

The Outer Rovuma Fan

Hunting for Petroleum Systems in the Western Indian Ocean.

**GREGOR DUVAL
and MADHURIMA
BHATTACHARYA, CGG**

After decades of oil and gas exploration, large swathes of the globe remain unexplored. In frontier regions, such as the Western Indian Ocean, hydrocarbon exploration starts by delineating areas where continental crust may be present. This is usually where thick sedimentary basins may have developed, and the main elements of a working petroleum system may be present. At first glance, the Western Indian Ocean region may appear as barren oceanic crust with little potential, but there is tantalising evidence to suggest otherwise. The discovery of world-class gas fields in the Rovuma Basin of Northern Mozambique and Southern Tanzania in the last two decades have shed light on the prospectivity of the East African Region and the Western India Ocean islands at large. In recent years, International Oil Companies have started looking at new plays in hitherto uncharted territories such as Comoros, Seychelles and Mauritius. Exploration success in Mozambique in particular has renewed interest in the western blocks of the Comoros Archipelago on the part of independent companies such as Rhino Resources (Blocks 17 and 24), Western Energy and Safari Petroleum (Blocks 38, 39 and 40). The entry of Tullow Oil in 2019 (Blocks 35, 36 and 37 in partnership with Discover Exploration) has attracted further interest in Western Comoros to explore the Outer Rovuma Fan.

Re-evaluation of opportunities offshore East Africa and in the Western Indian Ocean has suggested that a new multi-client long-offset 2D regional seismic programme linking some of these recent discoveries along with additional potential fields data will provide better insight into the prospectivity of this region. This may be achieved using an advanced broadband imaging workflow to achieve deeper penetration for crustal imaging with low-frequency content, delivering better resolution of thin beds and stratigraphic traps to enhance the overall interpretation.

Knowledge Base and Common Understanding

Legacy geophysical and geological data suggest that oceanic crust is pervasive throughout the Western Indian Ocean, forming the Comoros Islands, the Gloriosos Islands, Mauritius and much of the submarine ridge between Mauritius and the Seychelles (i.e., the Mascarene Ridge, Figure 1). This legacy information includes regional gravity and magnetics data, refraction and 2D reflection seismic, deep sea drilling project (DSDP) data and ocean drilling program (ODP) wells, and geological field studies. However, based on several recent studies, there is overwhelming evidence for the existence of slivers of continental crust in the Western Indian

Ocean which were previously thought to be purely of intra-oceanic magmatic origin.

The obvious micro-continent in this region is the Seychelles Bank. This was proven in 1981 when Amoco drilled a series of three exploration wells about 120 km west of the main islands. These wells also proved the presence of a working petroleum system with oil and gas shows, and a mature source rock in the pre-rift Lower–Middle Jurassic sediments. A handful of DSDP wells were drilled around the Seychelles islands and two of them found oceanic crust to the north buried below a thin layer of Tertiary sediments. However, to the south, none were drilled deep enough to penetrate to the basement and prove/disprove whether pre-rift or syn-rift sediments could be present.

CGG's kinematic plate reconstruction models over the Western Indian Ocean region show the complexity of the poly-phased breakup of Gondwana. It suggests that there may be many more continental fragments like the Seychelles Bank scattered over the region (Figure 2). For example, the Mascarene Ridge fits exactly in the space and time of complex breakup between Madagascar and India. The Saya de Malha Bank is usually referred to as a sliver of continental crust, but the nature of the Nazareth Bank is often questioned. Several other promontories fitting in that space between Madagascar and India are indiscriminately mapped as part of the oceanic crust.

New Evidence for the Presence of Continental Crust

Further to the west of the Seychelles Bank, refraction seismic and gravity data studied in 2013 by Hammond et al. show the potential continental nature of the Amirante Ridge (Figure 1). Gravity modelling and seismic receiver function analysis both suggest a crustal thickness of 24 km at Desroche Island, which is located on the northern half of the

Amirante Ridge, about 150 km away from the western edge of the Seychelles Bank. In comparison, oceanic crust rarely exceeds a thickness greater than 10 km. Furthermore, in 2012, Mukhopadhyay and Karisiddaiah suggested that the Amirante Ridge and its associated Trench Complex to the west are parts of a subduction zone. They noted the occurrence of calc-alkaline Eocene syenite covering some of the islands in the area. This type of rock is typically found in

thick continental crustal areas and subduction zones. Also, the bathymetric profile, geometry and gravity signature are found to be very similar to other known subduction systems. These observations support the presence of continental crust at the heart of the Amirante Ridge. It is believed that the subduction zone was formed by rotational opening of the Mascarene Basin (Figure 1) with rapid accretion of oceanic crust in the south whilst a compressional front was temporarily formed in the north near the Seychelles Bank, analogous to the action-reaction principle of a lever.

Further south, results published by Torsvik et al. (2013) from their field work and laboratory analyses showed that zircons found on Mauritius had varying ages of 660 Ma to 1971 Ma. Zircons are highly stable minerals that resist weathering and high heat. Torsvik et al. proposed that these zircons were assimilated from ancient fragments of continental crust brought to the surface by volcanic activity. The unanswered question remains: How far did those zircons travel to be found on the Mauritius island? Were they assimilated from nearby continental crust?

As we move westwards, the Comoros Archipelago, located to the west of Madagascar, is formed by four volcanic islands oriented in a WNW–ESE direction. From east to west, they are

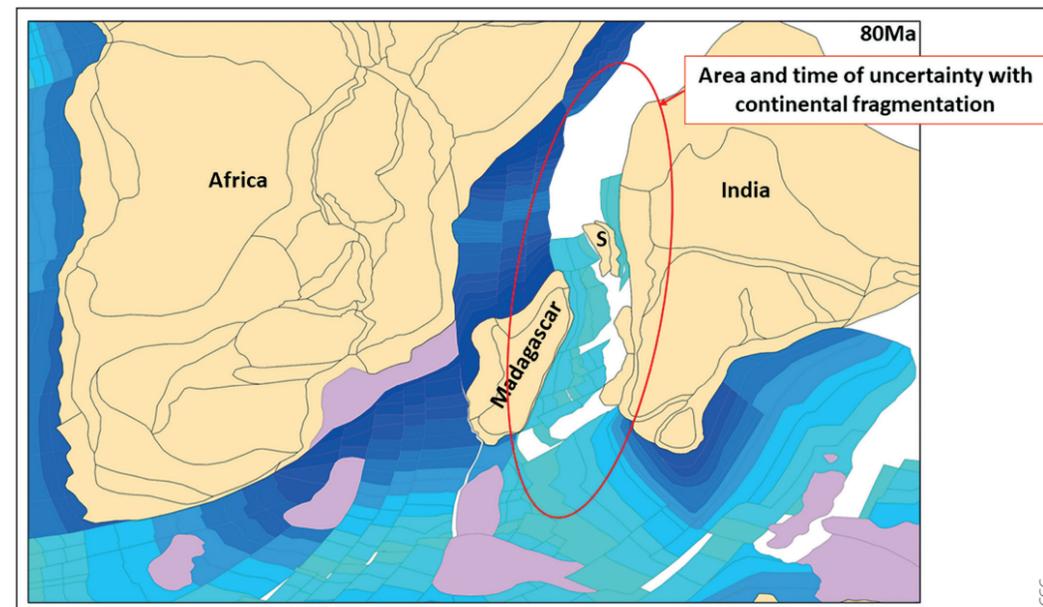


Figure 2: Plate Kinematics reconstruction at 80 Ma (Late Cretaceous–Campanian).

Mayotte, Anjouan, Mohéli and Grande Comore. The islands are generally of volcanic origin (Tertiary to Recent) formed by lithospheric deformation in the general context of the East African Rift system. However, various authors such as Esson et al. (1970), and Roach et al. (2017) have presented evidence of the presence of sandstone xenoliths on the island of Anjouan as well as sandstone inclusions in the lavas on Grande Comore and Mohéli, alluding to the continental nature of the underlying crust. These authors considered it as a critical piece of evidence to suggest that the western part of the Comoros Archipelago is underlain by continental crust or crustal fragments. Analysis of sedimentary rocks of the Anjouan islands by Roach et al. (2017) shows that they are derived from an alkali-granite source terrain and were deposited prior to the breakup of Gondwanaland. Zircon U-Pb dating indicates an age of ~533 Ma for sediment source terrain comparable to the ages found in the Pan-African belt of Madagascar.

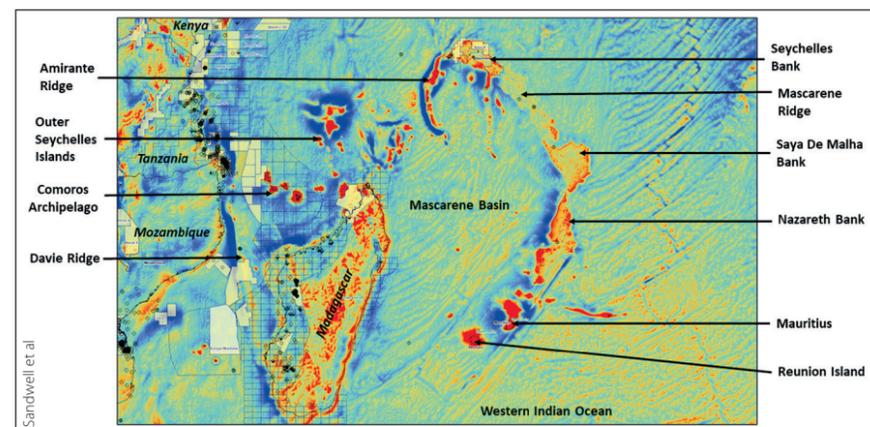
Unproven Hydrocarbon Potential

Roach et al. (2017) also analysed tar balls collected from the island of Grand Comore and have proven them to be indigenous crude strandings derived from a carbonate-marl source rock system of Triassic to Early Jurassic age. The lack of heavy degradation is

indicative of them being local in origin. These observations were combined with offshore seismic reflection data acquired west of the Comoros Islands and east of the commonly accepted Davie Fracture Zone that show tilted fault blocks with stratal growth at depth and suggest that there is a rifted continental section at depth. Based on geophysical data, Davison and Steel (2017) also observed that these grabens are small and probably situated on an extended continental crust. They also implied the possible presence of Jurassic source rocks buried in the oil window providing a case for hydrocarbon potential in the western blocks of the Comoros Archipelago. However, this interpretation has yet to be proven by drilling.

The Comoros Archipelago is separated from the East African margin by the Davie Fracture Zone (DFZ) considered for several years to be a simple transform margin. The DFZ accommodated the southward movement of Madagascar away from present-day Kenya and the Somalian coast during the Jurassic. In recent years, the crustal nature of the DFZ has been explored by several authors. The full crustal extent of the DFZ to the west of Comoros is questioned by Klimke and Franke (2016) in an abstract published for Terra Nova. Based on seismic data interpretation, they argue for a lack of evidence to interpret the presence of the

Figure 1: Satellite free air gravity anomaly map v29.1 highlighting the main geological features of the West Indian Ocean crust. (After Sandwell, 2014.)



Exploration

DFZ northwards beyond the Rovuma Delta. This suggests there was a larger expanse of continental shelf to fill the space between Madagascar and the African coast before rifting started. In turn, this would mean that the present-day Madagascan continental shelf may extend further north of the island and possibly as far as the Comoros Islands. The latest piece of evidence alluding to the idea of the larger extent of the Madagascan continental shelf was brought by Bassias et al. in 2016 [8]. They looked at the regional magnetic data available in the area (Figure 3).

The presence of oceanic crust is typically inferred by the regular pattern of magnetic stripes. These are visible on the north-east side of the Comoros Islands but do not seem to be present on the south side in the space between Madagascar and Mayotte, casting doubt on the presence of oceanic crust there. Finally, Vormann and Jokat (2021) looked at five refraction lines along the Mozambique margin crossing the DFZ and attempted to refine the kinematic model for the East Africa margin. Based on their crustal interpretation, they identified the presence of continental fragment beneath the southern part of the Davie Ridge which concurs with observations made by Klimke and Franke (2016). They noted the presence of a wider continental-oceanic transition zone (COT) than previously stated along the south-west Madagascar and Tanzania/Kenya DFZ margin and that the COT gets broader from south to north along this margin. They also noted that the evolution of the northern DFZ as compared to the southern DFZ is more complex.

The Future Ahead

The East African margin has become a focus of exploration activity since the discovery of world-class gas fields in Mozambique, Tanzania and Kenya. This focus has brought with it a wealth of data, observations and models which highlight the likelihood that several isolated continental basins may exist and have been overlooked for hydrocarbon exploration along offshore East Africa and in the Western Indian Ocean. Based on our review of available data, there appears to be considerable hydrocarbon potential in these areas. We believe that a new long-offset 2D multi-client regional seismic programme spanning the Rovuma and West Somali Basin, the Comoros Archipelago, north-west Madagascar and extending out across the Indian Ocean in conjunction with gravity and magnetics data will give better insight into the prospectivity of the larger extent of the Western Indian Ocean. Hopefully, it will also provide answers to some of the enduring questions as to the nature of the crust, localised rifting history and eventually the evolution of the micro-continents of the Western Indian Ocean.

References

Bassias, Y. 2016. Was the Mozambique Channel once scattered with islands? *GEOExPro*, 13(5), pp.58–62.

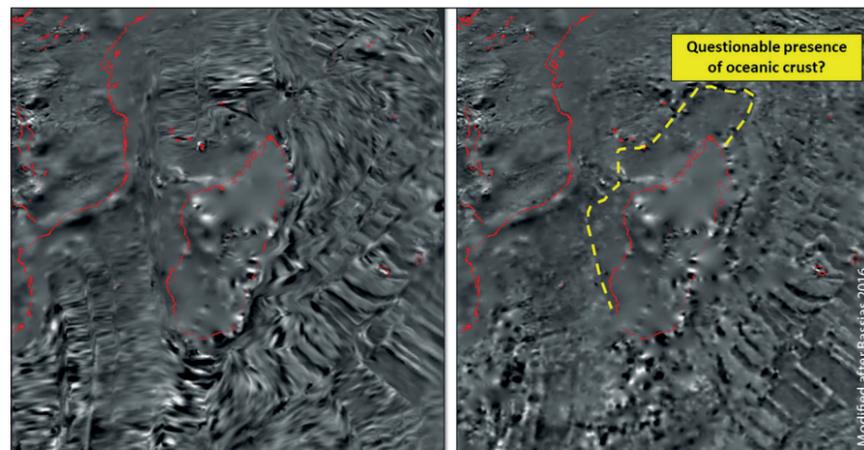


Figure 3: EMAG2 v3 regional magnetic data without directional gridding, highlighting the area of uncertainty north of Madagascar with regards to the presence of oceanic crust.

Davison, I. and Steel, I. 2018. Geology and hydrocarbon potential of the East African continental margin: a review. *Petroleum Geoscience*, 24, pp.57–91.

Esson, J., Flower, M.F.J., Strong, D.F., Upton, B.G.J. and Wadsworth, W.J. 1970. Geology of the Comores Archipelago, Western Indian Ocean. *Geological Magazine*, 107(6), pp.549–557.

Hammond, J.O.S., Kendall, J.-M., Collier, J.S. and Rumpker, G. 2013. The extent of continental crust beneath the Seychelles. *Earth and Planetary Science Letters*, 381, pp.166–176.

Klimke, J. and Franke, D. 2016. Gondwana breakup: No evidence for a Davie Fracture Zone offshore northern Mozambique, Tanzania and Kenya. *Terra Nova*, 28(4), pp.233–244.

Mukhopadhyay, R. and Karisiddaiah, S.M. 2012. Geodynamics of the Amirante Ridge and Trench Complex, Western Indian Ocean. *International Geology Review*, 54(1), pp.81–92.

Roach, P., Milsom, J., Toland, C., Matchette-Downes, C., Budden, C., Riaroh, D. and Houmadi, N. 2017. New Evidence Supports Presence of Continental Crust Beneath the Comoros. Abstract from the PESGB-HGS Africa Conference, London, August 2017.

Sandwell, D.T., Müller, R.D., Smith, W.H.F., Garcia, E. and Francis, R. 2014. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. *Science*, 346(6205), pp.65–67.

Torsvik, T.H., Amundsen, H., Hartz, E.H., Corfu, F., Kuznir, N., Gaina, C., Doubrovine, P.V., Steinberger, B., Ashwal, L.D. and Jamtveit, B. 2013. A Precambrian microcontinent in the Indian Ocean. *Nature Geoscience*, 6, pp.223–227.

Vormann, M. and Jokat, W. 2021. Crustal variability along the rifted/sheared East African margin: a review. *Geo-Marine Letters*, 41(2), n.19. ■

Foldout 02 Placeholder