Introduction

Despite the discovery of the multi-billion barrel Tsimiroro and Bemolanga heavy oil fields in the early 20th Century, the basins of Madagascar, as well as conjugate areas such as the Seychelles, Comoros and East Africa, remain frontier exploration areas. The paucity of subsurface data, and concerns about the presence and effectiveness of key play elements (notably charge systems and reservoir) have provided a disincentive to exploration and drilling. Recent works in the region, including extensive fieldwork analysis (of more than 100 outcrops) integrated with the interpretation of 2D seismic, well and regional plate tectonic data (Watkinson, 2018), indicate periods of major clastic sediment input into these basins during the Mesozoic and Cenozoic, as well as episodes of elevated TOC in marine shales.

Onshore Madagascar is a rarely visited part of the world but includes spectacular coastal and inland sedimentary successions that record the complex tectonic evolution of the Indian Ocean. The application of ground-truthed sequence stratigraphic and tectono-stratigraphic analysis, incorporating the increasingly well-constrained tectonic and oceanographic evolution of the Indian Ocean (Davis et al., 2016; Reeves, 2017), provides a framework which can be utilised in risk reduction of the offshore basins. We highlight how key events in the break-up of Gondwana, the separation of India-Seychelles and Madagascar, and subsequent shifts in spreading in the Indian Ocean can be directly linked to reservoir presence, quality and provenance, as well as the distribution of potential source rock intervals.

Correlating the Onshore to the Offshore

Large structures and potential stratigraphic traps are known to be present in the deep-water offshore of Madagascar. However, due to the lack of well penetrations in the area, it is difficult to accurately predict the presence and distribution of play elements (reservoir, source and seal) in these offshore basins. Utilising sequence stratigraphy techniques it is possible to correlate the geology at outcrop onshore (along the western margin of Madagascar) to the offshore, and more accurately predict the presence and distribution of play elements into the frontier deep-water basins (Figure 1). Field studies have the advantage of being able to prove the presence and timing of significant clastic sediment supply into offshore basins, as well as identify regional events which may be conducive to deposition of widespread source and seals.

The stratigraphy of NW Madagascar can be sub-divided into several mega-sequences, which are related to: ‘Karoo’ pre- and syn-rift extension; Early Jurassic rifting between East Africa and Madagascar and the opening of the Somali Basin-Mozambique Channel; Cretaceous strike-slip tectonics; Late Cretaceous rifting between West India/Seychelles and NE Madagascar; and subsequently changes in ocean spreading in the Indian Ocean during the Latest Cretaceous and the Cenozoic.

There is a marked spatial change in structural style in offshore NW Madagascar. The Ambilobe Basin passes directly to oceanic crust and can be thought of as a failed rift, separated from the oceanic Mozambique Channel by an outer high called the Levan Bank. Here, Mesozoic and Cenozoic rocks are in shallow water and less thick, although syn-depositional tectonics and salt-tectonics can be demonstrated to greater local depocentres. The Majunga Basin, to the SW (Figure 1), is a more conventional passive margin and separated from the Ambilobe Basin from a major basement lineament-controlled transfer system which extends through the Ampasindava Peninsula. The Majunga Basin and SW Ambilobe Basins contain thousands of metres of Mesozoic and Cenozoic stratigraphy, with large structures associated with inversion and often complex salt tectonics. The Ampasindava transfer zone acted as an important clastic input zone through which sediments were fed to offshore basins throughout the Jurassic, and possibly Cretaceous.

Although mega-sequence boundaries can be directly related to regional tectonic events, internal mega-sequence and sequence architecture is modified by salt and gravity tectonics. This is most notable in salt kinematics, triggered by renewed sediment loading in the Eocene. It is also likely that salt...
tectonics was active in this basin during the Cretaceous (Watkinson et al., 2007). Although Palaeogene successions onshore are dominated by shallow marine carbonates, separated by significant hiatuses, offshore basins contain deltaic and deeper water clastic successions.

**Figure 1** Integration of seismic, field, onshore well and re-interpreted geological maps within a tectono-sequence stratigraphic framework can be used to better predict nature and presence of offshore play elements.

**Major Jurassic & Cretaceous Delta Complexes**

Several thousand metres of pre- and syn-rift continental clastics (‘Karoo’) have a mixed sedimentary provenance from East African Gondwana and what would become India. These are overlain (Lower Jurassic) by a retrogradational parasequence set developed in mixed storm-influenced carbonate ramp and deltaic facies overlain by delta front and slope deposits.

Throughout the Early Jurassic (Toarcian), and probably into the Late Jurassic, the greater Ampasindava area was a major and long-lived deltaic complex (Figure 2 & 3), where delta lobe shifting and abandonment led to establishment of non-deltaic shelf facies adjacent to active delta systems. These systems were sourced from the Indian/Madagascan plate. During this time, palaeo-flow data indicate major sediment input feeding deep-water systems into the newly formed Mozambique Channel offshore. Areas of clastic by-pass at this time (around inactive footwall highs) saw the establishment of now exhumed isolated carbonate platforms, which have been an exploration target in onshore Madagascar, and exhibit facies variations controlled by rift architecture and related to prevailing wind directions.

During the Jurassic and Early Cretaceous, potential reservoir sandstones are frequently overlain by marine shales with elevated TOC, indicating that anoxic or oxygen-poor conditions were present in the more distal offshore throughout the Mesozoic and spread onshore during transgressions. Major periods of clastic input occurred in the Apto-Albian, Turonian, Maastrichtian and late Paleogene and, in some case, regressive clastic depositional systems at outcrop can be correlated offshore to the subsurface on seismic data. These regressive phases are expected to have fed deep-water marine turbidite systems (e.g. basin floor fans, slope channels) in the newly formed passive margin.
Figure 2 Major deltaic complex developed in the Nosy Be, Ampasindava and northern Majunga areas during the Jurassic and Early Cretaceous is likely part of a larger distributary system draining Madagascar and the Indian subcontinent prior to strike-slip tectonics (break-up) between India and Eastern Madagascar.

Figure 3 Example of a Middle Jurassic ~8m thick delta distributary channel sandstone at outcrop along the north-western margin of Madagascar, part of a long-lived post-rift delta system feeding sands into offshore deep-water during the Jurassic and Cretaceous.

Potential Source Rocks

Published geochemical studies suggest that the Sakamena and Isalo I (Triassic) shales are likely to represent the primary source of isotopically light hydrocarbons in the giant exhumed Bemolanga and Tsimiroro fields – although this is a subject of significant debate in the literature.

Organic rich Jurassic and Cretaceous shales (and carbonates) have been proven at outcrop (Figure 4) and in onshore / marginal wells, but apart from the lacustrine and restricted marine shales of the Lower and Middle Jurassic (which have been shown to have TOC’s up to 19% and HI up to 840mg/g at outcrop), source facies where analysed have typically not yielded TOC’s of more than a few percent (although locally higher TOC, up to ~23% have been measured). However, the repeated presence of potential source prone intervals throughout the Jurassic and Cretaceous sequence (associated with late
transgressive and early highstands), may be explained by prolonged phases of anoxia in offshore, deeper water environments, relating to some form of upwelling (leading to a high demand for oxygen caused by high organic productivity on the eastern margin of the Mozambique Channel). Anoxic, or oxygen-poor, conditions were spread most widely around times of maximum flooding.

Figure 4 Example of organic rich slope facies at base of the Lower Jurassic succession. Pro-delta or distal delta slope with thin hyperpycnal density flow sands and slump fold units.

**Exploration Implications**

The new stratigraphic analysis for northwest Madagascar provides insights into the link between regional tectonics and the nature and distribution of key play elements (source, reservoir, seal) in the subsurface across the region and an improved understanding of the controls of major sand input points in the Jurassic and Cretaceous (which is critical to predicting the distribution of deeper water depositional systems in the offshore basins). In particular, the inter-fingerling of potential deep water turbidite reservoirs and organic rich source intervals during the Jurassic and Cretaceous has significant implications for the prospectivity of the region.

The predictive frameworks and improved understanding of play elements developed for the Ambilobe and Majunga Basins of NW Madagascar also provides new insights into the prospectivity of the equally under-explored offshore Morondava Basin further to the south (Hyden et al., 2007).

**References**


