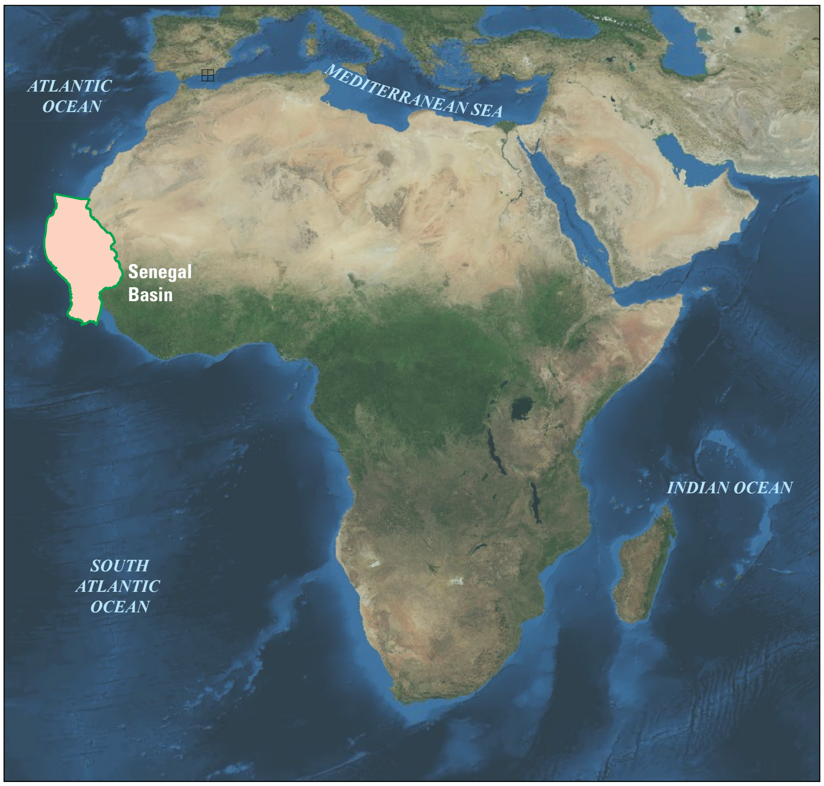
Assessment of Undiscovered Oil and Gas Resources of the Senegal Province, Northwest Africa

By Michael E. Brownfield



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Volume Title Page

Chapter 2 of
Geologic Assessment of Undiscovered Hydrocarbon Resources of Sub-Saharan Africa

Compiled by Michael E. Brownfield

Digital Data Series 69–GG

U.S. Department of the Interior
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U.S. Geological Survey, Reston, Virginia: 2016

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Suggested citation:
Brownfield, M.E., 2016, Assessment of undiscovered oil and gas resources of the Senegal Province, northwest Africa, *in* Brownfield, M.E., compiler, Geologic assessment of undiscovered hydrocarbon resources of Sub-Saharan Africa: U.S. Geological Survey Digital Data Series 69–GG, chap. 2, 20 p., http://dx.doi.org/10.3133/ds69GG.

ISSN 2327-638X (online)

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Abbreviations Used in This Report

kg/ton	kilogram per ton
m	meter
mg HC/g TOC	milligrams of hydrocarbon per gram of total organic carbon
AU	assessment unit
HI	hydrogen index
TOC	total organic carbon
TPS	total petroleum system

Assessment of Undiscovered Oil and Gas Resources of the Senegal Province, Northwest Africa

By Michael E. Brownfield

Abstract

The main objective of the U.S. Geological Survey's National and Global Petroleum Assessment Project is to assess the potential for undiscovered, technically recoverable oil and natural gas resources of the United States and the world. As part of this project, the U.S. Geological Survey completed an assessment of the Senegal Basin Province, with a total land area of about 929,900 square kilometers that covers parts of Western Sahara, Mauritania, Senegal, The Gambia, Guinea-Bissau, and Guinea. The Senegal Province includes both onshore and offshore parts of the Senegal Basin to a water depth of 4,000 meters.

Although several total petroleum systems may exist in the province, the U.S. Geological Survey defined only one composite system, the Cretaceous-Tertiary Composite Total Petroleum System. This system contains one assessment unit, the Coastal Plain and Offshore Assessment Unit that was assessed in this study. The assessment unit's area, about 807,760 square kilometers, is underexplored on the basis of its limited exploration history.

Hydrocarbons were generated from Cenomanian and Turonian marine shale. Turonian Type II source rocks range from 7 to 10 weight percent total organic carbon. Hydrocarbon generation started in the Miocene and continues to the present. Generated hydrocarbons migrated into Cretaceous and Tertiary reservoirs. Hydrocarbon traps include (1) salt-related structures, (2) structures related to volcanic intrusions, (3) growth-fault-related traps, (4) slope truncations along the present day and Mesozoic shelf edges (the Senonian unconformity), (5) Mesozoic and Tertiary pinch-outs along the eastern basin margin, and (6) reef buildups along the shelf edge. The Upper Cretaceous and Tertiary marine mudstone and shale rocks are the primary seals. A passive-margin analog was used for assessment sizes and numbers because of similar source and reservoir rocks and traps.

The U.S. Geological Survey estimated the undiscovered, technically recoverable conventional oil and gas resources in the Senegal Province as part of the World Petroleum Assessment 2012. The mean volumes are estimated at 2,350 million barrels of oil, 18,705 billion cubic feet of gas, and 567 million barrels of natural gas liquids; the estimated expected mean oil field size is 579 million barrels of oil and gas field size is 3,505 billion cubic feet of gas.

Introduction

The main objective of the U.S. Geological Survey's (USGS) National and Global Petroleum Assessment Project is to assess the potential for undiscovered, technically recoverable oil and natural gas resources of the United States and the world (U.S. Geological Survey World Conventional Resources Assessment Team, 2012). As part of this project, the USGS assessed the Senegal Basin Province (fig. 1), which has a total land area of about 929,912 square kilometers that covers parts of Western Sahara, Mauritania, Senegal, The Gambia, Guinea-Bissau, and Guinea. This assessment was based on data from oil and gas exploration well, producing fields (IHS Energy, 2009), and published geologic reports.

The Senegal Province was assessed as part of the World 2000 Assessment (U.S. Geological Survey World Energy Assessment Team, 2000) and was reassessed in 2009 because of recent discoveries (IHS Energy, 2009), increased energy exploration activity, and interest in its future oil and gas resource potential. The province is considered to be underexplored on the basis of its limited exploration history. The Senegal Province (fig. 1), which includes onshore and offshore parts of the Senegal Basin to a water depth of 4,000 meters (m), is situated along the northwest African coast. Figure 2 shows generalized geology of northwest Africa and the location of the Senegal and adjoining provinces (Klett and others, 1997; Persits and others, 2002). The northern limit of the Senegal Basin is the Precambrian Reguibate Shield, and the southern limit is the West African Shield of Guinea. The eastern edge of the basin is separated from the Taoudeni Basin by Precambrian rocks of the Mauritanide Mountains that were uplifted during the late Paleozoic Hercynian orogeny (fig. 2).

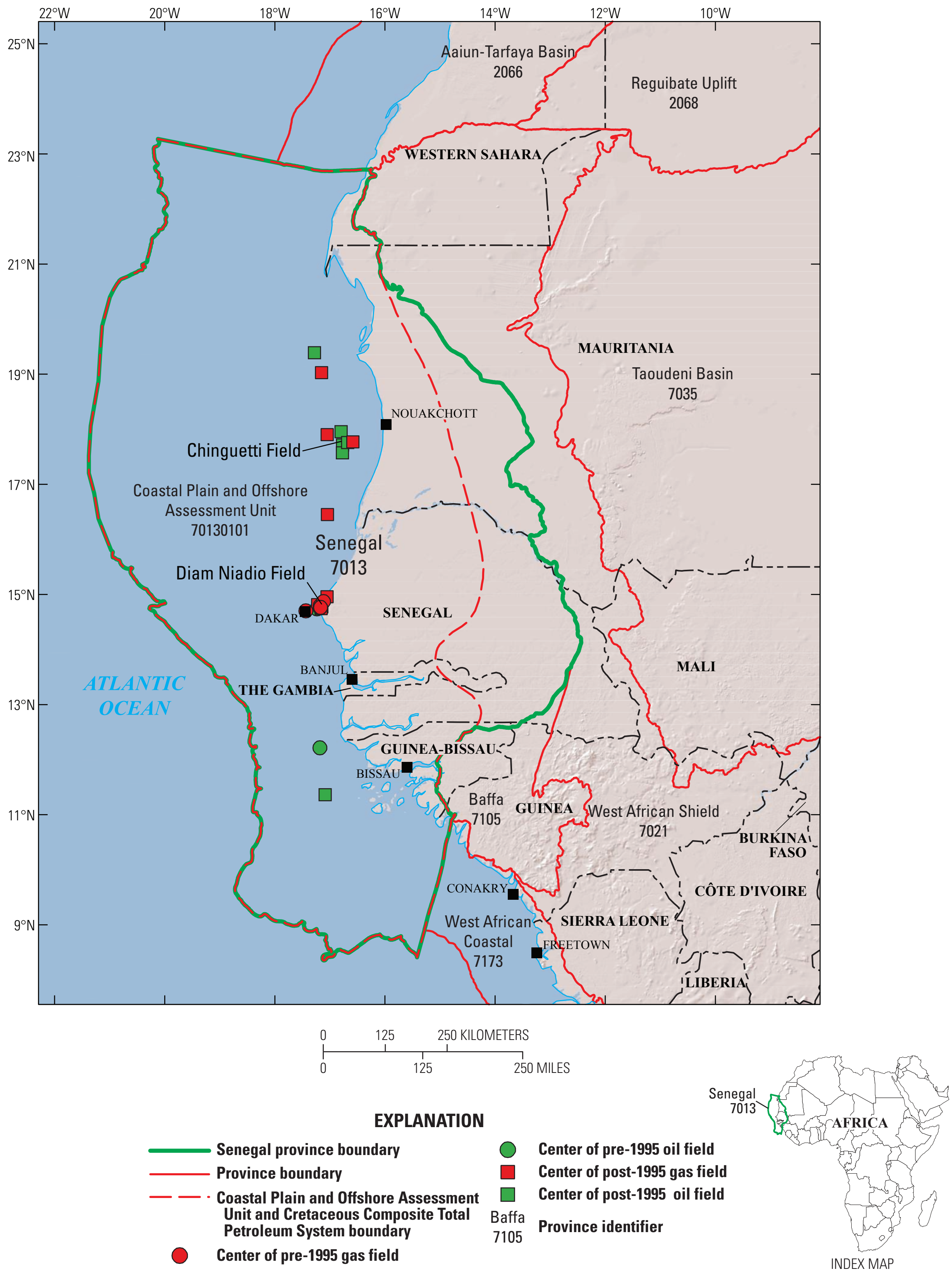


Figure 1. Location of the Senegal Province (7013), the Cretaceous-Tertiary Composite Total Petroleum System (701301), the Coastal Plain and Offshore Assessment Unit (70130101), and center points of oil and gas fields. Offshore boundary of Senegal Province set at water depth of 4,000 meters.

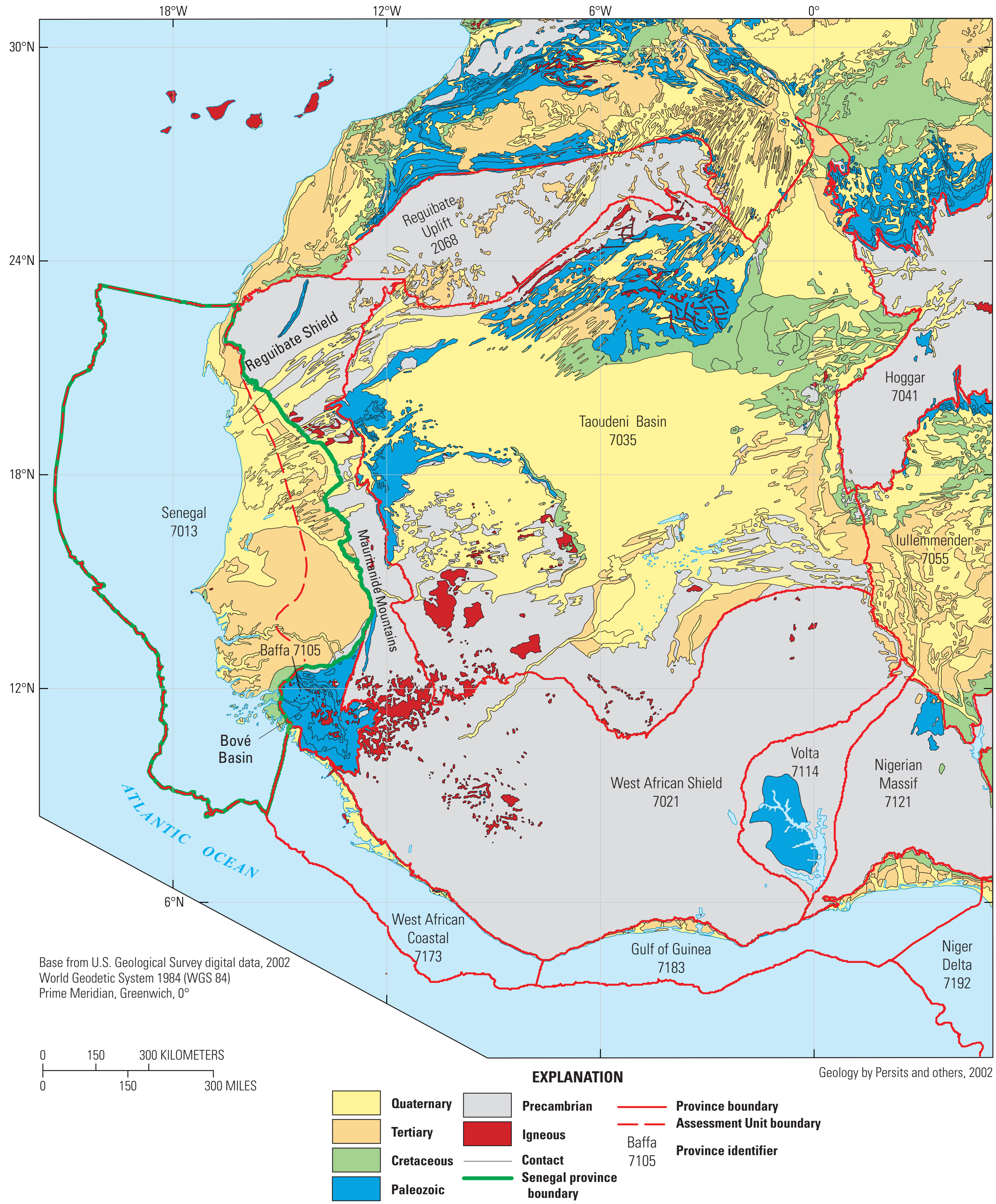


Figure 2. Generalized geology of northwest Africa (Persits and others, 2002) showing province boundaries, 12 province names and codes as defined in Klett and others (1997), and the boundary of the Coastal Plain and Offshore Assessment Unit for the Senegal Province.

Tectonic History and Geology of the Senegal Province, Northwest Africa

The Senegal Basin formed at the culmination of a Permian to Triassic rift system that developed throughout an extensive Paleozoic basin during the breakup of North America, Africa, and South America. The Senegal Basin has undergone a complex history that can be divided into pre-rift (upper Proterozoic to Paleozoic), syn-rift (Permian to Triassic), and post-rift (Middle Jurassic to Holocene) stages of basin development. The basin can be divided into a number of subbasins aligned in a north-south direction and delimited by an east-west fault system and other structural dislocations related to syn-rift tectonics.

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 and is represented by syn-rift rocks in the Senegal Basin (Uchupi, 1989; Vear, 2005).

The syn-rift section of the southern Senegal Basin consists of thick Triassic to Lower Jurassic evaporites overlying inferred Triassic clastic rocks (figs. 3, 4), which may include organic-rich lacustrine rocks (Uchupi, 1989; Vear, 2005). The syn-rift evaporite section in the Casamance subbasin (fig. 5) may be as much as 2,000 meters (m) thick and consists mostly of salt with an anhydrite cap, whereas the underlying clastic section may be as thick as 1,500 m (Dumestre, 1985). In the Northern and Mauritania subbasins, the evaporite section might be as thick as 2,000 m, whereas the thickness of the underlying Triassic clastic section is unknown but may have a thickness similar to that of the Casamance subbasin (Dumestre, 1985; Dumestre and Carvalho, 1985; Fusion Oil and Gas, 2001).

Except for a few salt structures in the Casamance and Mauritania subbasins and offshore Guinea-Bissau (fig. 5), drilling has not yet penetrated these rocks, but new seismic data have imaged this section in some parts of the Senegal Basin (Bungener and Hinz, 1995; Fusion Oil and Gas, 2001). In the southern Senegal Basin, the evaporite section has undergone extensive salt tectonics as shown by salt diapirs intruding the overlying Cretaceous and Tertiary rocks (Dumestre, 1985). Seismic studies have shown salt diapirs in offshore Mauritania, confirming that this section is present in the northernmost part of the basin (Fusion Oil and Gas, 2001). Salt diapirs have not been recognized in the Northern subbasin (fig. 5).

The onshore part of central Senegal Basin has a thinner syn-rift section consisting of probable Triassic continental clastic rocks and organic-rich lacustrine shale (Dumestre, 1985). The northwest Africa basins have been subjected to drift and passive-margin sedimentation since the Jurassic (Lambiase, 1989).

The Senegal Basin is the largest of the northwest Africa Atlantic margin basins. The offshore portion of the basin was limited for this study to water depths of 4,000 m or less (fig. 1). Three major subbasins (fig. 5) have been recognized in the Senegal Basin: the Mauritania offshore subbasin, which extends north from the Senegal River to the southern part of Western Sahara; the Northern subbasin, which extends north of the Gambia River to the Senegal River; and the Casamance subbasin, which extends south from the Gambia River through the Casamance region into Guinea-Bissau (Dumestre, 1985).

The post-rift, passive-margin rocks are of Late Jurassic to Holocene age; they increase in thickness from east to west across the Senegal Basin (fig. 6). The basal unit of the post-rift sequence is a thick carbonate shelf of Middle to Upper Jurassic to Neocomian age that is related to the Tethys Sea. The carbonate unit ranges in thickness from 2,300 to 3,200 m in the Mauritania, Northern, and Casamance subbasins (figs. 7, 8) (Dumestre, 1985; Dumestre and Carvalho, 1985). During the Aptian and Albian, this unit continued to be deposited in the central offshore part of the basin, whereas in the northern Mauritania subbasin and southernmost part of the Casamance subbasin it was replaced by deeper-water sediments. The Cenomanian rocks of the post-rift section are represented by thick marine shale interbedded with marginal-marine sandstone, deposited after the opening of the Atlantic. Minor carbonate banks and reefs are present. The Turonian marks the time of maximum Cretaceous transgression and is represented by widespread black and commonly bituminous shale that is an important source rock in the basin (Dumestre and Carvalho, 1985). The Turonian ranges in thickness from 50 to 150 m. The Senonian stage was a time of major marine regression that culminated with the deposition of widespread and thick sandstone units in the Maastrichtian (Dumestre and Carvalho, 1985). Tertiary sedimentary rocks are unconformable with Upper Cretaceous rocks and consist primarily of marine shale and carbonate. The thickness of the post-rift section is about 12,000 m in the Guinea-Bissau part of the basin (Dumestre and Carvalho, 1985).

Two major stratigraphic domains delimited by the shelf edge are recognized within the Senegal Basin: the shelf edge and slope, and the carbonate platform (figs. 9, 10) (Bungener and Hinz, 1995). The Mesozoic shelf edge and western edge of the Jurassic−Lower Cretaceous carbonate platform (fig. 5) roughly parallels the 200-m bathymetric contour (Bungener and Hinz, 1995). Several potential hydrocarbon areas have been identified in the Mauritania subbasin offshore. Commercial hydrocarbon accumulations have been found since the 2000 USGS assessment (U.S. Geological Survey World Energy Assessment Team, 2000; Brownfield and Charpentier, 2003; HIS Energy, 2009), Oil-prone source rocks (total organic carbon (TOC) as much as 5 weight percent) within the Albian-Turonian and potential Upper Cretaceous deltaic reservoir sands with porosities of 17–25 percent have been identified. Lower Cretaceous carbonate rocks are untested in this part of the basin. Miocene turbidite fans are also prospective.

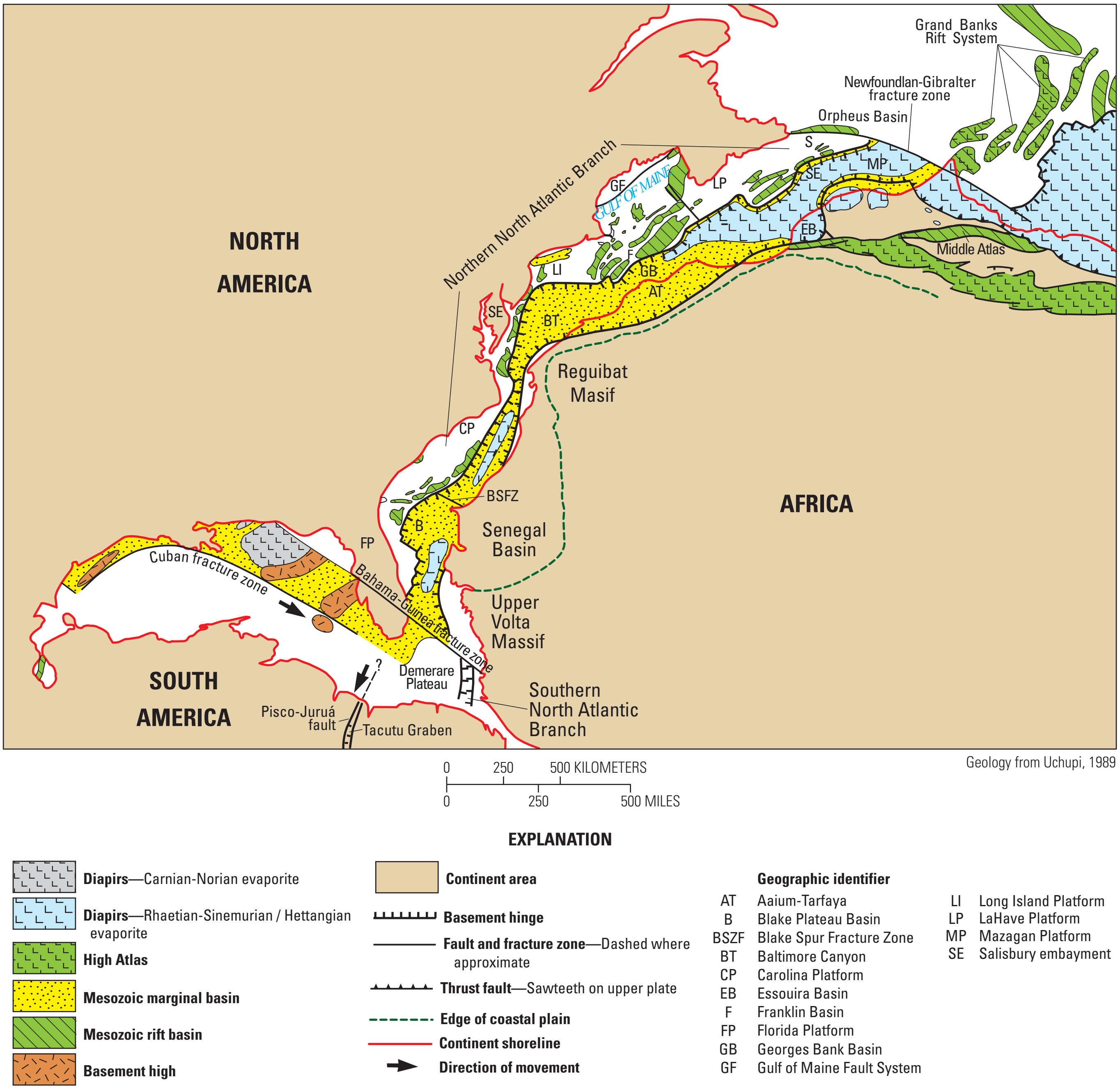
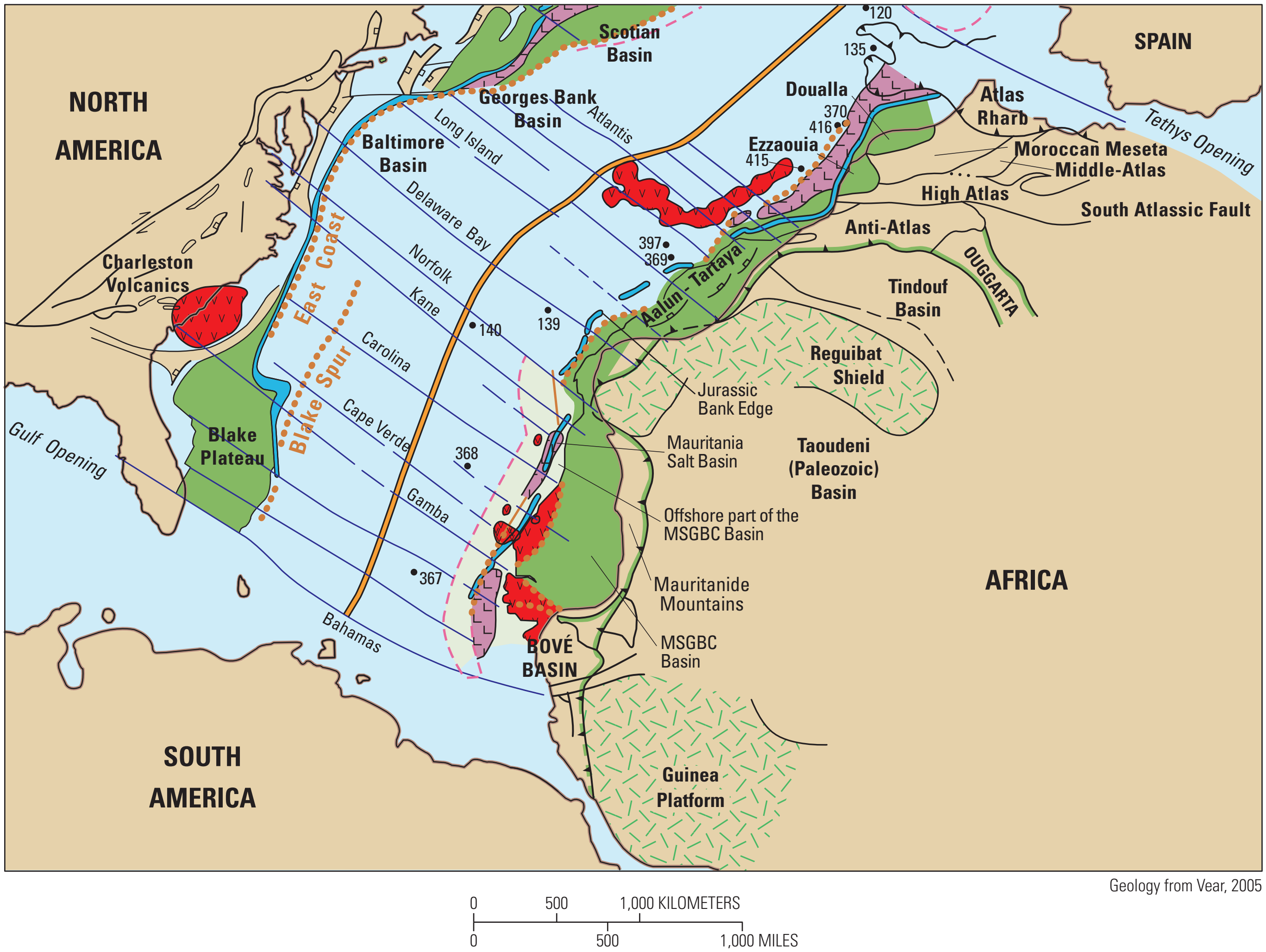


Figure 3. Early Jurassic reconstruction of the North Atlantic showing basement highs, evaporites, and rifts just prior to the initiation of seafloor spreading at the northern end of the Northern North Atlantic branch. Evaporites in the Gulf of Mexico are younger (Middle Jurassic). FZ, fault or fracture zone. AT, Aaium-Tarfaya Basin; B, Blake Plateau Basin; BSFZ, Blake Spur fracture zone; BT, Baltimore Canyon; CP, Carolina Platform; EB, Essouira Basin; F, Franklin Basin; FP, Florida Platform; FZ, fracture zone; GB, Georges Bank Basin; GF, Gulf of Maine fault system; LI, Long Island Platform; LP, LaHave Platform; MP, Mazagan Platform; SE, Salisbury Embayment. Modified from Uchupi (1989).



EXPLANATION

- **Marginal basin**
- **Carbonate bank**—Jurassic Age
- **Triassic-Liassic salt basin**
- **Triassic-Liassic salt basin**—Volcanics
- **Crystalline basement high**
- **Continent area**
- **Fault**—Dashed where location approximate. Dotted where location is concealed
- **Thrust fault**—Sawteeth on upper plate
- **Mauritanide thrust fault, Hercynian age**—Sawteeth on upper plate
- **Detachment fault**—Boxes on upper plate
- **Strike-slip fault**—Arrows show relative motion
- **Mid-Atlantic Ridge**
- **Continental-oceanic boundary**
- **Continental-transitional crust**
- **Magnetic anomaly**
- **Fracture zone**—Dashed where location approximate
- 368 **Deep Sea Drilling Project site and identifier**
- MSGBC **Mauritania-Senegal-Gambia-Bissau-Conakry**

Figure 4. Late Jurassic reconstruction of Africa, North America, and South America. DSDP, Deep Sea Drilling Project; FZ, fracture zone; MSGBC, Mauritania–Senegal–Guinea-Bissau–Conakry Basin. Modified from Vear (2005).

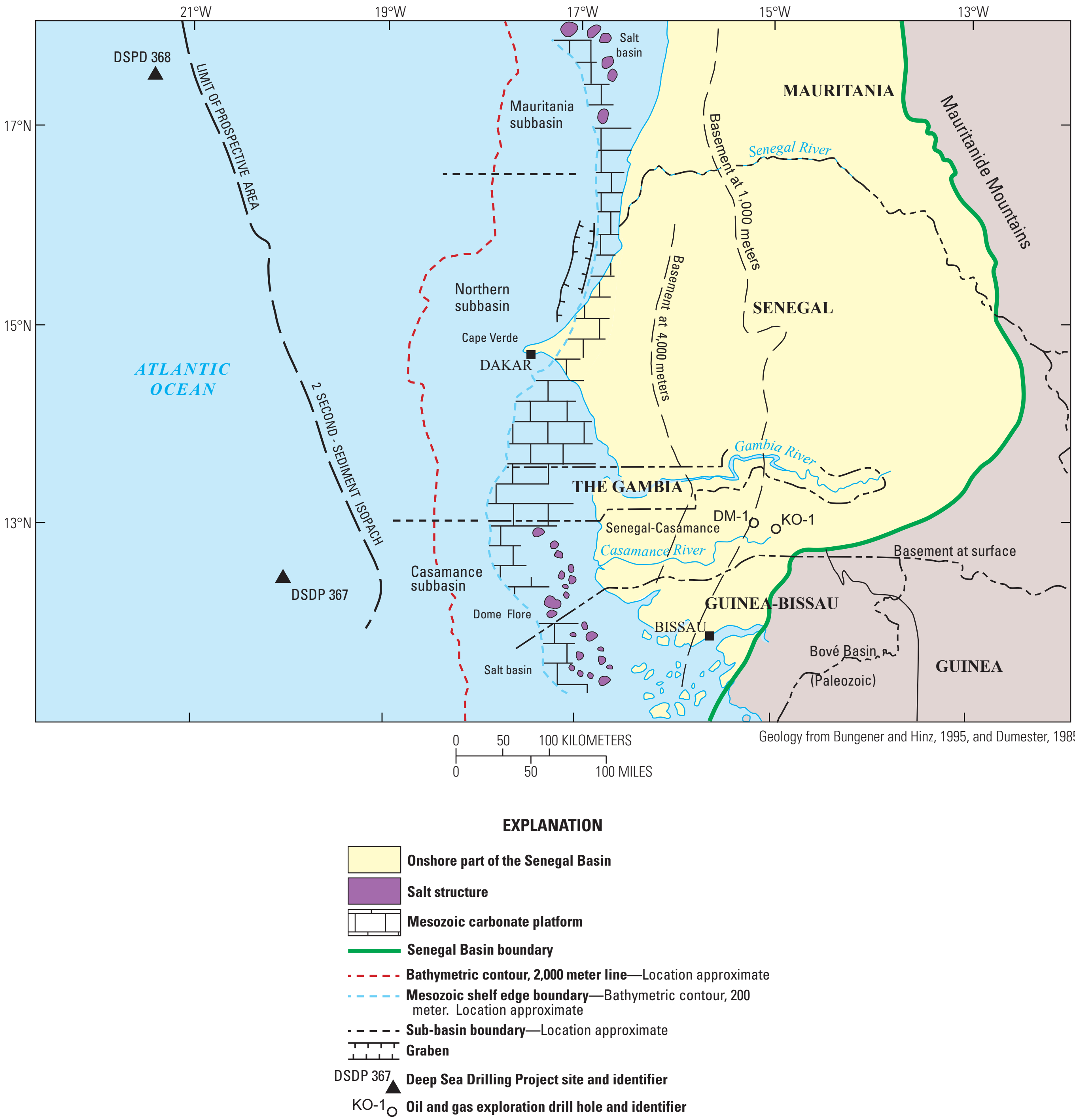


Figure 5. Generalized map of the central and southern parts of the Senegal Basin showing part of the Senegal Province, the Mauritania, Northern, and Casamance subbasins, the Mesozoic carbonate platform edge, the northern and southern salt basins, the Mauritanide Mountains, the Bové Basin, Deep Sea Drilling Project sites 367 and 368, the 2-second sediment isopach, and the onshore depth to basement isopachs. Also shown are the approximate locations of the Diana-Malari (DM-1) and Kolda (KO-1) wells that penetrated Silurian source rock (Buba Shale). Modified from Dumestre (1985) and Bungener and Hinz (1995).

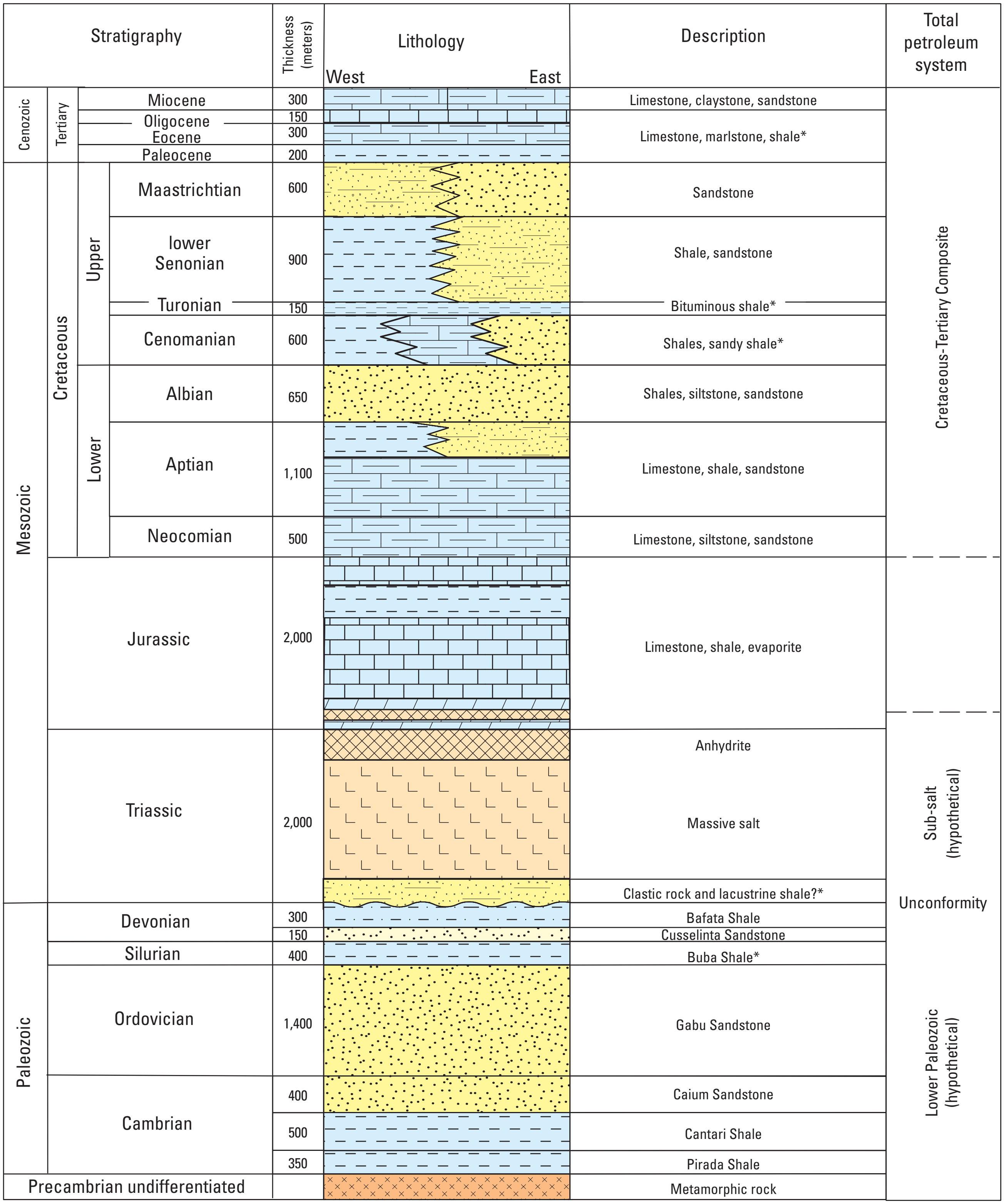


Figure 6. Generalized stratigraphy of rocks in the Casamance region of southern Senegal and Guinea-Bissau and showing the three total petroleum systems in the Senegal Basin. Paleozoic portion of the column represents the Bové Paleozoic Basin, which is an extension of the Taoudeni Basin of Mauritania and Mali. *, potential source rocks. Modified from Dumestre and Carvalho (1985), and Brownfield and Charpentier (2003).

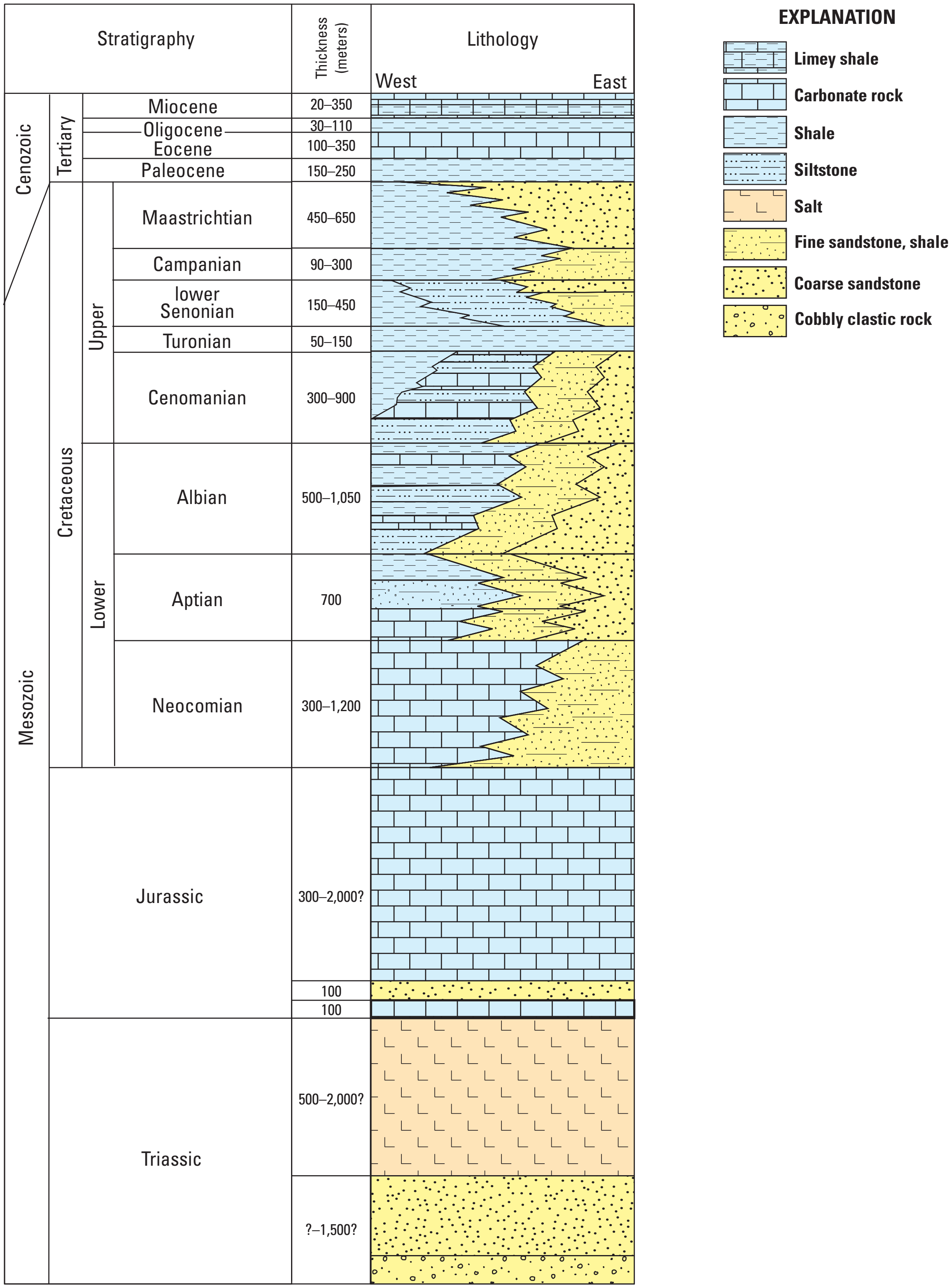


Figure 7. Generalized stratigraphy of the Casamance offshore subbasin, south of Cape Verde (fig. 5), Senegal Basin Province, northwest Africa. In the Casamance subbasin the best source rocks are in Cenomanian and Turonian units. Possible source rock may exist in the clastic section below Triassic evaporites. Modified from Dumestre (1985).

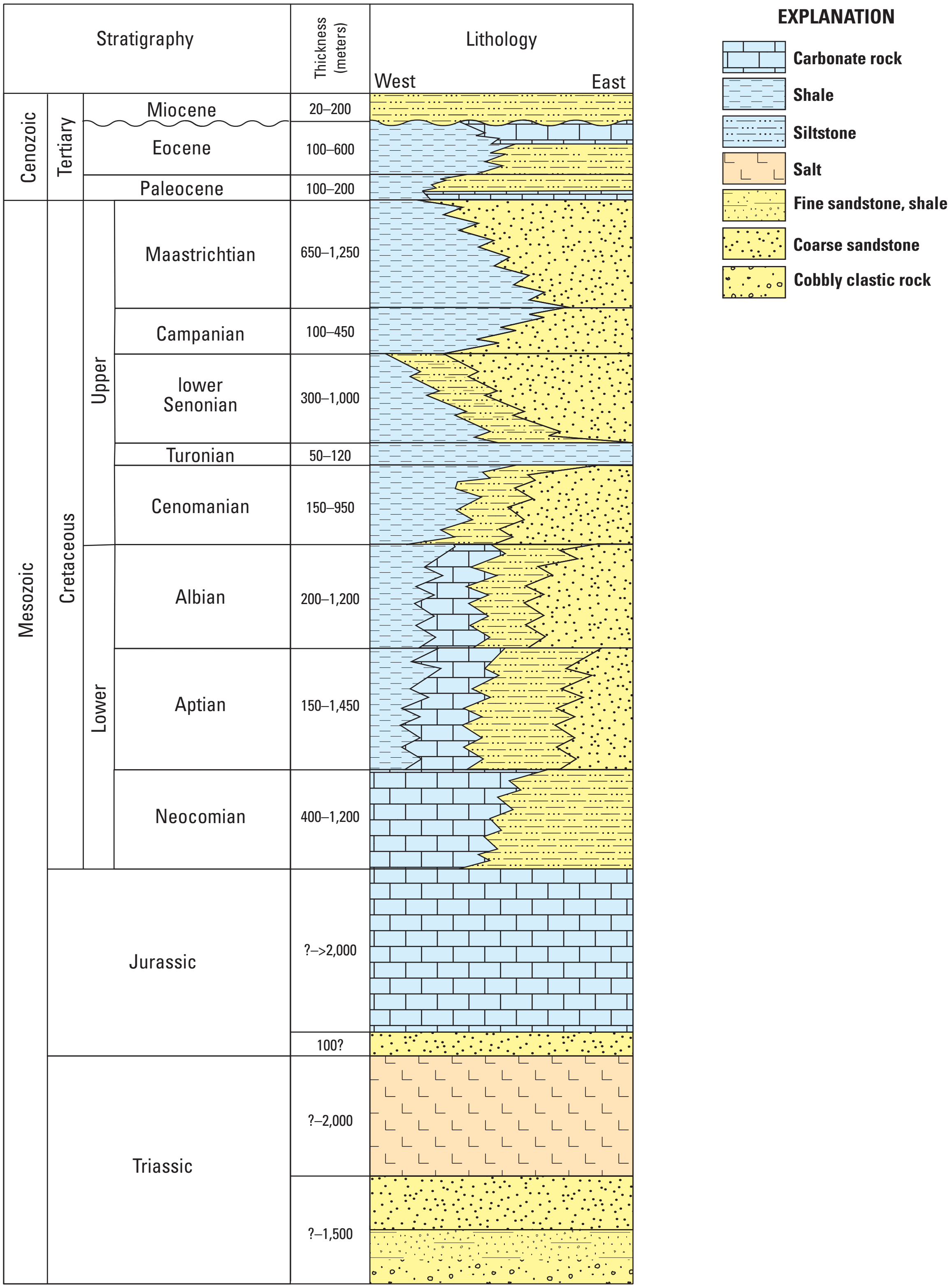
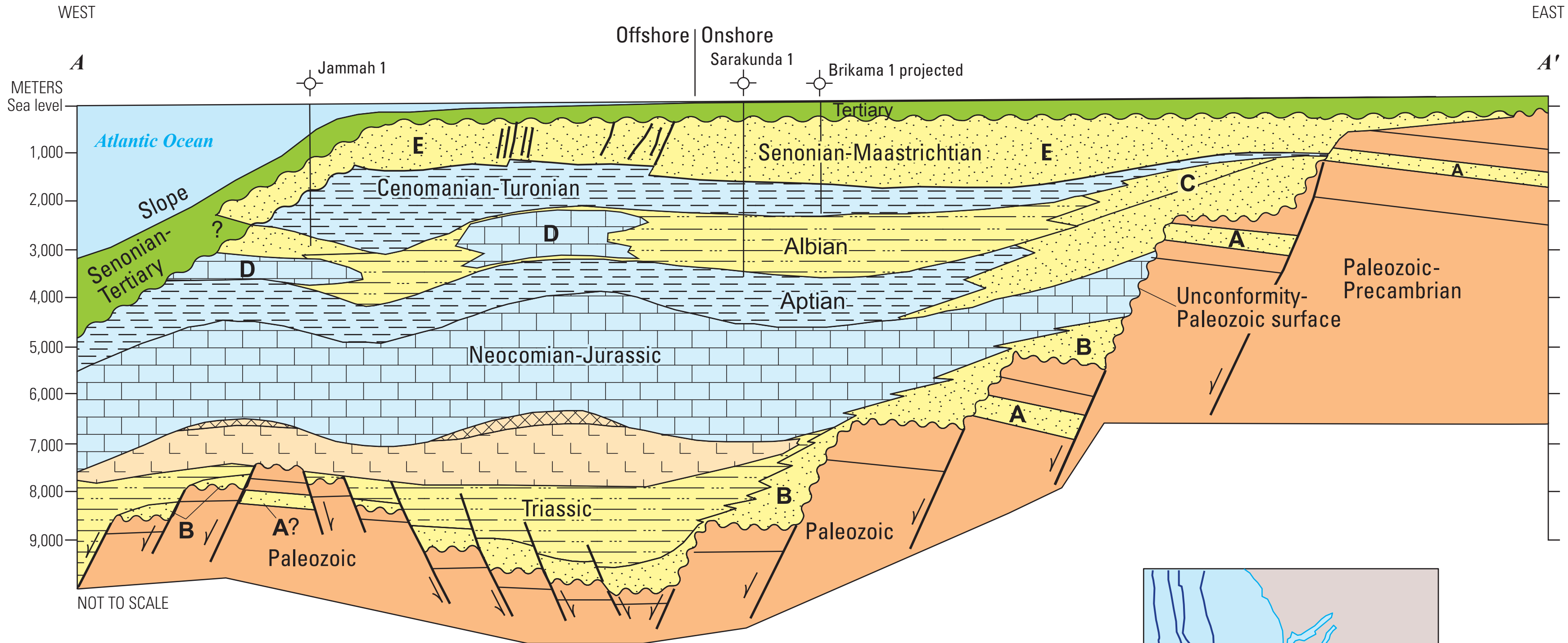


Figure 8. Generalized stratigraphy of the Northern subbasin and the southern part of the Mauritania subbasin (fig. 5). Type II and III source rocks are found in the Cenomanian and Turonian units. Modified from Dumestre (1985).



EXPLANATION

- Shale
- Clastic rock
- Sandstone
- Carbonate
- Salt
- Anhydrite
- Contact
- Unconformity
- Fault—Arrow shows relative motion
- Ocean floor depth—Contours in meters

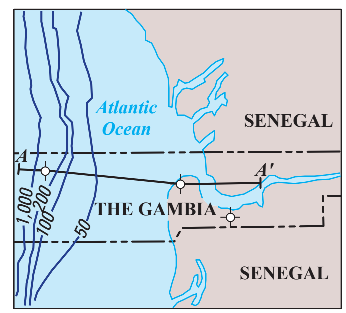
- A—A′ Line of section
- Jammah 1 Well site and identifier

Total petroleum system with potential oil prospect

- **A** **Lower Paleozoic Total Petroleum System**—Unassessed
  Ordovician-Devonian reservoirs, Silurian source?
- **B** **Sub salt Total Petroleum System**—Unassessed
  Lower Paleozoic? and Triassic reservoirs, Triassic and/or Silurian source?

Cretaceous-Tertiary Composite Total Petroleum System—Assessed

- **C** Albian/Aptian reservoirs, Turonian(or)Cenomanian source
- **D** Albian carbonate and sandstone reservoirs, Turonian/Cenomanian source
- **E** Tertiary/Upper Cretaceous reservoirs, Turonian/Cenomanian source



INDEX MAP

Figure 9. Schematic cross section through The Gambia showing locations of potential oil prospects with their associated total petroleum systems, reservoirs, and source rocks. Modified from Bungener (1995).

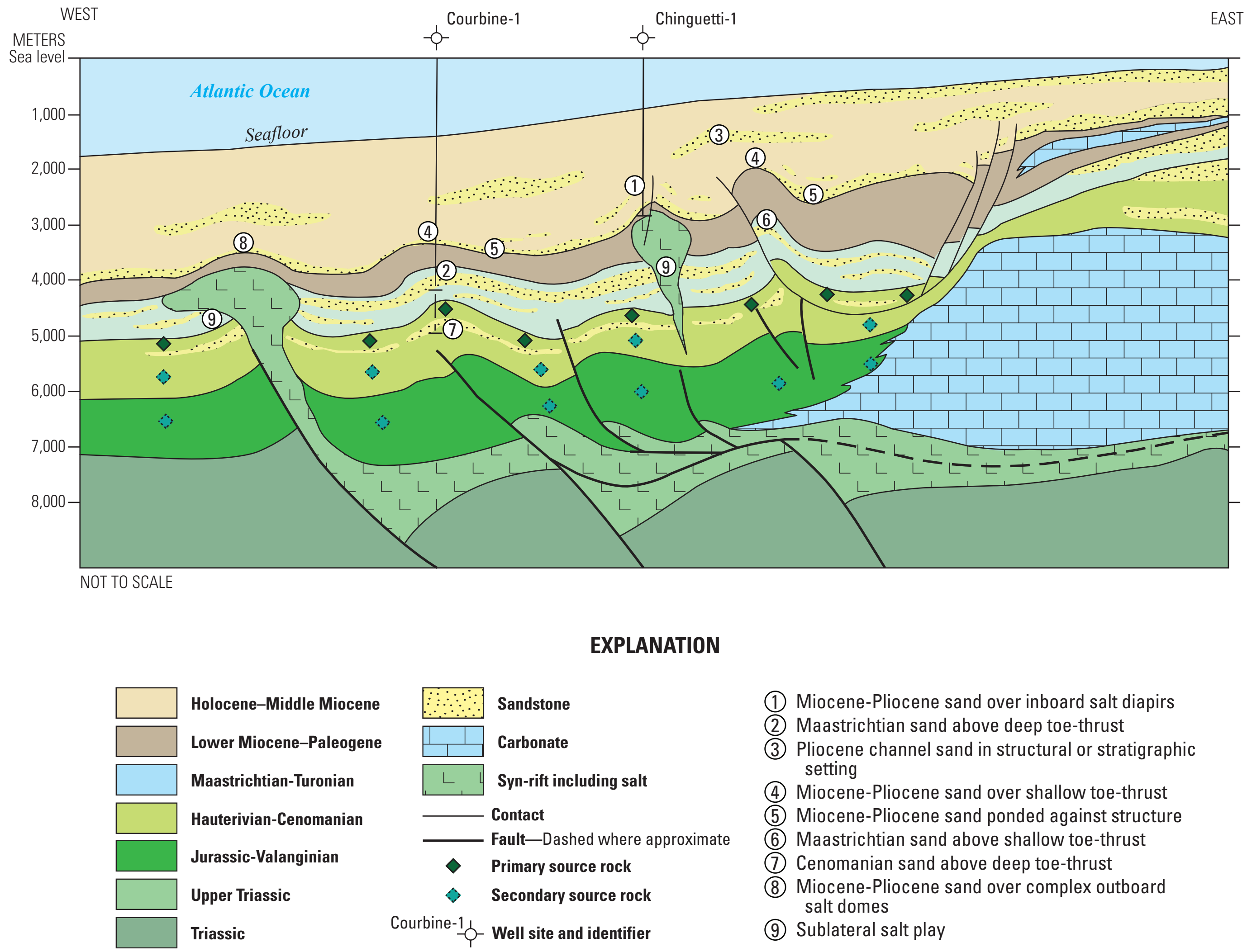


Figure 10. Schematic cross section of offshore Mauritania, northern Senegal Basin, northwest Africa. Modified from Fusion Oil and Gas (2001).

East of the Mesozoic shelf edge (fig. 5) is a gently westward dipping Mesozoic and Cenozoic shelf characterized by prograding marine deposits separated by regressive episodes and regional unconformities (fig. 10) (Fusion Oil and Gas, , 2001). The section thins eastward so that the Paleozoic sequence is accessible to drilling throughout a large area (fig. 9). The Mesozoic section has not undergone any orogenic or compressional stress. Normal faults generally strike north-south and are predominantly downthrown to the west, reflecting the predominant tensional structural style during the Mesozoic and Cenozoic. Salt diapirs in the offshore Casamance and Mauritania subbasins have pierced the Mesozoic section and are prominent structural targets for oil and gas exploration (Dumestre and Carvalho, 1985; Fusion Oil and Gas, 2001).

West of the Mesozoic shelf edge (fig. 5), where the sedimentary thickness can reach an excess of 12,000 m, the regional structural style is dominated by gravitational features such as listric faulting and slumping and toe-thrusts, reflecting a slope environment and the influence of the opening of the Atlantic Ocean (fig. 10) (Fusion Oil and Gas, 2001). The current sedimentary depocenter is located west of the shelf edge in water depths of 1,000–2,000 m (Dumestre and Carvalho, 1985).

Petroleum Occurrence in Senegal Province, Northwest Africa

Source Rocks

In the Senegal Basin, the Cenomanian-Turonian and Albian marine shale units are the most effective Cretaceous source rocks related to hydrocarbon discoveries and production (figs. 7, 8) (Dumestre, 1985). Cenomanian to Turonian source-rock units developed in two subbasins (fig. 11) (Reymond and Negroni, 1989). The first area is located north of Cape Verde and includes the Mauritania and Northern subbasins (fig. 5) where samples from wells located along the shelf boundary have contained good source rocks as much as 380 m thick. These source rocks contain Type II and Type III organic matter (fig. 11) with source potentials between 3 and 21 kilograms per ton (kg/ton) (Reymond and Negroni, 1989). The second area is located south of Dakar in the Casamance subbasin. Reymond and Negroni (1989) stated that the richest source rocks contain Type II organic matter surrounded by a large area containing Type III organic matter (fig. 11). In this area, source potentials range between 5 and 75 kg/ton and thickness from 330 to 490 m. The Turonian interval contains bituminous shale as much as 150 m thick that was probably deposited under anoxic conditions (Kuhnt and Wiedmann, 1995) (fig. 6). Samples from the Casamance Maritime 1 well (fig. 11) contain Type II kerogen with TOC values ranging from about 7 to more than 10 weight percent (Reymond and Negroni, 1989). PETROSEN (2011a) stated that the Cenomanian source rocks contained TOC of 8.72 weight percent and had a hydrogen index (HI) of 660 milligrams of hydrocarbon per gram total organic carbon (mg HC/g TOC) and that Turonian samples contained 5.25 weight percent TOC and an HI value of 638 mg HC/g TOC. Geochemical data obtained from Deep Sea Drilling Project well samples (fig. 5, wells DSDP 367 and 368) identified potential Neocomian to Cenomanian source rocks beyond the 2-second sediment isopach (fig. 5) in the Senegal Basin (Tissot and others, 1980). The source rocks contain mostly Type II kerogen with TOC values ranging from about 3 to more than 10 weight percent. Minor sources within the post-rift section have been identified (Dumestre and Carvalho, 1985; Reymond and Negroni, 1989) including the Senonian and Maastrichtian (2–5 kg/ton, Type II and III), the Paleogene (greater than 5 kg/ton, Type II with detrital Type IV), and the Miocene to Pliocene (2–5 kg/ton, Type II) rocks.

A second important source rock consists of graptolitic Silurian shale as much as 400 m thick (fig. 4) in the southern half of the Senegal Basin in the Bové Basin (fig. 5) (Dumestre, 1985; Dumestre and Carvalho, 1985; Whaley, 2010). The Buba Shale (fig. 6) may be equivalent to the oil-prone Silurian Tannezzuft Formation of North Africa, which is an important source rock in North Africa and the Middle East. Samples from the Diana-Malari (DM–1) and Kolda (KO–1) wells (fig. 5) and outcrops in the Bové Basin and the Guinea Paleozoic Basin contain moderate amounts organic matter and have TOC values ranging from 1 to 5.5 weight percent (Reymond and Negroni, 1989; Whaley, 2010; PETROSEN, 2011b).

A potential third regional source rock is related to the syn-rift section in the Senegal Basin (Dumestre, 1985; Dumestre and Carvalho, 1985; Vear, 2005). These source rocks are the inferred lacustrine rocks below the thick Triassic salt unit (fig. 6). Seismic studies have delineated this clastic section below the salt in the Casamance region of southern Senegal (fig. 9). The syn-rift section does not crop out in the Senegal Basin and drilling has not penetrated the section (Dumestre and Carvalho, 1985).

Reservoirs, Traps, and Seals

The Mesozoic-Cenozoic section of the Senegal Basin can exceed 10,000 m in thickness and contain at least three primary reservoirs and seals: a Jurassic–Lower Cretaceous carbonate section sealed by Cenomanian shale or other Lower Cretaceous shale; Upper Cretaceous sandstone units and overlying shale units; and lower Tertiary clastic and carbonate units and shale units (figs. 6, 9, 10) (Dumestre, 1985; Dumestre and Carvalho, 1985; Fusion Oil and Gas, 2001). Although the Jurassic–Lower Cretaceous carbonate platform has never been fully penetrated by drilling, it does show good porosities ranging from 10 to 23 percent where sampled (Clifford, 1986; Whaley, 2010). Reefal prospects on the shelf edge remain to be investigated. Upper Cretaceous sandstone units in the eastern part of the basin become interbedded with shale on the western part of the offshore area. Maastrichtian sandstone as much as 30 m thick occurs at Dome Flore (figs. 5, 11), with porosities ranging from 20 to 30 percent, and it contains light oil (33.6 API) (Dumestre and Carvalho, 1985). In the Dome Flore area, an excellent Oligocene carbonate reservoir contains as much as 1 billion barrels of heavy oil (10° API, 1.6 percent sulfur) (Dumestre, 1985). About 40 km east of Dakar (fig. 1), several shallow oil and gas discoveries were made in the 1950s. Following a geologic reinterpretation of the area in 1984 these older wells and two new wells were found to be productive, with rates as much as 300 barrels of oil per day and 2.4 million cubic feet of gas per day (Dumestre, 1985).

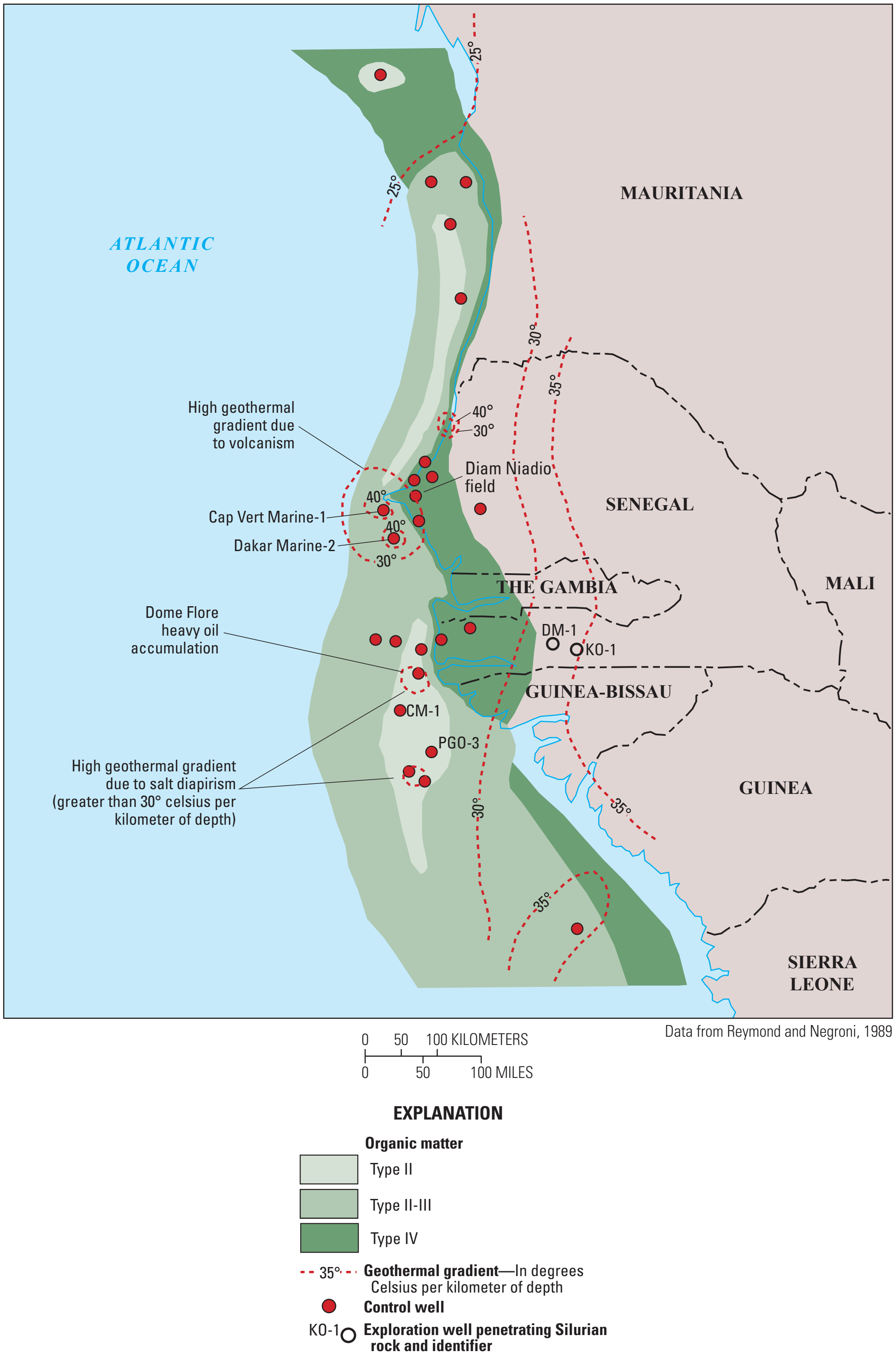


Figure 11. Distribution of organic matter in Cenomanian to Turonian source rocks. The Diana-Malari (DM–1) and Kolda (KO–1) wells penetrated the Silurian Buba Shale source rocks (fig. 6; TOC as much as 5.5 weight percent); the Casamance Maritime 1 (CM–1) well penetrated the Turonian bituminous shale (fig. 6; TOC from 7 to more than 10 weight percent). Modified from Reymond and Negroni (1989).

The Mesozoic-Cenozoic section in the Senegal Basin contains diverse oil and gas trapping mechanisms and configurations. These include salt-related structures, structures related to volcanic intrusion, growth-fault-related traps, slope-truncation traps along the present shelf edge, sandstone pinch-outs along the eastern basin margin (Dumestre and Carvalho, 1985; Fusion Oil and Gas, 2001; Vear, 2005), Lower Cretaceous–Jurassic carbonate bank deposits, and possible turbidite-related stratigraphic traps. Seals consist of Mesozoic and Cenozoic marine shale and faults.

Sandstone reservoirs are abundant in the lower Paleozoic section on the basis of measured sections in the Bové Basin and samples analyzed from the DM–1 and KO–1 stratigraphic test wells (fig. 5) (PETROSEN, 2003). The Ordovician sandstone is intensely fractured and provides good secondary reservoirs, whereas the Devonian fine- to coarse-grained sandstone beds have porosities ranging between 15 and 20 percent (PETROSEN, 2011b). In the onshore portion of the Paleozoic basin, regional seismic data have shown that the Paleozoic section has been faulted and, in conjunction with the Paleozoic unconformity, the faulting could form traps (figs. 6, 9). Interpretation of seismic data proposed that the Paleozoic unconformity is at a depth of about 10,000 m at the exploration well PGO-3 (fig. 11) (Dumestre and Carvalho, 1985) exploration hole in the Guinea-Bissau offshore.

Total Petroleum Systems of the Senegal Province, Northwest Africa

At least three total petroleum systems may be present in the Senegal Basin: the Lower Paleozoic Total Petroleum System (TPS) consisting of Silurian source rocks and Ordovician to Devonian and Triassic reservoir rocks; the Subsalt TPS consisting of Jurassic(?) lacustrine source rocks and clastic reservoirs capped by Jurassic salt; and the Cretaceous-Tertiary Composite TPS consisting of Cenomanian-Turonian source rocks and Cretaceous and Tertiary reservoirs. Only the Cretaceous-Tertiary TPS was considered for this assessment because current production and exploration data are almost entirely limited to the Cretaceous (IHS Energy, 2009). The USGS defined one assessment unit, the Coastal Plain and Offshore Assessment Unit (AU), to be included in the USGS National and Global Petroleum Assessment Project.

Lower Paleozoic and Subsalt Total Petroleum Systems

Two hypothetical total petroleum systems are present in the Senegal Basin: the Lower Paleozoic TPS and the Subsalt TPS. Events charts (figs. 12, 13) for the Lower Paleozoic and Subsalt TPSs summarize the age of the source, seal, and reservoir rocks and the timing of trap development and generation and migration of hydrocarbons. Limited drilling and seismic information are available for the Lower Paleozoic TPS, whereas no drilling and only limited seismic information are available for the Subsalt TPS (IHS Energy, 2009; Whaley, 2010).

The source rocks for the Lower Paleozoic TPS are oil-prone graptolitic Silurian shale that may be as much as 400 m thick (fig. 6, Buba Shale) in the southern half of the Senegal Basin (Whaley, 2010). Measurements carried out in outcrop and well samples show that these source rocks contain moderate amounts of organic matter and have TOC values ranging from 1 to 5.5 weight percent (Reymond and Negroni, 1989; Whaley, 2010; PETROSEN, 2011b). Sandstone reservoirs are abundant in the lower Paleozoic section in the Bové Basin and samples analyzed from stratigraphic test wells (fig. 5). The Ordovician and Devonian sandstone reservoirs are good potential secondary reservoirs (fig. 6) (PETROSEN, 2011b).

The Subsalt TPS is related to the syn-rift section and has never been tested in the Senegal Basin (Dumestre, 1985); however, seismic data suggest that this total petroleum system may be present and an important future hydrocarbon target (Bungerer, 1995). The source rocks are the inferred lacustrine rocks below the thick Triassic salt unit (Whaley, 2010). Recent seismic studies have delineated this clastic section below the salt in the Casamance region of southern Senegal (figs. 6, 9; Fusion Oil and Gas, 2001). Hydrocarbon generation is inferred to have started near the beginning of the Cretaceous to the middle Cretaceous (Reymond and Negroni, 1989). Reservoir rocks are inferred to be Triassic clastic units along the margins of the rift valleys and clastic rocks along the landward margins of Jurassic to Neocomian limestone (figs. 6, 9).

The hypothetical Lower Paleozoic TPS and Subsalt TPS were not assessed because current production and exploration data are almost entirely limited to the Cretaceous. These two Petroleum Systems have potential to be substantial hydrocarbon targets in the future.

Cretaceous Composite Total Petroleum System

The Cretaceous-Tertiary Composite Total Petroleum System was defined in the Senegal Basin. An events chart (fig. 14) summarizes the age of the source, seal, and reservoir rocks and the timing of trap development and generation and migration of hydrocarbons.

The principal source rocks in the Cretaceous-Tertiary Composite TPS are Late Cretaceous Cenomanian and Turonian rocks (fig. 14). Turonian rocks, which can be as much as 150 m thick, contain TOC values ranging from 3 to 10 weight percent and Types II and III organic matter

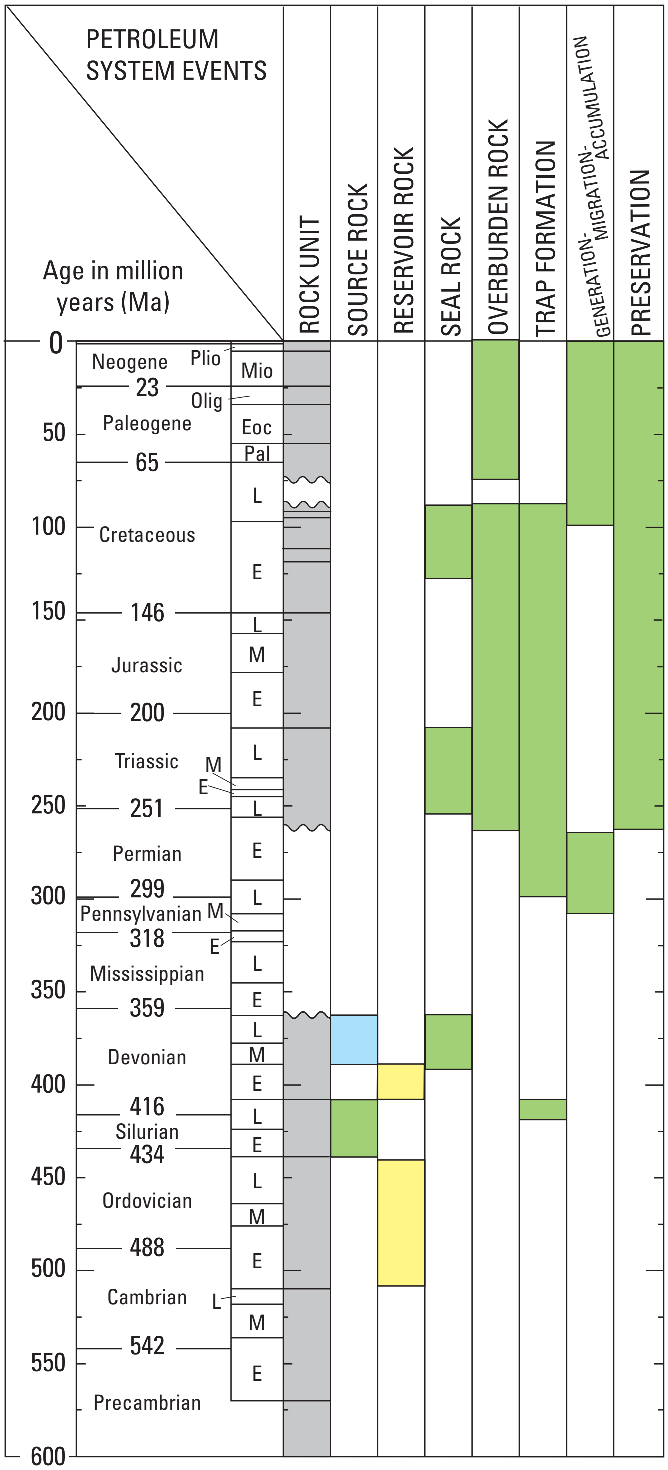


Figure 12. Events chart for the hypothetical Lower Paleozoic Total Petroleum System, Senegal Province, northwest Africa. Gray, rock units present; blue, secondary or possible source rocks depending on quality and maturity of the unit; yellow, age range of reservoir rock; green, age ranges of source, seal, and overburden rocks and the timing of trap formation and generation, migration, and preservation of hydrocarbons; wavy line, unconformity. Divisions of geologic time conform to dates in U.S. Geological Names Committee (2010). Ma, million years ago; Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, late; E, early; M, middle.

(Reymond and Negroni, 1989; PETROSEN, 2011a). Petroleum generation is presumed to have begun during the Miocene and continues to the present. Migration and charge most likely occurred shortly after generation along faults and through porous Cretaceous and Tertiary reservoirs.

Reservoir rocks can be found throughout the section and include Upper Cretaceous sandstone and Tertiary clastic units and carbonate. The Lower Cretaceous carbonate platform and Cretaceous reef units have not been explored (figs. 6, 7, 8, 9, 10). Oligocene carbonate reservoirs exist, such as the Dome Flore discovery (figs. 5, 11) that contains as much as 1 billion barrels of heavy oil (Dumestre, 1985; Whaley, 2010). The Dome Flore reservoir was charged with oil originating in Turonian rocks. The oil underwent degradation due to an insufficient seal that allowed water washing or biodegradation or both.

The Mesozoic-Cenozoic part of the Senegal Basin contains diverse trapping mechanisms (figs. 9, 10), including salt-related structures, structures related to volcanic intrusions, growth-fault-related traps, slope truncations along the present day and the Mesozoic shelf edge (the Senonian unconformity) (Reymond and Negroni, 1989; Whaley, 2010; PETROSEN, 2011a), Mesozoic and Tertiary pinchouts along the eastern margin, and reef buildups along the shelf edge. The Upper Cretaceous and Tertiary marine mudstone and shale rocks are the primary seals for the reservoirs in the Cretaceous-Tertiary Composite TPS.

Two limiting factors in the development of hydrocarbon accumulations in the Senegal Basin may be the timing of hydrocarbon migration and the lack of effective deeper seals. Many of the early exploration wells, however, were drilled on structures on the basis of interpretations of low-quality seismic data. Currently, many of the seismic lines are being reinterpreted and new lines have been run.

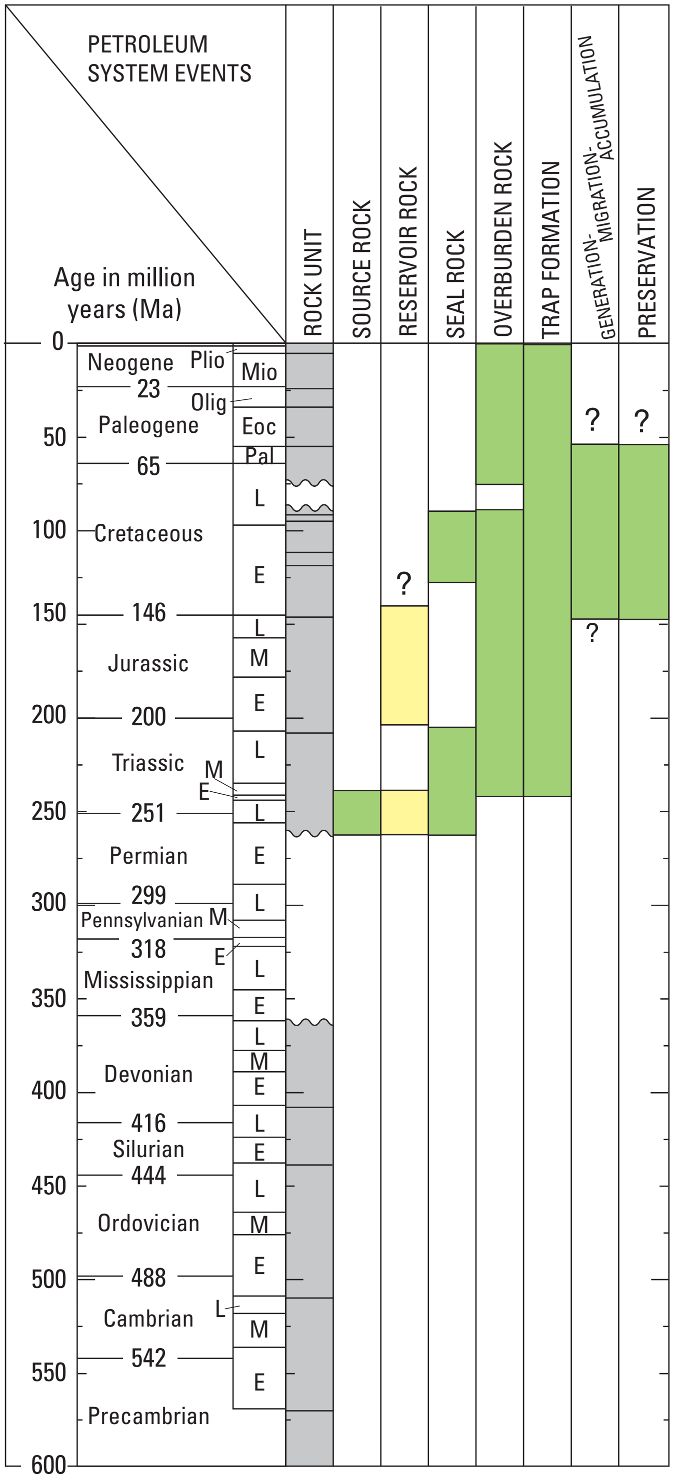


Figure 13. Events chart for the hypothetical Subsalt Total Petroleum System in the Senegal Basin, northwest Africa. Gray, rock units present; yellow, age range of reservoir rock; green, age ranges of source, seal, and overburden rocks and the timing of trap formation and generation, migration, and preservation of hydrocarbons; wavy line, unconformity. Divisions of geologic time conform to dates in U.S. Geological Survey Geologic Names Committee (2010). Ma, million years ago; Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, late; E, early; M, middle.

Exploration

Several formations in the Senegal Basin contain both offshore and onshore hydrocarbon accumulations (Fusion Oil and Gas, 2001; Whaley, 2010; PETROSEN, 2011a). The best-understood hydrocarbon accumulations in the Senegal Basin are in Cretaceous and Tertiary reservoirs. The lower Paleozoic rocks contain oil-prone organic matter, and seismic data delineated a Permian-Triassic clastic section that may contain hydrocarbon source rocks. Jurassic and Lower Cretaceous carbonate rocks have been explored only nearshore and are considered to be underexplored (Whaley, 2010). These reservoirs have porosities ranging from 10 to 23 percent and are overlain by thick marine shale.

Hydrocarbon production and exploration activity was limited at the time of a previous assessment in year 2000 (Brownfield and Charpentier, 2003), and only several small oil and gas fields around Cape Verde (also known as the Dakar Peninsula) produced hydrocarbons from Upper Cretaceous sandstone reservoirs.

Since the 2000 assessment (U.S. Geological Survey World Energy Assessment Team, 2000; Brownfield and Charpentier, 2003), 14 new oil and gas fields have been discovered in the Senegal Basin—8 gas and 6 oil fields, 10 of which are offshore (IHS Energy, 2009). Exploration wells and discovered accumulations offshore provide evidence for the existence of an active petroleum system containing Cretaceous marine source rocks that have produced hydrocarbons most likely since the Late Cretaceous, and the migration of hydrocarbons into Cretaceous and Paleogene reservoirs. Currently only a small amount of gas is being produced from the Diam Niadio field in Senegal (figs. 1, 11), and oil is being produced from the Chinguetti field (fig. 1), offshore Mauritania (IHS Energy, 2009). The Senegal Basin Province is considered underexplored on the basis of its limited exploration history.

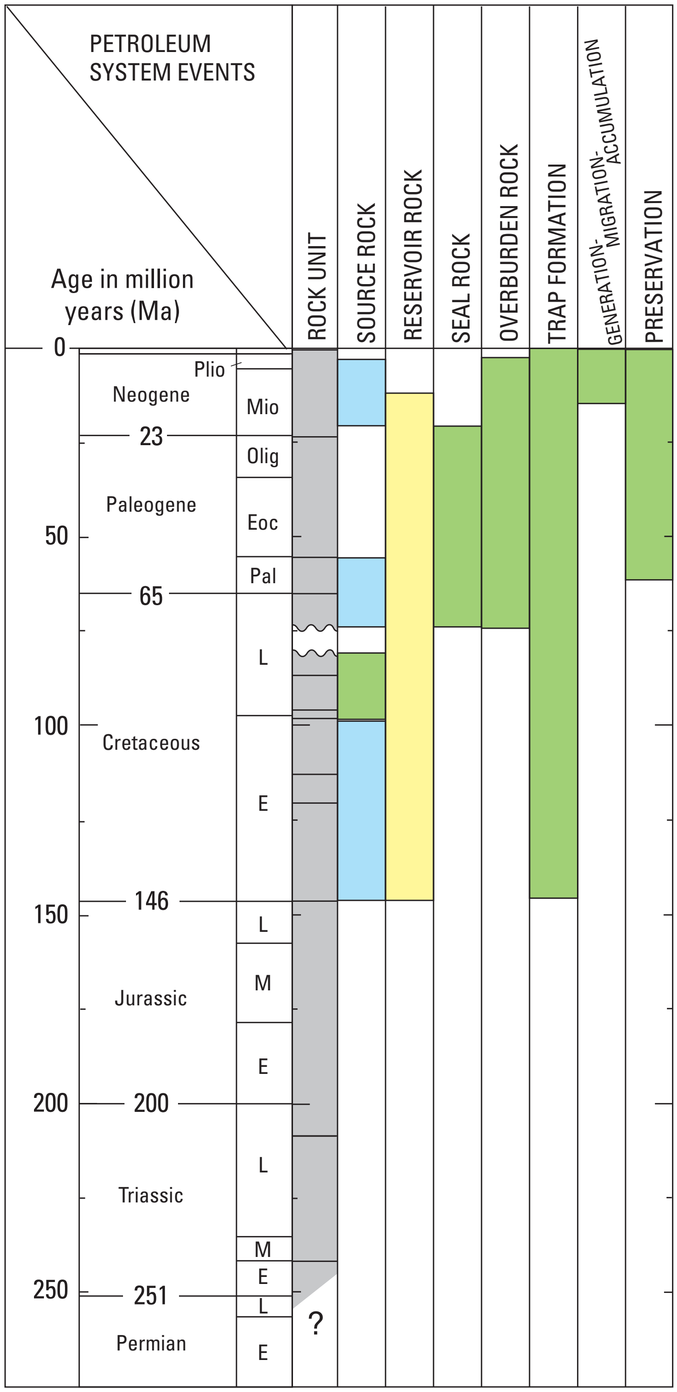


Figure 14. Events chart for the Cretaceous-Tertiary Composite Total Petroleum System (701301) and the Coastal Plain and Offshore Assessment Unit (70130101). Gray, rock units present; blue, secondary or possible source rocks depending on quality and maturity of the unit; yellow, age range of reservoir rock; green, age ranges of source, seal, and overburden rocks and the timing of trap formation and generation, migration, and preservation of hydrocarbons; wavy line, unconformity. Divisions of geologic time conform to dates in U.S. Geological Survey Geologic Names Committee (2010). Ma, million years ago; Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, late; E, early; M, middle; ?, uncertain.

Geologic Model

The geologic model developed for the assessment of conventional oil and gas in the Senegal Basin Province and the Coastal Plain and Offshore AU is as follows:

1. Hydrocarbons were generated from Cenomanian and Turonian marine shales. Turonian Type II source rocks range from 7 to 10 weight percent total organic carbon. Hydrocarbon generation started in the Miocene and continues to the present. Possible source rocks may also exist in the clastic section below the Triassic salt.
2. Generated hydrocarbons migrated into Cretaceous and Tertiary reservoirs.
3. Hydrocarbon traps include salt-related structures, structures related to volcanic intrusions, growth-fault-related traps, slope truncations along the present day and Mesozoic shelf edge (Senonian unconformity), Mesozoic and Tertiary pinch-outs along the eastern basin margin, and reef buildups along the shelf edge.
4. The Upper Cretaceous and Tertiary marine mudstone and shale rocks are the primary reservoir seals.
5. Passive-margin analog (Charpentier and others, 2007) was used for assessment field sizes and numbers because of similar source and reservoir rocks and traps.

Events charts (figs. 12, 13, 14) for the hypothetical Lower Paleozoic TPS, the hypothetical Subsalt TPS, and the Cretaceous-Tertiary Composite TPS and its Coastal Plain and Offshore AU summarize the age of the source, seal, and reservoir rocks and the timing of trap development and generation and migration of hydrocarbons.

Resource Summary

At the time of the 2009 assessment, here reported, 17 oil and gas fields had been discovered in the Senegal Basin Province—10 gas and 7 oil fields, 10 of which are offshore and exceed the minimum size of 1 million barrels of oil equivalent. The province is considered underexplored based upon its limited exploration history.

Using a geology-based assessment, the U.S. Geological Survey estimated mean volumes of undiscovered, technically recoverable conventional oil and gas resources for the Coastal Plain and Offshore Assessment Unit in the Senegal Province (table 1). The mean volumes are estimated at 2,350 million barrels of oil, 18,706 billion cubic feet of gas, and 567 million barrels of natural gas liquids. The estimated mean size of the largest oil field that is expected to be discovered is 579 million barrels of oil and the estimated mean size of the expected largest gas field is 3,505 billion cubic feet of gas. For this assessment, a minimum undiscovered field size of 5 million barrels of oil equivalent was used. No attempt was made to estimate economically recoverable reserves.

Table 1. Assessment results for undiscovered, technically recoverable oil, gas, and natural gas liquids for the Senegal Province, Sub-Saharan Africa.

[Largest expected mean field size in million barrels of oil and billion cubic feet of gas; MMBO, million barrels of oil; BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas accumulations, all liquids are included as natural gas liquids (NGL). Undiscovered gas resources are the sum of nonassociated and associated gas. F95 represents a 95 percent chance of at least the amount tabulated; other fractiles are defined similarly. Fractiles are additive under assumption of perfect positive correlation. AU, assessment unit; AU probability is the chance of at least one accumulation of minimum size within the AU. TPS, total petroleum system. Gray shading indicates not applicable]

Province, Total Petroleum Systems (TPS) and Assessment Units (AU)	Field type	Largest expected mean field size	Total undiscovered resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Senegal Province–Cretaceous—Tertiary Composite TPS														
Coastal Plain and Offshore AU	***Oil***	579	720	2,073	4,914	2,350	1,343	3,914	9,519	4,465	35	105	261	121
	Gas	3,505					4,353	12,563	29,747	14,241	134	391	942	446
Total Conventional Resources			**720**	**2,073**	**4,914**	**2,350**	**5,696**	**16,477**	**39,266**	**18,706**	**169**	**496**	**1,203**	**567**

The province has the greatest potential for hydrocarbon discoveries in offshore targets. The undiscovered gas resources may be significant and accessible in areas where the zone of oil generation is relatively shallow.

For Additional Information

Assessment results are available at the USGS Central Energy Resources Science Center website: http://energy.usgs.gov/OilGas/ or contact Michael E. Brownfield, the assessing geologist (*mbrownfield@usgs.gov*).

Acknowledgments

The author wishes to thank Mary-Margaret Coates, Jennifer Eoff, Christopher Schenk, and David Scott for their suggestions, comments, and editorial reviews, which greatly improved the manuscript. The author thanks Wayne Husband for his numerous hours drafting many of the figures used in this manuscript, and Chris Anderson, who supplied the Geographic Information System files for this assessment.

References

Brownfield, M.E., and Charpentier, R.R., 2003, Assessment of the undiscovered oil and gas of the Senegal Province, Mauritania, Senegal, Gambia, and Guinea Bissau, northwest Africa: U.S. Geological Survey Bulletin 2207–A, 28 p.

Bungener, J.A., 1995, The Gambia/Gambia, *in* Kulke, H., ed., Regional petroleum geology of the world: Stuttgart, Germany, Gebruder Borntraeger, p. 103−104.

Bungener, J.A., and Hinz, K., 1995, Senegal/Senegal, *in* Kulke, H., ed., Regional petroleum geology of the world: Stuttgart, Germany, Gebruder Borntraeger, p. 99−102.

Charpentier, R.R., Klett, T.R., and Attanasi, E.D., 2007, Database for assessment unit-scale analogs (exclusive of the United States), Version 1.0: U.S. Geological Survey Open-File Report 2007−1404, 36 p., CD–ROM.

Clifford, A.C., 1986, Africa oil—Past, present, and future, *in* Halbouty, M.T., ed., Future petroleum provinces of the world: American Association of Petroleum Geologist Memoir 40, p. 339−372.

Dumestre, M.A., 1985, The petroleum geology of Senegal: Oil and Gas Journal, October 28, 1985, p. 146−152.

Dumestre, M.A., and Carvalho, F.F., 1985, The petroleum geology of the Republic of Guinea Bissau: Oil and Gas Journal, September 9, 1985, p. 180−191.

Fusion Oil and Gas, LLC, 2001, The northwest frontier Mauritania to Guinea-Bissau—A new deepwater petroleum province?: Africa Upstream conference, Cape Town, South Africa, October, 17–19, 2001, Proceedings, 37 p.

IHS Energy, 2009, International petroleum exploration and production database [current through December 2009]: available from IHS Energy, 15 Inverness Way East, Englewood, Colo. 80112 USA.

Klett, T.R., Ahlbrandt, T.S., Schmoker, J.W., and Dolton, G.L., 1997, Ranking of the world's oil and gas provinces by known petroleum volumes: U.S. Geological Survey Open-File Report 97−463, CD–ROM.

Kuhnt, Wolfgang, and Wiedmann, Jost, 1995, Cenomanian-Turonian source rocks—Paleobiogeographic and source rocks, *in* Huc, Alain-Yves, ed., Paleogeography, paleoclimate, and source rocks: American Association of Petroleum Geologists Studies in Geology 40, p. 213–231.

Lambiase, J.J., 1989, The framework of African rifting during the Phanerozoic: Journal of African Earth Science, v. 8, no. 2/3/4, p. 183−190.

Persits, F.M., Ahlbrandt, T.S., Tuttle, M.L., Charpentier, R.R., Brownfield, M.E., and Takahashi, K.I., 2002, Map showing geology, oil and gas fields, and geologic provinces of Africa: U.S. Geological Survey Open-File Report 97–470A, Version 2.0, CD–ROM.

PETROSEN, 2003, The hydrocarbon potential of the Senegal Paleozoic Basin, Senegalese National Oil Company (PETROSEN), 8 p. Available at http://www.petrosen.sn/images/stories/downloads/Paleozoic-senegal.pdf. Last accessed April 2, 2013.

PETROSEN, 2011a, The Mesocenozoic Basin: Senegalese National Oil Company (PETROSEN), 2 p. Available at http://www.petrosen.sn/index.php?option=com_content&view=article&id=18&Itemid=67&lang=en. Last accessed April 2, 2013.

PETROSEN, 2011b, Paleozoic Basin, Senegalese National Oil Company (PETROSEN), 4 p. Available at http://www.petrosen.sn/index.php?option=com_content&view=article&id=17&Itemid=66&lang=en. Last accessed April 2, 2013.

Reymond, A., and Negroni, P., 1989, Hydrocarbon occurrence in NW Africa's MSGBC area: World Oil, June 1989, p. 53–58.

Tissot, B., Demaison, G., Masson, P., Delteil, J.R., and Combaz, A., 1980, Paleoenvironment and petroleum potential of middle Cretaceous black shales in Atlantic basins: American Association of Petroleum Geologists Bulletin, v. 64, no. 12, p. 2051–2063.

Uchupi, Elezar, 1989, The tectonic style of the Atlantic Mesozoic rift system: Journal of African Earth Sciences, v. 8, nos. 2, 3, 4, p. 143–164.

U.S. Geological Survey Geologic Names Committee, 2010, Divisions of geologic time: U.S. Geological Survey Fact Sheet 2010–3059, 2 p. Available at http://pubs.usgs.gov/fs/2010/3059/.

U.S. Geological Survey World Energy Assessment Team, 2000, U.S. Geological Survey World Petroleum Assessment 2000—Description and results: U.S. Geological Survey Digital Data Series DDS–60, 4 CD–ROMs.

U.S. Geological Survey World Conventional Resources Assessment Team, 2012, An estimate of undiscovered conventional oil and gas resources of the world, 2012: U.S. Geological Survey Fact Sheet 2012–3042, 6 p. Available at http://pubs.usgs.gov/fs/2012/3042/.

Vear, A., 2005, Deep-water plays of the Mauritanian continental margin, *in* Dore, A.G., and Vining, B.A., eds., North-west Europe and Global perspectives—Conference on Petroleum Geology, 6th: Geological Society, London, Proceedings, p. 1217–1232.

Whaley, J., 2010, Country profile—Senegal: Geo ExPro, v. 7, no. 4, p. 32–40. Available at http://www.geoexpro.com/article/Country_Profile_Senegal/a3ad6ecd.aspx. Last accessed April 2, 2013.

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