

Prospectivity and Petroleum Systems Modelling of the Offshore Lamu Basin, Kenya: Implications for an Emerging Hydrocarbon Province*

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Abstract

While recent years have seen major discoveries along the East African margin, the Lamu Basin in Kenya remains underexplored. Located in northern Kenya and covering both onshore and offshore, the Lamu Basin forms part of the Kenyan passive continental margin. The geology is controlled by tectonic movements that led to the break-up of Gondwana in the Jurassic and by Cretaceous activity on the Anza rift.

Large discoveries in Tanzania and Mozambique indicate hydrocarbon potential in East Africa, as do heavy oil deposits on the conjugate margin in Madagascar. Exploration in the offshore Lamu Basin is limited, with only seven wells, but 52 m net gas pay was discovered in channel and turbidite sands at Mbawa-1 in 2012. This indicates an active petroleum system, as do hydrocarbon shows in a number of wells and brightening on seismic data.

2D seismic interpretation will be combined with analysis of regional gravity data to constrain the tectonic history and structural geology of the offshore Lamu Basin. The survey covers from 1–4 km water depth, and comprises 1035 km of regional 2D lines, giving an overview of the basin and intersecting DSDP well 241. 9600 km of new 2D seismic data currently being acquired also will be included. Seismic attributes constrain stratigraphic zones, including shale intervals providing potential source rocks, and sand-rich deposits which may act as reservoirs. Hydrocarbon plays are interpreted to range from pre-rift Karoo deposits, found in tilted fault blocks; through Jurassic syn-rift units terminating against faults and in drape and rollover anticlines; and into Cretaceous and Tertiary stratigraphic plays, reefs, turbidites, and fans. The maturity and nature of source rocks in the Lamu Basin remains a key question.

This study will utilize the petroleum systems concept, incorporating the presence of an active source rock a key element along with reservoir, trap and seal, with development of the system controlled by the timing of these elements. A selected regional line traversing the northern offshore Lamu Basin from west to east is modelled and source rock intervals are identified, based on regional stratigraphy, constraining

maturity and timing of generation. Combining regional studies with seismic data and the petroleum systems concept enables improved understanding of the prospectivity of the offshore Lamu Basin and indicates that all the required components of a petroleum system are present.

Introduction

While recent years have seen major discoveries along the East African margin, the Lamu Basin in Kenya remains underexplored. Located in northern Kenya and covering both onshore and offshore, the Lamu Basin forms part of the Kenyan passive continental margin. The geology is controlled by tectonic movements that led to the break-up of Gondwana in the Jurassic and by Cretaceous activity on the Anza rift.

Large discoveries in Tanzania and Mozambique indicate hydrocarbon potential in East Africa, as do heavy oil deposits on the conjugate margin in Madagascar. Exploration in the Lamu Basin is limited, with only thirty wells, but 19 of these are associated with hydrocarbon shows. Of the eight offshore wells, 52 m net gas pay was discovered in channel and turbidite sands at Mbawa-1 in 2012, and a 14 m gross oil column was encountered by Sunbird-1 in Miocene reefs in 2014, placing the Lamu Basin as an emerging hydrocarbon province. These discoveries indicate at least one active petroleum system, as do hydrocarbon shows in a number of wells and brightening on seismic data (Mbede 1987).

2D seismic interpretation will be combined with analysis of regional gravity data to constrain the tectonic history and structural geology of the offshore Lamu Basin. A petroleum systems model is then constructed to analyze the maturity and prospectivity of the basin. Interpretation of the prospectivity and petroleum systems of the Lamu Basin will be constrained by 9600 km of 2D broadband seismic data acquired in 2013-2014, and 1035 km of legacy 2D data ([Figure 1](#)). This study focuses on the deep water Lamu Basin, with the data lying between 2000-4000 m water depths. The seismic data intersects Deep Sea Drilling Project well 241 and the Pomboo-1 well, which are used to tie the interpretation.

Tectonics and Regional Gravity Interpretation

The hydrocarbon potential of offshore Kenya can be understood in terms of the tectonic history of the East African margin. The major tectonic events in the region influence the formation, uplift, and subsidence of the basin and therefore the environment of deposition. The Lamu Basin in Kenya is one of several basins along the margin that relates to the separation of Madagascar, India, Antarctica, and Australia from Africa and America during the break up of Gondwanaland at the culmination of Jurassic rifting (Coffin and Rabinowitz 1987). Other basins related to this rifting event include the Somali Basin, the Tanzanian Pemba and Mafia Basins, the Rovuma Basin in Mozambique, and the Morondova Basin in Madagascar (Mbede and Dualeh 1997). These basins share a similar rift history with common structural and stratigraphic characteristics, and some are highly prospective with large discoveries in recent years. The Lamu Basin is classified as belonging to a passive continental margin, and is unusual in that it lies in a transitional position between a rifted margin to the north in Somalia and a transform margin to the south. [Figure 1](#) shows the position of the basin and the seismic data that will be used to illustrate the interpretation of the area. The history of the basin is dominated by the break-up of Kenya from Madagascar, and can be divided into pre-rift (late Proterozoic to Triassic), syn-rift (Triassic to Late Jurassic), and post-rift phases (Late Jurassic to Holocene).

The major structural features of the offshore Lamu Basin can be seen on the gravity data ([Figure 2](#)). The Davy-Walu Ridge is the termination of the Davie Fracture Zone, and is visible as a gravity high, as is the Pemba-Simba Ridge (Rais-Assa 1987). The Tembo and Maridadi Troughs

lie between the highs, and the inversion axis is found between the Davy-Walu Ridge and the Maridadi Trough. These major troughs can be seen to be significant depocenters in the seismic data.

The Davy-Walu Ridge is the dominant feature in the data offshore, and this ridge may act as a migration focus for hydrocarbons to migrate up-dip, as may the Pemba-Simba Ridge to the south. The Davy-Walu Ridge terminates in the Walu-Kipini High. Either side of the ridges and troughs are found the Maridadi and Tembo Troughs. These troughs indicate basement lows and thick sedimentary successions, and therefore are likely to represent good hydrocarbon source kitchens. There is also an inversion axis parallel to and just to the south-west of the Davy-Walu Ridge, indicating reactivation of existing faults, and affecting the depth and thermal history of source and reservoir rocks. These faults all follow a regional NW trend discernable on the gravity map, as do the small folds in the area, the Tana and Pate Synclines. Variation in the gravity to the north of the Davy-Walu Ridge may suggest the limits of the diapiric province that is believed to exist in the area, while a basement high approximately 150 km in diameter may indicate a large anticlinal structure in the region, as is observed on the seismic.

Interpretation

Initial interpretation of nine unconformities was carried out on the study area and tied to the two wells. The major basin source, reservoir, and seal intervals were identified and used to understand the petroleum systems present in the Lamu Basin and to identify the major plays. Seismic attributes and facies analysis constrain stratigraphic zones, including shale intervals providing potential source rocks and sand-rich deposits that may act as reservoirs ([Figure 3](#)). A basin model was constructed, using the seismic interpretation and well data, which revealed the stratigraphic and sedimentary history of the basin ([Figure 4](#)).

The use of seismic facies interpretation as an exploration tool is justified with broadband data and reveals with greater clarity the nature of the reflections within, as well as between, lithological units. Broadband data enhances both external shape and internal reflectivity due to its broader frequency spectrum. For example, within the survey area, a large four-way anticlinal structure has pinchouts of chaotic units towards its crest. The internal reflections within these packages indicate that these are likely basin floor fans with high energy deposits. When combined with free-air gravity data, we see that the pinchouts are associated with a basement high creating the overlying fold. There is also a thick, low-reflectivity unit that extends across the whole survey area, which is interpreted as a shale horizon based on attribute analysis.

Attribute analysis is improved with broadband seismic as the frequency spectrum is broader and the wavelet is better defined. This shale unit acts as a detachment surface for overlying sediments, resulting in toe-thrust structures northwest of the study. A highly faulted unit overlies the shale layer, and the faults terminate within the more ductile underlying unit. The termination of faults is more clearly resolved due to the seismic's broadband nature. The broadband nature of the seismic data greatly aids in interpreting both lithological variations, helping to identify major unconformities and lateral facies changes, and of structural features such as faults.

Hydrocarbon plays are interpreted to range from pre-rift Triassic-Jurassic deposits found in tilted fault blocks through Jurassic syn-rift units terminating against faults and in drape and rollover anticlines, into Cretaceous and Tertiary stratigraphic plays, reefs, channels, turbidites, and fans ([Figure 4](#)). Large Tertiary channels can be mapped across the area, and their infill can be differentiated based on the nature of the high frequency internal reflections and attribute analysis. High-amplitude continuous reflectors in the base of the channels suggest sands, possibly

gas-filled, while more chaotic, low-amplitude reflections near the top of the channel imply higher energy deposits of varying grain size, which may act as a seal.

Petroleum Systems Modelling

To improve understanding of the petroleum systems and hydrocarbon generation in the basin, a selected 430 km 2D line was used as input into petroleum systems modelling (PSM) in PetroMod. A velocity model was created for the line and the seismic data and interpreted horizons were converted to depth.

The horizons were identified and dated based on correlation to DSDP well 241 and subdivided into the appropriate stratigraphic units according to understanding of the regional stratigraphy. As no heat flow data was available, the heat flow was modelled based on regional heat flow measurements. A variety of end member scenarios were run to determine the maturity of the source rocks if the heat flow and water depth varied within geologically reasonable values.

In the Lamu Basin, the initial interpretation of the 2D seismic indicates the maturity of the syn-rift Jurassic Maji ya Chumvi shales, with the generation of gas or oil dependent on the depth of the unit within the associated rotated fault blocks ([Figure 5](#)). It is the Cretaceous marine shales, however, which lies currently in the oil window. The Eocene Pate and Kipini source rocks are modelled as immature.

Conclusions

Regional studies and interpretation of seismic data can be combined with petroleum systems modelling to provide improved understanding of basin prospectivity. Here, over 10,000 km of 2D seismic data was interpreted to give an analysis of the regional basin stratigraphy, while attributes highlighted possible reservoir and source intervals, contributing to plays ranging from Jurassic syn-rift fault blocks through Cretaceous basin floor fans to Tertiary channels, reefs, and turbidites. The regional seismic interpretation and attribute analysis is applied to construct a 2D petroleum systems model. In the Lamu Basin, the modelling indicates the maturity of the syn-rift Jurassic Maji ya Chumvi shales, with the generation of gas or oil dependent on the depth of the unit within the associated rotated fault blocks. The Cretaceous deep marine shales are modelled to currently lie in the oil window. The Eocene Pate and Kipini source rocks are modelled as immature. The petroleum systems study also indicates that the elements of the systems formed in the correct order for hydrocarbon accumulation to occur. Combining regional studies with seismic data and the petroleum systems concept enables improved understanding of the prospectivity of the offshore Lamu Basin and indicates that all the required components of a petroleum system are present in the required order for hydrocarbon accumulation.

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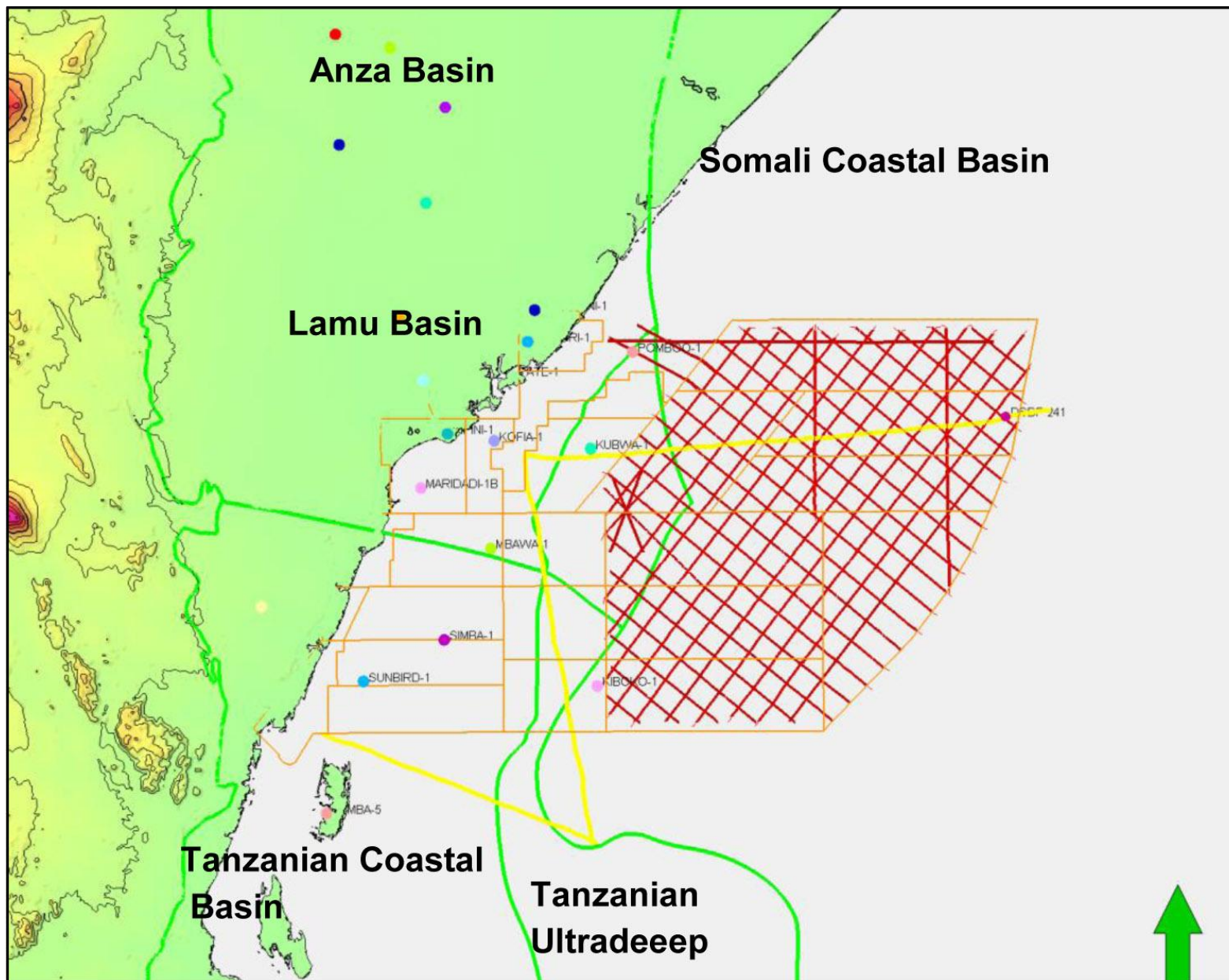


Figure 1. Basin location offshore Kenya. The 2013 broadband survey is indicated in red and the legacy lines in yellow. Basin boundaries are outlined in green and block boundaries in orange.

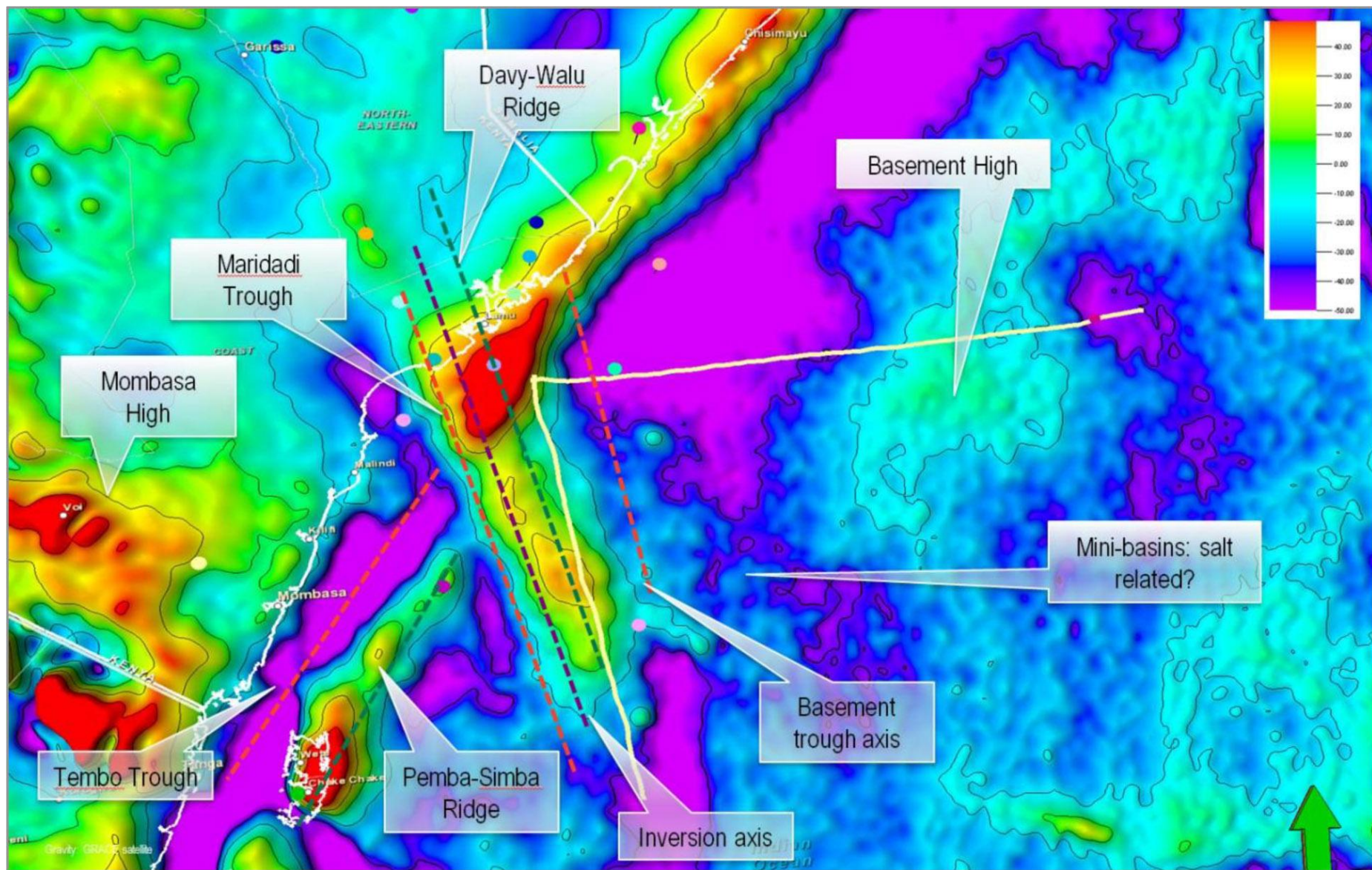


Figure 2. Regional gravity map of the Lamu Basin. The major features are labelled in white, including the Maridadi and Tembo Troughs and the Davy-Walu and Pemba-Simba Ridges. The scale indicates the free air gravity anomaly in mGal.

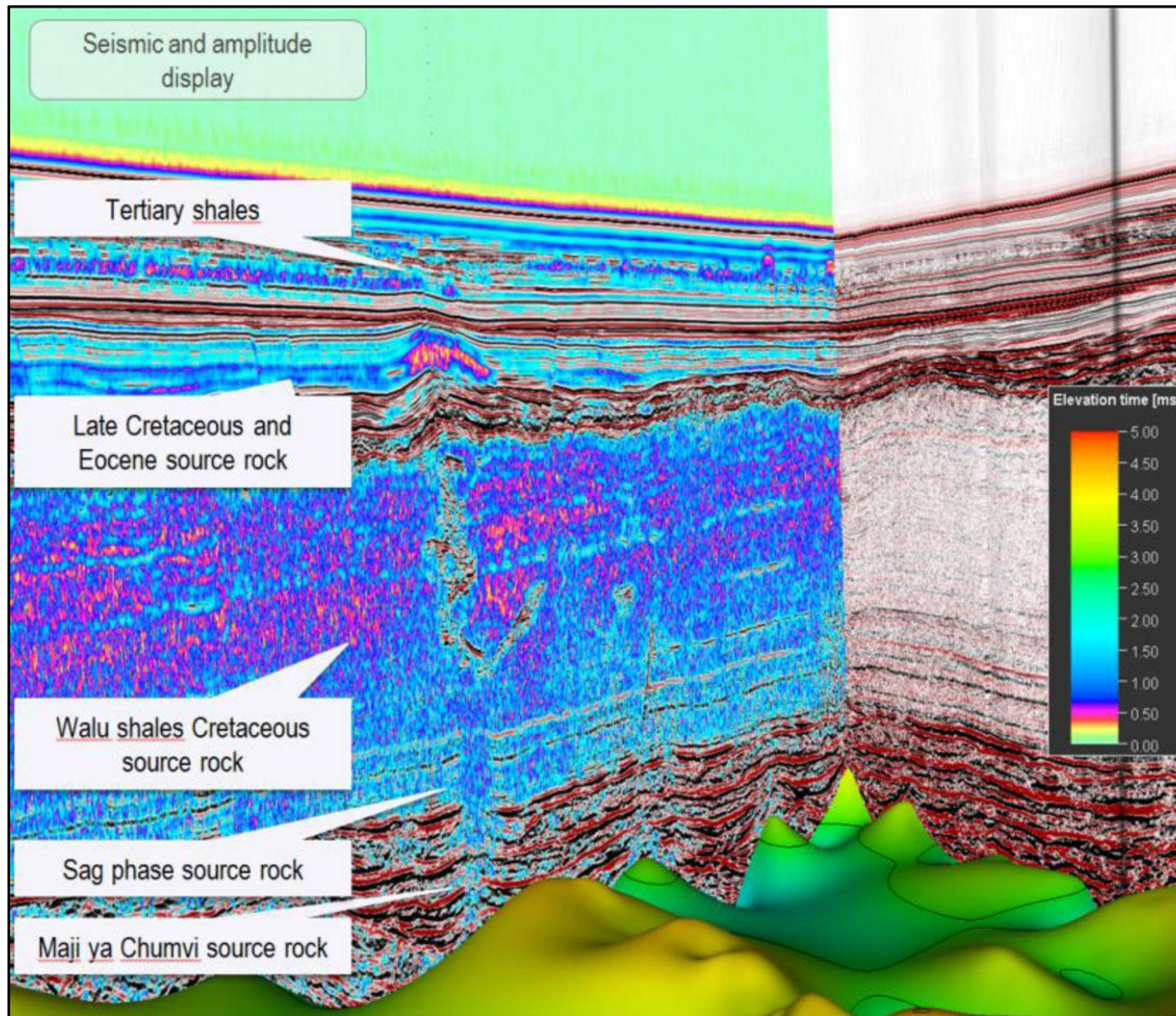


Figure 3. Use of seismic attributes in highlighting petroleum systems elements. Low amplitudes are highlighted in blue and purple, correlated with shale intervals in the section, with the possible source rock units labelled.

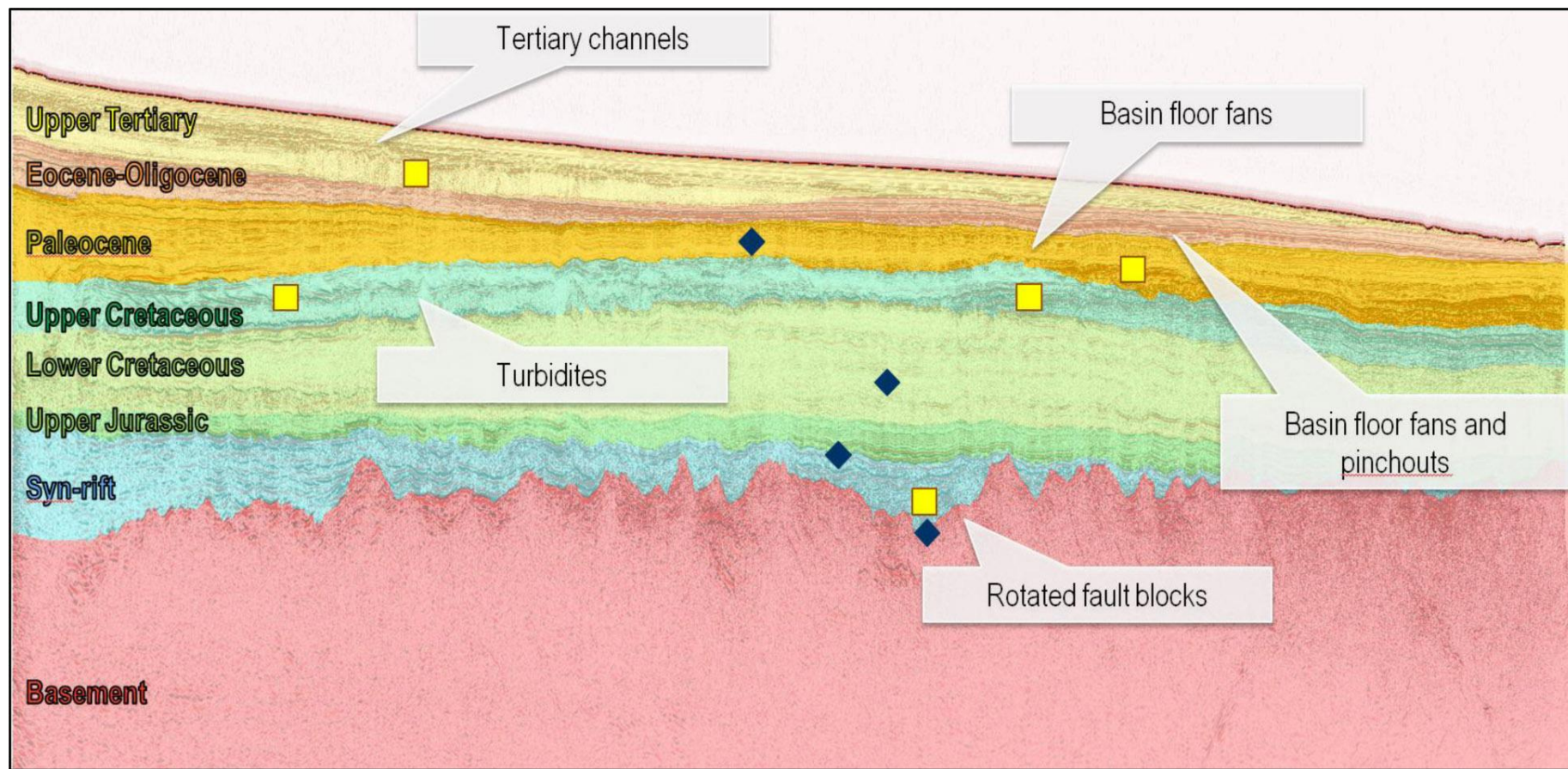


Figure 4. Representative geoseismic section. The different packages are labelled on the left, with the source intervals highlighted by blue diamonds and the reservoirs by yellow squares. Possible traps are labelled.

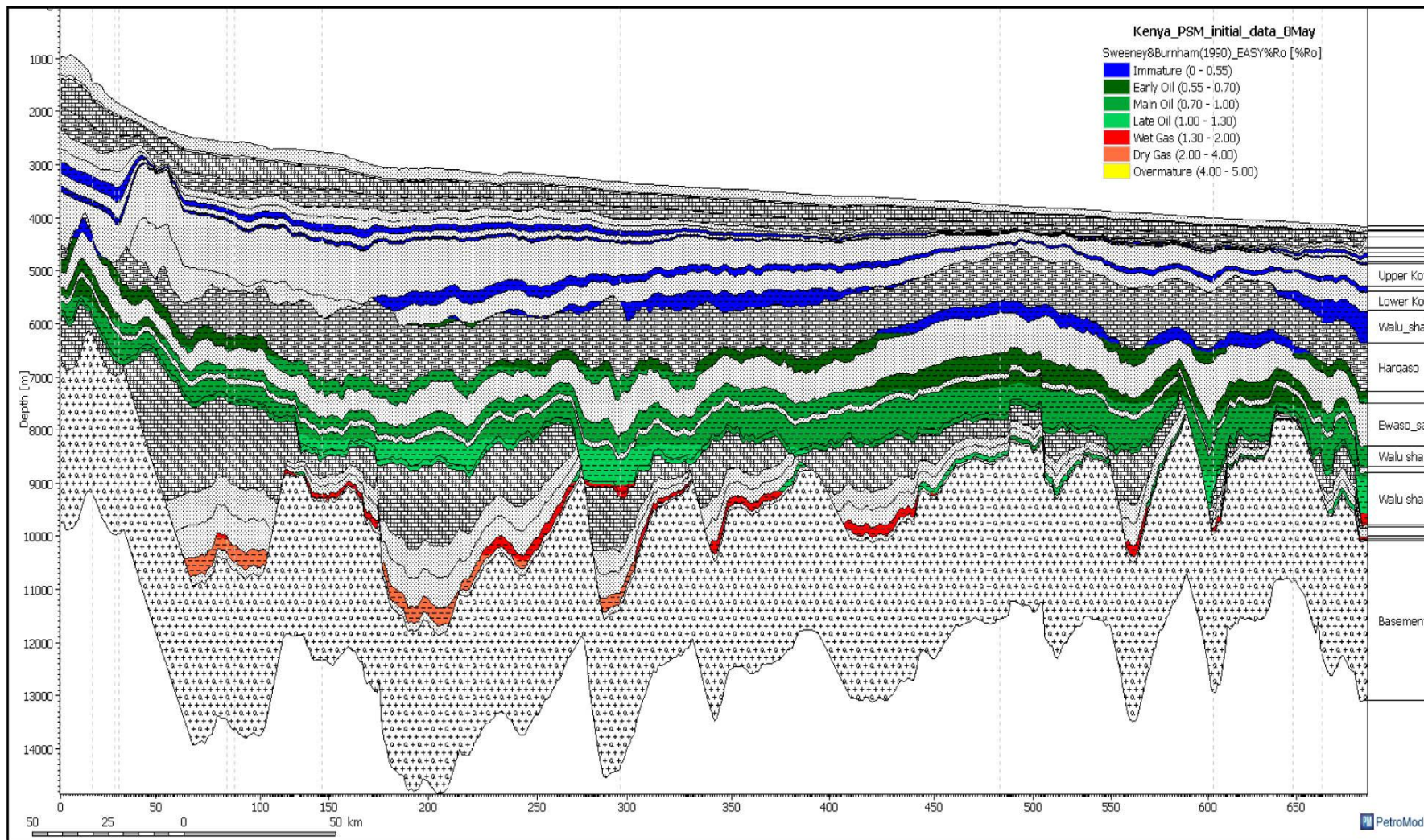


Figure 5. Maturity of Lamu Basin source rocks. This regional line highlights the modelled source rock maturity based on the Sweeney and Burnham (1990) scale. Blue indicates immature, green the oil window, and red the gas window. This indicates the present day maturity only.