Emerging plays and alternative petroleum systems in Mozambique revealed by multi-disciplinary data integration

Rachael Harrison[1*], Max Norman[1], Javier Martin[1] and Nick Rudd[1] assess the petroleum potential for plays beyond the limited stratigraphic and geographic sweet spots proven to date.

Introduction

Identifying new plays and alternative petroleum systems is an important part of the exploration process. It requires a holistic review of the available data, interpretations and knowledge and a fresh look into understanding basin evolution and dynamics. The workflow begins by creating a structured digital database, defining the tectonostratigraphic framework and critically assessing the source, reservoir and seal potential of the different stratigraphic units. The process relies on the systematic integration of multi-disciplinary data from all sources at all scales. Where direct evidence is lacking, play potential can be assessed using analogues and a model-driven approach.

Around the world, the collation and storage of legacy geological knowledge and available data for partially explored basins is often disparate and disjointed. The data may have been created by long-extinct operating companies, it may be stored as reports in cardboard boxes in cavernous warehouses or may be located on now-obsolete media. With several waves of exploration since the 1940s, our record and understanding of the Mozambique Basin is no exception. With a handful of fields and discoveries concentrated in a single Late Cretaceous play, the exploration success to date leaves several questions unanswered. This article addresses two such questions:

1. What is the petroleum potential for plays beyond the limited stratigraphic and geographic sweet spots proven to date?
2. How can the integration of available data help to identify and qualify emerging plays and additional petroleum systems? For example, can palaeogeographic reconstructions and drainage models assist with understanding the evolution of the ancestral Zambezi Delta and the potential for an oil play in the pre-, syn- and early post-rift sections?

Geological background and technical challenges

Located in Southeast Africa, the Mozambique Basin lies on a passive margin, formed during the Early Jurassic break-up of Gondwana (Figure 1). The presence and nature of break-up volcanics and pre-rift Karoo strata is variable and locally debated, as are the influence of pre-existing structure, the nature of the crust and location of the continent-ocean boundary (e.g. Mueller et al., 2016 and Davison and Steel, 2018).

The proven petroleum system lies in the post-rift sequences and comprises the Late Cretaceous Lower Grudja and Domo sands, speculatively charged from the Early Cretaceous Lower Domo Shale. Thermogenic gas and condensate are currently produced from the Pande and Temane fields, whilst biogenic gas (Nemo-1X, Sofala-1X and Mupeji-1), oil rims (Inhassaro (Sasol, 2014)), oil shows (Zambezi-1 and Micaune-1) and seeps (Davison and Steel, 2018) have all been recorded from drilled wells and outcrops located across the basin. These additional hydrocarbon occurrences point towards untapped, diverse and

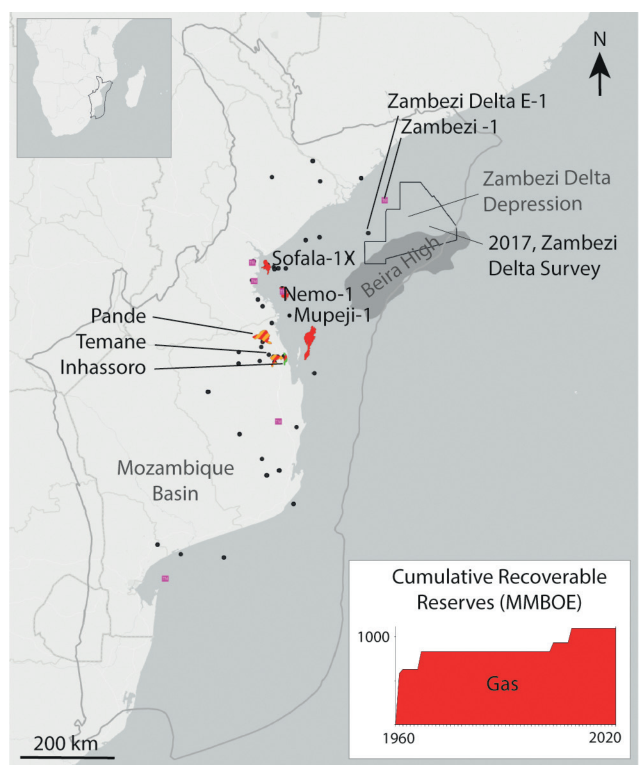

Figure 1 Location map showing the Mozambique Basin, fields and discoveries, key wells, seismic, 1D modelling locations (pink squares) and major structural features.

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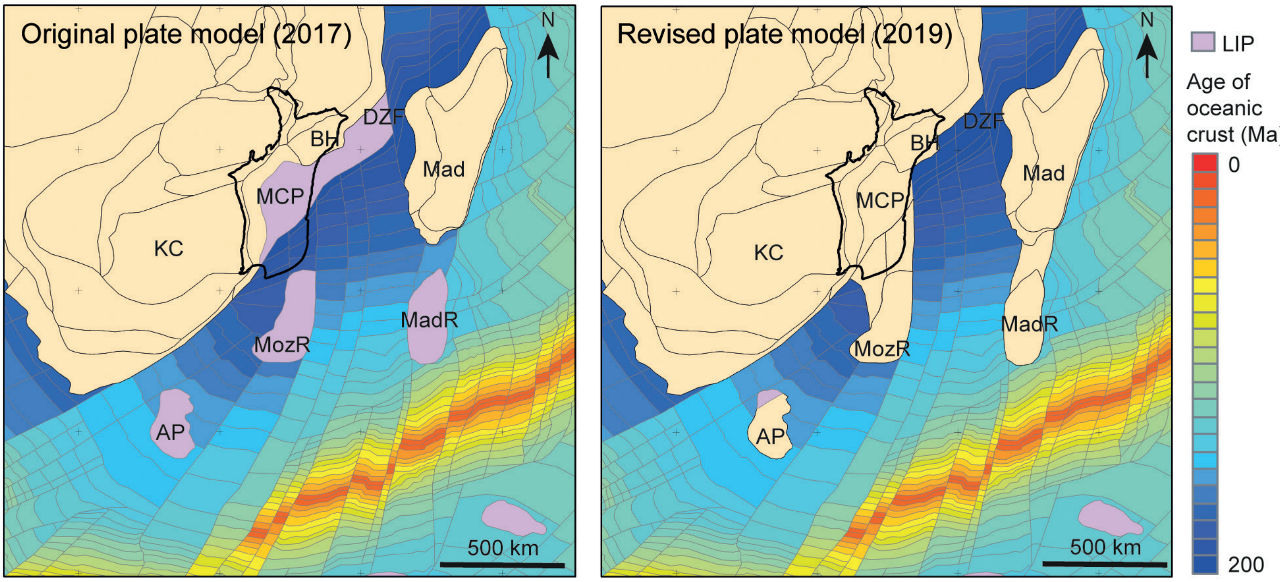

Figure 2 Comparison between the original plate model used as a starting point to understand the regional tectonic development and the new plate model based on observations and insights from new and additional data sources. DZF – Davie Fracture Zone, BH – Beira High, MCP – Mozambique Coastal Plain, KC – Kongo Craton, MozR – Mozambique Ridge, AP – Agulhas Plateau, MadR – Madagascar Ridge, Mad – Madagascar.

potentially more extensive petroleum systems than those proven to date and, tantalisingly, the potential for oil.

Petrophysical analysis of key wells suggests reservoir potential occurs throughout the Cretaceous and Oligocene to Holocene intervals onshore and in the shallow offshore. Further offshore, the presence of Jurassic and Permo-Triassic carbonates and clastics on the Beira High have been inferred from integration of newly acquired and processed seismic data with a deep understanding of the tectonic and paleogeographic evolution of the area. This deep understanding was derived by incorporating geological evidence with geophysical data in two recently completed studies.

Three technical challenges were identified as key to unlocking the undiscovered petroleum potential of Mozambique:

1. There are knowledge gaps in the tectonostratigraphic evolution that limit our understanding of the overall petroleum potential.
2. The source rock evolution is poorly constrained and understood. Is there evidence for oil away from the few discrete locations where it has been found to date and is there the potential for a more extensive petroleum system?
3. Reservoir potential is poorly defined outside the relatively small play fairway. What is the potential in the Cretaceous and in the Cenozoic?

These challenges are addressed lightly in the following sections of this article and more deeply in CGG's recently completed GeoVerse Interpretation play fairway mapping project and JumpStart™ integrated geoscience studies focusing on Mozambique.

Digitally transformed, integrated, multi-disciplinary data sets

CGG's GeoVerse database was used to address the exploration challenges outlined in this article. The tool provided global geological coverage with uniquely rich, multi-disciplinary data from all of the world's hydrocarbon basins. Data from all three access models were used to support our exploration workflow and address the key challenges outlined above.

GeoVerse Primary Data provided access to a digitally transformed database derived from the full suite of CGG's geological multi-client data and reports, including a legacy of 600 Robertson 'Red Book' Studies and CGG's rich geochemical database. The geochemical database was used to provide information on the quality and types of source rocks deposited in the Mozambique Basin and for analogues from the wider African margin.

For the Mozambique Basin, Primary Data comprises more than 1000 pieces of information from 150 unique sites and 1800 data files. Primary Data continually grows with the addition of new studies targeted at addressing today's emerging exploration challenges.

GeoVerse Interpretation is a next-generation play fairway mapping product for selected key basins including Mozambique. GeoVerse Interpretation is generated by geoscience teams with full access to GeoVerse Primary Data, CGG's Seismic data, JumpStart fully integrated multi-client geoscience packages and CGG GeoWells products. The new mapping product incorporates consistent play-level map layers and new mapping methodologies to provide an integrated view of the key known and emerging plays.

GeoVerse Interpretation Mozambique benefited from access to CGG's recent JumpStart geoscience study of the Zambezi Delta. This study was primarily based on a 15,000 km² high-resolution 3D seismic data set, acquired and imaged by CGG with its advanced technologies as part of a multi-client programme agreed between CGG and Mozambique's Instituto Nacional de Petroleo (INP) in 2017. Shipborne and satellite-derived gravity and magnetics data were also used alongside analysis of well data provided by INP. The study provided integrated analysis of all available geological and geophysical data, framed within the wider regional context.

GeoVerse Palaeospace provided access to CGG's deformable global plate model and the results of high-level Earth Systems Dynamics and methodologies for predicting petroleum system elements. CGG's deformable plate model and associated tool were used as a starting point to understand the regional tectonic development and adapted to honour observations and insights from new and additional data sources (Figure 2). The results of the palaeo-Earth systems models (Harris et al., 2017) were used in combination with CGG's paleogeographic maps to predict source rock development in its present day and original geometric context on the Mozambique margin.

These data were interrogated and integrated with additional information drawn from technical publications to identify and describe the petroleum potential of key stratigraphic units in the Mozambique Basin, including the emerging Oligocene to Holocene Sandstone Play and the potential for Permo-Triassic and Jurassic oil-prone source rocks described in this article.

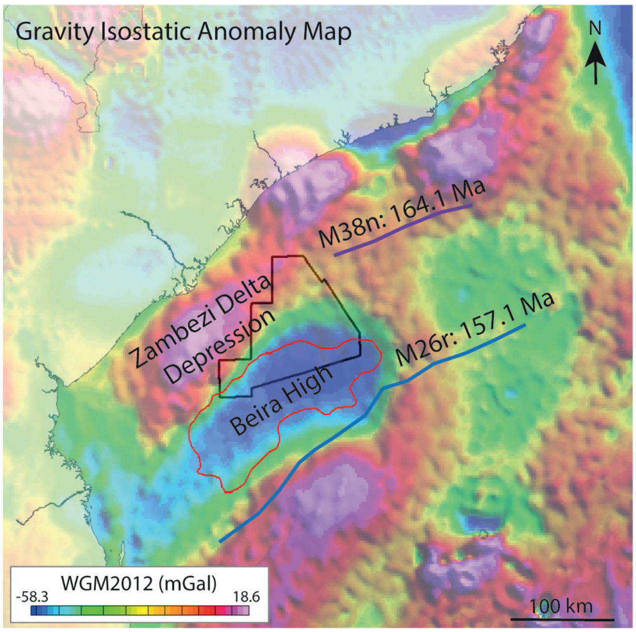

Figure 3 Gravity Isostatic Anomaly map showing the transition from continental to oceanic crust. In the northeast the transition is marked clearly by the M38n magnetic anomaly and the edge of a prominent gravity high. As we move south and east the transition becomes less clear, the gravity high continues into the Zambezi Delta Depression, but the first magnetic anomaly (M26r) occurs outboard of the Beira High coincident with the edge of a different magnetic high.

An improved tectonostratigraphic framework and its wider implications

The early stratigraphy of the Mozambique Basin is inferred from outcrop geology, a small number of well penetrations and seismic imaging of the deeper parts of the basin. The nature of the underlying crust is largely inferred from regional gravity and magnetics data, all of which lack a unique solution. The paucity of rock data from the pre-, syn- and early post-rift sequences has led to much uncertainty over the nature of the crust in the Zambezi Delta Depression and questions regarding the presence and nature of Permo-Triassic or older stratigraphy in the Beira High.

The absence of magnetic spreading anomalies in the Zambezi Delta Depression and the presence of a package of tilted reflectors inboard of the Beira High have led to differing interpretations of the continent ocean boundary and the inference of Seaward Dipping Reflectors and Large Igneous Provinces in a number of areas, including between the Beira High and Mozambique mainland (e.g. Senkans et al., 2019) (Figures 2 and 3). These observations may lead to the discounting of a Jurassic or older petroleum system in the Zambezi Delta Depression and Beira High areas.

The nature of the crust and early development of the margin also impacts the depositional setting and the types of sediments expected in the early post-rift sequence. In the absence of direct evidence, the source, reservoir and cap rock potential of these intervals is largely dependent on the geological model(s) used to predict their characteristics. An oceanic crust model may promote earlier marine source rock development through more rapid subsidence. In this model the source rock is subject to greater depth-decay of organic matter in overall deeper marine conditions. A continental model may promote more stable subsidence and longevity of organofacies B (after Pepper and Corvi, 1995) source rock development in overall shallower marine conditions.

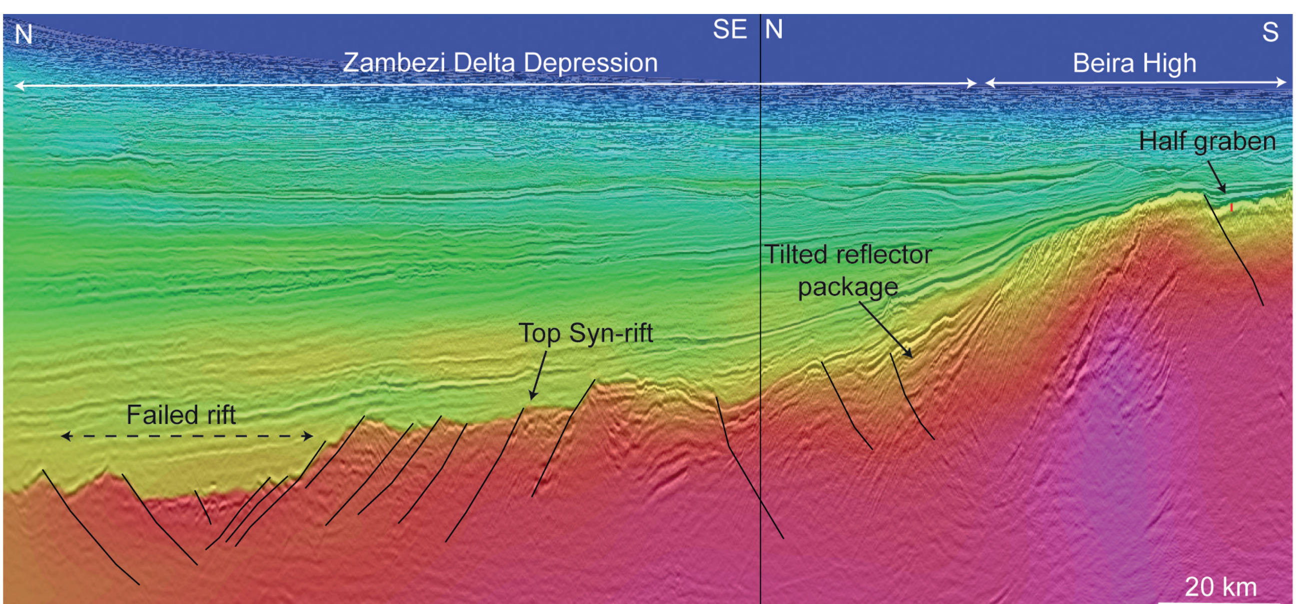

Figure 4 Arbitrary seismic line from the 2017, Zambezi Delta survey showing the relatively low seismic velocities (indicated by yellow and orange colours) in the tilted reflector package on the northern flank of the Beira High.

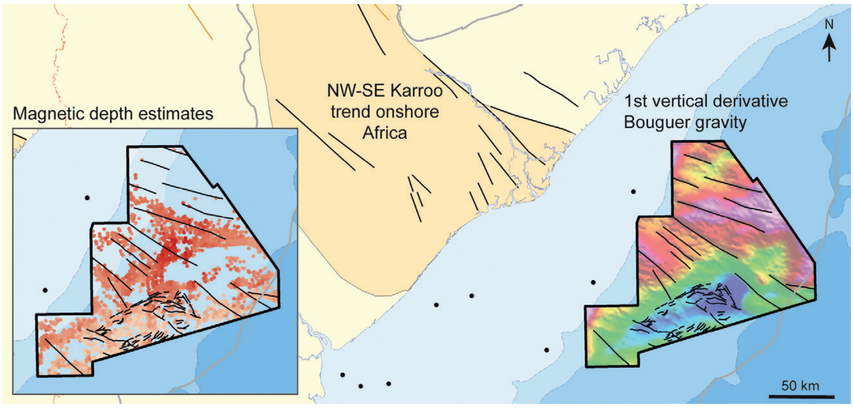

Figure 5 Magnetic depth estimates and first vertical derivative Bouguer gravity map showing the continuation of northwest southeast trending Karoo structures, seen in mainland Mozambique.

In addition, the nature of the crust along the Mozambique margin has a major impact on the timing and maturity predictions for candidate source rocks. Oceanic crust cools quickly and releases little radiogenic heat into the system, while continental crust, rich in radiogenic minerals, has a higher and more sustained heat flow. The adoption of an oceanic model in the Zambezi Delta Depression, for example, may lead to an underestimation in maturity of post-rift sediments and consequently late timing of hydrocarbon expulsion. For this reason, sensitivity modelling was used to consider the impact of the crustal type on the maturity of source rocks at key 1D modelling locations.

Furthermore, observations from the high-resolution, 3D Zambezi Delta survey suggest that there are Jurassic-age syn-rift sediments preserved in a tilted reflector package as well as half grabens located close to the Beira High. Whilst we do see evidence for sills or volcanics, the associated amplitude anomalies appear to be relatively small features. In addition, the interval velocities for the wedge (Figure 4) are below what you would expect for a pure basalt (5500 m/s), suggesting a non-negligible quantity of interbedded terrigenous sediments.

Older pre-rift sediments have also been identified from the Zambezi Delta seismic survey (Figure 5). This recognition of a thick pre- and syn-rift terrigenous sedimentary package at this location in the basin has major implications for the petroleum system and future prospectivity. Our results suggest that it is possible for source rocks preserved in these intervals to contribute to the petroleum system.

Detailed structural interpretation of Zambezi Delta gravity and magnetics data collected in parallel with the seismic survey support this assertion, showing the continuation of northwest-southeast Karoo trends through the Zambezi Delta depression and further into the Beira High (Figure 5).

This recognition of a thick pre- and syn-rift terrigenous sedimentary package on the north western flank of the Beira High has major implications for the petroleum system and future prospectivity.

Is there evidence for oil away from the few discrete locations where it has been found to date and is there the potential for a more extensive petroleum system?

With an improved understanding of the tectonostratigraphy and the nature of the crust in the Mozambique Basin we are better able to constrain the source rock potential. Refining the detail of the plate model (Figure 2) provided the basis for development of an improved paleogeographic framework onto which predictions of source rock development, using the principles of palaeo-Earth systems modelling, can be made. This insight placed in a wider regional context, provided by our global plate model (Figure 6), can help us to identify areas and times conducive to source rock development.

Using this methodology, a number of potential source rocks have been mapped and modelled to investigate likely source rock presence, organofacies type and maturity. Sensitivity modelling was also carried out to explore the remaining uncertainty within the improved tectonostratigraphic framework.

The Early Cretaceous Lower Domo Shale is the only proven source rock in the basin. Despite well data suggesting that the source rock is relatively lean, it has been speculatively correlated to accumulations in the Late Cretaceous Lower Grudja Formation. This correlation has been based on evidence such as the presence of oleanane, indicating Cretaceous or younger-aged source rocks (Loegering and Milkov, 2017; Butt and Gould, 2018). Several other potential source rocks have been identified including Permo-Triassic intervals in the pre-rift, Jurassic intervals in the syn-rift and Late Jurassic, Cretaceous and Cenozoic intervals in the post-rift, although the maturity profile of any of the younger intervals may restrict the petroleum potential to biogenic gas.

Permo-Triassic source rocks are identified at several different locations; onshore southern Africa they are predominantly coal source rocks, suggesting, where present (and mature), that the contribution from these source rocks is likely to be gas. Interestingly, age-equivalent analogues from the west coast of Madagascar are lacustrine shales. Lacustrine shales suggest that there is the potential for both oil-and gas-prone source rocks in the Permo-Triassic of the Mozambique Basin, which is located between these two systems. Furthermore, the preservation of Permo-Triassic intervals is strongly inferred in the Beira High from interpretation of high-resolution 3D seismic and gravity and magnetics data (Figures 4 and 5) (Robertson, 2019).

The syn-rift sequences have not typically been considered for source potential in Mozambique due to the common perception of the margin as volcanic-rich. Observations of tilted and rotated strata on the flanks of the Beira High, however, suggest that the volcanics may not be as dominant or widespread as previously believed. We consider these syn-rift sediments as likely to be terrestrial and they may consequently have the potential for coal and lacustrine shale, organofacies F, and C respectively, holding significant potential for oil and gas derivatives.

The Late Jurassic, early post-rift interval should also be considered for its source potential. The revised plate model demonstrates regional restriction with narrow seaways between Africa and Madagascar to the north and between Antarctica and the Mozambique Ridge to the south (Figure 6). There may also have been areas of localized restriction at this time, for example, on the western margin of the Beira High where we have interpreted/observed the development of a rimmed carbonate platform and lagoon settings from the Zambezi Delta survey data (Figure 6). Source rocks developed here may be organofacies A, owing to limited clastic input and increased carbonate productivity.

In summary, observations from new data and an improved contextual understanding have changed our view of the early tectonostratigraphic development of the Mozambique Basin. The new tectonostratigraphic model identifies three previously unconsidered source rocks, all with the potential for both oil and gas expulsion.

Potential for additional reservoirs in the Cretaceous and Oligocene to Holocene Sandstone play

The Late Cretaceous Lower Grudja and Domo Formations sands are the only proven reservoirs in Mozambique. Eight fields/discoveries clustered in a relatively small part of the Basin produce from these formations (Figures 1 and 7). In order to understand the play potential outside of this localized sweet spot, we need to identify the key controls on reservoir quality. This allows us to

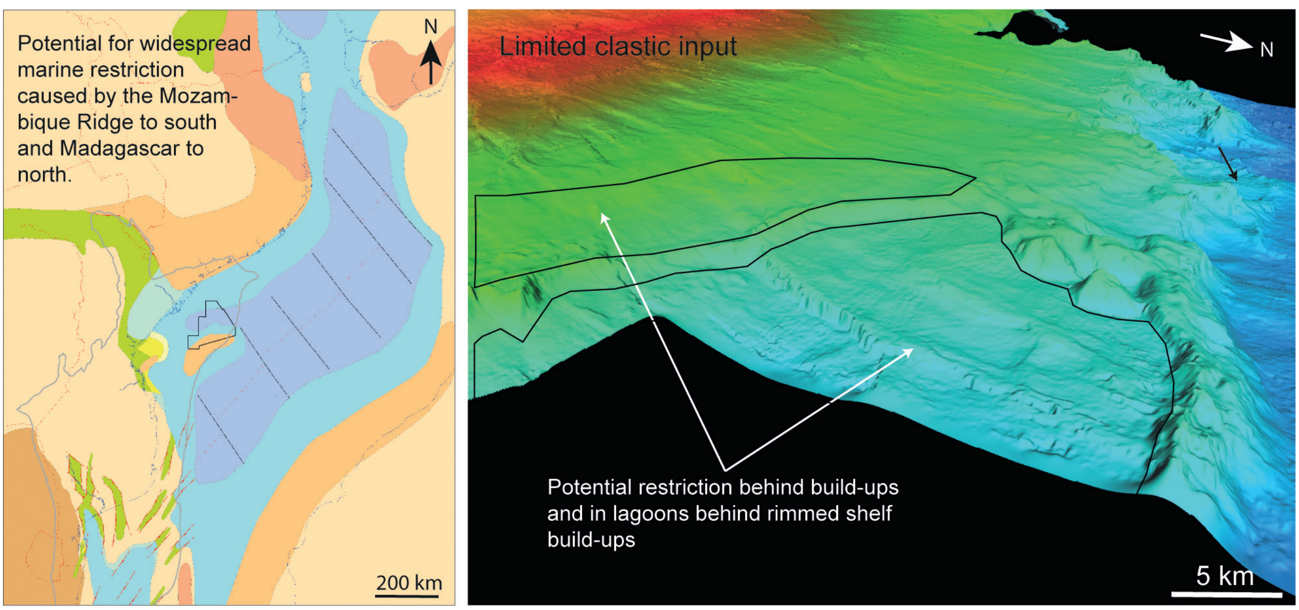

Figure 6 Paleogeographic reconstruction of the Late Jurassic showing the potential for widespread marine restriction caused by the Mozambique ridge to the south and Madagascar to the north. There is further potential for localized restriction behind build-ups and in lagoons around the Beira High.

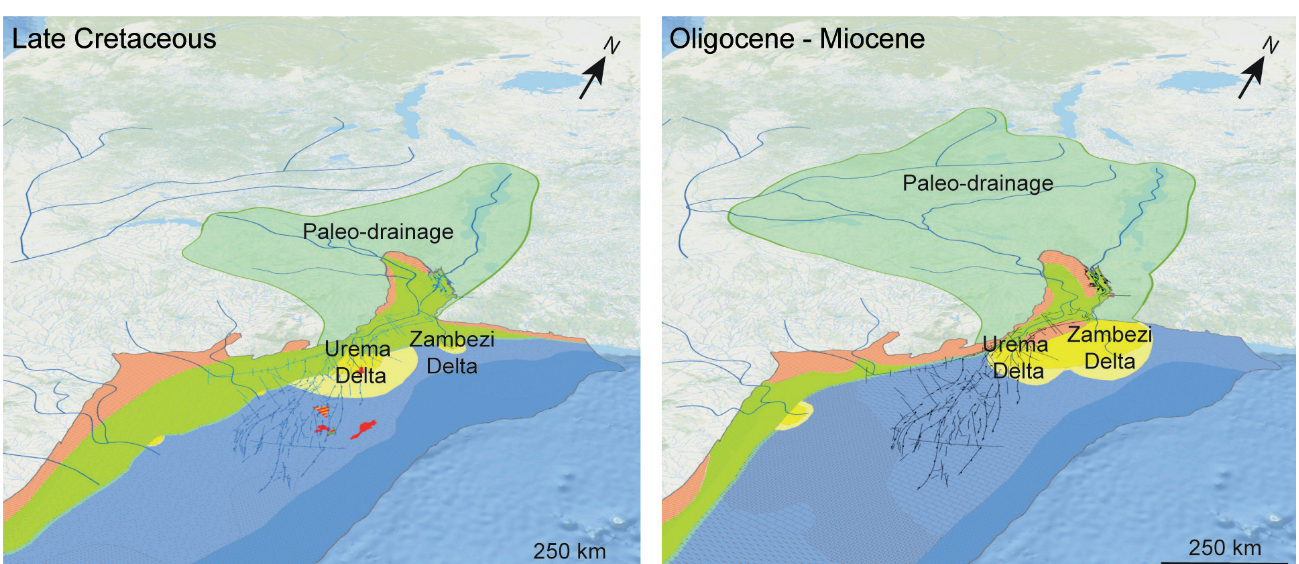

Figure 7 Gross depositional environments maps for the Lower Grudja and Oligocene to Holocene sandstone plays from CGG GeoVerse Interpretation. The dark green polygons show the hinterland and paleo-drained system.

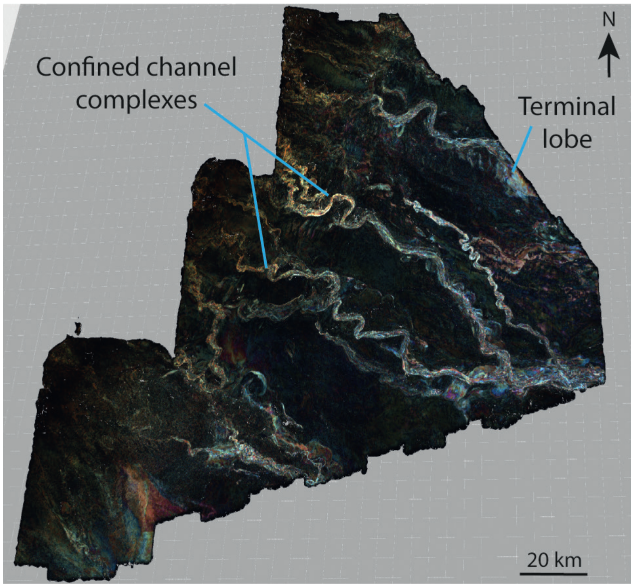

Figure 8 Spectral Decomposition, using a short time Fourier Transform on 14, 35 and 56 cycles/unit in a 28 m window size, showing well-developed confined channel complexes and a terminal lobe on the 2017, Zambezi Delta survey.

build a picture of how the reservoir might change, both laterally and stratigraphically.

In clastic systems, the primary controls on reservoir quality are:

1. Depositional controls: linked to the energy of the depositional environment and resulting grain size and sorting.
2. Post-depositional controls: related to burial, compaction, cementation, dissolution and mineral replacement.
3. Hinterland characteristics: recognizing the importance of the sediment source, its geology/composition and the size and climate of the drainage area, which influence sediment volume, chemistry and mineralogical maturity.
4. Structural controls: associated with the stress fields, any pre-existing planes of weakness and fracturing.

From our knowledge of the regional tectonostratigraphic development we know that significant structural changes occurred in the hinterland and have affected the onshore drainage system as well as the depositional environments in the Mozambique Basin.

In the 'sweet spot', the Lower Grudja Formation comprises deltaic and shallow marine reservoir facies suggesting that a large delta system was active in the Urema area during the Late Cretaceous period (Figure 7). The present-day geomorphology, observed on satellite imagery, demonstrates that the Zambezi Delta is now the major distribution point for sediments on this part of the Mozambique margin. This fits with observations from well data in the area (e.g. Sofala-1), interpretation of the 3D seismic data (Figure 8) and published work on the evolution of the drainage system by Moore and Larkin (2001), Stankiewicz and de Wit (2006) and Moore et al. (2007).

The implications are that the Lower Grudja Formation reservoir is likely to change character, linked to changes in the depositional environment with increasing distance from the Urema Delta sweet spot. This does not necessarily limit the Late Cretaceous play to the Urema area, but it does imply that we need to consider the mechanisms for transporting and depositing sand into other parts of the basin. Longshore drift and deepwater depositional processes are likely to be important.

The onset of the proto-Zambezi delta in the Oligocene, instigated by structural changes in the hinterland, linked to the onset of the East African Rift System, introduces the opportunity for a new deltaic play to the north of the existing sweet spot. The Zambezi wells (Zambezi-1, Zambezi Delta E1 and Zambezi-3) show that this interval contains good-quality reservoir with oil staining and minor gas shows. Well-developed confined channel complexes and terminal lobes have been observed and interpreted from attribute analysis of the 3D seismic volume (Figure 8). The drainage system analysis of Moore and Larkin (2001), Stankiewicz and de Wit (2006) and Moore et al. (2007) indicates that the Oligocene to Holocene Zambezi delta drains a much larger area than the Late Cretaceous Urema delta (Figure 7) suggesting that reservoir sweet spots associated with the Zambezi play are likely to be more extensive.

Conclusions

The integration of all available data, at all scales, onshore and offshore Mozambique, undertaken as part of our Jumpstart and GeoVerse Interpretation workflows, has improved our understanding of the tectonostratigraphic evolution and how the geological evolution influences the sedimentary record and petroleum systems. New insights of both proven and potential reservoirs and improved predictions of the presence, type and maturity of source rocks have enabled the development of new play concepts including channel complexes and deepwater sediments in the Oligocene to Holocene. A review of source rock data and petroleum systems analysis has demonstrated the potential for an oil play associated with Permo-Triassic and Jurassic-age source rocks.

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