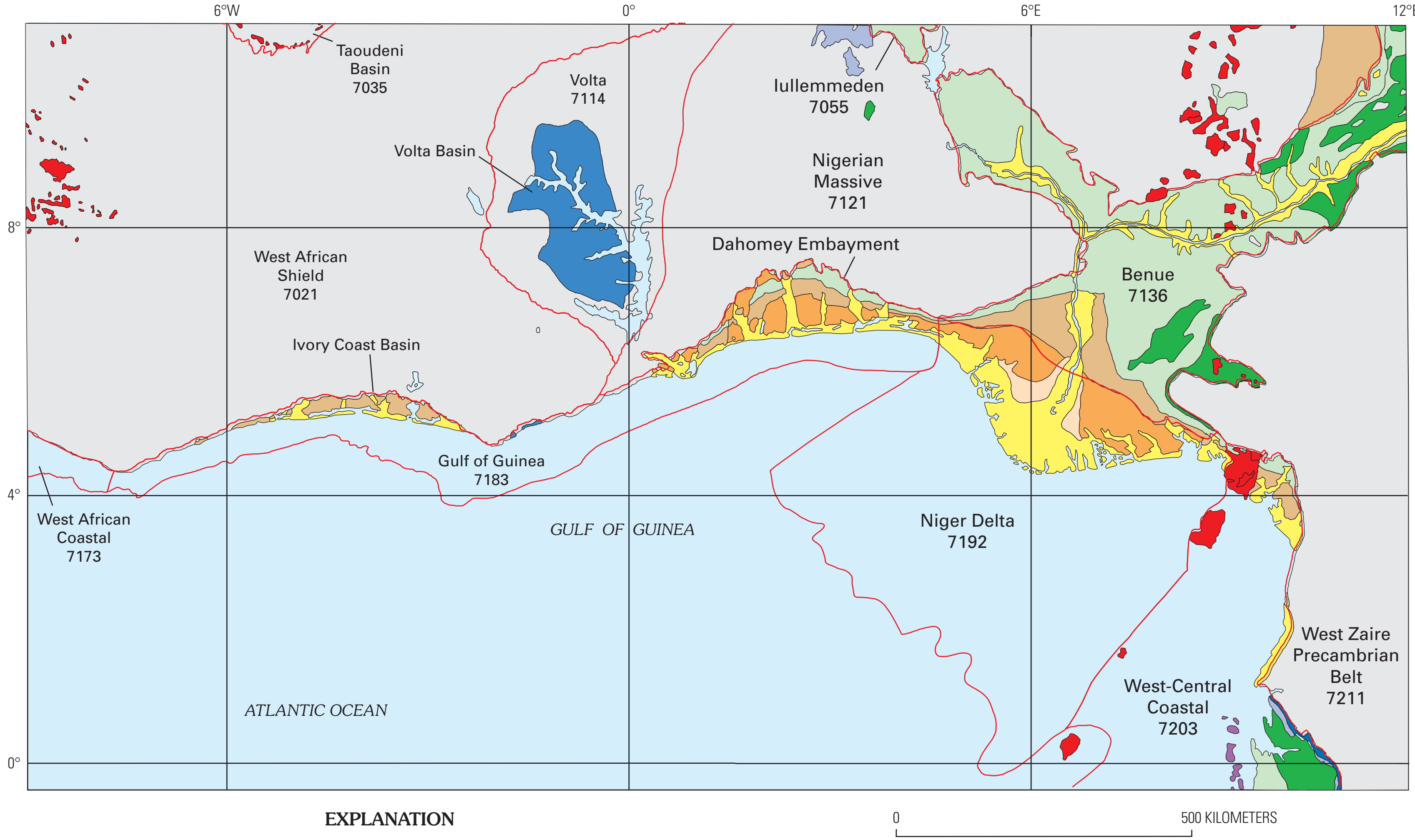
The Gulf of Guinea Province is divided structurally by three major transform fault zones (figs. 3, 8): (1) the St. Paul fracture zone along the northwestern boundary, (2) the Romanche fracture zone that separates the Ivory Coast and the Central and Saltpond Basins from the Keta Basin, and (3) the Chain fracture zone along the eastern boundary. Sedimentary fill within the Ivory Coast Basin is more than 6,000 m thick (fig. 8) north of the Romanche fracture zone, which acted as a dam to the transport and accumulation of sediments to the south.

The three-stage tectonic evolution in the Gulf of Guinea Province allows the stratigraphic section to be divided into three main sequences (fig. 9): (1) Precambrian to Triassic intracratonic rocks and Jurassic to Lower Cretaceous continental to marginal marine rocks representing the pre-transform stage, (2) Lower Cretaceous to latest Albian rocks representing the syn-transform stage, and (3) Cenomanian to Holocene rocks representing the post-transform stage.

An understanding of the geology of both the African and South American margins of the Atlantic, and an appreciation of their resource potential, have increased greatly in the last decade. Some suggested references for general geology and structural evolution of the African Atlantic margin are Blarez and Mascle (1988), Uchupi (1989), Doust and Omatsola (1990), Teisserenc and Villemin (1990), Brown and others (1995), Cameron and others (1999), Mello and Katz (2000), and Arthur and others (2003).

Pre-Transform Stage

The pre-transform section consists of Precambrian to Triassic rocks that crop out in the Volta and Tano Basins of Ghana (Volta Province, figs. 3, 4). This section has been penetrated by drilling in the Saltpond, Tano, and Keta Basins (fig. 3) in the central and eastern parts of the Gulf of Guinea Province (Dumestre, 1985; Kesse, 1986; Kjemperud and others, 1992; Tucker, 1992). In the Volta Basin (figs. 3, 7), the pre-transform section consists of intracratonic Proterozoic to Cambrian rocks. The upper Precambrian Buem Formation overlies the Precambrian basement, and includes sandstone,



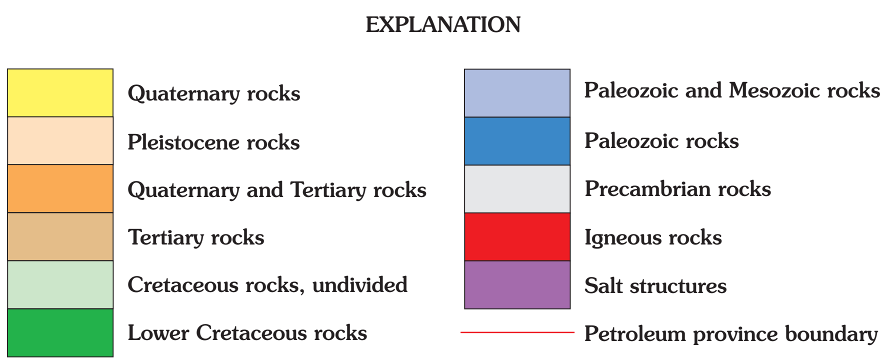


Figure 7. Generalized geology of the Gulf of Guinea area, showing selected petroleum provinces and the Dahomey Embayment and the Ivory Coast and Volta Basins. Modified from Persits and others (2002).

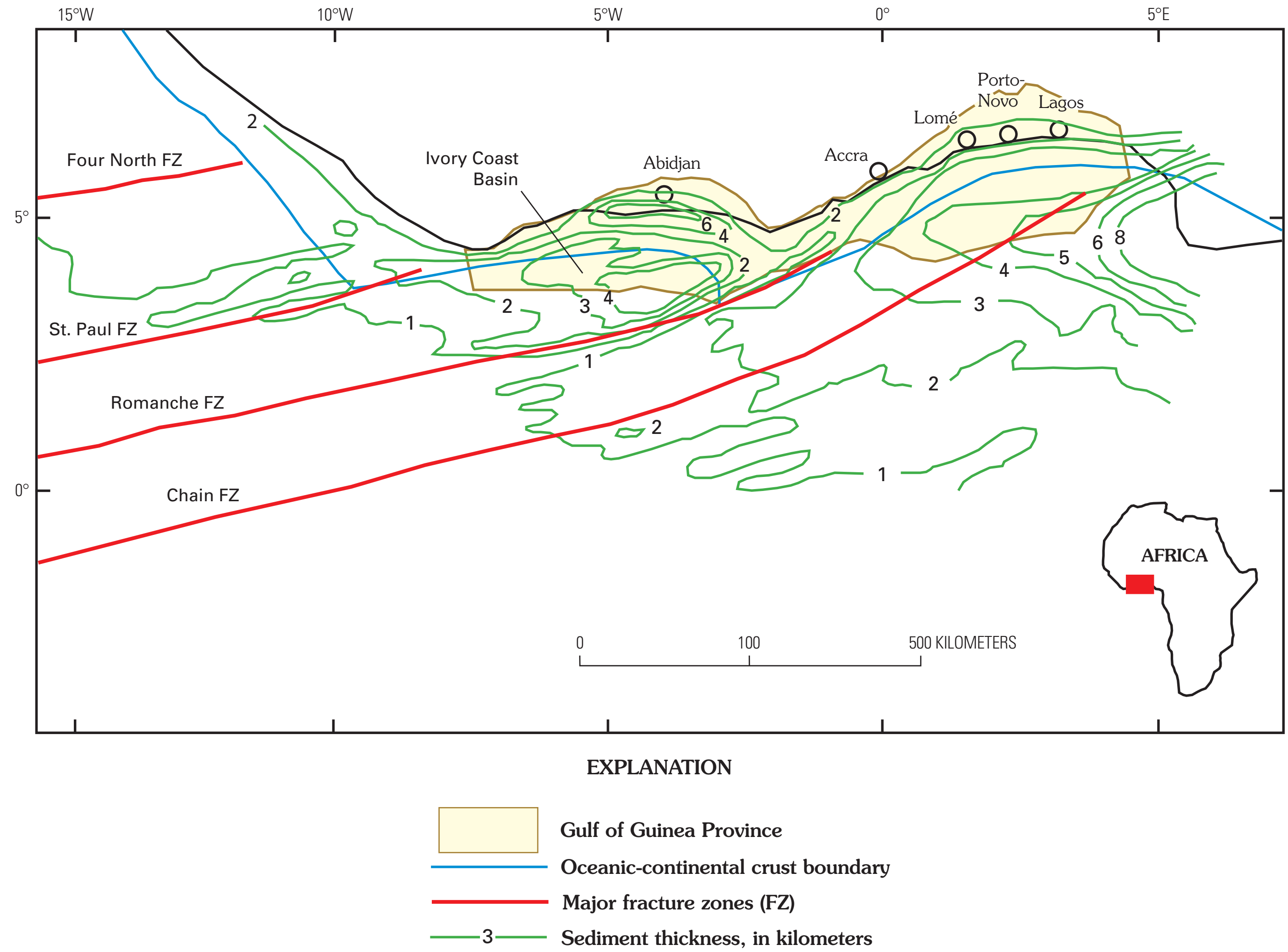


Figure 8. Sketch map showing major fracture zones (FZ), sediment thickness, and oceanic-continental crust boundary for the Gulf of Guinea Province. Modified from Emery and Uchupi (1984) and MacGregor and others (2003).

shale, and volcanics (Kesse, 1986). The Voltaian Series overlies the Buem Formation, and includes sandstone, shale, mudstone, conglomerate, limestone, and tillites deposited in continental and shallow-marine environments (Kesse, 1986: Kulke, 1995).

In the Central, Keta, and Saltpond Basins (figs. 9, 10, 11) of central and eastern Ghana, the pre-transform rocks range in age from Ordovician to Triassic (Kjemperud and others, 1992; Tucker, 1992). The Ordovician to Silurian lacustrine Ajua Formation consists of laminated shales; it is overlain by the fluvial and lacustrine Elmina Formation, composed of feldspathic sandstone and minor conglomerate. Both formations are present only in the Central and Saltpond Basins (Kjemperud and others, 1992). The distribution of marine Silurian rocks (Clifford, 1986), which are known to contain oil-prone black graptolitic shales in northern Africa, is shown on the Silurian paleogeographic map in figure 12; as indicated, Silurian deposition possibly continued eastward to the Benue Trough, in Nigeria. Devonian marine sandstones and shales (fig. 11) were penetrated in the Dzita-1 well (Kjemperud and others, 1992) but drilling did not reach the basement. The Upper Devonian Takoradi Formation, consisting of sandstone, shale, and organic-rich shale, was deposited in a shallow to restricted marine environment. The Upper Devonian to Carboniferous Efia Nkvanta Formation is composed of nonmarine and marine sandstones and cherty shales with limestone deposited in continental to shallow marine environments. The Carboniferous to Triassic Sekondien Series includes red sandstones and red-brown shales deposited in a fluvial environment. Middle Devonian to Lower Cretaceous pre-transform rocks consisting of continental interbedded conglomerate, sandstone, and shale were observed in the onshore part of the Saltpond Basin (Kesse, 1986).

Pre-transform rocks have not been identified with certainty in the Ivory Coast Basin (fig. 3), but there are Lower

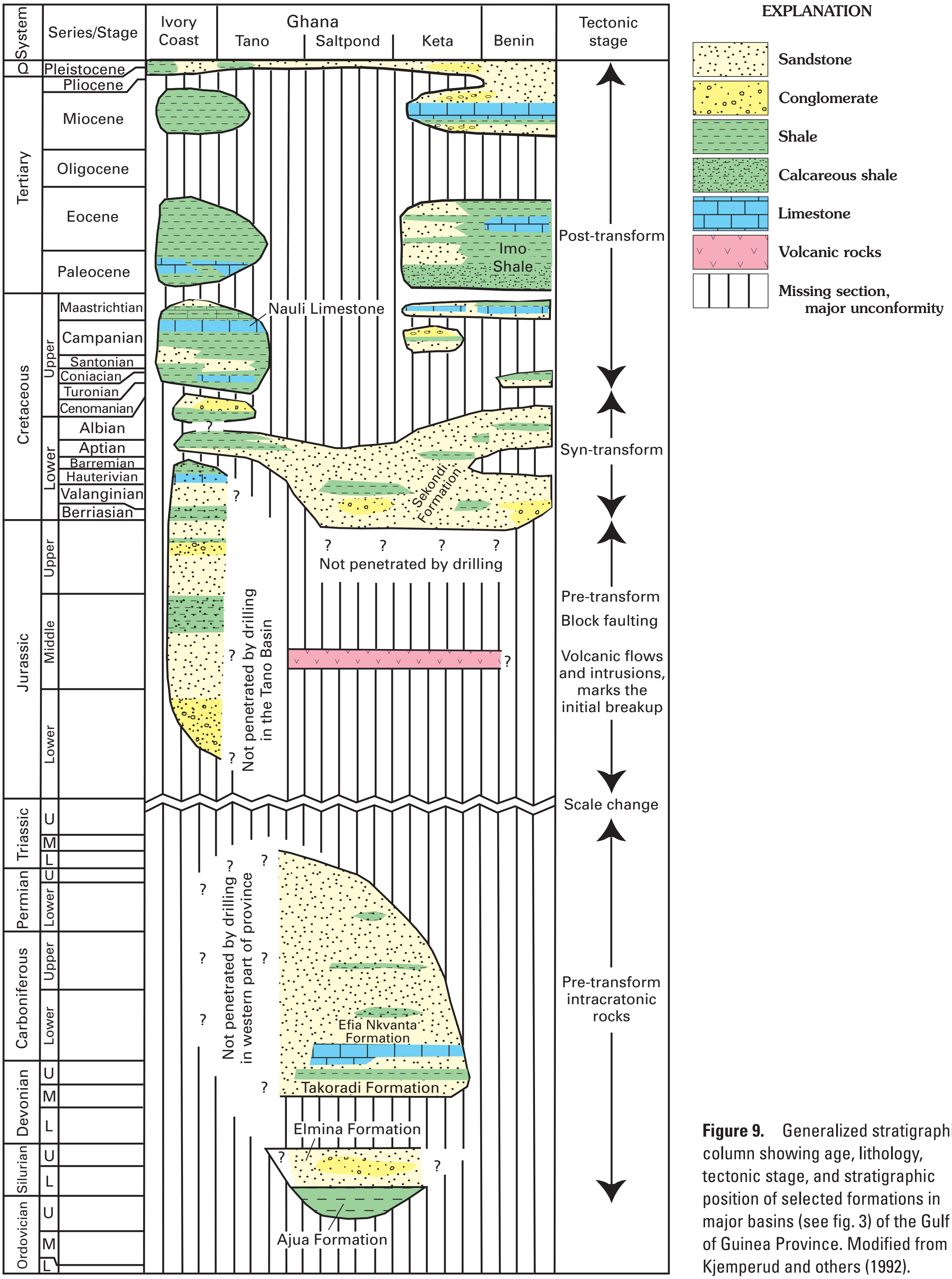
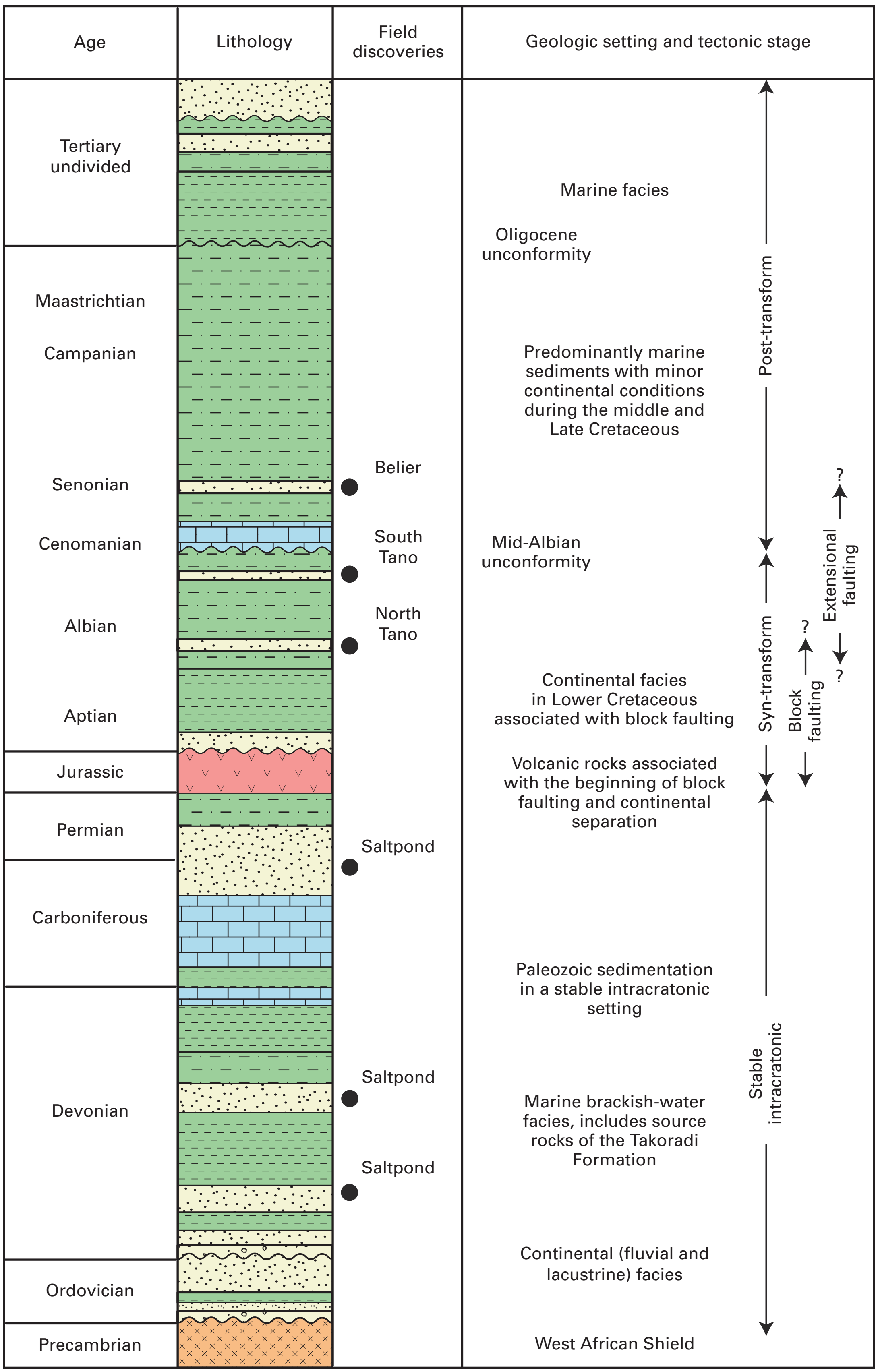


Figure 9. Generalized stratigraphic column showing age, lithology, tectonic stage, and stratigraphic position of selected formations in major basins (see fig. 3) of the Gulf of Guinea Province. Modified from Kjemperud and others (1992).



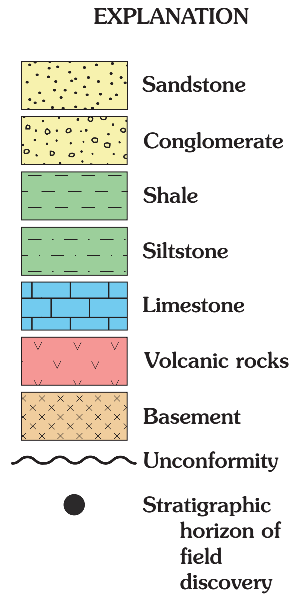
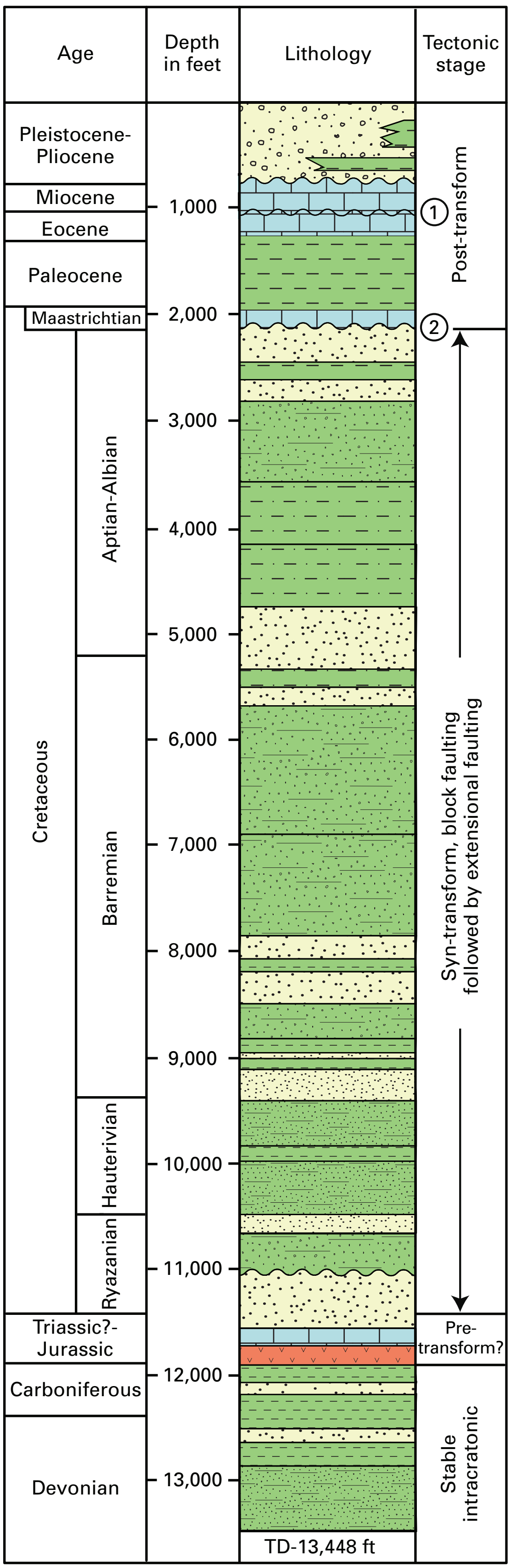


Figure 10. Generalized composite stratigraphic column showing age, lithology, approximate stratigraphic horizon of field discoveries, geologic setting, and tectonic stage for offshore and onshore parts of Saltpond and Tano Basins, Ghana, Gulf of Guinea Province. See figure 3 for location of field discoveries. The middle and upper parts of the Devonian section contain marine source rocks in the Takoradi Formation. See figure 9 for stratigraphic position of selected formation names. Modified from Tucker (1992). Cretaceous stage boundaries were not shown by Tucker (1992).



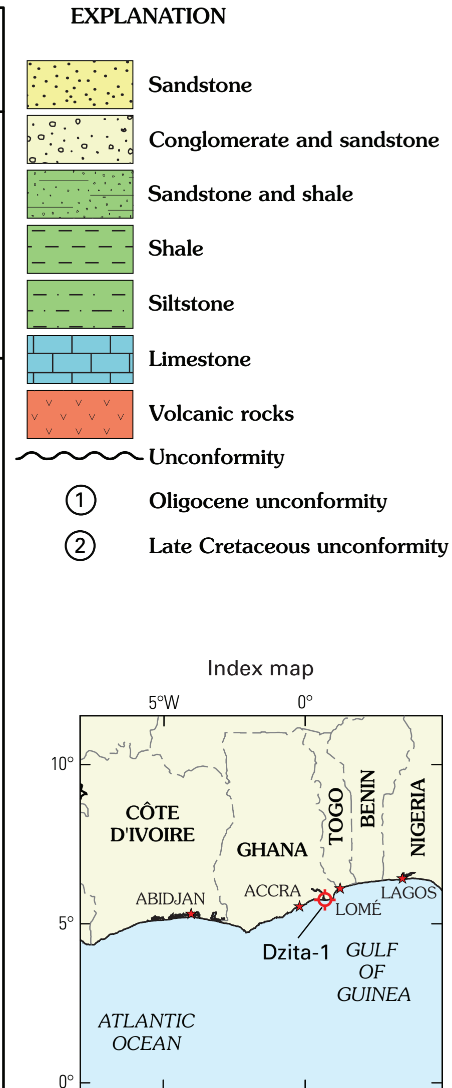


Figure 11. Generalized stratigraphic column showing age, depth, lithology, and tectonic stage of drill hole Dzita-1, Keta Basin, eastern Ghana. Jurassic volcanics represent the onset of block faulting in the province. Late Cretaceous unconformity at the base of the Maastrichtian represents a major period of erosion where it is estimated that more than 1,300 m of Upper Cretaceous (Albian to Campanian) rocks were removed. The middle Oligocene unconformity represents a period of erosion where as much as 390 m of Tertiary rocks was removed. Modified from Kjemperud and others (1992).

and Middle Jurassic rocks (fig. 9), consisting of thick beds of conglomerate and sandstone deposited in a continental setting, which were interpreted to be older than syn-transform-related volcanics (Kjemperud and others, 1992). Chierici (1996) also reported a sequence of rocks overlying the basement (figs. 13, 14) and below a thick section of syn-transform rocks in the basin.

The only Paleozoic rocks observed in the Tano Basin of eastern Côte d'Ivoire and western Ghana are Lower Carboniferous siliciclastic rocks (Tucker, 1992) penetrated in the CTS-1 well (fig. 3). Seismic data indicate that this sequence is underlain by strata equivalent to the Ordovician and Devonian rocks in the onshore part of the Saltpond Basin and the offshore part of the Keta Basin. The CTS-1 well Lower Carboniferous and underlying rocks represent the western limit of Paleozoic rocks in the Gulf of Guinea Province. Similar Paleozoic rocks crop out at Cape Three Points (fig. 3) and are present offshore.

Upper Jurassic pre-transform sedimentary rocks have not been identified with certainty in the Keta Basin (fig. 9) in eastern Ghana (Kjemperud and others, 1992), although the lower part of the continental Upper Jurassic to Lower Cretaceous Sekondi Formation (fig. 9) may correlate to the Upper Jurassic to Lower Cretaceous Ise Formation in the offshore part of the Benin Basin (fig. 15; Elvsborg and Dalode, 1985), and may represent the uppermost part of this stage. The Ise Formation contains conglomerates, sandstones, and shales which were deposited in continental and deltaic environments. The dating of the lower part of the Sekondi Formation is uncertain because of the fluvial depositional environments where preservation of

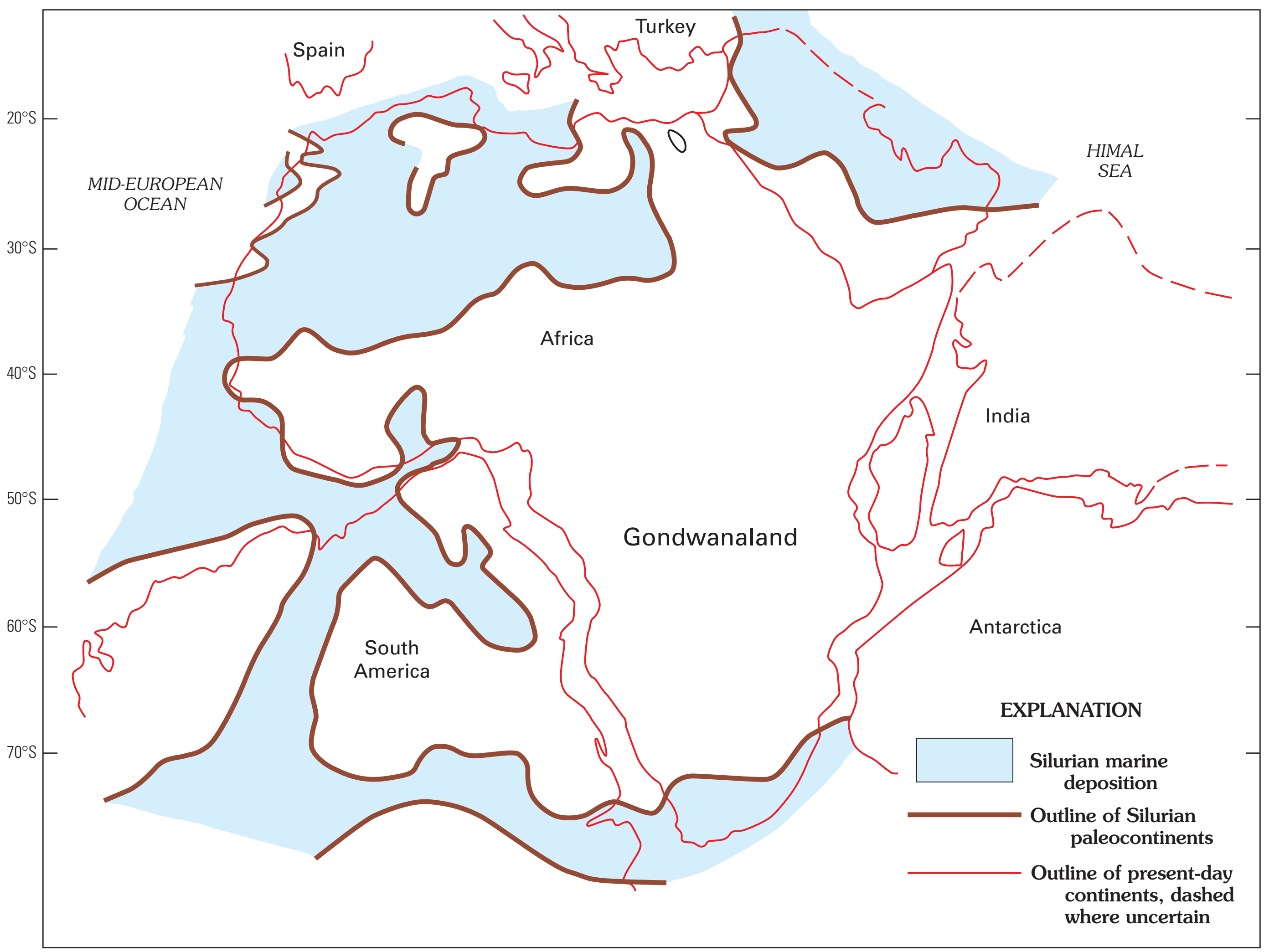


Figure 12. Paleogeographic reconstruction of the Silurian Period showing relative positions of paleocontinents and areas of deposition for marine Silurian rocks, of which oil-prone graptolitic shales constitute a major part. Outline of present-day continents shown in relative position with areas of known Silurian rocks. Modified from Clifford (1986).

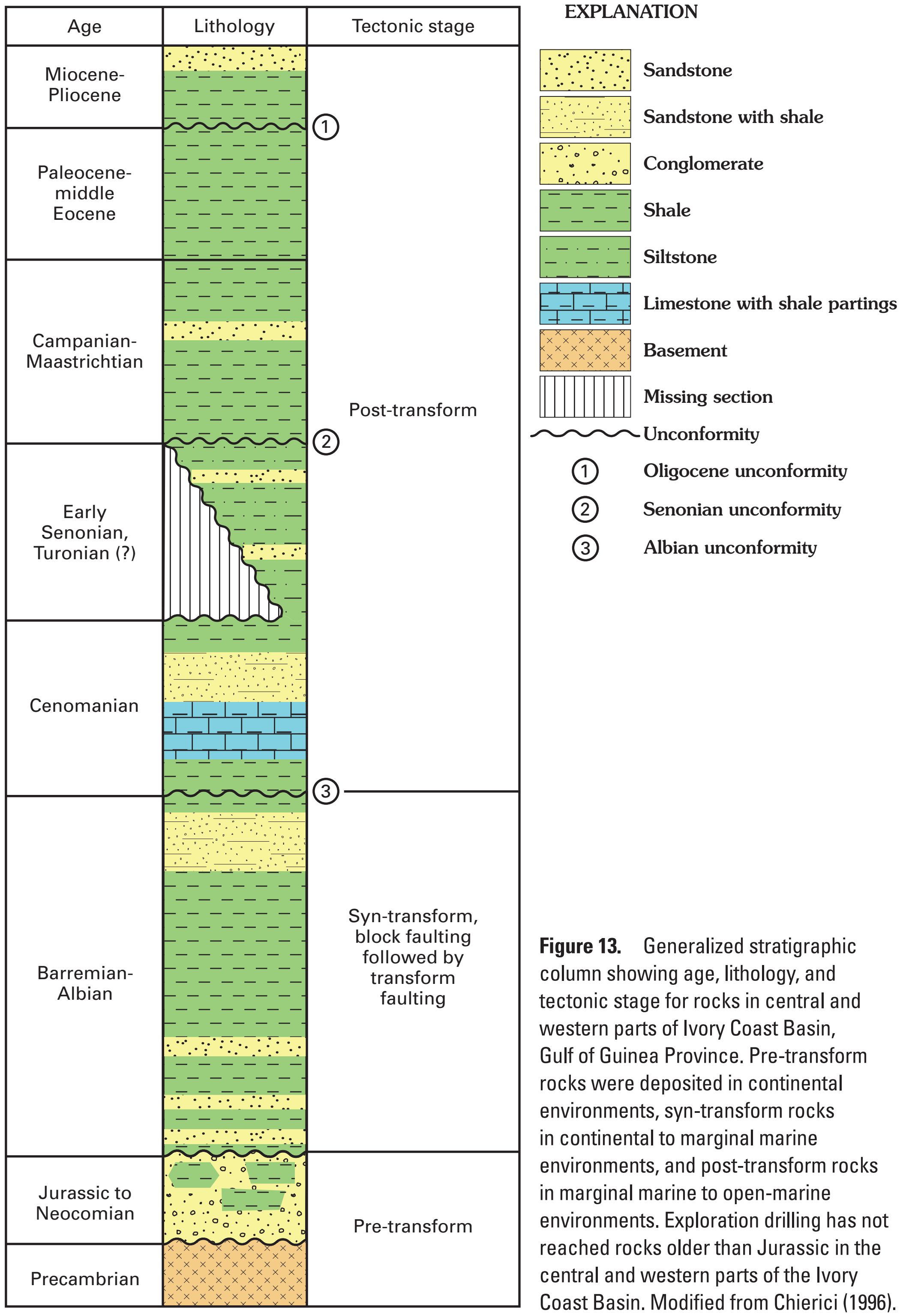
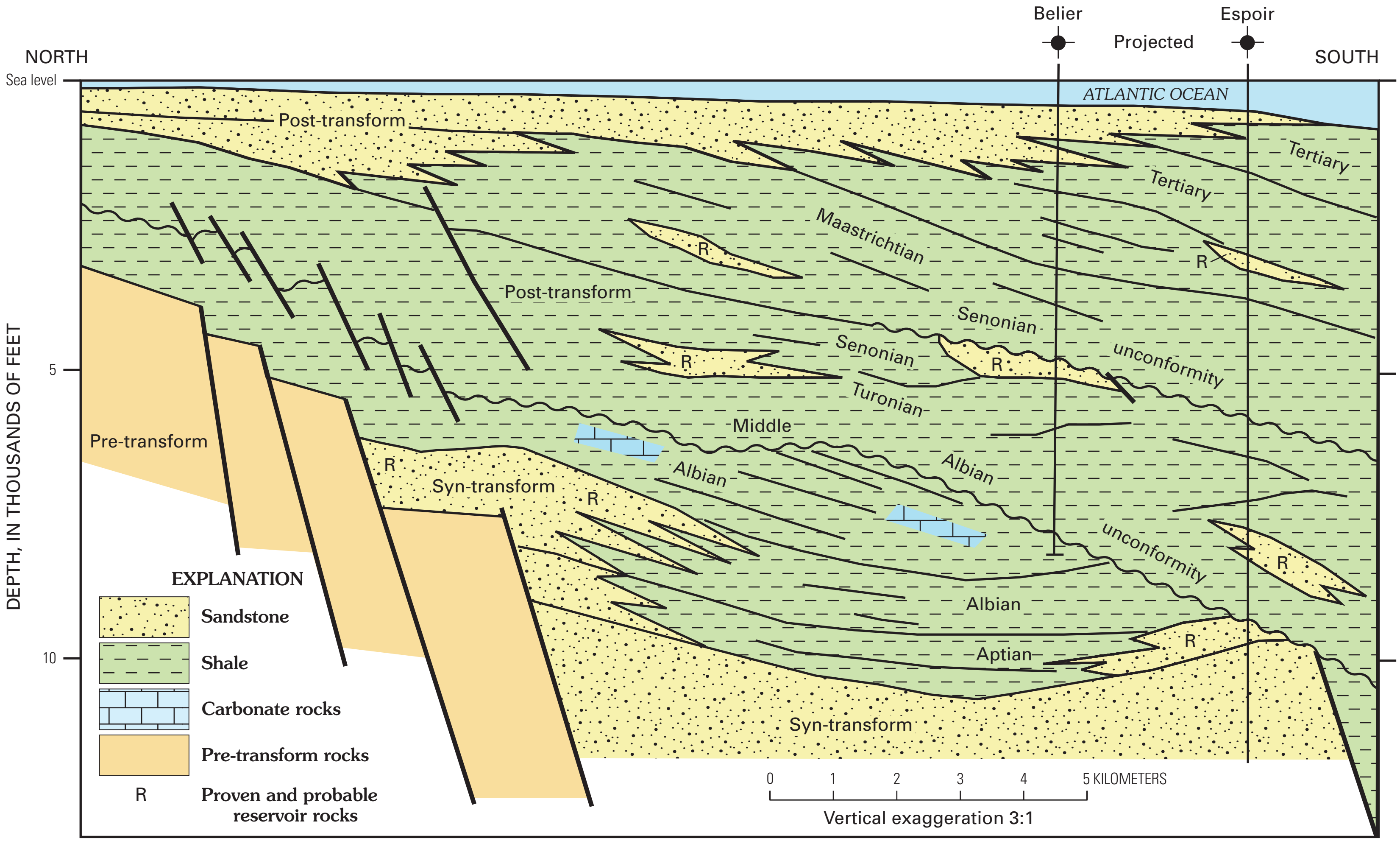


Figure 13. Generalized stratigraphic column showing age, lithology, and tectonic stage for rocks in central and western parts of Ivory Coast Basin, Gulf of Guinea Province. Pre-transform rocks were deposited in continental environments, syn-transform rocks in continental to marginal marine environments, and post-transform rocks in marginal marine to open-marine environments. Exploration drilling has not reached rocks older than Jurassic in the central and western parts of the Ivory Coast Basin. Modified from Chierici (1996).



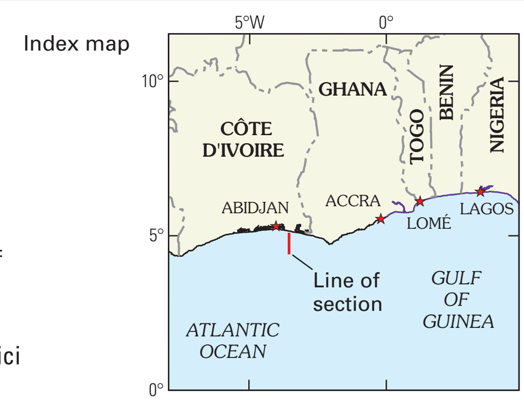


Figure 14. Schematic cross section across the Belier and Espoir fields in Ivory Coast Basin, Gulf of Guinea Province. The Senonian unconformity separates the continental and marginal marine syn-transform rocks from the post-transform or passive margin rocks. Espoir and Belier field discovery wells are projected into the section (see fig. 3). Modified from Clifford (1986), Kulke (1995), and Chierici (1996). Heavy black line, fault.

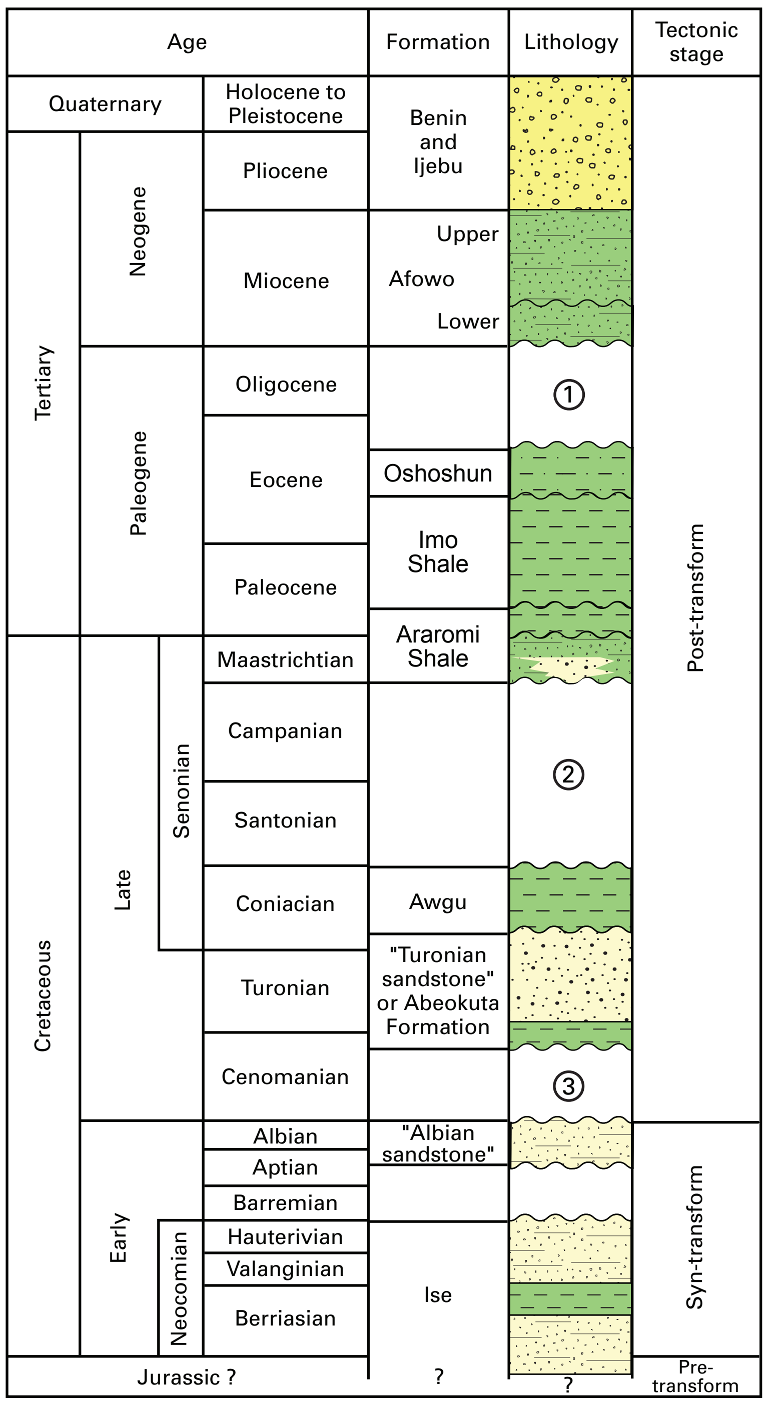
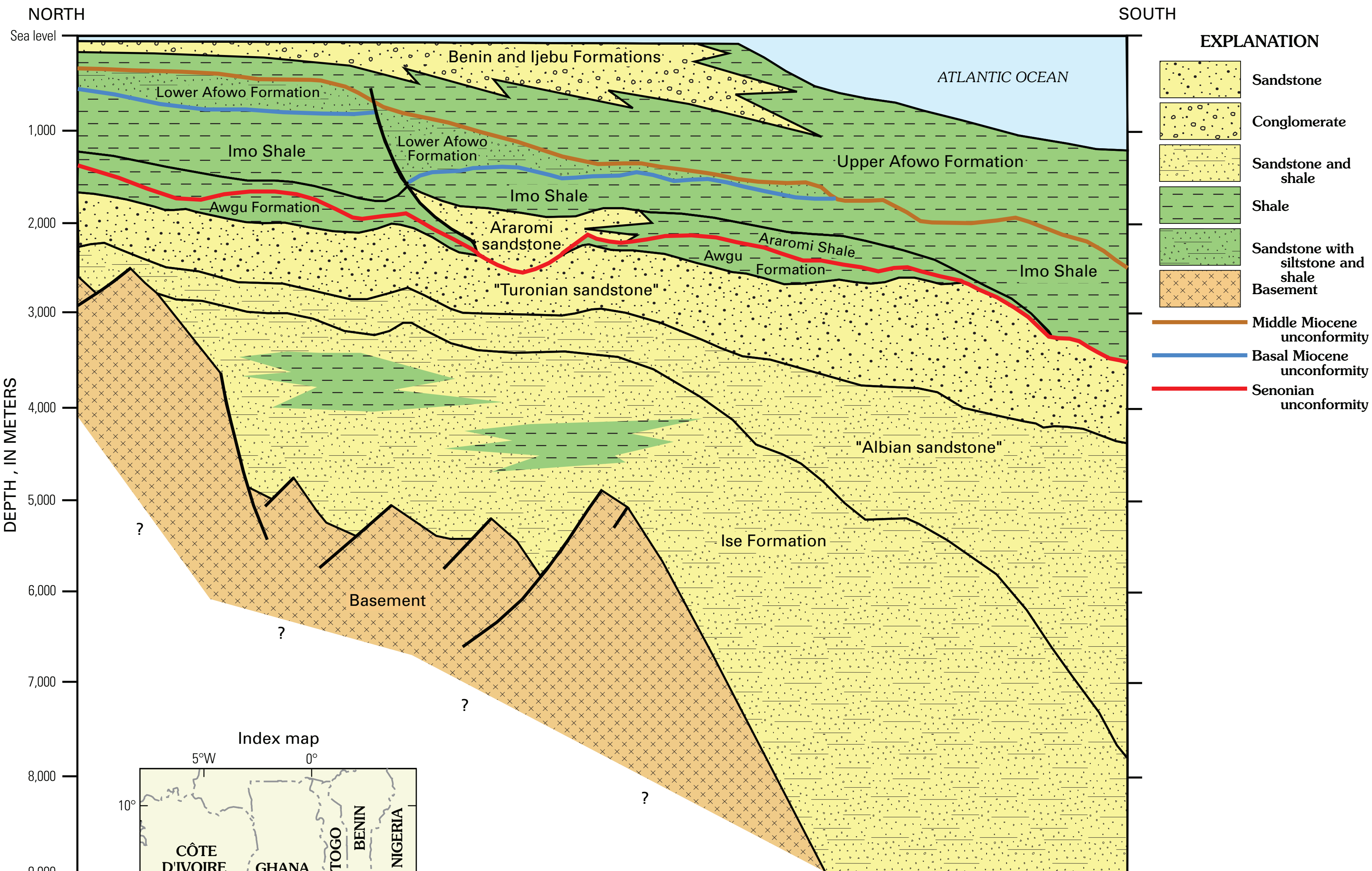


Figure 15. Generalized stratigraphic column for offshore part of Benin Basin, Gulf of Guinea Province. The lower part of the Ise Formation is considered to be Upper Jurassic and part of the pre-transform tectonic stage. The "Turonian sandstone" is also known as the Abeokuta Formation in Benin. Modified from Elvsborg and Dalode (1985) and MacGregor and others (2003).



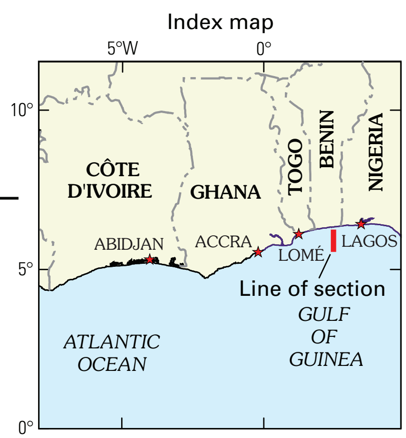


Figure 16. Generalized geoseismic cross section of offshore part of Benin Basin, Gulf of Guinea Province. The Albian unconformity at base of the "Turonian sandstone" is the top of the syn-transform rocks. The Senonian unconformity at base of the Araromi Shale is related to tectonism in the Benue Trough; the Miocene unconformity at base of the Upper Afowo Formation is related to a depositional hiatus from the Eocene to the Miocene. The Oshoshun Formation is included with the Imo Shale. Some unconformities are not shown. See figure 15 for stratigraphic positions of formations and unconformities. Modified from Elvsborg and Dalode (1985). Heavy line, fault. Basement extent queried where no data.

fossils is low. However, the pre-transform stage is interpreted to be largely a period of erosion and nondeposition in the Keta Basin. The eroded sediments were transported westward, and are most likely preserved as the Jurassic pre-transform rocks in the Tano and Ivory Coast Basins.

The pre-transform rocks in the Benin Basin and Dahomey Embayment are represented by the lower part of the Ise Formation (Dumestre, 1985; Elvsborg and Dalode, 1985; MacGregor and others, 2003). The Upper Jurassic to Neocomian Ise Formation (fig. 15), as much as 2,000 m thick, is composed of sandstone, shales, and conglomerate deposited in fluvial and deltaic environments. Drilling has not reached the base of the formation, but seismic data indicate that it directly overlies basement rocks (fig. 16) in the offshore part of the Benin Basin.

Syn-Transform Stage

Data on the age of volcanic intrusives associated with initial block faulting in Liberia, southern Sierra-Leone, and Ghana (fig. 3) indicate that faulting started no later than the Middle Jurassic and may be as old as Early Jurassic (Dumestre, 1985; Kjemperud and others, 1992). Continental syn-transform rocks in the Ivory Coast Basin (figs. 3, 9, 13) also show evidence that volcanic and fault activity may have started in the Early Jurassic. Orientation of the intrusives indicates that the initial fracturing and graben formation were subparallel to the present coastline. Block faulting and graben filling characterized the initial stage of tectonism, followed by transform or extensional faulting in the Gulf of Guinea.

The oldest Mesozoic syn-transform sedimentary rocks are extensive, continental Jurassic conglomerate and sandstone (Dumestre, 1985), with thicknesses as much as 2,000 m in the Ivory Coast Basin (location, fig. 3). A comparable sequence has not been penetrated by drilling in Ghana, indicating a period of nondeposition and (or) erosion in that area (Kjemperud and others, 1992). Drilling has not encountered rocks older than Jurassic in the Ivory Coast Basin.

During Neocomian, Aptian, and probably early and middle Albian time, more than 5,000 m (Chierici, 1996) of syn-transform sediments were deposited in continental to marginal marine environments in the Ivory Coast Basin (figs. 9, 13, 14). The oldest marginal marine strata are in the upper Albian, and the lack of evaporites in the Lower Cretaceous section indicates that in the Gulf of Guinea Province the syn-transform sediments were deposited in a humid equatorial climate.

Lowermost Cretaceous syn-transform sediments in the Tano and Saltpond Basins (figs. 3, 10) were deposited under mostly continental conditions (Kjemperud and others, 1992; Tucker, 1992), resulting in interbedded sandstone, shale, and limestone (figs. 9, 10). The environment became mostly marine during the late Aptian to early Albian, resulting in a syn-transform sequence of alternating sandstone and shale with some black shale, coarse sandstone, conglomerate, and minor limestone.

The Keta Basin of eastern Ghana (figs. 9, 11) contains syn-transform rocks of Early Cretaceous age (Kjemperud and others, 1992), including the Sekondi Formation (fig. 9), in both offshore and onshore areas. The Sekondi Formation consists of alternating red-brown to red sandstone, siltstone, and shale deposited in a continental environment. During the earliest Cretaceous, the basin underwent gradual subsidence, block faulting, and graben filling followed by extensional faulting. The Aptian to Albian rocks (fig. 9) are characterized by marine sandstone and shales with some organic-rich black shales, coarse sandstone and conglomerates, and minor limestone (Kjemperud and others, 1992). Graben filling continued until the middle of the Cenomanian, when uplift of the basin brought about extensive erosion and the peneplanation of the Gulf of Guinea Province. The Campanian is represented by marine sandstone, shale, and minor limestone and conglomerate (fig. 9). The unconformity at the base of the Maastrichtian in the Dzita-1 well (fig. 11) represents a major period of erosion, during which it is estimated that more than 1,300 m of Upper Cretaceous rocks were removed (Kjemperud and others, 1992).

In the Benin Basin (location, fig. 3), syn-transform rocks are represented by the Neocomian part of the Ise Formation (figs. 15, 16); they are composed of sandstone, shale, and conglomerate deposited in fluvial, lacustrine, and deltaic environments (Dumestre, 1985; Elvsborg and Dalode, 1985; MacGregor and others, 2003). The base of the formation has not been reached by drilling, but seismic data indicate that deposition was in a series of grabens and half grabens in the basin (fig. 16) and that the strata may be equivalent to the Lower Cretaceous rocks in the Keta Basin. The upper part of the Ise Formation contains lacustrine algae similar to those present in the lacustrine Bucomazi Formation of the Lower Congo Basin (Haack and others, 2000; Brownfield and Charpentier, 2006) in the West-Central Coastal Province of west Africa (fig. 4). The Ise Formation is unconformably overlain by the transgressive "Albian sandstone," which consists of sandstone with some interbedded shale (figs. 15, 16) and forms the upper boundary of the syn-transform stage in the Benin Basin (Elvsborg and Dalode, 1985).

The end of the syn-transform stage is delineated by a major unconformity, which separates it from the marine post-transform rocks of the uppermost Albian and Cenomanian (Dumestre, 1985; Kjemperud and others, 1992; Chierici, 1996; MacGregor and others, 2003). This major unconformity is also readily recognized in the Brazilian marginal basins, which supports the interpretation that the two continents were close to one another during the Early Cretaceous and that their geologic histories were similar during that time.

Post-Transform Stage

The post-transform stage rocks in the Gulf of Guinea Province consist predominantly of marine Cenomanian to Holocene sandstones, shales, and minor carbonate rocks (fig. 9) deposited in alternating regressions and transgressions (Dumestre, 1985; Chierici, 1996; Kjemperud and others, 1992;

MacGregor and others, 2003) that resulted in several Late Cretaceous and Tertiary unconformities (figs. 9–11, 13, 15). In general, continental-margin tectonics of the province's post-transform stage were driven by thermal subsidence (Kjemperud and others, 1992).

A marine transgression in the Ivory Coast Basin in the early Cenomanian (fig. 13) signaled the beginning of the post-transform stage, resulting in the deposition of limestone on fault-block crests and of organic-rich black shale and turbidites in the grabens (Dumestre, 1985; Chierici, 1996). Paleontological evidence indicates restricted water circulation and low oxygen content. Following this transgression, a middle Cenomanian regression and uplift resulted in erosion of the upper Albian to lower Cenomanian sequence in the eastern part of the Ivory Coast Basin (figs. 13, 14). During the regression more than 3,000 m of middle and upper Cenomanian sediments were deposited in the central and western parts of the basin, as evidenced by strata encountered in the Attoutu-1 well (fig. 3) in the northwestern part of the basin (Chierici, 1996). In the Turonian, a major transgression took place that established the first communication between Atlantic and Tethyan waters. Paleontological analysis indicates that restricted water circulation and a low oxygen content continued through the Turonian. Mainly marine shale with some sandstone characterizes the overlying Coniacian to Santonian interval (figs. 13, 14).

An episode of intense deformation occurred in the Benue Trough (fig. 6) at the end of the Santonian that was reflected by erosion and the development of a major unconformity (labeled "Senonian unconformity" in figs. 13, 14) in the east half of the Ivory Coast Basin (Dumestre, 1985; Chierici, 1996). Campanian rocks, predominantly shale with minor sandstone deposited during a transgression, lie unconformably on the older Cretaceous rocks. Paleontological evidence indicates improved bottom-water circulation, but the waters were still anoxic. The Maastrichtian is the interval best represented throughout the onshore part of the Ivory Coast, where it includes sandstone and shale deposited in fluvial and near-shore environments; on the continental shelf, it includes more marine facies.

The Paleocene sequence represents a major transgression in the Ivory Coast Basin, where it consists of glauconitic shale with sandy shale and minor limestone. These strata are overlain by lower and middle Eocene shales and marls with thin beds of limestone (Chierici, 1996), which, in turn, are overlain by a major unconformity (figs. 13, 14) that apparently developed in Oligocene time. Marine Miocene rocks lie above this unconformity in the offshore part of the Ivory Coast Basin, and no Oligocene rocks have been identified in offshore exploration wells.

The Tano Basin is located in the easternmost part of the Ivory Coast Basin (fig. 3), and the post-transform period in the Tano Basin generally has the same tectonic and stratigraphic history as the rest of the Ivory Coast Basin. Post-transform continental margin tectonism was driven by thermal subsidence, beginning in the Cenomanian (figs. 9, 10) with the first marine transgression into the Gulf of Guinea Province. The marine waters most likely inundated the remaining syn-transform block faulted terrain. The Cenomanian rocks include sandstone, shale, siltstone, mudstone, and limestone (Kjemperud and others, 1992; Tucker, 1992); black shale and limestone were deposited on the crests of the horsts, whereas turbidites accumulated in the grabens. Turonian to Maastrichtian rocks (fig. 9) include marine sandstone, shale, limestone, and minor conglomerates (Kjemperud and others, 1992). Major unconformities bound the Cenomanian to Maastrichtian rocks in the Tano Basin as in the Ivory Coast Basin. The unconformably overlying Tertiary rocks are marine sandstone, shale, and limestone. The regional Oligocene unconformity is present in the Tano Basin (figs. 9, 10) separating Miocene from the underlying Eocene rocks.

Post-transform rocks range in age from Campanian to Holocene in the Keta Basin (figs. 9, 11, 17). Campanian strata, including marine and continental conglomerate, sandstone, shale, and limestone (fig. 9), unconformably overlie Albian syn-transform rocks, and are unconformably overlain by Maastrichtian rocks. The Maastrichtian includes limestone and shale with sandstone and claystone deposited in a marine environment; these strata grade into continental clastics eastward toward the Benin Basin. Tertiary post-transform rocks unconformably overlie the Maastrichtian rocks, and include Paleocene to Eocene marine shale interbedded with sandstone, siltstone, and limestone. These rocks are separated from the upper Miocene marine sandstone, conglomerate, shale, and limestone (fig. 9) by a major Oligocene to Miocene unconformity. During the erosional period represented by this unconformity, as much as 365 m of Tertiary rocks (Kjemperud and others, 1992) was removed, as evidenced by the stratigraphic sequence penetrated in the Dzita-1 and Keta-1 wells (figs. 3, 11, 17). An unconformity separates the upper Miocene and lower Pliocene in parts of the onshore and shallow shelf (fig. 9). The Pliocene to Holocene offshore units consist of unconsolidated sands and muds.

The Cenomanian to Santonian part of the post-transform stage in the Benin Basin and Dahomey Embayment was influenced by transform or extensional faulting, and also was affected by deformation that took place during the Santonian in the Benue Trough to the east (fig. 6; Elvsborg and Dalode, 1985); these episodes of tectonic activity resulted in the development of the Senonian unconformity in the Benin Basin (figs. 15, 16). The "Turonian sandstone" (fig. 15) consists of a gray to white coarse-grained, poorly sorted sandstone interbedded with thin shale beds overlying a shale and siltstone sequence deposited as a reworked fan delta in a marginal marine to inner shelf environment. The "Turonian sandstone" unconformably overlies the syn-transform "Albian sandstone" and is the oldest post-transform unit in the Benin Basin. It is present over the entire Benin Basin, and, in places, directly overlies crystalline basement. The depocenter is located in the eastern part of the basin, where thicknesses are as much as 1,000 m; the unit thins to the north and west. The Miocene unconformity cuts out the "Turonian sandstone" beyond the shelf edge, whereas the Senonian unconformity cuts into the unit in the eastern part of the shelf and along the shelf edge (Elvsborg and Dalode, 1985).

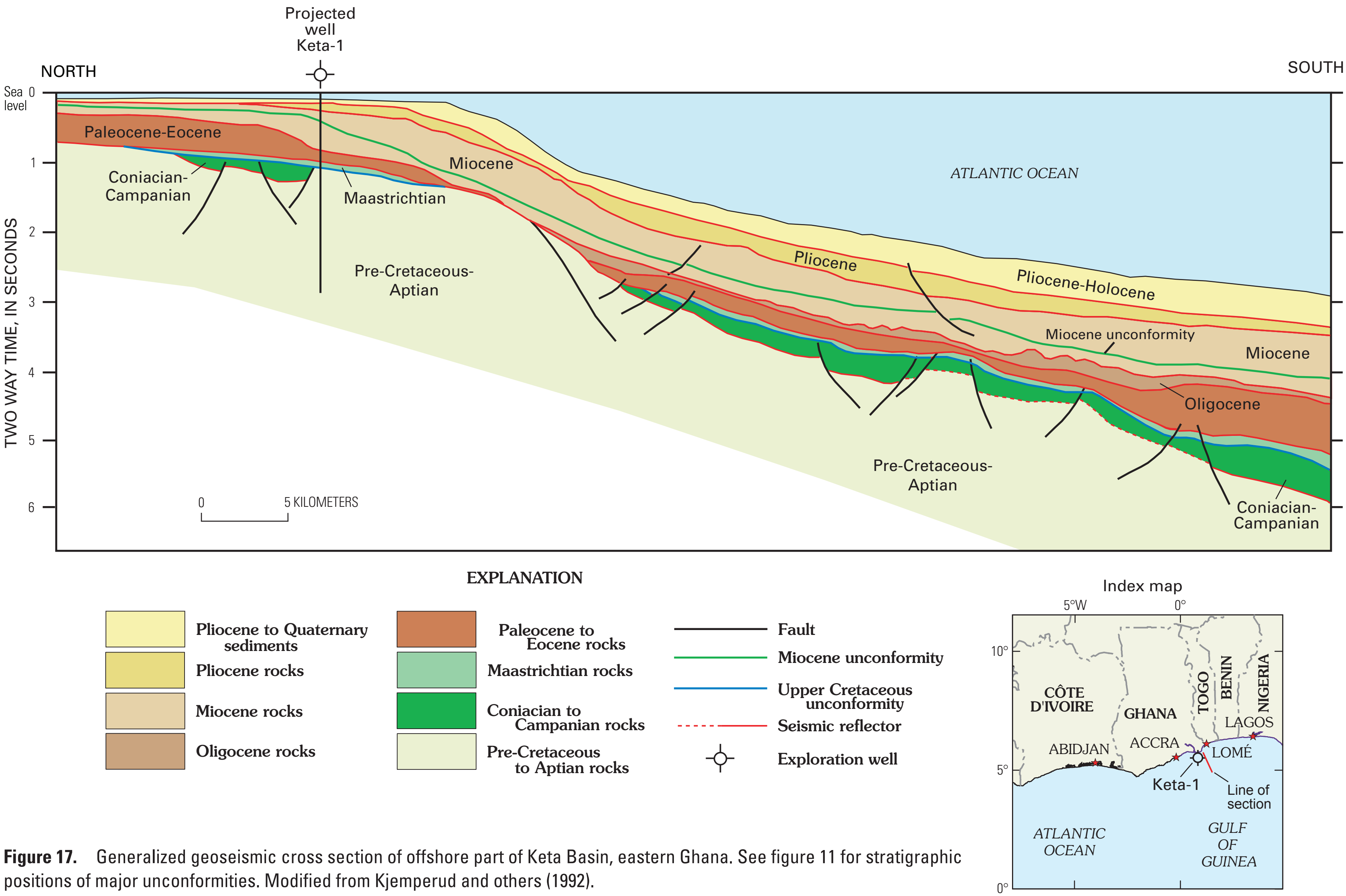


Figure 17. Generalized geoseismic cross section of offshore part of Keta Basin, eastern Ghana. See figure 11 for stratigraphic positions of major unconformities. Modified from Kjemperud and others (1992).

The Coniacian Awgu Formation (fig. 15), which is present over most of the Benin Basin, unconformably overlies the "Turonian sandstone." The formation, consisting of dark-gray calcareous shale interbedded with calcareous siltstone and fine-grained sandstone, was deposited in an anoxic marine environment; below the Senonian unconformity (fig. 15), it is preserved in grabens. Six Maastrichtian to Holocene post-transform stratigraphic units have been identified in the Benin Basin (fig. 15): (1) the Maastrichtian to Paleocene Araromi Shale; (2) the Paleocene to Eocene Imo Shale; (3) the Eocene Oshoshun Formation; (4) the Miocene Afowo Formation; (5) the Pliocene Benin Formation; and (6) the Pliocene(?) to Holocene Ijebu Formation. The units become coarser grained toward the top and include argillaceous sandstone and siltstone, and shale. Sediment transport was from the north, and rapid sedimentation rates initiated growth faults (Elvsborg and Dalode, 1985) that sole out in most cases in the Araromi Shale. A depositional hiatus from the late Eocene through the Oligocene resulted in a major unconformity between the Eocene Imo and Oshoshun Formations and Miocene Afowo Formation (figs. 15, 16). A second Miocene unconformity separates the lower and upper members of the Afowo Formation.

Petroleum Occurrences in the Gulf of Guinea Province

Oil and gas occurrences in the Gulf of Guinea Province are concentrated in Cretaceous reservoirs on the continental shelf and adjacent onshore extensions in two basin areas (fig. 3): (1) the Ivory Coast to Tano Basins (Espoir field) of Côte d'Ivoire and Ghana, and (2) the Keta Basin (Lomé discovery) to the Benin Basin (Aje field) of westernmost Nigeria. These areas are associated with oil seeps and tar sand accumulations along Upper Cretaceous outcrops west of Cape Three Points (fig. 3) in the onshore parts of the Ivory Coast and Tano Basins, and in the Dahomey Embayment from Togo to western Nigeria. Most discoveries in the province to 1995 have been located in water depths less than 500 m. Oil has also been produced from Devonian to Carboniferous Takoradi Formation sandstones sourced from Devonian shales in the Saltpond field (figs. 3, 10).

Hydrocarbon Source Rocks

The oldest hydrocarbon source rocks in the Gulf of Guinea Province are postulated to be shales in the Middle to Upper Devonian Takoradi Formation (figs. 9, 10) in the Saltpond Basin and field (fig. 3) of western Ghana (Kjemperud and others, 1992). These source rocks were deposited in a brackish marine environment. Oils from the Lomé field in Keta Basin (fig. 3) are interpreted to be sourced from correlative Devonian shales (MacGregor and others, 2003), and seismic data indicate that similar source rocks are preserved in the Tano Basin (Tucker, 1992). Upper Albian reservoirs in Sémé and Aje fields (fig. 3) may also have been sourced from Devonian shales (MacGregor and others, 2003), as the alternative of an Upper Cretaceous source (see paragraph on anoxic conditions) seems unlikely.

Oil seeps in outcrops of the Upper Cretaceous tar sands in the northern Dahomey Embayment are interpreted to be sourced by Neocomian lacustrine strata (fig. 15), such as were drilled into in the Ise-2 well (Haack and others, 2000). These source rocks contain Type I kerogen, with total organic carbon (TOC) contents as much as 4 percent and the richest source-rock intervals having hydrogen indices (HI, mg (milligrams) hydrocarbon/g (grams) organic carbon) greater than 500. The geochemical characteristics are similar to those of the lacustrine source rocks in the Neocomian Bucomazi Formation of the Lower Congo Basin in the West-Central Coastal Province (fig. 4). Lower Cretaceous lacustrine strata are identified as far west as the Ivory Coast Basin (fig. 13) and may include similar source rocks (Elvsborg and Dalode, 1985).

Lower to middle Albian gas-prone source rocks have been identified in the Ivory Coast and Tano Basins (MacGregor and others, 2003) (figs. 9, 10, 13). These source rocks are part of a sequence consisting of as much as 5,000 m of Lower Cretaceous continental to marginal marine rocks deposited in grabens in the Ivory Coast and Tano Basins (Chierici, 1996). Similar source rocks are likely present in the Keta and Benin Basins (figs. 9, 11, 17).

Anoxic oceanic conditions that characterized the middle Cretaceous worldwide also affected the Gulf of Guinea during the Cenomanian (fig. 5), resulting in the deposition of the sediments forming the Albian and Cenomanian black shale source rocks in the Ivory Coast and Tano Basins. This depositional event marks the first marine transgression in the Gulf of Guinea and was accompanied by a decrease in rate of subsidence in the province. Anoxic conditions continued into the Turonian. Samples analyzed from deep sea drilling sites both north and south of the Gulf of Guinea indicate that these source rocks (fig. 13) contain more than 10 weight percent organic matter consisting of Type II kerogen. In contrast, the Dahomey Embayment and Benin Basin are characterized by nonmarine to marginal marine conditions with the deposition of coarse sandstone and interbedded shale and carbonaceous shale (fig. 9) representing the last "land bridge" during the opening of the Atlantic Ocean (Chierici, 1996). Middle Cretaceous source rocks in this area are expected to contain gas-prone Type III kerogen.

The Coniacian Awgu Formation, the Maastrichtian Araromi Shale, and the Paleocene to Eocene Imo Shale (fig. 15) contain marine source rocks in the offshore part of the Benin Basin. These source rocks contain Type II and Type II-III kerogen with TOC contents ranging from 2 to more than 5 weight percent; they were deposited from the northwestern part of the Niger Delta westward to the Keta Basin (Haack and others, 2000). The richest source rock intervals have hydrogen indices greater than 500. Coniacian to Paleocene rocks are present in the offshore part of the Keta Basin (fig. 17) and may contain Type II and Type II-III source rocks similar to those in the Benin Basin.

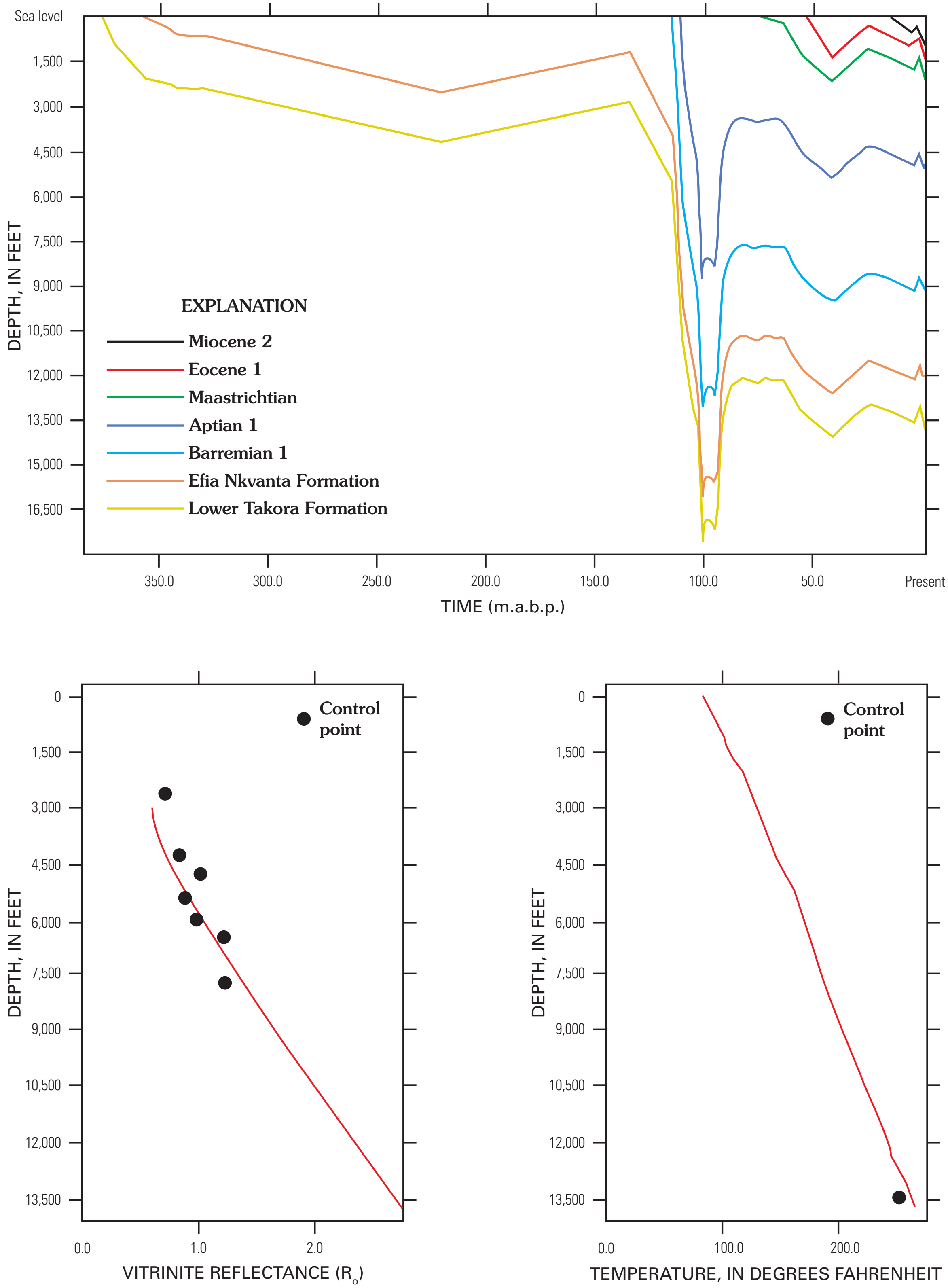


Figure 18. Modeled burial history curves and vitrinite reflectance and temperature plots of Dzita-1 well (figs. 3, 11) in Keta Basin, Ghana (fig. 3). Factoring in major erosion in the Cretaceous and minor erosion in the Tertiary produces a good fit with measured R_o values. Total amount of erosion was 1,800 m. Modified from Kjemperud and others (1992); (m.a.b.p.), millions of years before present.

Hydrocarbon Generation and Migration

The most important hydrocarbon generation within the Gulf of Guinea Province is from the upper Albian and Cenomanian source rocks, which are distributed throughout the offshore part of the province; these strata are expected to increase in thickness and source rock quality into deep water. Two main areas of hydrocarbon generation were interpreted by MacGregor and others (2003) to exist in the province: (1) the offshore parts of the Ivory Coast and Tano Basins and (2) the offshore parts of the Keta and Benin Basins and the Dahomey Embayment (fig. 3) eastward to the Niger Delta (fig. 7) just east of the Gulf of Guinea Province. These two probable oil kitchens are only present in the deep-water parts of the province, where the source rocks have reached a temperature of at least 100°C and a vitrinite reflectance (R_o) of 0.6 percent (MacGregor and others, 2003), which are values equivalent to having source rocks subjected to about 2,700 m of overburden. The source of hydrocarbon generation in the Saltpond Basin, which lies between the two areas of generation just listed, is more problematic, and may involve deeper source rocks, such as the Devonian Takoradi Formation and Lower Cretaceous lacustrine rocks. Hydrocarbon generation started in the Late Cretaceous and continues to the present in the Ivory Coast and Tano Basins, whereas hydrocarbon generation started in the late Miocene and continues to the present in the Keta and Benin Basins and Dahomey Embayment (fig. 3) eastward to the Niger Delta (fig. 7).

Examples of a burial-history curve and R_o and temperature plots of the Dzita-1 well in the Keta Basin are shown in figure 18. This well was drilled in 1973 to test the hydrocarbon potential of Devonian and Cretaceous sandstones; figure 11 shows the stratigraphic sequence recorded in the drilling, as interpreted by Kjemperud and others (1992). A model of the burial history that factors in both a major Cretaceous (middle Albian) unconformity and a minor Tertiary (Oligocene) unconformity, marking time intervals during which 1,300 m and 360 m of material, respectively, are estimated to have been removed by erosion, indicates a good fit with the measured R_o values (fig. 18). This model is in agreement with the maturity mapping of the Cretaceous unconformity by MacGregor and others (2003), who placed the top of the oil-generation window (R_o about 0.6) at about 2,700 m below the sea bed.

At least two areas of hydrocarbon generation related to Lower Cretaceous lacustrine source rocks are present in the Gulf of Guinea Province (Haack and others, 2000; MacGregor and others, 2003). These areas are associated with oil seeps and tar sand accumulations along Upper Cretaceous outcrops west of Cape Three Points in the onshore parts of the Ivory Coast and Tano Basins as well as in the Dahomey Embayment (fig. 3); in particular, there are large in-place volumes of hydrocarbons in the eastern tar belt of the Dahomey Embayment. The total tar-belt volumes likely exceed the published reserves of any field in the Gulf of Guinea Province including the largest, which is Espoir field in the Ivory Coast Basin, whose reported field size is 400 million barrels (MacGregor and others, 2003). Hydrocarbon generation began in the Late Cretaceous and may be active to the present.

Hydrocarbon Reservoirs, Traps, and Seals

The oldest proven reservoir rocks in the Gulf of Guinea Province are Devonian to Carboniferous sandstone beds in the Saltpond field in Ghana (fig. 3). The sands forming the Devonian reservoirs were deposited in shallow to restricted marine environments, whereas those forming the Carboniferous reservoirs were deposited in a fluvial environment.

Seismic data indicate that a thick Lower Cretaceous syn-transform section in the offshore part of the Benin Basin contains probable sandstone reservoir units (Elvsborg and Dalode, 1985) deposited in fluvial to deltaic environments. Sandstone units with favorable reservoir characteristics have been encountered below the “Albian sandstone” (fig. 15) in drilling in the Sémé field (fig. 3). Similar reservoir rocks may exist westward across the province; for example, as much as 5,000 m of Lower Cretaceous continental to marginal marine sandstone and shales (fig. 9) was deposited in the Ivory Coast Basin (Chierici, 1996). Similar reservoir rocks should also be present in the Keta and Tano Basins (fig. 9).

Stratigraphic units that contain proven reservoirs in the shallow-water discoveries in the Gulf of Guinea Province are mainly late syn-transform Albian sandstones and Cenomanian to Maastrichtian post-transform marginal marine and turbidite clastic rocks. Clastic Albian rocks are the dominant reservoir type in the Espoir and Belier fields (fig. 3) in the Ivory Coast Basin and are also known in the Tano and Keta Basins. These rocks are interpreted to have been deposited in several different depositional settings, including lacustrine, fluvial through fluviodeltaic, and marginal marine to marine and submarine fans. Marginal marine to marine upper Albian sandstone reservoirs in the Ivory Coast Basin (fig. 13) contain the best petrophysical qualities, with porosities as much as 25 percent and permeabilities in the hundreds of millidarcies (MacGregor and others, 2003). Many of the sandstone reservoirs are characterized as being laterally discontinuous and exhibiting variable petrophysical properties across short distances. Similar Albian reservoirs have been penetrated in the Tano and Keta Basins (figs. 10, 11) below the mid-Albian unconformity (Kjemperud and others, 1992; MacGregor and others, 2003). Only the transgressive “Albian sandstone” represents the marine Albian interval in the offshore part of the Benin Basin (fig. 15), and the upper Albian section is missing (Tucker, 1992). The potential middle Albian reservoir rocks in the Ivory Coast Basin were deposited in a fluvial continental environment and are characterized by poorer petrophysical qualities.

A steep shelf began to develop during the Cenomanian along the continental margin of the Gulf of Guinea Province. MacGregor and others (2003) speculated that several south-flowing rivers supplied clastics to the continental margin prior to their capture by the ancestral Niger River. These rivers—for example, a large ancestral Tano River in western Ghana and a major south-flowing river in the Benin Basin—would have drained extensive areas to the north during the early post-transform period in the province and deposited large amounts of clastic sediment during the Cenomanian to Maastrichtian (Elvsborg and Dalode, 1985; Tucker, 1992; MacGregor and others, 2003) now represented by the "Turonian sandstone" (figs. 15, 16) or the equivalent Abeokuta Formation (fig. 15). The downslope projections of deltas that were formed at that time would be prospective for probable turbidite channel and ponded turbidite sandstone reservoirs (fig. 14). Because the continental shelf is steep and was subjected to several low stands along the continental margin, conditions favored the deposition of detached, deep-water sandstone units, ponded turbidite sands, and clastic fans (fig. 14). Recent seismic data indicate that large turbidite channels developed in the Ivory Coast Basin during the Maastrichtian (MacGregor and others, 2003). The presence of large turbidite channels supports the interpretation that large fans or detached sandstone bodies may lie in the deeper parts of the basin. In general, reservoirs in the early post-transform section are likely to be of better quality than those in the syn-transform section.

Seismic data indicate that the Tertiary section has fewer reservoirs than the Cretaceous section in the Gulf of Guinea Province. Some slope fans have been identified in the Araromi Shale (fig. 15; Elvsborg and Dalode, 1985) in the overlying section above the regional Maastrichtian unconformity (MacGregor and others, 2003). The Araromi sandstone unit (fig. 16) has been interpreted as a slope fan in the Benin Basin. Other probable reservoir rocks could be present in the deep-water part of the continental margins in the form of detached sandstone units resulting from ponded turbidite sands (fig. 14).

Proven hydrocarbon accumulations associated with fault-block traps (fig. 19) are in the upper part of the syn-transform section throughout the Gulf of Guinea Province in shallow to moderate water depths (MacGregor and others, 2003). This trap type characterizes both the Espoir field (Grillot and others, 1991) and the Tano field (fig. 3; MacGregor and others, 2003), and extends offshore onto the continental slope. Fault-block traps are also along the Romanche fracture zone (fig. 3) and in the western part of the Ivory Coast Basin, including the 2001 Baobab deep-water discovery.

Syn-transform anticlinal traps (fig. 19), detected only from seismic data and as yet untested, are associated with the terminations of regional fracture zones in two areas: (1) the offshore parts of the Dahomey Embayment and Keta Basin, and (2) the western offshore part of the Ivory Coast Basin (MacGregor and others, 2003). Proven hydrocarbon accumulations associated with post-transitional anticlinal traps are in the Tano Basin and the eastern part of the Ivory Coast Basin (fig. 3) in the Belier field.

Known hydrocarbon accumulations are associated with erosional channel-fill traps (fig. 19) in the post-transform section of the Gulf of Guinea Province in both shallow- and deep-water areas (MacGregor and others, 2003). This type of trap characterizes the Aje field of westernmost Nigeria (fig. 3), where the west end of the reservoir is sealed by a shale-filled channel. Seismic data indicate that undrilled channel-erosion traps are commonly associated with the regional Oligocene unconformity from Benin westward, in the deep-water part of the province.

Seismic data indicate that syn-transform ponded turbidites lying directly above the upper Albian unconformity in the western part of the Ivory Coast Basin (MacGregor and others, 2003) could be trapped against existing faults (fig. 19). Ponded turbidite traps are also observed as detached sandstone bodies in the post-transform section in the Ivory Coast, Keta, and Benin Basins, where stratigraphic trapping and updip seals are the critical factors in defining potential targets. Some of the high-amplitude traps associated with the late Albian unconformity may be limestone units located on syn-transform highs (Kjemperud and others, 1992; MacGregor and others, 2003).

Untested stratigraphic traps consisting of mounded sandstones and channels interbedded with the Cenomanian source rocks are interpreted from seismic data in the post-transform section in the Gulf of Guinea Province (fig. 19). Thick and extensive sandstone units were observed by MacGregor and others (2003) above the late Albian unconformity, covering areas of more than 80 km^2 in the deep-water parts of the province, where the shelf is steeper and a greater probability exists for detached sandstone units and up-dip seals. An example of a stratigraphically sealed channel is Dana's (British Independent) Maastrichtian West Tano oil discovery (figs. 3 and 19).

Seals associated with syn-transform reservoirs are formed by both shales and faults (fig. 19), whereas the seals associated with post-transform reservoirs are generally shales.

Total Petroleum Systems of the Gulf of Guinea Province

At least five total petroleum systems (TPS) exist in the Gulf of Guinea Province (7183): (1) the Lower Paleozoic TPS, consisting of Devonian source rocks and Devonian to Lower Cretaceous reservoir rocks; (2) the Lower Cretaceous TPS, consisting of Lower Cretaceous lacustrine source rocks and Cretaceous reservoir rocks; (3) the middle Albian Terrestrial TPS, consisting of gas-prone source rocks and Albian reservoir rocks; (4) the upper Albian TPS, consisting of marine transgressive oil-prone source rocks and Albian reservoir rocks; and (5) the Cenomanian-Turonian TPS, consisting of open marine oil-prone source rocks and Albian to Upper Cretaceous reservoir rocks. The three youngest systems were combined into the Cretaceous Composite TPS consisting of Albian to Turonian marine and terrestrial source rocks and Cretaceous reservoir rocks. Only limited exploration and production information is available for the Lower Paleozoic TPS and Lower Cretaceous TPS. Oil production from the Lower Paleozoic TPS is limited to the Saltpond and Lomé fields (fig. 3), whereas Lower Cretaceous TPS oils have only been identified in Upper Cretaceous tar sands and oil seeps at Cape Three Points and the Dahomey Embayment. Only the Cretaceous Composite TPS was

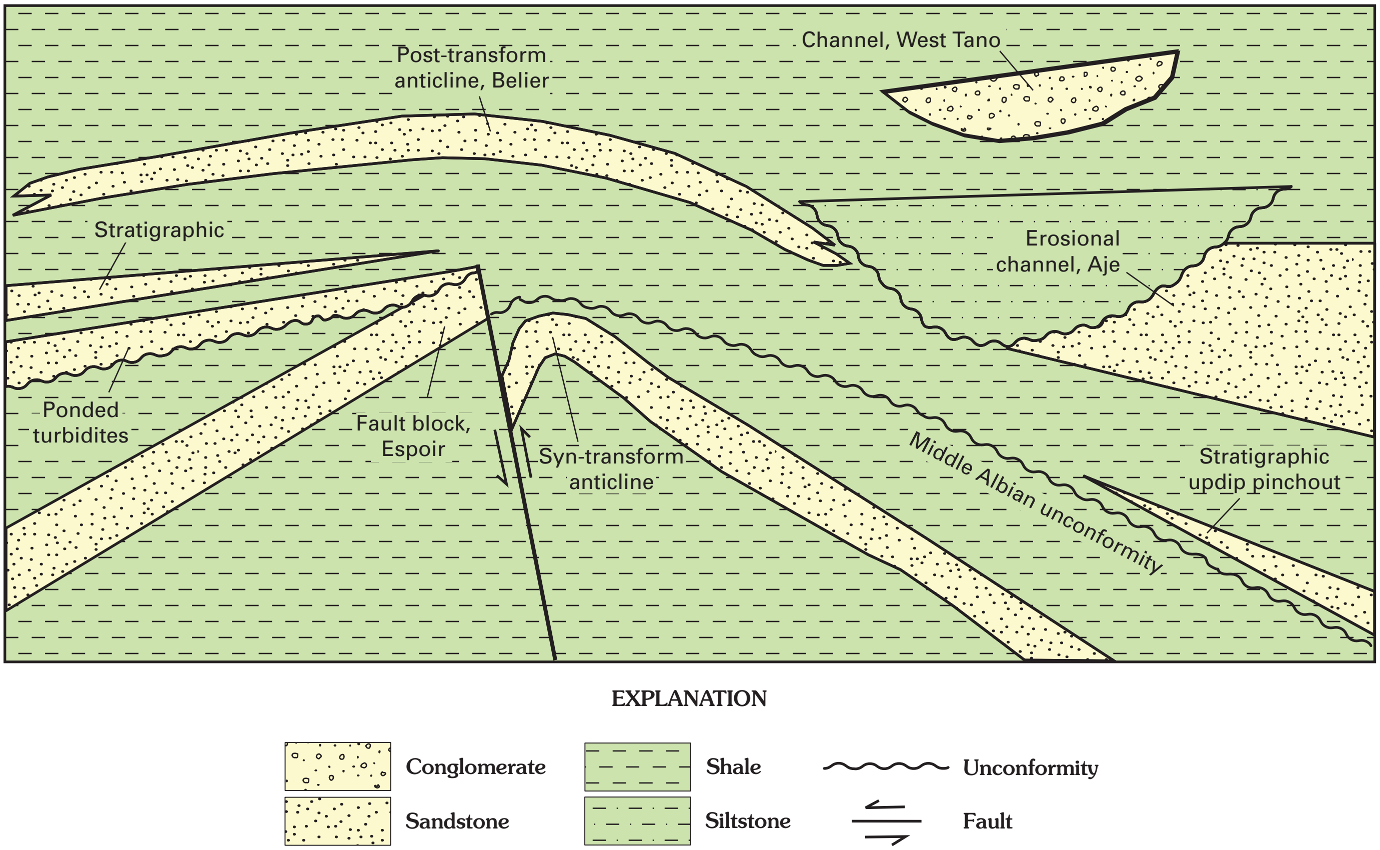


Figure 19. Schematic cross section showing common trap types and oil- and gas-field analogs (see fig. 3) in Gulf of Guinea Province. Many of the traps are present only in the deep-water parts of the province and have not been tested. Barbs on fault (heavy line) show relative movement. Modified from MacGregor and others (2003). No scale.

considered for assessment, because (1) it is the most extensive, and (2) current exploration and production are mostly limited to this system. One assessment unit (AU) was defined within the Cretaceous Composite TPS—the Coastal Plain and Offshore AU. Input data describing the assessment unit are given in the U.S. Geological Survey World Petroleum Assessment 2000—Description and results, Disk 3 (U.S. Geological Survey World Energy Assessment Team, 2000).

Lower Paleozoic and Lower Cretaceous Total Petroleum Systems

Events charts (figs. 20, 21) for the Lower Paleozoic TPS and Lower Cretaceous TPS graphically portray the ages of source, seal, and reservoir rocks, as well as the timing of trap development, and generation, migration, and preservation of hydrocarbons, and the critical moment. The critical moment is defined as the beginning of hydrocarbon generation and migration. These total petroleum systems were not assessed but are documented in the Gulf of Guinea Province report.

The likely source rocks for the Lower Paleozoic TPS are organic-rich brackish marine shales in the Middle to Upper Devonian Takoradi Formation in the Saltpond field. Lomé field (fig. 3) oils are sourced from these shales (MacGregor and others, 2003), and seismic data indicate that they are preserved in the Tano Basin (Tucker, 1992), although potential targets are presently untested. Reservoir rocks consist of Devonian and Carboniferous to Permian sandstone beds (fig. 10) in the Saltpond area (fig. 3). Currently it is assumed that upper Albian reservoirs in Sémé and Aje fields are sourced from Devonian shales (MacGregor and others, 2003), because downward migration from Upper Cretaceous-sourced oils seems unlikely. Hydrocarbon generation most likely began in the Late Carboniferous and may have continued into the early Tertiary.

The Lower Cretaceous TPS was defined because lacustrine source rocks deposited in early rift grabens have been recognized in the central and eastern parts of the province, as evidenced by the presence of lacustrine oils from Upper

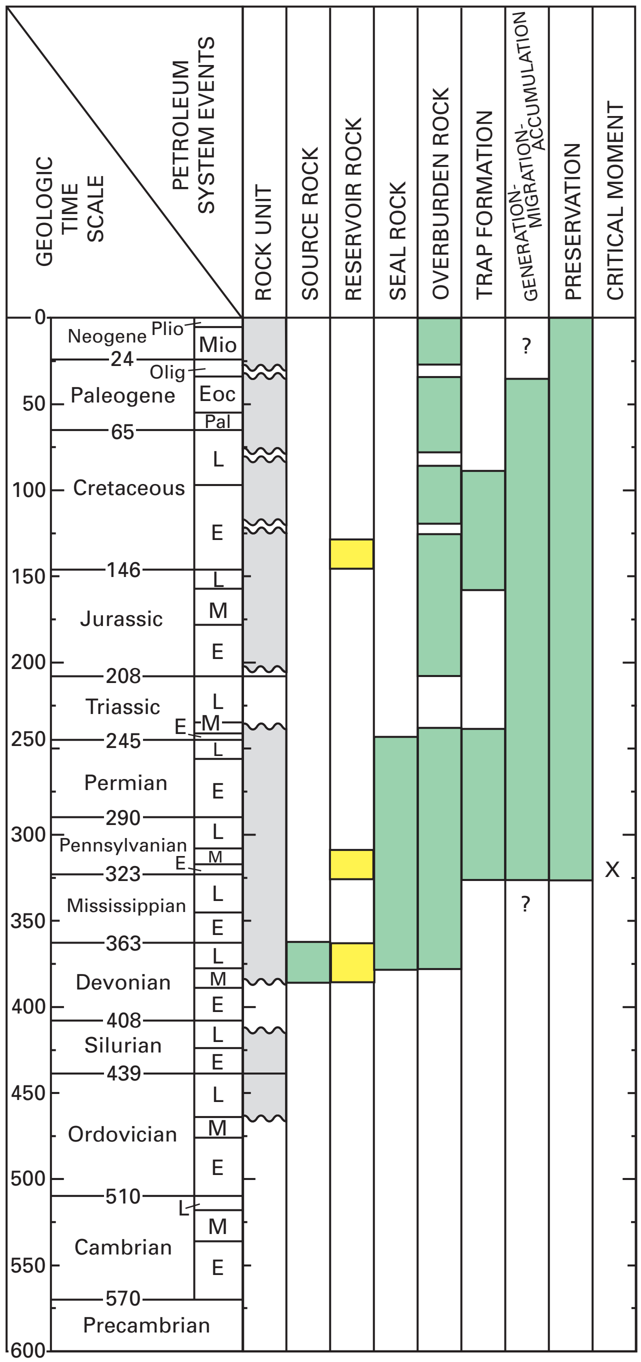


Figure 20. Events chart for the Lower Paleozoic Total Petroleum System in the Saltpond, Keta, and Tano Basins, Gulf of Guinea Province. Light-gray shading indicates rock units present (fig. 9); wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and the timing of trap formation and generation, migration, and preservation of hydrocarbons are shown in green and yellow. Queried where uncertain. Critical moment is defined as the beginning of hydrocarbon generation and migration.

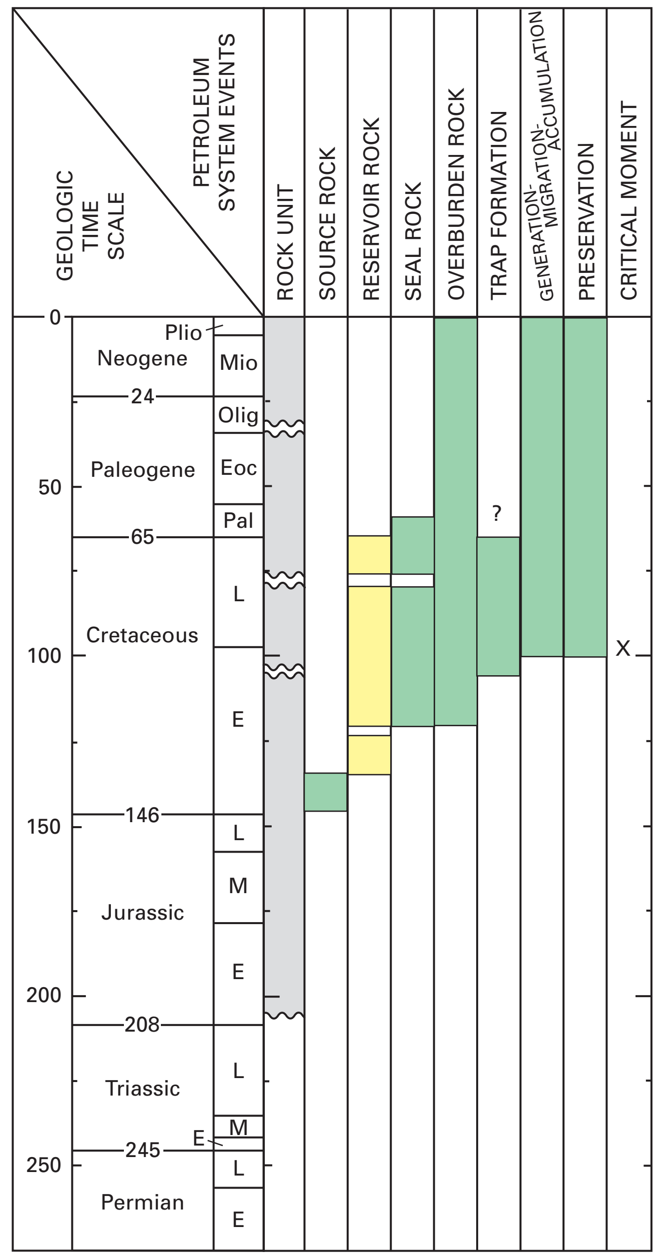


Figure 21. Events chart for the Lower Cretaceous Total Petroleum System in the Ivory Coast, Tano, Keta, and Benin Basins, and the Dahomey Embayment, Gulf of Guinea Province. Light-gray shading indicates rock units present (fig. 9); wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and the timing of trap formation and generation, migration, and preservation of hydrocarbons are shown in green and yellow. Queried where uncertain. Critical moment is defined as the beginning of hydrocarbon generation and migration.

Cretaceous tar sands and oil seeps in areas west of Cape Three Points in western Ghana, as well as in the Dahomey Embayment (fig. 3). Neocomian Ise Formation source rocks encountered in the Ise-2 well (fig. 3) have been correlated to Upper Cretaceous oil seeps and tar sands in the northern Dahomey Embayment (Haack and others, 2000). The Ise Formation source rocks (fig. 15) contain Type I kerogen with TOC contents as much as 4 percent and hydrogen index (HI, mg hydrocarbon/g organic carbon) values greater than 500 in the organically richest intervals. These Neocomian lacustrine shales have similar geochemical characteristics to the Lower Cretaceous lacustrine source rocks of the Bucomazi Formation in the Congo Delta (MacGregor and others, 2003; Brownfield and Charpentier, 2006). Lower Cretaceous lacustrine rocks are identified as far west as the Ivory Coast Basin (fig. 13) and may contain source rocks (Elvsborg and Dalode, 1985).

Cretaceous Composite Total Petroleum System (718301)

The Cretaceous Composite TPS was defined in the Gulf of Guinea Province (fig. 1). An events chart (fig. 22) for this total petroleum system graphically portrays the ages of the source, seal, and reservoir rocks, as well as the timing of trap development, and generation, migration, and preservation of hydrocarbons, and the critical moment. The critical moment is defined as the beginning of hydrocarbon generation and migration.

The principal source rocks for the Cretaceous Composite TPS are Albian, Cenomanian, and Turonian marine shales with Type II and II-III oil-prone kerogen and Type III terrestrial kerogen. Lower to middle Albian Type III source rocks were identified in the Ivory Coast and Tano Basins (figs. 9, 10, 13) by MacGregor and others (2003). These organic-rich sediments were deposited in fluvial and deltaic environments; in the Ivory Coast Basin as much as 5,000 m of Lower Cretaceous continental to marginal marine sediment was deposited in grabens (Chierici, 1996). Similar source rocks should be present in the Keta (Kjemperud and others, 1992) and Benin Basins (figs. 9, 11, 17). Worldwide anoxic ocean conditions during the Cenomanian (fig. 5) resulted in the deposition of the Cenomanian to Turonian black shale source rocks in the Ivory Coast and Tano Basins. These source rocks (fig. 13) contain more than 10 weight percent TOC consisting of Type II kerogen. In contrast, the Dahomey Embayment and Benin Basin are characterized by nonmarine to marginal marine conditions resulting in the deposition of middle Cretaceous gas-prone source rocks containing Type III kerogen (Chierici, 1996). The Coniacian Awgu Formation and the Maastrichtian Araromi Shale (fig. 15) contain marine source rocks in the offshore part of the Benin Basin. These source rocks contain Type II and Type II-III kerogen with TOC contents ranging from 2 to more than 5 weight percent; area of original deposition was from the northwestern extension of the Niger Delta westward to the Keta Basin (Haack and others, 2000). The richest source rock intervals have HI values greater than 500.

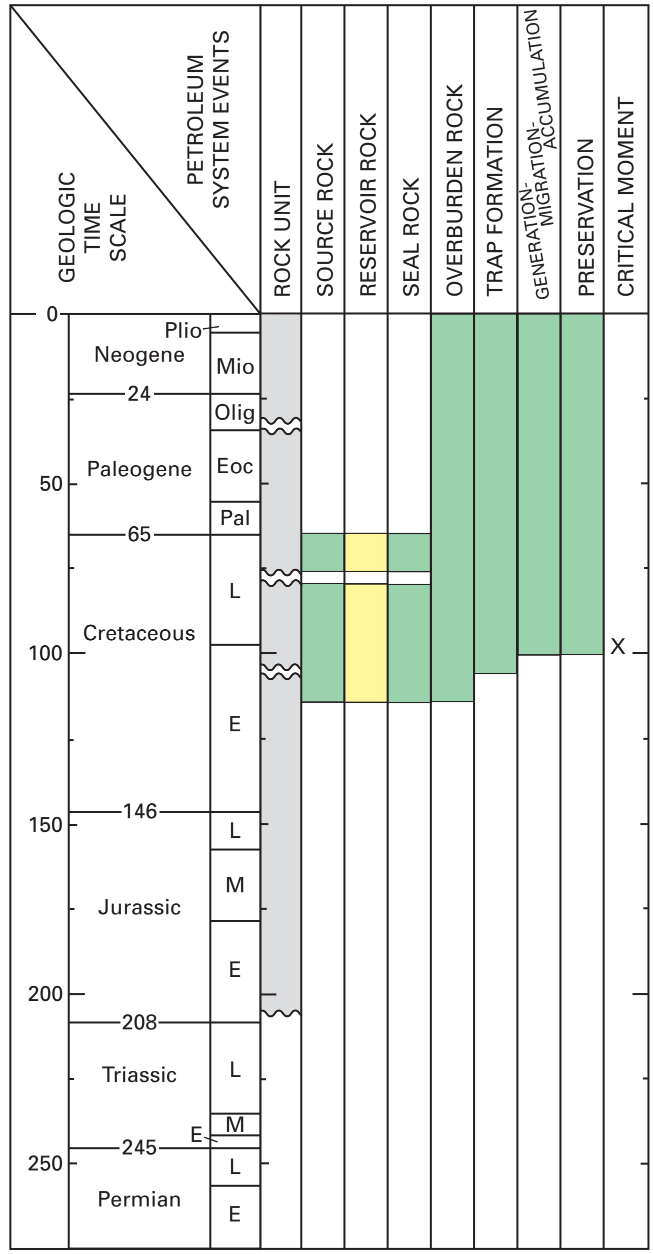


Figure 22. Events chart for the Cretaceous Composite Total Petroleum System (718301) in the Ivory Coast Basin, Gulf of Guinea Province. Light-gray shading indicates rock units present (fig. 9); wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and the timing of trap formation and generation, migration, and preservation of hydrocarbons are shown in green and yellow. Queried where uncertain. Critical moment is defined as the beginning of hydrocarbon generation and migration.

Coniacian rocks are present in the offshore part of the Keta Basin (fig. 17); some of these may be source rocks.

Hydrocarbon generation started in the Late Cretaceous for the Albian to Cenomanian source rocks and continues to the present. For the Turonian and Coniacian source rocks, hydrocarbon generation possibly started in the early Tertiary and also continues to the present. Migration was either directly from adjacent source rocks or upward along faults from deeper sources.

Reservoir rocks are mostly Cretaceous turbidite sandstones with minor potential limestone units. The traps include pre-transform traps related to fault blocks, syn-transform structural and stratigraphic traps, and post-transform stratigraphic traps. Seals are marine shales and shale-filled channels with minor fault-related seals.

Assessment Units of the Gulf of Guinea Province

The Coastal Plain and Offshore Assessment Unit (AU; 71830101) (fig. 2) includes Cretaceous reservoirs associated with pre-transform fault blocks and syn- and post-transform ponded turbidites, turbidite channels, and slope fans in basins between the major fracture zones (fig. 3). This assessment unit was defined to be co-located geographically with the Gulf of Guinea Province boundary, with the northern boundary of the assessment unit defined as the northern limit of the Cretaceous rocks and the southern boundary drawn at a water depth of 2,000 m. Although potential reservoirs in this assessment unit could exist in the shallow-water part, most of the prospectivity is expected to be in the deep-water part of the province.

Coastal Plain and Offshore Assessment Unit (71830101)

Exploration in the 1970s and 1980s resulted in the discovery of several moderate-sized oil fields, including Espoir (1980; 400 million barrels) and the large Foxtrot gas field (1982; about 1 trillion cubic feet) in the assessment unit (fig. 3). Exploration through 1995 was considered to be relatively immature with the discovery of only 33 fields (Petroconsultants, 1996), only 4 of which are in deep-water areas. The presence of one large gas field coupled with the relative lack of exploration for stratigraphic traps indicates a promising potential for future discoveries. Since the 2000 assessment (U.S. Geological Survey World Energy Assessment Team, 2000), eight discoveries have been made, with four of them in deep water (IHS Energy Group, 2003).

The USGS assessed mean undiscovered volumes in the Coastal Plain and Offshore AU of 1,004 MMBO, 10,071 BCFG, and 282 MMBNGL (table 1). The estimated sizes of the largest undiscovered oil and gas fields are 201 MMBO and 1,138 BCFG, respectively. Most of the undiscovered resources are expected to be in the deep-water parts of the assessment unit. Compared to other provinces along the Atlantic coast of Africa, the Gulf of Guinea Province has only modest potential for undiscovered resources (table 2) and ranks as the third province in Sub-Saharan Africa (table 2) in terms of mean undiscovered oil.

Summary

The Cretaceous Composite Total Petroleum System (TPS; 718301) consists of middle Albian to Maastrichtian Type II, II-III, and III oil-prone kerogen and Type III gas-prone kerogen and Cretaceous reservoirs. Worldwide middle Cretaceous anoxic ocean conditions resulted in the formation of the Cenomanian to Turonian Type II oil-prone kerogen source rocks containing more than 10 weight percent TOC. Cretaceous marine mudstones and shales are the primary seals. Hydrocarbon generation began in the Late Cretaceous and continues to the present.

Two other total petroleum systems were recognized in the Gulf of Guinea Province: (1) the Lower Paleozoic TPS, consisting of Devonian source rocks and Devonian to Lower Cretaceous reservoir rocks, and (2) the Lower Cretaceous TPS, consisting of Lower Cretaceous lacustrine source rocks and Cretaceous reservoir rocks. Although these total petroleum systems are considered to have hydrocarbon potential, they were not assessed: current exploration and production data are limited to the overlying Cretaceous Composite TPS.

Two important geologic differences contrast the Gulf of Guinea Province with the passive-margin basins south of the Niger Delta: (1) the influence of transform tectonics in the Gulf of Guinea Province, and (2) the absence of evaporites and salt deformation. The province also lacks long-lived delta systems that provide depositional conditions for rapid source rock burial and abundant high-quality reservoirs.

The Gulf of Guinea Province is estimated to have mean undiscovered resources of 1,004 MMBO and 10,071 BCFG in undiscovered fields. Compared to other provinces in Sub-Saharan Africa, the province has a moderate potential for undiscovered resources. All of the undiscovered resources are offshore and mostly in deep water.

Critical factors controlling oil and gas accumulations in the Gulf of Guinea Province are the presence of good reservoirs, quality and preservation of hydrocarbons, and the ability to produce hydrocarbons at a rate that would be economic in a deep-water setting. Offshore core samples and seismic data indicate that erosion on the structural highs and on the province shelf and slope is extensive, exposing the Albian rocks on the sea bed and removing potential reservoir and source rocks.

Although the deep-water parts of the Gulf of Guinea Province are underexplored, they are considered to contain many potential prospects. Gas resources may be substantial, and may also be accessible in areas where the zone of hydrocarbon generation is relatively shallow.

Table 1. Summary of estimated undiscovered volumes of conventional oil, gas, and natural gas liquids for undiscovered oil and gas fields for the Coastal Plain and Offshore Assessment Unit in the Cretaceous Composite Total Petroleum System of the Gulf of Guinea Province, west Africa, showing allocations of undiscovered volumes to the onshore.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. MFS, minimum field size assessed (MMBO or BCFG). Prob., probability (including both geologic and accessibility probabilities) of at least one field equal to or greater than the MFS. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

Field Type	MFS	Prob. (0-1)	Undiscovered Resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Cretaceous Composite Total Petroleum System														
Coastal Plain and Offshore Assessment Unit Offshore (100% of undiscovered oil fields and 100% of undiscovered gas fields allocated to offshore)														
Oil Fields	2	1.00	225	901	2,117	1,004	918	3,846	9,845	4,420	29	124	339	146
Gas Fields	12						1,256	5,064	12,000	5,650	28	118	303	136
Total		1.00	225	901	2,117	1,004	2,174	8,910	21,846	10,071	57	242	642	282

Table 2. Summary of estimated undiscovered volumes of conventional oil, gas, and natural gas liquids for undiscovered oil and gas fields for Sub-Saharan Africa, showing allocations by oil and gas province.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. MFS, minimum field size assessed (MMBO or BCFG). Prob., probability (including both geologic and accessibility probabilities) of at least one field equal to or greater than the MFS. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

Code and Field Type	Prob. (0-1)	Undiscovered Resources											
		Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
7013 Senegal Province													
Oil Fields	1.00	15	120	430	157	33	255	968	345	2	15	59	21
Gas Fields						83	414	1,276	510	3	18	58	22
Total	1.00	15	120	430	157	116	669	2,244	856	5	33	118	43
7183 Gulf of Guinea Province													
Oil Fields	1.00	225	901	2,117	1,004	918	3,846	9,845	4,420	29	124	339	146
Gas Fields						1,256	5,064	12,000	5,650	28	118	303	136
Total	1.00	225	901	2,117	1,004	2,174	8,910	21,846	10,071	57	242	642	282
7192 Niger Delta Province													
Oil Fields	1.00	17,487	39,975	65,123	40,487	28,703	70,120	133,579	74,056	903	2,292	4,608	2,459
Gas Fields						28,845	57,910	90,585	58,660	1,741	3,517	5,594	3,574
Total	1.00	17,487	39,975	65,123	40,487	57,548	128,030	224,165	132,716	2,643	5,808	10,202	6,034
7203 West-Central Coastal Province													
Oil Fields	1.00	9,033	27,917	56,465	29,747	17,693	56,368	123,798	61,608	827	2,739	6,483	3,080
Gas Fields						5,268	23,152	58,794	26,436	217	989	2,715	1,164
Total	1.00	9,033	27,917	56,465	29,747	22,961	79,520	182,592	88,044	1,044	3,727	9,198	4,244
7303 Orange River Coastal Province													
Oil Fields	1.00	23	87	312	116	46	186	701	256	3	11	43	15
Gas Fields						629	2,829	7,889	3,348	26	121	361	147
Total	1.00	23	87	312	116	675	3,015	8,590	3,603	28	132	404	163
7 **Total: Sub-Saharan Africa**													
Oil Fields	1.00	26,783	68,999	124,447	71,512	47,393	130,775	268,891	140,685	1,763	5,180	11,533	5,722
Gas Fields						36,081	89,369	170,545	94,604	2,015	4,762	9,031	5,044
Total	1.00	26,783	68,999	124,447	71,512	83,474	220,144	439,436	235,290	3,778	9,942	20,564	10,766

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