Assessment of Undiscovered Oil and Gas Resources of the West African Coastal Province, West Africa

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Compiled by Michael E. Brownfield

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Contents

Figures

Table

Abbreviations Used in This Report

km^2	square kilometer
m	meter
BCFG	billion cubic feet of gas
USGS	U.S. Geological Survey
TPS	total petroleum system
AU	assessment unit
TOC	total organic carbon

Assessment of Undiscovered Oil and Gas Resources of the West African Coastal Province, West 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, in 2011, the U.S. Geological Survey completed an assessment of the West African Coastal Province, an area of about 202,715 square kilometers that covers parts of Guinea, Liberia, and Sierra Leone. This assessment was based on data from oil and gas exploration wells and published geologic reports. At the time of the assessment, the province contained no discovered fields and only 10 exploration wells had been drilled; it is considered to be underexplored on the basis of its exploration activity.

The West African Coastal Province was assessed because of increased energy exploration activity and interest in its future oil and gas resource potential. The assessment was geology based and used the total petroleum system concept. The geologic elements of a total petroleum system consist of hydrocarbon source rocks (source-rock maturation and hydrocarbon generation and migration), reservoir rocks (quality and distribution), and traps where hydrocarbon accumulates. Using these geologic criteria, the U.S. Geological Survey defined the Cretaceous Composite Total Petroleum System with one assessment unit, the Mesozoic-Cenozoic Reservoirs Assessment Unit. This assessment unit encompasses about 188,550 square kilometers and includes the offshore parts of the province to a water depth of 4,000 meters.

Hydrocarbons were generated from Aptian, early to middle Albian, Cenomanian, and Turonian marine shale. Turonian Type II source rocks contain total organic carbon values ranging from 3 to 10 weight percent. Hydrocarbon generation started in the Late Cretaceous and continues to the present. Once generated, the hydrocarbons migrated into Cretaceous sandstone reservoirs and perhaps into Paleogene sandstone reservoirs. Structural traps include (1) growth-fault-related structures, (2) rotated fault blocks within the continental shelf and below the mid-Cretaceous unconformity, (3) stratigraphic traps related to deep-water fans, turbidite units, slope truncations along the present-day shelf and paleoshelf edge, and (4) Cretaceous and Paleogene stratigraphic pinch-outs along the eastern basin margin. The Upper Cretaceous and Tertiary marine mudstone and shale rocks are the primary seals. A passive-margin analog was used because of similar source and reservoirs rocks and traps.

In this 2011 assessment, the U.S. Geological Survey estimated mean volumes of undiscovered, technically recoverable conventional oil and gas resources for the Mesozoic-Cenozoic Reservoirs AU in the West African Coastal Province. The mean volumes are estimated at 3,200 million barrels of oil, 23,629 billion cubic feet of gas, and 721 million barrels of natural gas liquids. The estimated mean size of the largest oil field that is expected to be discovered is 783 million barrels of oil, and the estimated mean size of the expected largest gas field is 4,695 billion cubic feet of gas. For this assessment, a minimum undiscovered field size of 5 million barrels of oil equivalent was used.

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 completed an assessment in 2011 of the West African Coastal Province (fig. 1), an area of about 202,715 square kilometers (km^2) and that covers parts of Guinea, Liberia, and Sierra Leone. This assessment was based on data from oil and gas exploration wells (IHS Energy, 2009) and published geologic reports. At the time of the assessment, the province contained no discovered oil and gas fields and only 10 exploration wells had been drilled. This province is considered to be underexplored on the basis of its limited exploration.

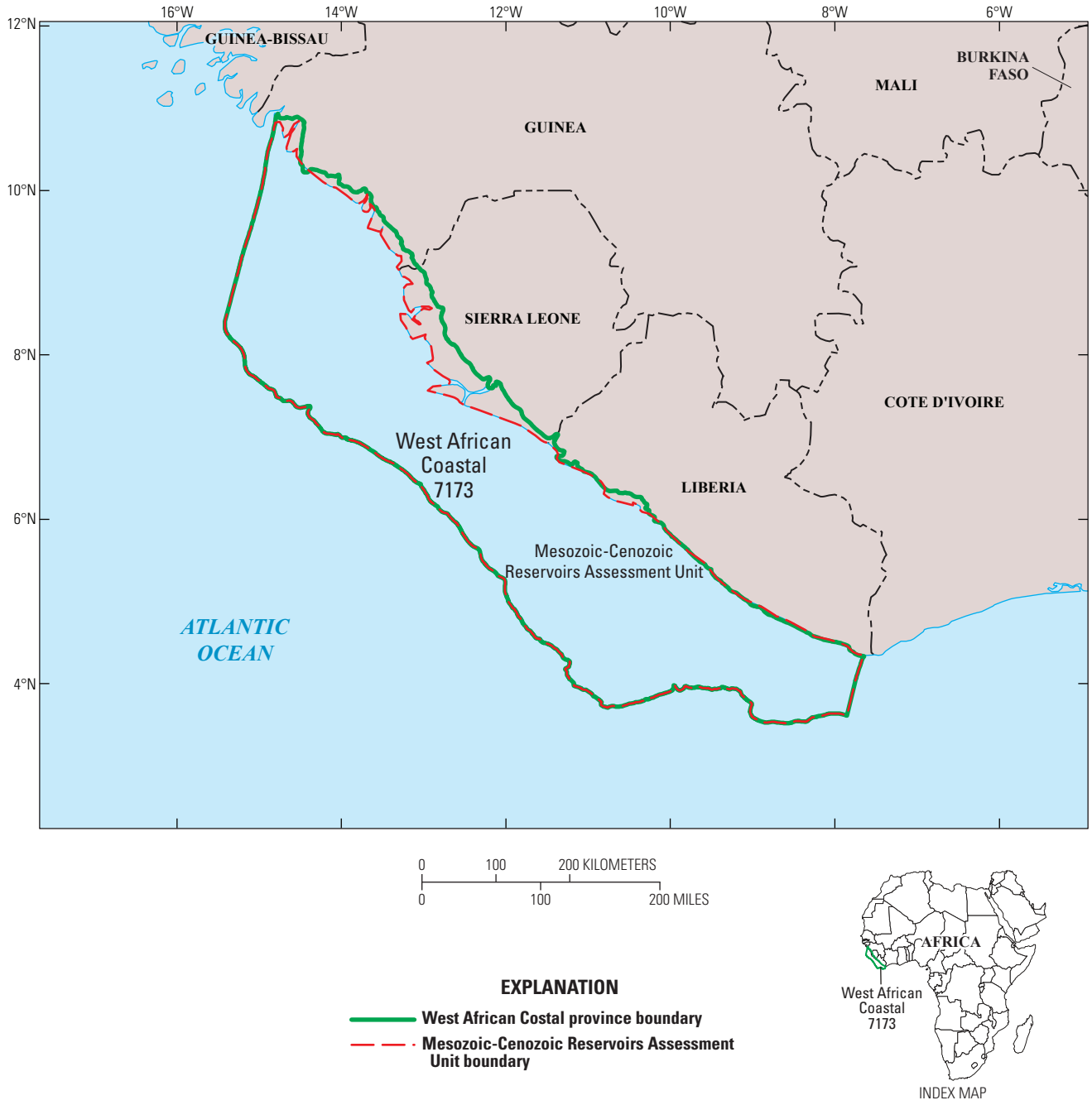

Figure 1. Location of the West African Coastal Province and the Mesozoic-Cenozoic Assessment Unit, west Africa.

The West African Coastal Province was assessed because of increased exploratory activity and interest in its future oil and gas potential. The assessment was geology based and used the total petroleum system concept. The geologic elements of a total petroleum system consist of hydrocarbon source rocks (source-rock maturation and hydrocarbon generation and migration), reservoir rocks (quality and distribution), and traps (for hydrocarbon accumulation). Using these geologic criteria, the USGS defined the Cretaceous Composite Total Petroleum System (TPS) with one assessment unit, the Mesozoic-Cenozoic Reservoirs Assessment Unit (AU) (fig. 1), encompassing about 188,550 km^2, which includes the offshore parts of the province to a water depth of 4,000 meters (m).

Tectonic History of the West African Coastal Province, West Africa

The West African Coastal Province was dominated by continental sedimentation during the late Paleozoic Hercynian event until rifting began in Late Jurassic time (Bennett and Rusk, 2002). The West African Coastal Province developed in two phases: the syn-rift phase, which initiated during the Early Cretaceous (fig. 2), resulted in the formation of deep grabens and half-grabens; and the passive margin–transform phase, which began in the late Albian and continues to the present (Mascle and others, 1988). The Paleogene to Neogene is dominated by passive-margin sedimentation consisting of channel-fed fans and turbidites. Three major transform fault systems divide the offshore of the province into subbasins along the coast of Sierra Leone, and Liberia (fig. 3) (Bennett and Rusk, 2002). The total thickness of the Mesozoic to Cenozoic section is about 5,000 m on the outermost part of the continental shelf and thickens to as much as 10,000 m in the basin depocenters (Bennett and Rusk, 2002).

Geology

The West African Coastal Province and the Mesozoic-Cenozoic Reservoirs AU is located along the west coast of Africa (fig. 4). Rocks associated with the Late Jurassic to mid-Cretaceous syn-rift phase (figs. 1, 5) resulted from tectonic subsidence and stretching of the continental crust (Mascle and others, 1988; Grand and others, 2009). Extensional block faults are associated with extrusive volcanic rocks, and continental clastic rocks were deposited into grabens.

During the Aptian and Albian ages, continental-clastic sediment was deposited in fluvial and lacustrine environments in rapidly subsiding basins along regional transform faults. By late Albian time, shallow-marine transgressions flooded the rifted basins.

Cenomanian to Turonian sediments were deposited over the late Albian unconformity (figs. 5, 6) and consist of fluvial-deltaic and shallow-marine to deep-marine rocks (Bennett and Rusk, 2002; Grand and others, 2009). A Senonian erosional event is marked by an unconformity along the inner shelf.

The post-rift or passive-margin phase began in the Late Cretaceous (Grand and others, 2009). As thermal subsidence and sea-floor spreading continued, a Late Cretaceous transgression progressed over the Senonian unconformity (Bennett and Rusk, 2002). Marine clastic sediment consisting of channel-fed fans and turbidites was deposited on the steep continental slope. Marine clastic and carbonate rocks were deposited during a Paleocene transgression. Following the Oligocene global sea-level fall and the resulting unconformity (figs. 5, 6), marine deposition resumed in the Miocene and continued throughout the Neogene (Bennett and Rusk, 2002).

Petroleum Occurrence in West African Coastal Province, West Africa

Source Rocks

The Cretaceous Composite TPS was defined to include Cretaceous marine source rocks, reservoirs, and seals. Early to middle Albian oil-prone source rocks contain Type II kerogen with total organic carbon (TOC) values ranging from 1.9 to 5 weight percent (TGS, 2012). The Cenomanian-Turonian source rocks are assumed to be in the deeper offshore parts of the province (figs. 5, 6). These organic-rich, oil-prone source rocks are known both north and east of the province and contain Type II kerogen ranging from 3 to 10 weight percent TOC (Tissot and others, 1980; Grand and others, 2009; TGS, 2012). Possible lacustrine source rocks may be present in grabens that developed during the Early Cretaceous (Bennett and Rusk, 2002).

The top of the present-day oil window ranges from about 2,500 m near the eastern part of the continental margin (Bennett and Rusk, 2002) to more than 7,000 m in the western part of the continental slope (fig. 7). Hydrocarbon generation began in the Late Cretaceous and continued in a second period of generation in the late Tertiary owing to deeper burial (Grand and others, 2009).

An events chart for the Cretaceous Composite TPS and the Mesozoic-Cenozoic Reservoirs AU summarizes the age of the source rocks, seals, and reservoirs rocks and the timing of trap development and generation and migration of hydrocarbons (fig. 8).

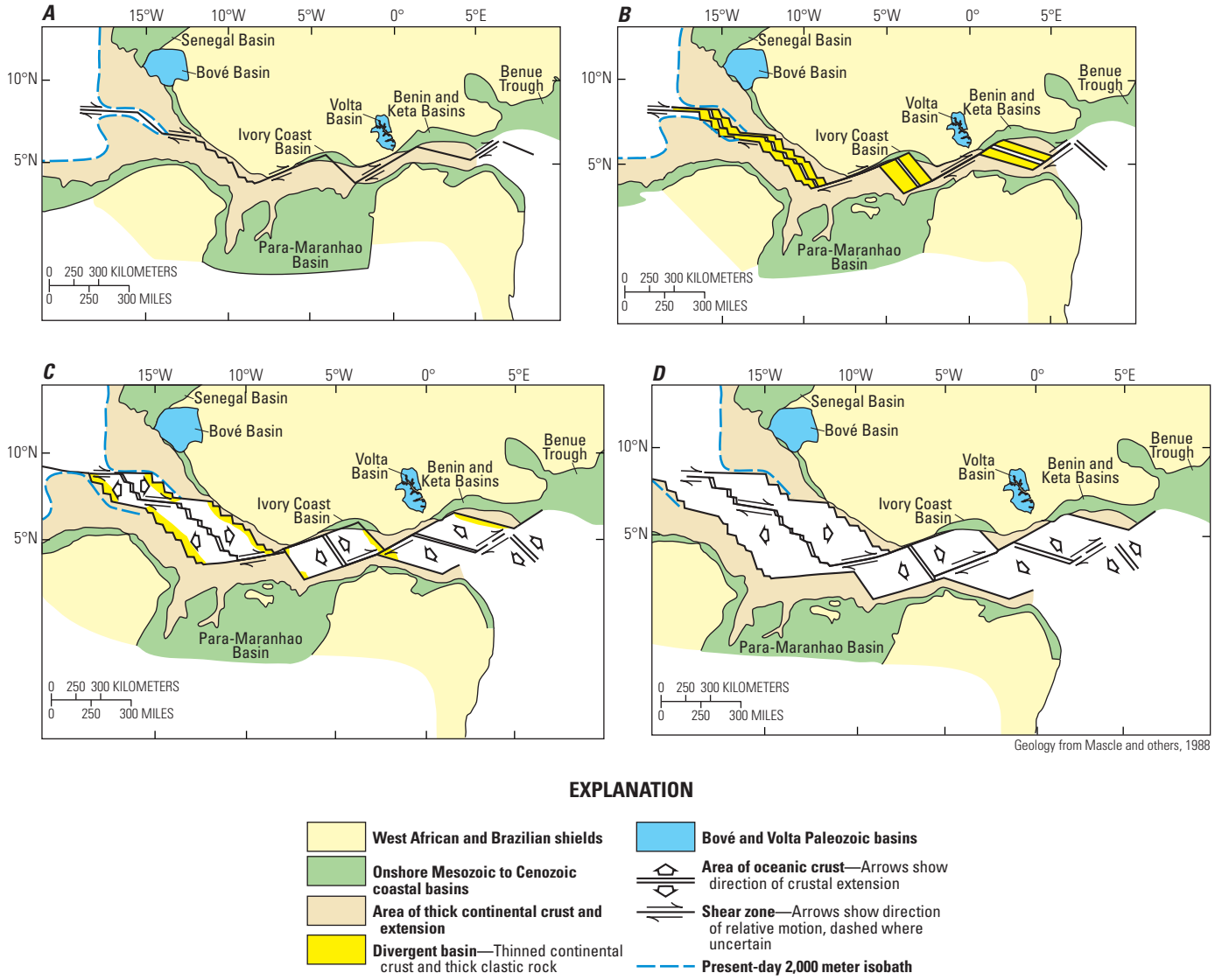

Figure 2. Schematic Cretaceous stages in the Mesozoic breakup of Africa and South America and the tectonic evolution of the Equatorial Atlantic, showing the approximate locations of the Bové, Benin, Ivory Coast, Keta, Senegal, and Volta Basins and the Benue Trough of Africa and the Para-Maranhao Basin 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).

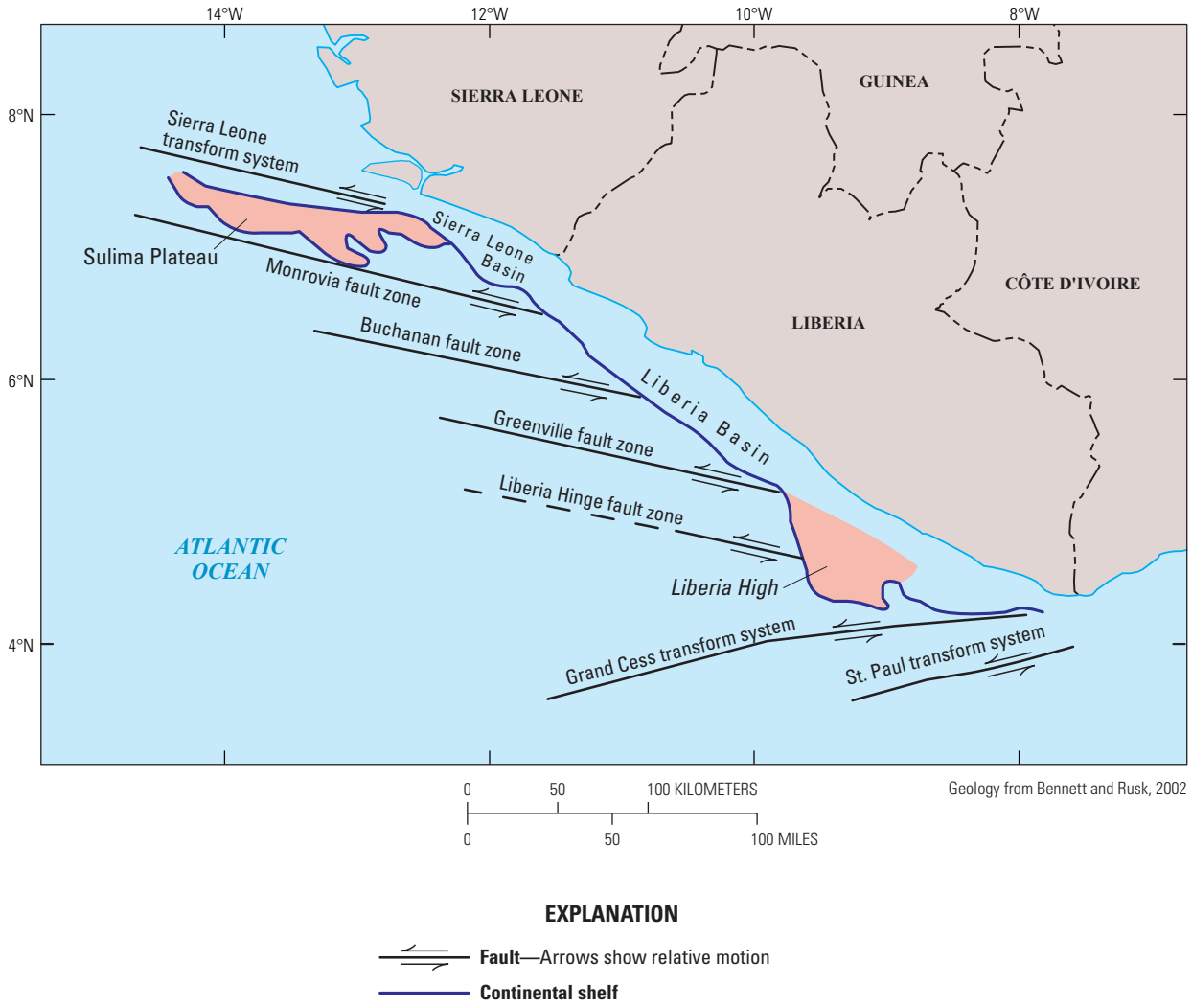

Figure 3. Major transform systems along the Sierra Leone, Liberia, and Côte d'Ivoire coast, west Africa. Intersection of fault zones and the continental shelf shown as red line. Modified from Bennett and Rusk (2002).

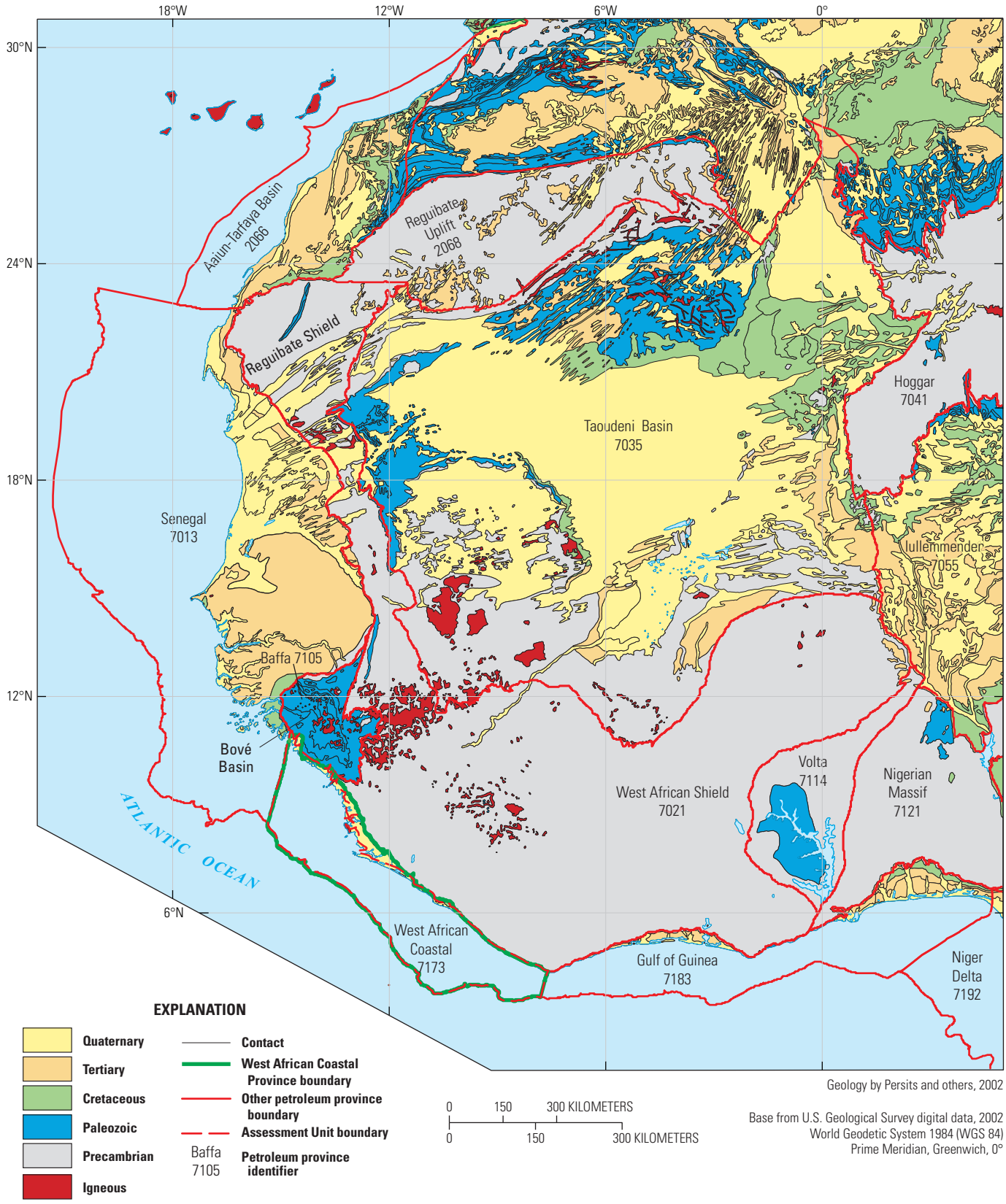

Figure 4. Generalized geology of west Africa (from Persits and others, 2002), showing province boundaries and 13 province names and codes as defined by Klett and others (1997).

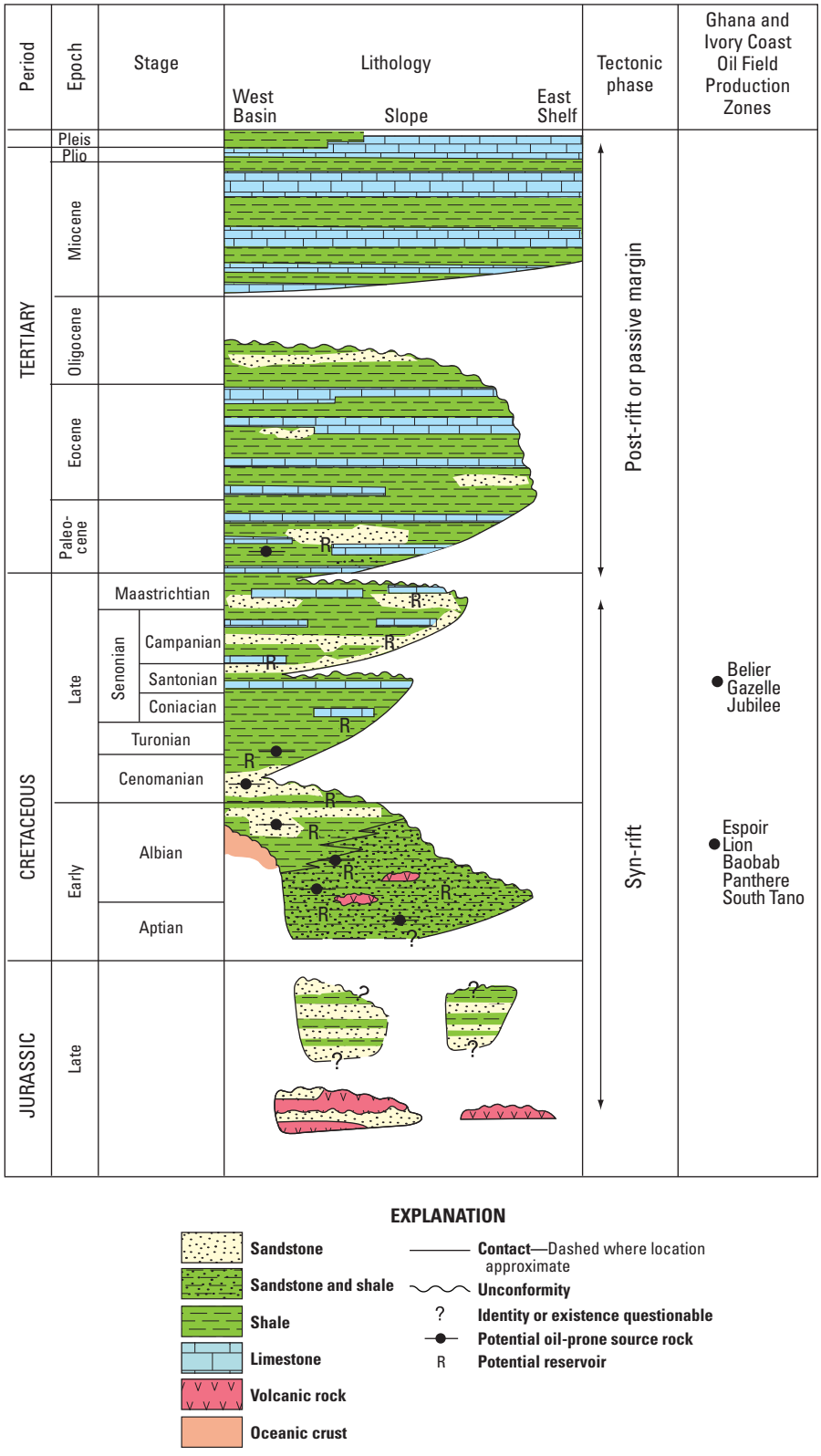

Figure 5. Stratigraphy of offshore part of Sierra Leone and Liberia showing potential reservoirs and source rocks. Modified from Grand and others (2009).

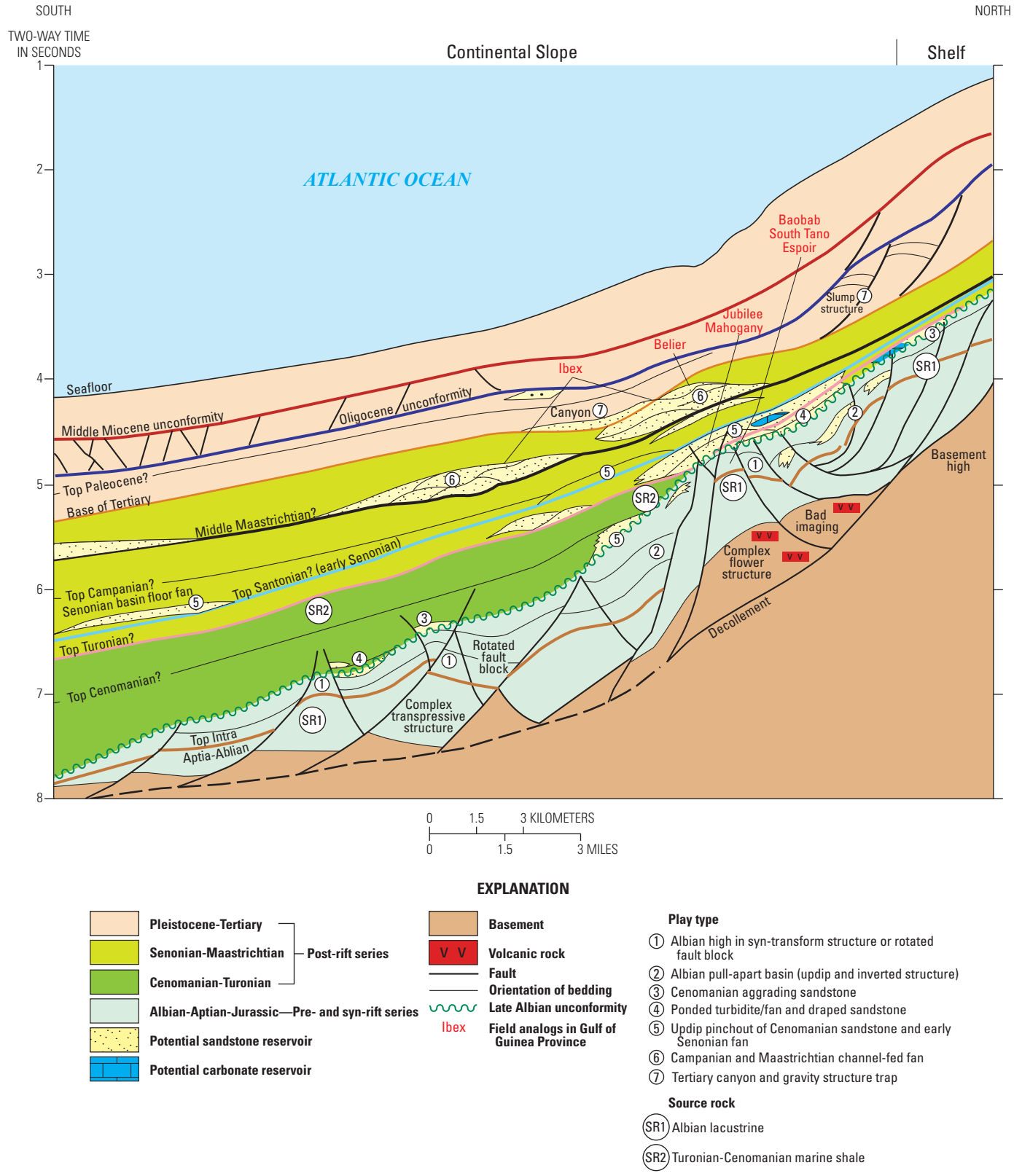

Figure 6. Cross sectional stratigraphy based on seismic data of offshore Sierra Leone margin showing field analogs with Côte d'Ivoire offshore basin. Modified from Grand and others (2009).

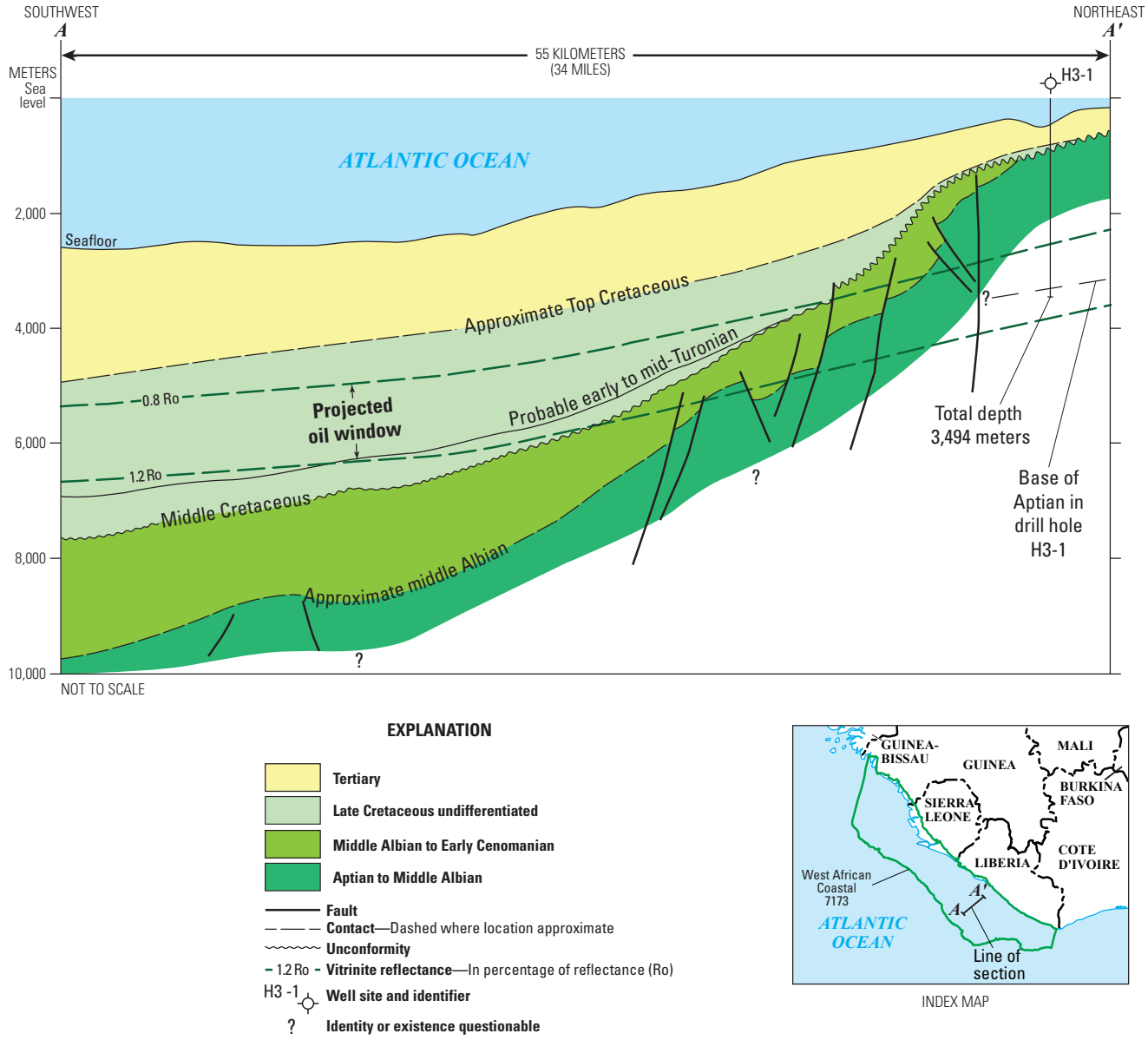

Figure 7. Stratigraphic cross section based on seismic data of offshore Liberia showing projected present-day oil window. Source rocks are found in early to middle Albian and Cenomanian-Turonian rocks. Modified from Bennett and Rusk (2002).

Reservoirs, Traps, and Seals

The Mesozoic-Cenozoic Reservoirs AU contains Cretaceous and Paleogene clastic reservoirs and traps that are primarily associated with growth-fault-related structures, such as rotated fault blocks within the continental shelf and below the mid-Cretaceous unconformity (Bennett and Rusk, 2002), and stratigraphic traps related to deep-water fans, turbidite units, slope truncations along the present-day shelf and paleoshelf edge, and Cretaceous and Paleogene stratigraphic pinch-outs along the eastern basin margin (fig. 6) (Flinch and others, 2009; Grand and others, 2009). The primary seals are interbedded Cretaceous shale and with updip Neogene to Paleogene marine mudstone and shale.

Exploration

Only 10 exploration wells were drilled before 2009; these wells were sited in water depths ranging from 100 to 470 m on the continental shelf and upper slope in the West African Coastal Province (IHS Energy, 2009). The wells demonstrated the existence of an active petroleum system containing Cretaceous marine source rocks that have generated hydrocarbons most likely since the Late Cretaceous; those hydrocarbons migrated into Cretaceous and Paleogene reservoirs (Grand and others, 2002). After the 2011 assessment, three deep-water discovery wells were drilled in the Sierra Leone offshore part of the Liberia Basin (fig. 3) (Jewell, 2011; Canadian Overseas Petroleum Limited, 2012).

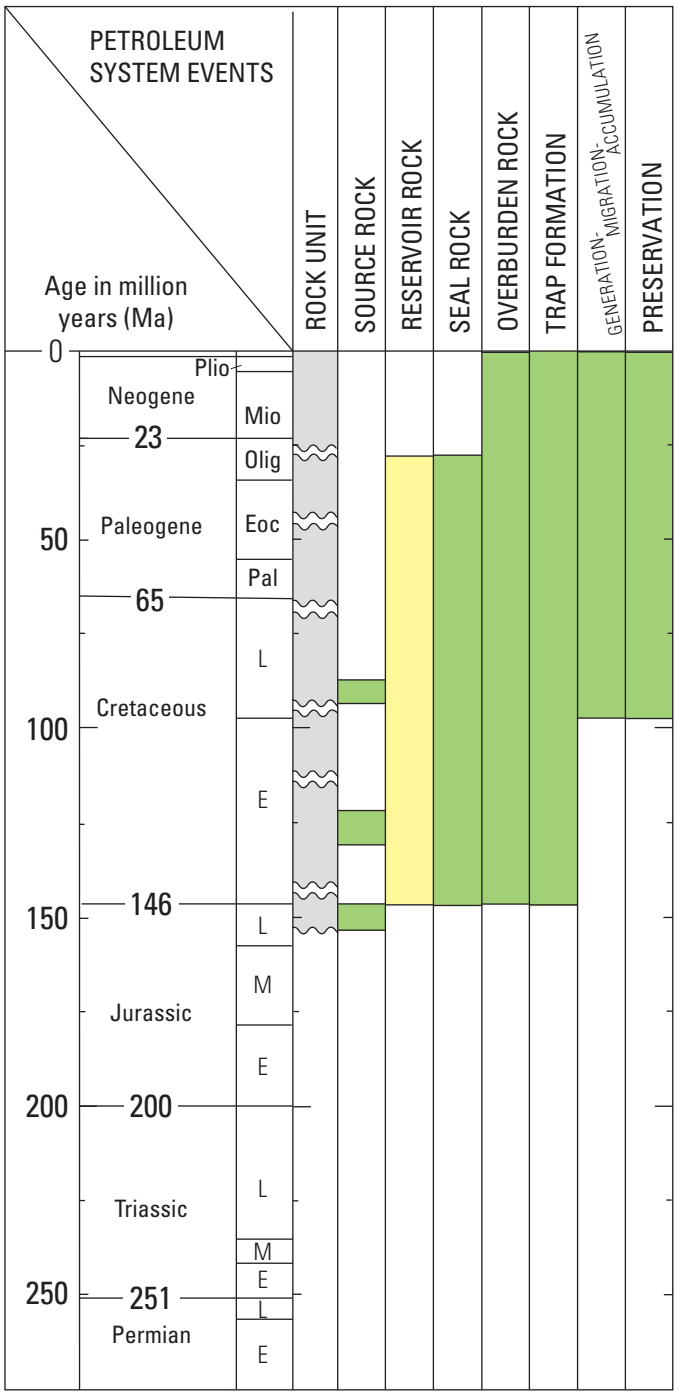

Figure 8. Events chart for the Mesozoic Composite Total Petroleum System (717301) and the Mesozoic-Cenozoic Reservoirs Assessment Unit (71730101). Gray, rock units present; yellow, age range of reservoir rock; green, age ranges of source, seal, and overburden rocks and the timing of trap formation and 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; ?, uncertain.

Geologic Model

The geologic model developed for the assessment of conventional oil and gas in the West African Coastal Province and the Coastal Plain and Offshore Assessment Unit is as follows:

1. Hydrocarbons were generated from Aptian, early to middle Albian, and Cenomanian and Turonian marine shales. Type II kerogen ranges from 3 to 10 percent in Turonian source rocks. Hydrocarbon generation started in the Late Cretaceous and continues to the present.
2. Generated hydrocarbons migrated into Cretaceous reservoirs and possibly into Paleogene sandstone reservoirs.
3. Structural traps include growth-fault-related structures, such as rotated fault blocks within the continental shelf and below the mid-Cretaceous unconformity. Stratigraphic traps are related to deep-water fans, turbidite units, slope truncations along the present day shelf and paleoshelf edge, and Cretaceous and Paleogene stratigraphic pinch-outs along the eastern margin of the basin.
4. Upper Cretaceous and Tertiary marine mudstone and shale rocks are the primary seals.
5. A passive-margin analog (Charpentier and others, 2007) was used because of similar source and reservoirs rocks and traps.

Figure 8 summarizes the age of the source, seal, and reservoir rocks and the timing of trap development and generation and migration of hydrocarbons for the Cretaceous Composite PS and the Mesozoic-Cenozoic Reservoirs Assessment Unit geologic model.

Resource Summary

Using a geology-based assessment, the U.S. Geological Survey estimated mean volumes of undiscovered, technically recoverable conventional oil and gas resources for the Mesozoic-Cenozoic Reservoirs Assessment Unit in the West African Coastal Province (table 1). The mean volumes are estimated at 3,200 million barrels of oil, 23,629 billion cubic feet of gas, and 721 million barrels of natural gas liquids. The estimated mean size of the largest oil field that is expected to be discovered is 783 million barrels of oil, and the estimated mean size of the expected largest gas field is 4,695 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. West African Coastal Province and Mesozoic-Cenozoic Reservoirs Assessment Unit results for undiscovered, technically recoverable oil, gas, and natural gas liquids.

[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
West African Coastal Province—Cretaceous Composite TPS														
Mesozoic-Cenozoic Reservoirs AU	***Oil***	783	801	2,713	7,305	3,200	1,047	3,662	10,847	4,492	27	98	297	121
	Gas	4,695					4,862	16,202	43,437	19,137	149	506	1,374	600
Total Conventional Resources			801	**2,713**	**7,305**	**3,200**	**5,909**	**19,864**	**54,284**	**23,629**	**176**	**604**	**1,671**	**721**

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*).

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Volume Title Page