Oil prospects in the Mozambique Channel: where incipient subduction meets passive margin

Anongporn Intawong[1]*, Neil Hodgson[1], Karyna Rodriguez[1] and Phillip Hargreaves[1] demonstrate encouraging play prospects identified together with sea surface oil slicks within the Davie Subduction Zone concept in the Mozambique Channel.

Introduction

After several major gas discoveries made offshore Tanzania and northern Mozambique, the entire East Africa margin has been assumed to be a gas province. We present evidence for a new oil province along this margin based on an interpretation of Spectrum's recently acquired modern Broadband 2D seismic data in the offshore Angoche/Mozambique Basin. The new seismic data lying south of the Rovuma Basin and across the Davie Ridge in the Mozambique Channel (Figure 1) are considered together with an integration with sea surface oil slicks identified on satellite imagery and other direct hydrocarbon indicators (DHIs).

Understanding the nature and origin of crustal architecture in the Angoche Basin and Davie Ridge is a vital input to plate reconstruction, as well as enabling an assessment of petroleum potential. We discuss potential source rocks and variation in geothermal gradient in the region and evaluate various plays in the

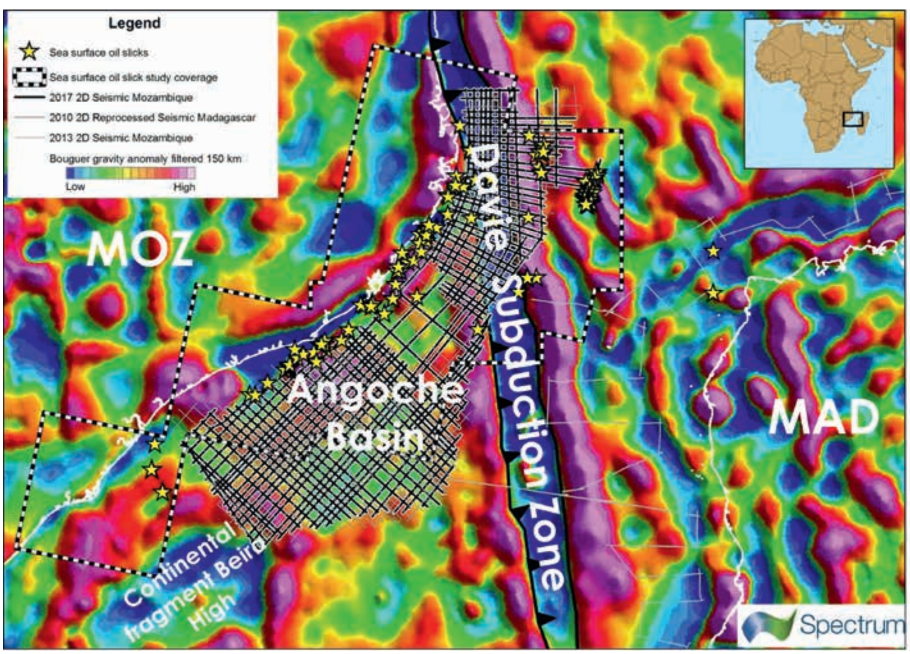

Figure 1 Sea surface oil slicks location and Spectrum's recently acquired 2D seismic data in the Angoche Basin and the Davie Ridge (subduction zone) overlaying on satellite Bouguer gravity anomaly filtered 150 km. White outline represents continental coast line. Abbreviations: MOZ: Mozambique and MAD: Madagascar.

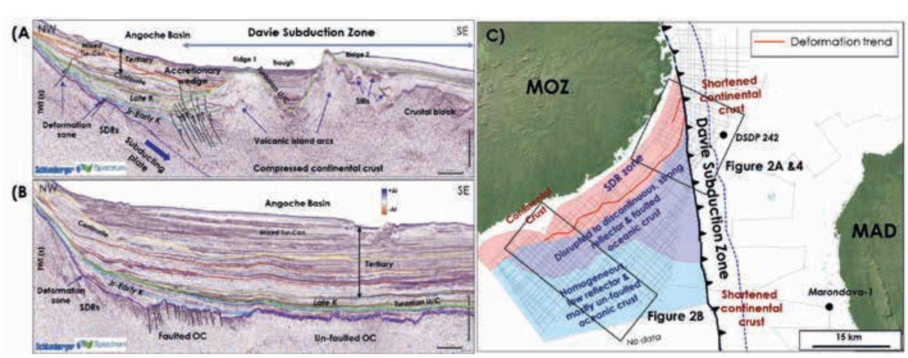

Figure 2 Regional dip seismic sections demonstrating regional subsurface geology in the Angoche Basin (B) and DSZ (A). (C) Crustal architectures identified within the Angoche Basin and DSZ. Blue dashed line represents Bouguer gravity low anomaly area along the DSZ.

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light of the new geological findings within the new Broadband 2D seismic dataset.

Geological background

The offshore Angoche Basin is a result of the break-up of the Africa-Antarctic Corridor between the East-Gondwana (Africa and South America) and West-Gondwana (Antarctica, India, Madagascar and Australia) super-continents in the Middle Jurassic period (Mueller and Jokat, 2019), and this is based on an identification of magnetic anomaly chron M38n indicating that the first oceanic crust formed in the Angoche Basin at 164 Ma (late Callovian) (Mueller and Jokat, 2017). The Angoche Basin is also commonly referred to as a conjugate margin to the Larsen Sea offshore Antarctica (e.g. Leinweber and Jokat, 2012; Mueller and Jokat, 017; Klimke et al., 2018).

The Africa-Antarctic Corridor break-up is recently interpreted to be formed by a major sinistral strike-slip deformation along a lithospheric weakness of the Namama-Orvin Shear Zone of the East African-Antartic Orogen (Mueller and Jokat, 2019). The corridor extends from the coast of Mozambique in SE-Africa to the coast of the Dronning Maud Land in East-Antarctica along the Davie-Discovery Fracture Zone to the east and the Du Toit Fracture Zone to the west (Mueller and Jokat, 2019). The continental break-up also resulted in the fragmentation of the Gondwana super-continent such as the Beira High, showing a remaining pre-rift sedimentary unit on seismic sections (Mueller and Jokat, 2016; Mahanjane et al., 2014; Senkans et al., 2019).

Crustal structures and basin architectures of the Angoche Basin

Based on interpretation of new 2D seismic data, the Angoche Basin demonstrates a narrow restricted zone of Seaward Dipping Reflectors (SDRs) identified between the inboard uplifted continental crust and outboard oceanic crust, characteristic of a passive margin. The margin shows a considerably narrower area of SDRs

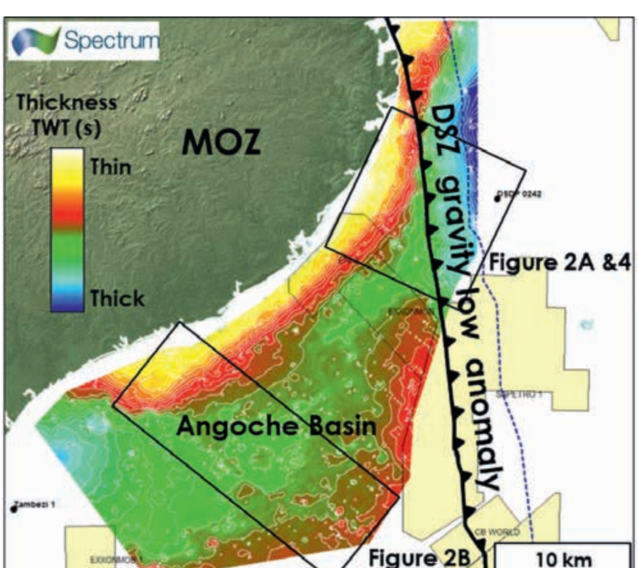

Figure 3 Post-rift thickness map in TWT (s) demonstrating basin architecture and sedimentary overburden in the Angoche Basin and DSZ.

compared to other magma-rich rifted margins for instance the South Atlantic margin of Namibia and South Africa.

We identify two types of oceanic crust outboard of the SDRs zone within the Angoche Basin; Type 1: disrupted and discontinuous yet high amplitude seismic reflectors, representing semi-stratified volcanic layers and associated with faulting, and Type 2: homogenous and low amplitude seismic reflectors, and mostly un-faulting (Figure 2). Identification of the magnetic reversal isochron in the Angoche Basin (Leinweber and Jokat, 2012; Mueller and Jokat, 2017) indicates that the age of the oceanic crust becomes younger southward along the Davie Ridge. The diverse characters of the oceanic crusts can be related to different crustal compositions, and it could be an indication of different timing for crustal formation. These oceanic crusts are recognised along the passive margin of the Angoche Basin until they meet the Davie Ridge where we observe a shortening of continental crust with thick sedimentary overburden, which is interpreted to be an incipient (or failed) subduction zone (Figures 2 and 4). We subsequently propose the 'Davie Subduction Zone (DSZ), and it will be discussed in a later section.

The Angoche Basin is a narrow elongate basin as seen on the post-rift sedimentary TWT (s) thickness map (Figure 3). The basin depocentre is situated along the basin axis, with an indication of thick post-rift sedimentary overburden of up to 5.5 TWT (s) in the south of the new 2D dataset towards the Zambezi Delta. The basin depocentre becomes narrower towards the DSZ (Figure 3).

The post-rift sedimentary unit of the Angoche Basin shows typical features of a passive margin, characterized by mixed turbidite and contourite depositional system especially in the upper section (Figure 2). Several high porosity turbidite reservoirs from this mixed system make up important reservoirs in the Rovuma Basin (Palermo et al. 2014), north of the study area.

The early post-rift sedimentary sequence consists of mainly mudstones of possibly late Middle Jurassic age based on the initial spreading age formed in the Angoche Basin of 164 Ma (late Callovian) (Mueller and Jokat, 2017). Some large contourite mounded drift depositional systems started to dominate in the Early Cretaceous suggesting their depositional environment to be influenced by deep water bottom current systems. Several large Cretaceous to early Tertiary contourite mounded drifts have a package of high amplitude reflectors of possible basin floor fans and turbidite channels deposited against them. The upper Tertiary section is entirely dominated by a mixed turbidite and contourite depositional system.

Incipient (Failed) Subduction Zone (DSZ)

The Davie Ridge has long been observed as a prominent morphological feature in the Mozambique Channel. It shows a north-south trending zone of relative gravity low anomaly bounded to the east by a gravity high anomaly striking across the continental margin of Madagascar and Mozambique. The ridge was discovered by Heirtzler and Burroughs (1971), upon noticing a bathymetric elevation in the Mozambique Channel, and they subsequently proposed that the Davie Ridge represents the expression of the transform fault resulting from the relative southward motion of Madagascar with respect to Africa. The entire feature has subsequently been termed the 'Davie Fracture Zone' by Scrutton (1978).

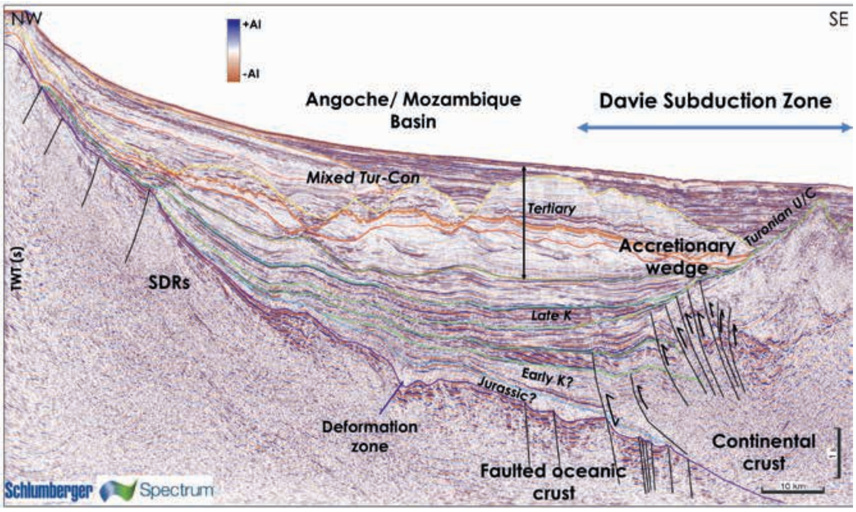

Figure 4 2D seismic sections across the Davie Subduction Zone demonstrating compressed features interpreted to be an accretionary wedge. Line location is in Figure 3.

Most modern plate tectonic reconstructions also recognize a major transform fault, the Davie Fracture Zone, as the western limit of the West Somali Basin, along which Madagascar migrated southwards following the Gondwana break-up in the late Early Jurassic (e.g. Coffin and Rabinowicz, 1987; Geiger et al., 2004; Kusky et al., 2007; Papini and Benvenuti, 2008; Gaina et al., 2013; Reeves, 2014; Phethean et al., 2016). The Davie Ridge was interpreted to represent either the western transform fault of the West Somali Basin (Coffin and Rabinowicz, 1987), continent-ocean transform margin (Gaina et al., 2013), or ocean-ocean transform margin (Phethean et al., 2016), associated with the southward movement of the Madagascar-India continent in relation to Kenya-Somalia.

The Davie Ridge appears to be a neotectonic feature, but it in fact is an old structure. The ridge is actually a composite of several topographic highs making 'the Davie Zone' a better term, based on its display on satellite Bouguer gravity anomaly and seismic data. This zone comprises compressed sedimentary ridges and troughs, and is made up of thick sedimentary layers, younger well stratified and older compressed sediments (Figures 2 and 4). A compressed sedimentary unit has been observed by Klimke et al. (2018) and in this study (Figures 2 and 4) running north-south along the gravity minimum of the Davie Zone (Figure 1). We have interpreted this to be a crustal thickening accretionary wedge front which stratigraphically continues offshore the Morondava Basin of Madagascar. We believe that these structural features were developed during an incipient stage of the Davie subduction during the Cretaceous as oceanic crust converged with the continental crust of the Madagascar microplate.

Two trends of small-scale intensely deformed structures are identified within the SDRs zone in the centre and north of the Angoche margin, and these trends are almost parallel to the Mozambique coast line (Figure 2). The intensely deformed structures are reverse faults or reactivated normal faults, deformed within the early post-rift sedimentary unit. These intensely deformed structures are probably the result of a combination of a compressional force from the DSZ and movement of evaporitic or under-compacted shale layer underneath the early post-rift sedimentary unit.

The edge of shortening tectonics of the accretionary wedge is correlated to the Turonian Unconformity marker in the offshore Morondava Basin. The top part of the compressed sedimentary unit of the accretionary wedge has a very robust erosional surface suggesting subaerial exposure prior to the deposition of the younger Turonian sedimentary unit above the Turonian Unconformity (Figures 2, 4 and 6). The Turonian elevated ridge morphology possibly divided the initial West Somali Basin from the initial Angoche Basin, when the two oceans were still small, especially the Angoche Basin. We also observe some volcanic intrusion creating the ridge morphology along the subduction zone, and it is interpreted to be an incipient stage of failed Cretaceous volcanic arc of the DSZ.

The Davie Ridge marks an ocean-continent boundary at present-day. We propose that in the Cretaceous the Davie Ridge was an ocean-continent convergent plate boundary in the Mozambique Channel, represented by an incipient subduction zone where the Angoche's oceanic crust converged with the continental crust of the Madagascar microplate from possibly the Early Cretaceous to at least the Turonian. We also propose that the Cretaceous volcanism along the DSZ represents the incipient volcanic island arc of the DSZ formation. The Angoche Basin can therefore be viewed as a forearc basin to the DSZ formation. Interestingly, the Turonian andesitic basalts at Manamana onshore southern Madagascar show similar compositions and spidergrams to subduction origin, but they have been interpreted to be originated from subcontinental lithospheric mantle by Bardinzeff et al. (2009) due to considering non-subduction environment in to account. The Turonian Manamana andesitic basalts could indeed be originated from the incipient Davie subduction.

Oil slicks in the Angoche Basin and Davie Subduction Zone

More than 240 optical satellite images acquired over the Mozambique Channel from 2013 to 2017 have been analysed to quantify the number and distribution of sea surface oil slicks in the Angoche Basin, and the northern part of the Davie Subduction Zone (Figure 1). Various methods were used to determine the origin of slicks, whether they are geological seeps or superficial anthropogenic discharges. By looking for locations with persistently reoccurring slicks found on images taken on different days, and over months and years, we can rule out random pollution events, and can be

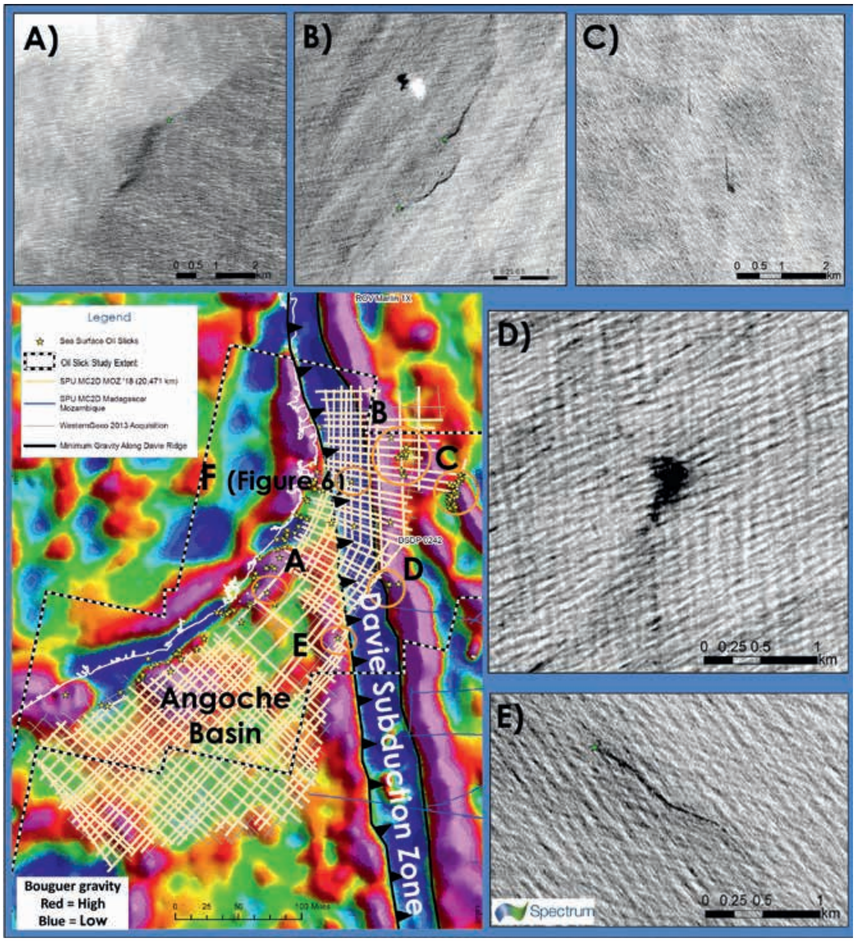

Figure 5. Sea surface oil slicks in the Angoche Basin and Davie Subduction Zone. Oil slick location courtesy of Spectrum, and oil slick imagery courtesy of US Geological Survey.

confident that the oil slicks are indicative of a naturally occurring thermogenic oil source. These slicks are then correlated with seismic data to investigate the geological relationship of hydrocarbon migrating from the source rock to a seep point where the oil enters the sea and finally to the oil slick location. With this workflow integrating, the identified oil slicks are classified as indicative of a naturally occurring thermogenic oil source.

In total, 120 sea surface slicks were identified in the study extent (Figure 1 and 5). Some of these were found in clusters reoccurring over time. Examples of such sea surface oil slicks are illustrated in Figure 5. The majority of the slicks found at the shelf break along the coast of Mozambique. However, there is a noticeable trend of the oil slicks identified along the DSZ, and some of the oil slicks comprise clusters reoccurring over time. A very prominent cluster of slicks classified as oil slicks are observed from a single image, grouped together over a 10 km area and away from shipping routes. This unusual distribution of oil slicks appears in correlation with the Grandidier Seamount, which we interpret to be part of the incipient volcanic island arc of the DSZ (location B on Figure 5). Two similar groups of slicks are also observed within the region of the subduction zone (location A and C on Figure 5). Some oil slicks are found above the thickening accretionary wedge and a relative position of the Angoche forearc basin to the DSZ deformation, with strong geological correlation to DHIs and their migration routes (Figure 5 and 6). These oil slicks provide a strong indication of a naturally occurring oil source in the Mozambique Channel.

Other direct hydrocarbon indicators (DHIs) have been identified within the modern 2D seismic data such as Bottom Simulating Reflectors (BSRs), pock marks, fluid escape features and shallow high amplitude reflectors (Figure 6). Some of the oil slicks appear to have a strong correlation to pock marks, fluid escape features and shallow high amplitude reflectors, and are supported by geological features such as fault and erosional surface for the oil slick's escape route (Figure 6).

Potential source rocks and geothermal gradient and its implication for hydrocarbon maturity

On seismic data we observe that post-rift sedimentary sequences of the Angoche Basin dip upward towards the steep present-day shelf edge and the DSZ (Figures 2 and 4), therefore, it is likely that a mature oil source in the depocentre of the basin is responsible for hydrocarbon migration up-dip both east and west towards the Mozambique shelf and the DSZ respectively (Figure 7).

A simplified stratigraphic column and petroleum system of the Mozambique Channel is presented in Figure 7. The main source rocks in the Angoche Basin would be the restricted post-rift marine source rocks of the South Atlantic anoxic basin from Late Jurassic to Albian (Farquharson, 1983), which found in several DSDP and ODP wells drilled in this margin, including ODP 692 and 693 drilled in the conjugate Antarctica margin (Mohr, 1990). The ODP well 692B penetrated 45 m of Early Cretaceous (Valanginian) source rocks containing Type II marine kerogen, with an average of 10% TOC and HI of 300-600 mg/g TOC (Thompson and Dow, 1990). On seismic data these source rocks are observed to have strong soft kicks at the top of the sequence, clear type 4 AVO anomalies and reduction in frequency, showing classic characteristics of effective source rocks applying Loseth et al.'s (2011) methodology.

Within the DSZ, potential source rocks include pre-rift Permo-Triassic Karoo, syn-rift Jurassic lacustrine shales, and Early Cretaceous marine shales. The Karoo shale is the source rock of the exhumed tar sands in central Madagascar.

Wells drilled in the Zambezi Delta, south of the Angoche Basin, show geothermal gradients of c. 20-25º C/km (Duncan MacGregor, personal communication, October 10, 2018). The thickness of BSRs in northern Angoche Basin suggests geothermal gradients in the deep section of no more than 18º C/km. This is in contrast with the geothermal gradients of wells drilled in Rovuma Basin to the north, nearer to the Comoros hot spot and mantle plume. Therefore, in the Angoche Basin, the early post-rift Jurassic and Early Cretaceous source rocks may be calculated to lie in a peak oil window based on the thickness of sedimentary overburden. This analysis is also supported by 1D basin modelling of Mahanjane et al. (2014).

Prospective plays

In 2017 and 2018 Spectrum acquired a multi-client 2D regional broadband seismic survey designed to image the subsurface potential in the Angoche Basin and the Davie Subduction Zone, providing a more detailed understanding of the prospectivity where no wells have been drilled to date.

We have identified several structural and stratigraphic plays within the Angoche Basin and DSZ, including slope compressional structures related to DSZ, compressional structures near the DSZ, compressional structure within the accretionary wedge, basin floor

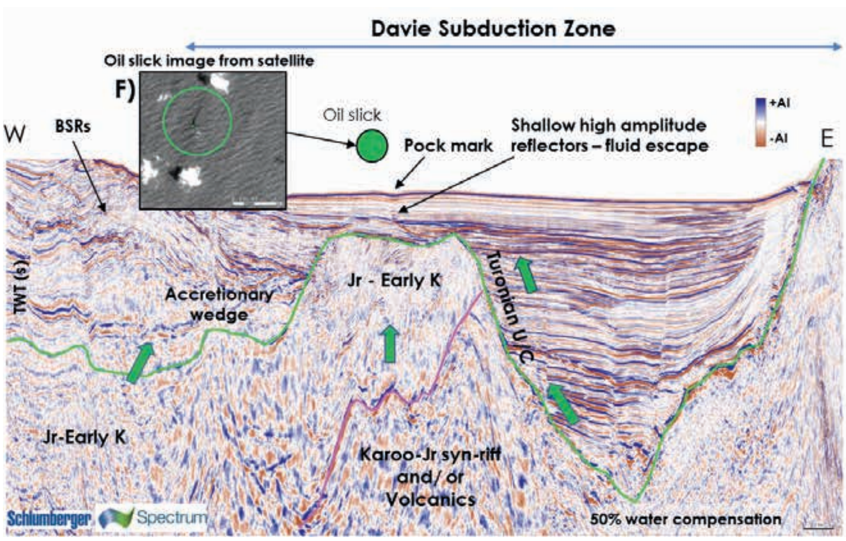

Figure 6. Example of sea surface oil slicks identified above the accretionary wedge of the incipient DSZ. The oil slick image is at the location F on the Figure 5.

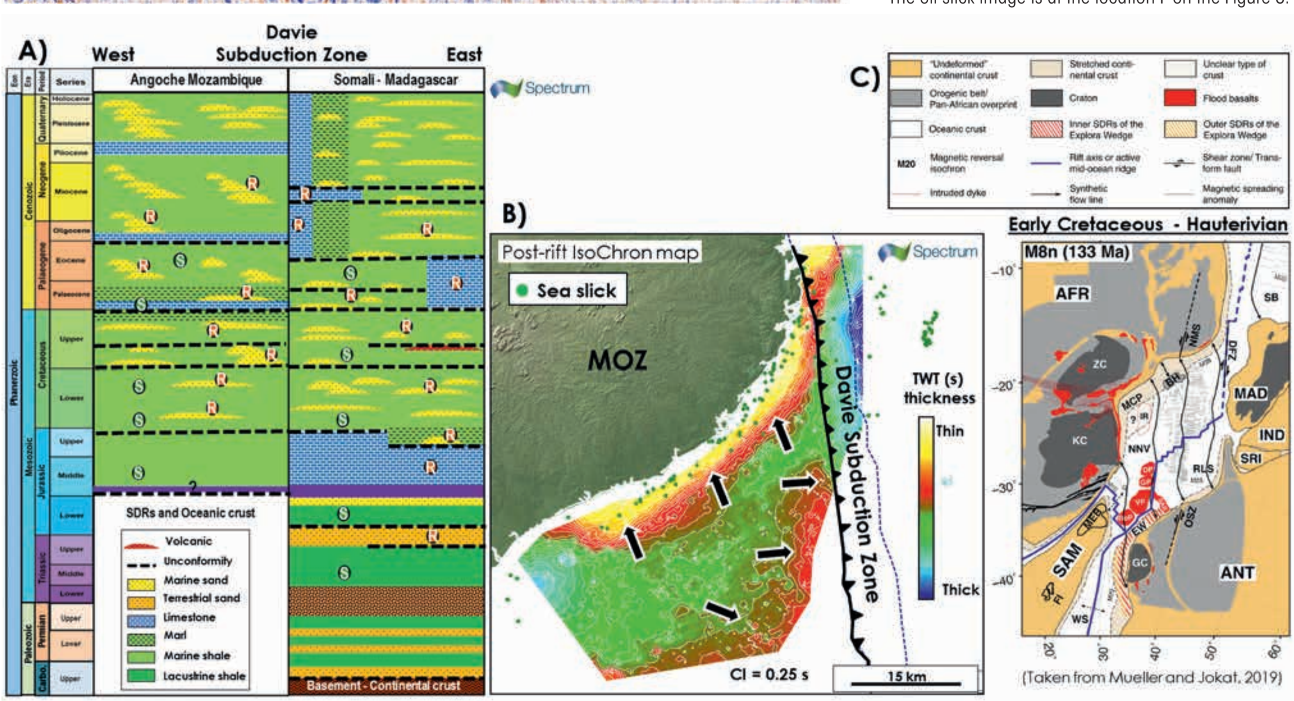

Figure 7 (A) Generalised stratigraphy and petroleum system of the Mozambique Channel in a geological concept of Davie subduction Zone. The Angoche stratigraphic column is modified from Mahanjane et al. (2014), (B) Post-rift thickness map in TWT (s) demonstrating the up-dip source rock migration pathway in the study area, and (C) Paleogeographical reconstruction of Mueller and Jokat (2019) at c. 133 Ma showing the relative position of Antarctica (ANT) Madagascar (MAD) and India (IND) relatively to Africa (AFR).

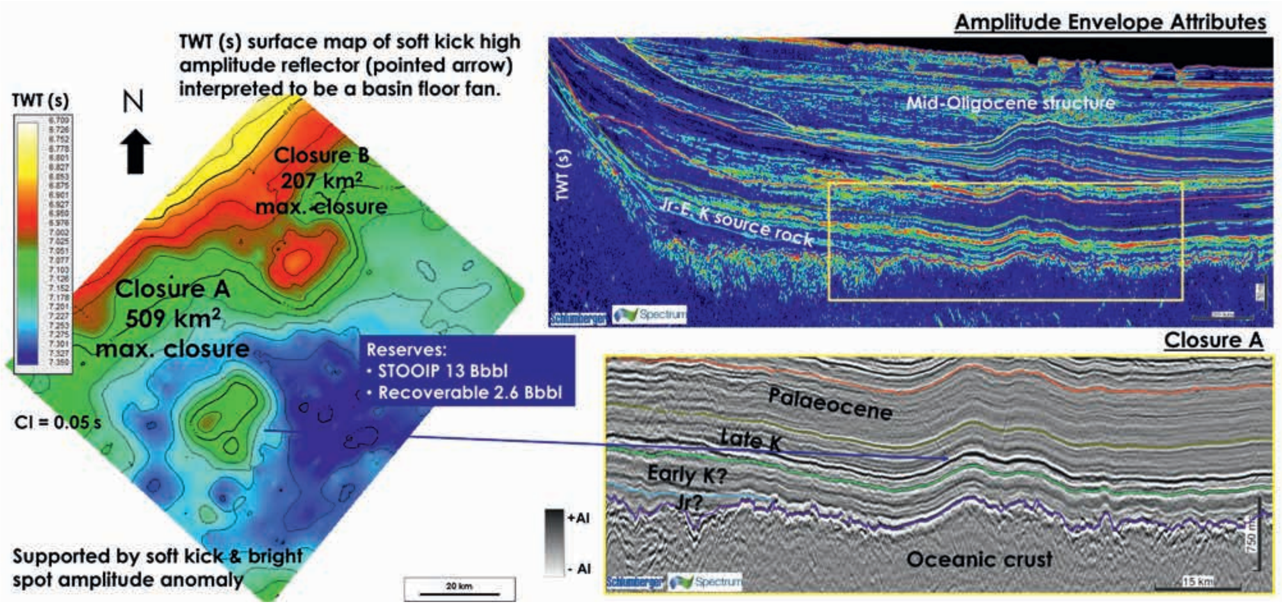

Figure 8 Example of potential Cretaceous basin floor fan play within the structural trap in the Early Cretaceous interval.

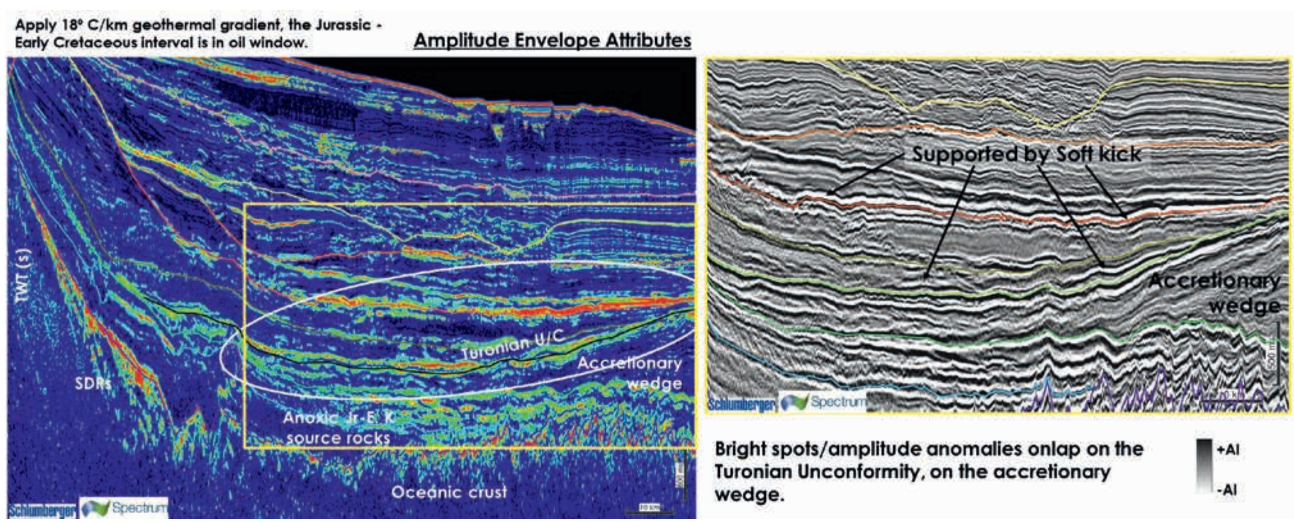

Figure 9 Example of Post-Turonian combined structural and stratigraphic trap associated with the accretionary wedge of the DSZ (in white circle).

fans and channel onlaps on the accretionary wedge, basin floor fan onlaps towards the uplifted shelf, sheeted sands within contourite waves, turbidite channels, sheeted sands and basin floor fans within mixed turbidite and contourite system, and carbonate build ups. Examples of Late Cretaceous basin floor fan four-way dip closures formed in the Mid Oligocene (closures A and B), are illustrated in Figure 8. These structures may be related to a late compression or reactivation of the DSZ. The four-way dip-closed A and B structures have up to 509 and 207 km2 maximum closure areas respectively. These closures are also supported by soft kick high amplitude reflector (pointed arrow in Figure 8) and bright spots on seismic envelope attribute.

An example of combined structural and stratigraphic trap onlapping on the Turonian Unconformity, the accretionary wedge of the DSZ, is demonstrated in Figure 9. There are two post-Turonian intervals of bright amplitude anomaly showing soft kick seismic reflectors. This post-Turonian onlapping play is commonly identified within the compressional structure of the accretionary wedge all the way along the DSZ within the Mozambique margin. This play could be sourced from the Jurassic and Early Cretaceous source kitchen all the way along through up-dip migration on the accretionary wedge structure. The Late Cretaceous nearshore marine sandstones (Grudja Formation) are the main reservoirs in the Pande, Buzi, Tamane and Inhassoro fields in southern Mozambique, exhibiting up to 30% porosity and up to 5000 mD permeability (Matthews et al., 2001).

Based on our observation, potential plays associated with a mixed turbidite and contourite system are mostly dominated within the upper post-rift section (post-Turonian Unconformity). Enhanced clastic reservoir quality is expected from turbidite systems interacting with strong contourite or slope parallel drift bottom currents which in such systems are thought to winnow turbidite currents flowing down dip, taking away the silty fines and leaving sand reservoirs of exceptional quality. The best examples are from the near-by Rovuma Basin, such as the Lower Eocene Coral reservoirs (Palermo et al., 2014).

Conclusion

New 2D seismic data acquired in the Angoche Basin has shed new light on the geology of the Davie Ridge. This is now observed to represent an incipient stage of a failed Cretaceous (pre-Turonian Unconformity) subduction zone, separating oceanic crust to the west from hyperextended continental crust to the east. This subduction ceased in the Late Cretaceous period (pre-Turonian Unconformity).

Petroleum systems in the Angoche Basin strongly indicate the presence of a working oil generative system. Low geothermal gradients are likely to have only buried the Jurassic and Cretaceous source rocks into the peak oil window recently, unlike the hotter more gas-prone Rovuma Basin to the north. A large number of structural and low-risk stratigraphic traps are observed within this basin indicating that the Angoche margin and Davie Subduction Zone is now ready to explore for its exciting, world-class oil potential.

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