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# Tectonics, Structural Style and Petroleum System Modeling to understand Generation and Migration of Hydrocarbon in Kerala Konkan Area, Western Offshore, India

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***Summary***

*The study area extends from Vengurla Arch in the north to Gulf of Mannar in the south in western offshore basin. Hydrocarbon exploration in Kerala Konkan and adjoining Gulf of Mannar area remains a challenge for sub trappean formations due to poor seismic imaging.*

*An integrated analysis of the seismic data with the help of newly acquired GXT data were carried out to identify the events corresponding to top of Mesozoic, older pre-rift and synrift sediments to understand the tectonics and sedimentation frame work of the area. Prominent seismic reflectors from seabed to Cretaceous were mapped in PSDM data and structure and thickness maps were prepared for the entire area.*

*The study has defined NNW-SSE and NE-SW striking tectonic elements and their relation to basin evolution. In addition to this, three major volcanic episodes with their relation to regional tectonic activity and implication on hydrocarbon prospectively have been firmed up.*

*The Gulf of Mannar has evolved as a failed rift due to drifting away of Sri Lankan massif from Indian craton and initiated the low in between where Mesozoic sediments were deposited. This area has witnessed least volcanic activity and remained as major low during Mesozoic and Tertiary. There could be a possibility that the Cochin Low in the Kerala Konkan basin was originated due to rifting prior to the separation of Madagascar, before it went into drift phase, and the low received the Mesozoic sediments.*

*The Lower Mesozoic sediments, equivalent of Andimadam Formation, show increase in thickness in the Gulf of Mannar and similar type of sediments are also expected in Cochin Low in southern part of Kerala. The Late Cretaceous Cochin Formation in Kerala area is sand dominated whereas it is dominantly argillaceous in the Gulf of Mannar.*

*Petroleum system modeling was carried out for better understanding of the potential petroleum systems within the intra-basalt Mesozoic succession, the Cochin Formation. The basin modeling analysis reveals that there are two Petroleum Systems, Cretaceous Cochin and Paleocene Kasargod Unit-1 working under certain assumptions. Source rocks show significant transformation ratios, within the southern Kerala sub basin, which forms the main kitchen area.*

*The Cretaceous source rock is expected in the Gulf of Mannar area and further exploration can be envisaged within synrift clastic fan complexes. Apart from this, Alleppy platform also appears to be interesting from exploration point of view.*

## Introduction

Integrated geological and geophysical studies bring out a tectono-sedimentation model and the Mesozoic sediment extension for hydrocarbon potential of west coast deep water area between Vengurla Arch and Gulf of Mannar within the frame work of plate tectonics, Kerala Konkan Basin.

Western Offshore shelf has proved hydrocarbon reserves in Bombay High and in surrounding fields. Southward Kerala Konkan shelf and beyond shelf areas (deepwater areas), no such success has, so far, been registered. The Gulf of Mannar offshore basin, located in the southernmost graben of Cauvery basin, trending NE-SW to NNE-SSW, flanked by the Pre Cambrian massif of India and Sri Lanka, has not encountered any hydrocarbon.

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## Regional geology and Tectonic setting

The Kerala Konkan basin lies on the western passive margin of the Indian craton and is underlain by continental crust, attenuated continental crust and oceanic crust. The Gulf of Mannar area is in continuation with Kerala sub basin and extends up to Mandapam Delft ridge.

The schematic diagram in Fig.1 shows the presence of pre-rift and syn-rift Mesozoic sediments in Laccadive Low in Kerala basin indicating the existence of basinal low prior to the separation of Madagascar, before drift phase and accumulation of Mesozoic sediments. The Lower Mesozoic sediments, equivalent of Andimadam Formation, show increase in thickness in the Gulf of Mannar and similar type of sediments are also expected in Cochin Low in southern part of Kerala. The Late Cretaceous Cochin Formation is sand dominated, whereas it is argillaceous in the Gulf of Mannar area.

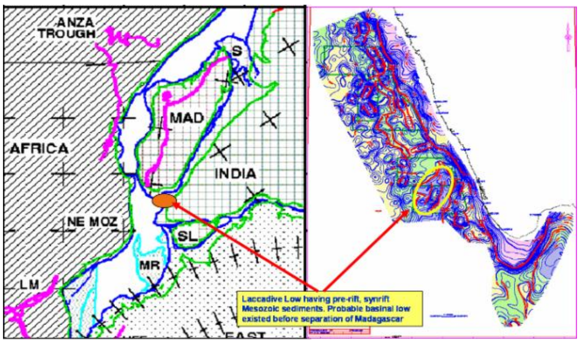


Fig. 1: Plate tectonic position of India at 89 Ma and present day. It can be assumed, that the Laccadive Low was existing prior to separation of India and Madagascar.

On the basis of sediment character, geological analogy with adjacent Cauvery basin, lower Cretaceous (older Mesozoic) sediments contains the best possible hydrocarbon source rock. Data from Cauvery suggests that there are two intervals of organic rich sediments, the older Albian and the second in the Late Cretaceous. The Late Cretaceous section was encountered at greater depth in the Kerala area, whereas in Gulf of Mannar it is interpreted at shallower depth.

## Volcanic activity

The breakup of India and Madagascar which occurred in the Early Late Cretaceous is marked by widespread volcanism and eruption of continental flood basalt.

**Phase1:** Continental Flood Basalts (CFB's) ~88-102Ma, distributed during separation of Madagascar. These flood basalts are found in Madagascar and St. Mary Island (85.96 Ma) and are dated as 89Ma.

**Phase 2:** Deccan Trap Continental Flood Basalts (CFB's) ~65-66 Ma, mainly restricted to continental and shelf part.

**Phase 3:** Hotspot activity 62~58 Ma has formed numerous eruption centers mainly in Konkan area. One example is the Telichery Arch, dividing Kerala and Konkan sub basins.

## Structural style

The regional structural set up of the Kerala Konkan basin can be very well understood from the structural map at Cretaceous top (Fig.1) showing the regional fault pattern and disposition of grabens and horsts. These structural trends explain a rift type set up as elsewhere in the world. The dominating rift fill sediments are mostly of Paleocene age. The rift segments are separated by the well demarcated cross trends providing accommodation zone (pre-existing structural grain). The crustal extension which has been triggered by magmatic upwelling during Late Cretaceous – Paleocene time along pre existing NW-SE weakness zones is observed in a NE-SW direction (Fig.2).

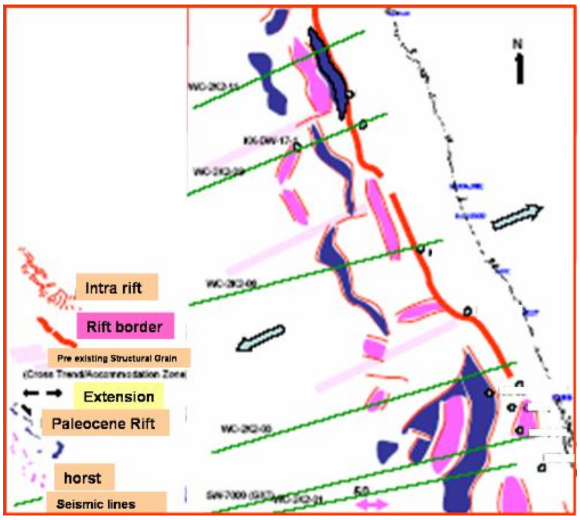


Fig. 2: Spatial disposition of Paleocene rift Graben and horst blocks

Structural modeling by Midland Valley's 2D move software was carried out, which has shown at top of pre-rift surface a total extension of 36.9 kms in Kerala basin, and 32.3 kms in Konkan basin. The post- basalt / pre-Palaeocene extension of 9.8 kms and Paleocene extension of 2.83 kms has been computed for Kerala area in the southern part and 8.3 kms post-basalt (Paleocene level) extension in Konkan area in the northern part of the area.

## Petroleum System Modeling

The petroleum system modeling study gives a better understanding of the potential petroleum systems within the intra-basalt Mesozoic succession, the Cochin Formation. It illustrates the maturation of a source rock and the migration into potential traps. Secondary objective is to understand the potential post Deccan petroleum systems and their maturation and hydrocarbon potential.

Eight 2D models over the entire Kerala Konkan Basin have been built by using GXT and long offset data. A simplified regional 3D model has been built out of 2D seismic data and furthermore a local 3D high resolution model around deepwater well inside the Kerala sub-basin has been built up (Fig.3).

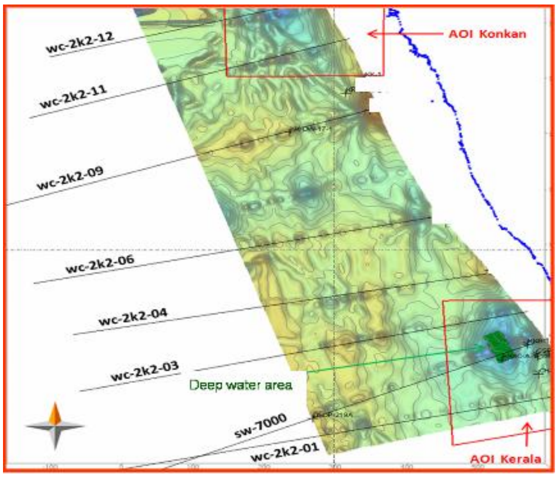


Fig. 3: Location map showing 2D / 3D models and Kerala Konkan study area The depth map in the background (Top of Cochin Formation) and location of the regional 3D model with two areas of interest (AOI).

## Geochemical data

Geochemical data, TOC, HI, S2 Temp and Vro are taken from the wells drilled in the area. Boundary conditions (HF, PWD, SWIT) are validated in the area (Fig.4).

**Heat Flow Trends** used are different for shelfal area and basinal part. Trends are validated by the use of calibration data of the wells along the different 2D lines. Seismic sections without well data were validated by pseudo-wells and are calibrated with wells drilled in adjacent areas with similar geological setting (basin shape, sediment thickness).

**Paleo Water Depth:** Basin evolution through time, information was derived from analysis of sediment composition related to their depositional environment (e.g. carbonates in water depth less than 200m) structural evolution (e.g. age of rise of ridges) data taken from Petroleum System Sequence Stratigraphy study in the area.

**Sediment Water Interface Temperature:** Sediment temperature for study area through geologic time inside PetroMod software

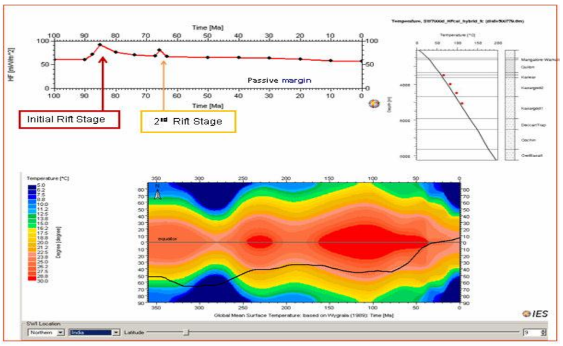


Fig. 4: Boundary Conditions for Modeling (HF, PWD, SWIT)

## Source Rock

The classification of the different source rocks were derived by analogue laboratory data from adjacent basins and the interpretation of the geological history and depositional environment of the area. The different source rocks and their features are shown in Table 1. The measured HI values are very low for Type II source rocks, which underlines that the results of the modeling concerning the hydrocarbon potential are very conservative. The Cochin source rock is assumed to be a Type III, generally gas-prone with organic matter being mainly woody and coaly.

| Source Rock Layer | Age | Av. TOC | HI | SR Type |
|---|---|---|---|---|
| | | | | |
| Quilon | 21.8 - 18.2 | 2.5 | 200 | Type II |
| Karwar | 48.0 - 45.2 | 3.5 | 200 | Type II |
| Kasargod-2 | 51.6 - 50.4 | 4 | 150 | Type II |
| Kasargod Unit-1 | 57.0 - 55.8 | 1.5 | 200 | Type II |
| Cochin | 78.1 - 74.6 | 1.5 | 120 | Type III |

Table 1: Source Rock names, depositional ages, HI and TOC values as required input for the 2D/3D basin models.

The modeling results show that only the two oldest Petroleum systems - Cretaceous Cochin and Paleocene Kasargod Unit-1 are mature. The source rocks younger than these are immature. There are two main kitchen areas. In the northern Konkan sub basin, only the Cretaceous Cochin source rock show significant amounts of transformation ratios. In the southern Kerala sub Basin, the Cochin as well as the Kasargod Unit-1 source rocks shows significant transformation ratios. However, both working Petroleum systems are speculative.

Hydrocarbon migration has been tested by several 2D and 3D models. Potential reservoirs either in Cochin or in Kasargod Formation could be charged by the two effective source rocks.

Exploration efforts have been focused on the Tertiary succession in the KK Basin. However, drilling and modeling results have shown that source rocks within the Kasargod and Karwar formations are non to marginally mature for hydrocarbon generation. Because of low maturity, no working petroleum system is established in the Tertiary section of the basin. Therefore the focus of today's exploration efforts is on the Mesozoic in the basin. Not much is known about potential petroleum system elements within the Cochin Formation. Near shore wells have shown coarse clastic material which is partially derived from the underlying flood basalts. Cleaner sands could be sourced from exposed Proterozoic rocks exposed on the Indian sub-continent at the time of Cochin deposition. The Cochin sediments are restricted to the mapped depocenters in halfgraben bound by listric syn-sedimentary faults. This increases the likelihood of restricted water circulations with the open sea at that time. In the near shore well different lithological units within the Cochin Formation showed TOC contents of 0.3-1.6%. It is plausible that the TOC and thicknesses of potential source rocks in the Cochin Formation may have increased towards the center of the halfgraben. It is not clear where (in a vertical sense) exactly the potential source rock within the Cochin Formation is located (Fig.5). In our models we have taken a conservative approach, applying the petroleum system elements (source, reservoir and seal) to the uppermost three layers.

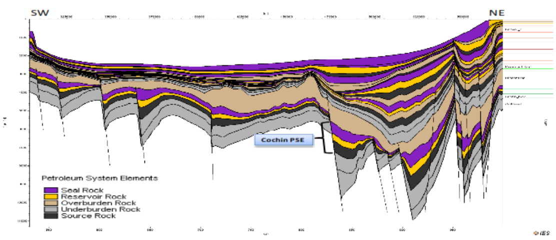


Fig. 5: Line GXT-1 illustration of the petroleum system elements (PSE) assigned to the 2D models. Note that the two lower layers within the Cochin Formation are considered as underburden.

In the regional 3D model only the Cochin and Kasargod Unit-1 Petroleum systems were analyzed, as results of 2D modeling had shown that the uppermost Kasargod-2 (and further shallower Karwar, Quilon formations) source rocks were immature. Two 3D models were created during project work: a high resolution model covering a local area around deepwater well and a regional 3D model. Out of the regional model, two areas of interest (AOI) were created, in the northern part the AOI Konkan and in the south the AOI Kerala.

The first 3D model consisting of high resolution maps with a grid point distance of 100 x 100 m., a PetroMod input model was created (Fig.6).

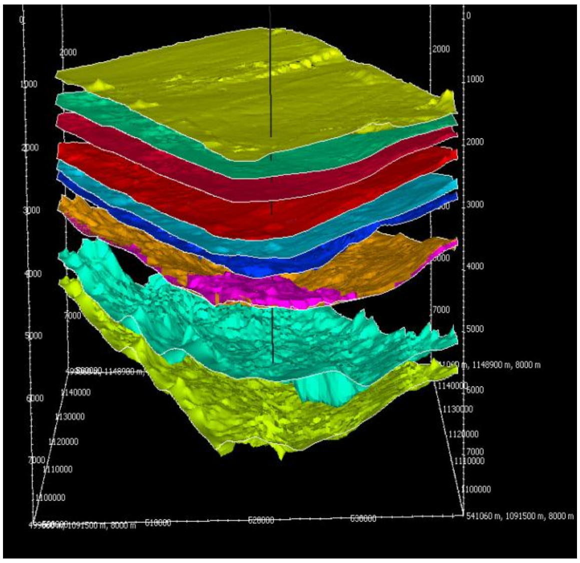

Fig. 6: 3D View of depth maps around deepwater well in PetroMod SeisStrat 3D

The maps for the regional 3D model were constructed by interpolating between the eight depth converted 2 D cross sections which had an average distance of 100km from each other (Fig.7).

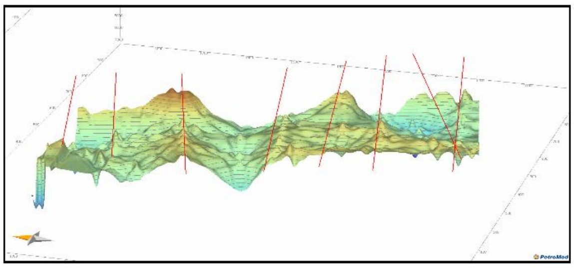

Fig. 7: Depth map of regional 3D model after interpolation and smoothing process (view to the East). This image shows clearly, that the structures are positioned along the seismic lines in red.

There are two main kitchen areas. In the northern Konkan sub basin, only the Cretaceous Cochin source rock show significant transformation ratios. In the southern Kerala sub basin, the Cochin as well as the Kasargod Unit-1 source rocks shows significant transformation ratios. However, both working Petroleum Systems are speculative. Migration modeling has shown Kasargod 2 Formation reservoirs charged with hydrocarbons. Accordingly timing for generation, migration and accumulation vs. trap formation are no risks in that Petroleum system. However, the absence of an effective source rock led to failure the exploration deepwater well.

The main expulsion peak for Kasargod Unit-1 source rock in Kerala sub-basin could be evaluated at about 45 Ma. The Cretaceous Cochin source rock shows the main expulsion peak in the Kerala sub-basin at about 60 Ma. While assuming pre Deccan reservoirs within Cochin Formation, it could be shown by migration modeling that these reservoirs can be charged.

The effect of volcanism (Deccan basalt) on maturation and hydrocarbon generation is in general very minor and insignificant. However, realistic basalt flow scenarios in the basin model have shown, that only the first basalt flow has a temperature effect on the sediments below and only in certain geological settings: If the Source Rock is already in an early mature stage, the contribution of temperature affects the curve of transformation (Fig. 8).

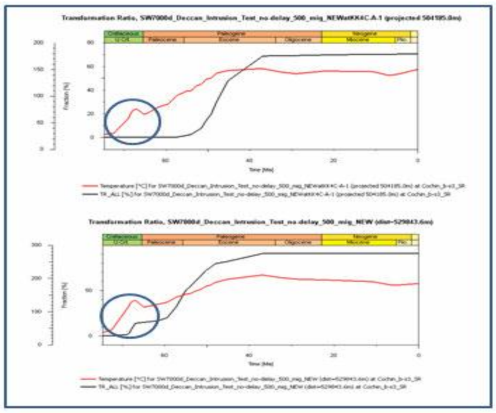

Fig 8: Time curves showing red curves for temperature and black curves for transformation ratio in two pseudo-wells. The kink in the black line (transformation ratio) shows the effect of the first intrusion event.

The Deccan basalt represents a special form of eruption with the wide distribution of lava. Although it could be proven, that there are local effects on the maturation, it does not affect the overall hydrocarbon production. The critical point of 50 % conversion of the Cochin source rock lies in the lows of Kerala and Konkan basin at approx. 50 Ma. Present day the source rock is over matured.

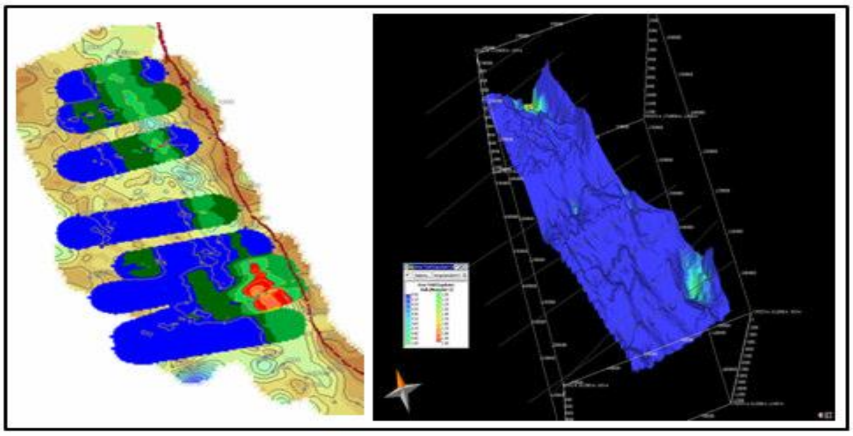

Fig. 9: Kitchen and generative centers of the Cretaceous source rock Cochin & Kasargod Unit-1 as a result of 2D (left) and 3D (right) modeling.

Hydrocarbon migration has been tested by several 2D and 3D models (Fig.9). Potential reservoirs either in Cochin or in Kasargod Formation could be charged by assuming effective source rocks. Depending on seal thickness and their absolute depth breakthroughs could be seen within different migration scenarios. In 'closed' (sealing) fault scenarios, faults may act as parts of a structural trap. In 'open' (non-sealing) faults scenarios hydrocarbon migration could be shown along faults. In order to better mitigate the charge risk for any potential prospect within the high graded areas a higher confidence level for the Cretaceous source rock presence and quality is required. Therefore, the first well drilled into the pre-Deccan succession should aim to encounter source rocks.

The Cochin source rock, derived from analogue basin, shows good hydrocarbon potential in certain sub basins. Because of a thicker sedimentary column in the Kerala sub basin, the extension of the mature Cochin source rock is bigger. The presence of a sub-basalt source rock or petroleum system is still to be proven.

## Conclusions

- Potential Petroleum Systems-Cretaceous Cochin and Paleocene Kasargod Unit-1 are working under certain assumptions. The younger source rocks are immature.
- The northern Konkan sub-basin, Cretaceous Cochin source rock show significant transformation ratios. In the southern Kerala sub-basin, the Cochin as well as the Kasargod Unit 1 source rocks shows significant transformation ratios. However both working Petroleum Systems are speculative. The main expulsion peak for Kasargod Unit 1 source rock in Kerala sub-basin could be evaluated at about 45 Ma and for Cretaceous Cochin at about 60 Ma. This result has been confirmed by simulating the outputs (sections) obtained by structural modeling (using MOVE software).
- The effect of volcanism (Deccan basalt) on maturation and hydrocarbon generation is very minor and insignificant. Realistic basalt flow scenarios have shown that only the first basalt flow has a temperature effect on the sediments below. However, only 50,000 years after the flow event, temperatures are equilibrated. Additionally, former basalt flow act as temperature insulator.
- Furthermore non sealing faults may act as hydrocarbon pathways through the Deccan basalt. A 3D open fault scenario show reservoirs within Kasargod Formation charged with hydrocarbons expelled from Cochin source rock.

## References

Biswas S.K., (1987): Regional tectonic framework, structure and evolution of the western margin basins of India. Tectonophysics, Vol. 135, pp. 307-327.

Hegde Dr. V.N., Radha Krishan, Paul Rama (2008): Tectono-sedimentation model of area between Vengurla Arch and Gulf of Manner within the framework of plate tectonics, Kerala Konkan Basin. Unpub. ONGC Report.

Mathur R.B., et al., (1993): Lithostratigraphy of Indian Petroliferous basins. Kerala Konkan. Document VI. Unpub. ONGC Report.

Siawal A., et al., (2005): Tectonostratigraphic evolution of East Coast basins of India. A regional synthesis through geoscientific study.

Suchy et al, (2004): Contact metamorphism of Silurian black shales by a basalt sill: geological evidence and thermal modeling in the Barrandian basin.

Radha Krishan, Paul Rama, Kaul Dr. Anil, Sundriyal Dr. R.R., Rawat, Rawat Sushma, 2009. Structural modeling and paleostructural analysis of Kerala Konkan basin. Unpub. ONGC Report.

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