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**FACULTY OF SCIENCE AND TECHNOLOGY**

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# STRATIGRAPHY AND PLAY MODELS OF MADAGASCAR

Thesis submitted to the "University of Stavanger" in partial fulfillment of the requirements for the degree of Master in "Offshore Technology", specialization: "Environmental Control".

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OMNIS

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# ABSTRACT

Three western sedimentary basins (Morondava, Majunga and Ambilobe) constitute the main area of interest regarding the hydrocarbon potential of Madagascar. They result from the separation of the island from Africa. Nine depositional sequences are observed in these basins leading to development of important geological formations such as *Sakoa*, *Sakamena, Isalo, Bemaraha and Sitampiky*. Moreover, nine potential reservoir rocks and four potential source rocks have been identified in the western sedimentary basins. Concerning the hydrocarbon potential, the Jurassic and the Cretaceous plays are the most attractive, respectively, in Majunga and Morondava basin. Many trapping mechanisms are found among Madagascar plays. Most of them contain rollover structures.

The hydrocarbon exploration in Madagascar Island started in early 1900. It is subdivided in four rounds or phases. Seventy five wells have been drilled so far. Most of them are located onshore Morondava. The exploration led only to few discoveries of gas accumulation (*Eponge, Mariarano, Sikily, and West Manambolo*), two heavy oil accumulation (*Maroaboaly and Tsimiroro*), one light oil accumulation (*Manandaza*) and one tar sand deposit (*Bemolanga*). The past explorations showed a general lack of success. The main reason was the poor quality of available seismic data used by companies. Nowadays, Madagascar has three hundred sixty three blocks which 94% are located offshore. The country also established petroleum activities regulations with regard to environment protection. The main texts are the Malagasy Petroleum code, the charter of environment and the MECIE decree.

**Key words**: Madagascar – stratigraphy - sedimentary basins - petroleum exploration
environmental regulations

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# List of abbreviations

B:R.G.M : Bureau de recherches géologiques et minière (France)

BEICIP : Bureau d'Etudes Industrielles et de Cooperation de l'Institut francais du Pétrole

EIA : Environmental Impact assessment

OMNIS: Office des Mines Nationales et des industries stratégiques

ONE : Office Nationale pour l'Environnement (National agency for the environment)

OLEP : Organe de Lutte contre l'Evènement de Pollution marine par les hydrocarbures (or coast guard)

MGA : Malagasy Ariary (Currency)

NPD: Norwegian Petroleum Directorate

NNW: North-North West

SSE: South-South East

NW: North West

SE: South East

$Km^2$ : square kilometer

md : millidarcy (permeability unit)

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# INTRODUCTION

Located in the Indian Ocean, Madagascar is one of the biggest islands in the world. The population of the Island has been estimated to be around twenty million (Encarta, 2009). Madagascar is separated from the east coast of Africa by the Mozambique Channel. The country has many resources: mineral (bauxite, chrome, Iron ore, sapphire, ilmenite and many others), halieutic and forestry.

The separation from Africa allows the formation of sedimentary basins along the western coast of Madagascar. In petroleum geology, the presence of such basins is of interest because they may offer potential for Hydrocarbon accumulations. The interest for petroleum exploration in Madagascar started in the early 1900's with the discovery of large accumulations of tar and heavy oil at Bemolanga and Tsimiroro, in the northern Morondava. Since this time, many oil companies performed exploration activities onshore and offshore Madagascar.

The present thesis is the result of the institutional collaboration between the Norwegian Petroleum Directorate (NPD) and the Office des Mines National et des Industries stratégique (OMNIS)-Madagascar. It was performed in Madagascar at OMNIS under the Hydrocarbon Direction within the exploration department as a part of the sub-project E (Resources management).

It aims to gather acquired information about the hydrocarbon potential of Madagascar based on reports found in OMNIS archives in order to direct future hydrocarbon exploration toward the zone with the most promising prospect or plays.

This thesis consists of four parts, respectively:

- Generality: this includes description of Madagascar's geology and stratigraphy,

- Reservoir and source rocks where the potential reservoir and source rocks are detailed with the possible trap mechanisms, the plays models and the regional tectonic,

- Exploration and development history: this part presents the evolution of the exploration activities in Madagascar and the acquired data

- Environmental issues related to petroleum activities where the legislation related to petroleum activities and the responsible institutions with their activities will be described.

# I-GENERALITY

## 1.1 OMNIS-NPD Project

OMNIS-Madagascar is a state owned agency responsible for petroleum management and mining development. Cooperation between Norway and Madagascar lead in 2007 the start of a project entitled:”Management of oil and gas in Madagascar” which will last until 2011. The agreement was signed on 3 May 2007 by the Norwegian Ministry of Foreign Affairs and the Malagasy Ministry of Finance and Budget. Agreements on Institutional cooperation have also been signed. Due to recent political crisis in Madagascar in January 2009, Norway has frozen its aid to Madagascar.

The budget of the project is 36.1 million Norwegian Kroner. The goal of the project is to help Madagascar manage its petroleum resources. It consists of 12 sub-projects (summarized in the following table):

***Table 1.1**: the 12 sub-projects*

| Sub-project and Title | |
|---|---|
| *Sub-Project A: Petroleum policy and strategy* | *Sub-Project G: Revenue Management* |
| *Sub-Project B: Legal and regulatory framework* | *Sub-Project H: Integrity building to control corruption in the petroleum sector* |
| *Sub-Project C: Updating office computer systems* | *Sub-Project I: The environment* |
| *Sub-Project D: Data management* | *Sub-Project J: Supervision* |
| *Sub-Project E: Resource management* | *Sub-Project K: Application for an extended continental shelf* |
| *Sub-Project F: Promotion* | *Sub-Project L: Other training* |

The table below summarizes the cooperating institutions in Madagascar and Norway.

***Table 1.2**: Cooperating Institution in the Project*

| Malagasy Institutions | Norwegian Institutions |
|---|---|
| -Office de Mines Nationales et des Industries stratégiques (OMNIS)<br>-the National Office for the Environment (ONE)<br>-the Malagasy Ministry of Finance and Budget (MFB) | -Norwegian Petroleum Directorate<br>-Ministry of Petroleum and Energy<br>-Petroleum Safety Authority in Norway<br>-Ministry of Finance<br>-Norwegian Pollution Control Authority<br>-Directorate for Nature Management |

## 1.2 General description of Madagascar's geology

Madagascar Island occupies 587,047 km$^2$ and comprises a central area of basement rocks surrounded by four extensive sedimentary basins on the western side and a large fault lineament and one small basin on the eastern side. Geological time scale and the major formations found in Madagascar are given in the table 2.1. Six typical formations (Sakoa, Sakamena, Isalo, Andafia-Beronono, Sitampiky, Ankarafantsika- Tsiandava and Katsepe) and four major rock types of interest can be found among the Malagasy formation which are sandstone, shale, marl and calcareous. The Figure 1.1 shows a simplified geology of Madagascar. Distribution of sedimentary rocks is also shown in the maps. According to the same figure the sedimentary rocks are located along the western coast.

According to Clark (1997), the Island can be divided into seven structural provinces: the Central Highlands, Ile Sainte Marie Basin, Alaotra Graben, Cap Sainte Marie Basin, Morondava Basin, Majunga Basin and Ambilobe Basin (see figure1.2). These three last basins resulted from the separation of Madagascar and Africa and cover 474,885 km$^2$.

### 1.2.1-Central Highlands

Covering most of the central and eastern part of Madagascar, they comprise granites and gneiss of Precambrian age, which form the Basement. These rocks have been uplifted and tilted to west, so that the eastern part of Madagascar is generally higher than the western part. The western and southern edges of the Highlands are bounded by series of Late Permian grabens, whereas the eastern margin is formed by the Ile Sainte Marie Lineament. This latter runs along the narrow coastal plain and is thought to have been formed as a result of the separation of the India from Madagascar. Four lineaments or shear zones can be recognized within the Highlands: *Maromandia, Bongolava* and *Vohimena* Lineaments and the *Ranotsara* Shear zone. Those are oriented NNW-SSE or NW-SE direction.

### 1.2.2-Ile Sainte Marie Basin

The Ile Sainte Marie Basin is situated on the east coast of Madagascar, near the Ile Sainte Marie. It covers an area of 28,300 km$^2$ and forms a narrow graben. It is thought to have formed as an extensional basin related to the separation of India and Madagascar. The aerial extent of the graben is limited and some of the bounding faults are oriented at 45° to the Ile Sainte Marie Lineament suggesting that the graben may be a pull-apart basin, related to the wrench faulting rather than simple extension. One implication of this is that the break-up of Madagascar and India may have been caused by a sharing movement.

***Table 1.3**: Geologic time scale (from Duval, 1999) and Madagascar formation*

| AGE(M y) | ERE | EPOCH | | STAGE | MAJOR FORMATION | | |
|---|---|---|---|---|---|---|---|
| 0.1 | CENOZOIC | ANTHROPOGENE | HOLOCENE | | POST - KAROO | | QUATERNARY (sandstone) |
| 1.64 | | | PLEISTOCENE | | | | |
| 5.2 | | NEOGENE | PLIOCENE | | | | PLIOCENE (sandstone) |
| 23.3 | | | MIOCENE | | | | TERTIARY (Shale/Calcareous) |
| 35.4 | | PALEOGENE | OLIGOCENE | | | | |
| | | | EOCENE | PRIBONIAN | | | KATSEPE (Calcareous) |
| | | | | LUTENIAN | | | |
| 56.5 | | | | YPRESIAN | | | |
| 65 | | | PALEOCENE | DANIAN | | | |
| | MESOZOIC | CRETACEOUS | | MAASTRICHTIAN | | | |
| | | | | CAMPANIAN | | | |
| | | | | SANTONIAN | | | |
| | | | | CONIACIAN | | | |
| | | | GALLIC | TURONIAN | | | |
| 97 | | | | CENOMANIAN | | | ANKARAFANTSIKA-TSIANDAVA (Sandstone) |
| | | | NEOCOMIAN | ALBIAN | | | |
| | | | | APTIAN | | | |
| | | | | HAUTERIVIAN | | | SITAMPIKY (sandstone) |
| | | | | VALANGINIAN | | | DUVALIA (Marl) |
| | | | | BERRIASIAN | | | |
| 145 | | JURASSIC | MALM | PORTLANDIAN | | | |
| | | | | KIMMERIDGIAN | | | |
| 157 | | | | OXFORDIAN | | | |
| | | | DOGGER | CALLOVIAN | | DOGGER | Marl |
| | | | | BATHONIAN | | | Shale/Calcareous/ sandstone |
| | | | | BAJOCIAN | | | |
| | | | | AALENIAN | | | Salt/Shale/Calcareous/ sandstone |
| 178 | | | LIAS | TOARCIAN | | | ANDAFIA BERONONO (shale) |
| | | | | PLEINSBACHIAN | KAROO | | ISALO2(sandstone/shale) |
| | | | | SINEMURIAN | | | |
| 208 | | | | HETTANGIAN | | | |
| | | TRIASSIC | LATE | RHETIAN | | | |
| | | | | NORIAN | | | |
| | | | | CARNIAN | | | |
| | | | MIDDLE | LANDINIAN | | | ISALO 1(sandstone) |
| 241 | | | | ANISIAN | | SAKA MENA | UPPER (sandstone) |
| 245 | | | EARLY | SCYTHIAN | | | MIDDLE (shale) |
| | PALEOZOIC | PERMIAN | LATE | | | | LOWER (Sandstone) |
| 260 | | | MIDDLE | | | | SAKOA (sandstone/shale/calcareous) |
| | | | EARLY | | | | |
| 290 | | CARBONIFEROUS | LATE | | | | |
| | | | MIDDLE | | | | |
| | | | EARLY | | | | |
| 363 | | DEVONIAN | | | | | |
| 409 | | SILURIAN | | | | | |
| 439 | | ORDOVICIAN | | | | | |
| 510 | | CAMBRIAN | | | | | |
| 570 | PRECAMBRIAN | | | | | | |

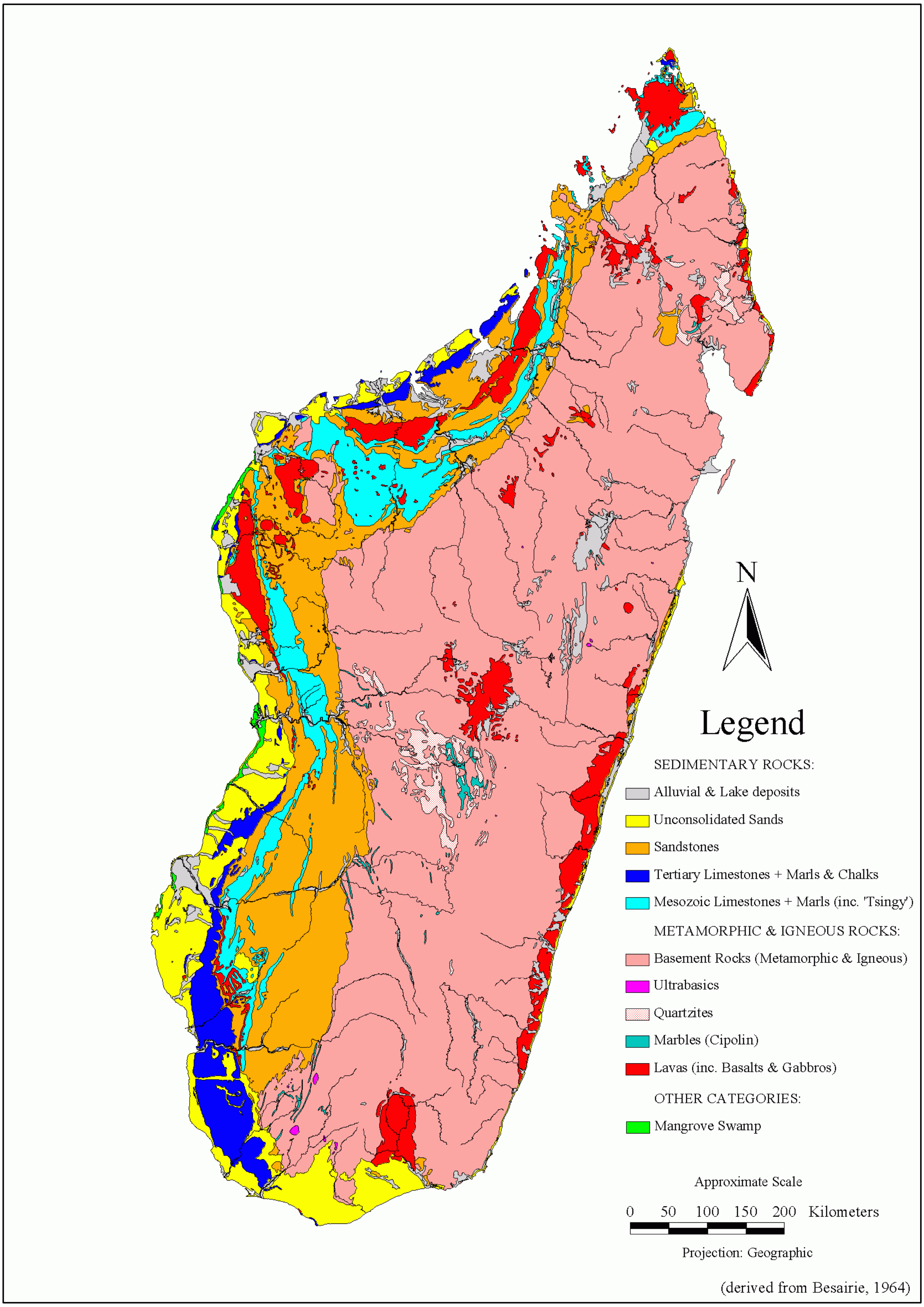


**Figure 1.1**: Madagascar simplified geology (from Du Puy et al, 1997)

### 1.2.3-Alaotra Graben:

Situated to the east of Antananarivo, it forms a narrow basin and extends northwards from *Moramanga* towards Lac Alaotra. The graben is generally regarded as a relatively modern feature but no data is available concerning the age and thickness of sediments that may be present in the subsurface. The fact that the graben is parallel to the eastern coastline, suggests that it may be a relatively old feature related to the separation of India and Madagascar.

### 1.2.4- Cap Sainte Marie Basin

The basin which has an offshore extension is situated at the southern tip of Madagascar and covers an area of 133,000 $km^2$. There is a liitle knowledge about the stratigraphy and the structural architecture of this basin. According to Besairie (1972), the sediment that crop out along the coast are Quaternary in age but SPT (1995) suggest that a wedge of Tertiary and Cretaceous sediments is developed and thickens progressively offshore. Beneath this wedge, series of dipping reflections can be recognized that may represent tilted fault blocks.

### 1.2.5- Morondava Basin

Considered to be the most well known basin in Madagascar in regards of number of drilled wells and seismic coverage, this basin is situated on the western side of Madagascar and covers an area of 296,600 $km^2$. It extends from Cap Saint André High in the north to Cap Sainte Marie in the South, and some 300 km from the boarders of the Central Highlands in the east to the edge of the Continental shelf in the west. The Basin shows three distinct structural zones:

- The *Permo-Triassic Rift* is a failed rift that is made up of the *Karoo Corridor* (Manandaza and Andafia Grabens) in the North, and the Berenty and Sakaraha Grabens in the south. This rift is thought to be Late Permian-Mid Triassic

- The *Bemaraha Platform* may be the surface expression of a structural high between the Permian Rift and the *Bemaraha-Ilovo* Fault. Massive Jurassic limestone is present in this zone.

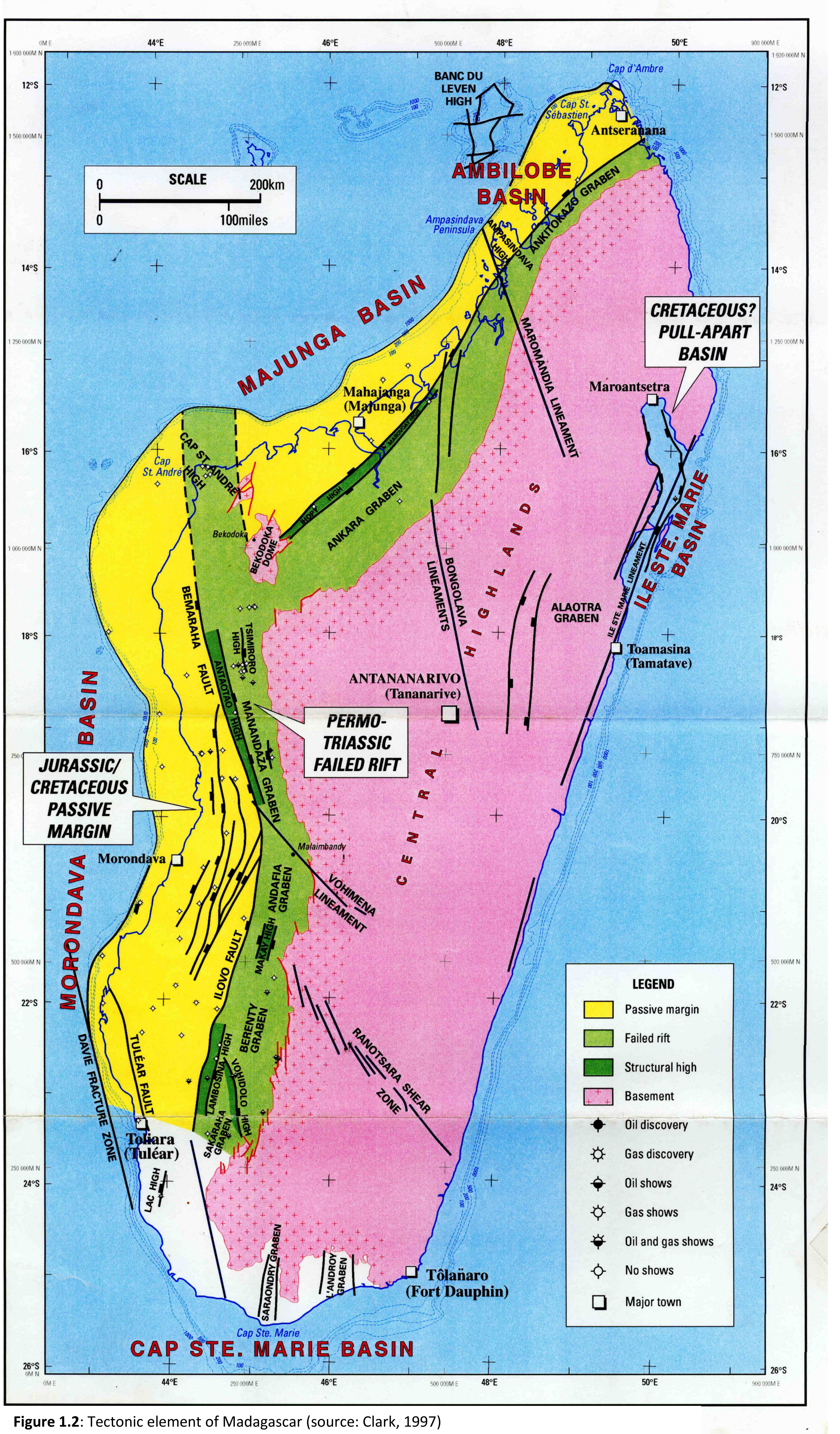


**Figure 1.2**: Tectonic element of Madagascar (source: Clark, 1997)

- The *western Passive Margin* is characterized by a series of east-dipping fault blocks, covered by a thick wedge of Jurassic, Cretaceous and Tertiary sediments. This wedge thickens progressively westwards, towards the edge of the Continental shelf. The passive margin appears to have started to develop in the late Liassic and has continued to subside until the present day.

### 1.2.6- Majunga Basin

The Majunga Basin which is located along the northwestern side of Madagascar, occupies approximately 146,285 $km^2$. It is bounded by the *Maromandia* lineament to the north. To the south, this basin is separated from the Morondava Basin by the complex Cap Saint André High. Majunga basin is about 400 km in length, extending northeastwards from the Cap Saint André to Ampasindava Peninsula. The width of the basin is approximately 200 km from the edge of the Central Highlands to the outer limit of the continental shelf. This basin is less well known than the Morondava Basin. Three distinct structural zones can be recognized:

-*the Ankara graben*: comprises a failed rift extending in a NE direction along the edge of the Central Highlands. The age of this rift is probably Late Permian

-the *Marovoay High* bounds the *Ankara Graben* at Northwest

-the *northwestern passive margin* occurs to the northwest of the “Flexure Cotière” which runs along the edge *Marovoay* High and is comparable to the *Bemaraha-Ilovo* Fault Complex of the Morondava Basin. This passive margin is thought to have started to develop in the Late Liassic.

### 1.2.7- The Ambilobe Basin.

The Ambilobe Basin, located in the northernmost area is separated from the Majunga Basin by the *Maromandia* lineament and covers an area of 32,000 $km^2$. It is situated between the Ampasindava High and Cap d’Ambre. It is predominantly an offshore basin as it probably represents the offshore continuation of the Majunga Basin. The Permo-Triassic Rift corresponding to the *Ankara* Graben is known as the *Ankitohazo* Graben and covers most of the southern area of the Basin. The younger Liassic passive Margin is situated mostly offshore, on the wide continental shelf that is present in this area.

## 1.3-General Stratigraphy of Madagascar

Clark (1997) gives the following depositional sequences which can be observed in the Morondava and Majunga Basins based on sedimentological, wireline log and seismic data. According to this author, comparable sequences can also be tentatively identified in the Ambilobe Basin from seismic.

### 1.3.1-Sakoa sequence (Early Permian)

During the Late Paleozoic, Madagascar was situated in the centre of Gondwana. Early Permian times, a series of rifts started to propagate across the continent and one of these intersected Madagascar. A narrow rift valley was formed and a thick succession of sandstones, shales and coals was deposited in braided river and swamps environments (Nichols and al, 1989). These sediments now comprise the *Sakoa formation* and they are preserved in a series of isolated grabens and half-grabens (*Berenty, Sakaraha , Manandaza and Ankara Grabens*)

### 1.3.2-Lower Sakamena Sequence (Middle-Late Permian)

Rifting appears in the Middle and Late Permian and renewed subsidence took place in many half-grabens whose development was contemporaneous with sedimentation. Marine conditions became established for the first time in Madagascar and this was accompanied by the deposition of the shallow marine *Vohitolia Limestone*. As extension progressed, individual fault blocks became tilted and uplifted and a series of fan-deltas spread directly into narrow seaways between the blocks (Westcott, 1988). A succession of the conglomerates, sandstones, shale and thin algal-bound stones were deposited in fluvial, deltaic and marginal marine environments. These now comprise the *Lower Sakamena formation.*

### 1.3.3-Upper Sakamena Sequence (Early-Middle Triassic)

By the end of the Permian, rifting appears to have intensified and a series of symmetrical grabens began to develop. The change from asymmetrical to symmetrical rifting was accompanied by the uplift of graben shoulders.

A widespread marine transgression also occurred at the beginning of the Triassic and a thick blanket of shale was deposited within the rejuvenated rift. The lower portion of the shale appears to have accumulated in a quiet, restricted marine environment and high concentrations of organic matter. The upper part, in contrast, appears to be brackish or lacustrine in character and is devoid of any significant organic matter. These sediments now form the *Middle Sakamena formation*.

At the end of the Early Triassic, progradation of fluvial deltas began into the grabens and the shale was succeeded by a thick unit of ripple cross-laminated and trough cross-bedded sandstones (Vroon, 1993). These sandstones comprise the *Upper Sakamena formation*. They are thought to have been deposited in the delta-front, mouth bar and fluvial channel environment.

### 1.3.4-Isalo sequence (Late Triassic –Early Liassic)

A period of uplift and erosion characterized the Late Triassic leading to the development of an angular unconformity which is overlain by trough cross-bedded sandstones and gravels. These latter overstep from the Upper Sakamena onto basement. These sandstones are known as the *Isalo*. The *Isalo* forms a thick blanket of sediment that is uniformly developed over a very wide area. This suggests that it represents a phase of basin sag, starting in the Late Triassic and continuing until the Early Liassic.

### 1.3.5- Upper Lias Sequence (Toarcian-Aalenian)

In the early Toarcian, a new rift developed to the west of the Failed Permo-Triassic rift and marine conditions returned to Madagascar for the first time since the Early Triassic. As the extension progressed, the *Isalo* sandstones were broken into a series of fault blocks and these rotated progressively through the late Liassic to form half-grabens. Thick wedges of organic-rich shale and thin argillaceous limestone were deposited to form the *Beronono and Andafia Formations* in the Majunga and Morondava Basins, respectively.

A series of bioturbated and cross-bedded sandstones occur towards the tops of the *Beronono* and *Andafia* sequences. Besairie (1972) classify these to be Aalenian in age. On the geological maps they are sometimes recorded either as *Isalo III* or as *Facies Mixte* but these terms are misleading because the sandstones are different to the proper Isalo.

### 1.3.6-Dogger Sequence (Bajocian-Bathonian)

Madagascar started to drift southwards away from Africa in early Bajocian, and western parts of the Morondava, Majunga and Ambilobe Basins developed into Passive margin. Basin sag again becomes the most important control on the sedimentation and a thick carbonate platform started to build out westwards across the Late Liassic half-grabens. The carbonates were deposited in a variety of situations ranging from a coastal barrier-lagoon complex to submarine slope and basin-plain environments. The barrier-lagoon sediments consist of massive, light grey carbonate mudstones, pelletoidal and oolithic grain stones, whereas the slope and the basin-plain deposits are made up of dark grey, organic-rich, laminated carbonate mudstones. Together, these sediments comprise the *Bemaraha* Limestone.

### 1.3.7- Malm sequence (Callovian-Berriasian)

In the earliest Callovian or possibly latest Bathonian times, a transgression occurred and open marine shale on lapped the exposed Bemaraha Limestone. This shale was deposited during the Late Jurassic-earliest Cretaceous high stand. Most of the sediments have now been eroded from the eastern margins of the Morondava and Majunga Basins. In the southern Morondava Basin, however, some Upper Jurassic sandstones are preserved. These may represent the initial pulse of coastal and deltaic sandstones prograding westwards away from the Central Highlands, as seen more commonly in the overlying Cretaceous sediments.

### 1.3.8- Cretaceous

This period is marked by the continuation of the passive margin subsidence. Three or four possible cycles of sedimentation occurred in response to changes in sea level (Valanginian-early Aptian, Late Aptian-Early Turonian and late Turonian-Maastrichtian). Each phase consists of a lower shale unit and an upper unit of thick sandstones and shale. The shale is interpreted as open marine deposits formed during high stand in sea level. The sandstones, in contrast, represent wedges of coastal and deltaic sediment that propagated rapidly into the basins at the end of each high stand. These sandstones now form the *Sitampiky, Ankarafantsika, Tsiandava and "Campanian- Conician*" formations.

The eastern part of the Central Highlands was uplifted concurrent with the separation of India from Madagascar in the early Turonian. Madagascar was then tilted gently to the west and progressive erosion of previously deposited Cretaceous and Jurassic sediments took place along the eastern edges of the basins.

### 1.3.9- Tertiary

A number of off-lapping units of sandstone and shale were deposited caused by the continuation of tilting process into the Tertiary. Carbonate sedimentation also occurred in the Tertiary, to form the *Mahabibo* (Paleocene) and *Katsepe* (Eocene) limestones. The *Katsepe* is thought to have been deposited as part of a coastal barrier-lagoon complex, and a barrier reef may be developed in the Morondava Basin, to the west of the present coastline.

The figures below, together with the Table 1.4 illustrate the Sakoa to Cretaceous sequences which has been described in the sections above. These figures and table show the main geological events which led to current geological formations and their structural styles.

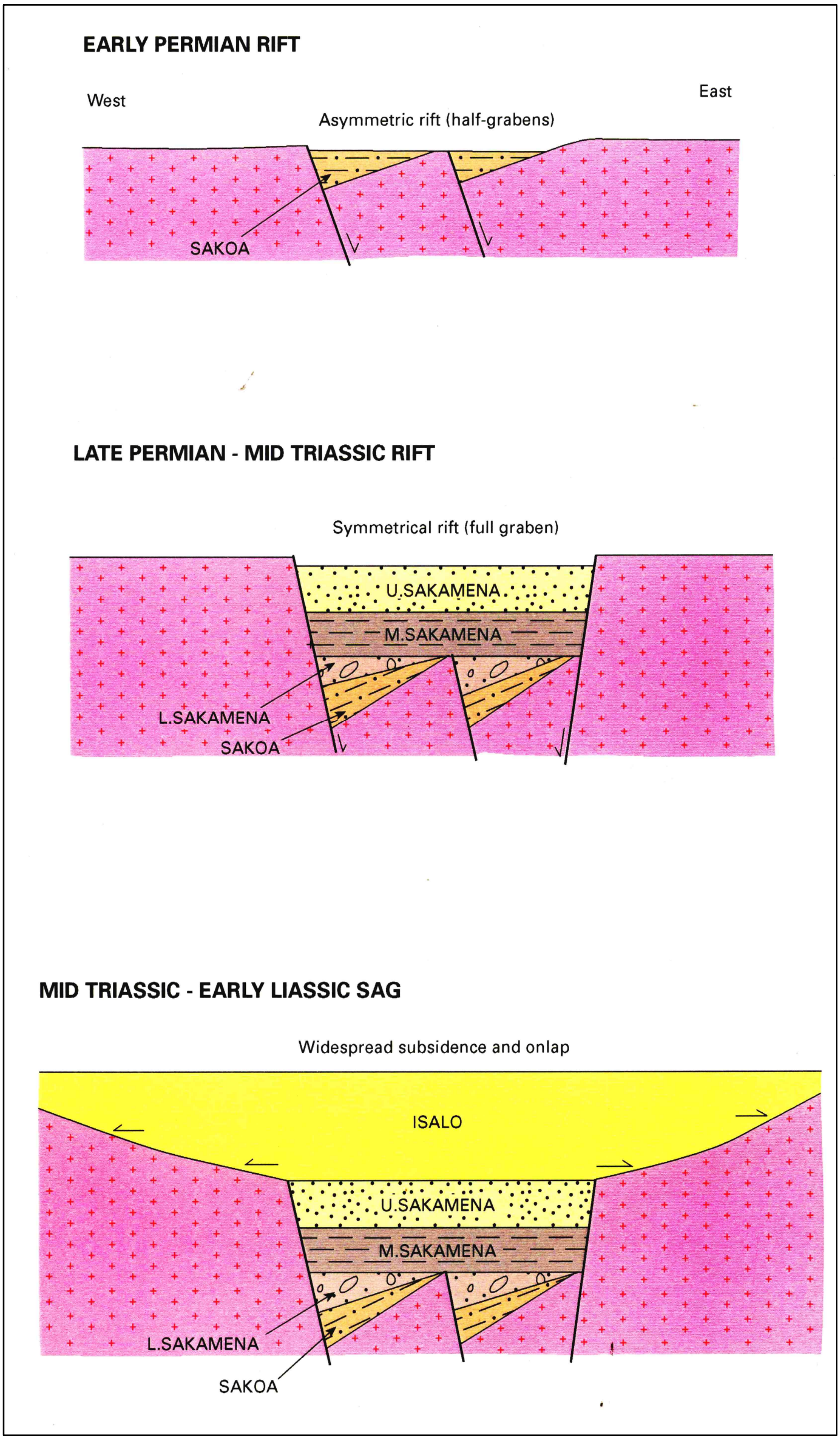


**Figure 1.3:** Permo-Triassic sequences (source: Clark, 1997)

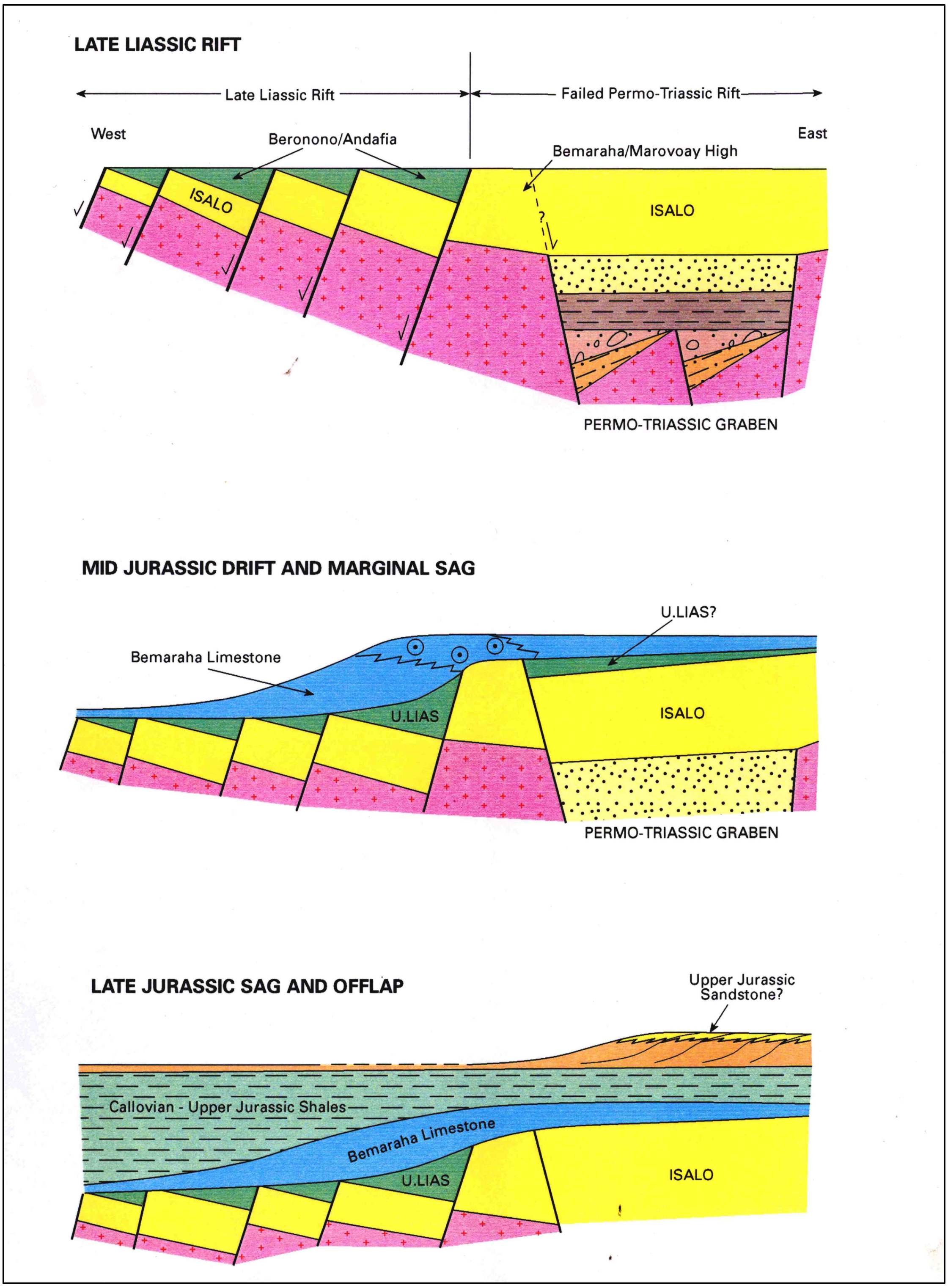


**Figure 1.4**: Liassic to Jurassic sequence (Clark, 1997)

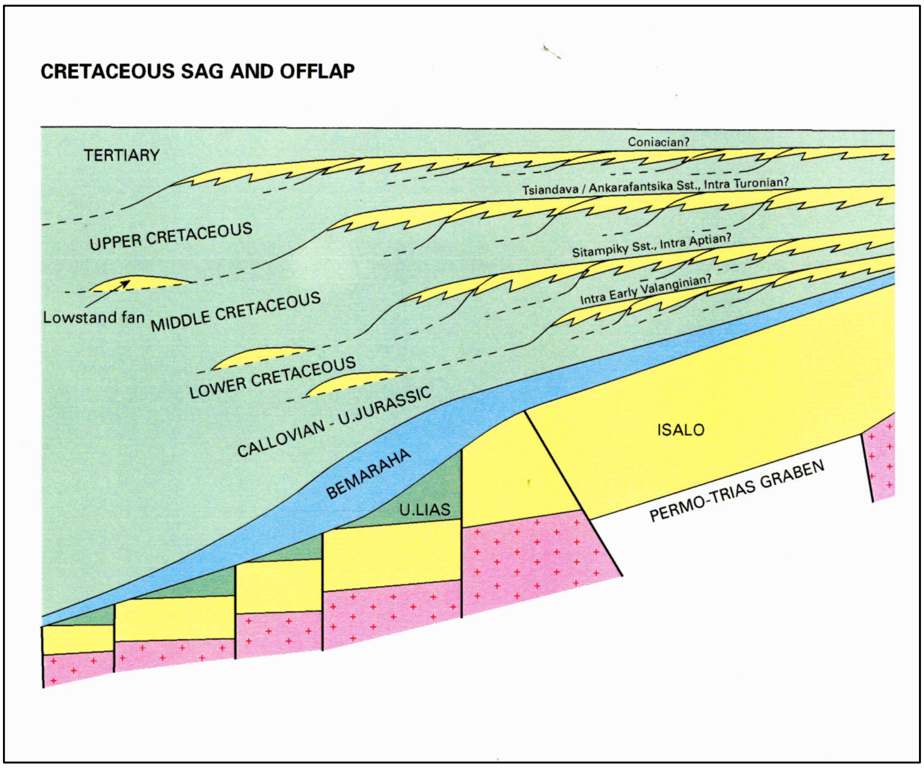


**Figure 1.5**: Cretaceous sag and off lap (source: Clark, 1997)

A summary of the stratigraphic sequence is given in the Table 1.4. The age of the exiting formations and the rock types among the passive margin and the failed rift is also shown.

***Table 1.4***: *Stratigraphic Sequence of Madagascar (Adapted from Clark, 1997)*

| | **DEPOSITIONAL SEQUENCE** | **AGE** | **PASSIVE MARGIN STRATIGRAPHY**<br><br>(West Morondava, Northwestern Majunga and Ambilobe Basins) | **FAILED RIFT STRATIGRAPHY**<br>(Ankitokazo, Ankara, Manandaza and Andafia Grabens, Berenty and Sakaraha Grabens) |
|---|---|---|---|---|
| POST KARRO | TERTIARY | Pliocene-Paleocene | Mio-Pliocene<br><br>Sandstones and Shales<br><br>Katsepe Limestone<br><br>Mahabibo Limestone | |

| | | | | |
|---|---|---|---|---|
| | UPPER CRETACEOUS | Maastrichtian-Late Turonian | Coniacian-Maastrichian Sandstones and shales | |
| | MIDDLE CREATACEOUS | Early Turonian-Late Aptian | Tsiandava Sandstone, Ankarafantsika Sandstone, Aptian-Albian shales | |
| | LOWER CRETACEOUS | Early Aptian-Volanginian | Sitampiky sandstone, Duvalia Marl | |
| | MALM | Berriasian-Callovian | Ankilizato Shale, Antsalova Shale, Beboka Marls | |
| | DOGGER | Bathonian – Bajocian | Bemaraha and Ankarana Limestones | Sakaraha Formation |
| | UPPER LIAS | Aalenian – Toarcian | Andafia and Beronono Shales | Andafia and Beronono Shales |
| KAROO | ISALO | Late Triassic-Early Liassic | Isalo sandstone | Isalo sandstone |
| | UPPER SAKAMENA | Middle Triassic | | Upper Sakamena Sandstone |
| | | Early Triassic | | Middle Sakamena Shale |
| | LOWER SAKAMENA | Late Permian | | Lower Sakamena Sandstone, Vohitolia Limestone |
| | SAKOA | Early Permian | | Sakoa Sandstones, Shales and Coals |
| | | Pre Cambrian | BASEMENT | |

(Table 1.4 cont'd)

## 1.4- Western Basins thickness

No map showing the basin thickness is available at OMNIS archives but data related to basin thickness, taken from BEICIP (1988) is given by the Table 1.5. According to this table, the thickness of the sediment varies from one basin to another and from one place to another within a same basin.

***Table 1.5**: Basin thickness (Adapted from BEICIP, 1998)*

| | PERIOD | EPOC/AGE | FORMATION | THICKNESS | |
|---|---|---|---|---|---|
| | | | | MAJUNGA BASIN | MORONDAVA BASIN |
| POST KAROO | NEOGENE | OLIGOCENE MIOCENE | | 600m (Ologocene offshore) | Up to 1000 m (Morombe) and decreases eastward |
| | | | | | 70-400m (oligocene) |
| | PALEOGENE | EOCENE | | 300-800m (Ambilobe Basin), 300m (Majunga) | 200-600 m (northern area), increase southward (up to 1000m. |
| | CREATCEOUS | CONICIAN MAASTRICHT | | 600m (Coniacian-Campanian), 10-70 m (Maastrichtian marine shale) | 1500m (north area Manambolo), decrease southwards 500m (Manja) |
| | | ALBIAN TURONIAN | | Strongly variable, 350-450m (albian-Cenomian), >100m turonian, in Ambilobe Basin)>240 m (Albian), >130 (cenomian) | 100-300m (northern area, 300-500 (Morondava area), 20-150 m (southward) |
| | | NEOCOMIAN APTIAN | | Increased thickness basinward, 110-270m (west Betsiboka, Berriasian to Valanginian), 100-300 (East Betsiboka,Neocomian) , up to 400 m (Sitampiky and Aptian sandstones) | <200m (Manambolo), increase westward (1000 m in North area), <500 m (central area) |

| | | | | | |
|---|---|---|---|---|---|
| | JURASSIC | CALLOVIAN TITHONIAN | | Increased thickness basinwards 20-100m (out crop), 24-312m (in well) | 200-250 m (North/central area), 300-900m (south of Morondava River) |
| | | BAJOCIAN BATHONIAN | BEMARAHA | 100-500 m (out crop) except in Ambilobe Basin (550-1278) | 400-600 m (east of Bemaraha Fault) and decrease westward (150-350)<br>400-1100 m (East of Ilovo Fault) |
| | | LATE LIAS | | 50-350m (Ambilobe basin), less than 100m (Majunga Basin out crop) and 3000 m (Nosy be) | 220m (Manambolo on Isalo Block crest), 500m (Namakia), >1500m (south) |
| | | | | | |
| KAROO | TRIASSIC | L TRIASSIC-E.LIAS | ISALO 2 | 2000m ( South Ambilobe Basin), 100-500 (Majunga Basin) | 1000-1300 (north), 2000m (Makay massif), >1600 m (Ranohira area) |
| | | MID TRIASSIC | ISAL O 1 | | |
| | | E.MID TRIASSIC | UPPER SAKAMENA | | Decrease nothward, 400-600 (south), 300 m (Makay area) 100-300 (north) |
| | | EARLY TRIASSIC | MID SAKAME NA | | 100-250m (outcrop), 0-400m (in well) |
| | CARBON-PERMIAN | LATE PERMIAN | LOWER SAKAMENA | 1000 m (near Ampasindava to 300m (in Barabanja area), 600 m in cap Saint Andre | Variable, 2000 (southern), 4000m (east and west Vohidolo) |
| | | L.CARBON E.PERMIAN | SAKOA | | 2000m (southern), 300 m (central) |

(Table 1.5: Cont'd)

## *1.5- Regional tectonic and structural history*

The present tectonic and structural configurations of Madagascar are the result of a geotectonic evolution involving India and Africa and related to the break-up of Gondwana.

Documentation about this section is taken from Clark (1997) who suggested that the timing of the main structural events described herein is only approximate.

### 1.5.1- Failed rift

In Early Permian, Madagascar was a part of the Gondwana supercontinent. By Late Permian times, a series of intracontinental rifts had developed, one of which propagated down the western side of Madagascar. The tectonic style and succession of lithofacies of this rift follow the classic pattern seen in many rifts within the geological record (Lambiase, 1990). The rift is preserved as a chain of grabens that include the *Ankitokazo, Ankara, Manandaza* and *Andafia* grabens (Besairie, 1972) and the *Berenty* and *Sakaraha* grabens (see *Figure1.2)*. No continental separation occurred, and the grabens should be regarded merely as a part of a failed intracontinental rift complex.

Limited sedimentation took place in the half-grabens in the Permian and these were filled by fluvial and marginal marine sediments (Sakoa and lower Sakamena). Crustal extension appears to have continued into the Early Triassic with the formation of a symmetrical rift complex. Subsidence within the graben was accompanied by a marine transgression, and a thick shale was deposited (Middle Sakamena). This shale was succeeded by deltaic and fluvial Sandstones (Upper Sakamena).

In the Late Triassic, the rift complex started to sag in response to thermal subsidence (see *Figure1.3)*. This process led to development of a chain of basins along the west coast of Madagascar, including the Ambilobe, Majunga, and Morondava. The newly formed basins continued to sag until the Early Liassic and a thick blanket of fluvial sandstones was deposited over a wide area (Isalo). These sediments overstep the edges of the grabens and onlap the adjacent basement shoulders.

### 1.5.2- Separation from Africa

In the Late Liassic (Toarcian), a new rifted started to form to the west of failed Permian rift (see *Figure1.4)*. An extensive series of half grabens developed and these were filled by marine shales and sandstones of Toarcian-Aalenian age. On this occasion, the rift was successful and Madagascar started to drift southwards away from Africa. The drift was accompanied by basin sag and a passive margin developed along the western side of Madagascar. The onset of the sag phase occurred at the beginning of the Bajocian and it is marked by the deposition of Bemaraha Limestone. The development of the passive margin continued into the Cretaceous, with the thick wedges of marine and coastal sandstones and the shales being deposited from the callovian or possibly the latest Bathonian onwards (see *Figure1.5)*.

### 1.5.3- Separation from India

A renewal of tectonic activity occurred in the Late Cretaceous as Madagascar started to separate from India. The break-up appears to have been the result of a shearing movement rather than a rift, because no passive margin was developed along the east coast. One or possibly two small basins are thought to have developed at this time, these being the cap Sainte Marie Basin and the Alaotra Graben. These features are tentatively interpreted as a pull apart basin related to strike-slip movement along the Ile Sainte Marie Lineament. Separation from India was also accompanied by the progressive uplift and westward tilting of the Central Highlands. Widespread erosion appears to have taken place in the western sedimentary basins in response to this uplift.

The T*able 1.6* gives a summary of the structural and stratigraphic history of Madagascar. Important geological events (tectonic, rifting and sag) and the major rocks and formations are given in the table.

***Table 1.6****: Structural and stratigraphic history of Madagascar (Adapted from Clark, 1997)*

| | AGE | PASSIVE MARGIN STRATIGRAPHY | FAILED RIFT STRATIGRAPHY | STRUCTURAL HISTORY |
|---|---|---|---|---|
| POST KARRO | TERTIARY | Mio-Pliocene | | Wrenching<br>Tilting, uplift and erosion |
| | | Katsepe Limestones | | |
| | UPPER CRETACEOUS | Coniacian-Maastrichian Sandstones and shales | | Wrenching<br>Punctuated by tilting and uplift<br>**Separation from India** |
| | MIDDLE CREATACEOUS | Tsiandava /Ankarafantsika Sandstones | | Basin sag<br>Passive Margin<br>**Separation from Africa** |
| | Late Jurassic – Early Createceous | Sitampiky sandstone, Duvalia Marl | | |

| | | | | |
|---|---|---|---|---|
| | Middle Jurassic | Beboka | Sakaraha Formation | |
| | | Bemaraha/ Ankarana Limestones | | |
| | UPPER LIAS | Andafia/Beronono Shales | Andafia/Beronono Shales | **Second rifting stage** |
| KAROO | Late Triassic- Early Liassic | Isalo sandstone | Isalo sandstone | Basin sag |
| | Middle Triassic | | Upper Sakamena Sandstone | **First rifting stage**<br>Failed Rift |
| | Early Triassic | | Middle Sakamena Shale | |
| | Late Permian | | Lower Sakamena Sandstone, Vohitolia Limestone | |
| | Early Permian | | Sakoa Sandstones, Shales and Coals | |
| | Pre Cambrian | BASEMENT | | |

(Table 1.6 cont'd)

## 1.6- Mineral resources potential of Madagascar

Madagascar's substratum contains many mineral resources. According to the OMNIS' Division of Mining Resources and Radioactive Mineral, minerals are distributed in various places in Madagascar, as shown in the *figure 1.6*. Mineral resources found in Madagascar consist of: precious metals (Gold, silver, Platinum group metals), precious stones (Emerald, Ruby, Sapphire…), semi-precious stones (Aquamarine, Beryl, Tourmaline, Topaz, Garnet, Amethyst, Citrine, rose Quartz), ornamental stones (Labradorite, Marble, Jasper, petrified wood…), Energy resources (Hydrocarbon, Uranium , coal), industrial minerals (Mica, graphite,…) and industrial metals (Chromium, Nickel, Titanium, Cobalt…).

The mineral resource exploration has been conducted in the frame of international partnership project: Ilmenite project with Qit Minerals Madagascar, Rio Tinto Group-Canada (1985 to now), Gold project with National Mineral Development Corp –India (2000-2001), Radioactive mineral project with the UNDP (1976-2000) and Platinoid Project with the B:R.G.M – France (1987-1991)

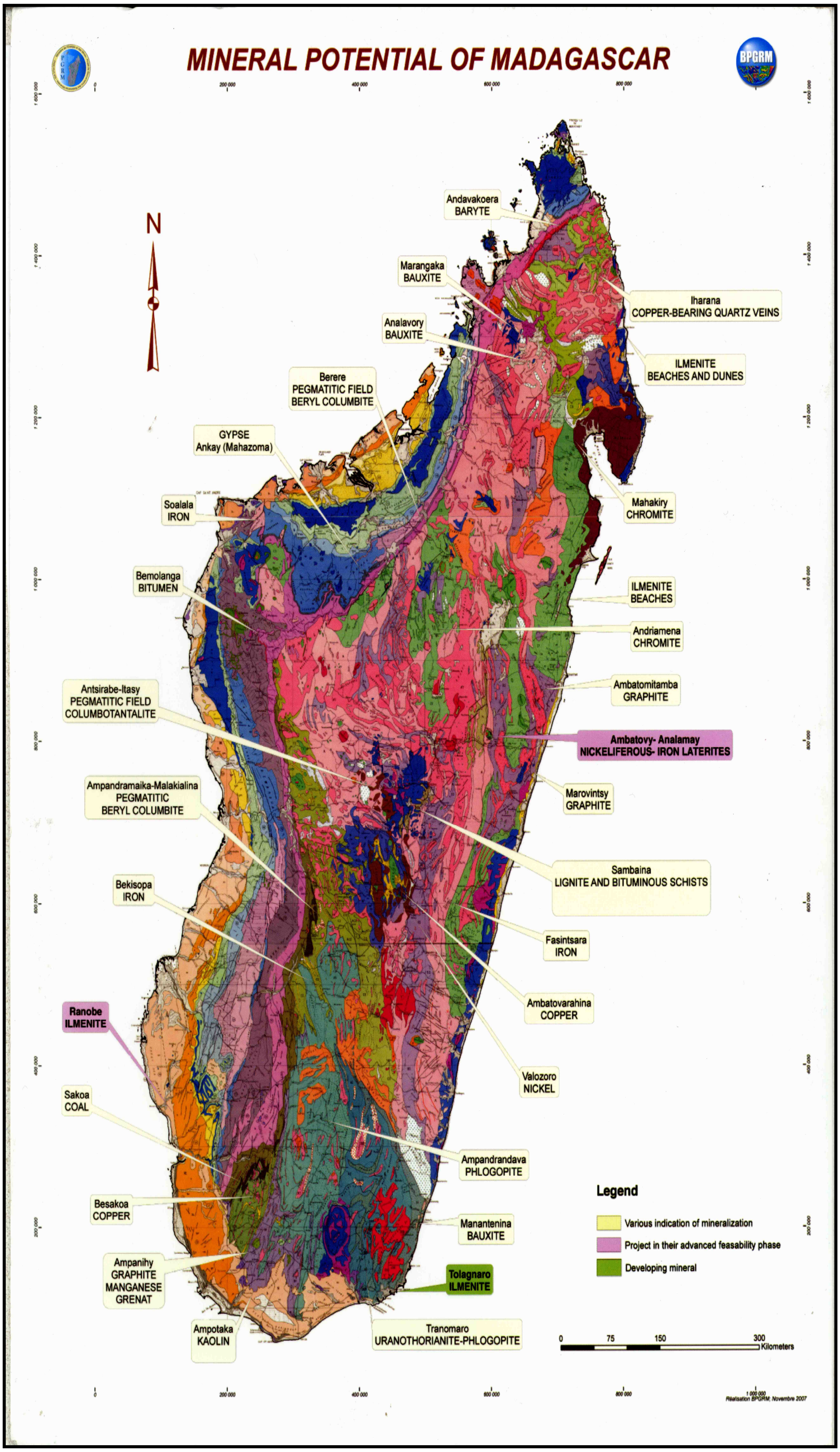


**Figure 1.6:** Mineral potential of Madagascar (Source: BPGRM, 2007)

# II-POTENTIAL RESERVOIR AND SOURCES ROCKS

## *2.1-Reservoir rocks*

Odland (2000) defined a reservoir as a porous and permeable underground formation containing an accumulation of hydrocarbons.

### 2.1.1-Majunga Basin

Reservoir with good characteristics exists in Tertiary, Mid Lower cretaceous and Isalo sandstones. The Mid Jurassic exhibits promising reservoirs in both limestone of the southern area and the sandstone of the northern area (BEICIP, 1988).

Piperi et al (2006) defined the Beronono Cretaceous and the Middle Sakamena – Sakamena/Isalo as speculative petroleum systems which can be found in the Majunga basin where the sandstone constitute the reservoir rock.

### 2.1.2-Morondava Basin

According to BEICIP (1988), sandstone represents the most interesting reservoirs in the Aptian to Cenomanian sequence and in the *Isalo* with fair to good characteristic in the whole basin. Good reservoirs are also observed in the Tertiary and in the Late Cretaceous of northern and southern areas. In the southern area, good reservoirs are identified in the Late Jurassic- Early Cretaceous and in the Mid Jurassic. The Mid Jurassic of the northern area, consisting of packstone-grainstone but partly cemented remains a potential play. The Late Lias and the *Sakamena* also contain perspective porous Sandstone. Shale intercalations form efficient seals for these reservoirs. *Tsimiroro* heavy oil field and the Tar sand *Bemolanga* accumulation contain important resources in place in the Isalo II.

### 2.1.3 – Majunga and Morondava Basins

According to Clark (1997) 9 potential reservoirs have been recognized in the Majunga and Morondava Basins where the most of the exploration drilling has been concentrated. These reservoirs are: Lower *Sakamena* (Late Permian), Upper *Sakamena*, (Mid Triassic), *Isalo* (Late Triassic – Early Liassic), “Aalenian” (Late Liassic), “Argovinian” (Late Jurassic), *Sitampiky* (Early Cretaceous), *Tsiandava* (Mid cretaceous), *Ankarafantsika* (Mid Cretaceous) and “Conician” (Late Cretaceous) sandstones**,** *Bemaraha* (Mid jurassic) and *Katsepe* (Eocene) Limestone. Presence of the same reservoirs is also possible in the Ambilobe Basin.

Description of these potential reservoirs is found in the Table 2.1. From this table, Madagascar reservoir rock is composed of two main rocks: sandstone and limestone. The sandstone is found in the formation such as *Sakamena* (Lower and Upper)*, Isalo* (II and III), *Sitampiky* (lower cretaceous) and *Ankarafantsika* (Mid Cretaceous). Limestone distribution is more restricted to only few formations (*Bemaraha, Mahabibo and Katsepe*). The sandstone seems to have a wider distribution than the limestone. The light oil discovery of Manandaza has sandstone of Lower *Sakamena* (Late Permian) as reservoir rock while *Bemolanga* and *Tsimiroro* reservoir is constituted by the *Isalo* II (Late Triassic-Early Lias). The reservoir quality varies with the rock type and its features (Porosity and permeability). No potential reservoir was found in the Sakoa formation.

***Table 2.1**: Potential reservoir description (adapted from Clark, 1997)*

<table>
<tr><th rowspan="2"></th><th rowspan="2">PERIOD</th><th rowspan="2">EPOC/AGE</th><th rowspan="2">FORMATION</th><th colspan="3">Potential Reservoir rocks</th></tr>
<tr><th>Type (description)</th><th>Porosity/Quality</th><th>Location</th></tr>
<tr><td rowspan="7">POST KAROO</td><td>NEOGENE</td><td rowspan="2">OLIGOCENE MIOCENE</td><td></td><td>Katsepe limestone (Along the coast of Majunga)</td><td rowspan="3">No data but these limestone comprises bioclastic grain stones and packstone</td><td rowspan="3">Croup out in the coastal areas of Morondava and Majunga Basins and extend offshore into shallow subsurface</td></tr>
<tr><td rowspan="2">PALEOGENE</td><td rowspan="2"></td><td rowspan="2">Mahabibo limestone (form a low scarp 12 km to the east of Majunga)</td></tr>
<tr><td>EOCENE</td></tr>
<tr><td rowspan="3">CREATCEOUS</td><td>CONICIAN MAASTRICHT</td><td>Upper</td><td>Sandstone : Campanian-Turonian (Majunga Basin)/( Morondava Basin)</td><td rowspan="3">Best quality found eastern Morondava and southeastern Majunga Basin (thick sandstone) and the poorest quality is found in the thinner, more basinal sandstone (western Morondava and northwestern Majunga basins)</td><td rowspan="4">Widely distributed on the passive margin of western Madagascar(Majunga/Morondava)</td></tr>
<tr><td>ALBIAN TURONIAN</td><td>Mid</td><td>Sandtsone: Ankarafantsika (Majunga Basin)/Tsiandava (Morondava Basin)</td></tr>
<tr><td>NEOCOMIAN APTIAN</td><td>Lower</td><td>Sandstone: Sitampiky (Majunga Basin)/ Sakanavaka series (Morondava Basin)</td></tr>
<tr><td>JURASSIC</td><td>CALLOVIAN – TITHONIAN</td><td></td><td>sandstone</td><td></td></tr>
</table>

| | | | | | | |
|---|---|---|---|---|---|---|
| | | BAJOCIAN BATHONIAN | BEMARAHA | limestone | Generally very poor reservoir quality (impermeable in the subsurface) | On the Passive Margins of the Ambilobe, Majunga and Morondava Basins |
| | | LATE LIAS (TOARCIAN-AALENIAN) | ISALO 3/Mixed facies | Sandstone | Appear to be very good reservoir(friable and porous at outcrop) but not confirmed by porosity and permeability measurement | On the Passive Margins of the Ambilobe, Majunga (southern) and Morondava (eastern) Basins |
| | | L TRIASSIC-E.LIAS | ISALO 2 | Sandstone (most popular exploration objective: good porosity at outcrop and hosting heavy oil of Tsimiroro and Bemolanga ) | Average Porosity 19% (Moulton, 1984) Good reservoir quality throughout (worley,1982) with slightly lower porosity in the shallow subsurface and very poor in deeper subsurface | Failed rift complex of western Madagascar and on the passive margin to the west of the failed rift |
| | | MID TRIASSIC | ISALO 1 | | | |
| KAROO | TRIASSIC | E.MID TRIASSIC | UPPER SAKAMENA | Sandstone | Good reservoir quality sands throughout (with an average of 19% in Manandaza log) (Worley,1982) | Failed Permo-Triassic complex of the southern and eastern Morondava and southeastern Majunga Basin |
| | | EARLY TRIAS SIC | MID SAKA MENA | | | |
| | CARBON-PERMIAN | LATE PERMIAN | LOWER SAKAMENA | Sandstone | Porosity up to 33% (surface). Poor quality (in deeper subsurface) but remains attractive due to light oil discovery (MANANDAZA) | Failed rift complex of southern and eastern Morondava and southeastern Majunga Basins |

(*Table 2.1 Cont'd*)

The Table 2.2 which has been adapted from BEICIP reports (1988) gives a wider view of the reservoir rock quality of Madagascar in comparison to reservoir described by Clark. It presents reservoirs quality among the plays found in western basins based on the parameters such as: rock type, location, porosity, permeability and thickness. The number of wells, from which reservoir parameter were obtained, are also given to refer on how relevant the data/parameter are. According to Table 2.2 reservoir rocks are distributed from the Carboniferous time to the Tertiary in the three western sedimentary basins. In these basins, no significant reservoir was found in the Late Jurassic (CALLOVIAN –TITHONIAN), Early Liassic and in the basement. In addition to these, especially in the Morondava basin, no reservoir was found in the following formation: Middle *Sakamena* (Early Triassic) and *Sakoa* (Late Carboniferous- Early Permian).

***Table 2.2**: Reservoir quality in the western sedimentary basins (BEICIP, 1988)*

<table>
<tr><th rowspan="3"></th><th rowspan="3">PERIOD</th><th rowspan="3">EPOC/AGE</th><th rowspan="3">FORMATION</th><th colspan="4">Reservoir quality</th></tr>
<tr><th colspan="2">Majunga –AmbilobeBasin</th><th colspan="2">Morondava</th></tr>
<tr><th>Location</th><th>Reservoir description</th><th>Location</th><th>Reservoir description</th></tr>
<tr><td rowspan="4">POST KAROO</td><td>NEOGENE</td><td>OLIGOCENE MIOCENE</td><td></td><td rowspan="2">onshore along the coast and in the offshore zone (2 wells)</td><td>Reservoir consists of thick porous carbonate and sandstones with porosity and permeability up to 21% and 20 md respectively. The net thickness is variable and can reach 300 m. no show detected</td><td rowspan="2">Limited to coastal and offshore of the north areas (11 wells)</td><td>Reservoir of Porous limestone intervals (Heloise-1, Eponge-1 and Andavadoaka-1) and sandstones layers observed in Morombe-1 or Vaucluse-1. Trace of gas (C1-C3) detected</td></tr>
<tr><td>PALEOGENE</td><td>EOCENE</td><td></td><td>Significant gas shows (C1-C4) have been observed and a test in Mariarano-1 recovered a gas flow with traces of gasoline. Depth in the offshore ranges from 1000-2500m.</td><td>Reservoirs of limestone, locally reefal, and of sandstone mainly located between Saronanala-1 and west Kirindy-1.Trace of gas (C1-C3) detected</td></tr>
<tr><td rowspan="2">CREATCEOUS</td><td>CONICIAN MAASTRICHT</td><td></td><td rowspan="2">Wide area onshore (4 wells)</td><td>Reservoir consisting of fluvial sandstone with porosity up to 40% and permeability reaching 1000md in out crop but decreases northward. No significant shows.</td><td rowspan="2">Western onshore and offshore areas (23 wells): oil shows located onshore</td><td>Fairly good sandstone reservoirs are observed onshore central area. Porosity reaches 20-25% and permeability expected to be good in the central onshore but lower offshore. Gas and condensate discovery in west Manambolo.</td></tr>
<tr><td>ALBIAN TURONIAN</td><td></td><td>Reservoir related to the Cenomanian sandstone but porous sandstone exists in the north of Betsiboka River. Onshore porosity reaches 28% and the permeability 130 md. The thickness attains 40 m. Trace of gas and oil shows.</td><td>Thick reservoir with fine/coarse-grained sandstone restricted to onshore zone. Porosity from 11 to 27% and net thickness varying from tens to hundreds meters. Best characteristic in Serinam-west Kirindy</td></tr>
</table>

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | NEOCOMIAN APTIAN | | | The most promising reservoirs are represented by the Neocomian Sitampiky sandstone (west of Betsiboka) and Aptian sandstone. Porosity and permeability in these reservoirs (outcrops) reach 30-40% and 1000md | | Sandstone reservoir restricted to the area south of Morondava river. Porosity from 15 to 30% with fair to good permeability.oil and gas show in Manambolo-1 |
| | JURASSIC | CALLOVIAN TITHONIAN | | Large part of onshore zone (6 wells) Reservoirs consist of limestone west of the Betsiboka River and of sandstone north this river | No significant reservoir identified | Onshore zone | |
| | | BAJOCIAN BATHONIAN | BEMARAHA | | Locally fissured limestone with a porosity and permeability reaching 20% and 40md. Net thickness attains tens of meters. Bitumen show (Majunga basin) | | -Northern area : reservoir of limestone locally dolomitized or fractured with porosity up to 20% but strongly cemented<br>-Southern area: reservoir of sandstone with a porosity up to 25% and permeability of tens md. Gas and trace of Bitumen detected in Bajocian-Bathonian.<br>Oil shows found in Sikily-1 (late Jurassic) and |
| | | LATE LIAS | | | Sandstone layers with 30% of porosity and a good permeability (Not found in the wells drilled on old structural high). Bitumen shows at Ankaramy (Ambilobe Basin) | | |
| | | L TRIASSIC-E.LIAS | | | | | |
| KAROO | TRIASSIC | | ISALO 2 | Isalo series extends in the whole basin. The Sakamena is | Isalo Reservoir of fluvial sandstone with porosity up to 30% both in wells and outcrops. Permeability fair to good. | Northern area east of Bemaraha Fault (Bemolanga and Tsimiroro fields reservoir) | Very thick sandstone with an average porosity: 20-25% and permeability reaches hundreds millidarcies. Bitumen traces detected and gas shows |

(Table 2.2 cont'd)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | MID TRIASSIC | ISALO 1 | observed in outcrops in the northernmost area (3 wells) | | Whole basin | Sandstone reservoir showing a progressive decrease of porosity and permeability toward the basement. Net thickness reaches several hundred meters. Bitumen traces detected and gas shows |
| | | E.MID TRIASSIC | UPPER SAKAMENA | | Sakamena sandstone with low porosity (<10%) in outcrops. | | |
| | | EARLY TRIASSIC | MID SAKAMENA | | | | |
| | CARBON-PERMIAN | LATE PERMIAN | LOWER SAKAMENA | | | Whole basin | Reservoir having highly variable characteristics. Porosity and permeability up to 20% and 3000md.Trace of oil (Sakaraha-1) |
| | | L.CARBON E.PERMIAN | SAKOA | | | | |
| | BASEMENT | | | | | | |

(Table 2.2 cont'd)

## 2.2-Source rocks

Clark (1997) reported that four potentials source rocks have been identified : the *Sakoa* coals (Late Permian), the *Middle Sakamena* (early Triassic) shale, the *Andafia/Beronono* shale (late Liassic) and the *Bemaraha limestone* (Middle Jurassic).The author reported that so far the Middle *Sakamena* is the most important source rock identified in the western Madagascar. The second most important one is probably the *Andafia Beronono* but a little is known about the quality and distribution of this unit. The *Bemaraha* may also be a good source rock in places but the knowledge about its quality is poor.

The Table 2.3 summarizes information on potential source rocks cited by Clark. It is based on information found in Clark and completed by BEICIP reports. This table gives the source rock type, the age of the major formations where source rock can be found and the approximate location of the source rocks in the basin. The Middle *Sakamena* reported by Clark (1997) to be the most important source rock is found in the eastern and southern Morondava basin. The shale constitutes the source rock and the oil generation is between middle to late mature.

A map illustrating the source rocks distribution in the western sedimentary basins is shown in the Figure 2.1. Information about source rock maturation is also found on the map. According to this map:

-In the Morondava Basin, the *Bemaraha limestone* and the *Andafia shale* located in the passive margin (respectively of Mid-Jurassic and Late Liassic of age), the oil and gas are mature. For the Middle Sakamena shale of early Triassic age which occurs in the Permo-Triassic rift, the oil is mature but a part of the gas is mature from west of Bezaha-1 bis (BW-1 bis) well to east of Ambalabe-1(AB-1) and another part is still immature located between the Leoposa wells (LW-1 and LW2) and south Malaimbandy. The Middle Sakamena is the source rock of the Bemolanga, Tsimiroro and Manandaza oil accumulation.

-In the Majunga-Ambilobe Basin, for the *Bemaraha limestone* (Mid Jurassic) and the *Beronono shale* of Late Liassic age (located in the Passive Margin), the oil is mature onshore and the gas is mature onshore and offshore. Both oil and gas are mature in the *Middle Sakamena shale* which is located in the Permo-Triassic rift.

The source rock maturation constitutes an important factor in petroleum geology. In Madagascar western basin, this factor varies from one play to another and from one basin to one another as shown in the Table 2.3.

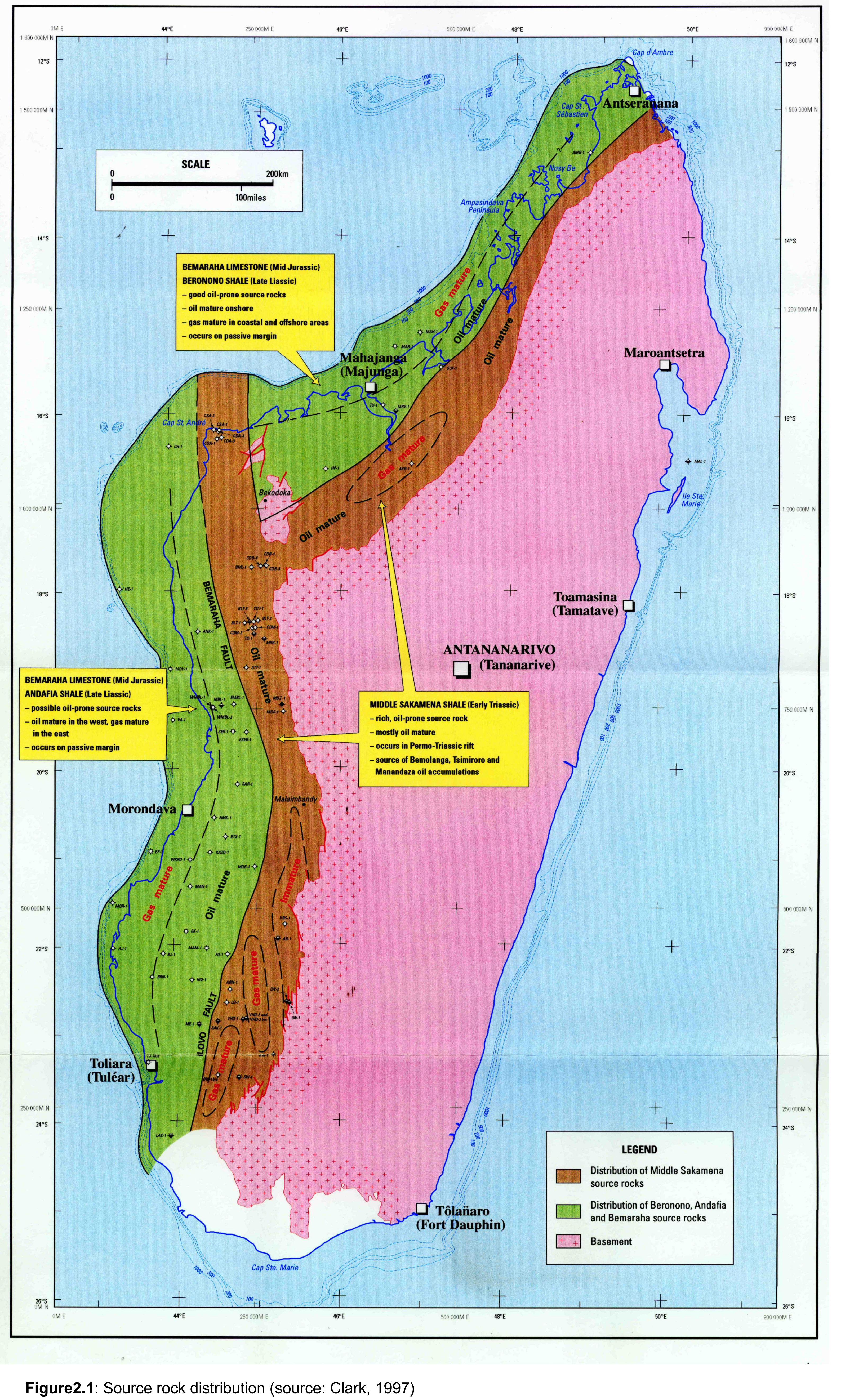


**Figure2.1**: Source rock distribution (source: Clark, 1997)

**Table 2.3**: Potential source rocks of Madagascar (adapted from Clark 1997and BEICIP 1988)

| | PERIOD | EPOC/AGE | FORMATION | **Potential Source rocks** | | | |
|---|---|---|---|---|---|---|---|
| | | | | Type | Maturity | TOC/ QUALITY | Location |
| POST KAROO | NEOGENE | OLIGOCENE MIOCENE | | | | | |
| | PALEOGENE | EOCENE | | | | | |
| | CREATCEOUS | CONICIAN MAASTRICHT | Upper | shale | Middle mature for oil generation | TOC: 1-2% | Betsimba, Manja, Saronanala, West kirindy (Morondava Basin) |
| | | ALBIAN TURONIAN | Mid | | | | Saronanala(Morondava Basin) |
| | | NEOCOMIAN APTIAN | Lower | | | | Serinam (Morondava Basin) |
| | JURASSIC | CALLOVIAN - TITHONIAN | | | | | |
| | | BAJOCIAN BATHONIAN | BEMARAHA | Limestone( Dark grey or black, organic rich carbonate mudstone) | Late to post mature | TOC:2% but 3.5% prior maturation (Carbonate mudstones can be a good quality oil to gas source rock) | N-S, central and western Morondava Basin and NE-SW, central and northern Majunga Basin |
| | | LATE LIAS (TOARCIAN-AALENIAN) | ISALO 3/Mixed facies | Andafia-Beronono shale | Late-post mature(Ambilobe basin),immature-early mature (Majunga Basin) | TOC: 7.6% (Ambilobe), 2.07-69.38% (Majunga), N.A (Morondava) **Excellent source rock** | Central part (Morondava and Majunga basins) and in coastal area (Ambilobe) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | LATE TRIASSIC-EARLY LIAS | ISALO 2 | | | | |
| | | MID TRIASSIC | ISALO 1 | | | | |
| | TRIASSIC | E.MID TRIASSIC | UPPER SAKAMENA | | | | |
| KAROO | | EARLY TRIASSIC | MID SAKAMENA | Organic shale forming two units: a lower (Black shale) and an over lying unit | Middle to late mature for oil generation | TOC: 4%for the lower Unit and 1% the upper unit | Eastern and southern **Morondava basin** (Elongated basins within the broader rift /Throughout the Permo-Triassic rift) |
| | | LATE PERMIAN | LOWER SAKAMENA | | | | |
| | CARBON-PERMIAN | L.CARBON E.PERMIAN | SAKOA | Coals and organic rich shale | Middle-post Mature for oil generation and immature for gas generation | shales TOC: 1.08-17.4% and coal's TOC from 27-69.7% | Southern Morondava Basin (Sakoa field) |
| | BASEMENT | | | | | | |

*(Table 2.3 cont'd)*

Table 2.4 gives information on the source rock maturation among the western basins. The maturation varies between basins- It even varies from one place to another within a same basin.

**Table 2.4**: Source rock maturation in Ambilobe-Majunga and Morondava basins (Adapted from BEICIP, 1988)

| | PERIOD | EPOC/AGE | FORMATION | Source rock maturation | |
|---|---|---|---|---|---|
| | | | | Ambilobe-Majunga | Morondava |
| POST KAROO | NEOGENE | OLIGOCENE MIOCENE | | -Immature down to 2000m and early mature below this depth (Mahajamba-1) but probably mature in deeper zone | -immature |
| | PALEOGENE | EOCENE | | | |
| | CREATCEOUS | CONICIAN MAASTRICHT | | Immature generally in the onshore zone. Lower part reaching oil window north of shore line area. | Generally immature but the base enters oil window along the coast and in offshore zone |
| | | ALBIAN TURONIAN | | -Immature south of Sofia-1/Tuilerie-1 trend and enter the oil in the distal onshore area<br>-immature in the Mariarano-1 | Mature in the western onshore and offshore (Eponge-1) |
| | | NEOCOMIAN APTIAN | | Increased maturity westward:<br>-immature to mature south of Tuilerie-Sofia<br>-over mature north thisTuilerie-Sofia | Located in oil window but enters gas zone in coastal to offshore areas |
| | JURASSIC | CALLOVIAN TITHONIAN | | -Immature in outcrop areas<br>-mature north of Tuilerie-Sofia Line<br>-over mature in the distal onshore zone | -immature to early mature () in the eastern area near the Bemaraha-Ilovo trend<br>- reaches oil window westward then the gas zone distal onshore |
| | | BAJOCIAN BATHONIAN | BEMARAHA | -Mid Jurassic entered oil window in Early Cretaceous and gas zone in Late Cretaceous in deeper zone | -offshore: entered oil window during the Cretaceous and gas zone in the Eocene<br>-onshore : oil reached in the latest Cretaceous |

| | | | | | |
|---|---|---|---|---|---|
| | | LATE LIAS | | | -Northern area (west of Bemaraha Fault): in oil zone<br>-southern area: in the gas zone with some exception |
| | | L TRIASSIC-E.LIAS | | | |
| KAROO | TRIASSIC | L TRIASSIC-E.LIAS | ISALO 2 | -Immature to mature south of Tuilerie-Sofia area and oveer mature north this trend<br>-lower Isalo attained oil window in late Jurassic time and the gas zone during the Lower-Mid Cretaceous | - Eastern side of Bemaraha-Ilovo fault : immature and enters the oil window and locally the gas zone<br>- west side of Bemaraha-Ilovo: in gas zone |
| KAROO | TRIASSIC | MID TRIASSIC | ISALO 1 | | |
| KAROO | TRIASSIC | E.MID TRIASSIC | UPPER SAKAMENA | | |
| KAROO | TRIASSIC | EARLY TRIASSIC | MID SAKAMENA | -Onshore area: Mature-immature in the southeastern half area and in the gas zone in the northwestern half<br>-coastal area: oil window and gas zone reached at the end of Mid Jurassic and at the end of Jurassic respectively | -immature to early mature(southern area)<br>- Early mature in easternmost part (east Tsimiroro)<br>-over mature (west of Bemaraha Fault) |
| KAROO | CARBON-PERMIAN | LATE PERMIAN | LOWER SAKAMENA | | |
| KAROO | CARBON-PERMIAN | L.CARBON E.PERMIA | SAKOA | | -Immature to mature in outcrops<br>-over mature since Triassic in the subsurface |
| | BASE MENT | | | | |

*(Table 2.4 cont'd)*

## *2.3-PLAY MODELS*

### 2.3.1 Majunga Basin

The basin remains underexplored and available data do not allow a full evaluation of the petroleum potential of this basin. However, BEICIP (1988) have defined four plays.

- The **Tertiary play**: considered as a play of secondary interest. It is found offshore and seems to be of Eocene in age. It is the only series to contain reservoirs, source rocks and significant gas shows**.** Stratigraphic traps are detected.

- The **Cretaceous play** is poorly explored. This play for oil or gas contains good reservoirs and seals but mature source rock seems poor to fair. The traps are poorly identified**.** The thick Lower Cretaceous porous sandstone restricted to the southern area and only known in outcrops need further investigations to assess its potential. No significant shows have been detected in this play but it remains attractive.

- The **Jurassic play which** is limited to the Mid Jurassic is one of the most attractive plays for oil and gas in the basin. Covering a wide part of the onshore, it extends to the present shore line. It contains porous limestone in the west and Sandstone in the east. Excellent source rock potential has been measured at *Beronono* and significant bitumen shows were found in the shallow *Ankaramamy* well but the extent of source rock remains unknown. Other hydrocarbon source could be *Sakamena* rock. Hydrocarbon trapped in the Isalo could have migrated into reservoir. The lack of seismic data leads to a poor identification of traps**.**

- **The Permian to Triassic play** (*Sakamena-Isalo*) is a play for oil and gas. It extends in the whole onshore basin and is related to the presence of a good reservoir, a possible source rock (*Sakamena* - Lias) and a tilted fault block. The presence of efficient seal and the potential of the source rock constitute the most critical points of this play**.** This play has been tested poorly and deserves a new exploration phase.

### 2.3.2 Morondava Basin

According to BEICIP (1988), the data concerning this basin is abundant compared to Majunga basin except some areas remaining underexplored such as “Karoo Corridor” (Manandaza and Andafia Grabens). The following plays have been identified:

- The **Tertiary** classified as a secondary play extends onshore along the coast and in the offshore. The presence of porous sandstone and limestone is proven but detailed studies are needed to evaluate the quality of the seals, trap and hydrocarbon migration from underlying units.

- The **Cretaceous play** where oil shows are common and attractive, especially in the central/Southern area. It extends from the outcrops to the proximal offshore. This play for oil and gas contains good source reservoir interval and seals. Traps are related to volcanic domes, faults or Channel/Turbidities. They seem of small size.

- The **Jurassic play which** is poorly explored. This is located in the southern area, from the *Ilovo* fault to the distal onshore. This play, for oil and gas in upper part, and only for gas in the lower part, displays few oil and gas shows. It contains fair to good sand reservoirs and potential source. The traps seem of small size except large roll over in the Mid Jurassic sequence. In the northern area only Mid Jurassic is considered as prospective along the Bemaraha fault where the reservoir is commonly tight and the presence of a seal is uncertain.

- The **Permian to Triassic play** (*Sakamena –Isalo*), located east of the *Bemaraha-Ilovo* Fault, and is a prospective for oil and gas. The reservoir characteristics are very good. There are 2 different areas for this play:

-The **northern area** where the heavy oil and tar Sand are present but remain underexplored. The presence of source rock is demonstrated and an interbedded seal is observed. This zone is considered as **one of the most promising plays**

-In the **southern zone**, classified as fair, oil and gas shows are observed but not significant, and seals are less efficient.

#### 2.3.3 Eastern Coast/Basin

It is an offshore sedimentary basin resulting from the separation of the India and Madagascar, initiated in Mid Cretaceous time was partly explored. Studies reveal the presence of Siliclastic Miocene series and bottomed in volcanic intervals or in the basement with a good oil show at the base of Miocene (BEICIP, 1988).

Very little is known about the eastern coast basin. The documents that we have been working on do not give any detail nor satisfying information about this basin. The main reason of lack of information about this basin is that the main exploration activities have been focused in the western sedimentary basin.

## *2.4- Structural styles and possible trap mechanism*

Clark (1997) gave the following description of structural styles found in Madagascar. Normal fault dominate the structural architecture of the western sedimentary basin. Other less common structures can also be found such as Wrench faults, reverse faults and anticlines. The interpretation of these features remained fairly consistent since the early 1970s. Recent improvements in the acquisition reprocessing of the seismic have improved knowledge about the mechanism and the timing formation of some faults and folds. It is now possible to recognize two distinct episodes of normal faulting. Many of the folds previously interpreted as roll-over structures are now thought to be compressional anticlines and flower structure. The Figure 2.2 illustrates examples of structural styles found in Madagascar.

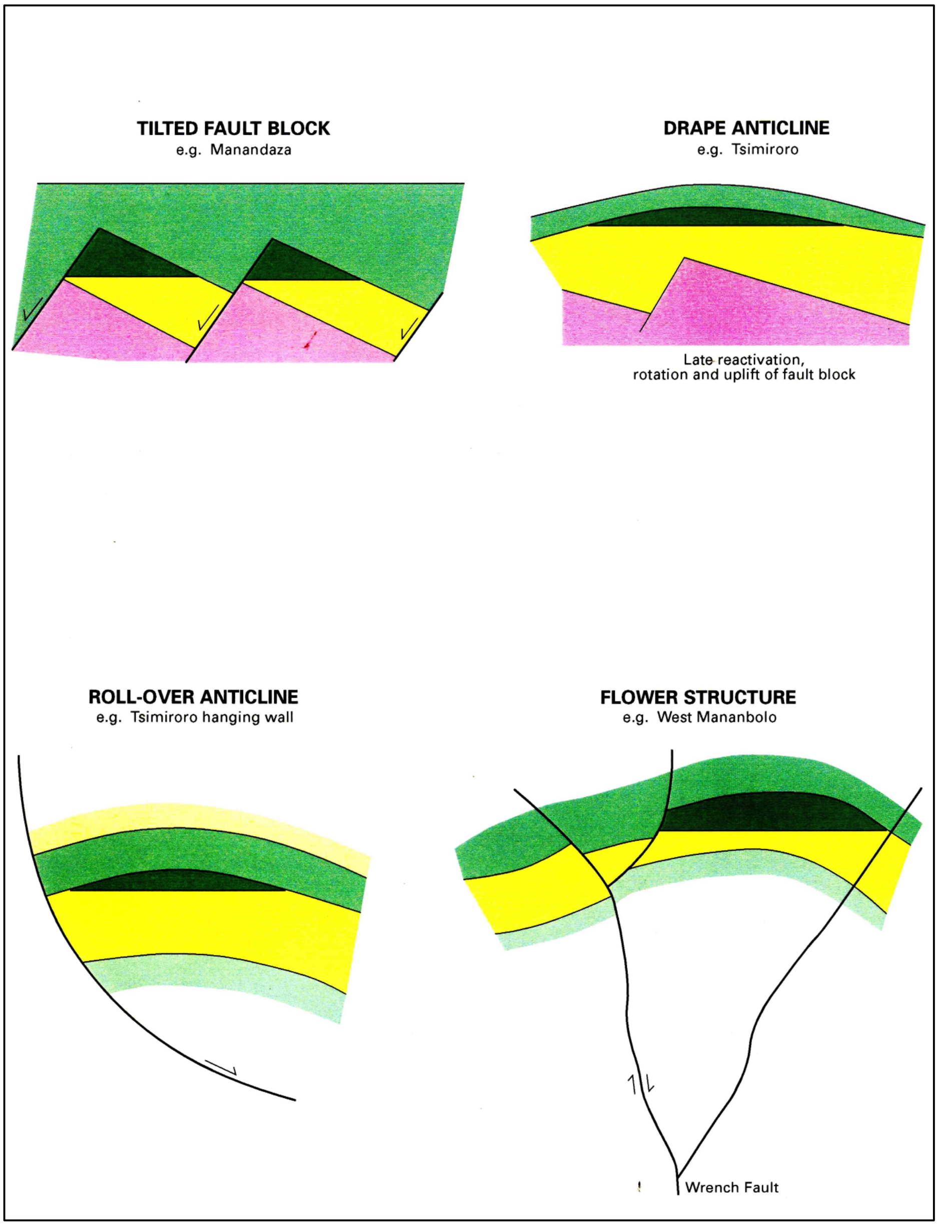


**Figure 2.2**: Examples of structural trapping style

### 2.4.1- Normal faults

Interpreted by most workers as extensional features related to rifting and continental drift, most of these faults are associated with rotated blocks. Two separated phases (Permian and Late Liassic) of the block faulting and extension can be recognized on seismic:

-Permian faults are found in the Permo-Triassic Rift (Morondava Basin and Ankara Graben). The fault blocks are formed by basement rocks. The bounding faults are shortened by the Middle *Sakamena* shale (Early Triassic) under which the *Sakoa* (Early Permian) and the Lower *Sakamena* shale (Late Permian) formation occur in the wedge shaped half-grabens.

-Late Lias faults, located only on the passive margin of the Ambilobe, Majunga and Morondava Basins, the rotated blocks comprise *Isalo* Sandstones and the bounding faults are truncated by the base of the *Bemaraha* limestone (Middle Jurassic). Beneath this horizon, the Upper Liassic shales (*Andafia/Beronono*) occur in wedge-shaped bodies that thicken towards the normal faults.

Various set of normal faults have been recognized in the coastal area of Majunga Basin (Weimer, 1993; Lalaharisaina and al, 1994) and possibly in the Ambilobe Basin. Occurring only in the Cretaceous and Tertiary sections, these faults are thought to have formed by collapse (Late Cretaceous) of the shelf margin under the influence of gravity.

### 2.4.2 - Wrench Fault

In Madagascar few wrench faults have been described from seismic data due to the poor resolution of the older seismic. On more modern lines such as those recently shot in the eastern Morondava and Majunga Basins, a number of flower structures can be recognized. Most of these features comprise symmetrical anticlines developed above flower-like fault complexes. These are interpreted as compressional anticlines or positive flower structures, formed by movement of strike-slip faults. Some negative flower structures are also possibly developed in the Majunga Basin.

In Morondava Basin, the wrench faults occur in all parts of the basin (affecting sediments from Permian to Tertiary). They are thought to follow the same trend as the *Bemaraha-Ilovo* Fault Complex. However, in the Majunga Basin the orientation of the faults is less clear and no strike-slip movement has been identified in the *Ankara Graben*. The faults are thought to post-date the deposition of Jurassic and Cretaceous sediment and many have propagated upwards through Tertiary sediments to the surface.

### 2.4.3 - Roll over Anticlines

Roll-over anticlines (extensional anticlines formed on the downthrown sides of listric faults) have long been postulated in the Morondava Basin. A number of dip reversals can be recognized on the downstream sides of some faults that are parallel to the Bemaraha-Ilovo fault Complex. A re-evaluation of these anticlines suggests that they may in fact be compressional anticlines, or possibly flower structures in some cases (Clark, 1997). True roll-over anticlines do occur, nevertheless, and several examples can be found in the *Manandaza* graben. One example occurs on the downthrown side of the *Tsimiroro* Fault where a large anticlinal structure is developed at the Middle Sakamena level. This anticline is possibly a Liassic feature but it may have started to form in the Triassic.

#### 2.4.4 - Compressional anticlines

These anticlines are relatively young in age with most of them forming in the latest Cretaceous or Early Tertiary. On seismic, folding has affected sediments as young as Early Tertiary in age, and at out crop in the Morondava Basin gentle folds are developed in Pliocene sediments. The folds appear to have formed as a result of a late stage reactivation of Permo-Triassic or Late Liassic normal faults. Most of the anticlines probably developed as compressional features associated with strike-slip movement along the faults.

Other type of traps can be found and detailed in BEICIP (1988) as shown in the table 2.5 where traps are described and regrouped per play and per basin. These traps comprise rollover, volcanic dome, stratigraphic, tilted block and worst, channel, coral build, submarine fans and unconformity.

***Table2.5**: Traps' description in western Basins (adapted from BEICIP, 1988)*

<table>
<tr><th>BASIN</th><th>PLAY</th><th>TRAPS' DESCRIPTION</th></tr>
<tr><td rowspan="4">Ambilobe-Majunga</td><td>Tertiary</td><td>-Volcanic domes: identified offshore and in Mariarano-1 where the seal is provided by the Eocene shale and the reservoir can be sourced by Cretaceous shale<br><br>-stratigraphic traps like channels are expected offshore but they appears to be problematic due to the seal, the reservoir quality and the hydrocarbons' migration.</td></tr>
<tr><td>Cretaceous</td><td>-roll over: identified in the Mid Cretaceous sequence and found along the talus northwest of Sofia-1 and Tuilerie-1 trend. The seal is formed by inter bedded shale.<br><br>- Channels, submarine fans or debris flows occur in the distal onshore. These features are identified along the Cretaceous talus in the whole Cretaceous sequence. They can be sourced by associated shale.<br><br>-Domes were identified in offshore and may be related to volcanic intrusions of Mid-Late Cretaceous age. They seem to be in good position due to possible presence of Cretaceous source rocks in the mature zone and sealed by Cretaceous shale</td></tr>
<tr><td>Jurassic</td><td>-rollovers identified in the Tuilerie-Sofia zone are early formed traps which are transgressed by the Upper Jurassic shale.<br><br>-Coral build ups found at Sofia-1, can have developed along the Mid Jurassic shelf (along Bemaraha Fault of Morondava Basin). They are sealed by Upper Jurassic shale.<br><br>-Debris flows along the talus are down dip in the basin and can be sourced at first by hydrocarbons generated in the deeper part of the Basin.</td></tr>
<tr><td>Permian-Triassic</td><td>-Tilted blocks and horsts were formed during the Late Lias have the Isalo sandstone as reservoir and Upper Jurassic shale as seal.<br><br>-Rollovers, identified between Tuilerie and Sofia constitute good traps if inter bedded shale are efficient seal. They can be sourced by Middle Sakamena or Isalo source rocks.<br><br>-Volcanic domes formed in Mid Late Cretaceous can provide good traps if the hydrocarbon migration occurred in Late Cretaceous</td></tr>
<tr><td rowspan="2">Morondava</td><td>Tertiary</td><td>- Numerous channels found in Miocene and Eocene can be filled by porous sandstone and sealed by the Miocene shale and sourced by underlying Cretaceous source rocks in the oil windows.<br><br>-Growth faults generating rollover structure are detected in Miocene. They can be considered as trap if efficient seal was deposited.</td></tr>
<tr><td>Cretaceous</td><td>-Numerous faults (antithetic and unconformity) can generate structural traps if they are impermeable. They are mainly of Late Cretaceous age and can be sourced by the Cretaceous or older source rocks which expelled hydrocarbons during tertiary burial.<br><br>-Rollover structures can be related to an antithetic fault system.<br><br>-tilted blocks on lapped by Paleocene sediment, they are formed by the local combination of Listric and antithetic fault and can be sealed by the tight Paleocene mudstone.</td></tr>
</table>

| | | |
|---|---|---|
| | | -*Channels* observed in the Middle Cretaceous sequence. Trapping can be improved by the existence of up dip impervious faults<br><br>-*Submarine fans* identified in west Manambolo-1 and the Tsiribihina river |
| | Jurassic | -*rollovers* identified in the southern area created numerous structures in Upper Lias and Mid Jurassic sequence. Inter bedded shale act as seal and possible source rock.<br><br>-*Traps* against gravity faults affecting the Late-Middle Jurassic will depend on the imperviousness of these faults. The Lower Cretaceous shale and the Jurassic/Lower Cretaceous formed respectively the seal and the source rocks<br><br>-*large unconformities* are related to volcanic domes and can form attractive leads<br><br>-*volcanic intrusions* are common in the basin and can generate doming in the Jurassic and Cretaceous sequence whose sandstone reservoirs are sealed by the Lower Cretaceous shale. |
| | Permian-Triassic | -*Tilted fault blocks* formed during the Upper Lias extensional phase were identified west of Bemaraha-Ilovo Fault trend.Isalo2 sandstone and Upper Lias or Mid Jurassic shale constitute the reservoir and the seal<br><br>-*Rollover structures* formed along large fault during the initial rifting phase. The trap can be sourced by the Middle Sakamena or the base shale of the Isalo 2 and sealed by the sealed by the Middle Sakamena<br><br>-*Drape over basement horsts* are one of the most interesting type of traps. They can exist between the Basement and the Ilovo-Bemaraha Fault trend. Isalo 1 or 2 can constitute the reservoir and the inter bedded shale formed the seal (Tsimiroro case)<br><br>-*Domal structures* correspond to large volcanic intrusions of Early-Mid Cretaceous age. Traps can be sourced by Middle Sakamena –Isalo 2 shale, and the Isalo shale act as seal |

(Table 2.5 cont'd)

# III-EXPLORATION AND DEVELOPMENT HISTORY

## *3.1 Exploration history*

According to Clark (1997) interest in hydrocarbon exploration in Madagascar started in 1909, with the discovery of an accumulation of heavy oil at *Folakara* in the northern Morondava Basin. From 1909-1917, an US company drilled seven wells where some of which encountered heavy oil and bitumen.

In the 1914 at Maroaboaly a discovery of more heavy oil was made by a British company. Six wells were drilled from 1913-1917, all of which encountered shows of heavy oil and bitumen.

In 1928 Bemolanga (a large tar sand deposit) was discovered in the north of Folakara where two wells were drilled and both of which encountered tar sands. To the west Tsimiroro which is a large accumulation of heavy oil and gas was found. Shows of heavy oil, bitumen and gas were encountered in the five wells drilled by the SERP (Syndicat d'Etude et de Recherche du Pétrole) and the Services des Mines. These accumulations were identified on the basis of surface oil seeps but the main problem was that none of them have proven to be commercial.

Clark (1997) divided the past exploration in four activity rounds. The first and the second occurred from 1950 to 1965 and from 1968 to 1975, respectively. The third round started in 1982 and the last round commenced in the early 1990's. The number of wells drilled during each phase is presented in the Table 3.1.

***Table3.1****: Exploration history (Source: Clark, 1997)*

| COMPANY | PHASE/PERIOD | NUMBER OF WELLS |
|---|---|---|
| **Pre-1970** | | |
| SPM (Elf-aquitaine) | 1952-1965 | 40 |
| **Early 1970s** | | |
| AGIP | 1970-1971 | 3 |
| Chevron | 1971-1975 | 7 |
| Conoco | 1971-1972 | 3 |
| COPETMA (CFP/Total) | 1971 | 3 |
| Tenneco | 1973 | 1 |
| **Mid 1980s** | | |
| Amoco | 1984-1990 | 6 |

| | | |
|---|---|---|
| Mobil | 1985 | 1 |
| Occidental | 1986 | 2 |
| Petro Canada/OMNIS | 1987-1990 | 2 |
| **Early 1990s** | | |
| Shell | 1991-1992 | 4 |
| **TOTAL WELLS DRILLED** | | 72 |

From this table, most of the wells were drilled during the first round. From 1952 up to now the company which drilled the highest number of well is the SPM (with 40 drilled wells), then come Chevron (7 wells) and Amoco (6 wells). The possible explanation that enables SPM to drill such number of wells could be the fact that Madagascar was colonized by French and the access to exploration by SPM (French company) was facilitated. After the independence (1960), obtaining exploration permit may have been more difficult for international companies.

## *3.2 - Objectives of past exploration*

It is stated in the BEICIP (1988) report that in Majunga and Morondava basins, the main onshore exploration objective during the three first rounds was the Karoo Group (*Sakoa, Sakamena* and *Isalo* formations). The discovery of the Bemolanga tar sand accumulation and the heavy oil of Tsimiroro field which are found in the Karoo play may also support this objective. Another possible justification of the Karoo exploration was the presence of a thick porous-permeable *Sakamena-Isalo* sandstone sequence deposited throughout the basins, and the widespread presence of the Middle *Sakamena* shale considered as the probable source rock.

Good reservoir units from the Jurassic and Cretaceous plays were not considered as primary objectives. Only few wells such as *Betsimba-1* were drilled to test the Jurassic play. The cretaceous was not really tested, except in west *Manambolo* (1987) which shows a very significant gas flow in the Conician sandstone. It results that, most of the onshore wells were located for the Mesozoic play.

Most of the offshore exploration occurred during the second and third rounds. Eight wells were drilled but the activity was mainly concentrated in 1970-1971 on the Mesozoic and especially on the Cretaceous play which exhibits several thick porous sandstone intervals onshore. The Karoo was estimated to be deeply buried and was not reached. Many of the wells were located on structural highs observed in seismic and generally related to volcanic intrusions of Mid Cretaceous age. Although significant gas shows have been recorded in the Tertiary section (containing reservoirs and seals), this latter was only considered as a secondary objective during these phase and was not really tested.

## 3.3 - Well locations analysis

Exploration did not begin in earnest until the early 1950s. Since then, 72 exploration and appraisal wells have been drilled in Madagascar (Clark, 1997). After 1992, 3 other wells have been drilled, 1 in Majunga basin and 2 in the Morondava basin. Figure 3.6 shows the well locations and hydrocarbon show. The location (onshore/Offshore) and the distribution of drilled wells among the sedimentary basins are presented in the Figures 3.1 to 3.4. According to Figure 3.1 most of the drilled wells (87%) are located onshore and only 9 wells representing (13%) were drilled offshore.

The drilled wells (offshore and onshore combined) distribution among the Malagasy sedimentary basins is shown in Figure 3.2. From this figure, 88% of the total drilled wells in Madagascar were located in Morondava basin. Exploration activity seems to have mainly been focused in the Morondava Basin both onshore and offshore while the Majunga, Ambilobe and Ile Sainte Marie Basins received less attention with respectively 10 %, 1% and 1% of the drilled wells. In fact around 90% of onshore drilled wells in Madagascar (Figure 3.3) are found in the Morondava basin. The offshore wells in Morondava basin represent also 67% of Madagascar's offshore wells (figure 3.4).

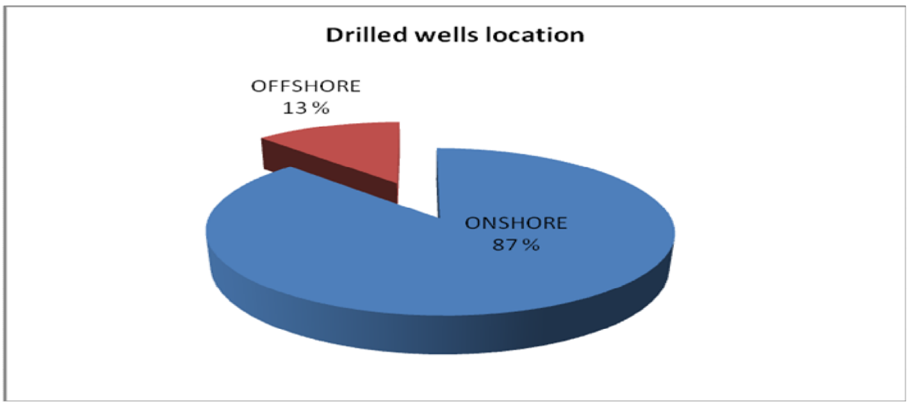


**Figure 3.1**: Drilled wells location in Madagascar

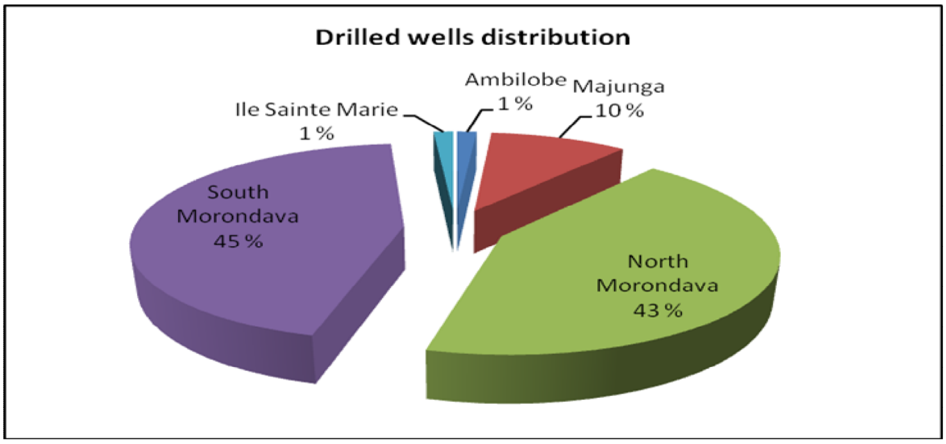


**Figure 3.2:** Drilled wells distribution among Madagascar basins

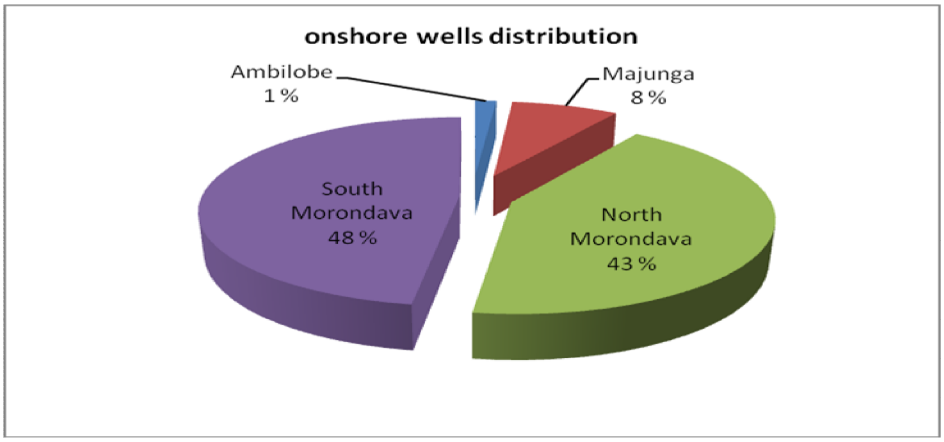


**Figure 3.3**: Onshore drilled wells distribution among the basins

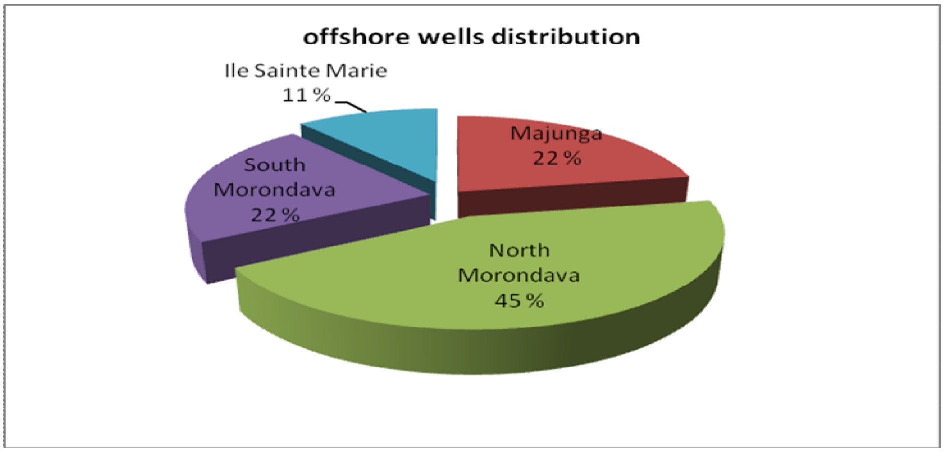


**Figure 3.4**: Offshore drilled wells distribution among the basins

The analysis of the well location during the 4 phases of exploration is given below. Maps representing the well locations during each exploration phase can be found in the appendices III.

### 3.3.1 -The first phase

This phase is comprised between 1952 and 1965 when a total of 40 wells were drilled onshore by the SPM (Société Pétrole de Madagascar). Most of these well were located in the Morondava basin (southern and northern). Only three wells are found in both Majunga and Ambilobe which are: *Ihopy 1(HP-1), Tuilerie-1 (TU-1) and Ambilobe-1(AMB-1).* No discoveries were made but there were a number of encouraging oil and gas shows in some wells (Clark, 1997). The location of the wells was based on poor seismic data or gravity anomalies and a few wells had a stratigraphic purpose (BEICIP, 1988). To test the Karoo reservoirs was the objective but the seismic was poor and did not allow correct well locations. According to Clark (1997), in the Majunga Basin only *Tuilerie-1* seems well located to test a small structure at the Mid Jurassic level. In Morondava Basin only few wells (*Belinta BLT-1, Vohidolo VHD-1, Lambosina LD-1, Ampandramitsetaka FD-1 or Manera ME-1*) appear well located structurally for the Karoo. Except for a few other wells with no data available, all the remaining wells were poorly located. Only Mandabe MDB-1 was located to test the Mesozoic sequence (Mid Jurassic).

### 3.3.2-The second phase

First offshore exploration occurred in this phase which started in 1970 with the Chesterfield-1. Five multi-national oil companies: (AGIP, Chevron, Conoco, COPETMA (CFP/Total) and Tenneco) commence to work in both the onshore and offshore areas of Madagascar. From 1970 to 1975, 16 wells were drilled among which seven were offshore wells (*Chesterfield-1, Eponge-1, Heloise-1, Mahajamba1, Mariarano-1, Morombe-1, and Vaucluse-1*). But, as before, no discoveries were made (Clark, 1997).

### 3.3.3 - The third phase

From the mid-1980s, three companies, Amoco, Mobil and Occidental awarded exploration right. Between 1984 and 1990, these companies drilled eight onshore wells and another offshore well. Petro Canada drilled two onshore wells but again without success (Clark, 1997).

In 1986, Amoco offered to OMNIS the West Manambolo prospect (northern Morondava Basin). Petro Canada International Aid Corporation (PCIAC) financed the project and exploration well was drilled in 1987 by Petro Canada. For the first time in the petroleum exploration in Madagascar, a significant gas discovery was made by this well in the Cretaceous sandstone reservoir. An appraisal well was drilled in 1990 by OMNIS but it was unsuccessful. It was concluded that the field was probably too small for commercial development. The west Manambolo discovery has shown beyond doubt that producible gas can be found in Madagascar. The challenge now is to find larger traps with better Cretaceous reservoir quality.

According to BEICIP (1988) during the second and third phase of onshore exploration, the *Sofia-1* (Majunga basin) well was located on the flank of a Mid-Jurassic structure. In the Morondava Basin the location of the wells drilled was based on seismic fair to good quality. The main objective of these wells was the Karoo, except in *Betsimba-1* and *west Manambola-1* which tested a Mid –Jurassic and a Cretaceous plays respectively. Fifty percent (50%) of the wells can be considered as located structurally for the main objective but in some of them the seal appears insufficient for the Isalo reservoir (*Ambanasa-1* or *Sakaraha-1*).

The offshore well drilled during the second and third phase, were located to test the Mesozoic sequence. Four wells (*Mariarano-1, Morondava-1, Vaucluse-1 and Eponge-1*) were located on top of large Cretaceous structures. The Location of the four other wells is not clearly defined with the data in hand (*Mahajamba-1, Chesterfield-1, Heloise-1, and Morombe-1*). In these wells only the Tertiary contains good reservoir with common gas shows. The Mesozoic reservoirs generally exhibits poor characteristic although sand intervals with gas shows have been found (*Eponge-1, Vaucluse-1, Morondava-1*).

### 3.3.4 - The fourth phase

The most recent phase of exploration took place in the early 1990s when Shell drilled four more onshore exploration wells. One of these wells, *Manandaza-1*, tested light oil from a Lower Sakamena reservoir. An appraisal well (*Manandaza South-1*) was drilled but the well was a dry one and it was concluded that the *Manandaza* discovery was too small to be economic. The *Manandaza-1* discovery is of importance since it is the first accumulation of light oil to be found in what was previously thought to be a heavy oil province (Bemolanga and Tsimiroro accumulations). Valuable information was also obtained with regards to the trapping mechanism and reservoir quality of the so-called Karoo sequence. For the first time the source rock from which the Bemolanga, Tsimiroro and Manandaza oils were derived, was positively identified. As a result of this work, it is now possible to delineate an additional light oil play in the Karoo which has yet to be tested.

One of the most difficult aspects of the exploration in Madagascar has been the almost complete lack of the technical success in finding producible hydrocarbons (Clark, 1997). This is despite the fact that there are many oil seeps at the surface and numerous shows in the subsurface, not to mention the large accumulations of tar and heavy oil at *Bemolanga* and *Tsimiroro*, respectively.

Figure shows the number of wells drilled during each exploration phase.

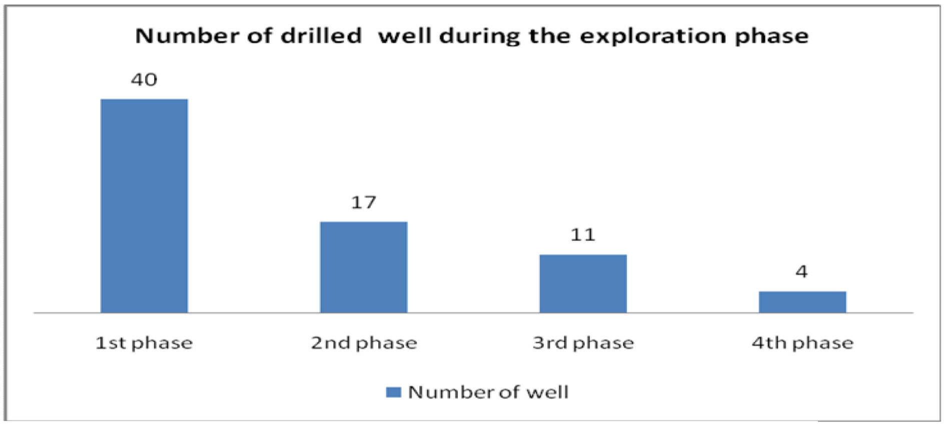


**Figure 3.5**: Number of well drilled during the exploration phase

According to this figure, exploration activities was more intense during the first phase compared to the other phase. The general trend of the exploration activity, in term of number of drilled well, shows a regressive behavior, probably due to difficulty in obtaining exploration permit. Nowadays, in order to reverse this trend, malagasy Government develop new strategy to promote petroleum exploration.

## *3.4- Reviews of seismic data*

Since 1950 to 2005, oil exploration in the Madagascar Basins by several companies has resulted in the following geophysical data (see Table 3.2):

***Table 3.2****: Geophysical data (Source BEICIP, 1988 and OMNIS, 2005)*

| Geophysical data types | Report sources | |
|---|---|---|
| | BEICIP (1988) | OMNIS report (2005) |
| Air magnetism | 170,000 km | 195,000 km |
| Gravity | 54,000 km | 87,000 km |
| 2D seismic | 46,000 km | 71,000 km |
| 3D seismic | - | 3,600 km2 |
| micro-magnetism | - | 11,000 km |
| magnetism | - | 33,000 km |

From this table, the amount of acquired data increased remarkably from 1988 to 2005. This could be explained by the opening of Madagascar petroleum blocks to many International companies and also the will of the Malagasy government to develop petroleum activities.

About the acquired data, BEICIP (1988) stated that numerous seismic surveys predate modern data gathering and processing techniques. Only around 12,000 km recently acquired data are of good quality. In the Majunga basin 1,300 km of good seismic (1983-1985) are available onshore in the *Tuilerie-Sofia* area while offshore around 6,000 km of seismic of fair quality have been acquired since 1976 but shallow water zone remains poorly surveyed. Onshore Morondava, around 6,000 km of seismic of poor to fair quality were shot between 1969 and 1986 while 11,000 km of seismic of good quality were recorded in the last five years. A wide area like the northern Karoo Corridor is not explored by a seismic survey and the western basin, south of *Manja* area, is underexplored with data of poor quality. Offshore Morondava, around 12,000 km of seismic have been shot from 1969 to 1986.

Most of the exploration effort during the first phase, in which 65% of the wells were drilled, was carried out with the support of poor quality seismic data. This seismic generally does not allow a good identification of the top of Karoo play which was the main objective of the exploration during this phase.

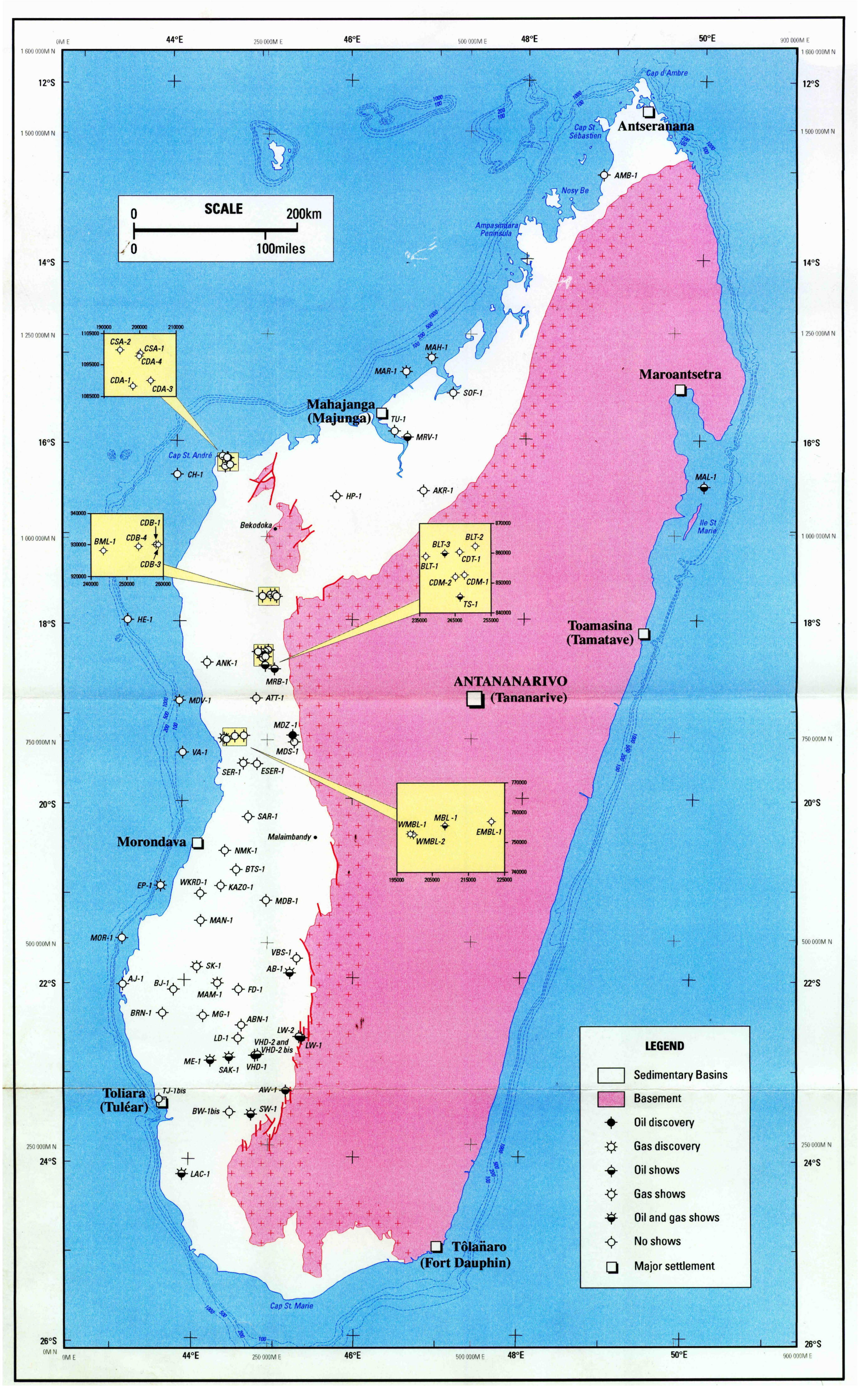


*Figure3.6: well locations, oil and gas shows and discoveries (source, Clark 1997)*

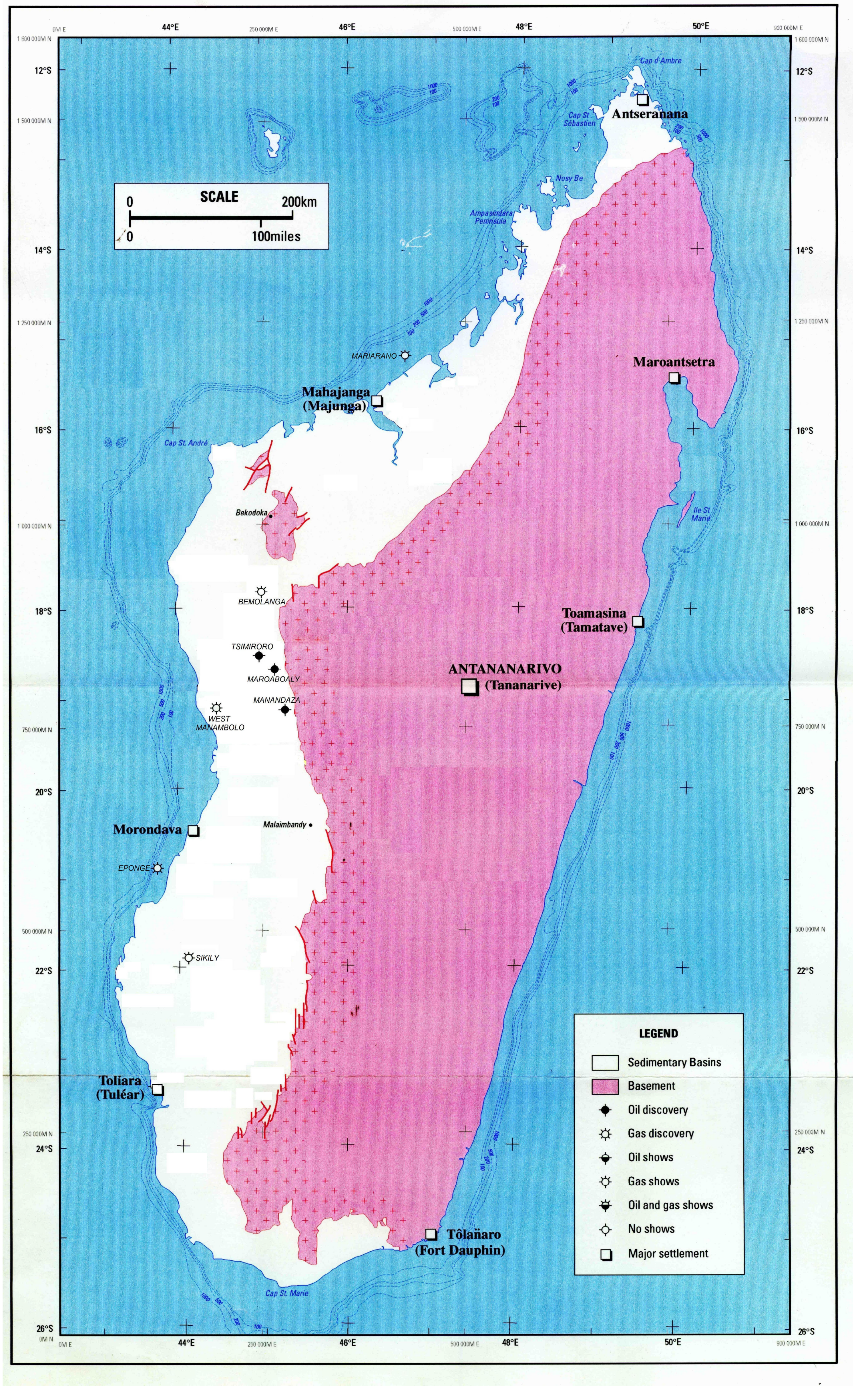


*Figure 3.7: Significant hydrocarbon discoveries of Madagascar (Adapted from Clark)*

### 3.5 - Main reasons of the lack of success in the past exploration

The lack of success is emphasized by the fact that 72 wells were drilled without a commercial discovery. According to Clark (1997), the following reason may explain the lack of success.

The poor quality of original seismic and the prospect cannot be recognized on newer or reprocessed lines. The poor to fair seismic data available during the exploration leads to a poor location of the wells. About 20 well were located structurally and that only about 10 wells exhibit a good combination of reservoir, seal and structure. In spite of this poor result about 68% of well contain oil and gas shows. The location of all the wells was based on present structural features but the timing of structures' formation and hydrocarbon migrations was rarely considered.

The 40 wells from the first petroleum exploration round were drilled prior to the advent of modern seismic techniques in the late 1960s. These wells were located using a combination of surface geology, analogue seismic, gravity and magnetic data and their validity is questionable. Due to difficulty to prove on the available prospect maps, the well results are difficult to assess because the seismic and log data are very primitive compared with modern data.

The limited distribution of source rocks and difference in traps timing are possible reasons suggested by Duey (2007) to explain failures during the past exploration.

To sum up, the lack of success in the past petroleum exploration is caused by the lack or non availability of good data (seismic or other), the possible lack of competent/experienced people among Malagasy authority (in term of data interpretation and petroleum exploration technique) and the lack of detailed research/study about Madagascar geology. Another reason which may have contributed to the lack of success during the past exploration is the indirect commitment of national authority/institution (such as OMNIS) in the petroleum activities and the acquisition of geologic data. Acquisition of seismic depended merely on companies.

Presently, with the new Malagasy mining policy which promote the development of petroleum activities and the opening of Malagasy petroleum blocks to international companies, hopes exist on the future acquisition of very good seismic data and finding of commercial discovery.

## 3.6 - Hydrocarbon shows and discoveries

### 3.6.1-Hydrocarbon shows

According to Clark (1997), hydrocarbons are commonly encountered in Madagascar, both in surface seeps and as subsurface shows in exploration wells. In the vicinity of Bemolanga and Tsimiroro occur the most notable seeps in the northern Morondava Basin. Smaller seeps have also been reported elsewhere. Fifty three (53) shows have been detected in the exploration wells drilled since 1952. From a geographical viewpoint, shows are widespread in the Majunga and Morondava Basins but the stratigraphic distribution is more restricted, with the most of the shows occurring in Cretaceous and Isalo Sandstones. Some shows are also found in the Bemaraha Limestone and the Lower Sakamena Sandstone but they are rarely recorded from the Tertiary.

The shows consist of gas, condensate, live oil and dead oil. The quality and reliability of many of the recorded shows are difficult to show because of a general lack of supporting documents. Many of the gas shows appear to be no more significant than strong background readings. On closer examination many of the so-called oil-shows appear to be dead oil. Shows of live oil occur but even these are of a residual nature in many cases. This is particularly true in the Majunga basin, where Shell re-assessed the oil shows reported from *Tuilerie-1, Sofia-1 and Marovoay-1* (Weimer, 1993). Shell noted that although the oil shows are ”live”, the oil is only found in residual quantities. The shows occur in reservoirs with no valid structural or stratigraphic closure. This, together with the widespread occurrence of shows, suggests that the residual oil owes its existence to an active charge system rather than the destruction of pre-existing traps (Clark, 1997).

### 3.6.2- Hydrocarbon discoveries

Discoveries of hydrocarbons have been found at eight different locations in western Madagascar basin. These discoveries comprise four gas accumulations (*Sikily, Eponge, Mariarano and west Manambolo),* one tar sand deposit at Bemolanga, two heavy oil fields at *Maroaboaly and Tsimiroro* and one accumulation of *light oil at*

*Manandaza*. With the exception of *Mariarano-1*, which is located in the Majunga Basin, all of the discoveries are situated in the Morondava Basin (see figure3.7).Two of the gas discoveries are located offshore, these being *Eponge-1* and *Mariarano-1* (Clark,1997).

According to Clark (1997) the known gas accumulations occur within the Jurassic-Cretaceous passive margin of the western Madagascar. The gas appears to be trapped exclusively in anticlinal structures and these reservoirs are predominantly Cretaceous sandstones. These sandstone reservoirs quality is generally very poor due to compaction or because the sands have a high clay content. Both wet gas and dry gas have been encountered and condensate is also possibly present at *West Manambolo*.

In contrast, oil accumulations have been found so far only in the Failed Permo-Triassic Rift Complex of the Morondava Basin. The oil is trapped in anticlinal structures that associate with tilted fault blocks. The reservoirs consist either of *Isalo* Sandstone or Lower *Sakamena* Sandstone. The productivity of these reservoirs is thought to be very low. The surface deposits at Bemolanga comprise tar, whereas the shallow subsurface accumulation at Tsimiroro consists of heavy oil and the deeper accumulation at Manandaza is much lighter oil. The range of gravity of the oils is thought to be the result of progressive biodegradation with uplift and exposure.

## *3.7-Current situation*

The contract type applied to all exploration block is the so-called Production Sharing Agreement between the oil companies and the OMNIS. The total number of petroleum blocks is three hundred sixty seven (367) among which twenty (20) is located onshore and three hundred forty seven or 94% of the total blocks are offshore (347). In 2008, there are one hundred sixty five (165) open blocks. Figure 3.8 represents the block status in 2005. Today, all the onshore blocks are all granted as shown in Figure 3.10 but many of the offshore blocks remain opened especially in the southern part of Morondava basin.

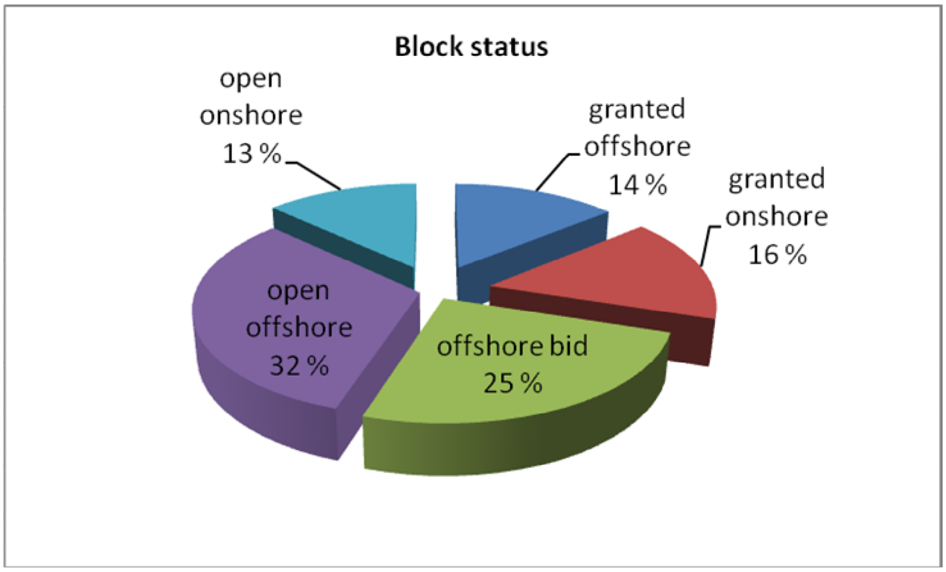


**Figure 3.8:** Madagascar petroleum blocks' status (source OMNIS 2005 report)

The figure 3.9 represents the petroleum blocks distribution which confirms the fact that the number of offshore blocks is more important compared to the onshore.

The figure 3.10 shows the block distribution and the associated companies. From this figure, on the twenty onshore blocks, the company Madagascar Oil Sarl obtained eight blocks (40% of the total blocks), Essar Energy Holding occupies 3 blocks (15% of the total blocks), the others companies owns one block each (EAX Exploration, Madagascar Northern Petroleum Company, Wilton Petroleum Energy, Madagascar Petroleum Energy, Amicoh Corporation, Tullow oil, Madagascar International Company, Madagascar Southern Petroleum Company, Petromad). The offshore blocks exploration is marked by the Presence of Exxon Mobil and Sterling Energy in the Majunga-Ambilobe basins and Enermad and Rock oil in the Morondava basin.

Based on past discoveries location, the company which hold the most interesting onshore block is Madagascar Oil. The Bemolanga, Tsimiroro, Manandaza and West Manambolo are found in the block that this company granted. Rabe (2008) gives further detailed about Madagascar Oil Company and its exploration activities in Bemolanga and Tsimiroro field. He concluded that the activities performed by Madagascar Oil company in Tsimiroro block is in midst exploration phase. Rabe (2008) reported also that the reserve in place in Tsimiroro remains unknown. He also added that Madagascar oil company does not have the fund to concurrently undertake the development of Tsimiroro and Bemolanga.

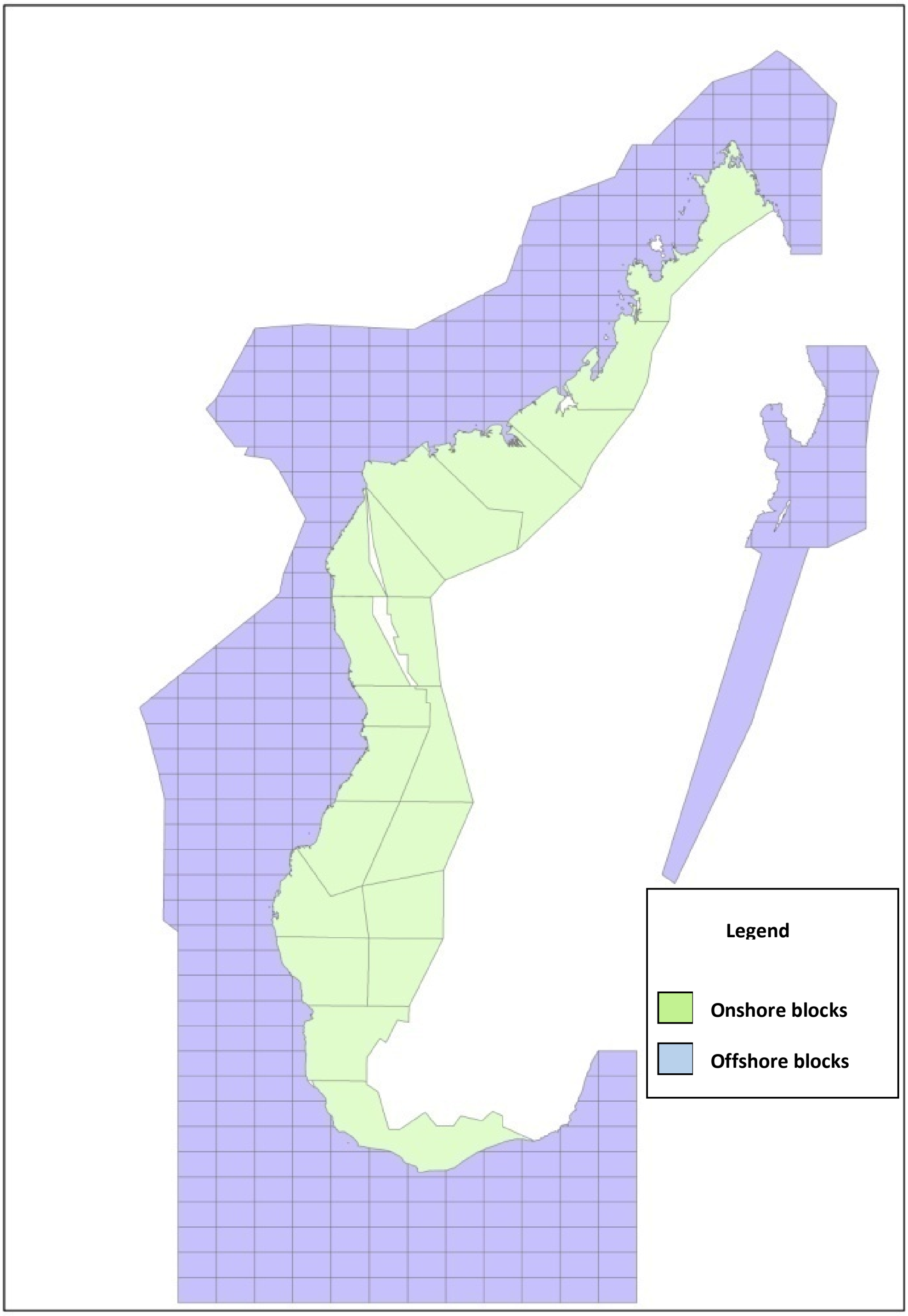


**Figure 3.9:** Petroleum blocks of Madagascar (source: OMNIS)

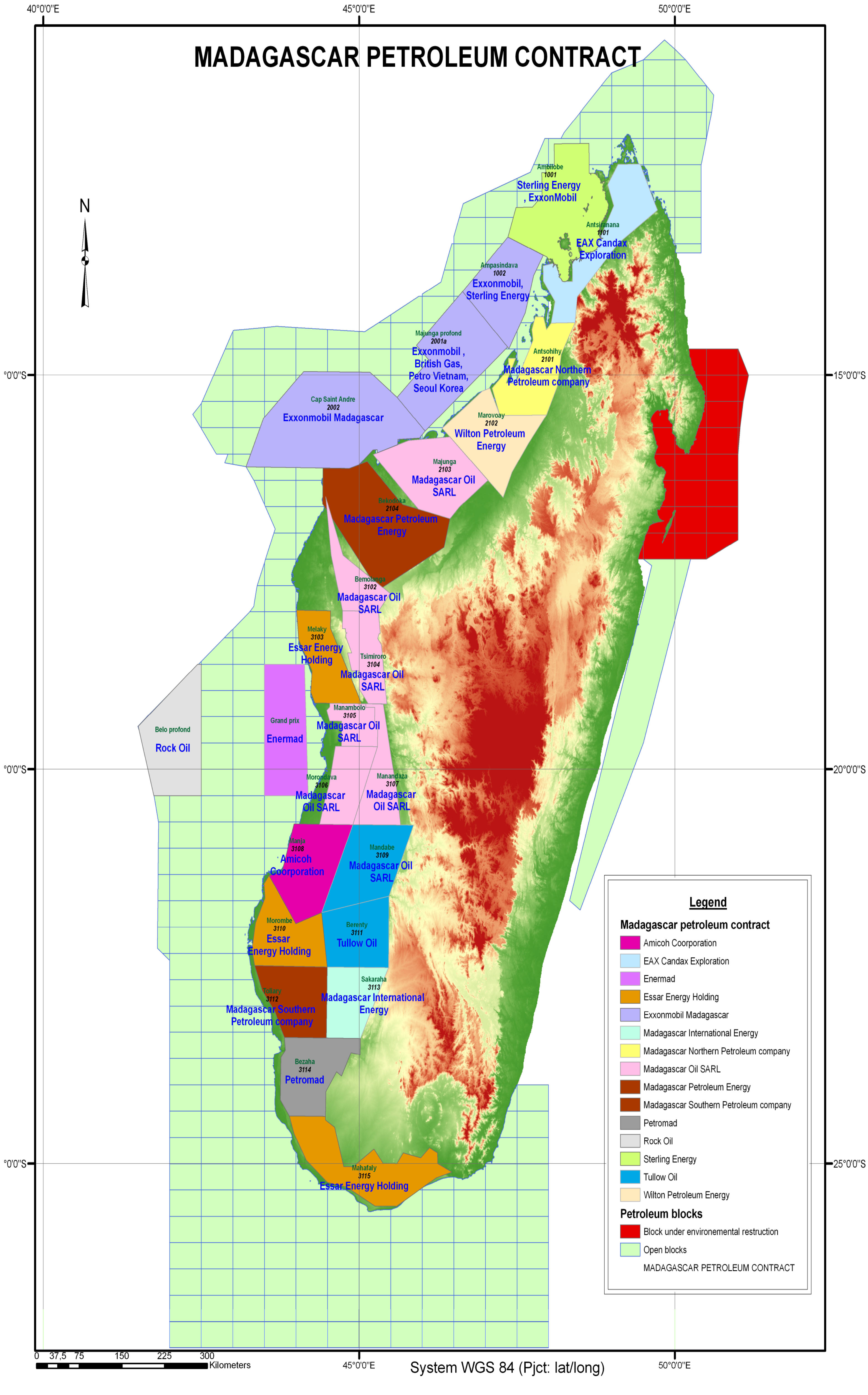


**Figure 3.10**: Madagascar petroleum contracts (Source: OMNIS)

The block names and the exploring companies are presented in the table below:

***Table 3.3**: Blocks and exploring Companies(source OMNIS)*

| BASIN | | Block Name | Exploring Companies |
|---|---|---|---|
| Majunga-Ambilobe | Offshore | Ambilobe | Sterling Energy, Exxon Mobil |
| | | Ampasindava | Sterling Energy, Exxon Mobil |
| | | Majunga Profond | Exxon Mobil, British Gas, Petro Vietnam, Seoul Korea |
| | | Cap Saint André | Exxon Mobil Madagascar |
| | Onshore | Antsiranana | EAX Candax Exploration |
| | | Antsohihy | Madagascar Northern Petroleum Company |
| | | Marovoay | Wilton Petroleum Energy |
| | | Majunga | Madagascar Oil SARL |
| | | Belobaka | Madagascar Petroleum Energy |
| Morondava | Offshore | Belo profond | Rock Oil |
| | | Grand Prix | Enermad |
| | Onshore | Bemolanga, Tsimiroro, Manambolo,Morondava, Manandaza, Mandabe, | Madagascar Oil SARL |
| | | Melaky, Morombe, Mahafaly | Essar Energy Holding |
| | | Manja | Amicoh Corporation |
| | | Berenty | Tullow Oil |
| | | Toliary | Madagascar Southern Petroleum Company |
| | | Sakaraha | Madagascar International energy |
| | | Bezaha | Petromad |

## 3.8-Future themes of exploration

Past exploration in Madagascar was merely based on poor seismic leading to only few discoveries. Reprocessing of acquired data may be necessary in some part of the sedimentary basin. Since the past exploration activities occurred mostly onshore, the future exploration could be focused on offshore exploration. Based on past exploration result, the following theme can be proposed:

-For the Morondava basin, explorations may concern the offshore Jurassic play which comprises the famous Tsimiroro and Bemolanga accumulation onshore. Another interesting offshore exploration theme would be the exploration of the Permian to which belongs the Manandaza light oil Morondava. Apart from these two themes, exploration of the Liassic to Jurassic (where Sikily discovery occurred) can also be undertaken. The southernmost part of Morondava may be an interesting theme of exploration. No well have been drilled so far in this part of sedimentary basin.

-For the Majunga Basin, future exploration could be focus on Jurassic offshore play where bitumen was found (*Ankaramamy* -1) in shallow zone. Onshore, Permian to Triassic play may be an interesting theme since interesting reservoir rock and possible source rocks were identified in the past exploration (BEICIP, 1988) but poorly tested.

# IV-ENVIRONMENTAL ISSUES RELATED TO PETROLEUM ACTIVITIES

Since the 1990’s, Malagasy governments started to emphasis the environmental protection by the adoption of the environment charter. Madagascar participated to the Durban Conference on the environment (2003). After this conference, the Government challenge to multiply by three the area of protected areas in the island. Nowadays, there are 143 protected areas in Madagascar. They are composed of four types : National park, extension of National park, New protected areas and protected areas with temporary status. These protected areas occupy an area of 7 140 000 hectares. The Figure 4.1 illustrates the distribution of the four categories of protected areas in Madagascar. The next Figure (4.2) shows the distribution of the protected areas and the petroleum blocks. It appears that protected areas are located in most of the onshore blocks. Environmental protection becomes an important issue with regards to exploration especially within these protected areas.

Various legislations (national and international) exist and are applied in Madagascar with regard to environmental protection. Responsible institutions (such as ONE, OLEP, OMNIS) have been created to ensure the protection of environment in relation with the industrial and mining activities.

The description of regulations for the environmental management and evaluation, and the responsible institutions can be found in SOGREAH report (2008).

## *4.1 - Regulation for the environmental management and evaluation*

### 4.1.1- Charter of the environment

The reference text of the law of the modern Malagasy environment is the “Charte de l’Environnement Malagasy” (CEM) or Charter of the Malagasy Environment, adopted in 1990 (CEM-Law No. 2004-015 of 19 August 2004 amending and supplementing certain provisions of the annex to the law No. 90-033 of 21 December 1990 Charter of the Malagasy environment and the law n ° 97-012 of June 1997). The charter recognizes the environment as a priority concern in the general interest of the State, and the duty and the right of everyone to protect it. The charter recognizes also the right of everyone to be informed of decisions likely to exert some influences on the environment and participate in decisions.

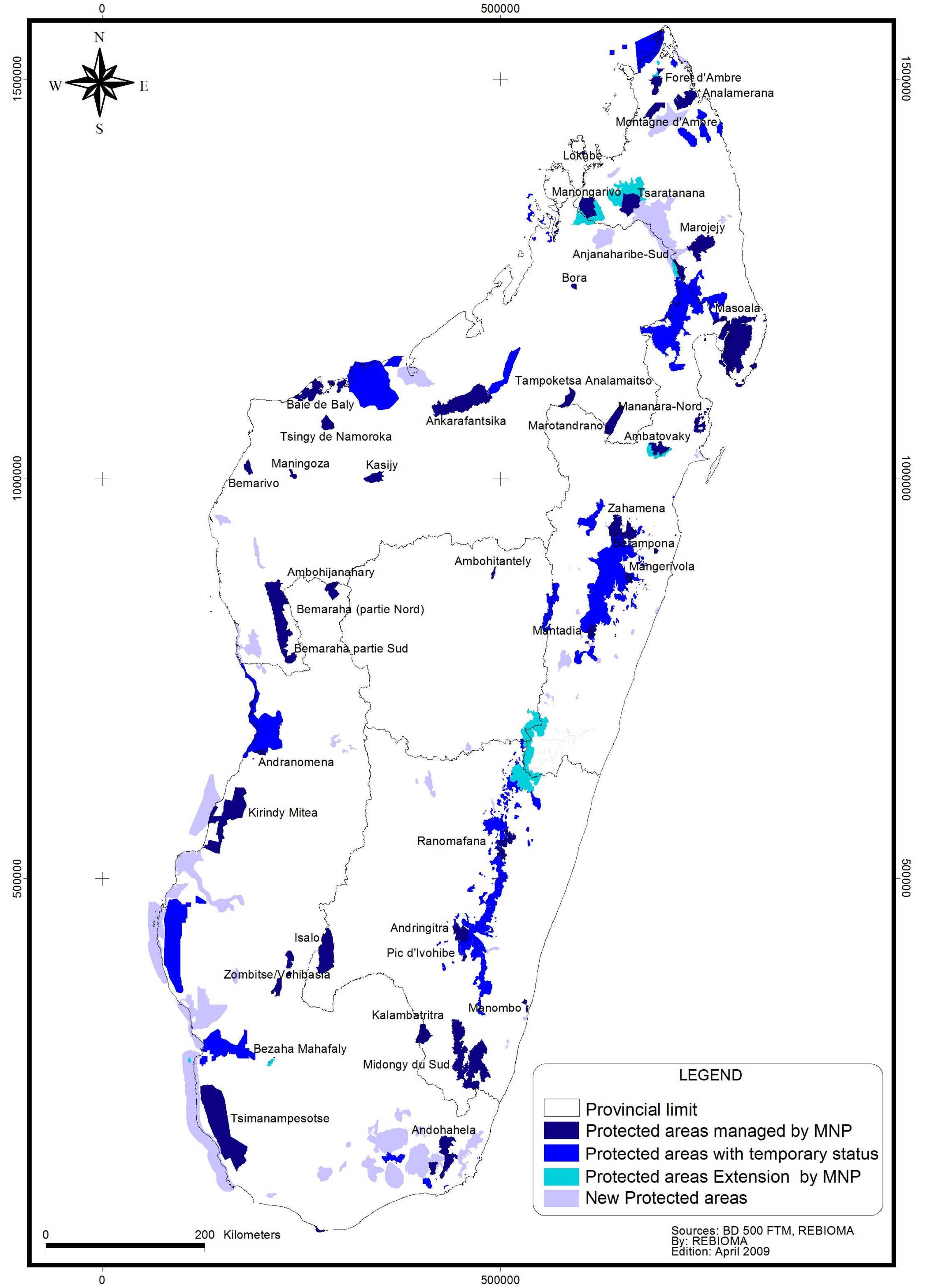


**Figure 4.1**: Distribution of protected areas in Madagascar

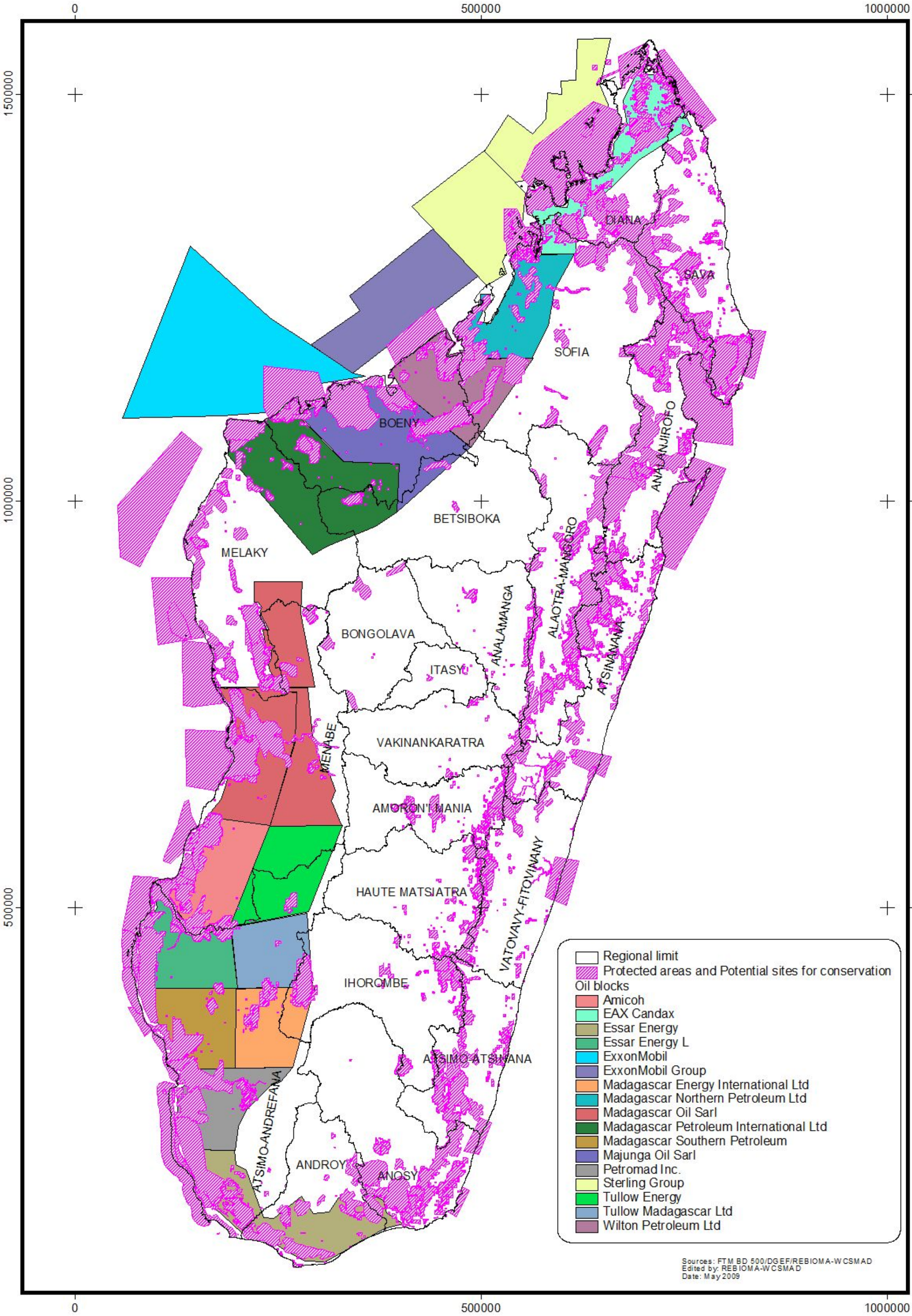


**Figure 4.2**: Petroleum blocks and protected areas distribution (Source: Rebioma, 2009)

The CEM sets out general principles and main lines of the National Environmental Policy. It defines the operational implementation by exposing the Environmental Action Plan (EAP) based on the implementation of priority projects, "Program Environment" (PE). It also establishes the creation of the institutional framework related to the constitutional and administrative authority in the country. It is therefore a strategic and planning document. The CEM has a number of major application decrees, including that of investments' compliance with the environment as well as the submission of bond operators to compensation or payments of penalties for activities which have adverse impacts to the environment.

#### 4.1.2 - MECIE Decree

Decree No. 99-954 (December 1999) establishes the rules and procedures to follow in order to achieve the investment compatibility with the environment or "Mise en Compatibilté des Investissements avec l'environnement" (MECIE). It specifies the nature, the respective responsibilities and the degree of authority of the institutions or bodies authorized for that purpose (Article 1). Decree No. 2004 - 167 of 03 February 2004 amends some provisions of MECIE Decree: changes aim to simplify the tasks related environmental impact and to maintain the role of the ONE (Office National de l'Environnement) as main and only responsible regarding the MECIE decree.

MECIE decree gives a large place to the obligations of investors for the implementation of a new development / project via the conduct of an Environmental Impact Assessment (EIA) process. The following articles of MECIE must be noted:

- *Article 6 of Decree No. 2004-167*, drilling operations cannot commence before the delivery of an environmental permit issued by the ONE, after a favorable evaluation of the impact assessment file, based on the advice of the Technical Evaluation Committee which is responsible of the evaluation
- *Article 4* specifies that an Environmental Management Plan of the Project (or Plan de Gestion Environnemental du Projet-PGEP) will be the environmental specifications of the project. This is a program for implementation and monitoring of measures envisaged by the EIA to remove, reduce and offset the potentially damaging consequences of the project on the environment. The ONE in collaboration with ministries is responsible for suggesting the limit values and environmental reference standards. Furthermore, it contributes to the development of technical and environmental guideline for each type of activity. It also provides the monitoring and

evaluation of the applicability of standards and procedures established for each sector concerned by the compliance of investments with the environment.

About the acceptable thresholds for the emission or concentration of elements that a recipient can accept, the norms advocated by international organizations affiliated with the United Nations can serve as a reference standard where national standards do not exist or are lacking. Decree MECIE establishes a link between the shortcomings of national and international standards

According to MECIE decree the following projects must be subject to EIA:

- exploration of oil or natural gas using seismic method and / or drilling
- extraction and / or transportation via pipeline of oil or natural gas
- extraction and industrial use of land or coal coke
- establishment of crude oil refinery, gasification and liquefaction with a capacity of more than 20 000 barrels oil equivalent / day
- offshore implantation
- extraction of minerals Bituminous over 500 m3/day
- storage of petroleum products and derivatives or natural gas with a combined capacity of more than 25 000 m3 or 25 million liters.

The drilling project is therefore subjected to an EIA because they fall into the category of arrangements and works. However, their technical nature, magnitude and sensitivity of the receiving environment, may have detrimental consequences on the environment.

#### 4.1.3 - Public consultation

In Madagascar, the Order No. 68307-2001 determine the methods and procedures for a public participation in environmental assessment, pursuant to the provisions of MECIE decree (Article 15 to 21, 24, 25 and 27). The essential elements of this text highlighted:

-Public participation in environmental assessment aims to inform the public about the project and gather opinions on this. It is either made on-site consultation of documents, either by public inquiry, either by public hearing. It shall include information on the project and a consultation phase. During this phase, there shall be a compilation of opinions of the public concerned by the project.

- The decision on the form of public participation in the evaluation is provided by ONE to the project sponsor at least 15 days prior to the assessment by the public. As an indication, the decision criteria are:

- On-site consultation documents may be required when the investment of the project is less than 2 billion MGA, or when the number of the population at the location, where the project will be implanted, is less than 10 000 people

- The public inquiry may be required when the investment is more than 2 billion MGA, or when the number of the population of the project is over 10 000 persons

- The public hearing may be required for projects demanding displacement of more than 500 people.

### 4.1.4 - Management and control of industrial pollution

*a- Law:*

The Law 99-021 (July 1999) defines the general framework of a policy of rational management and control of industrial pollution. It concerns the management of liquid effluents, solid waste, and atmospheric pollution. The law provides procedures for the inspection of industrial facilities.

*b- Emission standards*

- *Liquid effluents*: the water code was enacted as Low No. 98-029 in January 1999. It describes the general framework within which any operation of the water resource must be part. However it focuses on surface water and continental groundwater, and does not apply to marine waters. Its application decree (Decree No. 2003-943 on discharges into surface waters, and the decree n ° 2003-464 classifying surface water setting standards of water's effluent discharge), concern only polluting activities affecting inland waters

- *Floors*: Madagascar does not have such a law on the polluted sites and soils. The research for a responsible for a contaminated site remediation has its legal basis in the regulations related to establishment/place classified for the environmental protection in the Law 99-021 on the management and control of industrial pollution.

Thus, under Article 99 and Article 101, the operator of an industrial establishment which threatens the health, safety, public health, is required to stop, by all appropriate measures to this situation.

- *Air*: legislation setting the threshold values for discharges into the atmosphere does not exist.

### 4.1.5 - Sectorial texts

*a - Petroleum Code*

It has been established in 1996.It is a key law that governs all activities related to exploration, research, exploitation, processing and transport of hydrocarbons in the national mining sector in Madagascar. It also defines the administrative and technical procedures necessary for oil companies wishing to work in Madagascar. Articles on environmental protection are also included in this legislation (particularly Articles 15 and 34 which stipulate the responsibilities of the mine operators with respect to the environment)

*b - Maritime Code*

Established in 2000, it governs the administration, trade disputes and territorial waters of Madagascar. Chapter 10 of Book I of the first part of the Maritime Code describes measures for the protection and preservation of the environment. Section 1.10.04 on dumping of waste is particularly relevant with regard to the environment (for offshore activities). The article state the following:"The Malagasy State shall adopt laws and regulations to prevent, reduce and control pollution of the marine environment by dumping waste. The dumping of waste in the territorial sea and exclusive economic zone or continental shelf cannot take place without the express prior approval of the Malagasy State”

*c -Codes of Protected Areas*

This law had been established in 2001. It governs the creation and management of existing and future protected areas in Madagascar. The ANGAP (Association Nationale pour la Gestion des Aires protégées) or the Madagascar National Parks was then created to manage the network of protected areas. Their main function is the preservation of the environment but this can also include socio-economic development of coastal populations, development of ecotourism and research. The Code of Protected Areas was originally created for terrestrial protected areas, but today it also regulates the marine protected areas.

## *4.2 - International Conventions*

Madagascar has signed a number of multilateral agreements in the field of the environment, many of which concern the protection of biodiversity and the marine environment.

### 4.2.1 - Biodiversity

Relevant Conventions in regard of the environmental analysis of drilling activity are:

- *Ramsar (1971)* - Convention on Wetlands of International Importance especially as waterfowl habitats. Ratified by Law 98-003 (February 1998)
- *CBD-Rio (1992)* - Convention on Biological Diversity. Ratified by Law 95-013 (August 1995)
- *Nairobi (1985*) - Convention on the protection, management and development of marine and coastal areas of East Africa. Ratified by Law 98-004 (February 1998)
- *CMS-Bonn (1979)* Convention on the Conservation of Migratory Species of Wild Animals. Signed but not ratified
- *UNCLOS-Montego Bay (1982)* - United Nations Convention on the Law of the Sea Ratified by Law 2000-20 (November 2000)

### 4.2.2 - Marine pollution

Madagascar has not signed the London (1972) on the Prevention of Marine Pollution by dumping of waste. However, in the field of prevention of marine pollution related to oil, the country has ratified the two most stringent conventions:

-The *MARPOL Convention (1973/1978)* which is the main international convention aiming the prevention of pollution by ships of the marine environment. Ratified in November 2004 by Act 2004-37

-The *1990 International Convention on Oil Pollution Preparedness, Response and Cooperation* (OPRC Convention 90). Ratified in November 2001 by Low 2001-011

-*CLC-1992 - International Convention on Civil Liability for Oil Pollution* (persistent hydrocarbon). Ratified in 2001 by low 2001-012

-*IOPCF-92* - International Convention on the creation of an International Fund for Compensation of Oil Pollution

## *4.3 - RESPONSIBLE INSTITUTIONS*

### 4.2.1- OMNIS:

It is a governmental agency mandated to promote the development of petroleum resources in Madagascar. Pursuant to decree 96-133 as amended by Decree Law 99-033 and 99-697, the OMNIS is responsible in the mining field to valorize geological data and assume the function of the office for the mining promotion. In the hydrocarbons sector, the Office provides the implementation of the national policy on mining and oil exploration. With regard to the environment, OMNIS is member of EIA Technical evaluation committee.

### 4.2.2 -ONE:

This institution was created by decree 90-066 of 20 September 1990, after the promulgation of the Charter of the Environment in 1990. It is a public administrative institution under the Ministry of Environment and Waters and Forests. It is the executive body of the policy of environmental management. During the two first environmental programs, ONE was called to be a coordination body. During the PEIII (2007), two lines of activities are assigned to the ONE:

- development and management of MECIE system, management and prevention of pollution;
- management, production and distribution of environmental information, dashboards and tools environmental education and communication
- conduct of the environmental assessment process is overseen by the ONE which plays the role of:
    - Coordination and participation in the elaboration of the TORs (term of reference) of the EIA
    - Reception of EIA documents , examination and issuance of the notice of eligibility
    - Proposal to the Technical Evaluation Committee, participation in the Committee as Secretary
    - Delivery of the environmental permit

- Coordination and participation in control and monitoring of PGEP (Project's management plan) and review of the audit report in the framework of an environmental audit

#### 4.2.3-OLEP (Organe de Lutte contre l'Evènement de Pollution marine par les hydrocarbures) or coast guard:

It was established by decree 2004-994 of 26 October 2004 and placed under the authority of the Ministry of the Environment. Its mission is the preparation and coordination of operations against the event of pollution in marine and coastal environment. The role of OLEP is:

- develop, implement and update the fighting's plans in the marine and coastal environment of Madagascar
- coordinate and control fighting's operations
- organize the simulation exercises
- organize training courses (internal or external) for stakeholders involved in the fighting plans.

#### 4.2.4 - Mining Environment Unit within the Ministry of Mine:

It plays the role of interface between the mining operators and the environmental administration. It answers all questions of the operators concerning the interpretation of the regulation applicable to the mining sector with regard to the environmental protection, the evaluation of their EIA (as a member of Technical Evaluation Committee), the control of their PGEP and the procedures related to the environmental.

# Conclusion and outlook

Madagascar geology is formed by a central basement rock and three major sedimentary basins located in the western coast (Ambilobe, Majunga and Morondava). A small basin has been formed also in the east coast, the Sainte Marie basin. Nine deposition sequences occurred in the western sedimentary basins. They led to the current geological formation and their structural style. Several plays are found in Morondava and Majunga basins. Those two basins are by far the most explored basins in Madagascar. The most attractive plays with regard to hydrocarbon potential the Jurassic and Permian – Triassic for Morondava. In contrast the cretaceous play is the most interesting in Majunga basin.

Two major source rocks were identified among the Malagasy sedimentary basins: the limestone and shale. However, sandstone and limestone constitute the major types of reservoir rocks. They are mainly found in the western sedimentary basin. Furthermore, they present good features: the Isalo II sandstone (forming the Bemolanga and Tsimiroro reservoir), the Sakamena sandstone constituting the Manandaza light oil reservoir and the Cretaceous sandstone. Many trapping mechanism are found in the western sedimentary basin. The most abundant type is the normal fault.

Petroleum exploration activities started in early 1900's in Madagascar with oil seeps discovery. Since then, the petroleum exploration in Madagascar can be subdivided in four phases. During the first phase (from 1950 to 1965) intense exploration activities initiated by SPM occurred. The second phase marked the entry of multinational company in Madagascar. It took place from 1968 to 1975. The third round started in 1982 and the last round begun in the early 1990's. Until now, exploration activities were merely focused onshore with 87% of the total drilled wells. Morondava basin is by far the most explored basin.

The petroleum explorations in Madagascar were marked by lack of success until recent time. The possible explanations are probably the bad seismic quality used during the past explorations, the failure on well positioning and the lack of knowledge about Madagascar geology. Nevertheless, shows and discoveries were found in some wells.

Most of the shows were located in Cretaceous basin and in Isalo sandstones. Gas accumulations have been found within the Jurassic-Cretaceous passive margin. They were trapped in anticlinal structures. While Oil accumulations have been found only in the Failed Permo-Triasic rift complex of the Morondava Basin. The oil was trapped in anticlinal structures that are draped over tilted fault blocks. The reservoirs consist either of Isalo Sandstone or Lower Sakamena Sandstone.

In Madagascar, discoveries of hydrocarbon were identified in eight locations: the light oil accumulation in *Manandaza*, the heavy oil in *Maroaboaly* and *Tsimiroro*, the tar sand of *Bemolanga* and the gas in *Sikily, Eponge, Mariarano and west Manambolo*. They are situated in the Morondava Basin except *Mariarano-1* which is located in the Majunga Basin.

Today Madagascar has 367 petroleum blocks among which twenty are located onshore and are granted now. Madagascar Oil Sarl Company holds the most interesting blocks where most of the past discoveries occurred. Future theme of exploration will focus offshore of Jurassic play of Majunga and Morondava.

With the development of petroleum exploration activities, the environmental issues become very important for Madagascar. Besides, many protected area are located in the onshore petroleum blocks. Legislations (national and international) were established and are applied in Madagascar such as the petroleum code, the Malagasy environment charter and the MECIEE decree. And to assist Madagascar to well manage its petroleum resources, Institutional collaboration between NPD-Norway and OMNIS-Madagascar has been signed in 2007. The objective is to transfer the Norwegian competences in petroleum activities management into Malagasy institutions.

To terminate this thesis, the following recommendations are proposed:

- Implication of national authority (such as OMNIS and ONE) in exploration activities (field work). OMNIS gets most of their exploration data from the exploration company reports. It would be more beneficial for OMNIS and Madagascar to have Malagasy agent performing field works along with the companies. Both reports (from the exploring Company and from OMNIS agent) could then be compared to maximize data reliability.

- Reevaluation of doubtful acquired data can also be performed with the help of consultants. The obtained data can then be used more efficiently in well location

-Creation of unique seismic data base and reliable storage equipments. All the seismic data from the past should be gathered in one place to facilitate their exploitation and their management. Digitization of old data (Maps, logging, figures) could be also performed to ensure their safety and management.

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## *Appendices I: Analysis of wells drilled since 1970*

| Spud date | Well | Well code | Operator | Basin | Play | Reason for failure | Classification |
|---|---|---|---|---|---|---|---|
| 1970 | Chesterfield-1 | CH-1 | AGIP | North Morondava | Cretaceous, Isalo and Sakamena ? | Closure probably mapped on dolerite | Igneous anomaly |
| 1971 | Ankamotra-1 | ANK-1 | Conoco | North Morondava | Isalo | Incorrectly mapped tilted fault block with no structural closure | No closure |
| 1971 | Eponge-1 | EP-1 | COPETMA | South Morondava | Cretaceous | Small gas accumulation. Cretaceous sandstone reservoirs are impermeable. Closure also difficult to verify on old seismic data but good gas shows suggest that a trap is develop in the Cretaceous | Cretaceous anticline |
| 1971 | Heloise | HE-1 | COPETMA | North Morondava | Tertiary-Isalo | Mapped structure is a volcanic cone, with no closure in overlying sediment. No reservoir rocks encountered | Igneous anomaly |
| 1971 | Mahajamba-1 | MAH-1 | AGIP | Majunga | Tertiary | Thin gas pay with high water saturation in Eocene carbonate. No significant gas reserves | Katsepe anticline |

## *Appendices I: Analysis of wells drilled since 1970*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1971 | Mariarano-1 | MAR-1 | AGIP | Majunga | Cretaceous, Bemaraha, Isalo and Sakamena | Thin, non-commercial gas pay discovered in the Eocene but no potential reservoirs encountered at deeper levels. Questionable structural closure. Isalo and Sakamena not reached | Katsepe anticline? |
| 1971 | Morombe-1 | MOR-1 | Chevron | South Morondava | Cretaceous | Expected carbonate build-up found to be a buried Turonian volcano | Igneous anomaly |
| 1971 | Serinam-1 | SER-1 | Conoco | North Morondava | Isalo | Isalo reservoir found to be tight. Top Isalo map of Conoco corresponds to top Bemaraha. Thus closure probably does not exist at top Isalo level | No closure |
| 1971 | Vaucluse-1 | VA-1 | COPETMA | North Morondava | Cretaceous? | Anticlinal closure found to be a buried Turonian volcano | Igneous anomaly |
| 1972 | Sofia-1 | SOF-1 | Conoco | Majunga | Cretaceous, Bemaraha and Isalo | Original prospect was a dip-closed structure but subsequent re-interpretation suggests that no closure exists. Alternatively, the trap may be dependent on fault closure, with questionable up-dip fault seal. Isalo not reached | No closure? |

## *Appendices I: Analysis of wells drilled since 1970*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1973 | Ile Sainte Marie 1 | MAL-1 | Tenneco | Ile Sainte Marie | Tertiary and Cretaceous ? | Structured mapped on basement high according to final well report. Anticlinal feature is evident on seismic but seals are lacking | Tertiary anticline |
| 1973 | Mamakiala-1 | MAM-1 | Chevron | South Morondava | Mixed facies (Middle Jurassic) | Incorrect depositional Model using so-called *Faces Mixte* concept. Massive limestones encountered instead of interbedded sandstones and shales | Invalid reservoir concept |
| 1974 | East Serinam-1 | ESER-1 | Chevron | North Morondava | Bemaraha and Isalo | Predicted Bemaraha carbonate build-up id not present because of an incorrect depositional model. Impermeable slope mudstones found instead. Isalo is also impermeable and structural closure is lacking at this level | Invalid reservoir concept |
| 1974 | Lac-1 | LAC-1 | Chevron | South Morondava | Isalo | Structure poorly defined on seismic and no closure shown on Chevron's prospect map | No closure |
| 1974 | Sakaraha-1 | SAK-1 | Chevron | South Morondava | Sakamena | Impermeable reservoir sandstones in Upper and Lower Sakamena | Tilted fault block |
| 1974 | Tsimiroro-1 | TS-1 | Chevron | North | Isalo | Biodegradable oil, too heavy for | Appraisal of |

## *Appendices I: Analysis of wells drilled since 1970*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Moronda va | | commercial development | Tsimiroro heavy oil accumulation |
| 1975 | West Kirindy-1 | WKRD-1 | Chevron | South Moronda va | Cretaceous and Jurassic | Good reservoirs encountered nut structural closure is doubtful | No closure? |
| 1984 | Namakia-1 | NMK-1 | Amoco | South Moronda va | Isalo | Isalo reservoir found to be tight. Top Isalo map of Amoco corresponds to top Bemaraha. Thus closure probably does not exist at top Isalo level | No closure |
| 1985 | Antaotao-1 | ATT-1 | Amoco | North Moronda va | Isalo and Upper Sakamena | Trap probably lacking because structure seen on seismic appears to be a dolerite intrusion | Igneous anomaly |
| 1985 | Manambolo-1 | MBL-1 | Amoco | North Moronda va | Isalo | Reservoir quality of the Isalo is very poor | Tilted fault block |
| 1985 | Morondava-1 | MDV-1 | Mobil | North Moronda va | Isalo | Objective not reached and no reservoirs present in the Cretaceous and jurassic | Objective not reached |
| 1985 | Saronanala-1 | SAR-1 | Amoco | South Moronda va | Callovian | Expected carbonate build-up found to be a diorite intrusion | Igneous anomaly |

## *Appendices I: Analysis of wells drilled since 1970*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1986 | Ambanasa-1 | ABN-1 | Occidental | South Morondava | Sakamena | No seal present above the Upper Sakamena sandstones | Sakamena anticline |
| 1986 | Betsimba-1 | BTS-1 | Amoco | South Morondava | Mixed facies (Middle Jurassic) | Incorrect depositional model using so-called “Facies Mixte” concept. Massive limestones encountered instead of interbedded sandstones and shales | Invalid reservoir concept |
| 1986 | Vohibasia-1 | VBS-1 | Occidental | South Morondava | Lower Sakamena | Strong oil shows. Lower Sakamena reservoir found to be tight. Up-dip fault seal also questionable | Tilted fault block |
| 1987 | West Manambolo-1 | WMBL-1 | Petro Canada | North Morondava | Cretaceous | Small gas accumulation with poor reservoir quality. Expected turbidite mound not found. Dip-closed anticline more likely than predicted stratigraphic trap | Cretaceous anticline |
| 1990 | East Manambolo-1 | EMBL-1 | Amoco | North Morondava | Cretaceous stratigraphic trap | Expected stratigraphic closure lacking because of an incorrect depositional model. Reservoir flushed with Meteoric water indicating that up-dip seal is absent | Invalid trapping mechanism |

## *Appendices I: Analysis of wells drilled since 1970*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1991 | Manandaza-1 | MDZ-1 | Shell | North Morondava | Isalo and Sakamena | Small oil accumulation within very limited dip closure. Poor lower Sakamena reservoir quality and low productivity. Up-dip fault seal ineffective | Tilted fault block |
| 1992 | Ankara-1 | AKR-1 | Shell | Majunga | Upper Sakamena | No top seal beneath the base Isalo unconformity and up-dip seal | Tilted fault block |
| 1992 | Marovoay-1 | MRV-1 | Shell | Majunga | Isalo and Sakamena | Isalo reservoir found to be impermeable. Incorrect structural concept. Dip-closed anticline predicted at Isalo level but re-evaluation suggest tilted fault block with no up-dip seal against bounding fault | Tilted fault block |
| 1993 | Manandaza south-1 | MDS-1 | Shell | North Morondava | Isalo and Sakamena | Middle Sakamena sandstone wedge not found. Outside of dip closure at Lower Sakamena level. Lower Sakamena sandstone impermeable as in MDZ-1 | Appraisal of MDZ-1<br>Oil discovery |
| 1993 | West Manambolo-2 | WMBL-2 | OMNIS | North Morondava | Cretaceous | Poor quality reservoir sandstones, probably outside of the area of dip-closure mapped around WMBL-1 | Appraisal of WMBL-1 gas discovery |

***Appendices I: Analysis of wells drilled since 1970***

## *Appendices II: Block status and drilled well names and distribution*

Bloc status(Source Omnis report, 2005)

| | granted offshore | granted onshore | offshore bid | open offshore | open onshore | Total |
|---|---|---|---|---|---|---|
| Number | 51 | 59 | 92 | 117 | 48 | 367 |
| Percentage | 14 | 16 | 25 | 32 | 13 | 100 |

Well distribution(source: Clark, 1997)

| BASIN | NUMBER OF WELLS | | |
|---|---|---|---|
| | ONSHORE | OFFSHORE | Total |
| Ambilobe | 1 | 0 | 1 |
| Majunga | 5 | 2 | 7 |
| North Morondava | 27 | 4 | 31 |
| South Morondava | 30 | 2 | 32 |
| Ile Sainte Marie | 0 | 1 | 1 |
| Total | 63 | 9 | 72 |

## Exploration well names and codes (source OMNIS)

| Spud date | Well | Well code | Operator | Basin |
|---|---|---|---|---|
| 1951 | Bezaha-1 Bis | BW-1Bis | SPM | Morondava South |
| 1952 | Saloanivo-1 | SW-1 | SPM | Morondava South |
| 1953 | Leoposa west-1 | LW-1 | SPM | Morondava South |
| 1953 | Leoposa west-2 | LW-2 | SPM | Morondava South |
| 1953 | Antsokay west-1 | AW-1 | SPM | Morondava South |
| 1954 | Sikily | SK-1 | SPM | South Morondava |
| 1955 | Ambalabe | AB-1 | SPM | Morondava South |
| 1955 | Ampandriamitsetaka | FD-1 | SPM | Morondava South |
| 1956 | Lambosina | LD-1 | SPM | Morondava South |
| 1956 | Ambatolahy | MG-1 | SPM | Morondava South |

## *Appendices II: Block status and drilled well names and distribution*

| | | | | |
|---|---|---|---|---|
| 1956 | Andavadoaka | AJ-1 | SPM | South Morondava |
| 1957 | Tulear-1Bis | TJ-1 | SPM | South Morondava |
| 1957 | Befandriana-1 | BJ-1 | SPM | South Morondava |
| 1957 | Beravy-1 | BRN-1 | SPM | South Morondava |
| 1957 | Manera-1 | ME-1 | SPM | South Morondava |
| 1957 | Manja-1 | MAN-1 | SPM | South Morondava |
| 1958 | Vohidolo-1 | VHD-1 | SPM | South Morondava |
| 1958 | Ankazofotsy | KAZO-1 | SPM | South Morondava |
| 1958 | Mandabe-1 | MDB-1 | SPM | South Morondava |
| 1959 | Bemolanga CD-1 | CDB-1 | SPM | North Morondava |
| 1959 | Bemolanga CD-3 | CDB-3 | SPM | North Morondava |
| 1959 | Bemolanga CD-4 | CDB-4 | SPM | North Morondava |
| 1959 | Tsimiroro CD-1 | CDT-1 | SPM | North Morondava |
| 1959 | Maromokony CD-1 | CDM-1 | SPM | North Morondava |
| 1959 | Maromokony CD-2 | CDM-2 | SPM | North Morondava |
| 1959 | Cap St André CD-1 | CDA-1 | SPM | North Morondava |
| 1959 | Cap St André CD-3 | CDA-3 | SPM | North Morondava |
| 1959 | Cap St André CD-4 | CDA-4 | SPM | North Morondava |
| 1959 | Vohidolo-2 | VHD-2 | SPM | South Morondava |
| 1959 | Belinta-1 | BLT-1 | SPM | North Morondava |
| 1959 | Bemolanga-1 | BML-1 | SPM | North Morondava |
| 1959 | Vohidolo-2Bis | VHD-2Bis | SPM | South Morondava |
| 1959 | Belinta-2 | BLT-2 | SPM | North Morondava |
| 1959 | Belinta-3 | BLT-3 | SPM | North Morondava |
| 1960 | Maroaboaly | MRB-1 | SPM | North Morondava |

## *Appendices II: Block status and drilled well names and distribution*

| | | | | |
|---|---|---|---|---|
| 1960 | Cap St André-1 | CSA-1 | SPM | North Morondava |
| 1960 | Cap St André-2 | CSA-2 | SPM | North Morondava |
| 1963 | Ihopy-1 | HP-1 | SPM | Majunga |
| 1963 | Ambilobe-1 | AMB-1 | SPM | Ambilobe |
| 1965 | Tuilerie | TU-1 | SPM | Majunga |
| 1970 | Chesterfield-1 | CH-1 | AGIP | North Morondava |
| 1971 | Ankamotra-1 | ANK-1 | Conoco | North Morondava |
| 1971 | Eponge-1 | EP-1 | COPETMA | South Morondava |
| 1971 | Heloise | HE-1 | COPETMA | North Morondava |
| 1971 | Mahajamba-1 | MAH-1 | AGIP | Majunga |
| 1971 | Mariarano-1 | MAR-1 | AGIP | Majunga |
| 1971 | Morombe-1 | MOR-1 | Chevron | South Morondava |
| 1971 | Serinam-1 | SER-1 | Conoco | North Morondava |
| 1971 | Vaucluse-1 | VA-1 | COPETMA | North Morondava |
| 1972 | Sofia-1 | SOF-1 | Conoco | Majunga |
| 1973 | Ile Sainte Marie 1 | MAL-1 | Tenneco | Ile Sainte Marie |
| 1973 | Mamakiala-1 | MAM-1 | Chevron | South Morondava |
| 1974 | East Serinam-1 | ESER-1 | Chevron | North Morondava |
| 1974 | Lac-1 | LAC-1 | Chevron | South Morondava |
| 1974 | Sakaraha-1 | SAK-1 | Chevron | South Morondava |
| 1974 | Tsimiroro-1 | TS-1 | Chevron | North Morondava |
| 1975 | West Kirindy-1 | WKRD-1 | Chevron | South Morondava |
| 1984 | Namakia-1 | NMK-1 | Amoco | South Morondava |
| 1985 | Antaotao-1 | ATT-1 | Amoco | North Morondava |
| 1985 | Manambolo-1 | MBL-1 | Amoco | North Morondava |
| 1985 | Morondava-1 | MDV-1 | Mobil | North Morondava |
| 1985 | Saronanala-1 | SAR-1 | Amoco | South Morondava |
| 1986 | Ambanasa-1 | ABN-1 | Occidental | South Morondava |

## *Appendices II: Block status and drilled well names and distribution*

| | | | | |
|---|---|---|---|---|
| 1986 | Betsimba-1 | BTS-1 | Amoco | South Morondava |
| 1986 | Vohibasia-1 | VBS-1 | Occidenta l | South Morondava |
| 1987 | West Manambolo-1 | WMBL-1 | Petro Canada | North Morondava |
| 1990 | East Manambolo-1 | EMBL-1 | Amoco | North Morondava |
| 1991 | Manandaza-1 | MDZ-1 | Shell | North Morondava |
| 1992 | Ankara-1 | AKR-1 | Shell | Majunga |
| 1992 | Marovoay-1 | MRV-1 | Shell | Majunga |
| 1993 | Manandaza south-1 | MDS-1 | Shell | North Morondava |
| 1993 | West Manambolo-2 | WMBL-2 | OMNIS | North Morondava |

# AppendicesIII: Petroleun exploration phases (Madagascar)

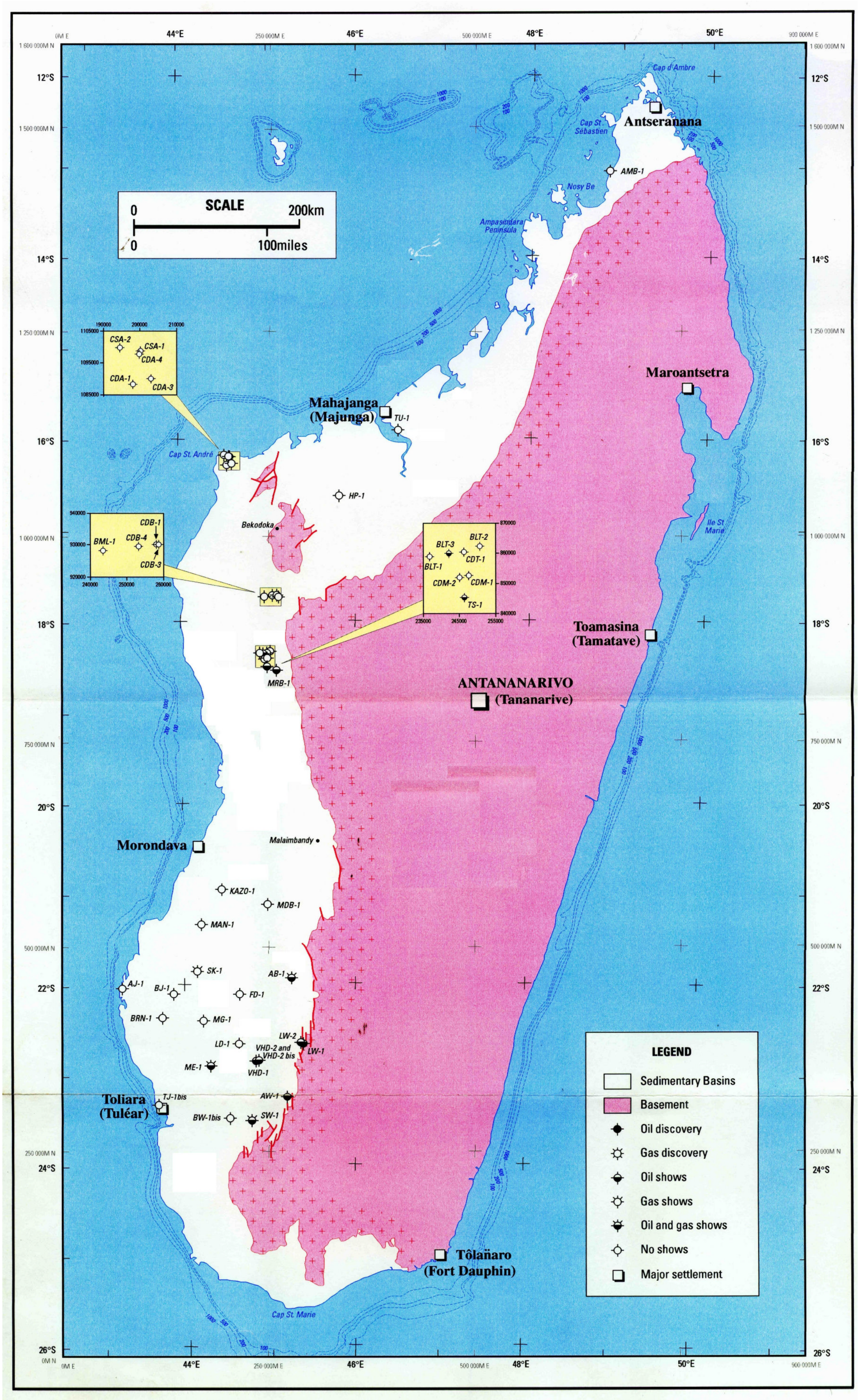


*Figure I: First round of petroleum exploration*

## *AppendicesIII: Petroleun exploration phases (Madagascar)*

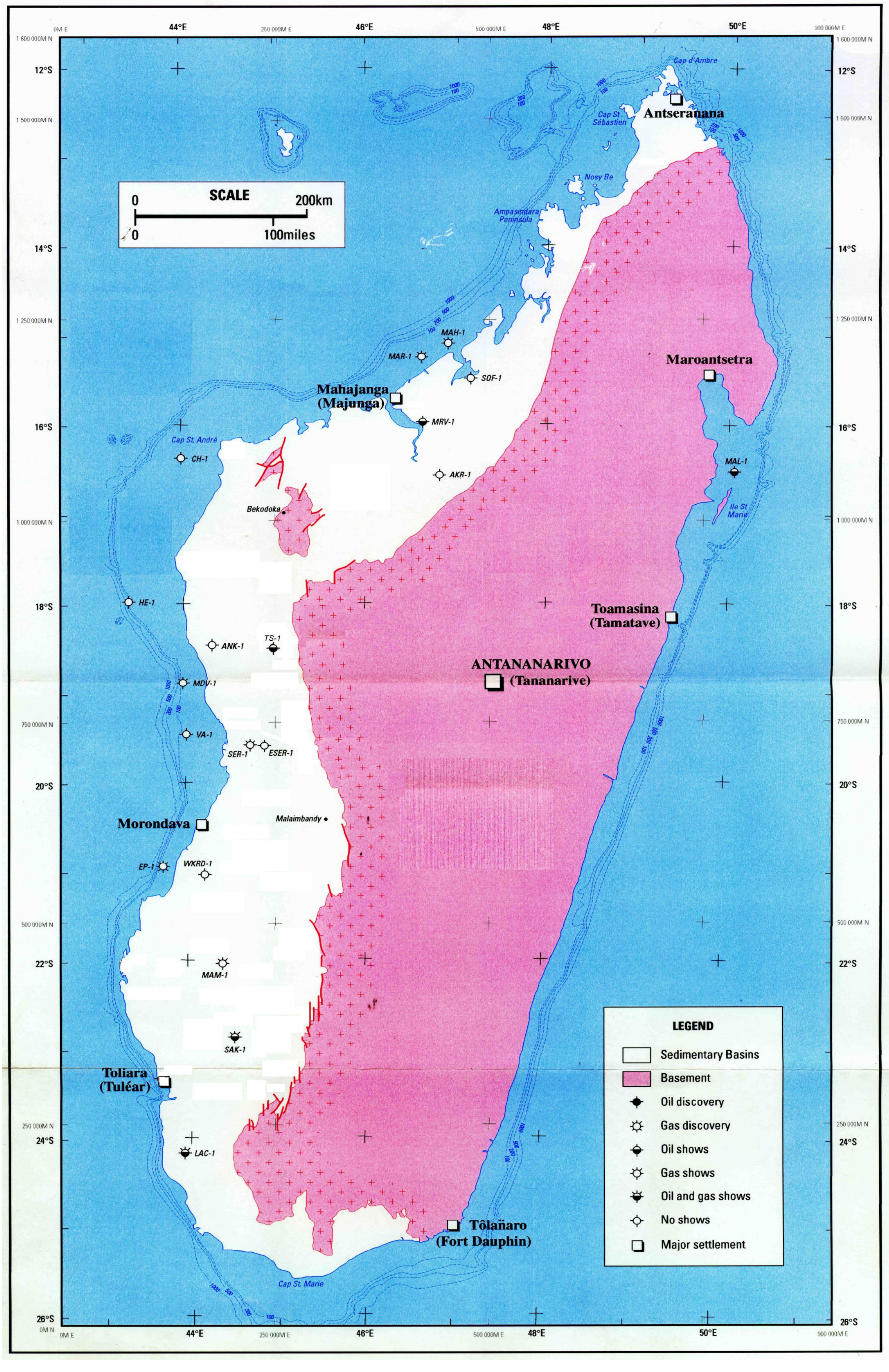


Figure II: 2nd round of exploration phase

# *AppendicesIII: Petroleun exploration phases (Madagascar)*

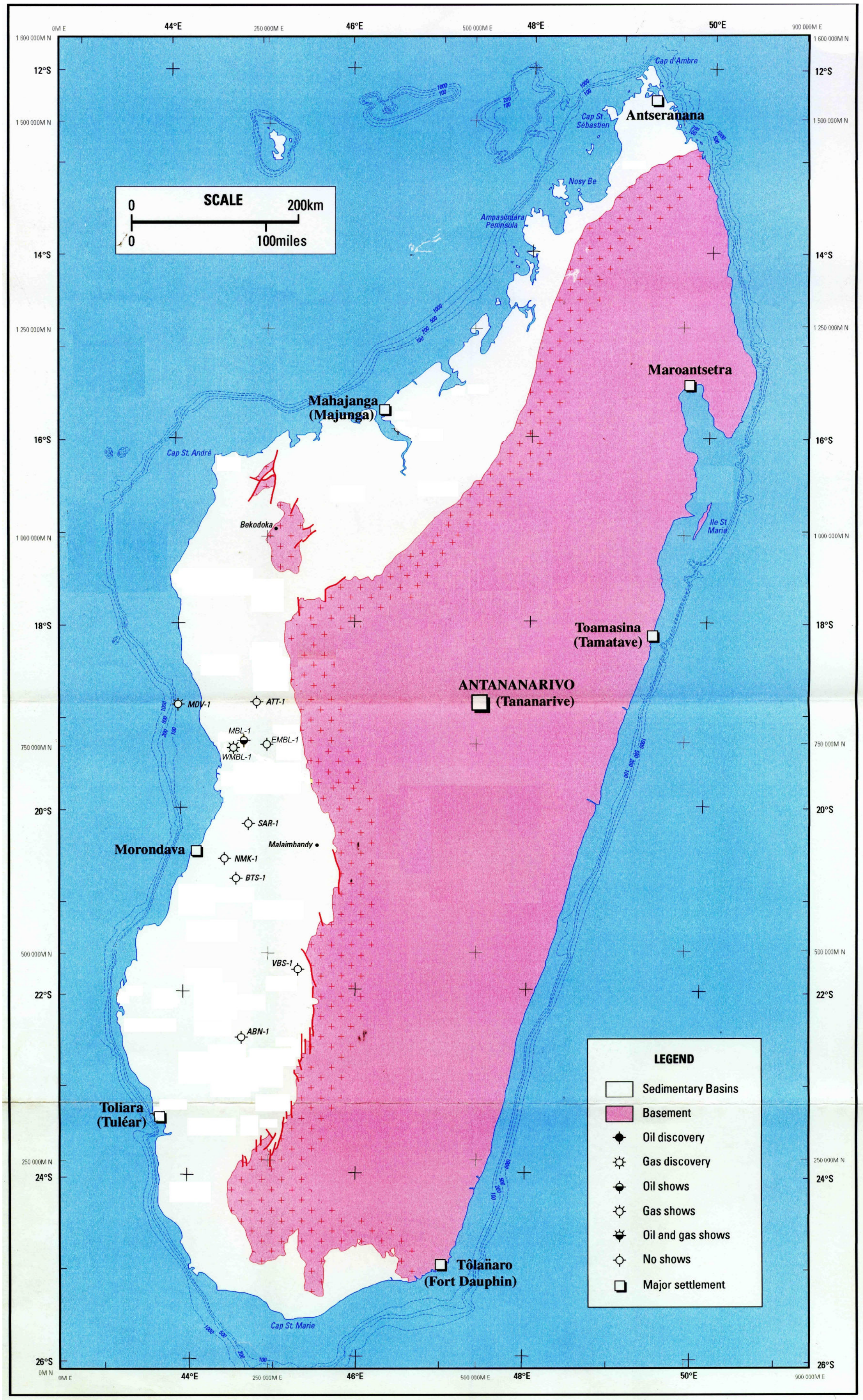


Figure III: 3rd round of exploration phase

## *AppendicesIII: Petroleun exploration phases (Madagascar)*

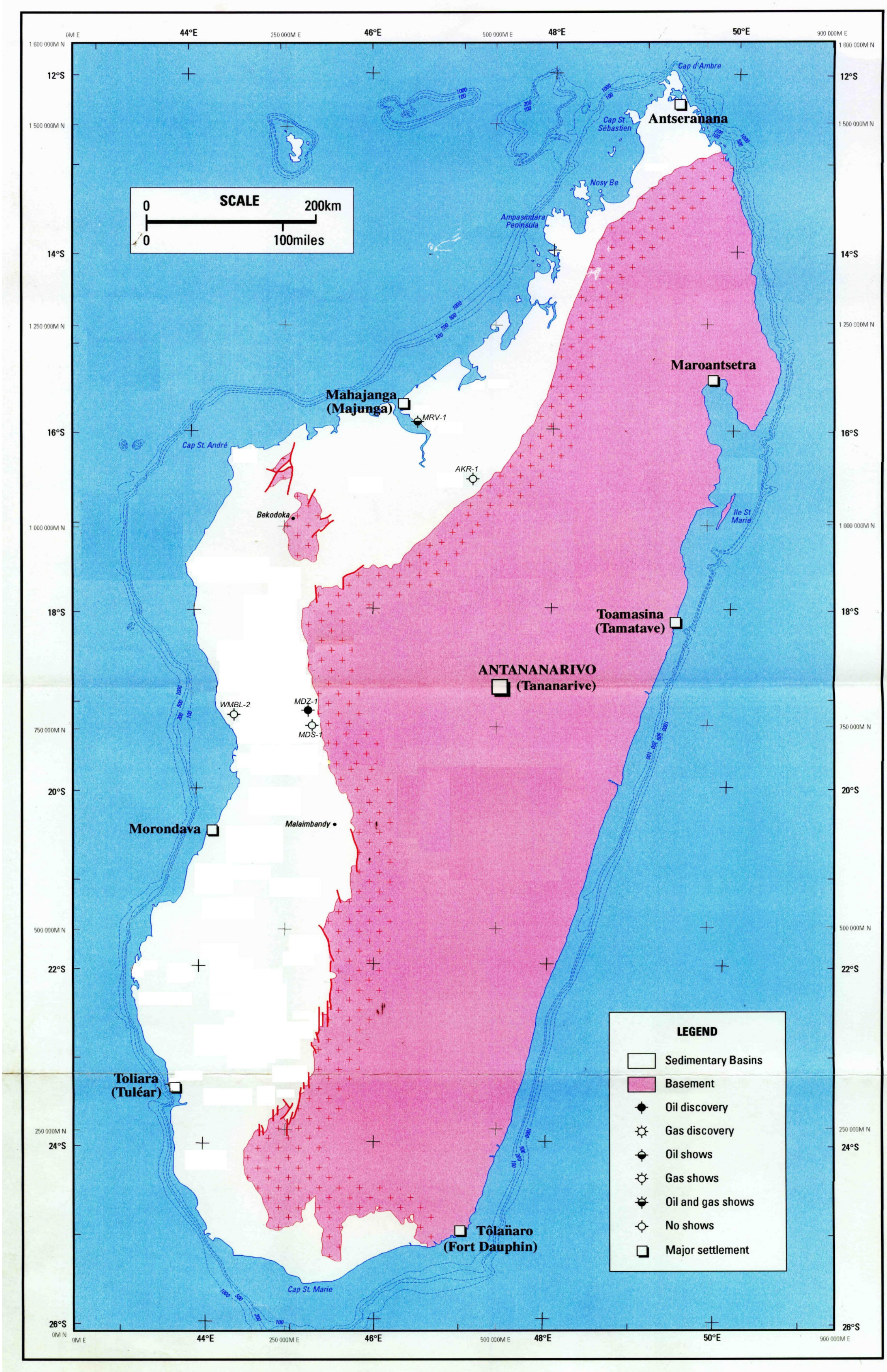


Figure IV: 4th round of exploration phase