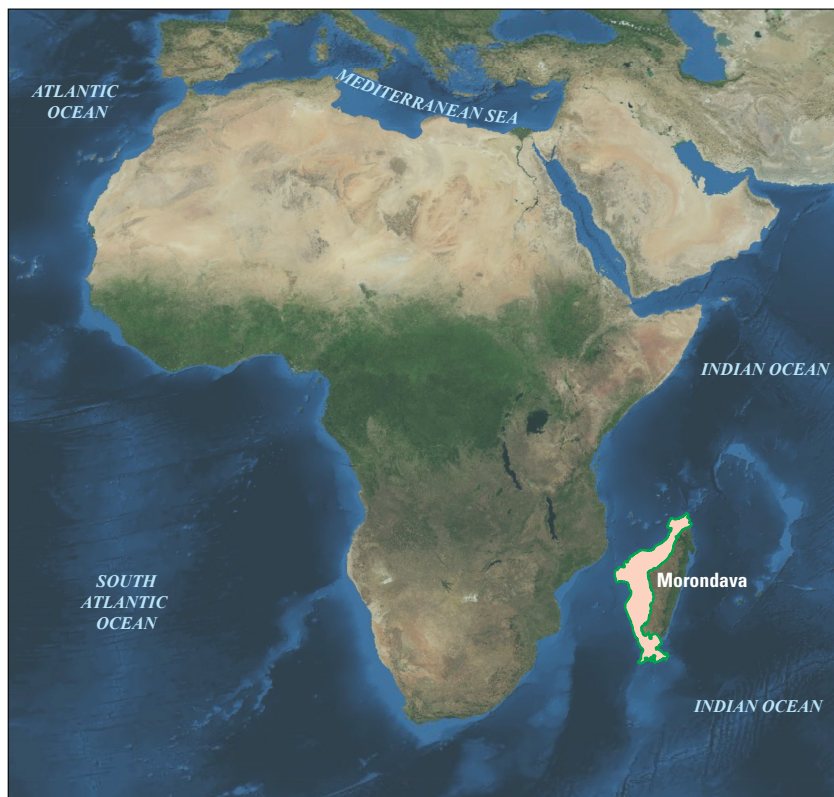


Assessment of Undiscovered Oil and Gas Resources of the Morondava Province, East Africa

By Michael E. Brownfield



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Chapter 11 of
**Geologic Assessment of Undiscovered Hydrocarbon Resources
of Sub-Saharan Africa**

Compiled by Michael E. Brownfield

Digital Data Series 69–GG

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Suggested citation:

Brownfield, M.E., 2016, Assessment of undiscovered oil and gas resources of the Morondava Province, East 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.11, 14 p., <http://dx.doi.org/10.3133/ds69GG>.

ISSN 2327-638X (online)

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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 Morondava Province, East 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 Morondava Province, located along the western part of Madagascar, an area of approximately 460,690 square kilometers. The Morondava Province is characterized by rift, marginal-sag, passive-margin, and drift rocks of Paleozoic to Holocene age. This assessment was based on data from oil and gas exploration wells, producing fields, and published geologic reports.

The Morondava Province and associated assessment unit was assessed for the first time because of increased exploratory activity and increased 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 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 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 440,410 square kilometers. The total petroleum system was defined to include Mesozoic to Paleogene lacustrine and marine source rocks and conventional reservoirs. At the time of the assessment, the Morondava Province contained two gas accumulations exceeding the minimum size of 5 million barrels of oil equivalent; the province is considered to be underexplored on the basis of its exploration effort.

Oil and gas were generated from Permian to Jurassic Karoo-age lacustrine and continental source rocks (rift stage) averaging 4.0 to 5.0 weight percent total organic carbon, from Early to Middle Jurassic restricted-marine rocks containing as much as 9 weight percent total organic carbon, and from Cretaceous Type II source rocks containing as much as 12 weight percent total organic carbon. Hydrocarbon generation

most likely began in the latest Jurassic or earliest Cretaceous, and it continues today in the offshore parts of the assessment unit. Most generated hydrocarbons migrated into Cretaceous and Paleogene reservoirs and traps. Traps are mostly structural within the syn-rift rock units and both structural and stratigraphic in the post-rift rock units. The primary reservoir 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 Morondava Province. The mean volumes are estimated at 10,750 million barrels of oil, 167,219 billion cubic feet of gas, and 5,176 million barrels of natural gas liquids. The estimated mean size of the largest oil field that is expected to be discovered is 1,016 million barrels of oil, and the estimated mean size of the expected largest gas field is 7,837 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 recently completed an assessment of the Morondava Province (fig. 1) (Klett and others, 1996), an area of approximately 460,690 square kilometers (km²). The Morondava Province is characterized by 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 (IHS Energy, 2009) and published geologic reports. A map showing generalized geology of east Africa, Madagascar, and the Morondava Basin is shown in figure 2.

2 Assessment of Undiscovered Oil and Gas Resources of the Morondava Province, Madagascar, East Africa

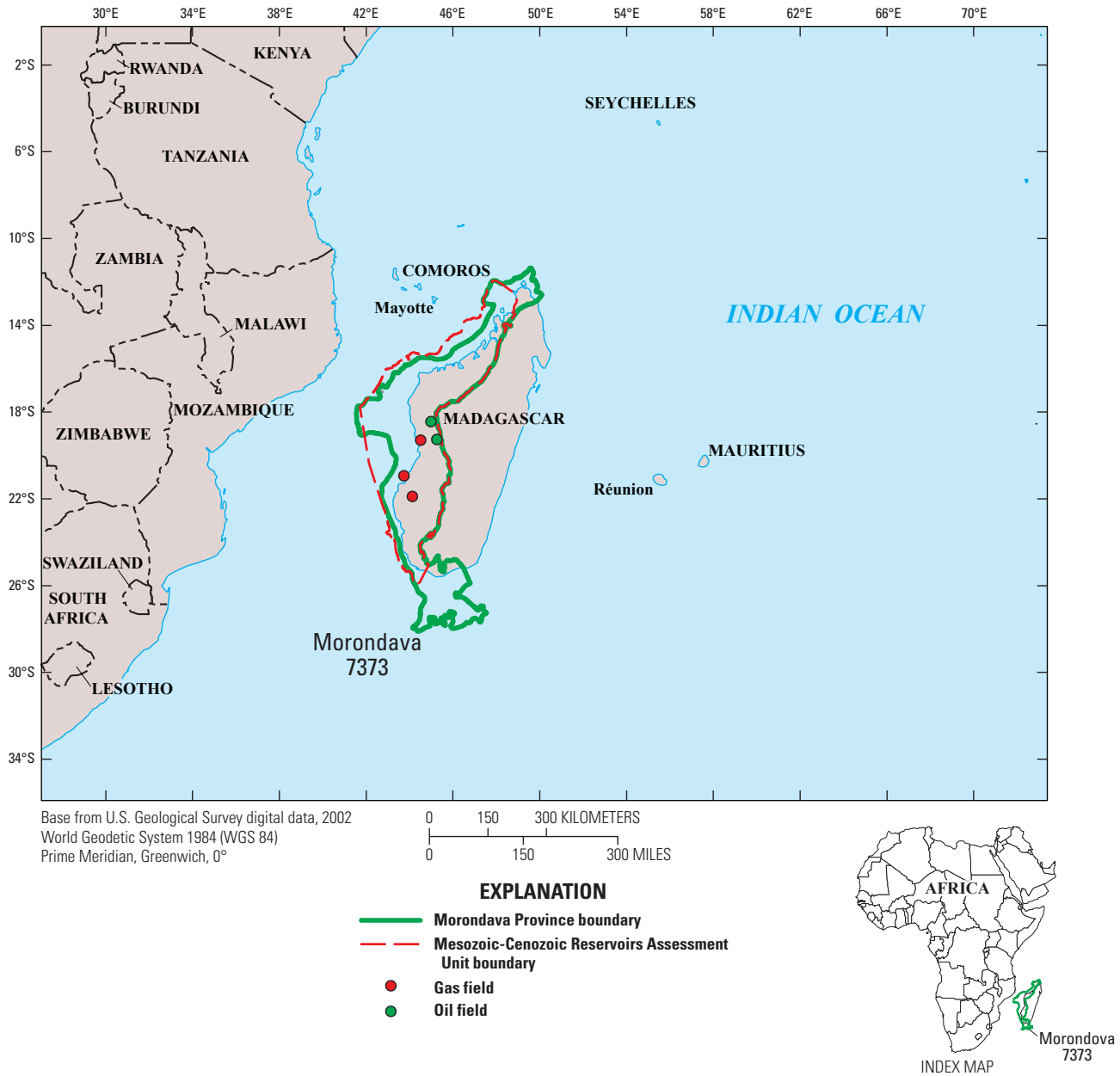
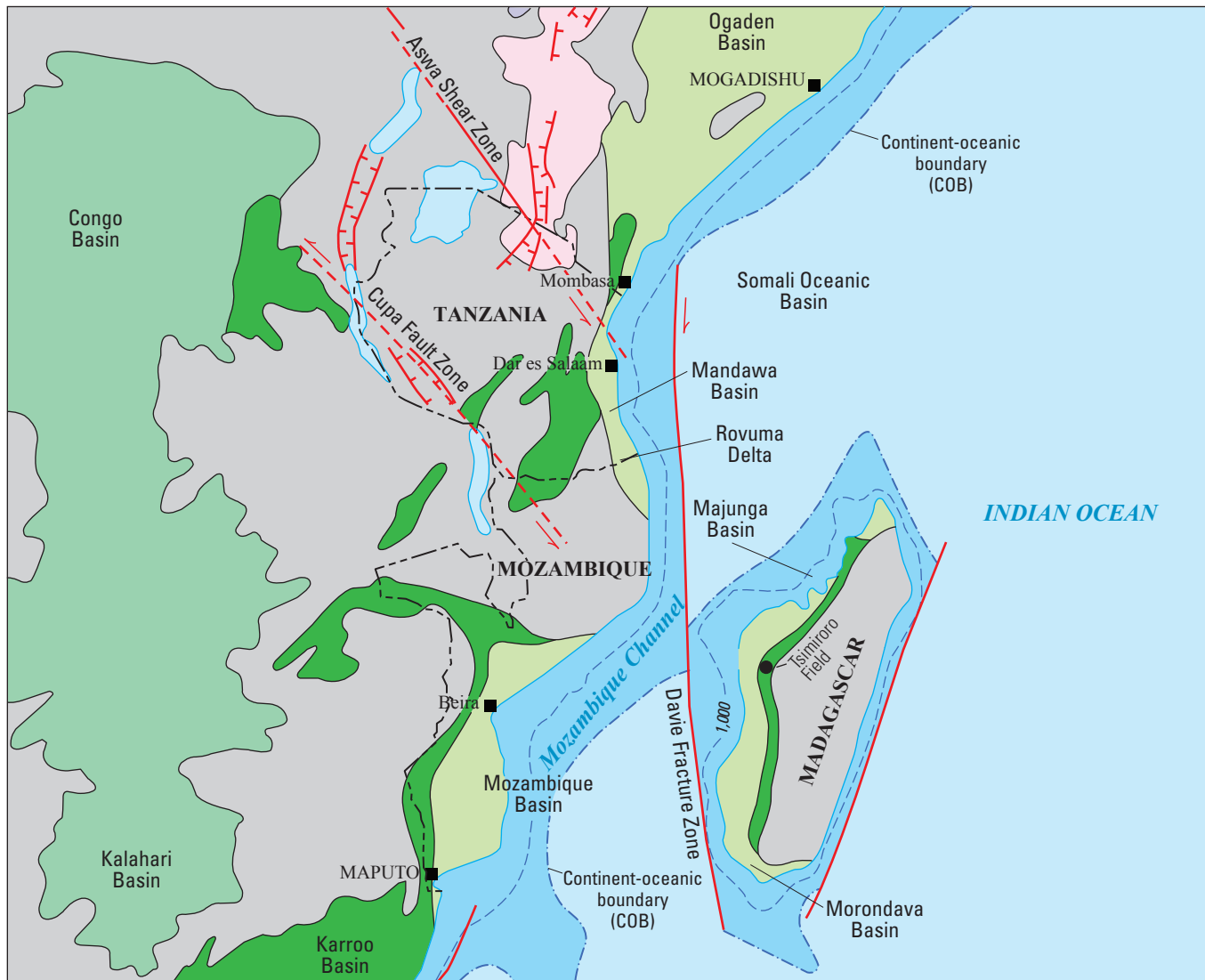


Figure 1. Morondava Province and the Mesozoic-Cenozoic Reservoirs Assessment Unit along the central coast of East Africa.



0 200 400 600 KILOMETERS
 0 200 400 600 MILES

EXPLANATION

- | | |
|---|---|
| Tertiary —Volcanic province | Continental crust —Palo fill |
| Post Early Jurassic —Passive margin basin | Contact |
| Permian-Triassic-Early Jurassic —Karoo-age rock | Fault or fault zone —Dashed where approximate. Arrows show relative motion |
| Phanerozoic —Intracratonic basin | Graben —Teeth on downthrown side |
| Undifferentiated —Precambrian basement | Bathymetric contour, 1,000 meter line —Location approximate |

Figure 2. Generalized geology of East Africa showing Madagascar, Majunga, and Morondava Basins, and the Tsimiroro heavy-oil field. Modified from Ophir Energy (2007).

The Morondava Province and its associated assessment unit were assessed because of increased energy exploration activity and increased 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 Mesozoic-Cenozoic Composite Total Petroleum System (TPS) with one assessment unit, the Mesozoic-Cenozoic Reservoirs Assessment Unit (AU) (fig. 1), an area of approximately 440,410 km². The total petroleum system was defined to include Mesozoic to Paleogene lacustrine and marine source rocks and conventional reservoirs.

Tectonic History and Geology of the Morondava Province, Madagascar, East Africa

The Morondava 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 four phases (Rusk, Bertagne & Associates, 2003; Stone and LeRoy, 2003a): (1) a pre-rift phase that started during 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, resulting in the formation of grabens and half-grabens and the deposition of possible lacustrine and continental source rocks; (3) a syn-rift-drift phase that began in the Middle Jurassic and continued into the Paleogene, depositing marine clastic units and carbonate with periods of restricted-marine conditions during which marine source rocks were deposited; and (4) a passive-margin phase that began in the late Paleogene and continues to the present. The stratigraphic section present in the Morondava Province is generally the same as the section present in the coastal Mozambique and Tanzania provinces (figs. 2, 4; Rusk, Bertagne & Associates, 2003).

The opening of the Indian Ocean began in the Permian and continued into the Jurassic (Plummer and others, 1998). During the syn-rift stage, Madagascar, India, and the Morondava Province separated from Africa in Middle Jurassic, forming a passive margin and a carbonate platform, which was later covered by Upper Jurassic to Cretaceous marine clastic deposits (figs. 4, 5). From the Late Cretaceous to the Holocene, the Morondava Province has been the site of marine deposition in a drift-passive-margin basin.

Petroleum Occurrence in the Morondava Province, Madagascar, East Africa

Source Rocks

The Mesozoic-Cenozoic Composite TPS was defined to include Paleozoic to Paleocene source rocks and conventional reservoirs (figs. 4, 5). The Permian to Triassic section contains fluvial and lacustrine source rocks averaging 5 to 6 weight percent total organic carbon (TOC), and some samples have as much as 17.4 weight percent (Envoi—Energy Venture Opportunities International, 2011). Early to Middle Jurassic rock 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). Early to Middle Jurassic restricted marine Type II source rocks contain as much as 12 weight percent TOC. 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). Type II and III kerogen source rocks of Cretaceous age with TOC contents up to 7.4 weight percent, have been identified in the Ruvuma Delta of northern Mozambique and southern Tanzania (fig. 2) and should be found in the offshore part of the Morondava Province (Cope, 2000; Envoi—Energy Venture Opportunities International, 2011). Ophir Energy Company (2007) reported that Cretaceous shale had TOC contents ranging from 1 weight percent to 9.3 weight percent.

Oil and gas generation most likely began in the Early Cretaceous for the Upper Jurassic syn-rift source rocks in the province. 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 in the early Paleogene, and it is most likely continuing today. Oil and gas generation windows are shown in figure 6 for the Mozambique Channel and the Morondava Basin (Envoi—Energy Venture Opportunities International), 2011).

Reservoirs, Traps, and Seals

The Morondava Province and the Mesozoic-Cenozoic Reservoirs Assessment Units contains Mesozoic and Cenozoic sandstone reservoirs (Cope, 2000; Banks and others, 2008; Matchette-Downes, 2009; Tamannai and others, 2010; Envoi—Energy Venture Opportunities International, 2011).

Triassic to Middle Jurassic syn-rift rocks contain possible alluvial fans, fan deltas, fluvial deltas, and lacustrine sandstone reservoirs (Banks and others, 2008). Late Jurassic post-rift rocks contain reef and platform carbonates that are potential



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

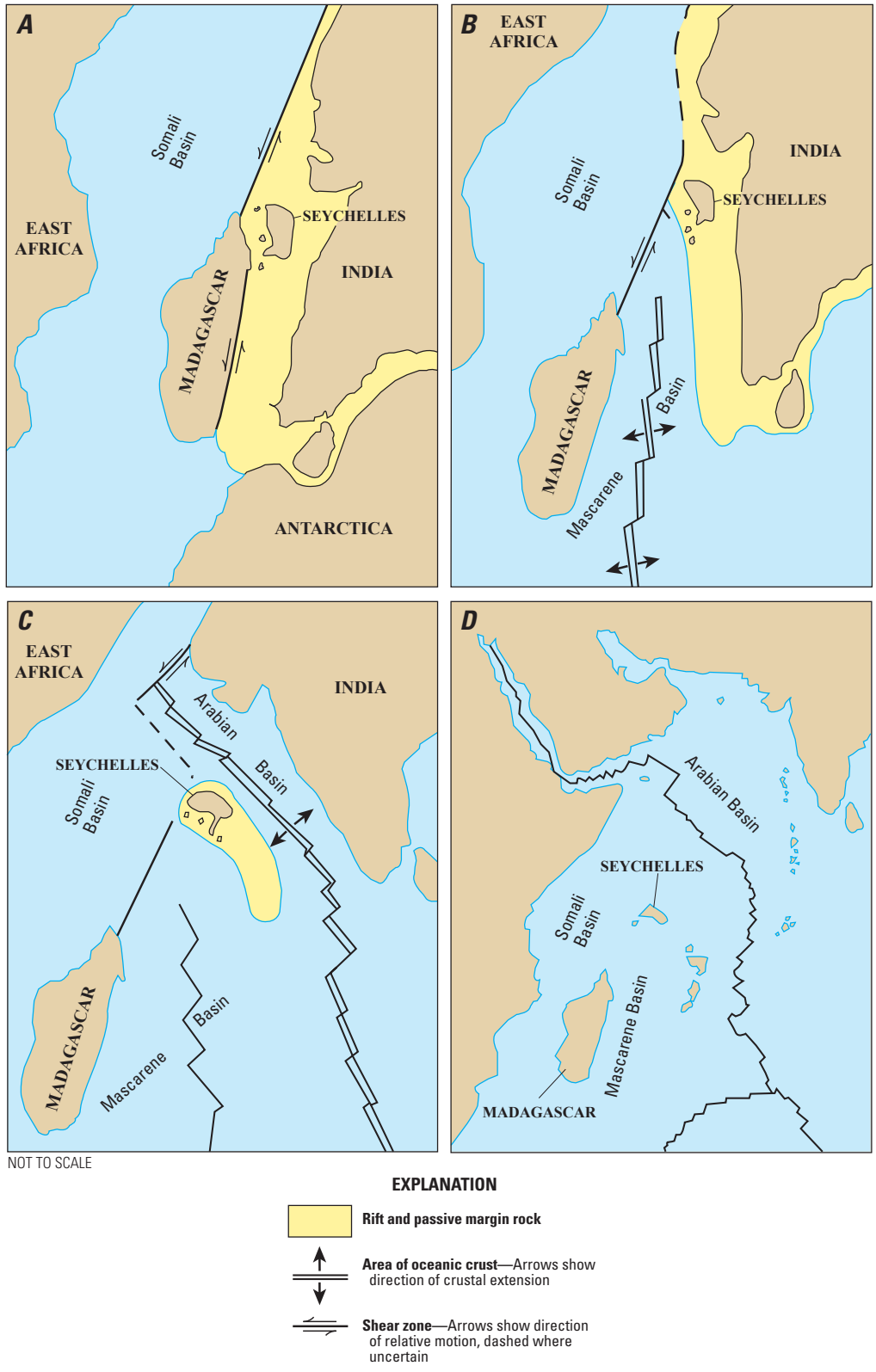
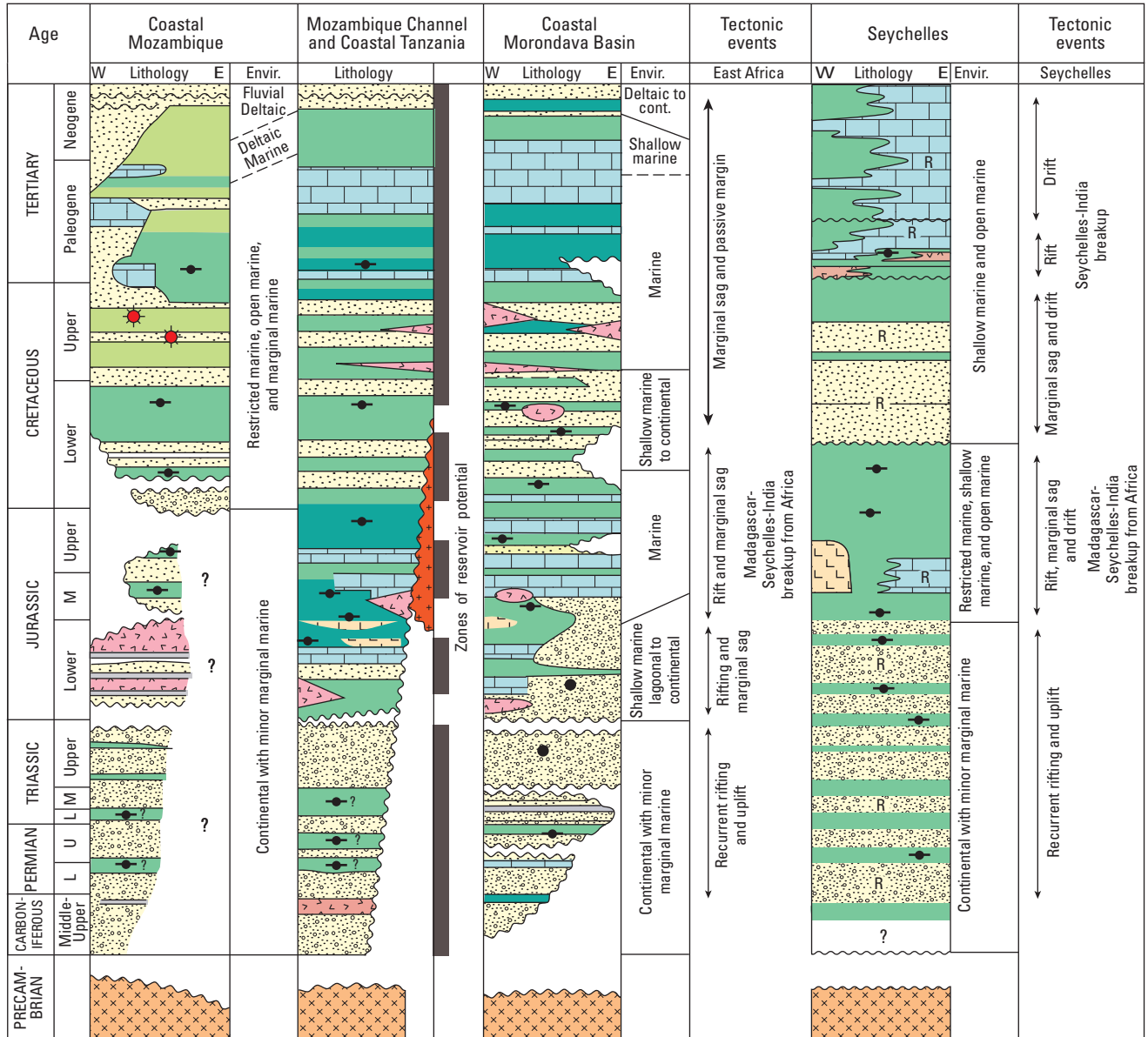


Figure 4. Generalized plate-tectonic development of the Madagascar Province: *A*, Early Cretaceous, following the separation of east and west Gondwana; *B*, early Late Cretaceous, during the separation of Seychelles-India from Madagascar; rotation of the plates shown in the Mascarene Basin; *C*, Paleocene,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



EXPLANATION

- Sandstone
- Sandstone and conglomerate
- Shale
- Sandy shale
- Limestone
- Salt
- Igneous rock—Extrusive
- Igneous rock—Oceanic crust
- Basement
- Reservoir rock, East Africa
- Potential reservoir
- Oil field
- Gas field
- Contact—Dashed where location approximate
- Unconformity
- Extent uncertain
- Source rock

Figure 5. Generalized stratigraphy of coastal Mozambique, the Mozambique Channel and coastal Tanzania, coastal Morondava Basin, and Seychelles along the east coast of Africa (fig. 1). Carb., Carboniferous; cont., continental; Envir., environment; L, Lower; M, Middle; U, Upper; W, west; E, east. Modified from Rusk, Bertagne & Associates (2003) and PetroSeychelles (2013).

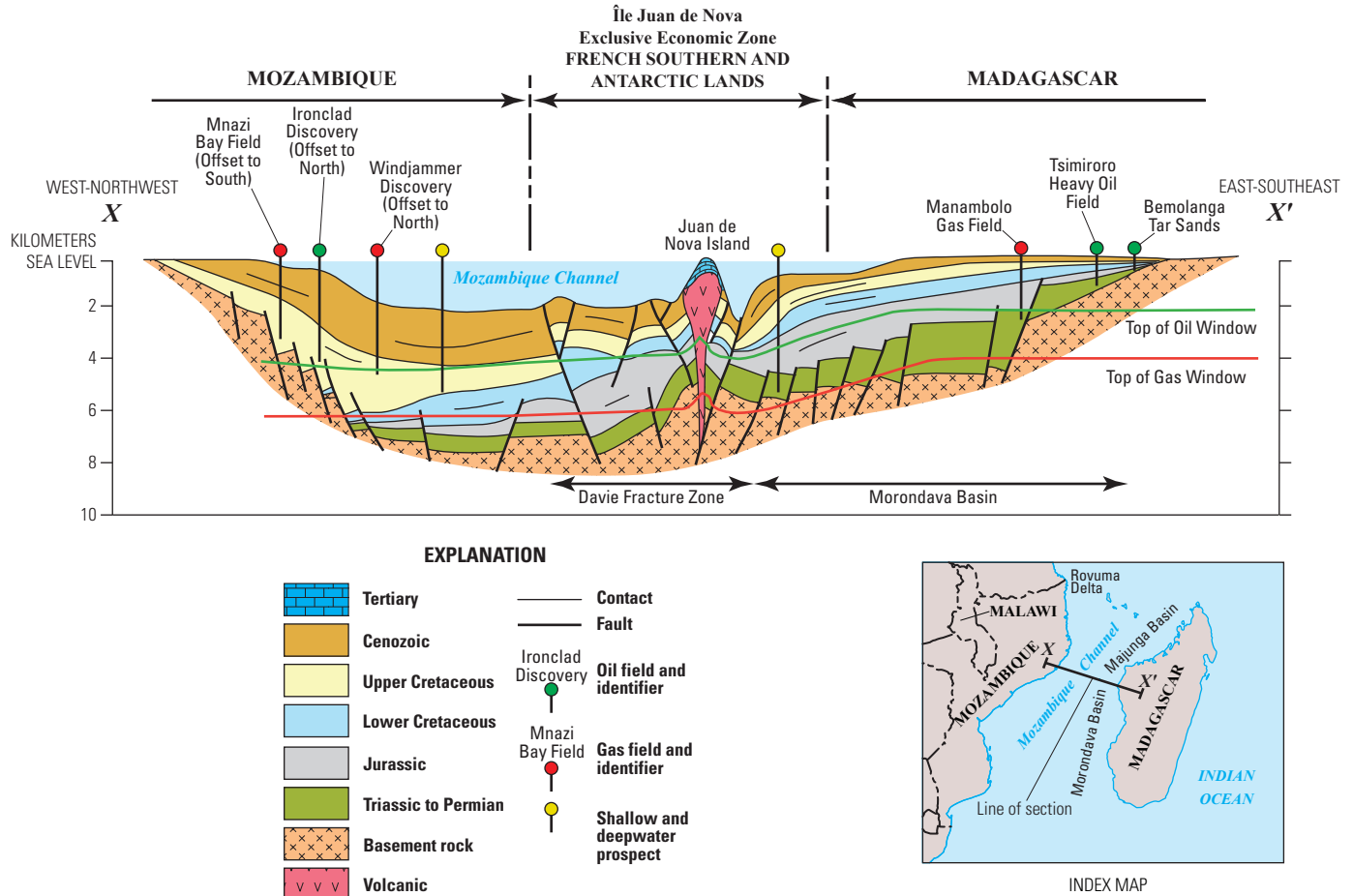


Figure 6. Cross section across the Mozambique Channel and the Morondava Basin (see index map) showing the top of the oil and gas windows. The Permo-Triassic and Lower Jurassic in Madagascar represent a failed-rift section. Modified from Envoi—Energy Venture Opportunities International (2011).

reservoirs (figs. 7, 8). Post-rift Cretaceous sandstone reservoirs include regressive and transgressive marine sandstone, slope turbidite sandstone units, and basin-floor fan sandstone reservoirs (Tamannai and others, 2010). Volcanic events in the Upper Cretaceous and Cenozoic may have degraded potential reservoirs by altering the matrix minerals, but volcanic rocks are generally present in the onshore part of the Majunga Basin (fig. 8) and not in the offshore parts of the basin (Stone and LeRoy, 2003b).

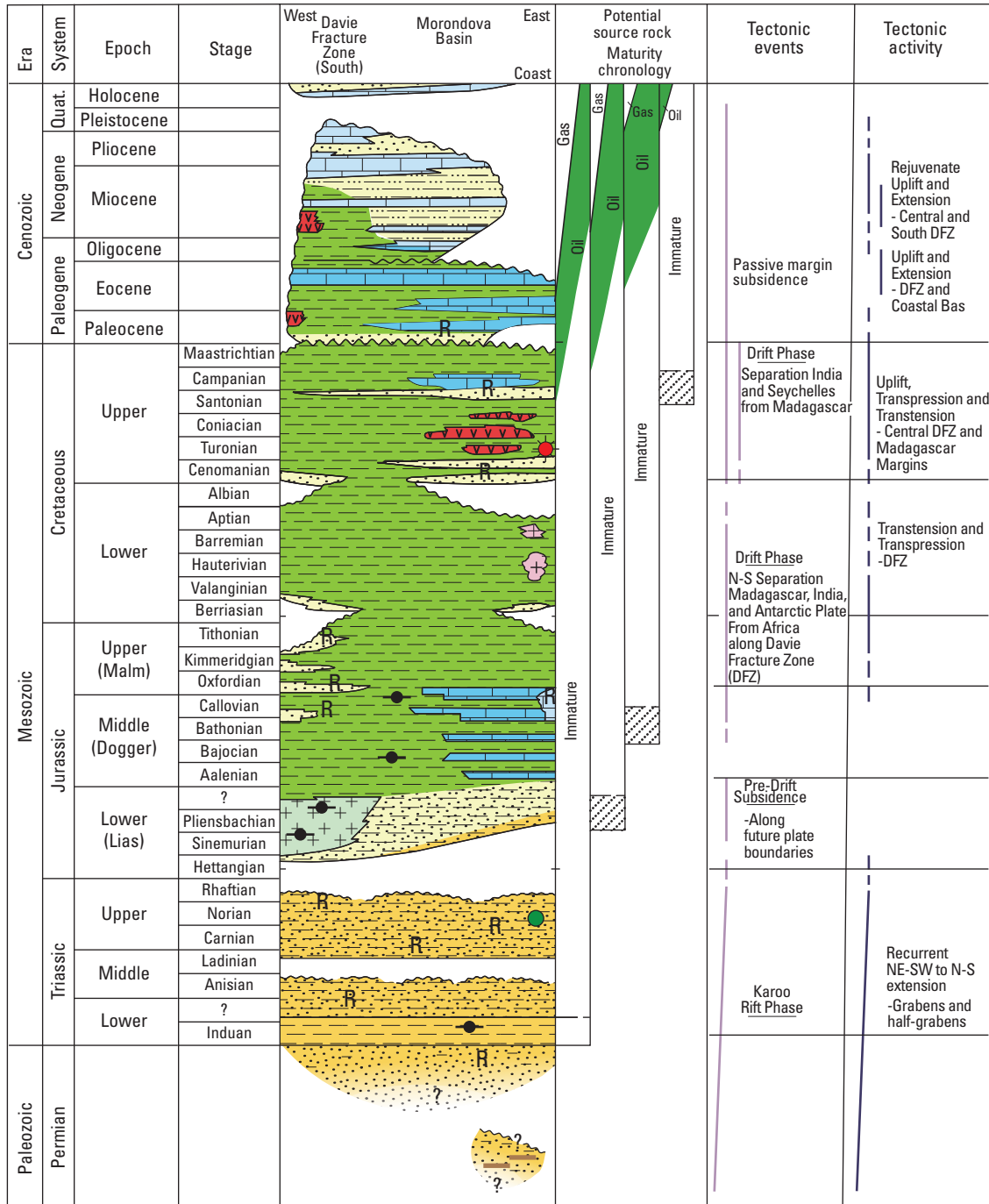
Triassic to Middle Jurassic syn-rift rocks contain traps related to grabens and half-grabens (fig. 8). Lower Cretaceous drift and passive margin post-rift units contain stratigraphic and structural traps such as transgressive and regressive sandstones, salt structures, drape anticlines, and flower structures (Banks and others, 2008). Upper Cretaceous and Paleogene post-rift rocks (drift and passive margin) contain both structural and stratigraphic traps. Structural traps include growth-fault-related structures and rotated fault blocks within the continental shelf. Stratigraphic traps include deep-water fans, turbidite sandstones, and slope truncations along the present day shelf and paleoshelf edge along western Madagascar.

In drift and marginal-marine rocks, the primary reservoir seals are Mesozoic and Cenozoic mudstone and shale. Within the syn-rift section, faults and salt diapirs may act as reservoir seals.

Exploration

At the time of this 2011 assessment, the Morondava Province contained one oil field and no oil and gas discoveries (IHS Energy, 2009); it is considered to be underexplored on the basis of its exploration effort. The Tsimiroro oil field (fig. 2) is a heavy-oil accumulation with a “grown” size of 229 million barrels of oil (IHS Energy, 2009). Hydrocarbon shows and recent exploration efforts are limited to the Cretaceous-Tertiary offshore drift and marginal-marine rocks.

Exploration wells on the continental shelf and upper slope provide evidence for the existence of an active petroleum system containing Mesozoic source rocks, the migration of hydrocarbons most likely since Late Cretaceous time, and the migration of the hydrocarbons into Cretaceous and Cenozoic reservoirs.



EXPLANATION

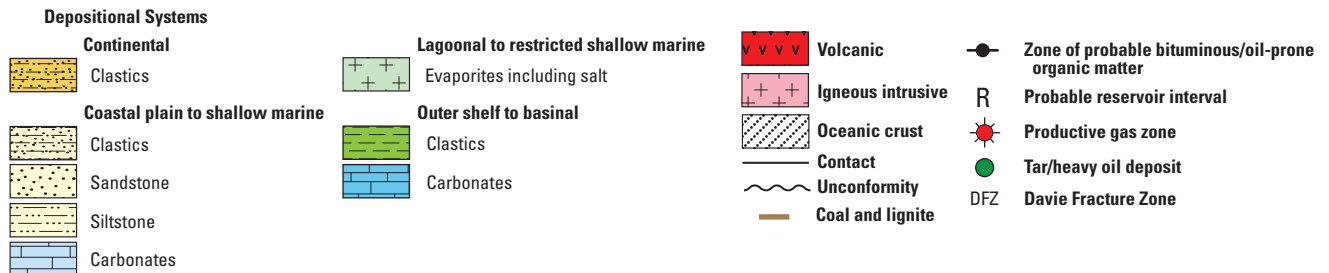


Figure 7. Generalized stratigraphic column of the Morondava Basin, western Madagascar. Red and black lines are the approximate duration of the tectonic events and activity. Modified from Matchette-Downes (2009). Quat., Quaternary; ?, extent uncertain.

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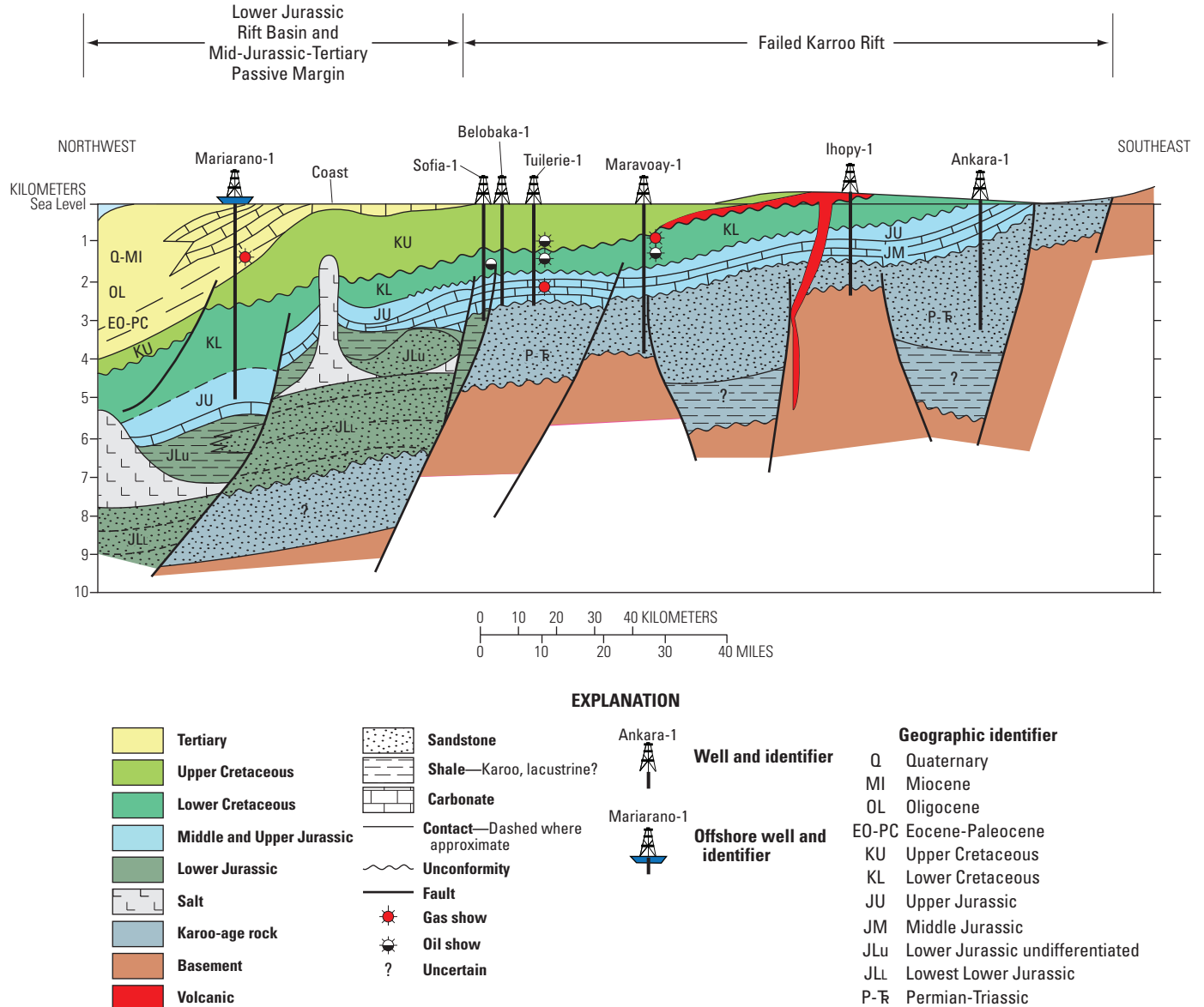


Figure 8. Schematic cross section across the Majunga Basin, northwest Madagascar. Modified from Banks and others (2008).

Geologic Model

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

1. Oil and gas were generated from Permian to Jurassic Karoo lacustrine and continental rocks (rift stage). Lacustrine rocks contain TOC values averaging 4.0 to 5 weight percent; Early to Middle Jurassic restricted marine rocks as much as 9 weight percent TOC, and Cretaceous source rocks contain Type II kerogen with TOC values as much as 12 weight percent. Hydrocarbon generation of syn-rift sources (Upper Jurassic) most likely began in the Early Cretaceous. Oil generation began in the Late Cretaceous for the early post-rift sources. Post-rift (Turonian) sources in parts of the offshore most likely are generating oil today.
2. Hydrocarbons migrated into mostly Cretaceous and Paleogene reservoirs and traps. Possible reservoirs could exist in the syn-rift section.
3. Hydrocarbon traps are structural within the syn-rift rock units and both structural and stratigraphic in the post-rift rocks.
4. The primary reservoir seals are Mesozoic and Cenozoic mudstone and shale.
5. 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 Composite TPS and the Mesozoic-Cenozoic AU summarizes the age of the source, seal, and reservoir rocks and the timing of trap development, generation, and migration of hydrocarbons.

Resource Summary

At the time of the 2011 assessment, the Morondava Province contained one oil accumulation exceeding the minimum size of 5 million barrels of oil equivalent; the province is considered to be underexplored on the basis of its exploration activity.

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 Morondava Province (table 1). Mean volumes are estimated at 10,750 million barrels of oil, 167,219 billion cubic feet of gas, and 5,176 million barrels of natural gas liquids. The estimated mean size of the largest oil field that is expected to be discovered is 1,016 million barrels of oil, and the estimated mean size of the expected largest gas field is 7,837 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.

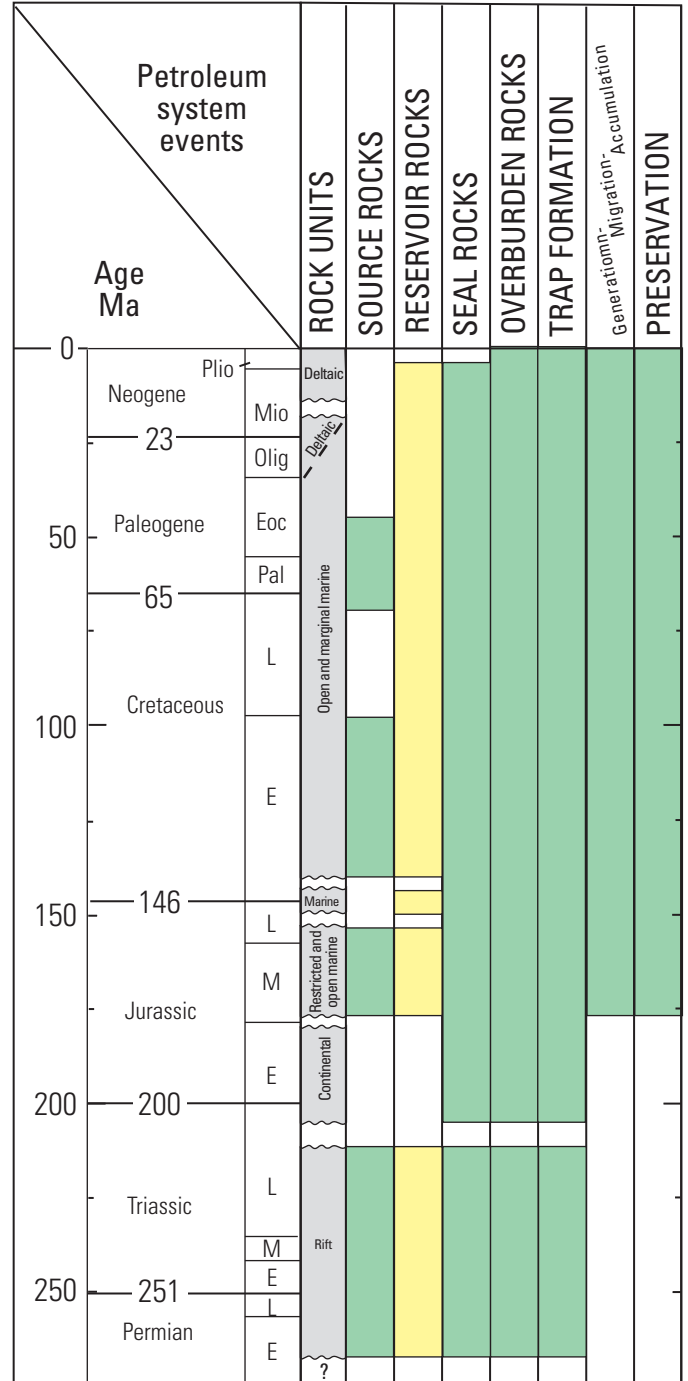


Figure 9. Events chart for the Mesozoic Composite Petroleum System (737301) and the Mesozoic-Cenozoic Reservoirs Assessment Unit (73730101). Gray, rock units present; yellow, age range of reservoir rock; green, age ranges of source, seal, and overburden rocks and the timing of trap formation and generation, migration, and preservation of hydrocarbons; wavy line, unconformity. Divisions of geologic time conform to dates in U.S. Geological Survey Geologic Names Committee (2010). Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, Late; E, Early; M, Middle; ?, uncertain.

Table 1. Morondava 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. 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]

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
Morondava-Mesozoic Composite TPS														
Mesozoic-Cenozoic Reservoirs AU	<i>Oil</i>	1,016	5,701	10,256	17,455	10,750	7,686	14,325	25,322	15,123	205	386	693	409
	<i>Gas</i>	7,837					85,291	145,683	242,887	15,2096	2,667	4,569	7,618	4,767
Total Conventional Resources			5,701	10,256	17,455	10,750	92,977	160,008	268,210	167,219	2,872	4,955	8,311	5,176

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).

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.

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