Frontier exploration offshore the Zambezi Delta, Mozambique

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The Republic of Mozambique is located on the southeast coast of Africa. Hydrocarbon discoveries to the north in Kenya and Tanzania prove the potential of East Africa, and there are significant onshore and offshore exploration opportunities along large prospective passive margin areas of the Indian Ocean. Following many years of civil war and political instability, Mozambique is becoming more open for hydrocarbon exploration. Recent natural gas discoveries in the offshore Rovuma Basin by operators including Anadarko and Eni highlight the enormous potential of the country. The authors have interpreted more than 55,000 km of 2D seismic data from offshore Mozambique. Gravity data is also available. This article focuses on 35,000 km of seismic data from the Zambezi Delta and investigates if proven successful trends in the north continue into this area, which will provide significant opportunities as much of the area is becoming available for licensing.

The Zambezi Delta is a tidal and wave dominated delta mix comparable to the Nile and Orinoco river deltas, although smaller. The Zambezi River has a drainage area of 1,400,000 km² (Hori et al., 2007; Walford et al., 2005). The Delta covers an area of 200,000 km² and has a sedimentary thickness of approximately 4 km according to Walford et al. (2005), who also state that its deposition has been almost continuous throughout Cenozoic times.

Exploration is currently mostly guided by the play concept, in which the focus is on where the hydrocarbons are found, accumulated and produced from – reservoir and trap. However, the industry perception is changing and the holistic approach of the petroleum system (Magoon and Dow, 1994) is replacing or complementing the play concept by incorporating the existence of an active source rock as a co-equal element next to reservoir, seal, and trap – governed by the timing of these elements. This study starts the process of utilizing the petroleum systems concept and shows how it can be incorporated in a frontier exploration environment.

Mozambique exploration history

Hydrocarbon exploration in Mozambique began in 1904 but for a long time there was no significant success. There was little activity until 1948, when an increase in exploration resulted in the discovery of the Pande gas field by Gulf Oil in 1961 (Figure 1). The Buzi and Temane onshore gas discoveries followed in 1962 and 1967 respectively with a combined potential of 5.5 tcf. By 2011, 141 wells (81 wildcat, 34 appraisal, 24 production, 2 injection) had been drilled (INP, 2012). Following the country’s second licence round, deepwater gas discoveries were made between 2010 and 2012 in the Rovuma Basin, including the Barquentine and Mamba fields (in Areas 1 and 4 of Figure 1) operated by Anadarko and ENI, with estimated potential of 150 tcf, confirming the region as a prolific gas province.

Structural framework

The structural geology of Mozambique is framed by a series of rifts in the Karoo sequence, which represents a wide age range from Carboniferous to Jurassic. The Jurassic rifts are important for the offshore petroleum systems. They mark the breakup of Gondwanaland linked to a mantle plume that gave rise to extensive uplift and volcanic activity centred on the Limpopo Triple Junction (Burke and Dewey, 1973) (Figure 2). Mantle plumes are a matter of interesting scientific debate that goes beyond the scope of this project.

The Karoo dykes and flood basalts date to around 180 Ma. The Limpopo dyke swarm formed at this time along the edge of the Kaapval Craton, the western limit of the study area. To the east of the study area an important transform formed along what is now the Davie fracture zone. Movement during the Early to Middle Jurassic started with crustal thinning and extension. Later, oceanic crust filled the gap as Antarctica moved south. Leinweber and Jokat (2012) report that the earliest oceanic crust predates the M33 magnetic anomaly marker of 159 Ma. The early phase of rifting 180-160 Ma will be important for the development of source rocks. Reconstruction of the continents prior to the breakup of Gondwanaland shows that Mozambique adjoins Dronning Maud Land, Antarctica (Jokat et al., 2003). Further research is required to explain two apparent anomalies in the detail of plate reconstruction. Firstly, Kerwanveggen, Antarctica overlaps the Mozambique plains. Second is the formation of the Mozambique ridge that extends to the south (Leinweber and Jokat 2011).

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Regional geology and stratigraphy

Sedimentary basins in Mozambique occupy an area of more than 500,000 km² of which 225,000 km² are offshore (Mathews et al., 2001). The two major basins – Ruvuma and Mozambique – are examples of passive continental margin basins formed along the eastern African margin. The geology varies from north to south delineated by a Karoo and a Post-Karoo rock sequence. Karoo outcrops from the Zambezi Valley and Mozambique Belt in the north show an eastward change in facies with increased clay content and the appearance of carbonates (Nairn et al., 1991). The offshore southern Mozambique Basin is mainly composed of Mesozoic and Cenozoic sediments dominated by extensional horst and graben structures. This part of the basin exhibits a transition from continental clastics to marine sediments from NW to SE due to global sea level changes. Figure 3 shows local stratigraphy for the northern Mozambique Basin (Zambezi Delta offshore) correlated with major seismic horizons.

Understanding the depositional systems

Depositional variations are observed between the pre-rift, syn-rift (Karoo Group) (Salman and Abdula, 1995) and post-rift section (Post-Karoo) offshore Mozambique. Worldwide, passive margin sedimentary deposition varies from basin to basin due to the evolutionary mechanism. Based on industry observations, Levell et al. (2010) list nine play types: deltaic depocentres (major and smaller); slope by-pass systems; carbonate platforms and their margins; deepwater fold belts;
arctic margins; deep water far-outboard; and syn-rift and pre-rift sections. Some of these plays exist throughout the offshore Zambezi Delta. Previous authors report continental, shallow marine, carbonates, deep-water, and deltaic systems (Rusk et al., 2002; Salman and Abdula, 1995; Nairn et al., 1991). Due to the complex tectonic history in the area, we also predict further important variations in the sedimentary sequence. However, these plays focus on reservoir and trap type rather than a complete petroleum system.

Building the 3D model
Figure 4 shows 2D seismic surveys and well locations overlaid on a map of Bouguer-corrected gravity offshore Zambezi Delta. The study area is bounded by the white dotted line. The investigation included four vintages of seismic data acquisition: SM81 (1981), GMC-GMR81 (1981), WG98 (1998), and WG99 (1999). The GMC81 survey was reprocessed in 1998. Reprocessing of the WG98 and WG99 surveys was completed in 2012. Approximately 35,000 km of time-migrated seismic data was interpreted to build a 3D model and improve the understanding of the development of the Zambezi Delta Depression (ZDD) over the Beira High and the Outer Beira High. The interpretation also incorporated free air gravity and Bouguer-corrected gravity processed by ARKeX in 2012. Hot colours (red and orange) in the gravity data were interpreted as basement highs and cold colours (blues) as basement lows with thick sediments. Wells in the area are all located on the shallow shelf. Well reports, checkshots, and logs used in the investigation were available for Nemo-1 (total depth (TD) 4122.8 m), Zambezi-1 (TD 4654 m), Zambezi-3 (TD 4306.2 m) and ZD-E-1 (TD 3220 m). Seven horizons were mapped, ranging from the Karoo-Belo up to the Tertiary-Quaternary. Figure 5 is an example interpreted seismic section over the Outer Beira High and Eastern flank of the Beira High. Figure 6 is an example interpreted seismic section over the ZDD. Figure 7 shows the seven interpreted 3D horizons.
Figure 4 Map of 2D seismic lines and well locations overlain on Bouguer adjusted gravity. The study area is bounded by the white dotted line.

Figure 5 Example interpreted seismic section from outer Beira High and eastern flank of the Beira High.

Figure 6 Example interpreted seismic section from Zambezi Delta Depression.
Basement and Mid Jurassic Karoo-Belo

There are thick sedimentary sequences in the ZDD, extending deeper than the record length of the available seismic data in the area. Horizons dip towards the central ZDD and onlap against the Beira high. In the central part of the ZDD some amplitude anomalies are found in the upper part of the section. They appear to be concentrated within a small area. These anomalies have been described by Mahanjane (2012) as lava flows. The section is probably finally overlain by end-of-rift volcanics and basalt flows (Mahanjane, 2012; Nairn et al., 1991; Salman and Abdula, 1995), which are mainly concentrated in the south west of the ZDD.

In the Outer Beira High, there are prominent rotated fault blocks in the basement. Fault planes are mostly aligned in a NE-SW direction, which is parallel to the coast line and indicates a south-easterly direction of extension (Mahanjane, 2012). The seismic data indicates fault growth during deposition of the Karoo section. Events dip at high angles due to the rotation and movement. Thick sedimentary sequences are also seen in the rotated fault blocks of the Beira High, and are inferred as representing the Karoo section (Nairn et al., 1991; Salman and Abdula, 1995). The Karoo is possibly made of terrigenous and carbonate formations (Nairn et al., 1990). The section in this northern part of the Mozambique basin is described by Salman and Abdula as ‘narrow marine embayment with barrier reefs separating a number of saline lagoons’. The Beira High probably worked as a barrier that enabled a narrow lake or lagoon to develop in what is now the ZZD.

Upper Jurassic

The character of the seismic data representing Mid Jurassic to Lower Cretaceous formations is parallel to sub-parallel, and amplitude contrasts are evident in the layering. The section has been described as syn-rift red beds continental sedimentary sequence (Salman and Abdula, 1995). The thickest section appears to be infill of the rotated fault blocks in the Outer Beira High, where it is equivalent to about 0.5 s two-way-time (twt). Thinning and absence of the section is also observable over the Beira High where it was probably eroded or not deposited. Deformation is noticeable on the Beira High area. The section thickens in the ZDD, reaching about 0.8 s twt. This section represents infill of the basin (sag) after the breakup of Gondwanaland.

Lower Cretaceous

The seismic character of the Lower- to Mid-Cretaceous sequence shows amplitude contrast variations between layers. Events in the ZDD are sub-parallel with a wedge-like geometry that indicates thickening of the section towards the central part of the ZDD, consistent with major deposition from the northern area of the Zambezi River. The section is also thick in parts of the northeast area of the Beira High; however it thins and is sometimes absent towards the High, probably due to erosion before deposition of the overlying Upper Cretaceous sequence. The section is described by Nairn et al (1991) as ‘shaly, glauconitic, marine sandstone lithology’. This represents initiation of marine sedimentation in the area. Transitional continental marine environment facies could probably exist in the section (Salman and Abdula, 1995). The section is represented by the Maputo and Lower Domo formations.

Upper Cretaceous

The Upper Cretaceous is predominately represented by deposition of the Domo Formation and possibly the Lower Grudja Formation (Salman and Abdula, 1995). Seismic events from the Mid- to Top Cretaceous are parallel in the ZDD but there are some chaotic layers in the upper section. Deep water deposition starts to show on the upper section in the ZDD. In the Beira High events are parallel with well-defined fractures. Section thickness is greater in the NE part of the Beira High, suggesting the possibility that sediment supply into the basin at the time came from a different source. Over the distal SE area of the High, events look like patch growths of drape geometry, possibly representing carbonate shelf build-ups and reefs. There is possible co-existence of siliciclastic input and carbonate build-up. The faulted Beira High provided a topographic high where the sea was shallow and carbonate precipitation in the sub-tropical region of the Mozambique Channel was possible (Wilson 2005). At the same time, subsidence of the ZDD, combined with the sea level, produced accommodation space and water depth for siliciclastic influx from inland streams.

Paleocene

The Top Cretaceous–Top Paleocene sequence corresponds to the Upper Grudja Formation. The onshore section is described to be from littoral to neritic sedimentary conditions (Nairn et al., 1991), hence its offshore sedimentation could be interpreted as a deepwater environment. The seismic character of the sequence is very different from one area to the next. In the ZDD, events have a chaotic expression and their geometry in the seismic profiles looks like a transverse cut of basin floor fans. Possibly, sudden sediment influx in the ZDD, combined with deep waters, produced deposition of the basin floor fans in the central area. The source of sediment in the fans appears to be south of the current position of the Zambezi River.

The Paleocene is hard to identify and interpret in the Outer Beira High, and it seems likely to have been eroded before the thick Tertiary sequence. Deep water wells in the area would assist this interpretation. Movement of the rotated fault blocks of the Beira High seems to have stopped by the end of the Cretaceous. The carbonate build-up of the Late Cretaceous appears to have subsided and the new
Eocene/Oligocene – Lower Miocene

The interpretation of the Top Paleocene to Mid-Miocene indicates thick sections in the central NE area of the ZDD and in the NE of the Beira High due to vast quantities of sediment influx to the basin. Sedimentation possibly comes from the southern part of the current location of the Zambezi River and a paleo-shelf break is recognised in the area offshore Beira. Salman and Abdula (1995) describe the section as ‘shelf slope or fore reef facies. Deepwater forma-

Figure 7 3D models for seven interpreted horizons in the Zambezi Delta offshore area. Yellow dashed lines in the Karoo-Belo sequence indicate the approximate fault plane position on the model. The yellow dashed line in the Eocene-Oligocene-Lower Miocene indicates the possible shelf position of the Paleo-Zambezi Delta.
tions are calcarenitic and calcilutitic, formed in conditions of continental slope and continental rise. Along the outer edge of the shelf, a chain of reefs is present. Nairn et al. (1991) describe the onshore section as ‘a dominantly carbonate unit’. The section corresponds to the Cheringoma Formation.

Prograding clinoforms are recognized in the seismic profiles in the area offshore Beira. The proto Zambezi Delta seems to be deposited from further south of its current position and also seems to be further inland (yellow dashed line in Figure 7). In the lower part of the central depression the seismic sequence develops a chaotic expression. More layering is present in the flexure area of the inner Beira High where subparallel events present amplitude variations. Channels are present within the sequence in this area. The sequence onlaps against the carbonate build-ups of the Lower Tertiary over the Beira High. Bypassing the carbonate build-ups, the section continues in the deep water and NE of the Biera High, where it is thicker.

Upper Tertiary and Quaternary
The thickest part of this section is in the central part of the ZDD. The seismic character of the sequence indicates progradation of the Zambezi Delta and shelf edge over the entire ZDD. Well-developed clinoforms are evident in the seismic profiles. In the west area of the Beira High, sedimentation of deepwater turbidites starts where the deltaic environment ends. In this area the sequence shows turbiditic and chaotic beds. Over the Beira High the sequence cuts through the underlying Lower Tertiary and Upper Cretaceous sequences. There is evidence of canyons up to 10 km wide that can also be seen in the present day seabed. Deepwater deposition predominates in the SE Outer Beira High, and slides and slumps are evidence of gravity driven processes. The seismic expression shows parallel and chaotic turbidite beds. The section corresponds to the deltaic complex of the Zambezi.

Prospectivity of the offshore Zambezi Delta
The study evaluated the five components of a petroleum system: source, reservoir, trap, seal, and migration. At this stage of the investigation timing is not yet evaluated. Four possible source rocks were identified: Late Karoo, Domo, Lower Grudja, and Cheringoma (Figures 8 and 9).

Potential source rocks
Coster et al. (1989) state that ‘the Late Karoo stage should have provided good conditions for oil prone source rock development’. The authors relate these possible conditions to be developed in early marine sedimentation in shallow-restricted conditions. However, De Buyl and Flores (1986) indicate marine or lacustrine sequences above the upper Karoo section. The interpretation of the 3D model in this article is that the Karoo section represents a narrow lake or lagoon where suitable conditions for development of oil bearing source rocks were possible. A thick Karoo section can be found in the ZDD and within the sediment fill of the rotated fault blocks of the Beira High. Seismic identification of the possible Late Karoo source rock is difficult in the ZDD; however, packages of low amplitude contrast can be seen in the rotated fault block section of the Beira High, which may indicate a low energy environment of deposition. It can be inferred that maturity of the Karoo source rock could vary from one place to another in the basin and it will strongly depend on thermal gradients and timing, as the section can be found at different depths throughout the basin.

The Domo formation was deposited during the Cretaceous when two periods of marine transgression and anoxia happened globally: one in the Barremian-Aptian and the other in the Cenomanian-Turonian (Coster et al., 1989). These periods could correspond to the Lower Domo shale and Upper Domo shale. According to Nairn et al. (1991) the potential source rock is described as euxinic, dark grey to black marly shales and its organic content is humic or mixed. The source rock can be distributed between the Lower and Upper Cretaceous seismic sequences described in the 3D model of this article. The thickest section appears to be in the NE extreme of the area of investigation, and thinner, possibly with narrower deposition in the central part of the ZDD. The seismic expression of the possible Domo source rock shows low amplitude contrast in the western margin of the Beira High.

Nairn et al. (1991) describe the onshore section of the Lower Grudja sequence as having organic content dominated by gas prone, humic material. The equivalent offshore section has more marine influence, which according to the authors could generate oil prone source rocks instead. The sequence was possibly deposited in lagoonal conditions of the Upper Cretaceous (Coster et al., 1989).

Nairn et al. (1991) mentioned after Kihle (1983) that shale layers in the Cheringoma Formation, as well as the Grudja Formation, are likely to be source rocks onshore, yet certain interpretation offshore is not confirmed.

Potential reservoirs
The study identified several potential reservoirs rocks in the offshore Zambezi Delta area. The possibly terrigenous and carbonate formations of the Upper Jurassic Karoo section could contain reservoir properties. Section thickness increases the chances of reservoir presence; however, burial compaction may have a negative effect on the reservoir levels.

Potential Lower Cretaceous reservoirs are represented by the marine Maputo Formation and Lower Domo Formation. Coster et al. (1989) report porosities from southern wells in Mozambique between 17% and 21%. They report that porosities in the Upper Cretaceous Domo Sands section of the Domo Formation can reach up to 28%. The seismic amplitude response of the sequence shows high contrast, indicating...
Figure 8 Top: 3D view of a seismic section showing interpretation of the complete sequence offshore Zambezi Delta (ZDD). Bottom: 3D view of combined seismic and amplitude extraction of the complete sequence offshore Zambezi Delta. Possible source rock and reservoir levels are identified by the contrast of amplitudes and indicated by the arrows.

Figure 9 Top: 3D view of a seismic section showing interpretation of the complete sequence offshore Zambezi Delta (Biera High and Outer Biera High). Bottom: 3D view of combined seismic and amplitude extraction of the complete sequence offshore Zambezi Delta. Possible source rock and reservoir levels are identified by the contrast of amplitudes and indicated by the arrows.
possible areas where the Domo sands are present. Paleocene reservoirs are represented by the deepwater basin floor fan and channels and carbonate sections of the Grudja Formation. Coster et al. report the average porosity to be between 15% and 30%. These possible reservoirs extend across a great area of the offshore Zambezi. In the Eocene–Oligocene–Lower Miocene, the Cheringoma Formation represents a possible reservoir level, although it has not yet been proven. In particular, the deepwater calcarenitic and calcilutitic successions (Salman and Abdula, 1995) may represent possible reservoir potential. In the Upper Tertiary, reservoirs are represented by the very well defined Zambezi Delta complex.

Potential traps
A variety of traps exist in the Zambezi offshore area, both stratigraphic and structural. Interpretation of the 2D seismic data allowed identification of the possible trapping style in the area. Analysis of seismic attributes aided the identification of stratigraphic traps. Potential stratigraphic traps dominate the ZDD whereas structural trapping is more evident in the Beira High. Stratigraphic traps include pinch-outs onlapping over the Beira High, truncations against unconformities, and channel fills. Structural traps are represented by rotated fault blocks possibly creating four-way dip closures. Combined traps are also present, such as pinch-outs truncated by faults.

Seal rocks and migration
Seals are represented by shale formations such as the Upper- and Lower Domo Formation (Coster et al., 1989). Intraformational seals are provided by environmental deposition of shales and muds of the Tertiary section. Important unconformities such as the Jurassic–Cretaceous boundary can also work as seals. Porous materials and fractures are the means of migration in the ZDD. Fractures and faults represent likely migration routes throughout the Beira High and the Outer Beira area.

Direct hydrocarbon indicators
Indications of hydrocarbon potential are evident throughout the 2D seismic lines from the Zambezi offshore delta area, represented by widespread amplitude anomalies. Amplitude pinch-outs and high amplitudes are scattered in the shallower sections and over the Beira High. Truncations against faults or unconformities are very common. Some amplitude anomalies are found in channels. The amplitude contrasts may indicate the presence of hydrocarbons, although this cannot yet be confirmed. Amplitude variation can also indicate lithology contrast from one event to the next. High-amplitude contrast usually indicates a higher energy environment of deposition (reservoirs) and lower amplitude contrast indicates a quieter environment of deposition (shales and muds: source rocks and seals). Amplitude anomalies seen in the Upper Karoo section possibly represent volcanics and basalt flows.

Conclusions
Mozambique is a changing frontier. Exploration has taken a positive turn following the discoveries since 2010 in the Rovuma Basin in the north of the country. Hydrocarbon potential extends to the Mozambique Basin including the Zambezi Delta area. The area’s complex tectonic history is still a subject of investigation. The passive margin structural framework provides the right conditions for the development of thick sedimentary basins. Integrating gravity maps in the exploration study has provided a better understanding of the big picture in the area. The use of 2D seismic data and seismic attributes benefit the exploration approach in a frontier basin like Mozambique. Interpretation of the available data enabled building of a 3D model to better visualize the basin development. Petroleum systems analysis of the Zambezi Delta offshore area suggests high prospectivity. Four possible source rocks are identified as having been present in the offshore Zambezi Delta at the time of global periods of marine transgression and anoxia. Reservoirs levels have been identified of different depositional environments. A range of traps exist in the basin. Sealing events and evidence of migration is also found. The authors conclude that all the elements exist for a working petroleum system offshore the Zambezi Delta.

What’s next?
Exploration offshore Mozambique is at an early stage, and exploration risks exist as in frontier areas everywhere in the world. Acquisition of more than 31,000 km of new long-offset 2D seismic data covering the majority of the offshore territory of Mozambique commenced in April 2013. The longer records will help evaluate the position and shape of the basement as well as the thickness of the sedimentary section. New gravity data will become available for integration into the geological model. Advanced processing techniques, including depth imaging, amplitude versus offset and angle (AVO and AVA) analysis will help reduce uncertainties in interpretation. Drilling will provide new downhole data enabling better calibration of the model. Further assessment of petroleum system models will improve understanding of the dynamic and timing elements of the basin.

References


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