China Geology 1 (2019) 56−66

China Geology

Journal homepage: http://chinageology.cgs.cn

Characteristics and potential analysis of Madagascar hydrocarbon-bearing basins

Da-tian Wu[a,*], Johanne Iomimalala Ramaniraka[b, c], Feng-ming Xu[a], Jian-bo Shao[a], Yong-heng Zhou[a], Yuan-dong Zhao[a], Bruno Ralison[c]

[a] *Shenyang Center, China Geological Survey, Ministry of Natural Resources, Shenyang* 110034, *China*
[b] *China University of Geosciences, Wuhan* 430074, *China*
[c] *Département des Sciences de la Terre, Faculté des Sciences, Université d'Antananarivo, Antananarivo 101, Madagascar*

ARTICLE INFO

Article history:
Received 15 October 2018
Received in revised form 7 November 2018
Accepted 7 December 2018
Available online 5 March 2019

Keywords:
Madagascar
Hydrocarbon-bearing basins
Characteristics of Malagasy basins
Potential analysis
Geology and stratigraphy

ABSTRACT

Madagascar becomes a large isolated island after its dislocation from East Africa at its western part during the opening of the Mozambique Channel and its separation from India at its eastern part during the opening of the basin of the Mascarene. From a stratigraphic point of view, Karroo of Madagascar shares substantial similarities with the stratigraphic strata of East Africa.While oil companies have taken a liking to the basins of East Africa, they also turn to the basins in the western part of Madagascar especially after the discovery of large oil fields at Tsimiroro and Bemolanga. According to the study of their geological history, the basins of Madagascar contain huge hydrocarbon potential. The western basins, which is more developed than the east coast of the island, have been the subject of many in-depth studies by numerous researchers. The cross-referencing of bibliographic data with geological studies, and knowledge of hydrocarbon formation and maturation stages, carried out in this study served to determine the nature of source rocks, reservoir rocks, bedrock and eventual trapping system of hydrocarbons in Madagascar. This study identified the properties of Madagascar source rocks, reservoir rocks, bedrock and the final oil and gas trap system by cross-referencing the literature and geological research, oil and gas formation and maturity stages, and shows that Madagascar has considerable hydrocarbon potential.

1. Introduction

Madagascar is the fourth largest island in the world and has an area of 5.92×10^5 km^2. It is located in the southern hemisphere, in the western part of the Indian Ocean, and is separated from Africa by the Mozambique Channel.

The African coastline is an important continental margin. The opening of the Atlantic rift left abundant organic matter in the geological strata which have given rise to a large number of oil basins. Several deposits, particularly in Nigeria, Angola, Congo, Côte d' Ivoire and other West African countries have attracted the attention of many researchers and oil companies for many years (Hemsted T, 2003; Bumby AJ and Guiraud R., 2005; Guan ZM and Li J., 2007; Zhang GY et al., 2018, 2018b). However, since 2006, East Africa has become a new oil and gas zone, although only few geologists believed its potential less than a decade ago (Zhang KB et al., 2007; Zhou ZQ et al., 2013; Ma J et al., 2008; Jin C et al., 2012; Wen ZX et al., 2012; Xu ZG et al., 2014a; Xu ZG et al., 2014b; Wen ZX et al., 2015; Yu X et al., 2015; Chen YH et al., 2016; Cui ZW et al., 2016). And in 2006, the discovery in Uganda made oil companies interested in East Africa region. Mozambique's offshore discoveries have also increased their interest in Tanzanian, Kenyan, Somali and Comorian offshore (Genik GJ, 1993; Harouna M and Philp RP, 2012; Wopfner H, 2002; Zhang GY et al., 2018).

Madagascar has a continuous Precambrian base comparable to East Africa before the rifting episodes that separated it from the African continent. Madagascar is also the subject of concentrated exploration efforts especially in its three main western sedimentary basins: Ambilobe, Mahajanga and Morondava (Wescott WA and Diggens JN, 1997; Pique A et al., 1999; He WX et al., 2017). It was the discovery of the two giant oil fields of Bemolanga and Tsimiroro at the beginning of the twentieth century that stimulated exploration activities in Madagascar. Since then, 75 exploratory wells on the island have been drilled, including 1 onshore in the Ambilobe Basin, 8 in the Mahajanga Basin, 65 in the Morondava Basin and 1 in the East Coast (OMNIS., 2018).

---

* Corresponding author: *E-mail address*: 373189713@qq.com (Da-tian Wu).

doi:10.31035/cg2018076
2096-5192/© 2019 China Geology Editorial Office.

The East African Rift is one of the biggest geological phenomena that led to the separation of Madagascar from Africa, and greatly influenced the deposit environments of the Malagasy basins. The formation of many traps in the western part of Madagascar is also linked to many rifting episodes and represents a huge hydrocarbon potential for the whole country (Christopher RS et al., 1988; Daly MC et al., 1989; Hankel O, 1994).

The purpose of this article is to assess the hydrocarbon potential of Madagascar's sedimentary basins, and their connection with the major geological phenomena that affected the island, particularly during its dislocation with Africa.

2. Geology background of five basins in Madagascar

2.1. Distribution characteristics of the five basins

Madagascar resulted from the dislocation of Gondwana. The island is made up of two main geological entities:The crystalline basement with several structures dating from the Precambian, which outcrops on 2/3 of its surface (Fig. 1a) ; Series of weakly metamorphosed and deformed sedimentary rocks, which rests on the crystalline base and represents the remaining 1/3 (Tucke RD et al., 2014 ; Giese J et al., 2016; Rafalimanantsoa G, 2016; Fig. 1b) .

Madagascar consists of five basins extending from the edge of the basement to the Exclusive Economic Zone (EEZ) off the coast. While the crystalline basement is very wrinkled, the sedimentary part has no significant orogenic action and has deposited regularly (Besairie H, 1971). The five basins presently have a very slight dip towards the sea.

The three main basins (Ambilobe, Mahajanga and Morondava) extend into the western part of the island. The two remaining small basins are both marine: the Cap Sainte Marie Basin in the south that could be linked to the big Morondava basin, and the East Coast Basin.

The sediments of Madagascar are constituted by two important systems: (1) Upper Permian Karroo Formation at Middle Jurassic containing thick continental sediments; (2) Post-Karroo mainly deposited in a marine environment.

2.2. Depositional environments of the five basins

The sedimentary basins on the west coast of Madagascar are governed by an essentially brittle tectonic plate. The series remained practically tabular and defined a western monoclinal in the Morondava basin and northwest monoclinal shallow dip in Mahajanga and Ambilobe.

The Karroo series described in Tanzania and Kenya have great similarities with the known sequence in Madagascar (Kent PE, 1974). This deposit regime corresponds to an intra-continental rift period. Most of the deposits are synrift and the sequences often ended in very sharp discordances. These are Sakoa, Sakamena, Isalo I and Isalo II for the Morondava basin. This period from the Permo-Carboniferous to the Lower Jurassic characterizes a rifting phase during which the observed subsidence is mainly of tectonic origin.

The resulting deposit scheme is mainly marine and shows a considerable development of post-rift deposits. Deposits are usually limestone, marl and shale, found almost in all East African coastal basins. This type of deposit began in the Low and Middle Jurassic and was marked by widespread unconformity across East African basins. The subsidence observed during this second type of deposit reflects a larger phenomenon, of regional scale. It effectively corresponds to a "drifting" phase during which the different basins have evolved into passive divergent margins.

2.3. Tectonic structures and basement evolution history of the five basins

The dislocation of Gondwana, at the end of Upper Lias, 180 Ma is an event subsequent to the Karoo (Geiger M et al., 2004). This is characterized by a Middle Permian rifting episode (250 Ma) which developed to the Callovian (154 Ma).

Indeed, the separation of Madagascar, Sri Lanka, India and Seychelles from the African Continent was preceded by a period of continental expansion: the Karoo. The Karoo deposit ranges from Neo-Carboniferous (300 Ma) to Middle Jurassic (183 Ma) (Rabinowitz PD et al., 1983; Duncan RA et al., 1997; Rakotosolofo NA et al., 1999; Bumby AJ and Guiraud R, 2005; Catuneanu O et al., 2005). In South Africa and East Africa, Karoo rifting is associated with large volcanic provinces that are dated from 184 Ma to 179 Ma (Duncan RA, 1997; Gall BL et al., 2002; Jourdan F et al., 2007; Aubourg C et al., 2008).

In Madagascar, the rifting episodes are identified on both sides of the Island: in the western part, the Karoo, which includes the establishment of the Mozambique sedimentary basin (Coffin MF and Rabinowitz PD, 1988; Salman G and Abdula I, 1995), and to the east, the initiation phases of the opening of the Indian Ocean. It consists of North-East, South-West and Nort shear zone of Mozambique (Reeves CV et al., 2002).

The evolution of the rifts in the South-West of the island (Morondava basin) is articulated in three phases (Schandelmeier H et al., 2004): On the one hand, two successive senestral traps, Meso-Neopermian (258 Ma) and Post-Neo Permian (250–245 Ma), generated basins transtension (direction to the South) ; And on the other hand, an extension of the northwest and the southeast gave rise to normal faults.

As for the dislocation of India and the Seychelles Islands, it took place in a rapid manner (Bertil D and Regnoult JM, 1998) and created the oceanic basin of Mascarene Large basaltic effusions are associated with this opening. Indeed, a large mass of volcanic rock effusions abounds on the east coast of Madagascar. Isotopic analyzes, coupled with paleogeographic studies, suggest that the source of these basalts corresponds to the Marion hot spot, which passed through the entire lithosphere (Storey M et al., 1995, 1997).

3. Characteristics of hydrocarbon systems in Madagascar sedimentary basins

3.1. Characteristics of source rocks, reservoirs and caps

Sedimentation in the sedimentary basins of Madagascar was controlled by the main tectonic movements that shaped it.

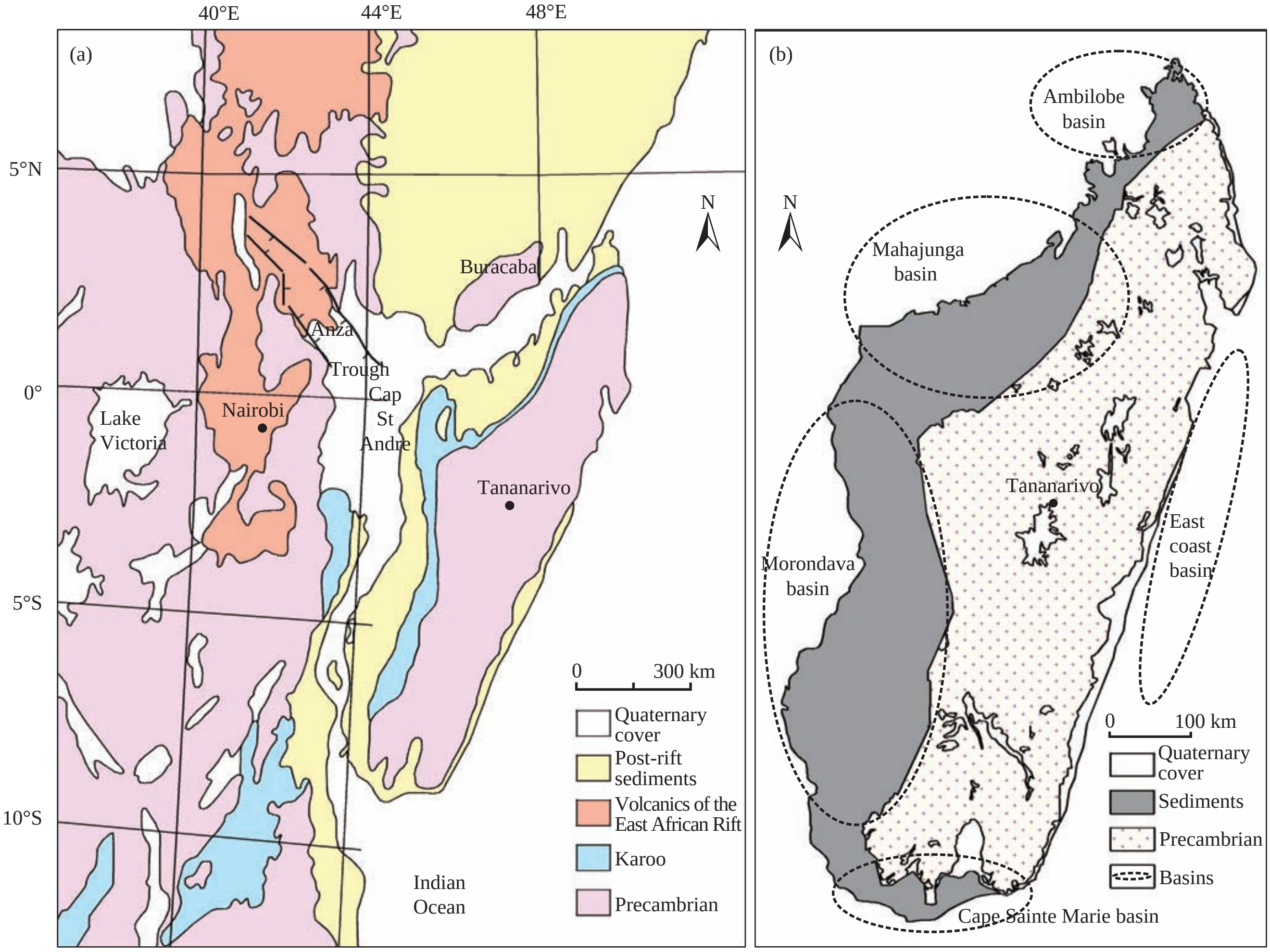

Fig. 1. Simplified map of Madagascar location and five basins location. a–Approximate location of Madagascar before Jurassic (after Reeves CV et al., 2002); b–simplified map of the geological formations of Madagascar (after Tucke RD et al., 2014).

The quality of the reservoir rocks of the Malagasy basins and their hydrocarbon potential are then linked to the various rifting episodes that Madagascar has known and to all its geological history including its stratigraphical deposits.

Therefore, traps in Malagasy basins are often structural traps related to tectonic events including aborted rifts and Stratigraphic traps.

The conditions for the existence of hydrocarbon deposits are more or less complete in the western basins.

In fact, the source rocks are generally clays or other layers rich in organic matters deposited earlier during the sedimentation. Reservoir rocks must be porous and permeable enough to accommodate hydrocarbons and store them after migration. They are generally represented by porous and permeable sandstones, laying over source rocks.

Malagasy Karroo formations are generally composed of clayey-sandstone complexes that constitute both good source rocks and good reservoir rocks.

Covered rock must be impervious to provide an effective trap to prevent oil from escaping. There may be mentioned the crystallized salt layer of the Mahajanga basin.

Here are some examples of traps in the western basins of Madagascar:

(i) Structures linked to failed rifts.

The traps linked to the failed rift consist of tilted blocks, flower structures set up on the shore of Madagascar to the southeast, settlement anticlines on a raised base or horst. These structures can be found in the Mahajanga basin, the Ankara depression, the Morondava basin, the Karroo corridor, the Berenty depression and the Vohidolo horst.

(ii) Strucures linked to passive margin.

The structures associated with the passive margin are located in the basins of Ambilobe, Mahajanga and Morondava. The limits of the Middle Jurassic slope and Lower Cretaceous paleo-valleys can be mapped.

The results of one well showed a good quality light oil index in the sands of the Albo-Cenomanian low-level prism.

3.2. Correlations of stratigraphic and depositionnal environments between five basins and East Africa basins

The basins of the west coast have a common geological history, initiated by intra-cratonic faults during the Neo-Permian/Eo-Triassic period. They contain thick clastic continental sequences covered by deltaic fluvial sequences from the Triassic to the Lias. The Toarcian rifts and the consequent drift of Madagascar to the South from the coast of

Somalia to its present location controlled the Jurassic deposits to the Neocomian, creating a passive margin along the coast. That leads to the formation of traps in Ambilobe, Mahajanga and Morondava basins.

The long subsidence period and westward tilt in response to Indian separation and drift to the northeast during the Late Cretaceous resulted in abundantly developed Mesozoic and Cenozoic sequences in each basin. The establishment of the salt basin of Mahajanga took place just before the drift towards the southwest of Madagascar.

The stratigraphic revision of the Ambilobe Basin in the extreme north-west of Madagascar, has made it possible to reconstruct the opening of the Mozambique Channel for the period from 210 Ma to 180 Ma (Dupont J, 1972; Papini M and Benvenuti M, 2008). Sediments in the Mahajanga Basin (Northwest) are composed of an underlying marine set, with some regressive episodes (Razafindrazaka Y and Randriamananjara T, 1999). The analyzes of the fission traces on the sediments of the Morondava basin (South-West) made it possible to date them from the Jurassic period. These are revisions of the Karoo. Pre-rifting phases have also been recorded in the South (Morondava basin), marked by the deposit of Isalo sandstones, which are of late Triassic age, 230 Ma–250 Ma (Rajaomazava F, 1992; Emmel B et al., 2006, Geiger M and Schweigert G, 2006).

The last two basins are poorly known: (1) The Cap Sainte Marie basin could have Permian and Mesozoic fills under the Neogene blanket; (2) The East Coast basin may have a thick section of Cretaceous under the lava flow flush along the narrow continental sedimentary basin.

The Big Island broke away from the Somali coast 165 million years ago. The drift lasted 65 million years and Madagascar reached its present position since the Aptian-Albian. Drift from India to the northeast began 84 million years ago. Madagascar, Somalia and Kenya have a common geological history through the deposition of the Karroo system, from the Permian to the lower Lias. The basins of Mahajanga and South-East Somalia were together and the Morondava Basin was assembled in Kenya and northern Tanzania. Sedimentation in Madagascar basins was controlled by the main tectonic movements that shaped Madagascar.

3.3. *Characteristics of oil-bearing systems*

Currently, oil exploration in Madagascar is concentrated mainly in the three main sedimentary basins: Morondava, Mahajanga and Ambilobe. However, the basins of the East Coast and Cape St. Mary also have some interests. The potentiality of this last basin can be extended to the Madagascar Plateau which is the continuation of the island of Madagascar to the South. The two major oil deposits of Tsimiroro and Bemolanga have their sources in the Triassic lagoon-lake-bottom, widespread in East Africa.

The Toarcian, the Middle Jurassic condensed series, and the Neocomian were found to be good source rocks containing Type I and II organic materials (OMNIS, 2018; Fig. 2).

The immature oil in the outcrops of the Senonian suggests that the Senonian could contain rocks of good quality in subsurface and especially for offshore surveys.

Concerning reservoir rocks, the Karroo system offers several sandy levels. These levels may have potential.

The reservoirs of the Post Karroo System are composed of sands, reefs and dedomomitized carbonates for the Dogger, turbidites, deep water enthusiasts and sandy units associated with low-level prisms.

Structural trapping systems are associated with the main tectonic events that affected sedimentation.

4. Petroleum system analysis of the basins

4.1. *Ambilobe basin*

The results of drilling and sampling conducted by Wilton Petroleum Society confirm the existence of source rocks but their level of thermal maturation, their organic carbon content and their potential to generate hydrocarbons remain to be verified. The source rocks are thus of Jurassic age inferior to Paleogene (Razafindrakoto S, 2016).

The results obtained in the Ambilobe basin make it possible to say that:

Lias source rocks at Nosy Be and Ampasindava have very high reflectance values of vitrinite, ranging from 2.55% to 3.72% indicating their over-maturity.

High levels of Source rocks in the Ambilobe Basin are due to tertiary intrusions and volcanism ; considering the level of thermal maturity and the alteration of the samples. Their organic carbon content varying from 0.48% to 3.55%, on the other hand, indicate that these rocks were well preserved during their deposit. The organic matter contained in these rocks is of Type III, and was very rich before the thermal alteration since the heats released by the intrusions and the volcanisms baked organic materials of Types I and II primary.

Ankarana and Ambilobe source rocks with Ro values ranging from 0.5%-1.3% indicate good source rocks as their organic carbon content is about the same.

Thus, hydrocarbon source rocks at Nosy Be and Ampasindava have had good potential, but intrusions and volcanism have modified it, while those at Ankarana and around the Ambilobe well are good source rocks for producing water, oil and gas. The age of the source rocks in this basin are Middle Jurassic Lias (Table 1).

4.2. *Mahajanga basin*

Data from the wells in this region (Wilton Petroleum Society) show the progression of sediment deposits from the oldest to the most recent. The wells drilled onshore crossed a section of Triassic-Cretaceous sediments, while the two offshore wells show the deep Jurassic, and a reduced Cretaceous section covered by a thick tertiary section reflect the migration of sediments to the sea from the deposits (Razafindrakoto S, 2016; Fig. 3).

In the boreholes, source rocks in the Mahajanga basin

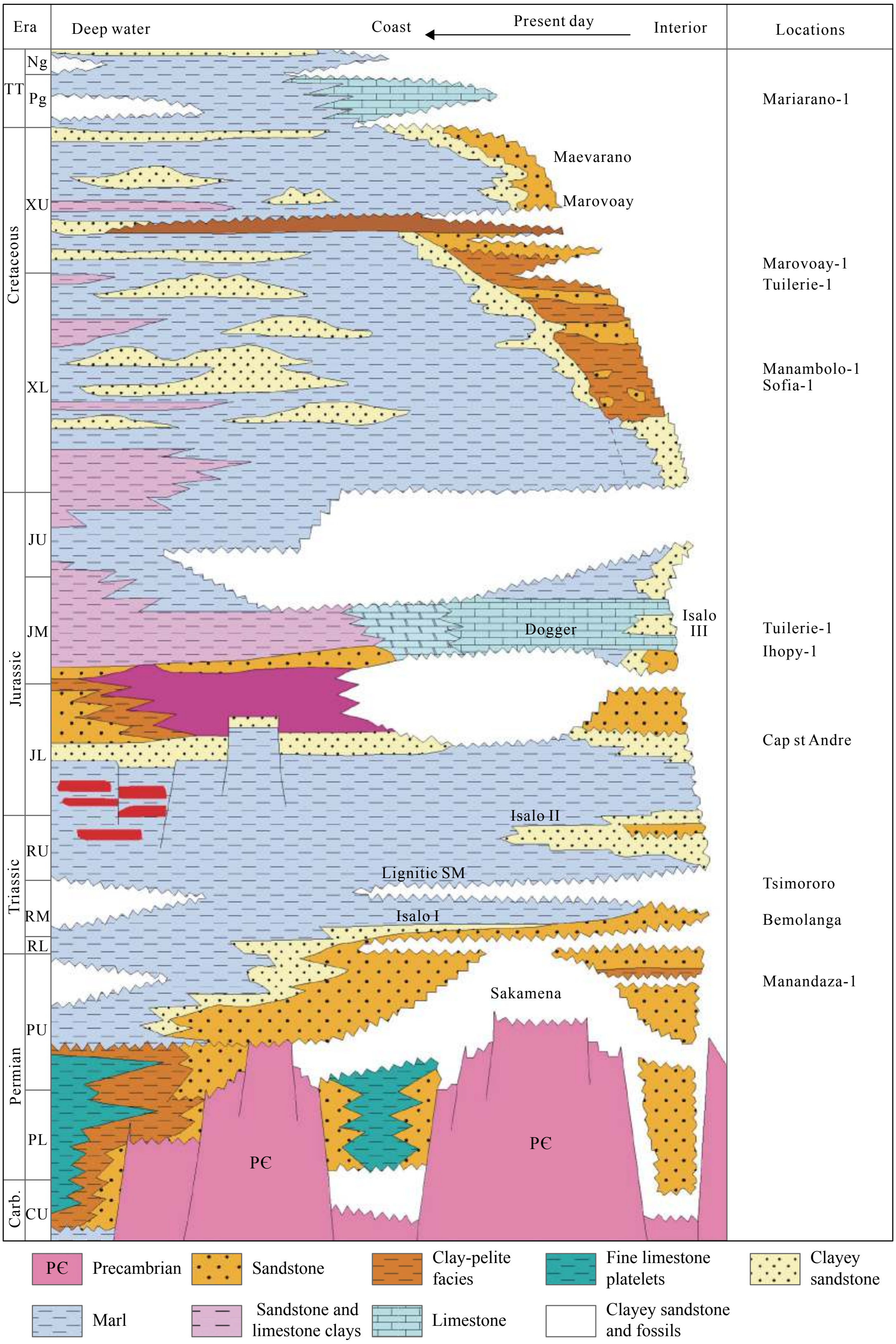

Fig. 2. Madagascar's chronostratigraphy (after OMNIS, 2018). TT–Tertiary; Ng–Neogene; Pg–Paleogene; XU–Upper Cretaceous; XL–Lower Cretaceous; JU–Upper Jurassic; JM–Middle Jurassic; JL–Lower Jurassic; RU–Upper Triassic; RM–Middle Triassic; RL–Lower Triassic; PU–Upper Permian; PL–Lower Permian; CU–Upper Carboniferous.

have low levels of organic carbon with values generally between 0.5% and 1.5%. The exceptions are the Cretaceous higher than SOFIA-1, which has a grade up to 9.3%. The potential of rocks to generate hydrocarbons is very poor, in most wells they do not exceed 0.5 mg/g and not more than 1 mg/g of rock. In terms of thermal maturation, they are more

Table 1. Synthesis of the potential of source rocks in Malagasy sedimentary basins.

Age	Lithology and organic carbon		Kerogen Type and maturity	Potential of the source rock	Future products
Late Cretaceous	Clays, marls, limestones	Poor to average	Generally Type IV, non-matured	Poor to rich	Carbon if matured
Early Cretaceous	Clays, marls, limestones	Very poor to rich	Type IV with high pourcentage of Type II and Type III	Poor to rich	Carbon, oil and gas if matured
Late Jurassic	Limestones, marls	Poor	Type IV, matured organic materials	Very poor to poor	Carbon
Early and middle Jurassic	Limestones, marls	Poor to rich	Type IV with high pourcentage of Type II and Type III. Non-matured to matured	Very poor to poor	Carbon, oil, gas
Toarcian	Isalo II	Poor	Type IV, late maturation	Very poor	Maybe carbon

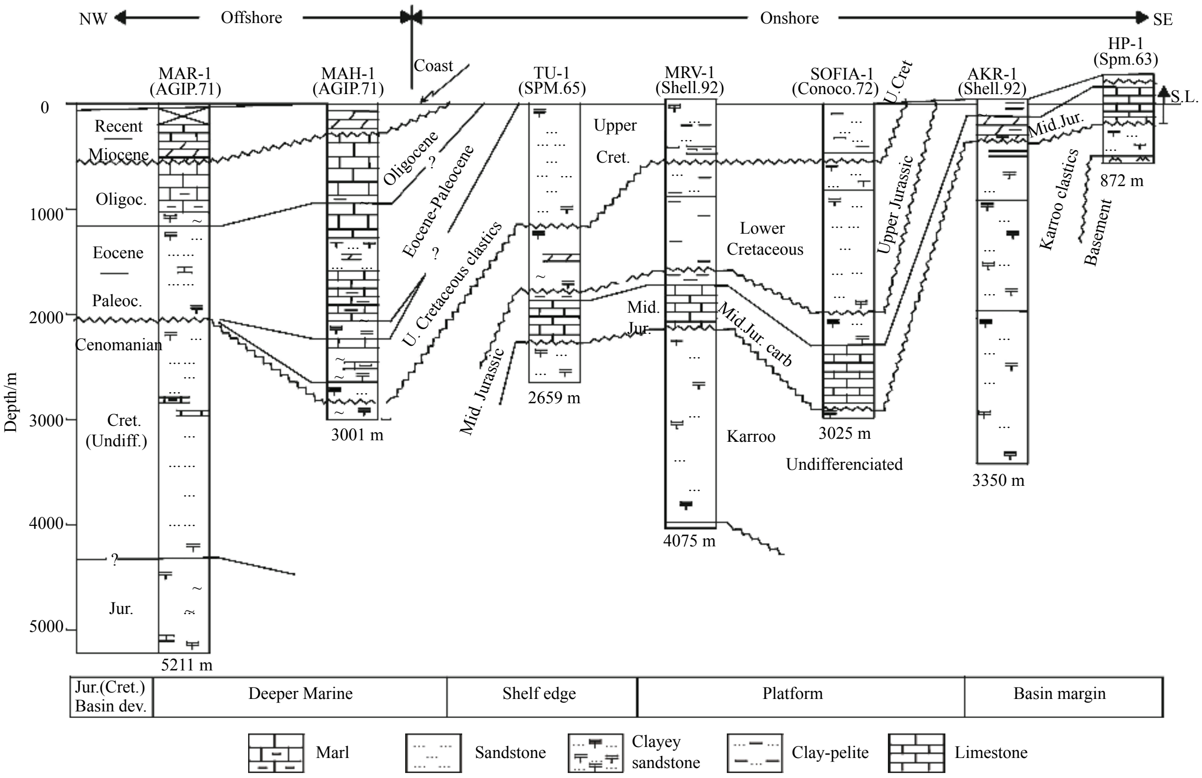

Fig. 3. Comparison diagram of the wells in the Mahajanga basin (after Razafindrakoto S, 2016).

and more mature towards the depths, but the evolution of the level of maturation in the offshore wells goes deeper, and this difference is due to a lower thermal gradient. The kerogens that the rocks contain are Type IV, which means the production of only a tiny amount of hydrocarbons even if the organic matter matures.

Thus, source rocks in the Mahajanga basin can not be considered as actual source rocks because the conditions are not fulfilled, and even if they have good potential to generate hydrocarbons, their maturation levels do not allow them to do so: thus their capacities for hydrocarbon generation are negligible. In addition, the kerogens they contain are Type IV. The source rocks in this basin are poor source rocks (Table 1).

4.3. Morondava basin

Results from drilling (Razafindrakoto S., 2016) indicate that the formations in the Morondava basin are highly varied (Table 1) .

4.3.1. In Tsiribihina North

The two most obvious aspects of this section are: The progression of the old sediments to the younger ones from east to west, demonstrating the general migration of the deposit centers towards the west (towards the sea), and the gradual deepening of the areas of organic ripening, also towards the west.

On the one hand, the amount of organic matter in this part of Morondava is very varied since there is an organic carbon content of up to 9% in the Cretaceous ducal marl, while the other levels are less than 0.2%. In general, the organic matter contained in these rocks is Type IV, but the exception are Upper Cretaceous source rocks with organic matter containing Type II and III kerogens.

On the other hand, the potential for these rocks to generate hydrocarbons range from low to good (0.5 –16 mg/g) and highly varied. The capacity of these rocks to generate hydrocarbons is between 1.2 mg/g to 16 mg/g of rock, In the dunes marls these values are high, but in the Jurassic and the Lias the values are average.

Also, the thermal maturation of organic matter mainly gave Type IV kerogens due to the late maturity or over-maturity of the sediments.

Thus, the source rocks in this section have varying potentials, but the Upper Cretaceous duodian marl is the best parent rock in this area and can produce oil later, since its organic matter percentages of Type II or III are fairly high. The rocks in the Jurassic are also fairly high, but their kerogens are mainly Type IV and their level of thermal maturation is from late maturity to over-mature, which generates a potential for poor mother rocks. Finally, the clays in the Lias will be able to produce gas later as organic matter is in the gas window, but remains poor source rocks.

4.3.2. In Tsiribihina South

Two wells, West Kirindy-1 and in particular Namakia-1, are in a Tertiary Cretaceous deposit zone, which is thicker than in the other four wells. West Kirindy-1 has a thick tertiary Cretaceous covered tertiary, whereas the Namakia-1 well contains a thick tertiary sequence on a smaller-sized upper Cretaceous. These two wells demonstrate progradation of sediment deposition to the sea. Areas of organic maturity occur at a greater depth in these wells than in others, which probably reflect a lower temperature gradient and less time exposed to high temperatures associated with deeper burial.

First of all, the quantity of organic matter in this last correlation is quite constant in the six wells ranging from medium to rich (1%–2%). But locally, it can reach up to 4%. The rocks in the Upper Cretaceous (especially Cenomanian) contain a pretty large amount of organic matter, since their percentages always exceed 1% in this part. Most organic matter is immature but contains a fairly large percentage of Type II and III kerogens, with values ranging from 10% to 30% in Cretaceous and Upper Jurassic.

Second of all, the potential of the rock, on the other hand is very varied (0.5–21 mg/g of rock). The potential of rocks to generate hydrocarbons is especially high in the Upper Cretaceous (Cenomanian, Albian and Maastrichtian). This value is between 2 mg/g to 7 mg/g of rock, that is to say that they have a medium to good potential. Upper Jurassic sediments in some wells like Ankazofotsy-1 also have good potential up to 10 mg/g of rock.

Finally, the quality of kerogens produced is predominantly Type IV kerogens as areas of organic maturity occur at greater depth, probably reflecting a lower temperature gradient and less time exposed to high temperatures associated with deeper burial.

Thus, in this correlation, only rocks in the Cretaceous have a good potential, especially in the Cenomanian (equivalent of ducal marl), since the quantities of kerogens of Type II and III that they contain can produce gases or oils. Yet the rocks in the Jurassic have only weak potentials in this section.Most bedrock layers that have been correlated with the discovered oil contain more than 2% organic carbon content. The formations with 1%–2% of content can be considered as having a certain production capacity.

4.4. The small basins of the eastern coast of Madagascar

The oil blocks of the basins of the eastern coast of Madagascar are all offshore because of the weak development of the sedimentary cover and the dominance of the basement. However, exploration work has already been done in this area, although results are still not definitive (OMNIS, 2018).

5. Potential analysis of Madagascar oil and gas exploration and exploitation

5.1. Exploration and production summary of the western basins of Madagascar

The following table summarizes the potential of hydrocarbon source rocks by age in Madagascar basins.

The activities of most of companies in onshore and offshore are summarized in the following Table 2 and Table 3.

5.2. Potentials of the east coast bassin

Currently, oil companies are taking an increasing interest in unconventional resources in Africa. The extra heavy oil and bitumen recorded in the northeastern part of Madagascar (Ramanampisoa L and Radke M, 2010) can then represent a potential still unexploited in Madagascar.

5.3. Onshore and offshore petroleum reserves prediction and offshore exploitation outlook

There are 25 international oil companies in Madagascar, of which seven are consortia and ten are working solo. They have signed 19 Production Sharing contracts for the exploration and exploitation of hydrocarbons. These oil companies are active on 17 onshore contract perimeters and six offshore contractual perimeters. 228 blocks are still available (OMNIS, 2018; Fig. 4).

Madagascar appears as a “new frontier” for oil exploration.The island is on a double frontier: A technological (and financial) frontier since the exploitation of the “unconventional” oil of western Malagasy could prove profitable in the short or long term; And a geographical (and political) frontier since the Malagasy west coast borders the Mozambique Channel, considered by some as a new energy eldorado due to the recent discovery of major gas fields off East Africa, although various geopolitical disputes exist over the possession of some of these offshore deposits.

6. Conclusions

Madagascar undeniably contains source rocks rich in organic matters and reservoir rocks for the migration of matured and non-maturing hydrocarbons. The dislocation of the island from continental Africa has lead to many structural, stratigraphic and mixed traps related to the various rifting episodes during the opening of the Mozambique Channel. All these phenomena are thus at the origin of all its potential in hydrocarbons.

Table 2. Companies with their activities in their onshore block (after OMNIS, 2018).

Companies	Concession	Current activities
Madagascar Oil Sarl	Bemolanga 3102 Tsimiroro 3014 Manambolo 3105 Morondava 3106 Manandaza 3107	Beginning of geological and geophysical studies: blocks 3105 - 3106 - 3107; preparation of technical files and data: search for new partners; receipt of Development Plan Approval Decree for Block 3104 on April 16th, 2015; attribution of mining title by the OMNIS (exploitation and transport for 25 years; multiplication of the number of wells: 10000 barrels/d from the end of 2015; establishment of a production unit before the complete development by Madagascar Oil and TOTAL; assessment and construction work in mid 2009; development project in 2013 (Madagascar Oil: 40% of the costs, TOTAL: 60%)
Oyster Oil Limited	Antsiranana 1101	Exploration effort until 2011; acquisition of 10% of Candax interest in this block; prospect mapping in Ambilobe and Ampasindava areas; realization of a well to test one of the structures of Ambilobe; drilling and core drilling operations in December, 2014; direct participation in an onshore block covering approximately 2.8 million acres in 2015
AFREN EAX	Antsiranana 1101	Drilling and core drilling campaign on August, 25, 2014:12 wells; environmental specifications for 2D seismic (north of Ambilobe); readjustment of the drilling campaign
MPIL	Bekodoka 2104	Evaluation of EIA for 2D seismic acquisition; seismic acquisition program
Tullow Oil	Mandabe 3109 Berenty 3111	Signature of a settlement agreement with OMV; 2D seismic acquisition on block 3109 (2014); drilling of a first exploration well on the Berenty block (early 2015); Approval of the Malagasy government: OMV acquires 35% interest in the Mandabe and Berenty block, 65% interest retention by operators
PETROMAD	Bezaha 3114	Preparation for the drilling of exploration wells
Amicoh coorporation	Manja 3108	Drilling a well in Ambatolava (north-west of the block); Looking for other companies to finance drilling; extension of the license for 2 years (2013)
Madagascar Southern Petroleum Company	Toliary 3112	Realization of the first drilling (August 2011); discovery of gas during a second drilling (end of 2011)
Varun Energy	Tambohorano 3101	Sale of 51% of its block to Da Qing Oil Field Co.; preservation of the remaining 49% of its block; opposition from the local population when allocating this block
Yanchang Petroleum Corp. (YAPEC)	Sakaraha 3113	Field work for EIAs and using 2D seismic; realization of the acquisition program

Table 3. Companies and their activities in their offshore blocks (after OMNIS, 2018).

Companies	Concession	Current activities
ExxonMobil Madagascar (EMM)	Cap Saint André 2002 Ampasindava 2001C deep Mahajanga 2001a	Basin modeling and seismic data processing in its 3 blocks; drilling in the deep Ampasindava and Mahajanga blocks; update of impact studies of its drilling activities
Sterling Energy Limited	Ambilobe 1002 Ampasindava 2001C	Public consultation for obtaining the environmental permit for a 3D seismic: Ambanja, Ambilobe and Nosy-Be
Pura Vida	Ambilobe 1002	Joint venture: Sterling Energy: 50%, Pura Vida: 50%; 3D seismic survey to target prospects for anticline and related salts (2014); filling of all work commitments for the second phase of exploration; completion of an exploration well in September, 2016
SAPETRO (South Atlantic Petroleum)	Belo profond	Acquisition of the 40% interests of Niko Resources which definitively left the consortium; new bulk operator grand prix; preparation of the 3D seismic acquisition of new partners (the southern part of the block); new partner of Tullow Oil in 2 blocks Madabe and Berenty (up to 35% interest)
Niko Resources	Grand prix	3D seismic mission in the Menabe region from 14 to 18 January, 2014; public Consultations for EIA Marine Seismic Acquisition Program: Belo / Tsiribihina and Morondava
ENERMAD	Grand prix	Consortium with NIKO Resources and OMV of the southern part by the seismic acquisition in 3D
Marex Petroleum Corporation	Juan de Nova (scattered island) Deep Belo	In partnership with Roc Oil Company in Australia, for New-Juan located on scattered islands; departure of Roc Oil Company in 2010; in partnership with SAPETRO on the 2 licenses; Realization of a 2D seismic survey (12500 km); 3D seismic survey (9000 km2) in 3 potential areas; core drilling program to demonstrate the presence of deep hydrocarbons that cause seepage detected on the surface of the sea; beginning of drilling in late 2014 and early 2015

For decades, researchers, oil companies have always tried to find the most effective methods to detect oil traps. Currently, advanced techniques are increasingly used in oil exploration (GIS, 2D modeling, 3D modeling, 4D modeling, ...).

In spite of the evolution of the techniques used, oil companies do not completely control the knowledge of the sedimentary basins, with some traps having even been detected by chance.

Madagascar is therefore supposed to be one of the hydrocarbon-producing countries, and as a result oil companies are intensely interested, as evident because currently there are about 15 companies which are distributed over the blocks seen in the map and are working on 24

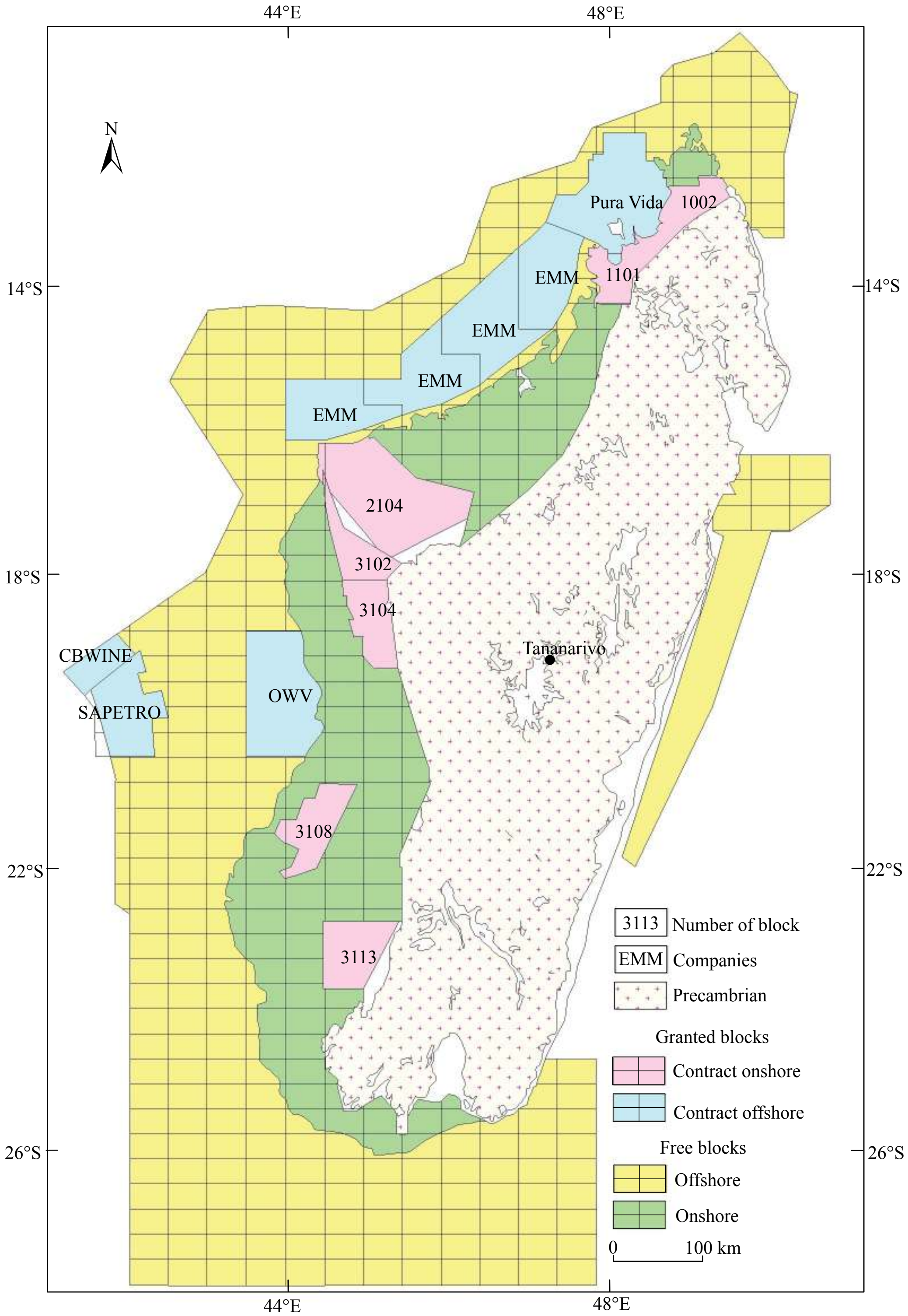

Fig. 4. Petroleum blocks of Madagascar (after OMNIS, 2018).

concessions: 18 onshore and six offshore. Similarly, according to the map of oil blocks, there are still several of them that are still available: Madagascar will therefore become an oil producer in the near future, especially an offshore one.

Acknowledgment

We thank the anonymous reviewers and Dr. Yang Yan for their comments and suggestions, which significantly improved the quality of the manuscript. This work was financially supported by the projects of the China Geological Survey (DD20190438, DD20160104, KE2010D2-3, 1212011220921, 2009DFA20840).

References

Aubourg C, Tshoso G, Gall BL, Bertrand H, Tiercelin JJ, Kampunzu

AB, Dyment J. 2008. Magma flow revealed by magnetic fabric in the okavango giant dyke swarm, karoo igneous province, northern botswana. Journal of Volcanology Geothermal Research, 170(3), 247–261.

Bertil D, Regnoult JM. 1998. Seismotectonics of Madagascar. Tectonophysics, 294(1-2), 57 –74. doi: 10.1016/S0040-1951(98)00088-2.

Besairie H. 1971. Géologie de Madagascar, les terrains sédimentaires, Ann. Géol. Madagascar, 35, 1–463, Tananarive. Burke K, Macgregor DS, Cameron NR. 2003. Africa's petroleum systems: four tectonic 'aces' in the past 600 million years. Geological Society London Special Publications, 207(1), 21–60.

Bumby AJ, Guiraud R. 2005. The geodynamic setting of the phanerozoic basins of Africa. Journal of African Earth Sciences, 43(1), 1–12.

Catuneanu O, Wopfner H, Eriksson PG, Cairncross B, Rubidge BS, Smith RMH, Hancox PJ. 2005. The Karoo basins of south-central Africa. Journal of African Earth Sciences, 43(1), 211–253.

Chen YH, Yao GS, Lü FL, Tang PC, Lu YT. 2016. Tectonic-sedimentary evolution process and petroleum geological characteristics in the deep water area of the Rovuma Basin, East Africa. Marine Origin Petroleum Geology, 21(2), 39–46 (in Chinese with English abstract).

Christopher RS, Lisa MG, Roger LL. 1988. Plate tectonic reconstructions of the cretaceous and cenozoic ocean basins. Tectonophysics, 155(1), 27–48.

Coffin MF, Rabinowitz PD. 1988: Evolution of the conjugate east African-Madagascan Margins and the western Somali basins. GSA Special Paper 226, p.78.

Cui ZW, Lou ZH, Zhu ZH, ZR, Jin AM, He HF, Shao Xinyul. 2016. Oil and gas geological characteristics and exploration prospects in the Mozambique Basin. Marine Geology Frontiers, 32(6), 1 –8 (in Chinese with English abstract).

Daly MC, Chorowicz J, Fairhead JD. 1989. Rift basin evolution in Africa: the influence of reactivated steep basement shear zones. Geological Society London Special Publications, 44(1), 309 –334. doi: 10.1144/GSL.SP.1989.044.01.17.

Dupont J. 1972. Etude de la marge continentale du Nord-Ouest de Madagascar. Bulletin de Liaison - ASEQUA.

Duncan RA, Hooper PR, Rehacek J, Marsh JS, Duncan AR. 1997. The timing and duration of the karoo igneous event, southern gondwana. Journal of Geophysical Research Solid Earth, 102(B8), 18127–18138. doi: 10.1029/97JB00972.

Emmel B, Geiger M, Jacobs J. 2006. Detrital apatite fission-track ages in middle jurassic strata at the rifted margin of w Madagascar-indicator for a protracted resedimentation history. Sedimentary Geology, 186(1), 27–38.

Gall BL, Tshoso G, Jourdan F, Féraud G, Bertrand H, Tiercelin JJ, Kampunzu AB, Modisi MP, Dyment J , Maia M . 2002. 40 ar/ 39 ar geochronology and structural data from the giant okavango and related mafic dyke swarms, karoo igneous province, northern botswana. Earth Planetary Science Letters, 202(3), 595–606.

Geiger M, Clark DN, Mette W. 2004. Reappraisal of the timing of the breakup of gondwana based on sedimentological and seismic evidence from the morondava basin, Madagascar. Journal of African Earth Sciences, 38(4), 363 –381. doi: 10.1016/j.jafrearsci.2004.02.003.

Geiger M, Schweigert G. 2006. Toarcian-kimmeridgian depositional cycles of the south-western morondava basin along the rifted continental margin of Madagascar. Facies, 52(1), 85. doi: 10.1007/s10347-005-0039-8.

Genik GJ. 1993. Petroleum geology of Cretaceous-Tertiary rift basins in Niger, Chad and Central African Republic, Am. Assoc. Petrol. Geol. Bull, 77(8), 1405–1434.

Giese J, Reiss MC, Rindraharisaona EJ, Rumpker, G, Schreurs G, Tilmann FJ, Yuan X. 2016. Brittle reactivation of inherited late Neoproterozoic/Cambrian lithospheric-scale structures during extension and break-up of Madagascar from Africa. AGU Fall Meeting. AGU Fall Meeting Abstracts.

Guan ZM, Li J. 2007. African Oil and Gas Resources and Exploration. Petroleum Industry Press (in Chinese with English abstract).

Harouna M, Philp RP. 2012. Potential petroleum source rocks in the termit basin, Niger. Journal of Petroleum Geology, 35(2), 165−185. doi: 10.1111/jpg.2012.35.issue-2.

Hankel O. 1994. Early permian to middle jurassic rifting and sedimentation in east Africa and Madagascar. Geologische Rundschau, 83(4), 703–710.

Hemsted T. 2003. Second and third millennium reserves development in African basins. Social Science Electronic Publishing, 207(1), 9–20.

He WX, Jiang KX, Wan H, Guo QZ, Li JJ, Zhao CS. 2017. Accumulation characteristics of Tsimiroro heavy oil field in Morondava Basin, East Africa. Geological Science and Technology Information, (5), 60–68 (in Chinese with English abstract).

Jin C, Chen AQ, Lou ZH, Jin AM, Zhu R, Tao L , Xu SL . 2012. Tectonic evolution and hydrocarbon accumulation law in East Africa. Journal of Jilin University (Earth Science Edition), (S2), 121–130 (in Chinese with English abstract).

Jourdan F, Féraud G, Bertrand H, Watkeys MK, Renne PR. 2007. Distinct brief major events in the karoo large igneous province clarified by new ^{40}Ar/ ^{39}Ar ages on the lesotho basalts. Lithos, 98(1), 195–209.

Ma J, Liu JP, Pan ZH, Wang JQ, Liu Q. 2008. Geological characteristics of the continental margin of East Africa and prospects for oil and gas exploration. World Geology, 27(4), 400 –405 (in Chinese with English abstract).

Kent PE. 1974. Continental Margin of East Africa-A Region of Vertical Movements. The Geology of Continental Margins. Springer Berlin Heidelberg.

OMNIS. 2018. [EB/OL]. http://www.omnis.mg/index.php?lang=en

Papini M, Benvenuti M. 2008. The toarcian-bathonian succession of the antsiranana basin (nw Madagascar): facies analysis and tectono-sedimentary history in the development of the east Africa-Madagascar conjugate margins. Journal of African Earth Sciences, 51(1), 21–38. doi: 10.1016/j.jafrearsci.2007.11.003.

Pique A, Laville E, Bignot G, Rabarimanana M, Thouin C. 1999. The initiation and development of the morondava basin[Madagascar] from the late carboniferous to the middle jurassic. Journal of African Earth Sciences, 28(4), 931–948. doi: 10.1016/S0899-5362(99)00070-6.

Rabinowitz PD, Coffin MF, Falvey D. 1983. The separation of Madagascar and Africa. Science, 220(4592), 67 –69. doi: 10.1126/science.220.4592.67.

Rafalimanantsoa G. 2016. Le pétrole, de l'exploration à la production (Master) . Université d'Antananarivo, Antananarivo. Madagascar.

Ramanampisoa L, Radke M. 2010. Thermal maturity and hydrocarbon generation in rocks from the sedimentary basins of Madagascar. Journal of Petroleum Geology, 15(3), 379–396.

Rakotosolofo NA, Torsvik TH, Ashwal LD, Eide EA, Wit MJD. 1999. The karoo supergroup revisited and Madagascar-Africa fits. Journal of African Earth Sciences, 29(1), 135 –151. doi: 10.1016/S0899-5362(99)00085-8.

Rajaomazava F. 1992. Etude de la subsidence du bassin de Morondava (Madagascar) dans le cadre de l'évolution géodynamique de la marge est- africaine. Thèse. Université des Sciences et Techniques du Languedoc, France.

Razafindrakoto S. 2016. Caractérisation géochimique des roche-mères d 'hydrocarbures - cas de Madagascar (Master). Université d'Antananarivo, Antananarivo, Madagascar.

Razafindrazaka Y, Randriamananjara T, Piqué A, Thouin C, Laville E, Malod J. 1999. Extension et sédimentation au paléozoïque terminal et au mésozoïque dans le bassin de majunga (nord-ouest de Madagascar). Journal of African Earth Sciences, 28(4), 949–959. doi: 10.1016/S0899-5362(99)00071-8.

Reeves CV, Sahu BK, Wit MD. 2002. A re-examination of the paleo-position of Africa's eastern neighbours in gondwana. Journal of African Earth Sciences, 34(3), 101–108.

Salman G, Abdula I. 1995. Development of the mozambique and ruvuma sedimentary basins, offshore mozambique. Sedimentary Geology, 96(1-2), 7–41. doi: 10.1016/0037-0738(95)00125-R.

Schandelmeier H, Bremer F, Holl HG. 2004. Kinematic evolution of the morondava rift basin of sw Madagascar--from wrench tectonics to normal extension. Journal of African Earth Sciences, 38(4), 321–330. doi: 10.1016/j.jafrearsci.2003.11.002.

Storey M, Mahoney JJ, Saunders AD, Duncan RA, Kelley SP, Coffin MF. 1995. Timing of hot spot-related volcanism and the breakup of Madagascar and india. Science, 267(5199), 852–855. doi: 10.1126/science.267.5199.852.

Storey M, Mahoney JJ, Saunders AD. 1997. Cretaceous basalts in Madagascar and the transition between plume and continental lithosphere mantle sources. Washington Dc American Geophysical Union Geophysical Monograph, 100, 95–122.

Tucker RD, Roig JY, Moine B, Delor C, Peters SG. 2014. A geological synthesis of the precambrian shield in Madagascar. Journal of African Earth Sciences, 94(2), 9–30.

Wescott W A, Diggens JN. 1997. Depositional history and stratigraphical evolution of the sakoa group (lower karoo supergroup) in the southern morondava basin, Madagascar. Journal of African Earth Sciences, 24(4), 585–601. doi: 10.1016/S0899-5362(97)00082-1.

Wen ZX, Tong XG, Zhang GY, Wang ZM. 2012. Petroleum geological characteristics and exploration potential of the East African rift basin group. China Petroleum Exploration, 17(4), 60–65 (in Chinese with English abstract).

Wen ZX, Wang ZM, Song CP, He ZJ, Liu XB. 2015. Structural differences and oil and gas exploration in the passive continental marginal basin of East Africa. Petroleum Exploration and Development, 42(5), 10 (in Chinese with English abstract).

Wopfner H. 2002. Tectonic and climatic events controlling deposition in tanzanian karoo basins. Journal of African Earth Sciences, 34(3), 167–177.

Xu ZG, Han WM, Sun YM. 2014a. The tectonic evolution process and oil and gas exploration potential of the continental margin of East Africa. China Geology, 41(3), 961–969 (in Chinese with English abstract).

Xu ZG, Han WM, Sun YM. 2014b. Analysis of hydrocarbon accumulation in the conjugated continental margin of East Africa. Natural Gas Geoscience, 25(5), 732–738 (in Chinese with English abstract).

Yu X, Hou GT, Dai SH, Han YC, Xie JL. 2015. Analysis of the tectonic evolution and hydrocarbon accumulation model of the continental margin in East Africa. Geological Science and Technology Information, 34(6), 147–154 (in Chinese with English abstract).

Zhang GY, Yu ZH, Chen ZM, Zhang W, Wen ZX, Huang TF, Wang YQ, Liu XB, Ma F, Zhao J. 2018. Basin evolution and hydrocarbon distribution in Africa. Earth Science Frontiers, (2), (in Chinese with English abstract).

Zhang GY, Liu XB, Zhao J, Wen ZX, Zhang W, Wang ZM, Zhang L, Ma F, Chen X. 2018. The main factors controlling the evolution of the passive continental marginal basin and the formation of the gas field in East Africa: taking the Luwuma Basin as an example. Earth Science Frontiers, (2), (in Chinese with English abstract).

Zhang KB, Shi BQ, Xu ZQ, Tong XG, Li Z, Dou LR, Pan XH. 2007. Analysis of oil and gas potential in sedimentary basins in East Africa. Natural Gas Geoscience, 18(6), 869–874 (in Chinese with English abstract).

Zhou ZQ, Tao Y, Li SZ, Ding WL. 2013. Oil and Gas Resource Potential of Key Basins in the East Coast of Africa. Petroleum Exploration and Development, 40(5), 543–551 (in Chinese with English abstract).