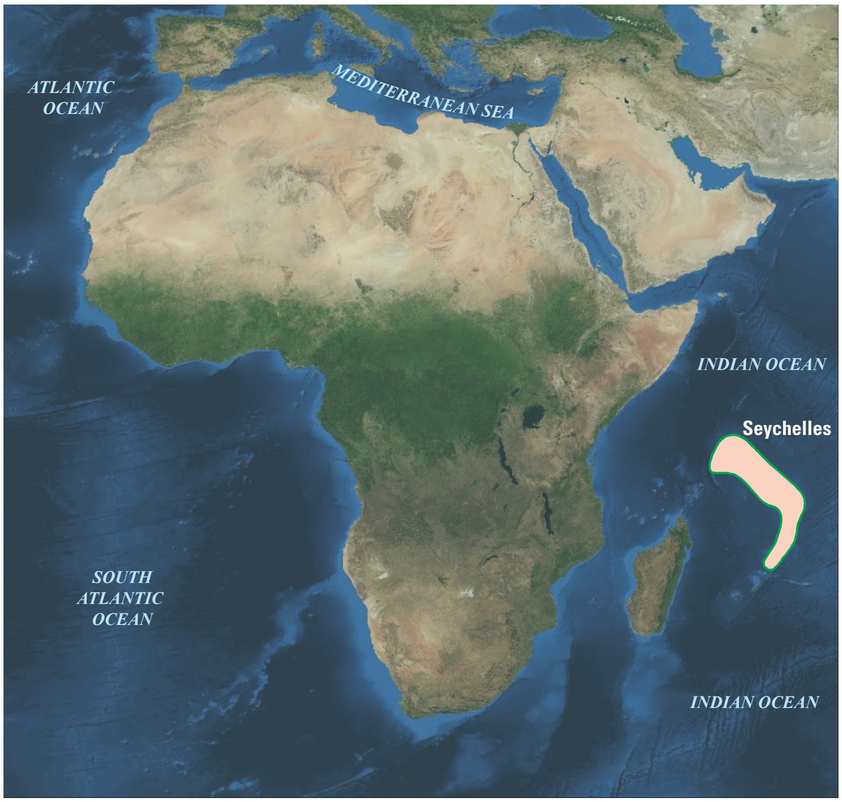
# Assessment of Undiscovered Oil and Gas Resources of the Seychelles Province, East Africa

By Michael E. Brownfield and Christopher J. Schenk

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Chapter 13 of
**Geologic Assessment of Undiscovered Hydrocarbon Resources of Sub-Saharan Africa**
Compiled by Michael E. Brownfield

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## Abbreviations Used in This Report

| | |
|---|---|
| $km^2$ | square kilometers |
| m | meter |
| AU | assessment unit |
| BCFG | billion cubic feet gas |
| HI | hydrogen index |
| MMBNGL | million barrels of natural gas liquids |
| MMBO | million barrels of oil |
| NGL | natural gas liquids |
| TOC | total organic carbon |
| TPS | total petroleum system |
| USGS | U.S. Geological Survey |

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## 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 recently completed an assessment of the Seychelles Province, an area of approximately 662,779 square kilometers. The Seychelles Province contains rift, rift-sag, passive-margin, and drift rocks of Paleozoic to Holocene age. This assessment was based on data from oil and gas exploration wells and published geologic reports.

The Seychelles Province and associated assessment unit were assessed for the first time because of increased energy exploration activity and increased interest in their future oil and gas potential. The assessment was geology based and used the total petroleum system concept. The basic 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 U.S. Geological Survey defined the Mesozoic-Cenozoic Composite Total Petroleum System with one assessment unit, the Seychelles Rifts Assessment Unit, an area of approximately 334,624 square kilometers. The total petroleum system was defined to include Mesozoic to Paleogene lacustrine and marine source rocks and conventional oil and gas reservoirs. The province is considered to be underexplored.

Oil and gas is postulated to have been generated from Permian to Jurassic lacustrine and continental source rocks (rift stage) with total organic carbon ranging from 2.38 to 6.7 weight percent. Oil and gas may also have been generated by Early to Middle Jurassic restricted-marine, marginal-marine, and deltaic rocks containing as much as 1.7 weight percent organic carbon, and by Maastrichtian to Paleocene marine rocks containing as much as 7.82 weight percent organic carbon. Hydrocarbons might have migrated into Mesozoic and Paleogene reservoirs and traps. Traps are mostly structural within the syn-rift rock units and both structural and stratigraphic within the post-rift units. The primary reservoir seals are Mesozoic and Cenozoic mudstones and shales. Rifted passive margin geologic analog was used for the assessment because of similar source, reservoirs, and traps.

The U.S. Geological Survey estimated mean volumes of undiscovered, technically recoverable conventional oil and gas resources for the Seychelles Rifts Assessment Unit in the Seychelles Province. The mean volumes are estimated at 2,394 million barrels of oil, 20,376 billion cubic feet of gas, and 739 million barrels of natural gas liquids. The estimated mean size of the largest oil field that is expected to be discovered is 793 million barrels of oil and the estimated mean size of the expected largest gas field is 4,765 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.

## 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 recently completed an assessment of the Seychelles Province (figs. 1, 2), an area of approximately 662,779 square kilometers (km$^2$). The Seychelles Province contains rift, rift-sag, passive-margin, and drift rocks of Paleozoic to Holocene age. This assessment was based on data from oil and gas exploration wells and published geologic reports.

The Seychelles Province and associated assessment unit were assessed for the first time because of increased energy exploration activity and increased interest in their future oil and gas potential. The assessment was geology based and used the total petroleum system concept. The basic 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 Mesozoic-Cenozoic Composite Total Petroleum System (TPS) with one assessment unit, the Seychelles Rifts Assessment Unit (AU), an area of approximately 334,624 km$^2$. The total petroleum system was defined to include Mesozoic to Paleogene lacustrine and marine source rocks and conventional reservoirs. The province is considered to be underexplored.

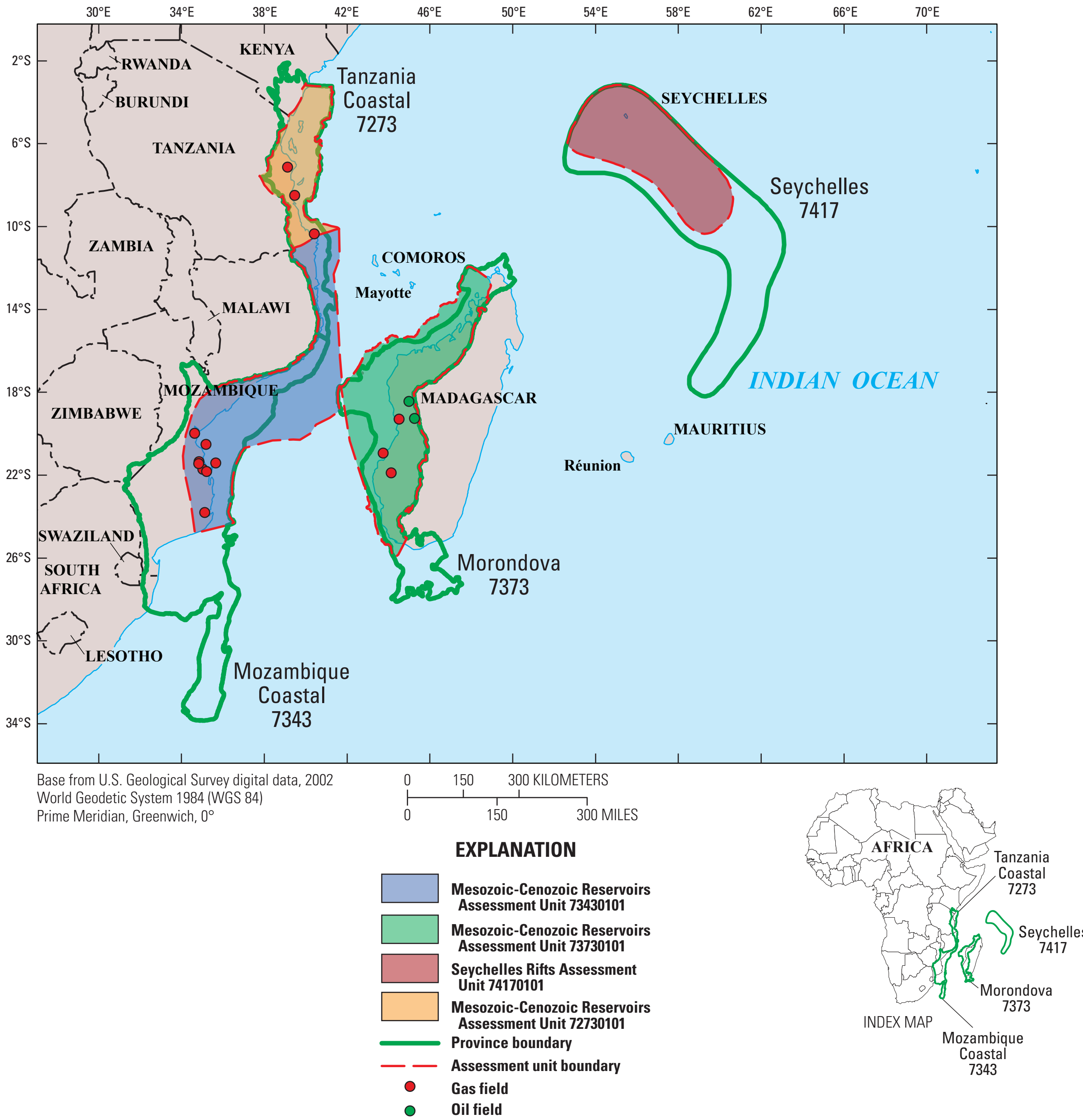



**Figure 1.** Seychelles Province and the Seychelles Rifts Assessment Unit and three other assessed geologic provinces and assessment units along the central coast of east Africa. These four provinces were related to the breakup of Gondwana, and their geologic history developed similarly. Field center points from IHS Energy (2009).

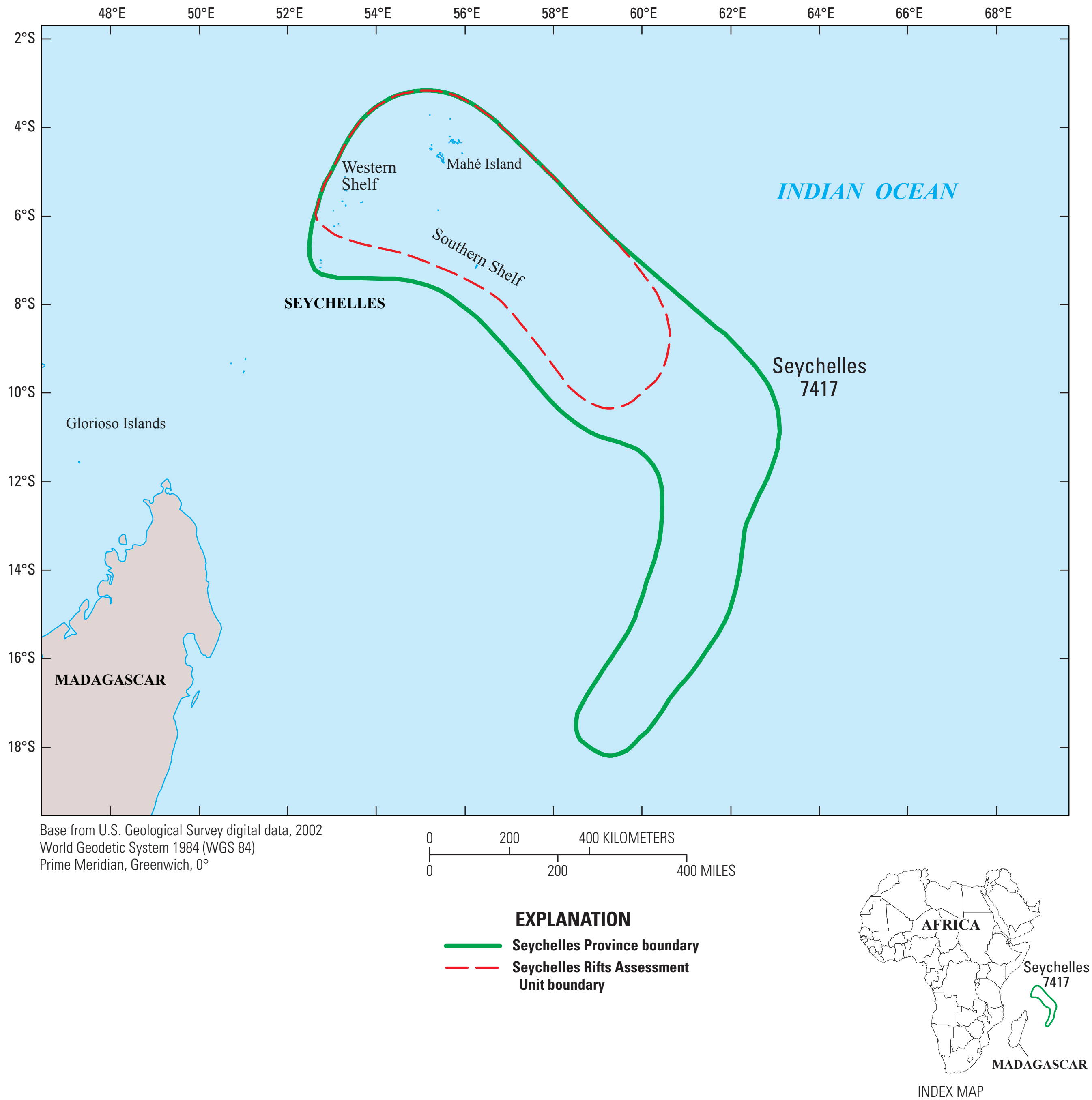



**Figure 2.** Locations of the Seychelles Province, the Seychelles Rifts Assessment Unit, Southern Shelf, and Western Shelf northeast of Madagascar near the central coast of east Africa.

# Tectonic History and Geology of the Seychelles Province, East Africa

The Seychelles Province is directly related to the breakup of Gondwana (fig. 3) in the late Paleozoic and Mesozoic (Reeves and others, 2002). The province developed in several phases:

1. a pre-rift stage that began in the Carboniferous, during which a mantle plume caused uplift, extension, microplate formation, rifting, and volcanism;
2. a syn-rift phase that started during the Permo-Triassic and continued into the Jurassic, during which grabens and half-grabens formed and possible lacustrine and continental source rocks were deposited (fig. 3);
3. a drift phase that began in the Late Jurassic and continued into the Early Cretaceous, during periods of open marine conditions marine clastic and carbonate rocks were deposited; during periods of restricted-marine conditions marine source rocks were deposited;
4. a syn-rift-drift phase at the beginning of the Late Cretaceous, when the Seychelles-India plates separated from Madagascar (figs. 4, 5);
5. a syn-rift phase that began in the latest Cretaceous and continued to the early Paleocene, during which the separation of the Seychelles and India continued (figs. 4, 5); and
6. a drift phase that began in the Paleogene and continues to the present, during which shelf carbonate rocks were (and still are being) deposited (figs. 4, 5).

The stratigraphic section present in Seychelles Province is generally the same as the section present in the coastal Mozambique and Tanzania and the Morondava Basin (figs. 2, 4; Rusk, Bertagne & Associates, 2003).

The pre-rift stage is preserved as possible failed rift rocks of Karoo age (fig. 6; Plummer and others, 1998). The first syn-rift stage was characterized by the opening of the Indian Ocean, which began in the Permian and continued into the Jurassic. In the Middle Jurassic, Madagascar, India, and the Seychelles separated from Africa, forming a passive margin and a carbonate platform that was later covered by Upper Jurassic to Cretaceous marine clastic deposits (figs. 5, 6). In the Lower Cretaceous, marginal, rift-sag, and passive-margin conditions developed, and the Seychelles again became the site of deposition of open-marine sediments. The breakup of India and the Seychelles began in the latest Cretaceous. Volcanic rocks mark the minor rift phase (figs. 5, 7). The Seychelles then entered a drift state that continues today.

Two generalized cross sections drawn across the western shelf of the Seychelles Province are shown in figures 7 and 8. Interpretations of recent seismic profiles have shown potential prospects in the offshore part of Seychelles Province (Plummer, 1994; Plummer and others, 1998; Matchette-Downes, 2010).

# Petroleum Occurrence in the Seychelles Province, East Africa

## Source Rocks

The Mesozoic-Cenozoic Composite TPS was defined to include Mesozoic and Paleogene source rocks and conventional reservoirs (figs. 5, 6). The Permian to Triassic section contains fluvial and lacustrine source rocks, and the Early to Middle Jurassic section contains restricted marine Type II kerogen source rocks and marginal marine and deltaic Types II and III kerogen source rocks (Plummer, 1994; Plummer and others, 1998). Late Jurassic to Early Cretaceous mudstone and siltstone source rocks were deposited during the Africa-Madagascar, Seychelles, and India drift stage. The Maastrichtian to Paleocene mudstone source rocks were deposited during the Seychelles-India drift stage. Generally the source rocks are dominated by Type III kerogen, but Type I and Type II source rocks have been identified. Triassic source rocks contain 2.38 to 6.7 weight percent total organic carbon (TOC) (Plummer, 1994). The Early to Middle Jurassic Type II and Type III source rocks contain as much as 1.96 weight percent TOC. Plummer and others (1998) report that early Middle Jurassic source rocks contain Type II and Type III with an average TOC value of 7.1 weight percent and hydrogen index (HI) value of 287 milligrams of hydrocarbon per gram of total organic carbon (mgHC/gTOC). Late Jurassic to Early Cretaceous marine strata contain Type II and Type III kerogen with as much as 1.7 weight percent TOC (Plummer, 1994) and includes an oolitic-carbonate source rock (fig. 7) containing Type II and Type III kerogen with as much as 1.32 weight percent TOC. This oolitic carbonate has also been found from Tanzania to Somalia and Madagascar to Pakistan (Plummer, 1994). The Maastrichtian to Paleocene marine source rocks contain as much as 7.82 weight percent TOC of mostly Type III kerogen (Plummer, 1994).

Maturity data derived from existing exploration holes indicate that the Jurassic to Early Cretaceous marine source rocks are within the oil generation window, whereas Middle Triassic lacustrine mudstone lies within the gas generation window (Plummer, 1994). The Maastrichtian to Paleocene source rocks are only marginally mature for oil, but they might be mature in areas off the Seychelles Province western shelf (Plummer, 1994).

## Reservoirs, Traps, and Seals

The Seychelles Province contains Mesozoic and Cenozoic clastic reservoirs. Triassic to Middle Jurassic syn-rift rocks contain possible alluvial fans, fan deltas, fluvial deltas, and lacustrine sandstones reservoirs. The Jurassic post-rift rocks contain reef and platform carbonate that are potential reservoirs. The post-rift Cretaceous rocks contain regressive and transgressive marine sandstone, slope-turbidite units, and


**Figure 3.** Reconstruction of the early breakup of Gondwana during the Early Jurassic (200 million years ago). Modified from Reeves and others (2002).

basin-floor fan sandstone reservoirs. Upper Cretaceous early drift rocks contain possible turbidite reservoirs, and basin-floor fans, whereas the Paleogene may contain carbonate reservoirs. Volcanic rocks found within the Karoo and Cretaceous section may have degraded some of the reservoirs by thermal alteration of the matrix minerals (fig. 8) (Matchette-Downes, 2010).

The Seychelles Rifts AU (fig. 2) contains reservoirs that are mostly associated with fault-related structures and with rotated fault blocks (fig. 8). Possible Cretaceous sandstone reservoirs may be present under the thick Cenozoic platform carbonate. For example, the Seychelles Province west shelf area (figs. 7, 8) contains fault-related sandstone reservoirs.

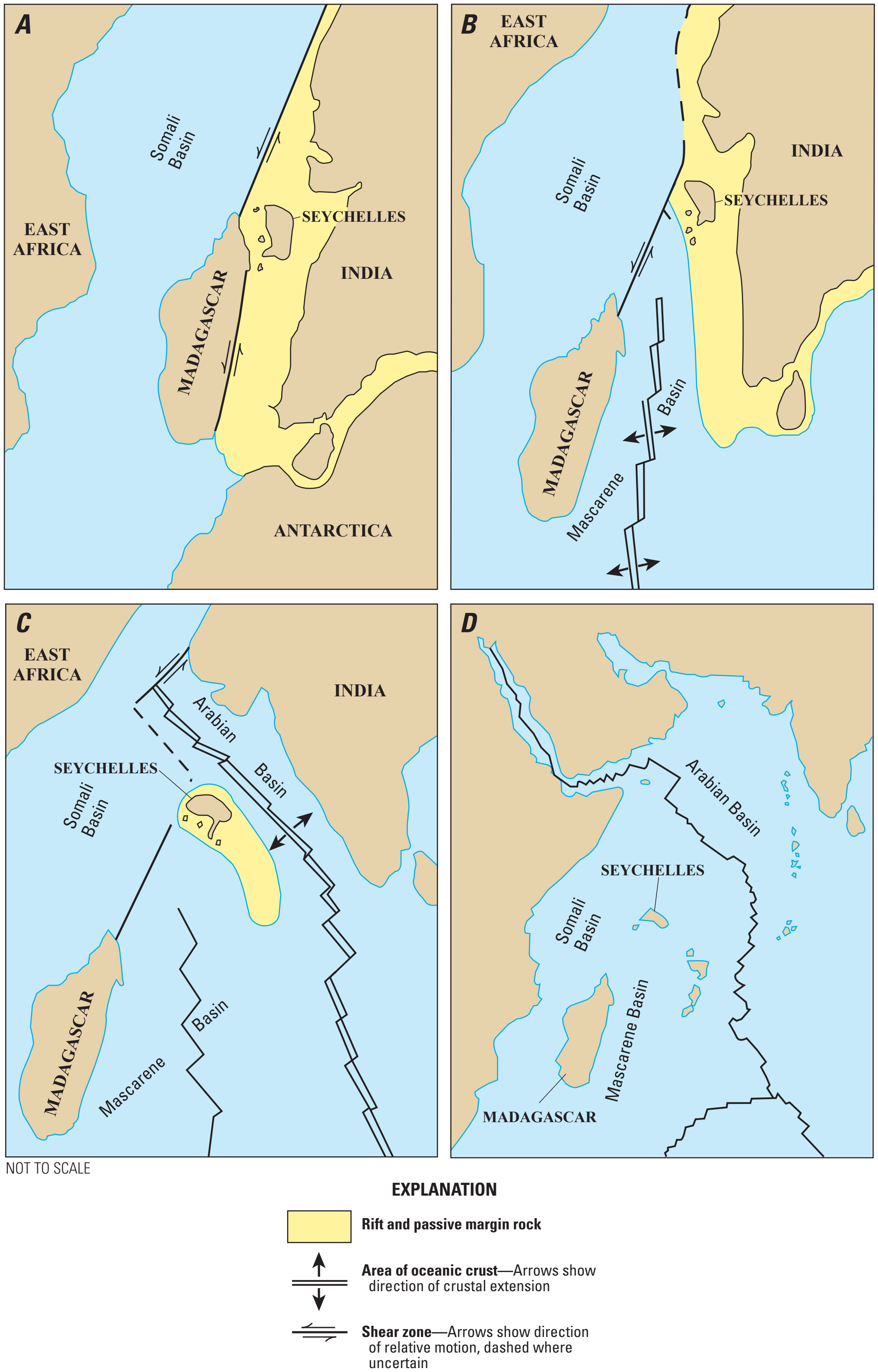
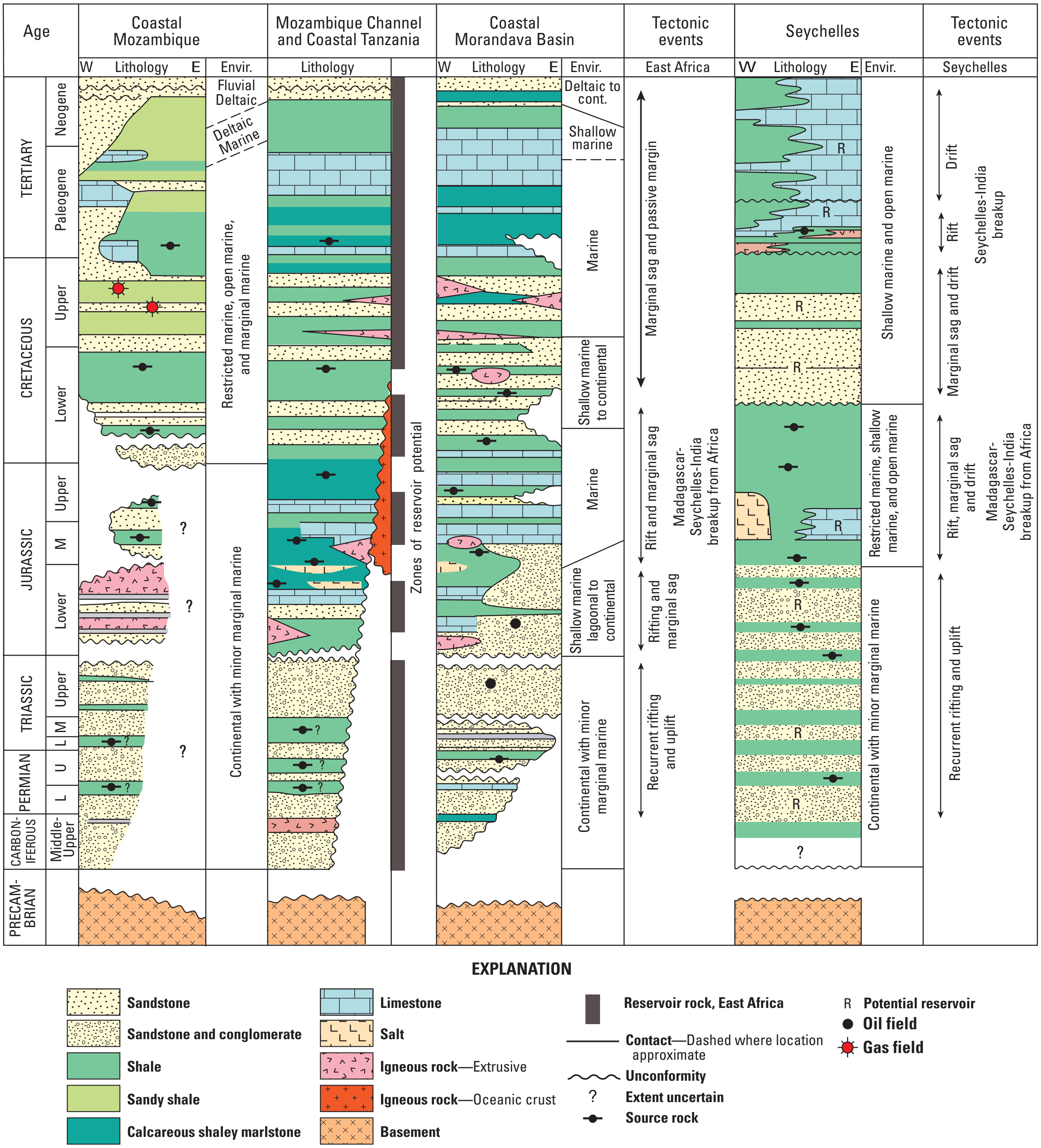



**Figure 4.** Generalized plate-tectonic development of the Madagascar Province: *A*, Early Cretaceous, following the separation of east and west Gondwana; *B*, early Late Cretaceous, during the separation of Seychelles-India from Madagascar; rotation of the plates shown in the Mascarene Basin; *C*, Paleocene, during the separation of India from the Seychelles. *D*, present day. S, Seychelles. Modified from Plummer and others (1998). Not to scale.




**EXPLANATION**



**Figure 5.** Generalized stratigraphic columns for Coastal Mozambique, the Mozambique Channel and the Coastal Tanzania, Coastal Morondava Basin, and Seychelles along the east coast of Africa (see fig. 1). Envir., environment; L, Lower; M, Middle; U, Upper; ?, uncertain extent. Modified from Rusk, Bertagne & Associates (2003) and PetroSeychelles (2013).

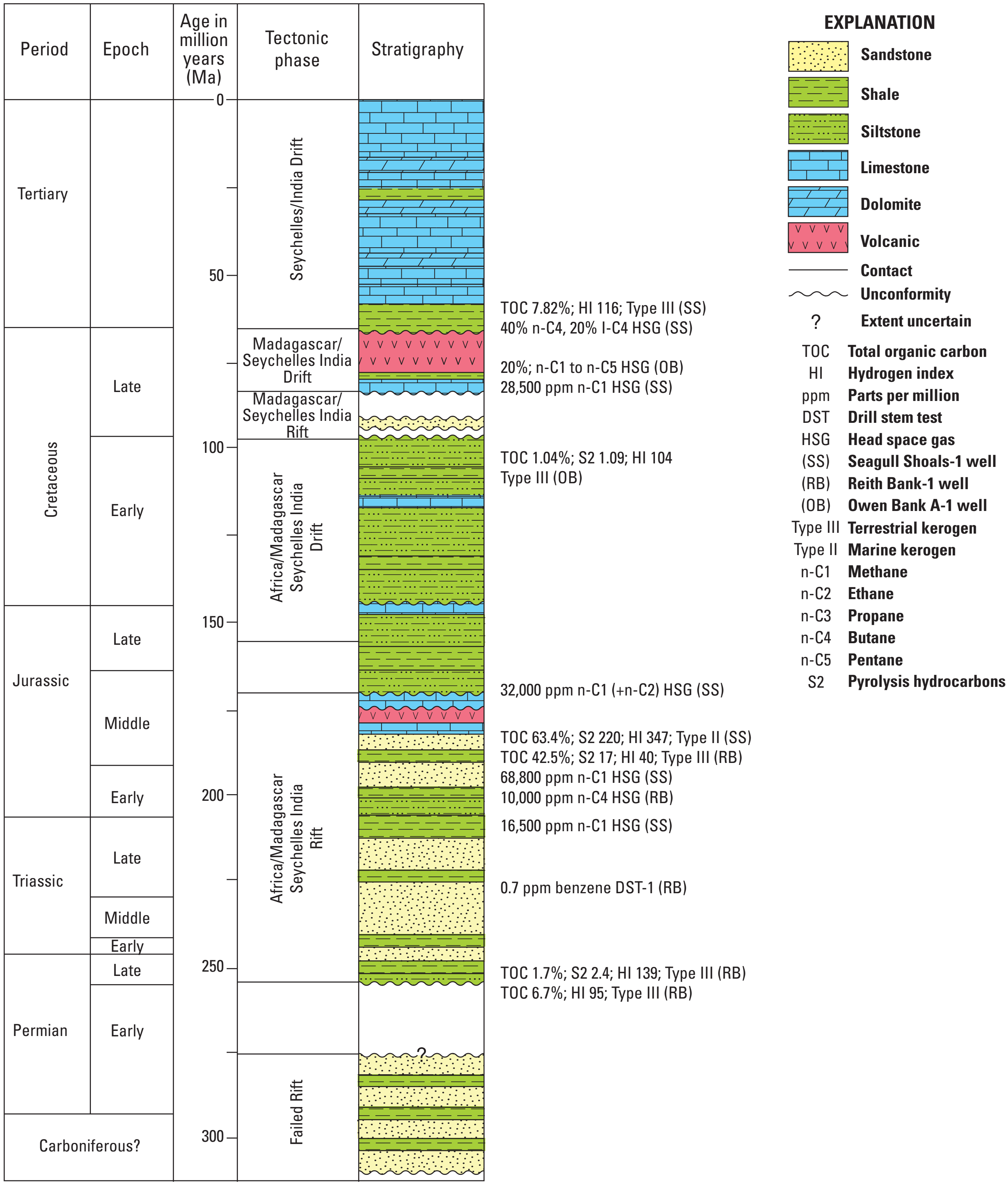



**Figure 6.** Generalized stratigraphy and tectonic phases of the Seychelles showing proven and potential source-rock units and hydrocarbon shows in wells in the offshore part of the Western Shelf. Modified from Plummer and others (1998).

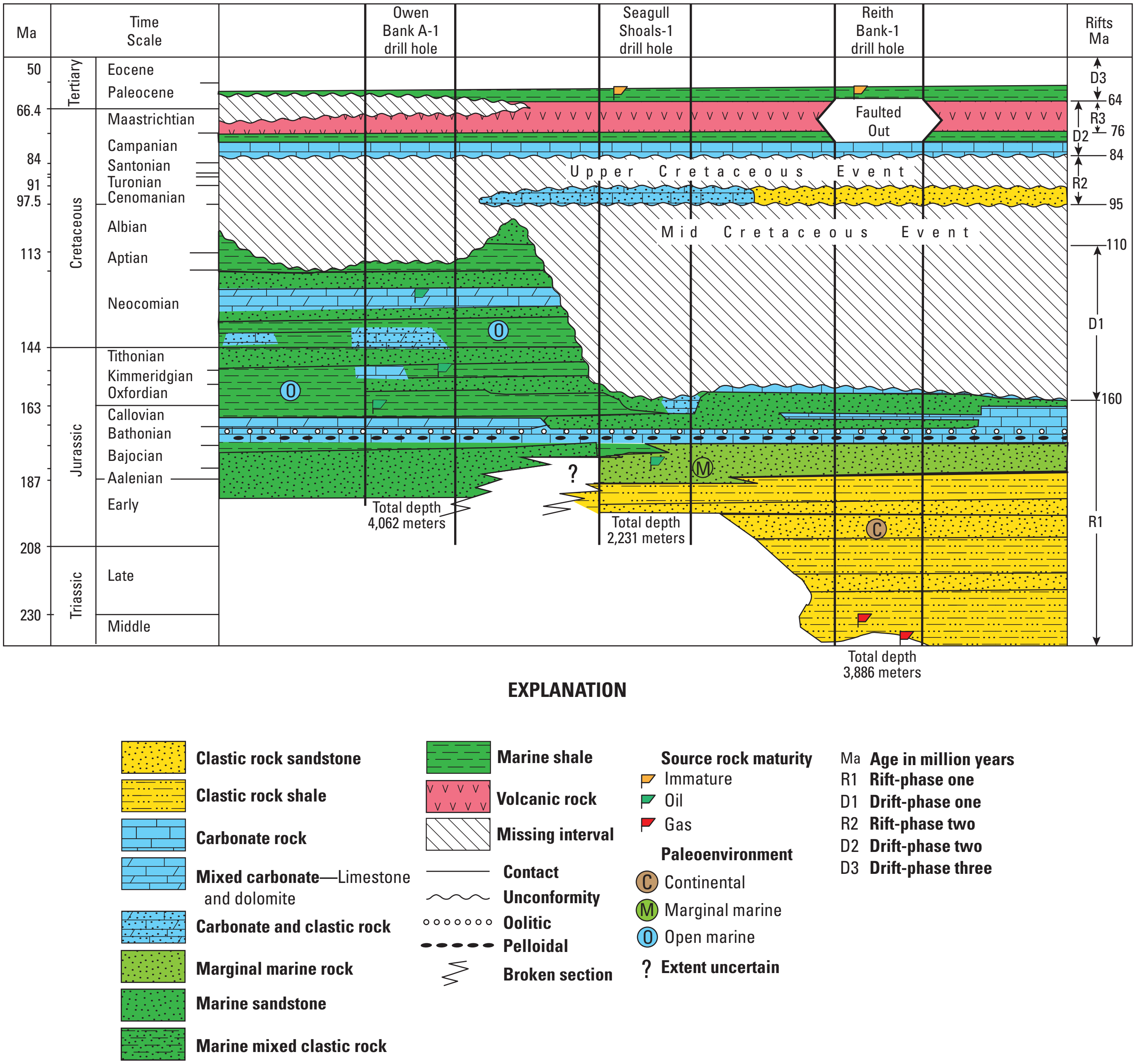



**Figure 7.** Chronostratigraphy of Mesozoic and Cenozoic rocks, offshore Seychelles. Ma, millions of years ago. Modified from Plummer (1994).

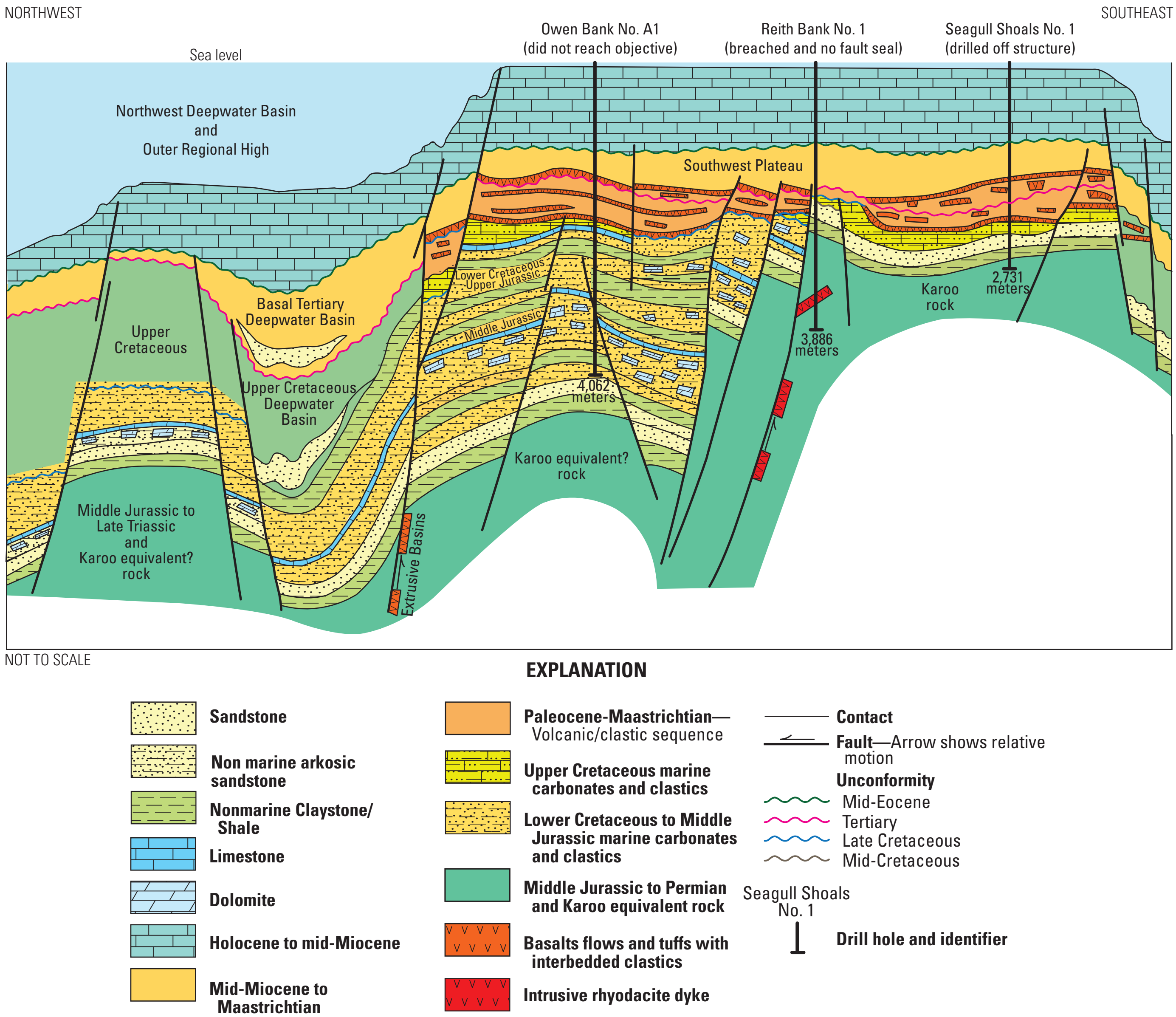



**Figure 8.** Schematic cross section of the Seychelles Western Shelf showing the Owen Bank No. A1, Reith Bank No. 1, and Seagull Shoals No. 1 drill holes. Modified from Matchette-Downes (2010).

The Triassic to Jurassic syn-rift section is postulated to contain graben and half-graben structures with trapping typically found in rift environments. The post-rift rocks (drift and passive margin) contain possible stratigraphic and structural traps in transgressive and regressive sandstones, drape anticlines, and flower structures (fig. 8). Cretaceous and Paleogene marginal-sag and drift rocks contain both structural and stratigraphic traps in fault-related structures, rotated fault blocks within the continental shelf, deep-water fans, turbidite units, and slope truncations (fig. 8).

The primary seals are Mesozoic and Cenozoic mudstone and shale found in the rift, drift, and marginal-marine rocks.

# Exploration

At the time of the assessment, the province contained no fields or discoveries (IHS Energy, 2009) and is considered to be underexplored for its size. Only four exploration holes have been drilled in the province; three of them penetrated the pre-Tertiary section and contained limited hydrocarbon shows.

Exploration wells on the continental shelf provide evidence for (1) the existence of an active petroleum system containing Mesozoic source rocks, (2) the migration of the hydrocarbons most likely occurred since the Late Cretaceous, and (3) the migration of the hydrocarbons into possible Mesozoic and Cenozoic reservoirs.

## Geologic Model

The geologic model developed for the assessment of conventional oil and gas in the Seychelles Province and the Seychelles Rifts Assessment Unit is as follows:

1. Oil and gas were generated from Permian to Jurassic lacustrine and continental rocks (rift stage) containing TOC ranging from 2.4 to 6.7 weight percent; Jurassic restricted marine and marginal marine and deltaic rocks containing as much as 1.7 weight percent TOC and Maastrichtian to Paleocene marine source rocks containing as much as 7.82 weight percent TOC may have also generated oil and gas. Hydrocarbon generation began in the Late Jurassic for the Permian to Early Jurassic lacustrine source rocks. Generation began in the Cretaceous for the Jurassic and Lower Cretaceous marine source rocks and the Maastrichtian to Paleocene marine source rocks began in the Neogene. Hydrocarbon generation continues today.
2. Hydrocarbons migrated into Mesozoic and Paleogene reservoirs and traps.
3. Hydrocarbon traps are mostly structural within the syn-rift rock section and both structural and stratigraphic in the post-rift-rock section.
4. The primary reservoir seals are Mesozoic and Cenozoic mudstone and shale.
5. 5. Rifted passive margin analog (Charpentier and others, 2007) was used for assessment numbers and sizes because of similar source, reservoirs, and traps.

An events chart (fig. 9) for the Mesozoic-Cenozoic Composite TPS and the Seychelles Rifts AU summarizes the age of the source, seal, and reservoir rocks and the timing of trap development, generation, and migration.

## 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 Seychelles Province (table 1). The mean volumes are estimated at 2,394 million barrels of oil, 20,376 billion cubic feet of gas, and 739 million barrels of natural gas liquids. The estimated mean size of the largest oil field that is expected to be discovered is 793 million barrels of oil, and the estimated mean size of the expected largest gas field is 4,765 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.

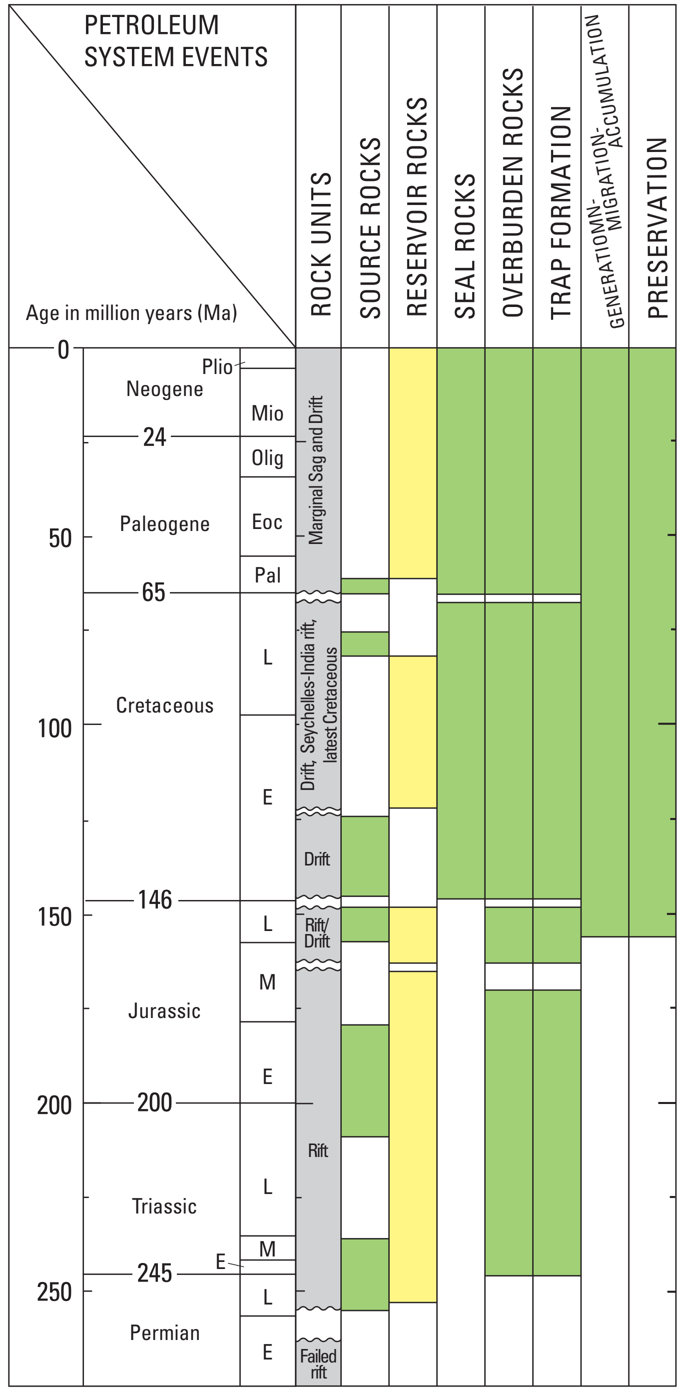



**Figure 9.** Events chart for the Mesozoic-Cenozoic Petroleum System (741701) and the Seychelles Rifts Assessment Unit (74170101). Gray, rock units present; yellow, age range of reservoir rock; green, age ranges of source, seal, and overburden rocks and the timing of trap formation and generation, migration, and preservation of hydrocarbons; wavy line, unconformity. Divisions of geologic time conform to dates in U.S. Geological Survey Fact Sheet 2010–3059 (U.S. Geological Survey Geologic Names Committee, 2010). Ma, millions of years ago; Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, Late; E, Early; M, Middle.

**Table 1.** Seychelles Province assessment 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. AU, assessment unit; AU probability is the chance of at least one accumulation of minimum size within the AU. TPS, total petroleum system. Fractiles are additive under the assumption of perfect positive correlation. Gray shading indicates not applicable]

| 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 |
| **Seychelles-Mesozoic-Cenozoic Composite TPS** | | | | | | | | | | | | | | |
| Seychelles Rifts AU | ***Oil*** | 793 | 585 | 1984 | 5574 | 2394 | 1328 | 4760 | 15038 | 6044 | 28 | 100 | 324 | 129 |
| | ***Gas*** | 4765 | | | | | 3538 | 11781 | 33660 | 14332 | 146 | 496 | 1467 | 610 |
| **Total Conventional Resources** | | | **585** | **1984** | **5574** | **2394** | **4866** | **16541** | **48698** | **20376** | **174** | **596** | **1791** | **739** |

# For Additional Information

Assessment results are available at the USGS Central Energy Resources Science Center website: http://energy.cr.usgs.gov/oilgas/noga/ or contact Christopher J. Schenk, the assessing geologist (*schenk@usgs.gov*).

# Acknowledgments

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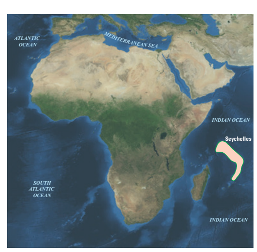

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