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Geology and hydrocarbon potential of offshore SE Somalia

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Abstract: Interpretation of a 20 550 line km 2D seismic survey acquired in 2014 by Soma Oil and Gas in the deep water offshore area of SE Somalia has identified three previously undocumented sedimentary provinces – Jubba Deep, Mogadishu Deep and Mid Somalia High – all of which have distinctive geological characteristics. Well and stratigraphic controls are limited, with inferred lithologies largely based on seismic stratigraphic interpretation.

The Jubba Deep has a thick Late Cretaceous–Early Tertiary deltaic section deformed by major gravitational collapses in the Paleocene-age Kismaayo Thrust Belt (KTB) and the Pliocene-age Baraawe Thrust Belt (BTB). It is proposed that the KTB has significant hydrocarbon potential in deltaic and pro-delta sands trapped in thrust anticlines and sourced with oil from Mid-Cretaceous mobile shales.

The Mogadishu Deep Basin has a thick Mesozoic and Tertiary section but is missing the thick deltaics seen in the Jubba Basin. Volcanics are present in this basin.

The Mid Somalia High has a relatively thinner sedimentary section where Cretaceous and Jurassic reservoirs and potential source rocks are at moderate burial depths. An extensive post-rift Mid–Late Jurassic carbonate platform is developed here with potential hydrocarbon targets in interpreted reefs and shoal facies.

Supplementary material: Additional seismic examples and map figures are available at https://doi.org/10.6084/m9.figshare.c.3902650

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Background and 2D survey acquisition

Following a review of the regional geology and hydrocarbon prospectivity of Somalia, Soma Oil and Gas acquired a 20 550 line km 2D seismic survey in the deep offshore area of SE Somalia in 2014. The location of the survey is shown in Figure 1.

The acquired data cover the deep-water area from close to the disputed border with Kenya to a point some 1200 km to the NE where major transform lineaments intersect the Somalia coast. The survey excludes the shallow-water areas where Pecten (a subsidiary of the Royal Dutch Shell Group) holds legacy exploration rights which are currently in force majeure. The outboard limit of the survey was set at a water depth of *c.* 3300 m. The 2D data were acquired on a basic grid of 10 × 20 km, and supplemented by an additional 4000 line km of infill over areas of interest identified from interpretation of on-board processed data.

The only previous seismic data in the survey area are three regional seismic lines in the south acquired by Lamont Doherty in 1980, now available through the University of Texas IOG website, which have been discussed by Coffin & Rabinowitz (1992), Cruciani & Barchi (2016) and Cruciani *et al.* (2017), while industry seismic acquired in shelfal waters in the 1970s and 1980s also have some limited extensions into the deeper water. However, the general structure and stratigraphy over most parts of the survey area were entirely unknown prior to the 2014 Soma 2D survey.

Basin configuration

From the 1960s to 1990, patchy 2D seismic surveys were acquired in the coastal onshore of SE Somalia and in shelfal areas offshore, with 25 wells drilled in the onshore coastal areas. Two offshore wells were drilled, Meregh-1 (1982), which is discussed below, and Garad Mare-1 (1977), which lies in a different geological province to the north of the survey area. Barnes (1976), Harms & Brady (1989*a*, *b*) and Bosellini (2008) established a stratigraphic nomenclature and basin structure in the onshore and shelfal regions. However, correlation of these stratigraphic units and basins to the deep-water offshore area is problematic due to the poor quality of the onshore and shelfal seismic, and the presence of a coast-parallel fault system downthrowing towards the deep offshore. Commercially available seismic also allow correlation to the Pomboo-1 well drilled in 2007 to the south of the survey area, as shown in Figure 1.

The onshore and shelfal basins adjacent to the deep-water study area have been named by Harms & Brady (1989*a*) as the Juba-Lamu Basin in the SW, the Coriole Basin in the area around Mogadishu and the Obbia Basin to the NE, as shown in Figure 2. However, the deep-water offshore basins are sufficiently different in depositional setting and tectonic development that a separate basin nomenclature is appropriate.

Hydrocarbon occurrences in several onshore wells in the area close to Mogadishu establish the presence of a working hydrocarbon system in this area. The Afgoi-1 well was completed as a non-commercial gas discovery (Harms & Brady 1989*a*), with a test in Late Cretaceous and Paleocene sandstones flowing at 7 MMcf/day gas plus 120 barrels (bbl) of condensate per day. Tests in Coriole-1 in the same area also recorded gas flows at lower rates and minor associated oil (44° API) from Late Cretaceous and Early Tertiary sandstones.

The deep-water basin configuration and nomenclature proposed herein is shown in Figure 2 and a schematic cross-section across the basins is provided in Figure 3. Three distinct deep-water offshore provinces are recognized: Jubba Deep to the SW, Mogadishu Deep in the central area and Mid Somalia High to the NE. Their boundaries are major transform and other faults related to Mesozoic oceanic spreading. These basins are interpreted to overlie stretched continental crust, although significant uncertainty remains in the

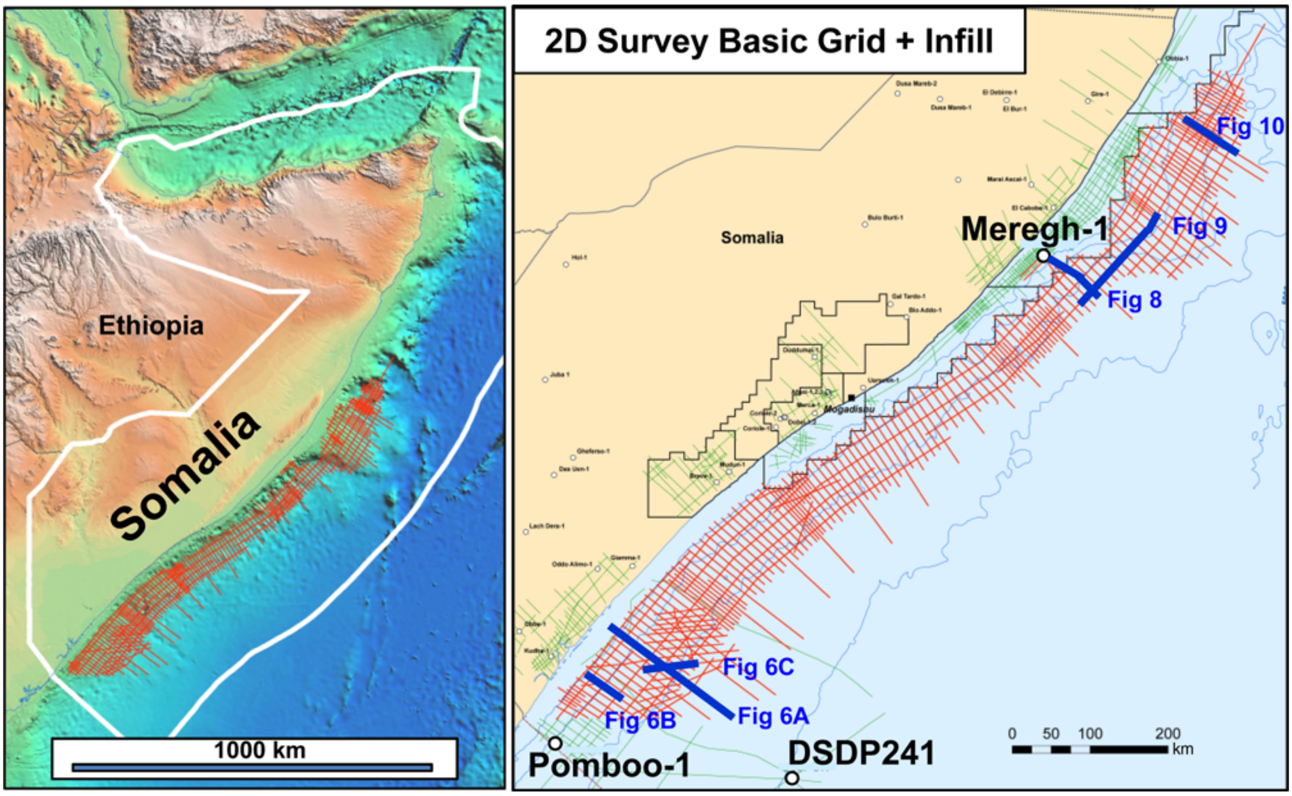


Fig. 1. Soma 2014 2D survey map and location of well ties. Soma data are shown as red lines; historical data as green lines. Locations of seismic Figures 6, 8, 9 and 10 are shown.

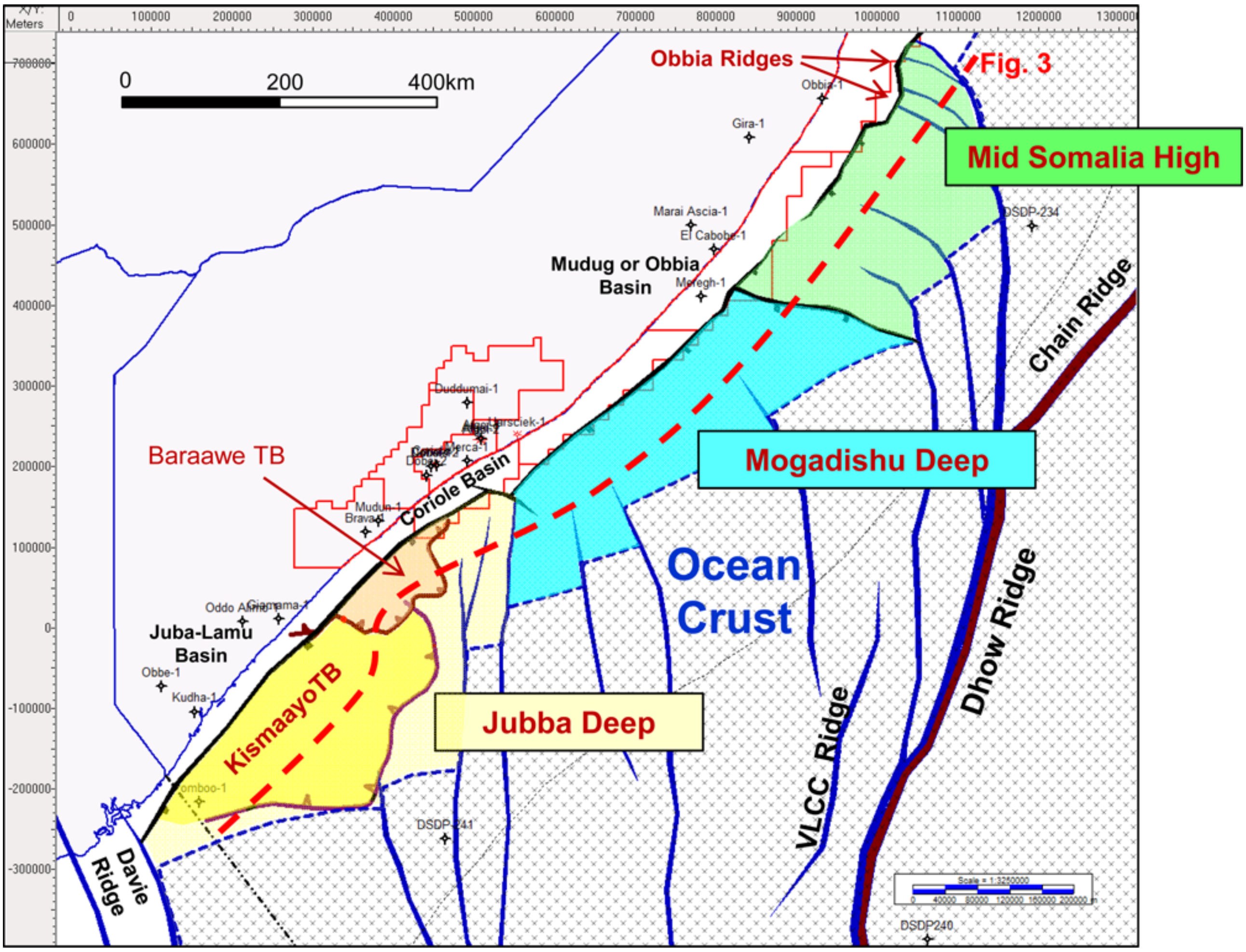


Fig. 2. Map of offshore SE Somalia provinces and tectonic elements. The line of the schematic cross-section (Fig. 3) is shown as a red dashed line.

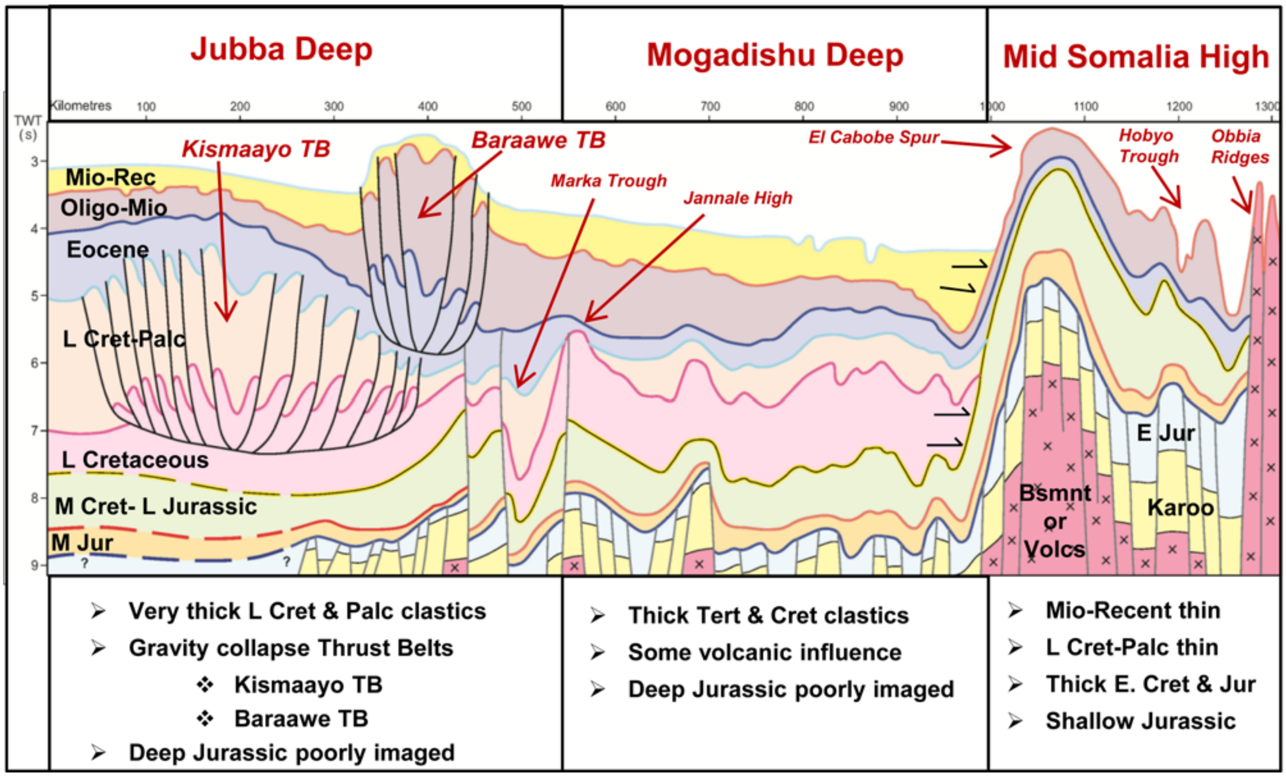


Fig. 3. Schematic SW–NE cross-section showing provinces, stratigraphy and structural elements in the deep offshore of SE Somalia. The line of the section is shown on Figure 2. TWT, two-way time.

position of the continent–ocean boundary and other interpretations are possible.

Early Jurassic rifting was followed by a period of ocean spreading between Madagascar and Somalia from the Mid-Jurassic until the Aptian when spreading ceased (Coffin & Rabinowitz 1992; Bosellini 2008). Structuring identified on the seismic data indicates that the region was subject to a number of post-Aptian tectonic pulses resulting in at least two significant unconformities of inferred Mid-Cretaceous and Miocene ages, reactivation of major faults and regional tilting. Seismic and gravity/magnetic data also provide evidence for Late Cretaceous–Eocene volcanic activity and WSW–ENE wrench faulting concentrated in the Mogadishu Deep Basin. A tentative stratigraphic chart for the three main areas is shown in Figure 4.

Jubba Deep Basin

The Jubba Deep Basin stretches from Kenyan waters northwards into Somalia to a series of large reactivated north–south transform faults which separate the Jubba Deep from the Mogadishu Deep. The basin is distinguished by a thick sequence of Late Cretaceous–Early Tertiary deltaic clastics, which were probably derived from river systems emanating from a proto-Anza Graben to the west.

Jurassic sediments probably underlie the entire Jubba Deep Basin where rotated fault blocks of pre-Jurassic age are overlain by a synrift sequence of presumed Early Jurassic age. The rift section is best imaged on seismic in the northern part of the basin where the younger deltaics are relatively thin.

Two extensive gravity collapse systems; the Kismaayo and Baraawe thrust belts, deform the Late Cretaceous and Early Tertiary deltaics in the Jubba Deep Basin, as shown in Figures 3 and 4.

Kismaayo Thrust Belt

The Kismaayo Thrust Belt (KTB), which covers some 60 000 km^2, developed mainly during the Paleocene with final movement in the Eocene, and is floored by a zone of décollement in mobile shales of interpreted Mid-Cretaceous age. The southern part of the KTB has previously been described by Cruciani & Barchi (2016) and Cruciani *et al.* (2017), who interpreted the Lamont Doherty seismic data. These authors reached similar conclusions to this paper on the age or the allochthonous section, the timing of gravity sliding and the mobile shale composition of the KTB slip plane. Elsewhere offshore East Africa, the similar, if smaller scale, gravity tectonics in the Rovuma Basin, Mozambique, have also been interpreted with a slip plane in mobile shales (Mahanjane & Franke 2014).

In 2007, Woodside drilled the Pomboo-1 well (under a licence issued by Kenya) on a thrust anticline at the southern end of the KTB. The well encountered a thick Late Cretaceous clastic sequence which included reservoir quality Campanian sands. No hydrocarbons were encountered. Possible reasons for failure might include trap formation post-dating hydrocarbon generation, migration barriers created by the thrust and slide planes, or a lack of effective source rock in this part of the KTB.

Figure 5 shows the tectonic elements recognized in the KTB. Most of the area is a compressional fold and thrust belt, with a central zone of translational and diapiric movement, and an updip extensional zone. The poor-quality onshore seismic data do not show any clear continuation of the extensional province into the onshore area.

A 190 km seismic transverse of the KTB is shown in Figure 6a, with details in Figure 6b and c. The early extensional listric faults over much of the updip part of the KTB were later reversed to form thrust anticlines in the shallower section (Fig. 6b). This late-stage inversion is interpreted to be due to a gradual build-up of friction on the downdip parts of the basal slip plane as the slide movement progressed, causing the compressional front to migrate updip as time progressed. No compression is observed in the section beneath the slip plane.

Diapiric structures in the Jubba Deep were previously interpreted by Coffin & Rabinowitz (1992) to be caused by Jurassic salt. However, the interpretation preferred here is that the mobile material in the KTB consisted of fluidized prodelta mud of Mid-Cretaceous

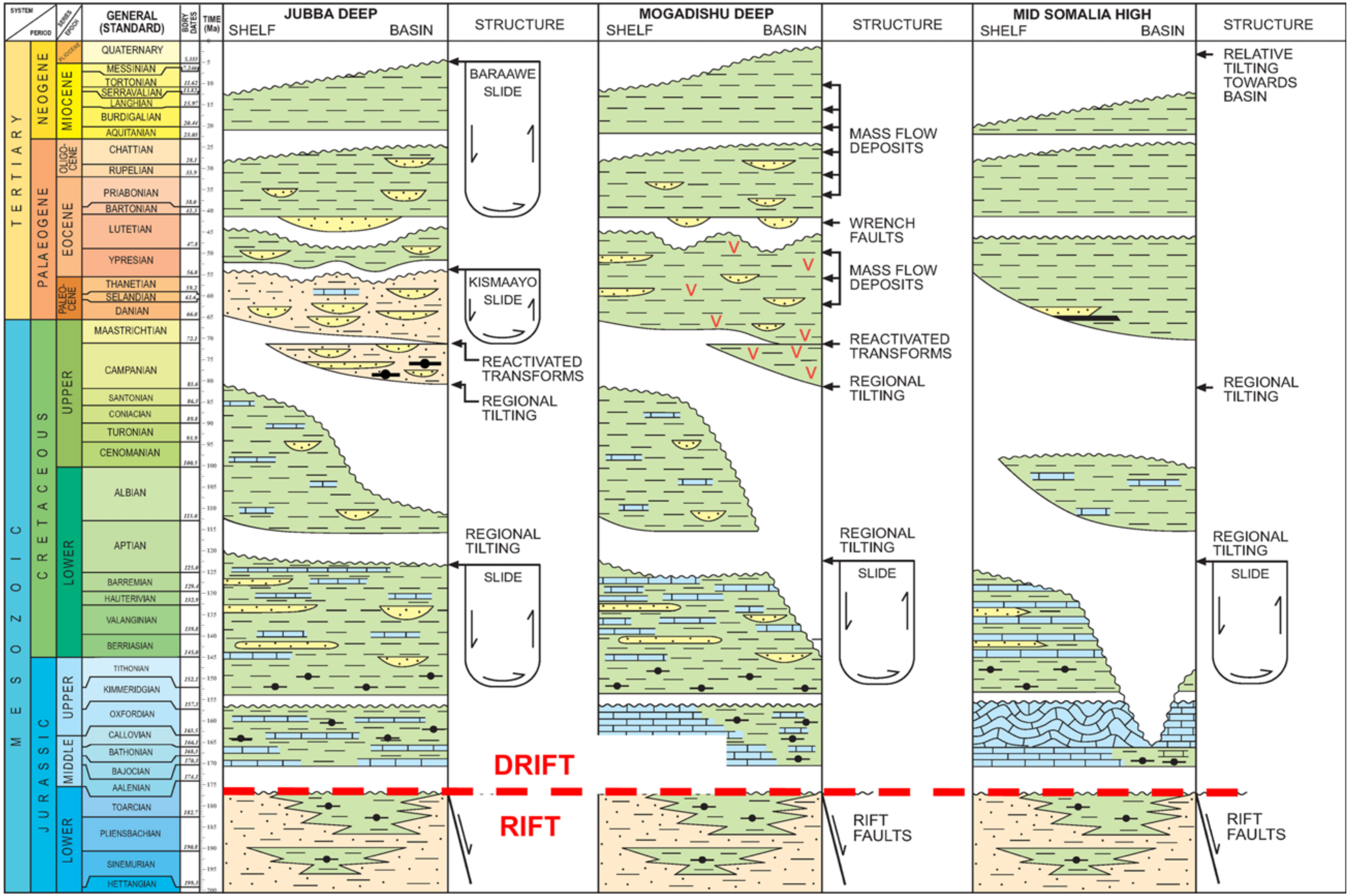


Fig. 4. Provisional stratigraphic chart for the three provinces of deep offshore SE Somalia. The chronostratigraphic interpretation is extrapolated from ties to three wells on the periphery of the survey and, hence, remains uncertain. Lithology is largely based on seismic stratigraphic interpretation.

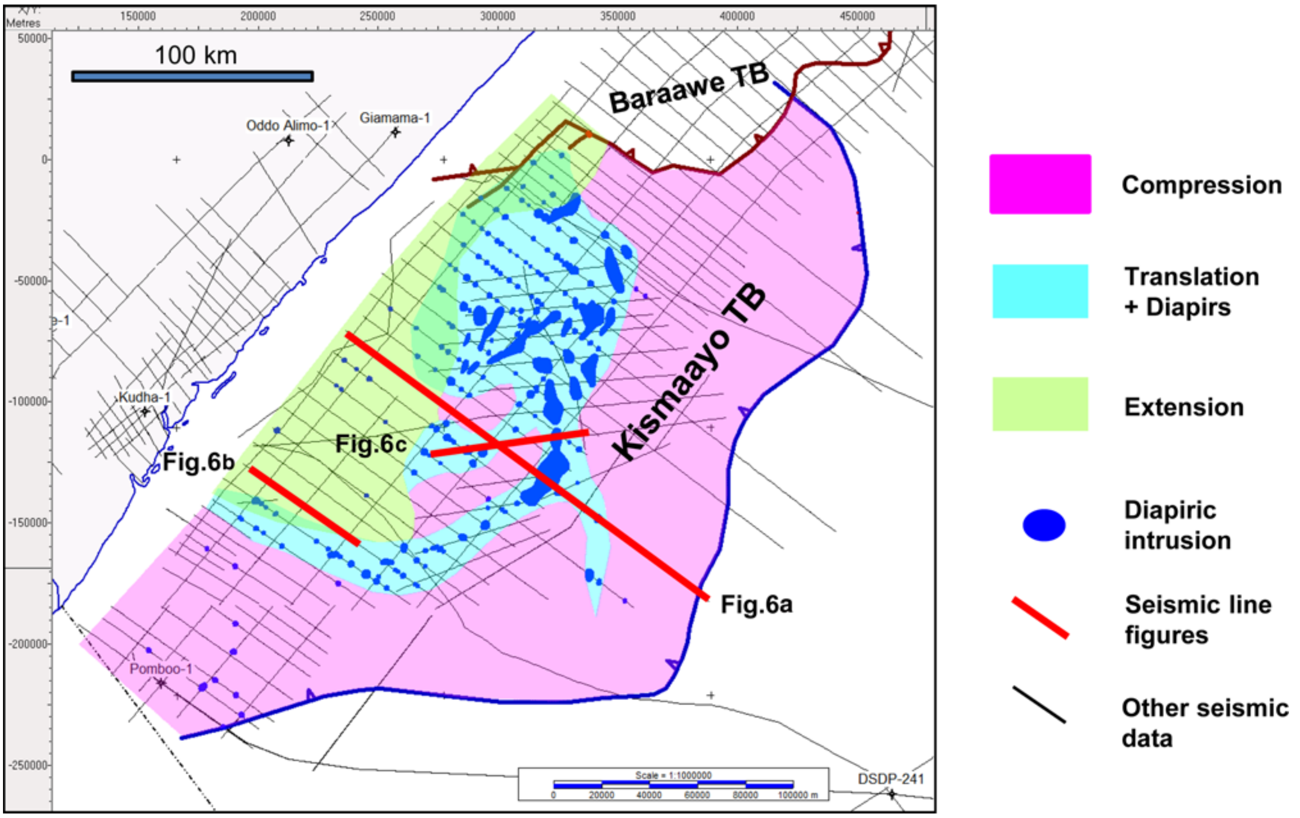


Fig. 5. Structural element map of the Jubba Deep Basin. The locations of the seismic lines in Figure 6 are shown.

age. This interpreted age is consistent with the long-distance well ties to DSDP241, Pomboo-1 and Meregh-1. Open-marine conditions prevailed in this area in the Mid-Cretaceous; hence, evaporite deposition would not have been not expected at this time.

The fluidized mud interpretation is supported by gravity modelling, which provides a good match to a mobile mud model but a poor match to salt, and is also consistent with the geometry of the diapirs which are thinner and more irregular than would be expected from salt (Morley *et al.* 2011). Interval velocities derived from the wide-spaced 2D seismic are not sufficiently accurate to be definitive on the lithology of the mobile layer, but the velocities that have been derived are lower than would be expected from evaporites.

Morley *et al.* (2011) stated that the presence of counter-regional thrusts in large deltas such as the Niger and Baram implies the presence of a thick mobile detachment layer, since thin detachments do not produce counter-regional faults. Hence, the presence of many counter-regional faults in the KTB supports the interpretation of thick mobile layer in this delta.

The outer parts of the KTB have a significant potential for hydrocarbon exploration. Thrusts in this area create very large structural closures, whilst the Late Cretaceous section shows ample seismic stratigraphic indications of deep-marine channel and fan sands which could provide potential reservoirs. Seismic amplitude anomalies, interpreted flat spots and amplitude v. offset (AVO) responses in the KTB suggest that trapped hydrocarbons may be present, as shown in Figure 7.

Baraawe Thrust Belt

The second major gravity collapse complex is the Baraawe Thrust Belt (BTB) located in Figures 2 and 5. The part of the BTB imaged by the Soma 2014 survey covers 12 000 km^2, and it extends NW of the survey limits towards the Somalia coast. Deformation in the BTB occurred in the Late Miocene–Pliocene, with a basal slip plane within the Eocene. The young age and relatively shallow burial of the BTB structures make them less prospective for hydrocarbon trapping compared to the KTB due to increased risks on migration, top seal and timing of trap formation relative to hydrocarbon generation.

Source rocks in Jubba Deep

Regional data (Webster & Ensign 2007; United States Geological Survey 2012) indicate that many of the proven source rocks in Madagascar and along the East Africa margin are Jurassic in age. However, the deep burial of the Jurassic in the Jubba Deep (overburden ranges from >9 km near the coast to *c.* 6 km at 200 km offshore) suggests that Jurassic sourced hydrocarbons would have generated at an early stage of basin fill and these sources are likely to be overmature in much of the basin at the present day. It is also likely that the basal slide plane of the KTB might form a barrier to the upwards migration of Jurassic-sourced hydrocarbons into the KTB thrust-related traps. No source rock facies are positively identified in the two onshore wells that penetrated the Jurassic in the area adjacent to Jubba Deep. However, one of these wells, Brava-1, drilled 200 km SW of Mogadishu in 1962, did penetrate Mid to Early Jurassic shales with a high gamma-ray log response, but no geochemical data are available to demonstrate source potential.

It is proposed here that a possible source rock for the Jubba Deep may lie in the thick mobile prodelta shales of Mid-Cretaceous age which form diapiric structures in the KTB and also constitute the slip zone for the KTB gravity tectonics. An analogy can be made to the Niger Delta where the mobile Early Tertiary Akata shales provide both a slip plane and hydrocarbon source (Bustin 1988), or the Baram and Mahakam deltas which are both associated with mobile shale and where the hydrocarbon sources are present within the deltaic depocentres according to Morley *et al.* (2011). These authors also note that mud diapirism in worldwide examples is generally associated with significant overpressure and that mobile muds often contain hydrocarbons. Overpressure may result from

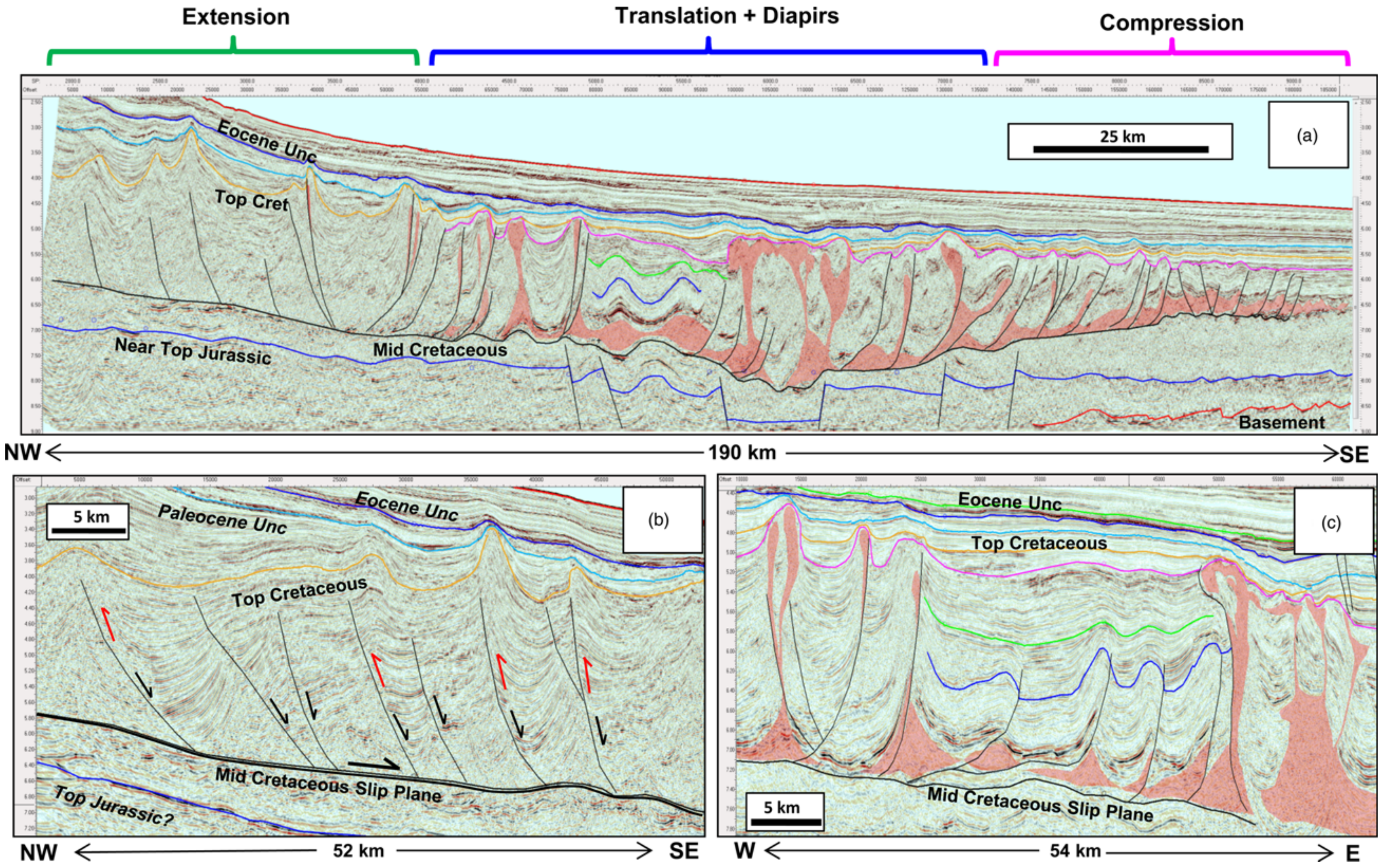


Fig. 6. (**a**) Regional NW–SE seismic line across Kismaayo Thrust Belt. (**b**) NW–SE line across the extensional zone, where late compression reversed early listric faults. (**c**) West–east line across the translational and diapiric zone of the KTB showing different periods of tectonic and diapiric growth. Locations are shown in Figures 1 and 5.

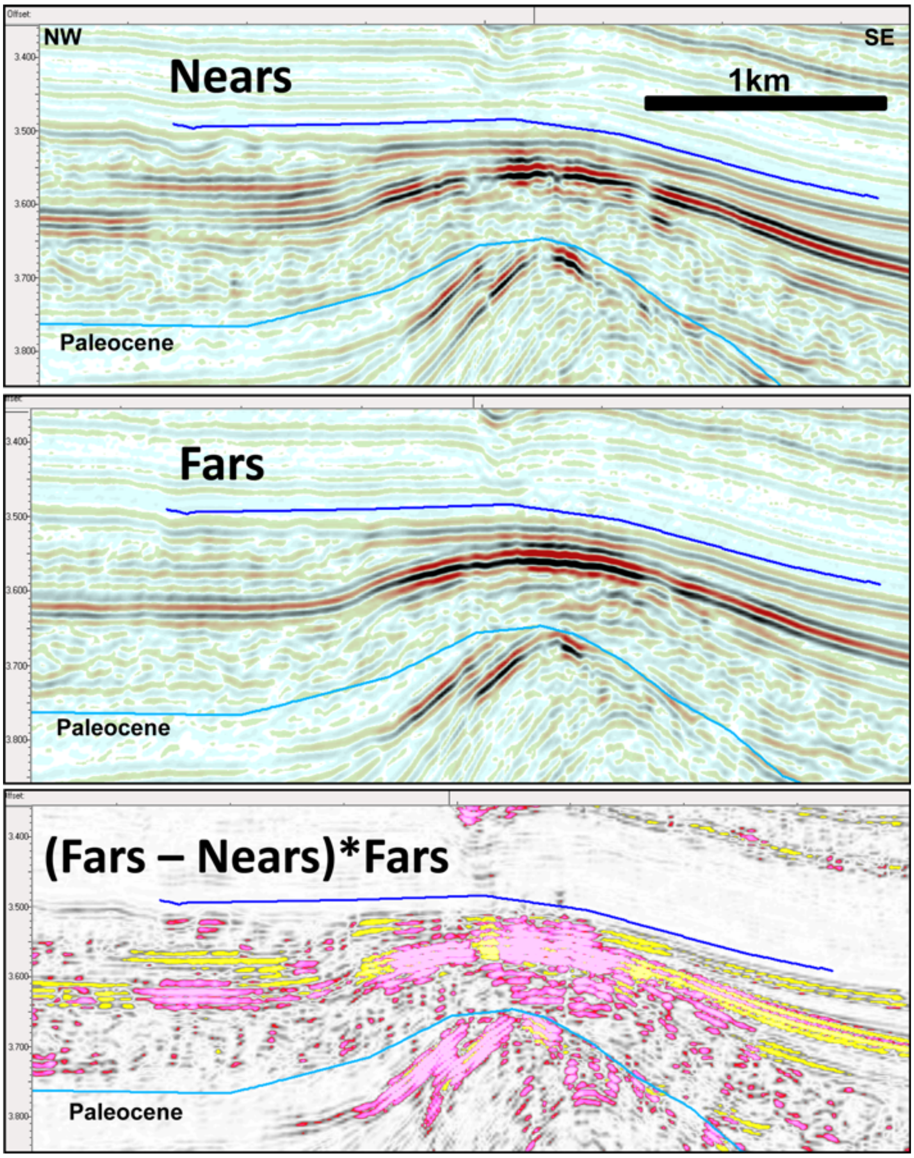


Fig. 7. Hydrocarbon indicators on the seismic line in KTB; the location not disclosed. Brightening from nears to fars and positive anomaly (pink) on (fars − nears) × fars suggests Class III AVO. Conformance to structure is consistent with a hydrocarbon presence. Wavelet analysis suggests that anomalies are due to low-impedance layers close to tuning thickness. Data are zero phase, SEG reverse polarity.

primary undercompaction during rapid burial but hydrocarbon generation may also contribute subsequent inflationary overpressure, and Cobbold *et al.* (2009) argued that hydrocarbon generation was responsible for the large-scale overpressures in the Akata shales.

Maturity modelling in the KTB shows that the mobile shales may have provided a viable and timely oil mature source to charge the overlying thrusted traps, particularly in the distal parts where burial is less deep. This source is also likely to be most effective in the central and outer areas of the KTB where extensive diapirism indicates the presence of a thick and highly mobile mud layer. However, the lack of hydrocarbons in Pomboo-1 suggests that the mobile mud source is not effective in some parts of the KTB. Possibly, this source facies is too thin in peripheral parts of the belt, while deep early burial of the source in more proximal areas of the KTB may have led to hydrocarbon generation predating trap formation. Clearly, this is a subject that requires further research.

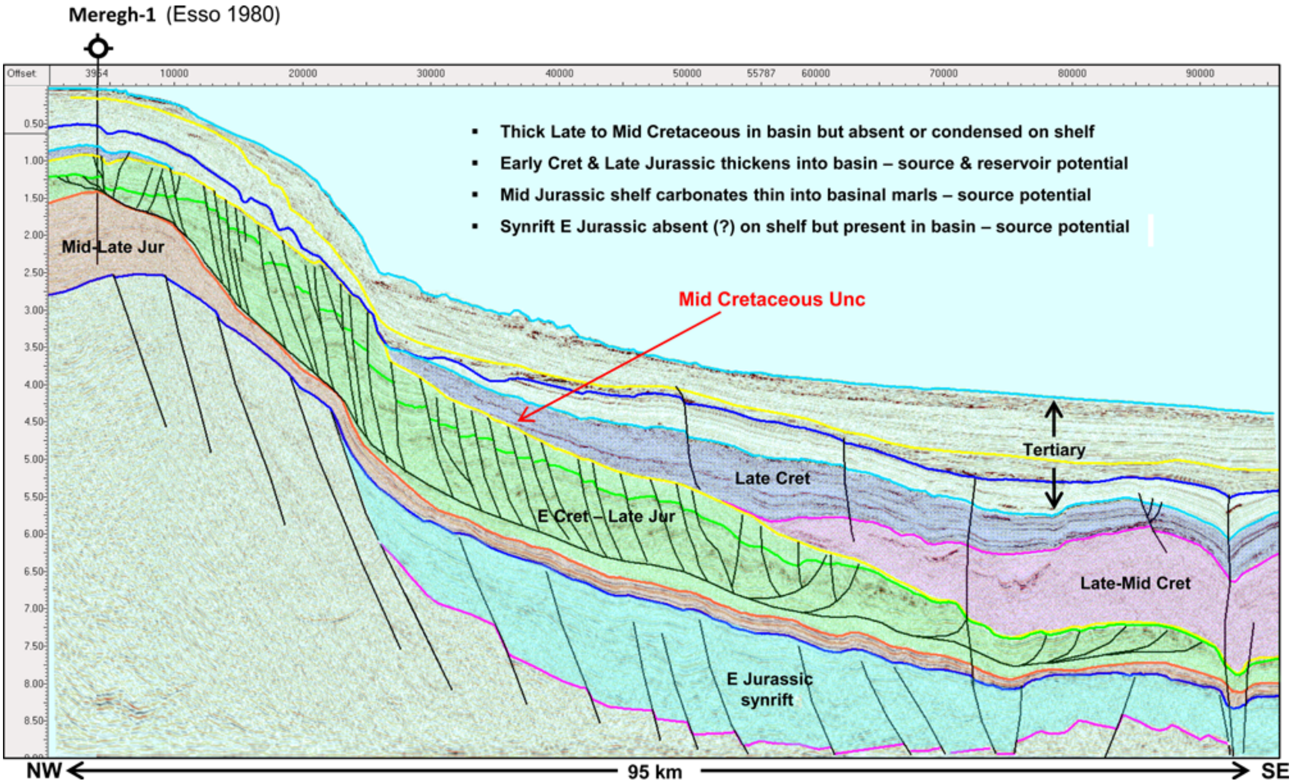
Mogadishu Deep Basin

The Mogadishu Deep Basin is separated from the Jubba Deep by a series of north–south-trending transform faults reactivated in the Late Cretaceous. The basin boundary to the NE is formed by a major east–west tectonic lineament related to the initial separation of Madagascar (Figs 2 and 3).

The Soma 2014 survey was extended onto the shelf to provide a tie to Meregh-1 drilled by Esso in 1980 as shown in Figure 8. Based on the original well reports, Meregh-1 penetrated mixed clastics of Miocene–Kimmeridgian age, although the Early Cretaceous–Late Jurassic section in the well has undergone significant tectonic thinning due to low-angle normal faults. In the deeper part of the well, a thick section of Jurassic carbonates, of Late Oxfordian–Bajocian age from original reports, was penetrated from 1550 to 4300 m. The seismic character of these carbonates suggests they represent shelfal facies, but wireline-log data demonstrate that they have minimal porosity. There were no hydrocarbon shows in the well.

A number of significant stratigraphic changes occur at the transition from the shelf to the deep basin, as shown in Figure 8:

- A thick basinal Mid- to Late Cretaceous section onlaps the Mid-Cretaceous unconformity and is absent or condensed on the shelf.
- At the drill location, the Late Jurassic–Early Cretaceous section is tectonically thinned by listric normal faults which sole out in a slip plane near the base of the Late Jurassic, probably in a shale package with possible source rock potential. This package thickens downdip into the Mogadishu Deep Basin.
- The Mid- to Late Jurassic carbonates form two thick shelfal units at the well location but each of these thins basinwards



- Thick Late to Mid Cretaceous in basin but absent or condensed on shelf
- Early Cret & Late Jurassic thickens into basin – source & reservoir potential
- Mid Jurassic shelf carbonates thin into basinal marls – source potential
- Synrift E Jurassic absent (?) on shelf but present in basin – source potential

Fig. 8. Seismic tie to Meregh-1 well and stratigraphic correlation from shelf into the Mogadishu Deep Basin. The location of the line is shown in Figures 1 and 11.

through a series of clinoforms to form a condensed deep-water facies. The basinal carbonates may have source properties by analogy to similar age rocks in Madagascar (Webster & Ensign 2007).

- A synrift section can be interpreted in the deep-water basin, whereas it is not imaged on the shelf and may be absent.

The Mid-Cretaceous–Early Tertiary section in the Mogadishu Deep is characterized by a relatively bland seismic facies onlapping the shelf slope, interpreted to consist of fine-grained contourite clastics. Seismic evidence is lacking for deltaic sequences similar to those observed in the equivalent-age section in Jubba Deep. Consequently, the hydrocarbon potential of the Mogadishu Deep

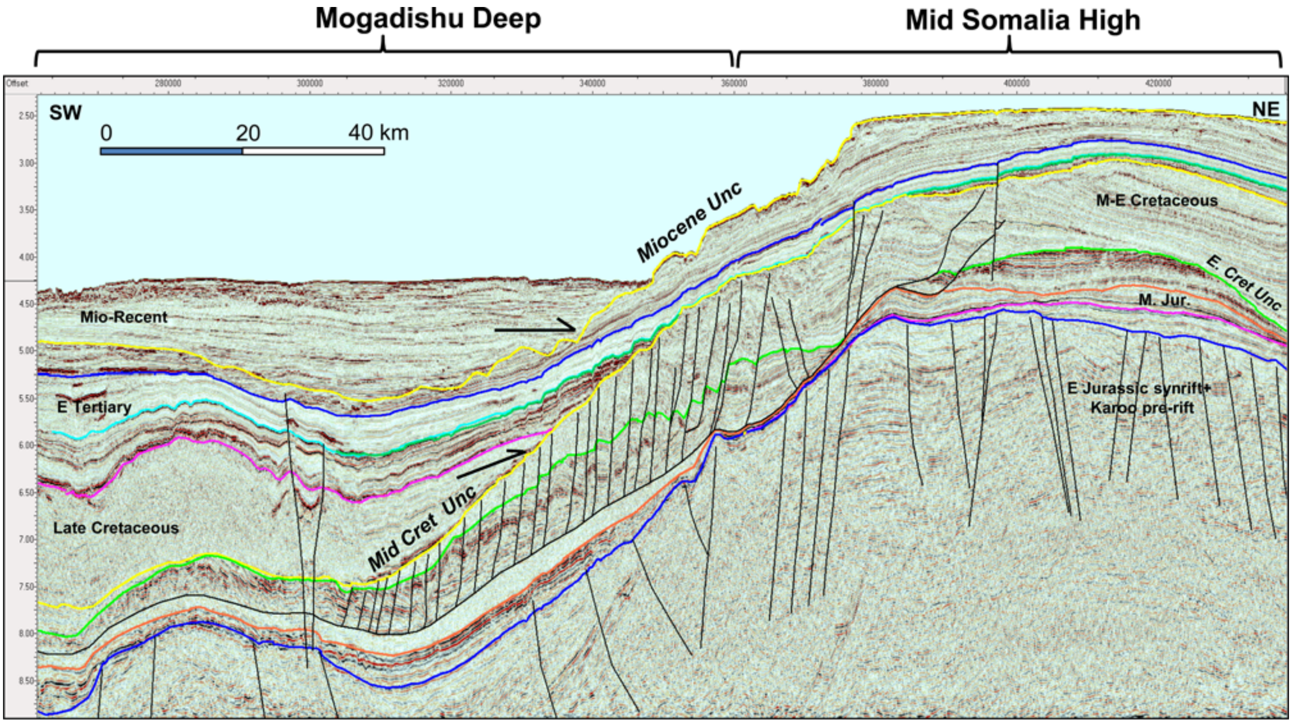


Fig. 9. Regional SW–NE seismic line showing the tectonostratigraphic transition from Mogadishu Deep to Mid Somalia High. The location of the line is shown in Figures 1 and 11.

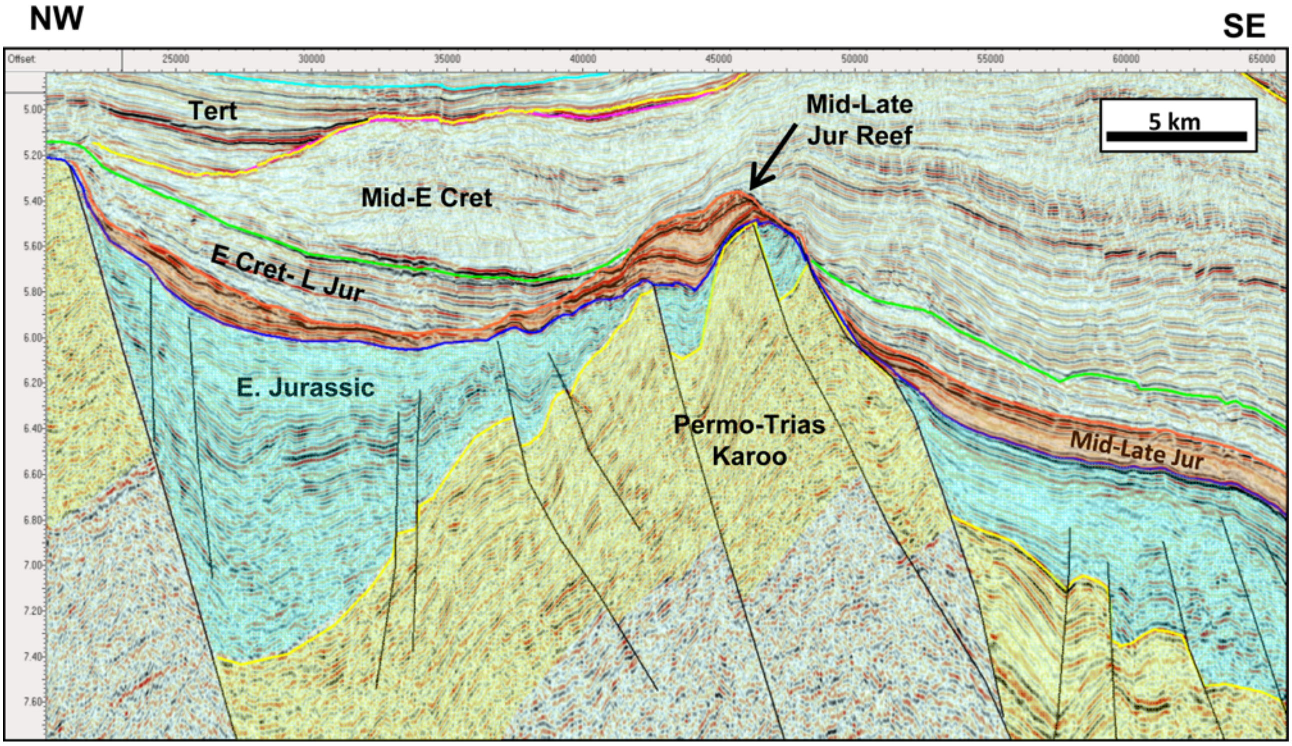


Fig. 10. Seismic line showing a rotated fault block with a Mid–Late Jurassic carbonate reef growth over the crest. Pre-rift interpreted to be Permo-Triassic Karoo, synrift Early Jurassic and post-rift Mid-Jurassic and younger. The location of the line is shown in Figures 1 and 11.

may be limited by a lack of reservoir. A variety of volcanic facies (intrusive and extrusive) are also interpreted in this section, with one large igneous complex apparent on seismic and magnetic response.

The post-rift tectonics of the Mogadishu Deep are dominated by a series of WSW–ENE strike-slip faults of Eocene age which exhibit both positive and negative flower structures on seismic.

Hydrocarbon prospectivity is less obvious in the Mogadishu Deep compared to the other basins. Jurassic sources, if present, are interpreted to be deeply buried and are likely to be gas generating, while seismic stratigraphic evidence for reservoir facies is generally lacking.

Mid Somalia High

The transition from the Mogadishu Deep to the Mid Somalia High occurs at a major WNW–ESE tectonic lineament (Fig. 2) which was probably established during the initial separation of Madagascar from Somalia. A seismic section across this transition (Fig. 9) shows significant relative vertical movement to have occurred in the Mid-Cretaceous and again in the Miocene, resulting in the formation of two major unconformities which are defined mainly by onlap of the basin slope.

The sedimentary section on the Mid Somalia High is relatively thin compared to the other basins but still exceeds 4 km in many areas. Significant differential erosion is evident at unconformities of approximately Early and Mid-Cretaceous ages, while post-Miocene section is condensed or absent.

A pre-rift section interpreted as Permo-Triassic ‘Karoo’ and a synrift section interpreted as Early Jurassic are well imaged in this area (Fig. 10).

Mid–Late Jurassic carbonate reef play

An extensive area of Mid–Late Jurassic carbonate reefs is interpreted on the Mid Somalia High. Figure 10 illustrates one reef developed on the crest of a large rotated fault block where footwall uplift provided shallower water to facilitate reef growth. This example shows a significant stratigraphic hiatus at the top of the reef facies, providing an opportunity for sub-aerial exposure and porosity-enhancing karstification. Figure 11 shows the regional distribution of the reef facies and also an interpreted shoal facies where stratigraphic thickening of the carbonate unit is observed over a structural high but lacking the steep-sided geometry associated with the reefs.

The typical seismic expression of the reef facies is a relatively steep-sided mounded geometry, with subhorizontal internal reflectors punctuated by zones of more chaotic reflectivity. These seismic characteristics are similar to those described in carbonate reef examples elsewhere: for example, the Malampaya Field of Oligo-Miocene age in the Philippines (Neuhause *et al.* 2004) or the Tengiz Field of Devonian–Carboniferous age in Kazakhstan (Kenter *et al.* 2008).

Kiessling *et al.* (1999) documented a worldwide bloom of Late Jurassic carbonate reef growth, and their reef distribution map for this time window indicates examples of reef occurrence in the Gulf of Aden region and in Madagascar. The Mid Somalia High was at a palaeolatitude of *c.* 25°S in the Late Jurassic.

Stratigraphically equivalent analogies can be found in the prolific hydrocarbon-bearing Late Jurassic reef reservoirs of the Amu Darya Basin in Turkmenistan and Uzbekistan where Ulmishek (2004) reported about 50% of the 230 Tcf (trillion cubic feet) of discovered resources to be reservoired in the carbonates. In this region, the best reservoir properties are in reef-core carbonates in both barrier and isolated pinnacle reefs where the limestones are commonly fractured, leached and dolomitized with porosities of up to 19%. The reef builders are predominantly coral and algae. However, the Amu Darya reservoirs have been buried to depths of 3000–5000 m, whereas the Mid Somalia reefs are significantly shallower with present-day sedimentary overburden in the range of 1200–3000 m.

By analogy to Amu Darya, the reefs on the Mid Somalia High are expected to provide attractive reservoir and trapping potential.

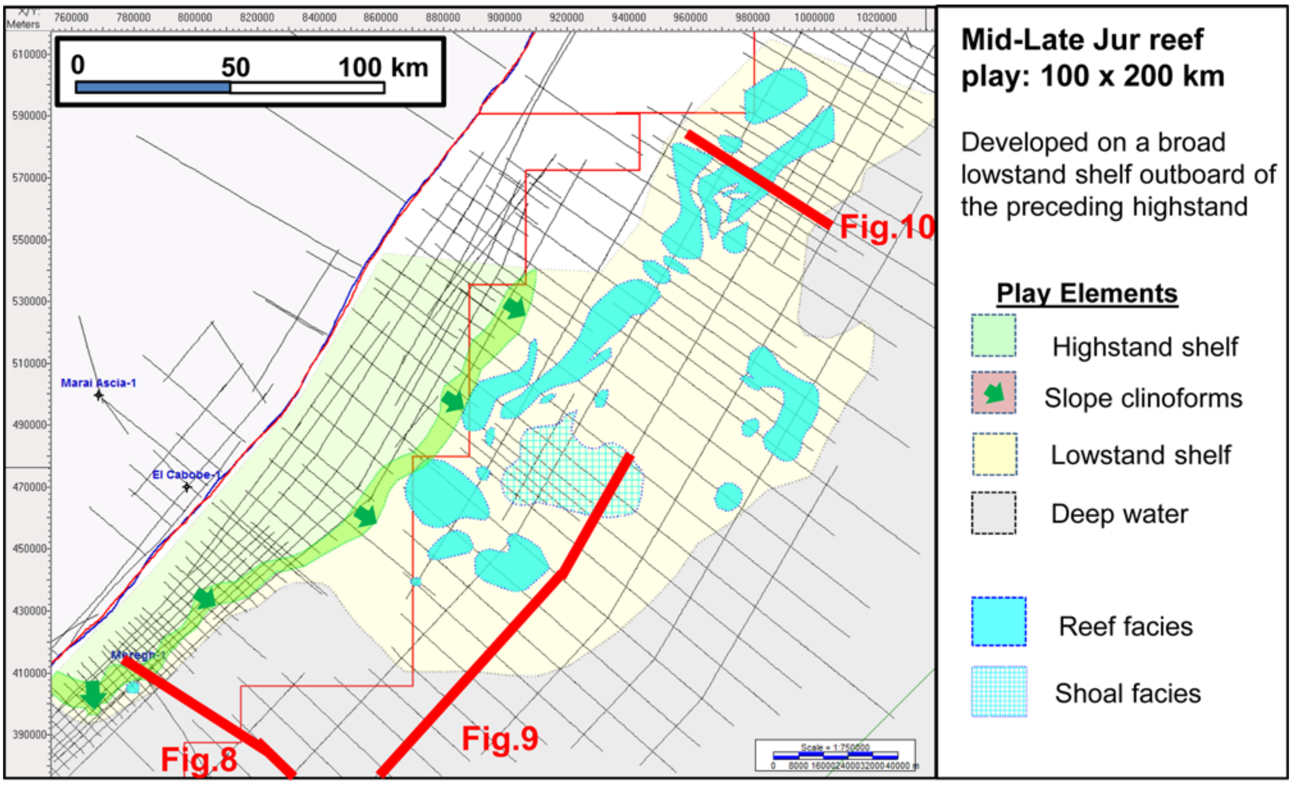


Fig. 11. Map of Mid–Late Jurassic carbonate reef and shoal facies. The locations of seismic Figures 8 – 10 are shown.

Source rocks in the Mid Somalia High

Regional data (Webster & Ensign 2007; United States Geological Survey 2012) indicate the Early Jurassic synrift half-graben may provide lacustrine or restricted marine source facies. Webster & Ensign (2007) reported outcrops of potential source shales of Liassic age in Madagascar with total organic carbon (TOC) values from 2.3 to 23.6%.

Other sources may also be present in the basinal equivalents of the Mid–Late Jurassic carbonates, or in Late Jurassic shales which are a prolific source worldwide. Webster & Ensign (2007) documented outcrops of the Toarcian–Bajocian-age Beronono shale in Madagascar with TOC values from 10 to 69%. Ulmishek (2004) stated that the Late Jurassic source rocks in the Amu-Darya region are represented by basinal black shale facies contemporaneous to the shallow-water carbonate reefs in that basin. Indeed, Greenlee & Lehmann (1993) and Kiessling *et al.* (1999) both noted a general correspondence between geological periods of carbonate reef growth and extensive source rock deposition in worldwide basins.

Conclusions

Interpretation of the Soma 2014 regional seismic survey offshore SE Somalia demonstrates the presence of three contrasting deep-water sedimentary basins: the Jubba Deep to the SE shows evidence of a major Late Cretaceous–Early Tertiary deltaic system that was deformed by regional gravity collapse to form the 60 000 km^2 Kismayo Thrust Belt (KTB). A hydrocarbon play is proposed in the KTB with reservoirs in deep-marine prodelta sands sourced by Mid-Cretaceous mobile muds and trapped by thrust anticlines. The central Mogadishu Deep Basin shows evidence of volcanic influences and is less prospective for hydrocarbon exploration. The Mid Somalia High to the NE has an extensive carbonate shelf of Mid–Late Jurassic age with multiple interpreted reef and shoal systems. In this area, the proposed hydrocarbon plays include clastic and carbonate reservoirs of Triassic–Early Cretaceous age, trapped in rotated fault block structures and sourced by Early Jurassic synrift shales.

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