# Offshore Somalia: crustal structure and implications on thermal maturity

**Roxana Stanca[1], Hannah Kearns[2*], Douglas Paton[1], Neil Hodgson[2], Karyna Rodriguez[2] and Abdulkadir Abiikar Hussein[3]** **integrate newly acquired long offset seismic data with wells and regional satellite gravity and magnetic data to critically assess the structural configuration, and map the continental to oceanic crust transition.**

The crustal structure along the passive margin of offshore Somalia has remained largely unknown, due to limited geological and geophysical data collection during the long period of political instability and civil war. The extent of geological information in the area has for many years been restricted to regional-scale features defined from poor quality legacy seismic data (Bunce and Molnar, 1977) and potential field data (Coffin and Rabinowitz, 1987; Rapolla et al., 1995). These observations allowed the development of early plate reconstruction models for Africa and Madagascar.

However, since 2012 the region has experienced a period of relative political stability following the inauguration of the Federal Government of Somalia. Two 2D seismic acquisition programmes were undertaken in 2014 and 2016. The newly acquired seismic data have facilitated the development of new theories and understanding of the evolution of the Somalian passive margin (Kearns et al., 2016). In this study, we integrate newly acquired long offset seismic data with wells and regional satellite gravity and magnetic data, to critically assess the structural configuration, and map the continental to oceanic crust transition. We use gravity modelling techniques to support our observations. We also discuss the possible implications of our findings on source rock thermal maturity.

## Geological background

Several regional tectonic events, primarily related to plate reorganisation associated with the closure of the Tethys Ocean and the opening of the Indian Ocean, have shaped the Somalian margin. These superimposed tectonic events are responsible for the present day structural complexity of the East African coast, its crustal architecture and overall geometry, and are crucial to understanding the evolution of the western Indian Ocean.

The initial Karoo rifting of Gondwana began in the Late Carboniferous/Early Permian and culminated in the separation of East Africa and East Gondwana (Macgregor, 2015). This rift-valley was orientated NE-SW, developing a central attenuated crust. However, break-up of Somalia and the Madagascar-Seychelles-India (MSI) block occurred in the Early Jurassic (Bossellini, 1992), as the separation axis was E-W, such that the MSI Block drifted due-south. The western margin of this transform movement was controlled by the N-S orientated Davie Fracture Zone to the west, whilst the Auxilliary Rescue and Salvage (ARS) Fracture Zone, Dhow Ridge and Very Large Crude Carrier (VLCC) Ridge accommodated extension to the east (Bunce and Molnar, 1977). This transform movement left the Somalian margin with a continental half-rift (or hyper-extended crust) fragment to the north, bounded by the ARS transform, and oceanic crust to the south, as will be discussed below.

We propose that the Jurassic rifting coincided with a marine transgression and the deposition of organic-rich marine sediments in a restricted embayment, where northerly transform faults created partial barriers to oceanic circulation. Following the separation of East Africa and the MSI Block, the Seychelles and India rifted from Madagascar, and India subsequently separated from the Seychelles and drifted northwards through the Late Cretaceous and Palaeogene.

Throughout the Cretaceous, northern Somalia saw the deposition of a marly-mudstone sequence, distal to an aggradational carbonate platform. Cenozoic sediments are characterized by a thick aggradational passive margin carbonate platform sequence or pro-platform marly mudstones. On the southern Somalian margin, clastic input from the Shabeelle/Juba/Tana River Deltas during the Early Cretaceous deposited a significant post-rift pro-deltaic sequence with a number of surfaces acting as décollements following slope failure events active through to the present day. This pro-deltaic sequence provides potential Late Cretaceous (Cenomanian/Turonian) and Eocene source rock intervals in the southern basin. The Palaeogene consists of predominantly deltaic clastics capped by thick marls, overlain by Miocene and younger deltaics and platform carbonates.

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## Methodology

Both the 2014 and 2016 2D seismic datasets have been used in this study. The 2014 dataset consists of 195 lines with a record length of 9s TWT, with variable line lengths extending as long as 230 km offshore, and line spacing of approximately 10 km; total line length is 20,500 km. The 2016 dataset consists of 76 lines with a record length of 15 s TWT, with variable spacing and line lengths extending up to 380 km offshore, totalling 20,185 km. Whilst the processing of the 2016 dataset was in progress at the time of writing, fast track processed pre-stack time migrated lines were available. Final PSTM products will be completed in December 2016.

The Meregh-1 well (shallow offshore, direct tie) and DSDP wells 234 (direct tie) and 241 (indirect tie) were used for age correlation. Meregh-1TD was in Middle Jurassic deposits, DSDP 241 reached 1174 m in Upper Cretaceous sediments, and DSDP 234 TD was in Lower Oligocene sediments.

Regional magnetic anomaly data are available as part of the Earth Magnetic Anomaly Grid (EMAG2) and represent a compilation of satellite, ship, airborne and ground surveys. The total magnetic intensity anomaly map has been used for mapping the extent of the oceanic crust towards the shore. Oceanic crust is characterized on magnetic data by linear anomalies that have developed perpendicular to the spreading direction. Gravity data used are residual Bouguer and free air gravity anomaly maps covering the East Africa region.

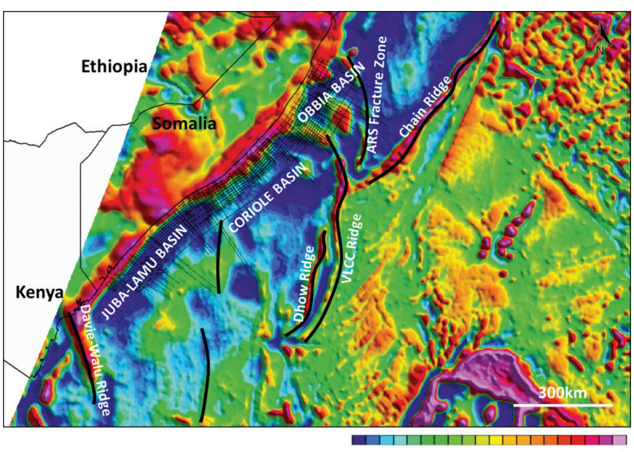


*Figure 1* *Free Air gravity anomaly map showing the three offshore sub-basins: Obbia, Coriole & Juba-Lamu. Spectrum 2D surveys shown in black.*

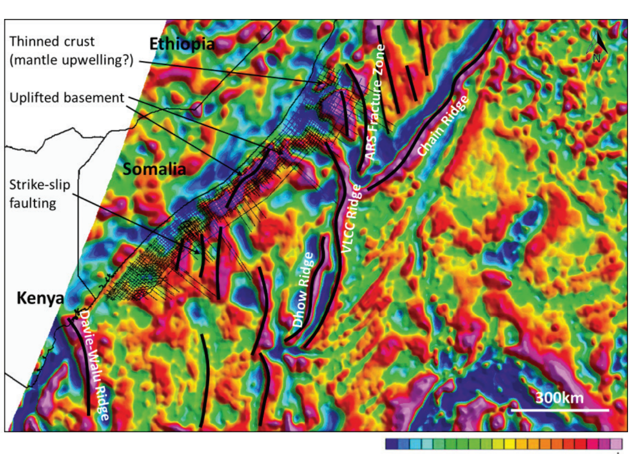


*Figure 2* *Residual Bouguer gravity anomaly map offshore Somalia showing interpreted lineaments.*

## Unravelling the crustal structure of the Somalian margin

Offshore Somalia can be divided into three basins based on the analysis of Free Air Gravity data: the Obbia Basin in the North, Coriole Basin in the centre, and the Juba-Lamu Basin which extends southwards into Kenya (Figure 1).

Residual Bouguer gravity anomaly data for the Somalian margin show extensive N-S to NNE-SSW linear features along the Chain Ridge, ARS Fracture Zone and the VLCC and Dhow Ridges; the VLCC Ridge extends perpendicular to the coast (see Figure 2). Smaller positive lineaments can be traced; their orientations correlate with the fracture zones. Other positive features do not appear to follow a trend and may be related to localized basement uplift or crustal thinning, as observed on the seismic data. Parallel to the coast, positive anomalies also indicate a shallow basement level.

Total magnetic intensity anomaly data are used as an initial guide for interpreting the extent of oceanic crust, which is characterized by linear, parallel anomalies (Figure 3). This is corroborated on seismic on many of the longer 2016 lines, which show 15 seconds of record length and allow the Moho and Continent-Ocean Boundary (COB) to be identified and mapped. Along the margin there is a large variation in the position of the COB relative to the coast and shelf, with the COB starting as close as 100 km to the present day coastline in the south, whilst extending to 300 km from the coast in the north.

In the north, the characteristic magnetic stripe pattern of oceanic crust appears sheared, which may be remnant deformation from the drift of Madagascar. Seismic data indicate that the continental crust exhibits a wide necking zone (around 200 km), reflecting a hyperextended margin up to 300 km offshore including an exhumed mantle domain. Such hyperextended crust is weak and deformation-prone due to crustal thinning and partial replacement of peridotite by serpentinite (Doré and Lundin, 2015), and this is reflected by significant inversion in the Coriole basin adjacent to north-south transform faults.

In the south, the necking zone of the crust is much narrower (around 80 km), as interpreted on seismic data by imaging of Moho underlying pillow basalt oceanic crust. Isolated positive anomalies along the margin are associated with the presence of basic intrusions and shallow basement. The COB is interpreted to lie close to the base of the continental slope. The magnetic response appears reduced here, however the acoustic appearance and thickness of the crust on the seismic data is characteristically oceanic. The reduced magnetic response may be due to the presence of a thick deltaic sediment pile, sourced by the Shabeelle/Juba/Tana River Deltas, or related to the 'Jurassic Quiet Zone'- an 11Ma gap between the onset of seafloor spreading and the development of the first conjugate magnetic anomalies in the Somali Basin (Davis et al., 2016).

The Somalian passive margin may be classified as a non-volcanic rifted margin as it displays limited volcanism associated with the Early Jurassic rifting, and no seaward dipping reflectors (SDRs) have been identified in the area. The low level of rift-related magmatism is considered a reflection of the slow spreading rate, and the nature of the southerly drift oblique to the pre-cursor NW-SE rifting. Early marine transgression during Jurassic rifting that accompanied the deposition of syn-rift source rocks would have precluded deposition of subaerial flood basalts (SDRs) in favour of mid ocean ridge pillow lavas typical of oceanic crust.

## Constraints on extension and compression deforming the post-rift section

As there is a marked difference in crustal architecture between the Obbia (north) and Juba-Lamu (south) Basins, it is unsurprising that the subsequent fabric of the post-rift/drift sections in these basins is also highly variable. Different transitional zones have been identified on seismic sections, forming as the rift propagated (Doré and Lundin, 2015). The structural pattern along the margin is complex, generated by superimposed deformation stages, from syn-rift-related normal faulting to strike-slip movement and inversion generated during the Mesozoic-Cenozoic plate reorganisation in the Indian Ocean. The sediment nature and distribution is also varied along the margin, with significant thickness variations controlled by the tectonics, sedimentary environment and

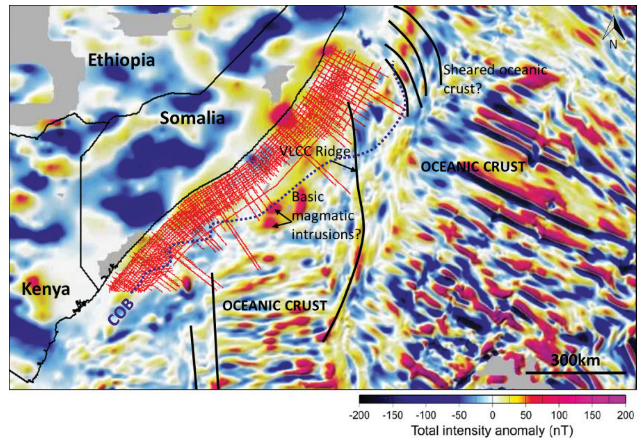


***Figure 3*** *Total magnetic intensity anomaly map offshore Somalia, showing interpreted intrusions and COB.*

sediment input from fluvial sources. We discuss the northern and southern basins separately below.

The Obbia Basin in the north is characterized by pre-rift Karoo and older sediments, rotated by large listric Jurassic faults. The half-grabens formed by this structuring are filled with syn-rift deposits (Figure 4). The Mesozoic post-rift sequence is associated with normal faults closest to the coast, suggesting later activity as a result of plate reorganisation following rifting. Indeed towards the shelf, onlapping Cenozoic strata indicate the basement may have been uplifted at a later stage, suggesting a complex development of sequences in this area. A rigid-body restoration was compiled to show the progressive stages (Figure 5).

The identification of significant pre-rift reflectivity and the presence of syn-rift packages imply a continental origin, transitioning into oceanic crust in the easternmost part of the line. At ~10 s TWT, a strong reflector has been

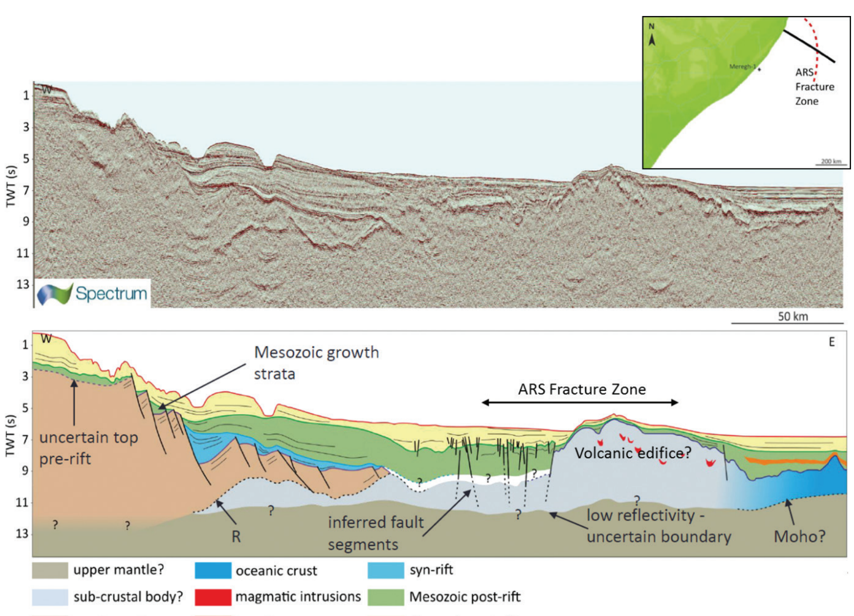


***Figure 4*** *Dip line in Obbia Basin. Structural high in the ARS Fracture Zone has an associated high gravity response and has been interpreted as a volcanic edifice, but could also be interpreted as exhumed mantle. We explore this line further using gravity modelling.*

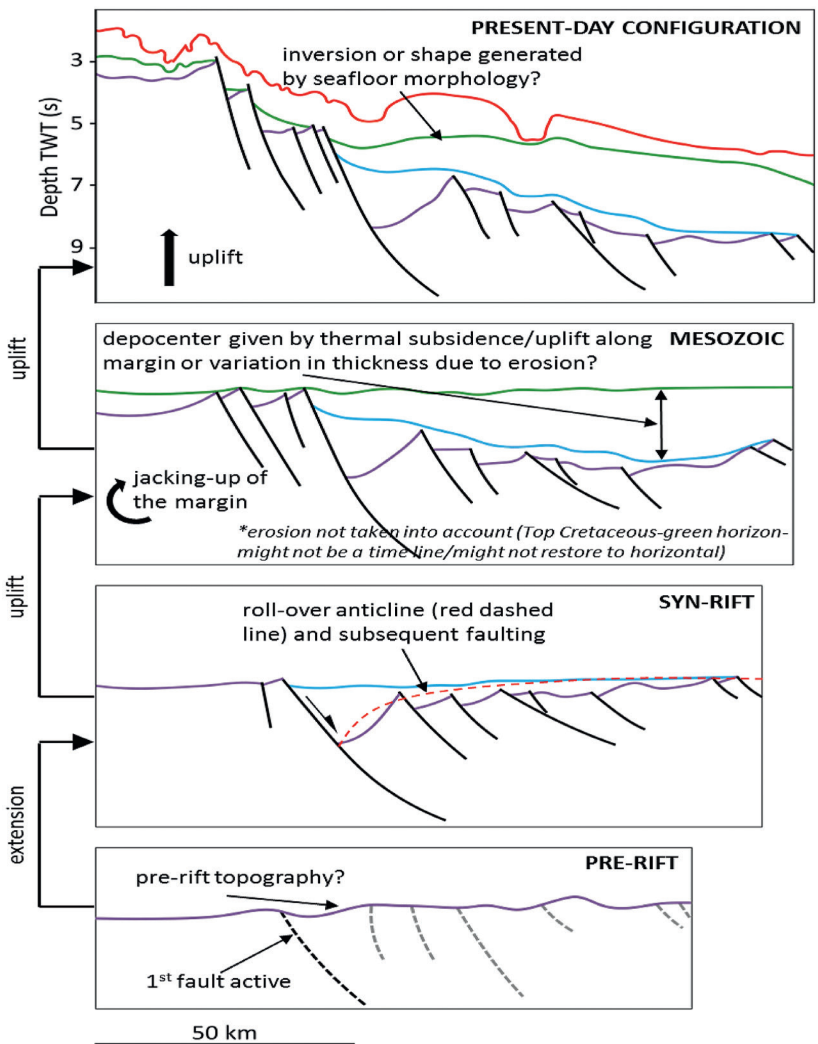


*Figure 5* *Restoration of the interpreted continental segment of dip line from the Obbia Basin (see line in Figure 4); key horizons restored are top Cretaceous (green), top syn-rift (blue) and top pre-rift (purple).*

identified that shallows basinward to 9 s TWT, which may be interpreted as either intra-crustal reflectivity, or the Moho discontinuity. In either scenario, the section shows evidence of crustal hyperextension, where the lower and upper crust are coupled and embrittled and major faults can be seen penetrating to the lower crust/mantle. This may lead to hydration and serpentinisation of the upper mantle (Doré and Lundin, 2015). It would imply a crustal thinning from 8.5 s TWT in the west to <1 s TWT outboard (with β potentially increasing to infinity into a possible exhumed mantle domain).

Outboard of the termination of the rotated crustal fault blocks, the section is highly deformed and may reflect the presence of exhumed mantle. Beyond this, which we interpret as having crossed a north-south transform zone, an uplifted body is observed. This is labelled ARS Fracture Zone in Figure 4, displaying a chaotic internal seismic structure, capped by a high amplitude reflector, and intruded by numerous saucer-shaped high amplitude reflectors (volcanic intrusions). The Moho reflector is indeterminable; this block has a number of possible interpretations, from a fragment of continental material or tectonically uplifted basement block drawn into the section from across the transform fault, to an exhumed mantle domain or a magmatic edifice. We discuss this uncertainty further when we consider the gravity response.

To the south, the Juba-Lamu basin is interpreted to be underlain by oceanic crust (Figure 6). A reflector observed at ~2 s TWT below the acoustic basement, and lying between 10 s and 11 s TWT is interpreted to be the Moho discontinuity. The oceanic crust here is highly faulted, consistent with a slow spreading rate.

The continent-ocean boundary occurs beneath thick Cretaceous and Tertiary clastic sequence, deformed by several episodes of gravity sliding and shelf collapse. Gravity sliding occurs in several discrete episodes; the first in the Late Cretaceous, with a Cenomanian-Turonian décollement surface, and the second in the Late Tertiary with an Eocene

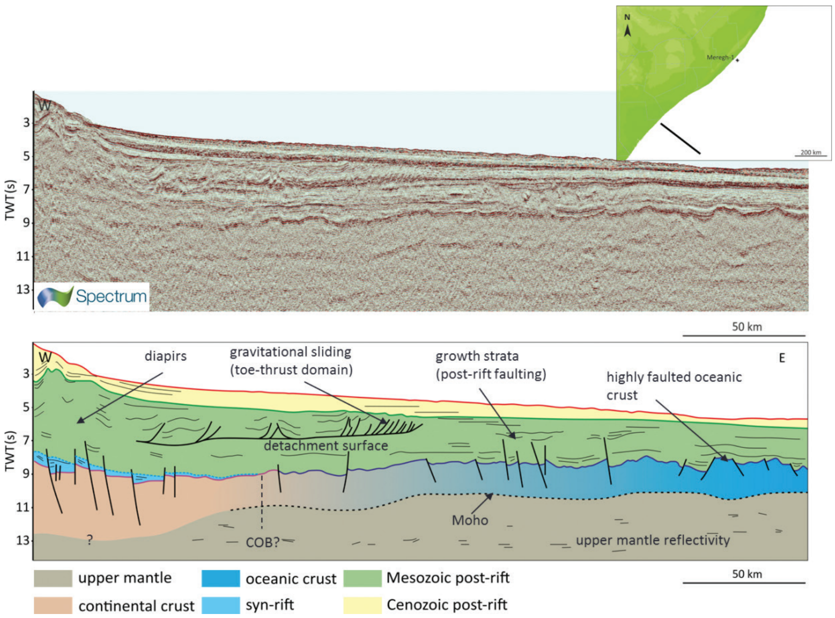


***Figure 6** Dip line in the Juba-Lamu Basin.*

décollement surface. It is proposed that these décollement surfaces are candidates for being source rock indicators, where sufficient burial had begun to mature organic material, reducing viscosity/ increasing pore pressure and facilitating low angle displacement. This suggests that we may have multiple, stacked source rocks in the Juba-Lamu Basin. An alternative explanation is that during northward drift of the African continent since the Jurassic, the basin has suffered repeated periods of rapid subsidence, resulting in over steepening of the margin.

Whilst the post-rift succession is affected by a younger generation of normal faults, shale diapirism is observed in parts of the gravity slides. Rabinowitz et al. (1982) describe the diapirs as comprised from Early Jurassic salt, as salt was drilled in an isolated basin along the coast of Tanzania. However, recent interpretations describe shale-cored anticlines, as Jurassic sections encountered by wells consist mainly of siliciclastic deposits and carbonates (Cruciani and Barchi, 2016). Modern data show coherent Cretaceous reflectivity below the in-slide diapirs with no associated velocity pull-up, indicating that these are likely to be disequilibrium compaction-related shale diapirs rather than Jurassic salt.

Three clearly defined structural trends on the margin are observed to have developed at various times (Figure 7). A Cretaceous-Cenozoic compressional/transpressional component overprints the dominantly rift and drift extensional character of the area. The driving force of the inverted structures observed along East Africa is considered to be due to: Periodic basin subsidence causing slope oversteepening and gravitational slumping/mass transport complexes, which develop down-dip localized toe-thrusts (Kearns et al., 2016); Far-field stresses causing a regional inversion of the basin (e.g. the influence of the Red Sea – Gulf of Aden spreading centres) (Morley et al., 1999), the rotation of India (Reeves, 2014), the opening of the Atlantic and the rotation of the African plate (Ernst and Buchan, 2001); Transpression related to the movement along transform faults as East

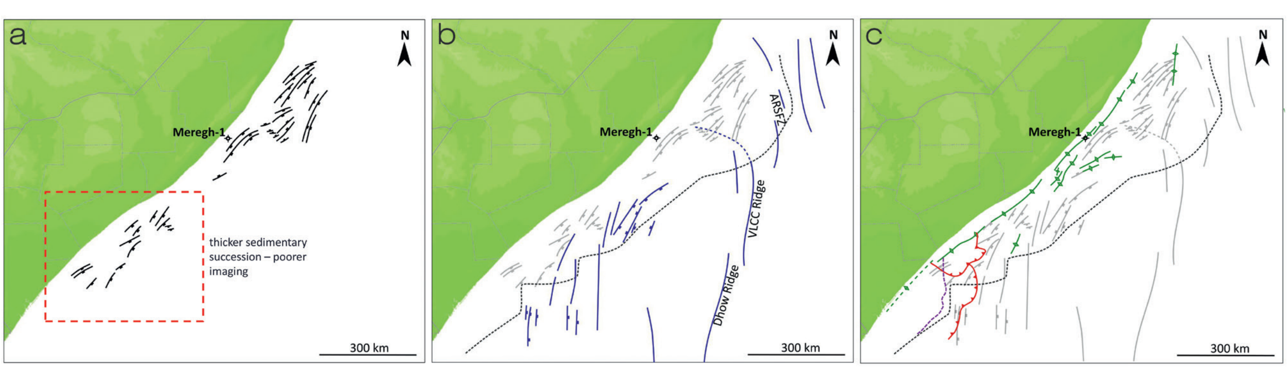


***Figure 7** Structural maps constructed using a combination of gravity, magnetic and seismic interpretation. (a) Early Jurassic rifting stage, characterized by NE-SW extensional faulting; (b) Late Jurassic drift stage, characterized by N-S orientated strike-slip faulting; (c) Cretaceous to Recent post-rift, characterized by NE-SW compression, with gravitational sliding and diapirism in the Juba-Lamu basin.*

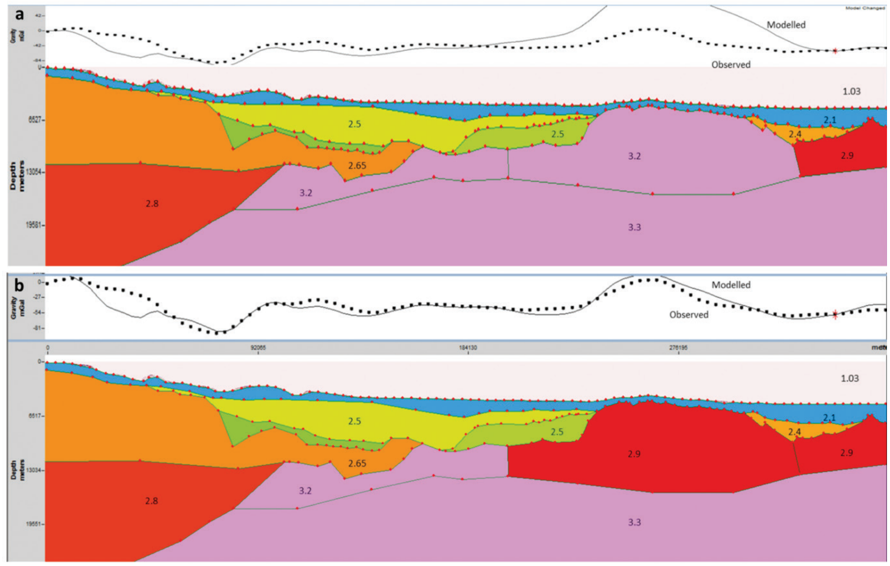


***Figure 8*** *a) Exhumed mantle scenario in the area of uncertainty between continental and oceanic crust (density of 3.2 g/cm²); b) Exhumed mantle outboard of the stretched continental crust but the edifice of magmatic origin (density of 2.9 g/cm²).*

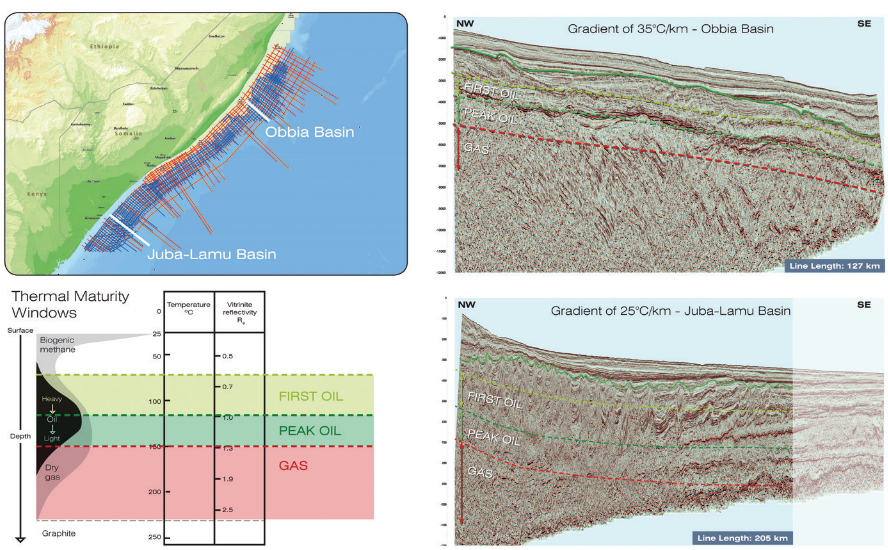


***Figure 9*** *PSDM examples from the Obbia and Juba Lamu Basins. Approximate oil windows are based on geothermal gradients measured from nearby wells.*

Gondwana drifted southward (Kearns et al., 2016), generating high relief inboard folds, and low relief broad basin inversion anticlines in outboard settings.

## Gravitational corroboration of seismic interpretation

The interpretation of the seismic profile across the Obbia basin (Figure 4) highlights that even with high fidelity data in frontier areas, there remains uncertainty in the definition of crustal type. To address this we model the gravity response of the profile and compare that with satellite-derived gravity observations. In all of the models, the gravity signature is consistent with a rapidly thinning continental crust in the east and oceanic crust in the west. As gravity modelling provides a non-unique solution, we undertake a suite of scenarios and show two alternative models to illustrate the key areas of uncertainty, which are located between stretched continental crust and the oceanic crust.

In the first scenario (Figure 8a) we model exhumed mantle (density of 3.2 g/cm²) across this zone and, while the middle of the section generates a close correlation between observed and modelled, there is a clear mismatch immediately prior to the west of the oceanic crust. Although hydrated/serpentinised mantle may have lower densities than that of exhumed mantle, it is difficult to have the bulk reduction in density required. The alternative scenario (Figure 8b) has exhumed mantle outboard of the stretched continental crust but has the edifice as a magmatic origin (density of 2.9 g/cm²). This provides a close match between observed and modelled gravity response. The preferred model is one in which the crust is hyper-extended but that the ARS fracture zone juxtaposes a volcanic edifice against the exhumed mantle.

## Crustal architecture to Source Rock Maturity – completing the circle

Onshore and shallow nearshore well data show trends of increasing geothermal gradients from south to north, and thus a shallowing of the oil window is expected towards the north. This observation ties to the observation of hyper-extended continental crust in the north, understood to have a higher heat flow, relative to interpretation of old (and cold) Jurassic oceanic crust in the south. A higher geothermal gradient in the north is modelled to put the syn-rift Jurassic source and pre-rift Karoo source rock in the present day oil window as post-rift sediments in the north are typically not more than 4s TWT thick in the deep offshore (Figure 9).

Wells onshore in the Juba-Lamu Basin in the south display much lower geothermal gradients consistent with being underlain by, or close to, Jurassic oceanic crust. The oil window in the south is therefore predicted to lie much deeper. The Juba-Lamu Basin has the thickest post-rift stratigraphy over the shelf and slope, up to 12 km. It comprises siliciclastic deltaic sediments, sourced by the Shabeelle/Jubba/Tana River Deltas, and is thought to consist of organic rich pro-delta shales and turbidite deposits. Source rock intervals are inferred from décollement surfaces in the Cenomanian and Eocene. As both of these intervals are shallower than the syn-rift source rock, assisted by low geothermal gradients we model these horizons to be in the oil window present day, as is the Jurassic syn-rift source in the outboard setting (Figure 9).

## Conclusions

An integrated study of modern high spec seismic, gravity and magnetic data, supported by gravity modelling, reveals a new understanding of the crustal structure of offshore Somalia. Hyper-extended continental crust is present in the north of the area (Obbia Basin) associated with high heat flow and shallow syn-rift source in the peak oil-generating window. Oceanic crust underlies the thick clastic sequence in the Juba-Lamu Basin in the south, where low heat flow puts the more deeply buried Eocene, Late Cretaceous and even syn-rift Jurassic source rocks in the oil-generating window.

This new understanding of crustal architecture suggests that the Somalian margin has a number of exciting exploration plays to provide the next wave of explorers with the rarest of east African prizes – rapidly monetizable oil.

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