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New Insight to Hydrocarbon Potential of Shelf Margin Basin West of DCS Area in Mumbai Offshore Basin, India

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Summary

Mumbai Offshore basin, a divergent passive continental margin basin, is located on the continental shelf off the west coast of India. NW-SE trending horst grabens bounded by normal faults are dissected by NE-SW trending cross faults resulting in formation of different tectonic blocks. The Shelf Margin block is bounded to its west by Kori-Comorin ridge and in the east by the Paleocene hinge. NW-SE trending local depression of Eocene and Oligocene age within Shelf Margin block has accommodated good quality potentially matured source rock deposited under restricted marine environment.

In the Shelf Margin basin, gravity driven tectonic activity has deformed sedimentary sequences resulting in episodic folding, faulting and shale diapirism during the period from Oligocene to Pliocene thus forming thick sequence of ponded sediments that represent wide range of depositional processes. During the period of low sea level, massive flow of sediments occurred through submarine canyon. Submarine canyons cut through these deformed zones and give rise to aggradational channel-levee-fan complex. Seismic expression show ambiguous reflection amplitude anomalies associated with channel & fan complex. Several prospects are identified in the study area for hydrocarbon exploration as stacked objects supported by flat spots / DHI.

Keywords: *Mumbai Offshore Basin, Shelf Margin Basin*

1. Introduction

Mumbai Offshore basin consists of series of rifted horst and graben including the paleo structure of Mumbai high. These horst and graben features are the Shelfal Horst-Graben complex, Kori-Comorin Ridge, Laxmi Depression, Laxmi-Laccadive Ridge and Arabian abyssal plain (Fig. 1). A narrow linear Kori-Comorin / Shelf Margin trough separates the Kori-Comorin Ridge from the Shelfal horst-graben complex. This NW-SE trending fault-bounded trough extends along the entire length of the western offshore passive margin setup.

In addition to the Shelfal horst-graben tectonics, Neogene gravity tectonics developed due to rapid loading of sediments. Collision of Indian plate with Eurasian plate and associated counter clockwise movement of the Indian plate resulted in NE-SW trending strike slip faults developing inverted structures. Possibility of deposition of shallow marine anoxic organic rick source rocks exist in this type of tectonic setting due to creation of restricted environment within the Kori-Comorin depression. High energy transgressive and regressive sedimentation cycles, coupled with sub areal exposures prevailed in the DCS area, resulting in the deposition of grainstone belt along the Shelf Margin (Roychoudhury and Deshpande, 1982). The restricted grabens allowed maturing of the source rock sediments, development of reservoir facies and sealing of the traps. The area of study is located in Shelf Margin block adjacent to the DCS area (Fig. 1).

2. Tectonics, Geological Setting & Stratigraphy

The Kori-Comorin Ridge is a prominent NW-SE trending linear fault-bounded structural high developed as a basement arch. It acted as a „synchronous high‟ during the deposition of the entire sedimentary section. The ancient NW-SE Dharwar trend, the NE-SW Aravali trend and the ENE-WSW Satpura trends are depicted as regional structural elements shown on the gravity map (Fig.1) Reactivation of these structural elements during and after

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rifting, has determined the shape, extent and subsidence histories of the Shelf Margin horst-graben complex.

The region of the Shelf Margin horst-graben complex, the Kori-Comorin depression and the Kori-Comorin ridge thus formed a unified interior graben system, with little structural differentiation between them. Almost all the rift-related horsts and grabens came into existence by end of Cretaceous-Paleocene. From Middle Eocene through to Middle Miocene shallow water carbonate platform developed intermittently on positive areas of the shelf including Mumbai High and DCS area. Early Oligocene transgression covered most part of the basinal area. During Late Oligocene due to global sea level fall, delta progradation brought in coarser clastic in the regional lows especially in Kori-Comorin depression. Further sea level fall resulted in formation of erosional unconformity at the end of Oligocene.

Sea level rise during Early Miocene submerged large area of the basin and terminated the Oligocene delta progradation. Subsequent to this and due to collision of India with Eurasia, regional uplift and continued rising of mountain ranges created a new source of clastic sediment influx during Mid Miocene. Clift mentioned peaks of sedimentation in Middle Miocene (Clift, 2006), with large volume of the sediments transported to southwards of the present day Indus fan through different processes. As a result of this tectonic activity the South to North sediment flow direction got reversed to North to South flow direction. This increased influx of coarser clastics during Mid Miocene resulted in gravity driven tectonics and in development of growth faults. During the same time in the Mumbai High and DCS area, Middle Miocene marked the last phase of the carbonate sedimentation (Basu et al., 1982). Neogene gravity tectonics was triggered due to sediment loading in the Kori-Comorin depression.

The increased clastic sediment supply in Mid Miocene also resulted in a significant progradation of Miocene shelf at places.

2.1 Growth fault development

After rifting ceased, gravity tectonics occurred due to high sedimentation in the Shelf Margin basin during Oligocene through to Miocene and resulted in shale mobility induced deformation process. Shale ridges were formed over the horst block due to the loading of poorly compacted, over pressured, prodelta and delta slope clays by higher density sands. Interplay of sediment supply, erosion, gravity tectonics, relative cycle of sea level changes and changing accommodation space resulted in rollover anticlines associated with growth faults and shale ridges (Fig. 2 and Fig. 3).

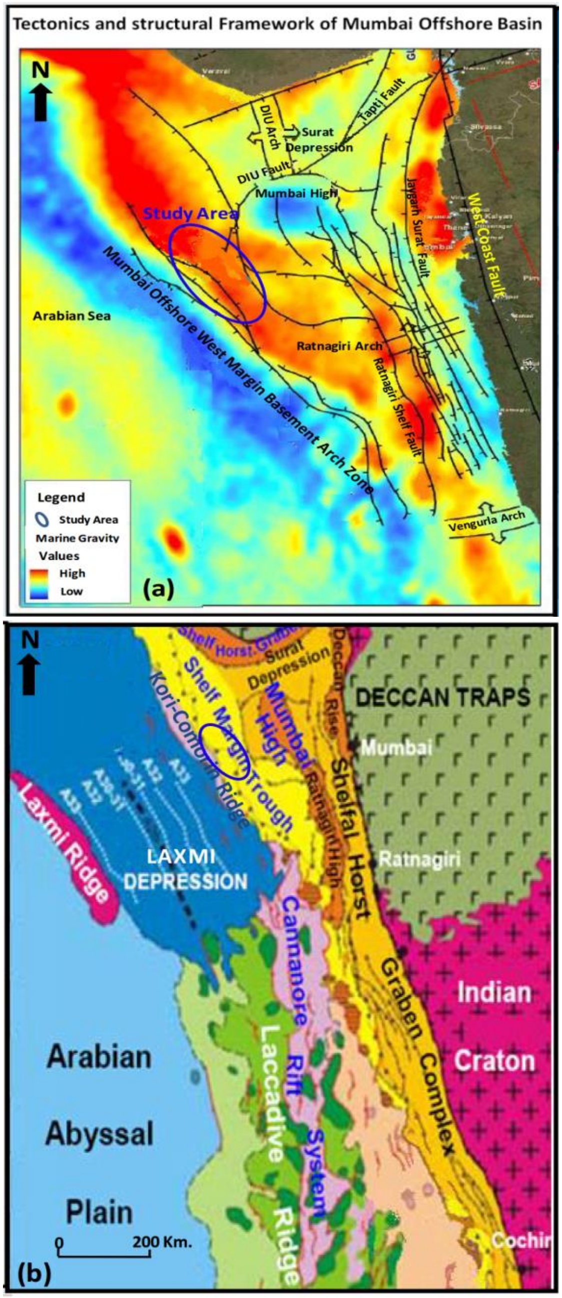

Fig. 1: (a) Regional structural elements on the marine gravity map showing influence of NW-SE Dharwar trend, NE-SW Delhi-Aravali trend and ENE-WSW Satpura trend (b) Map showing Regional Horsts, Grabens and Ridges

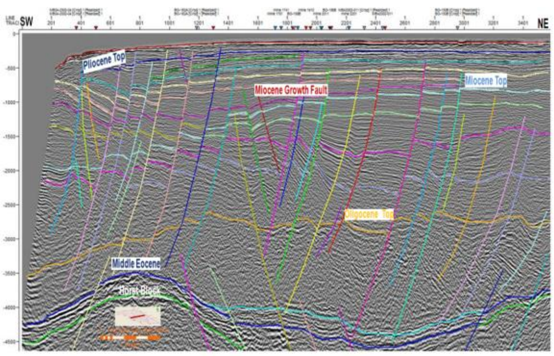

Fig. 2: Seismic line showing gravity driven growth faults and rollover anticline

3. Petroleum System

Several oil and gas fields are on production in Mumbai Offshore Basin. Also, the hydrocarbon discoveries on the Shelf Margin basin / DCS area are at various stages of delineation, development and production. The hydrocarbon pools are distributed in sandstone reservoirs of the Paleocene early rift sequence, limestone and sandstone reservoirs of the Eocene, Oligocene and Miocene sequences.

Source rocks are modeled for both Eocene and Oligocene sequences in the entire 600 sq km 3D seismic coverage in the study area. Three pseudo-well locations are identified in the NE-SW trending Paleocene-Eocene graben (Fig.4). The temperature gradient measured from the SM-1-2 well data varies from 25^0C/km to 29^0C/km and this is used for the basin modeling studies.

The lithology and facies distribution for these three pseudo well locations are also taken from well SM-1-2. Since the 1-2, the TOC (Total Organic Carbon) values of the Eocene source rock have been taken as 3%, based on published regional literature. For the Oligocene source TOC values of approx 2.5% is considered. Similarly, Hydrogen Index (HI) value of 300 is considered for both the Eocene and Oligocene source rock. Eocene source rock is mature and Vitrinite reflectance value at the present time for this source pod is greater than 1.4 % over the entire 3D area (Fig. 5).

The Eocene source is inferred to be in the dry gas window indicating late diagenetic cracking of organic matter. The huge pile of overburden on the Eocene section caused by the loading of thick Oligocene and Miocene sediments is possibly the main reason behind the cracking of source rock facies and generation of dry gas. For Oligocene source rock the temperature varies from 110-140 degree Celsius within the block area.

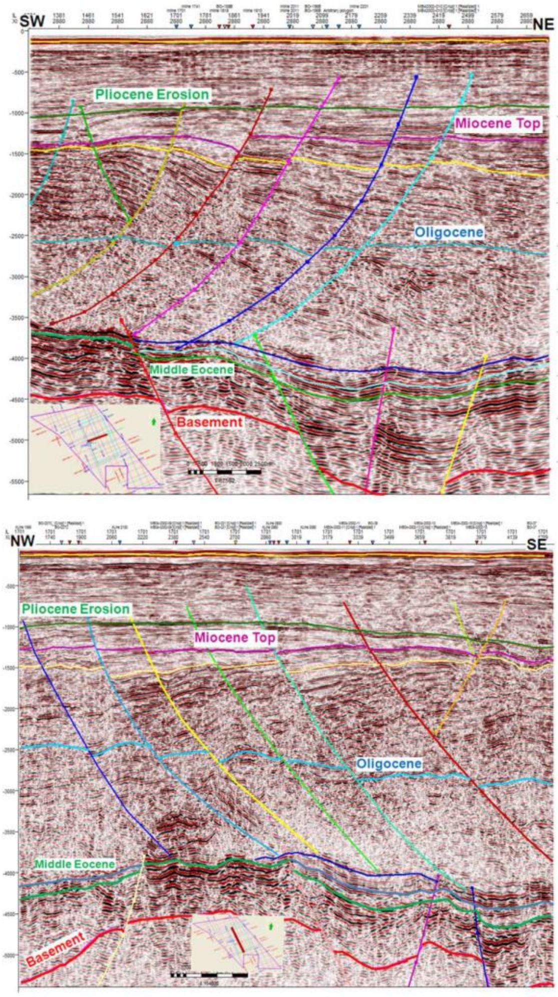

Fig. 3: 3D Seismic Inline and Cross Line showing growth faults and rollover anticlines

The vitrinite reflectance value at present day for the Oligocene source rock varies from 0.6% to 0.9% (Fig. 5). The Oligocene source rock is in the main oil window.

Transformation ratio for the Eocene source is greater than 94% over the entire 3D area and source rock is matured. It is inferred from the model that the expulsion of oil started in Late Eocene for Eocene source rock. However, peak oil generation occurred in Early Miocene.

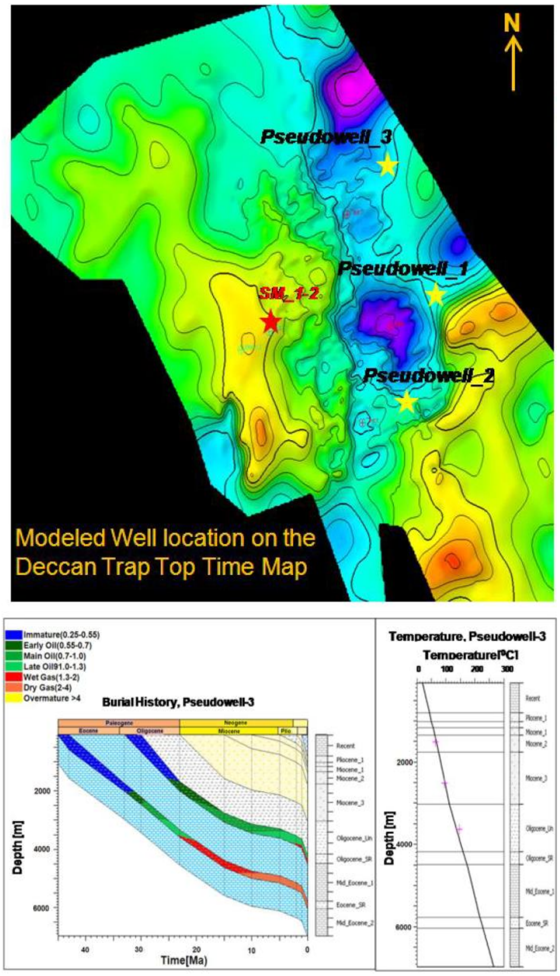

Fig. 4: Location of well SM-1-2 with the three pseudo wells. Burial History Model shows that Eocene source rock has passed through the oil window during Late Eocene to Early Miocene and is presently under gas window. Oligocene source rock is in oil window since Miocene

The Rate of transformation of Kerogen to Hydrocarbon of Oligocene source rock is higher in the northern part of the 3D area. Transformation ratio ranges from 20% to 75%. Structurally higher positions have lower transformation ratio. Oil expulsion from the sedimentary sequence started in Late Miocene and is yet to attain peak expulsion (Fig. 6).

3.2 Reservoir Development

Formation evaluation of well SM-1-2 (Fig. 7) within the study area indicates that the interval 3810-3986m is a limestone section. The section in the interval 3810-3803m is described as red claystone deposited in

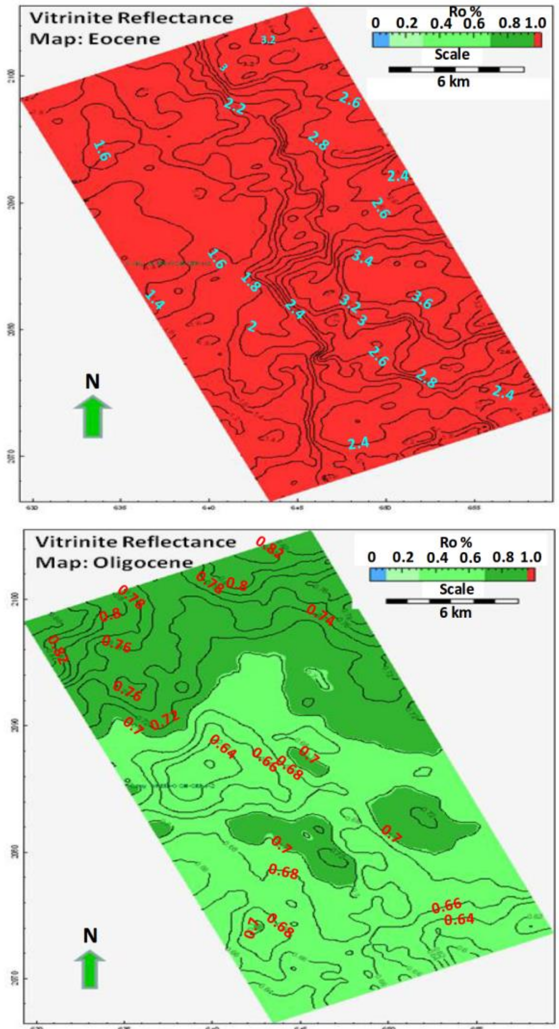

Fig.5: Present day Vitrinite Reflectance Maps for Eocene & Oligocene Source Rocks indicating Eocene source rock is in dry gas window and Oligocene source rock is in oil window

oxidizing environment, which corresponds to an unconformity between the limestone below and a thick monotonous claystone deposited above. Interval 1783-3803m is a shale section. The interval 1783-3700m is predominantly pressurized shale. Silts and silty shales are encountered in the interval 1149-1783m. The interval 552-1783m in the Mio-Pliocene section shows presence of sand & shale 675-1149 m with very good porosities. These Mio-Pliocene sands are interpreted to be deposited as channel fan complex.

Extensive carbonate platforms in association with shelf margin reefal bodies have been developed during Eocene

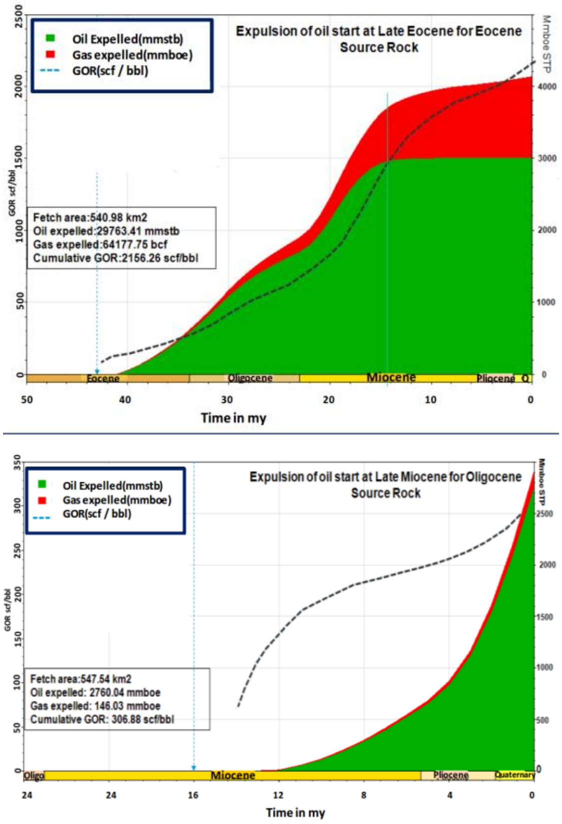

Fig. 6: Oil Expulsion Model for Eocene & Oligocene Source Rocks

to Miocene over almost the entire western part of the Mumbai DCS area, and on paleo highs in Kori Comorin Ridge including the Saurashtra rise. Abundant clastic reservoirs are developed within Eocene to Middle Miocene section in the eastern part of the Surat Depression, where a number of oil and gas pools have been discovered in these siliciclastic reservoirs. Also, sands are developed south of the Cambay basin which periodically overflow into deeper water along shelf margin by depositing in the lows and depression forming sand fairways (USGS) (Fig. 8).

Sea level rise during Early Miocene submerged large area of the basin and terminated the Oligocene progradation. Further, due to another cycle of sea level fluctuation during Miocene, influx of coarser clastic sediments occurred in the Shelf Margin area, which resulted in gravity tectonics and growth fault mechanism.

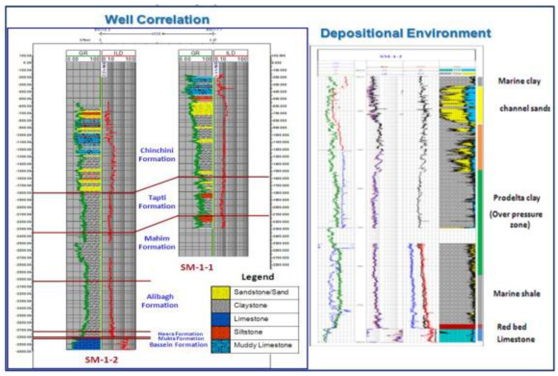

Fig. 7: Well correlation of SM-1-1 & SM-1-2 and interpreted depositional environment of Well SM-1-2. The sands are deposited as channel fan complex

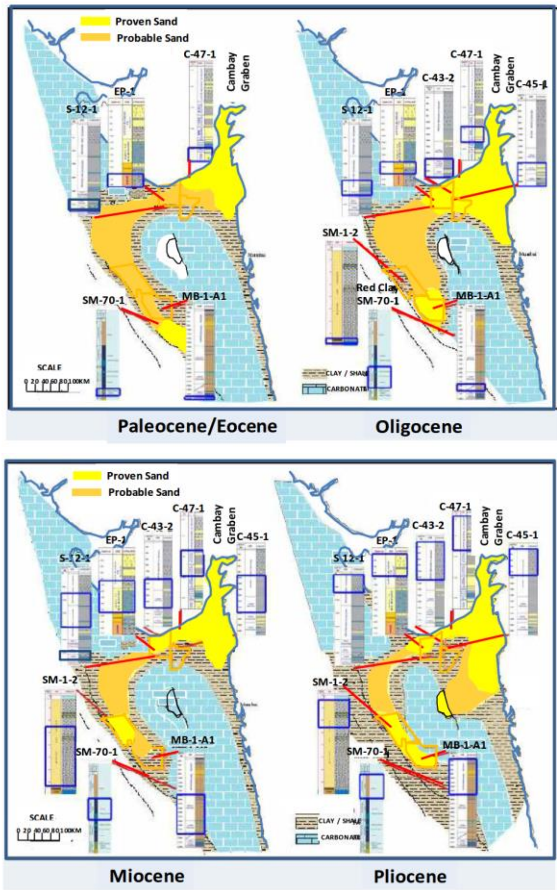

Fig. 8: Depositional facies distribution from Paleocene to Pliocene age showing clastic fairways (Source: USGS)

After rifting ceased, sediment loading occurred along Kori-Comorin depression triggering gravity driven tectonism and induced internal deformation due to shale mobility. Shale diapirs / ridges were formed over SM-1-1

& SM-1-2 paleo structures due to loading of poorly compacted over-pressured clays which were pushed towards the basinal side by the higher density sands. Complex structures, roll-over anticlines, collapsed growth fault crests, and closely spaced faults etc., were developed after Middle Miocene. Growth related faults offset the Oligo-Miocene section and these growth faults gently shape into detachment planes over the top of the Mid Eocene sequence.

Present day sediment influx is interpreted to be from NE-SW direction (Fig. 9). However, during period of low sea level, mass flow of sediments probably occurred via submarine canyon from NW direction. Submarine canyons cut across these deformed zones and give rise to NW-SE trending channel / levee system and fan complex (Fig. 10).

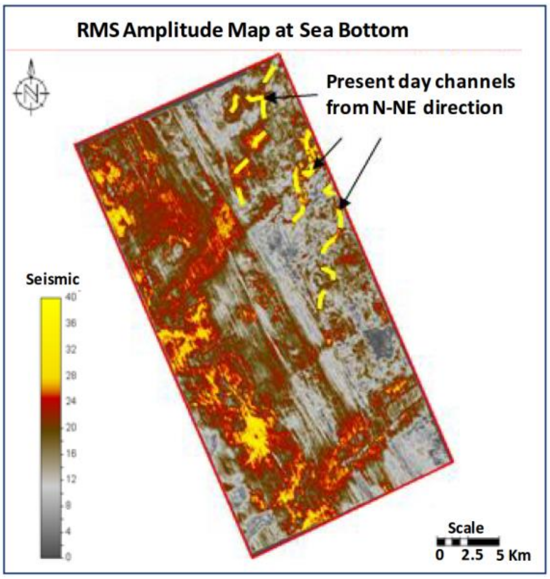

Fig. 9: Present day sediment input and flow direction

An alternative model is envisaged to explain NW-SE trending channel fan complex. The clastic influx from Indus fan got channelized along the Kori Comorin depression. The area to the east of the Kori-Comorin depression was developing as carbonate platform during Oligocene to Miocene age (Fig.11).

3.3 Direct Hydrocarbon Indicator (DHI)

Seismic amplitude anomalies, as direct hydrocarbon indicators (DHIs), are often used to assess the risk of prospects for hydrocarbon exploration. It can be used to interpret and differentiate seismic amplitude anomalies that may be related to the presence of hydrocarbons in low impedance ("soft") and high impedance ("hard") rocks. These are present in form of bright spots with phase reversal with respect to sea level. In the study area Bright amplitude anomalies are developed over a large area as seen on time slices over the 3D seismic volume (Fig.12). Several geobodies having similar type of DHI are seen in the Mio- Pliocene sequences.

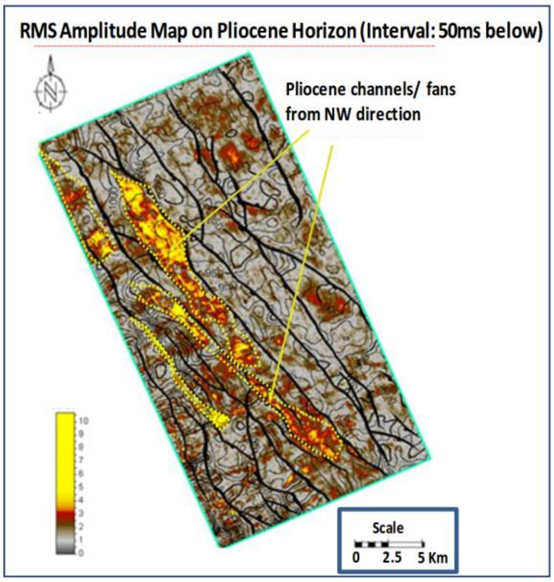

Fig.10: Sediment input and flow direction during Pliocene age

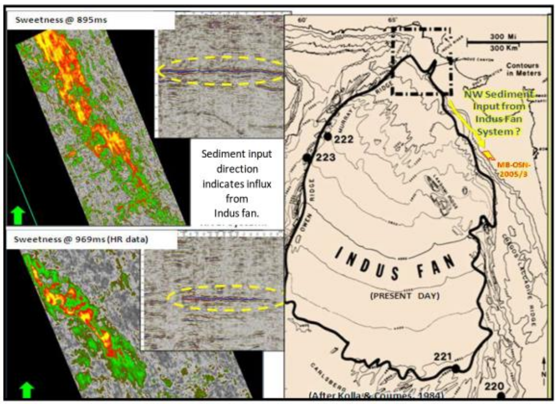

Fig. 11: Sweetness maps at Pliocene level showing meandering channels and fan complexes aligned in NW-SE direction indicating possible sediment influx from Indus along the Kori - Comorin depression

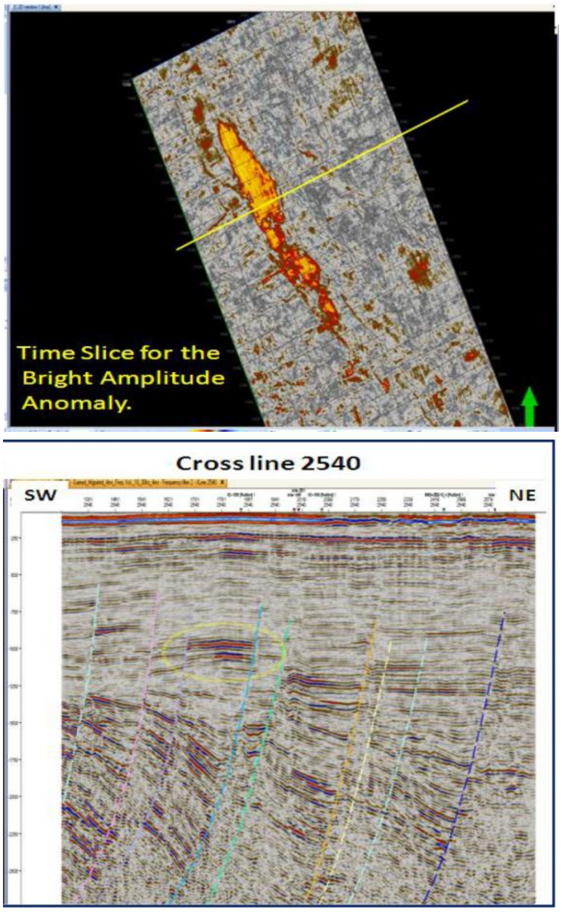

Fig. 12: Time Slice over 3D seismic volume showing Bright Amplitude anomalies associated with structural high

Growth fault related anticlinal reversal and fault closures provide entrapment conditions to majority of the structures in the area for oil & gas accumulation. These together with regional and local unconformity surfaces are likely to have provided favorable entrapment conditions. The seismic expression shows that the growth faults die out within Mio-Pliocene section in the eastern part providing favorable condition for vertical migration of hydrocarbon and for entrapment in the roll over anticlines and in the fault closures (Fig 13).

It is also evident that hydrocarbon, migrated vertically to Oligocene and Mio-Pliocene reservoir from Eocene / Oligocene source kitchen area via growth faults mechanism have bypassed the high pressured horst block. Also, the faults are seen surfacing out in the western part of SM-1 horst block which probably resulted in lack of hydrocarbons in the western part of the area.

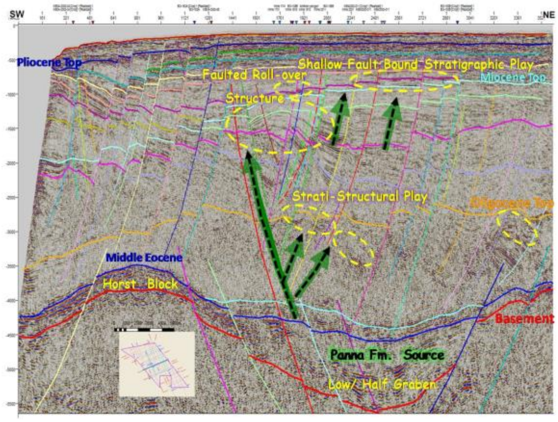

Fig. 13: Seismic section showing mechanism of vertical hydrocarbon migration and entrapment in the rollover anticline associated with growth faults

3.5 Generic Event chart

All essential elements, processes and results of the petroleum system analysis are mapped in the event chart, which indicates timing of source rock deposition, deposition of reservoir facies, trap formation, sealing, generation, expulsion, accumulation & preservation of hydrocarbons (Fig. 14).

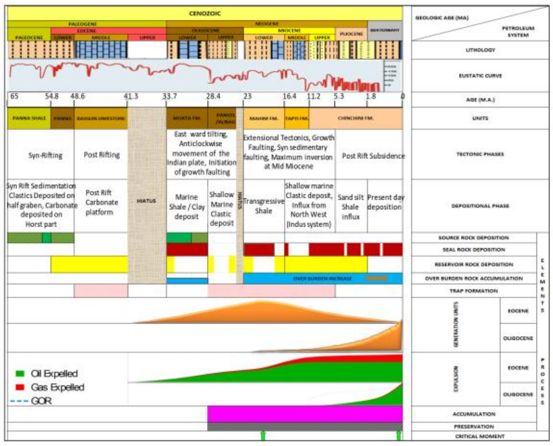

Fig. 14: Petroleum system event chart indicating timing of source rock deposition, reservoir development, sealing, trap formation, generation, expulsion, accumulation and preservation of hydrocarbons

The events chronology indicates favorable timing of generation & migration of hydrocarbon generated from Eocene and Oligocene source rock. By the time hydrocarbon migrated to Miocene section, many traps had already formed and were available to capture the oil and gas.

4. Conclusion

Paleocene-Eocene source rock of restricted marine deposit contributed the largest volume of hydrocarbon and contains good quality oil & gas prone source rock. Eocene source rock is matured in the study area. Maturity modeling of Vitrinite reflectance indicates that oil expulsion started in Late Eocene age and peak oil expulsion occurred in Early Miocene in the shelf margin area. At present, Eocene source rock is in the dry gas window. Oil expulsion from Oligocene source rock which started in Late Miocene is yet to attain peak expulsion.

High energy environment and transgressive - regressive cyclicity associated with growth faults resulted in deposition of reservoir facies during Miocene to Pliocene period along the shelf margin. Migration is primarily vertical, along the faults and fractures into the overlying sandstone reservoirs. Series of thick shales extending over the area from Eocene to present day provide effective sealing mechanism for hydrocarbon accumulation in the trap.

Shelf Margin basin holds good potential for future hydrocarbon discoveries as many potential prospects are yet to be probed and tested. Drilling of these prospects will open up a new area for future hydrocarbon exploration.

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