Assessment of Undiscovered Oil and Gas Resources of the Mozambique Coastal Province, East Africa

By Michael E. Brownfield

Chapter 10 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 kilometer
AU  assessment unit
TOC  total organic carbon
TPS  total petroleum system
USGS  U.S. Geological Survey
Assessment of Undiscovered Oil and Gas Resources of the Mozambique Coastal Province, East Africa

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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 completed a geologic assessment of the Mozambique Province in 2011, an area of approximately 648,650 square kilometers. The Mozambique 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 Mozambique Province is a priority province for the World Petroleum Assessment and was assessed in 2011 because of increased exploratory activity and increased 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 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 Mesozoic-Cenozoic Reservoirs Assessment Unit, an area of approximately 464,420 square kilometers. At the time of the assessment, the Mozambique Coastal Province contained only two gas accumulations exceeding the minimum size of 30 billion cubic feet of gas; the province is considered to be underexplored on the basis of its exploration history.

Oil and gas were generated from Permian to Paleogene source rocks. Jurassic Karoo-age lacustrine and continental rocks source rocks average 4.0 to 5.0 weight percent total organic carbon. Lower to Middle Jurassic restricted marine rocks contain as much as 9 weight percent organic carbon, and Cretaceous Type II source rocks contain as much as 12 weight percent organic carbon. Hydrocarbon generation of syn-rift Karoo-age sources began in the Middle Jurassic, whereas the generation from Middle Jurassic to Early Cretaceous syn-rift sources began in the Late Jurassic to Early Cretaceous.

Generation of hydrocarbons from drift and post-rift sources began in the Late Cretaceous and, in parts of the offshore, continues today. Hydrocarbons migrated into Cretaceous and Paleogene reservoirs and traps. Traps are mostly structural within the syn-rift section and are both structural and stratigraphic in the post-rift rock units. The primary seals are Mesozoic and Cenozoic mudstone and shale. Rifted passive margin analog was used for assessment sizes and numbers 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 Mesozoic-Cenozoic Reservoirs Assessment Unit in the Mozambique Coastal Province. The mean volumes are estimated at 11,682 million barrels of oil, 182,349 billion cubic feet of gas, and 5,645 million barrels of natural gas liquids. The estimated mean size of the largest oil field that is expected to be discovered is 1,041 million barrels of oil and the estimated mean size of the expected largest gas field is 7,976 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 program, the USGS completed an assessment of the Mozambique Coastal Province in 2011 (fig. 1), an area of approximately 648,650 square kilometers (km²). The Mozambique 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, discovered and producing fields (IHS Energy, 2009), and published geologic reports. Generalized geology of east Africa is shown in figure 2.
Figure 1. Locations of the Mozambique Coastal Province, Mesozoic-Cenozoic Reservoirs Assessment Unit, Mozambique Channel area, and the Ruvuma Delta along the central coast of East Africa. (Stratigraphic columns for the Mozambique Channel and Rovuma Delta are shown in figures 4 and 6.)
Figure 2. Generalized geology of East Africa. Modified from Ophir Energy Company (2011).
The Mozambique Province, which was a priority province for the World Petroleum Assessment, was assessed in 2011 because of increased energy exploration activity and increased 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 include 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 Mesozoic-Cenozoic Reservoirs Assessment Unit (AU) (fig. 1), an area of approximately 464,420 km². The total petroleum system was defined to include Mesozoic to Paleogene lacustrine and marine source rocks and conventional reservoirs.

Petroleum Occurrence in Mozambique Coastal Province, East Africa

Source Rocks

The Mesozoic-Cenozoic Composite Total Petroleum System was defined to include Mesozoic to Paleocene source rocks and conventional reservoirs (fig. 4). The Permian to Triassic section contains fluvial and lacustrine source rocks averaging 5 to 6 weight percent total organic carbon (TOC); some samples have as much as 17.4 weight percent TOC (Envoi—Energy Venture Opportunities International, 2011). The Lower to Middle Jurassic contains restricted marine Type II kerogen source rocks, marginal marine and deltaic Types II and III kerogen source rocks, and Type I lacustrine source rock (Cope, 2000; Rusk, Bertagne & Associates, 2003). The offshore part of Ruvuma Delta contains Early to Middle Jurassic restricted marine Type II source rocks with TOC contents as much as 12 weight percent (Cope, 2000). Late Jurassic to Early Cretaceous marlstone contains Type II and Type III kerogen with as much as 5 weight percent TOC (Envoi—Energy Venture Opportunities International, 2011). Ophir Energy Company (2007) reports that Aptian shale with TOC contents as much as 9 weight percent. Upper Cretaceous marine sources contain Type II and Type III kerogen with TOC contents as much as 7.4 weight percent and Eocene sources contain Type II and Type III kerogen with TOC contents as much as 12.1 weight percent (Cope, 2000). These source rocks have been found in the Ruvuma Delta in northern Mozambique and southern Tanzania.
Figure 3. Reconstruction of the early breakup of Gondwana during the Early Jurassic (200 Ma). Modified from Reeves and others (2002).
Figure 4. Generalized stratigraphic columns of Coastal Mozambique, Mozambique Channel and Coastal Tanzania, Coastal Morondava Basin, and the Seychelles along the east coast of Africa (fig. 1). W, west; E, east; Envir., environment; cont., continental; L, Lower; M, Middle; U, Upper. Modified from Rusk, Bertagne & Associates (2003) and PetroSeychelles (2013).
Oil and gas generation most likely began in the Early Cretaceous for the Upper Jurassic syn-rift sources in the province (Coster and others, 1989). Oil and gas generation began in the Late Cretaceous for the Barremian to Aptian post-rift sources and in the offshore parts of the province the Late Cretaceous post-rift sources began oil and gas generation began in the early Paleogene and is most likely continuing today (Coster and others, 1989; Envoi—Energy Venture Opportunities International, 2011). Oil- and gas-generation windows are shown in figure 7 for the Mozambique Channel and the Morondava Basin (Envoi—Energy Venture Opportunities International, 2011).

**Reservoirs, Traps, and Seals**

The Mozambique Coastal Province and the Mesozoic-Cenozoic Reservoirs Assessment Unit (fig. 1) contain Mesozoic and Cenozoic clastic reservoirs (Coster and others, 1989; Nairn and others, 1991; Cope, 2000; Rusk, Bertagne & Associates, 2003; Law, 2011). Triassic to Middle Jurassic syn-rift rocks contain possible alluvial fans, fan deltas, fluvial deltas, and lacustrine sandstones reservoirs. The Late Jurassic post-rift rocks contain reef and platform carbonate rocks that are potential reservoirs. The post-rift Cretaceous rocks contain regressive and transgressive marine sandstone, slope-turbidite sandstone and basin-floor fan sandstone reservoirs (Coster and others, 1989). Upper Cretaceous and Cenozoic passive-margin rocks contain possible carbonate reservoirs and Maastrichtian and Paleocene turbidite and basin-floor fan reservoirs (Cope, 2000). Volcanic rocks found within the Karoo age rocks and Cretaceous section may have degraded some of the reservoirs.

The Mesozoic-Cenozoic Reservoirs Assessment Unit (fig. 1) contains sandstone reservoirs that mostly are associated with growth-fault-related structures such as rotated fault blocks within the continental shelf, deep water fans, turbidite sandstone units, and slope truncations along the present-day shelf and paleoshelf edge (Cope, 2000; Rusk, Bertagne & Associates, 2003; Law, 2011). For example, the Rovuma River delta (fig. 5) contains turbidite sandstone units,
### Table 1: Stratigraphic Column for the Onshore and Projected Offshore Parts of the Rovuma Basin, Northern Mozambique

<table>
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<tr>
<th>Period</th>
<th>Epoch</th>
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**EXPLANATION**

- **Sandstone**
- **Conglomerate**
- **Paralic clastic rock**
- **Marine sandstone**
- **Continental clastic rock**
- **Marine shale, siltstone, and sandstone**
- **Marl**
- **Calcereous sandstone**
- **Shelf carbonate**
- **Contact**
- **Unconformity**
- **Present coastline**

**Figure 6.** Stratigraphic column for the onshore and projected offshore parts of the Rovuma Basin, northern Mozambique. Middle and Lower Jurassic units shown in figure 4, such as the Lower Jurassic salt, are not shown. Modified from Key and others (2008).
Figure 7. Cross section across the Mozambique Channel and the Morondava Basin (line of section on index map) showing the top of the oil- and gas-generation windows. Cross section is approximately 420 kilometers long, not to scale. Modified after Envoi—Energy Venture Opportunities International (2011).

deep-water fan, and growth-fault-related sandstone reservoirs (Law, 2011). A seismic profile reported by Walford and others (2005) interpreted the Late Cretaceous and Cenozoic section showing the Domo Sandstone, a potential reservoir and clinoform packages, channeling, slumping, and growth faults in the offshore part of the Zambezi Delta (fig. 8).

Triassic to Jurassic syn-rift rocks contains structural traps related to graben and half-grabens. Lower Cretaceous post-rift rocks (drift and passive-margin) contain stratigraphic traps such as transgressive and regressive sandstones and structural traps including salt structures, drape anticlines, and flower structures (Rusk, Bertagne & Associates, 2003; Law, 2011). Upper Cretaceous and Paleogene post-rift rocks (drift and passive-margin) contain both structural and stratigraphic traps in growth-fault-related structures, rotated fault blocks within the continental shelf, deep-water fans, turbidite units, and slope truncations along the present day shelf and paleoshelf edge.

The primary reservoir seals are Mesozoic and Cenozoic drift and marginal-marine mudstone and shale (Nairn and others, 1991; Cope, 2000). Secondary fault-related seals are found in Karoo-age grabens and Mesozoic half-grabens, faulted drape anticlines, and inversion-related anticlines (Cope, 2000; Rusk, Bertagne & Associates, 2003).

**Exploration**

At the time of the 2011 assessment, the Mozambique Province contained five gas fields and no oil fields (IHS Energy, 2009) and is considered to be underexplored on the basis of its limited exploration activity. Recent hydrocarbon shows are limited to the Cretaceous-Tertiary offshore drift and passive-margin section (Law, 2011).

Hydrocarbon shows in exploration wells on the continental shelf and upper slope provide evidence for the existence of an active petroleum system containing Mesozoic source rocks and for the migration of the hydrocarbons into Cretaceous and Cenozoic reservoirs, most likely since the Late Cretaceous.
Figure 8. Schematic cross section of the Zambezi Delta, Mozambique. Modified from Walford and others (2005).
Geologic Model

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

1. Oil and gas was generated from Permian to Jurassic Karoo-age lacustrine and continental rocks (rift stage). The lacustrine rocks contain TOC values averaging 4.0 to 5.0 weight percent. Early to Middle and Jurassic restricted marine rocks contain as much as 9 weight percent TOC, and Cretaceous marine rocks contain Type II kerogen with as much as 12 weight percent TOC. Generation of hydrocarbons in syn-rift Karoo-age source rocks most likely began in the Middle Jurassic, whereas generation of hydrocarbons in Middle Jurassic to Early Cretaceous syn-rift source rocks began in the Late Jurassic to Early Cretaceous. Generation of early post-rift sources most likely began in the Late Cretaceous. The drift and post-rift source rocks most likely began generating hydrocarbons in the Late Cretaceous. Hydrocarbon generation most likely continues today in the offshore parts of the assessment unit.

2. Generated hydrocarbons migrated into mostly Cretaceous and Paleogene sandstone reservoirs.

3. Hydrocarbon traps are structural within the syn-rift rock units and are both structural and stratigraphic in the post-rift rock units.

4. The primary reservoir seals are Mesozoic and Cenozoic mudstone and shale.

5. The rifted passive margin analog (Charpentier and others, 2007) was used for assessment sizes and numbers because of similar source, reservoirs, and traps.

An events chart (fig. 9) for the Mesozoic-Cenozoic Total Petroleum System (TPS) and the Mesozoic-Cenozoic Reservoirs Assessment Unit (73430101) in the Mozambique Coastal Province, South Africa. Gray, rock units present; yellow, age range of reservoir rocks; green, age ranges of source and overburden rocks, timing of trap formation, 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, thousands of years ago; Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene; L, Late; E, Early; M, Middle; ?, uncertain.

Resource Summary

At the time of this 2011 assessment, the Mozambique Coastal Province contained only five gas accumulations exceeding the minimum size of 30 billion cubic feet of gas; this province is considered to be underexplored on the basis of its level of exploration activity. Using a geology-based assessment, the USGS estimated mean volumes of undiscovered, technically recoverable conventional oil and gas resources for the Mesozoic-Cenozoic Reservoirs Assessment Unit in the Mozambique Coastal Province (table 1). The mean volumes are estimated at 11,682 million barrels of oil, 182,349 billion cubic feet of gas, and 5,645 million barrels of natural gas liquids. The estimated mean size of the largest oil...
field that is expected to be discovered is 1,041 million barrels of oil and the estimated mean size of the expected largest gas field is 7,976 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.

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 Michael E. Brownfield, the assessing geologist (mbrownfield@usgs.gov).

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References


