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Author **Loreta Pereira , ONGC , India**

Co-Authors **Ramah Murgudass, Bharti Jagtap, Dr. Alok Dave**

Integrated Play Based Exploration Study using 3D Petroleum System Modeling: A Case Study from Kutch-Saurashtra Basins

Abstract

3D petroleum system modeling is has been used in the present work to simulate in time and space the hydrocarbon volume generated by the Mesozoic and Cenozoic sedimentary succession of Kutch and Saurashtra basins. The work is based on integration of geological, seismic and geochemical studies carried out on the sedimentary successions encountered in wells drilled in onland and offshore areas. A standard methodology has been followed to identify basic elements of petroleum system i.e. source, reservoirs, traps/seals, paleo thermal history, migration and entrapment. The work has helped in establishing play fairways towards establishing plays and their hydrocarbon potential

Introduction

Exploration has witnessed a considerable improvement in recent years in the understanding of basin and reservoir geology aided by advancement in technology. In Indian context although all category I basins (Cambay, Krishna-Godavari, Mumbai Offshore etc.) have been producing oil and gas for decades, there remains certain geological risks (Source, Reservoir, Seal, Trap) associated with each basin. An understanding of basin's evolution and the related petroleum system risk is essential in hydrocarbon exploration and exploitation. It can be applied during all stages of exploration from frontier basins with no well control, to well-explored areas and charge assessments of single prospects or fields. Exploration in Kutch-Saurashtra basins began in the early sixties however, a major part of the basin remains underexplored namely Saurashtra Basin, the Kutch deep-water and the Mesozoic strata due to many technological and operational challenges in drilling and data acquisition. In this paper a complete workflow has been defined with case study from the Kutch-Saurashtra basins which are important but less explored offshore Mesozoic-Cenozoic petroleum province of India.

Regional Geology and Tectonics

Kutch basin is a pericratonic embayment through a marginal graben between Nagar Parkar and Saurashtra uplifts, respectively from north to south (Biswas, 1987). To the east, the basin is limited by Radhanpur arch. The regional slope of the basin is towards WSW and the depositional axis passes near the Saurashtra uplift in the south. Basinal hinge zone is marked by a first order basement high (Median high) across the middle of the embayment. This hinge zone is the extension of the Indus shelf hinge perpendicular to the depositional axis (Fig.1). Saurashtra Offshore basin trends NNW-SSE direction and is located to the southeast of the Kutch basin, the Saurashtra arch forming the northern boundary with it. The Saurashtra shelf is narrower and extends much less than its average extension of the western offshore (i.e. 160km). The shelf break also occurs at a water depth of 200m. Its straight eastern margin which separates it from the Onland Saurashtra Basin is also a faulted margin which follows the Dharwar trend. The deeper offshore Saurashtra borders with the Indus fan (to the abyssal plain of the Arabian Sea).

Major structural features of the Kutch basin include several E-W trending faults/folds. The rift zone is bounded by a north dipping Nagar Parkar fault (NPF) in the north and a south dipping Kathiawar fault (KF) in the south. Other major faults in the region are the E-W trending Allah Band fault (ABF), Island belt fault (IBF), Kutch mainland fault(KMF) and Katrol hill fault (KHF) (Fig.1). In addition, several NE and NW trending small faults/lineaments are observed. The Saurashtra peninsula forms a rocky highland. The major portion of the peninsula is occupied by the Deccan lava flow with Early Cretaceous sediments exposed in the northeastern part of the area. Deccan Trap basaltic flows overlain by a thin cover of Neogene and Quaternary sediments. Similar structural features as seen in outcrop studies of the Kutch Onland Basin have been mapped in the Kutch and Saurashtra offshore from seismic studies.

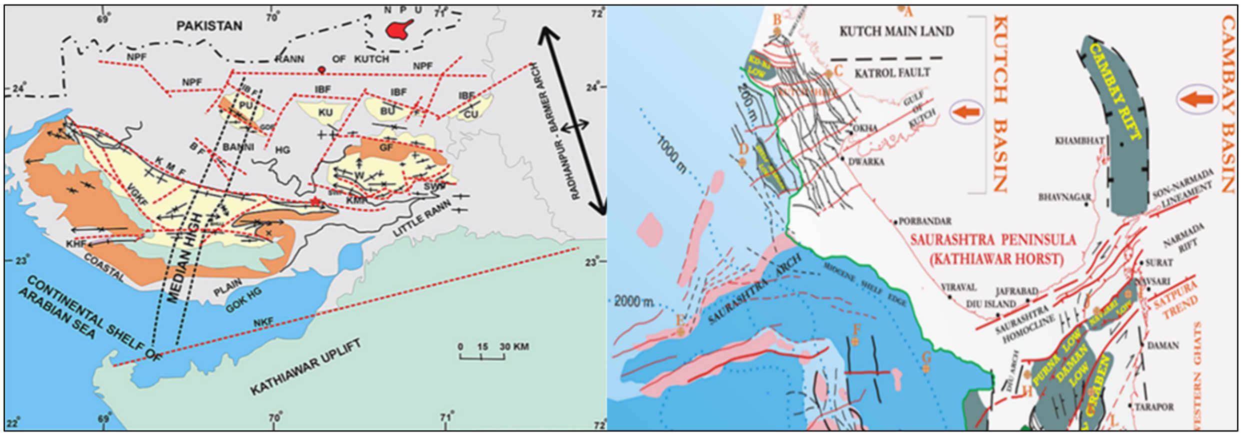

Fig.1: Tectonic Elements of Kutch and Saurashtra Basins showing major fault trends, arches, subsurface ridges and prominent lows.

Petroleum System Elements

Numerous discoveries within different plays in Tertiary and Mesozoic stratigraphic units prove the presence of multiple petroleum systems, which are working effectively in the basin. Based on stratigraphic correlation and geochemical data from drilled wells till date, four major source rock units Jurassic, Early Cretaceous, Paleocene and Early Eocene Ramah please) have been identified mainly in offshore region. The earliest known source rocks encountered in the basin are from Middle-Jurassic period which is organic rich and proven by the wells**.** The shallow marine shales of the Early Cretaceous Bhuj Formation indicate predominantly type III organic matter with minor type II inclusions of organic matter. Within the Tertiary sequences, lagoonal coal/shales of Paleocene sequence (Nakhtarana Formation) overlying the Deccan Trap host source rich facies. The shallowest source present is in Early Eocene (Jakhau Formation) sequence and is penetrated in most of the wells in Kutch offshore area and studied in detail. The organic matter for both Paleocene and Eocene is a mixture of Type II and III kerogen. However, in deep water carbonate facies no significant source characteristics are encountered till date.

The major reservoirs are the Eocene sands, which have proved to be the most prolific reservoirs in this basin and are represented by coarse to fine grained quartz arenite/wacke and siltstone with moderate to good intergranular porosity. The other major reservoirs are the fractured Deccan basalts, the Late Cretaceous clastics and some sporadic occurrences in the Jurassic succession. Lately, Middle Miocene clastics of proximal delta front are also proving to be hydrocarbon bearing in the Kutch basin. The transgressive shales of the Eocene age and shales of Miocene are effective lateral and vertical seals for the Tertiary reservoirs. The massive thickness of the Deccan basalt provides and effective vertical seal for the hydrocarbon bearing Mesozoic's formations. The interplay of initial Mesozoic rift basin trending NNW-SSE the cross-trending NE-SW Middle Miocene Himalayan collision tectonics have formed fault blocks which also have a role in forming good seals in the tertiary reservoirs.

3D Modeling Inputs

Different inputs such as depth maps, faults, erosion maps, facies maps, heat flow and paleowater depth maps, source facies, TOC and HI maps were used as input to construct the G&G model. Structure maps were prepared for thirteen levels using layer cake method and tied to well tops. The facies maps and paleowater depth maps were constructed using biostratigraphic, sedimentological and well data. Facies maps were made for the Mesozoic sequences with the help of a few drilled wells and considering analogues from onland Kutch and Scheylles Offshore Mesozoic basin. Once all the relevant input data types were processed to construct the G&G model, it was converted to a petroleum system model to understand how different exploration elements of petroleum system (source, reservoirs, seal and overburden) work effectively **(Fig.2)**. Once the petroleum system model was constructed using all available data from different source, the model was simulated in geological time to understand the process of source rock maturity, hydrocarbon generation, expulsion, migration and entrapment across the basin.

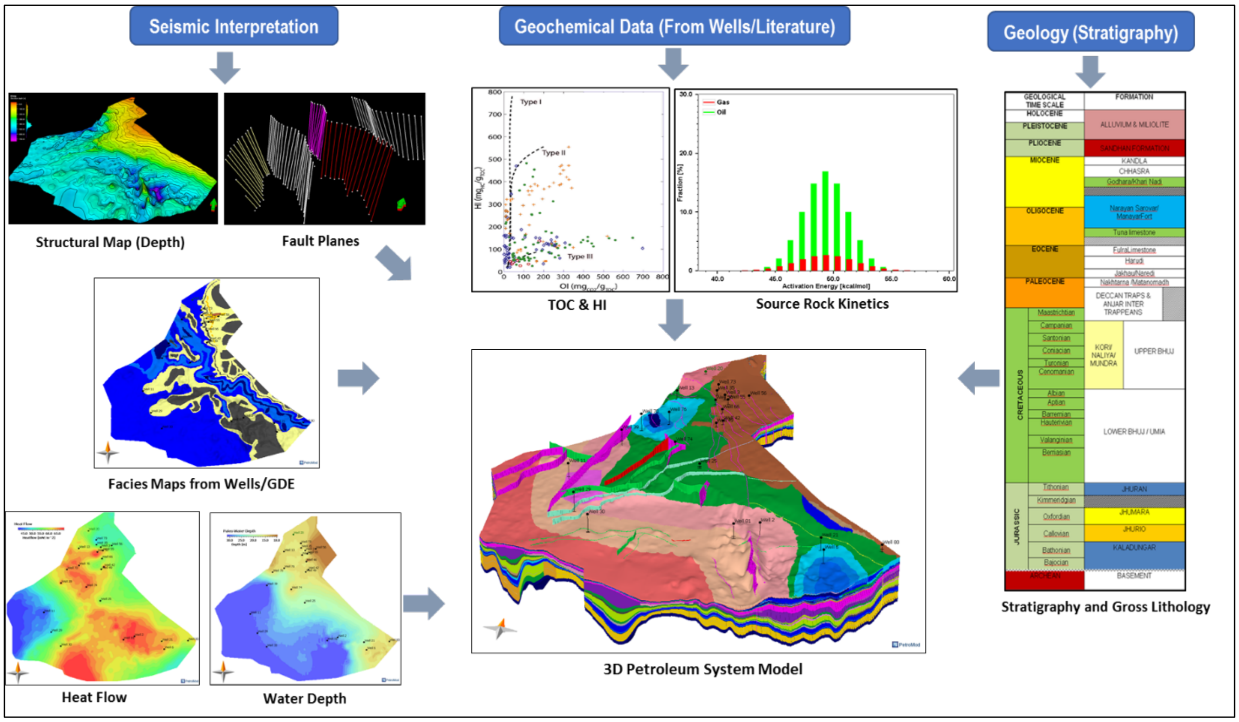

Fig. 2: Workflow showing how different domain interpretation and inputs were integrated to make a robust petroleum system model of Kutch-Saurashtra basin.

Petroleum Systems Modeling Output

The 3D petroleum system model of Kutch-Saurashtra basins was initially calibrated with porosity and pressure measured in wells across the basin **(Fig.3)**. Although regional, performing compaction and pressure calibration was an essential step towards achieving the best compaction model. This marks the initial step towards the heat flow modeling at basin scale. The calibration of model with multiple wells helped in QC of the model. For example, the uncertainty in heat flow can lead to substantial changes in source rock maturity profile, which can in turn influence the hydrocarbon generation. Subsequently, the 3D model was calibrated with measured temperature and vitrinite reflectance in key wells, spread across the entire onshore and offshore in Kutch-Saurashtra basins **(Fig.4)**.

Thermal calibration performed with key wells in Kutch-Saurashtra basins predicts the present-day heat flow values in shallow offshore Kutch in the range of 45-54 mw\m^2 where as in deeper areas of Kutch low, the heat flow values are in the range of 44-50 mw\m^2. The deep-water region in Saurashtra Basin is predicted to have heat flows in the range of 50-58 mw\m^2. Thermal maturity calibration status for key wells across the Kutch Saurashtra Basin. The maximum paleo heat flow predicted in Kutch offshore varies in the range of 65-70 mw\m^2, whereas in the Saurashtra Low, the values are in the range of 70-75 mw\m^2. Once the thermal calibration was achieved and a good prediction of heat flow was established for the basin, the 3D model was then simulated in geological time to predict the thermal maturity evolution along with hydrocarbon generation and expulsion potential for all key source rocks in Tertiary and Mesozoic successions.

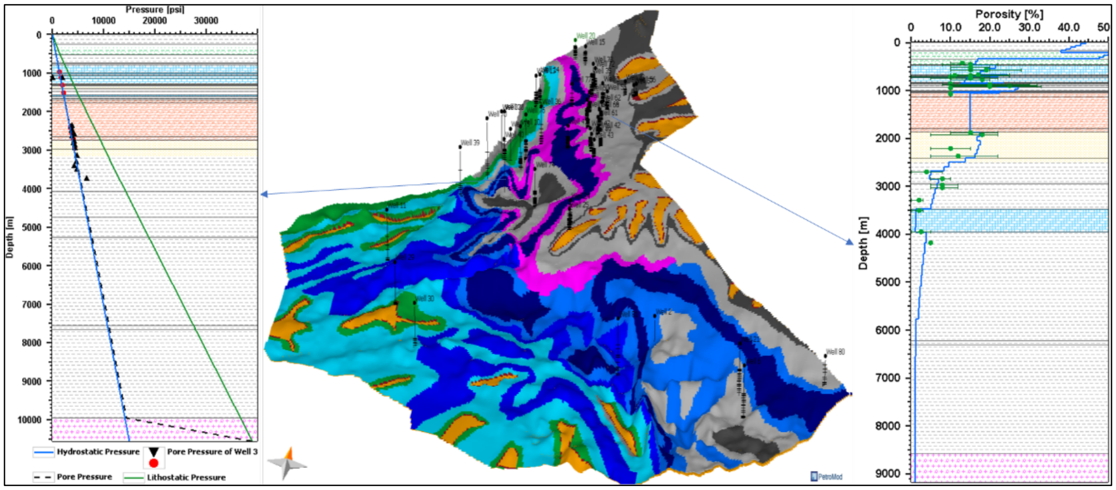

Fig. 3: Compaction and Pressure calibration was performed with all key wells having porosity data and pressure data from various sources (MW, MDT, Testing).

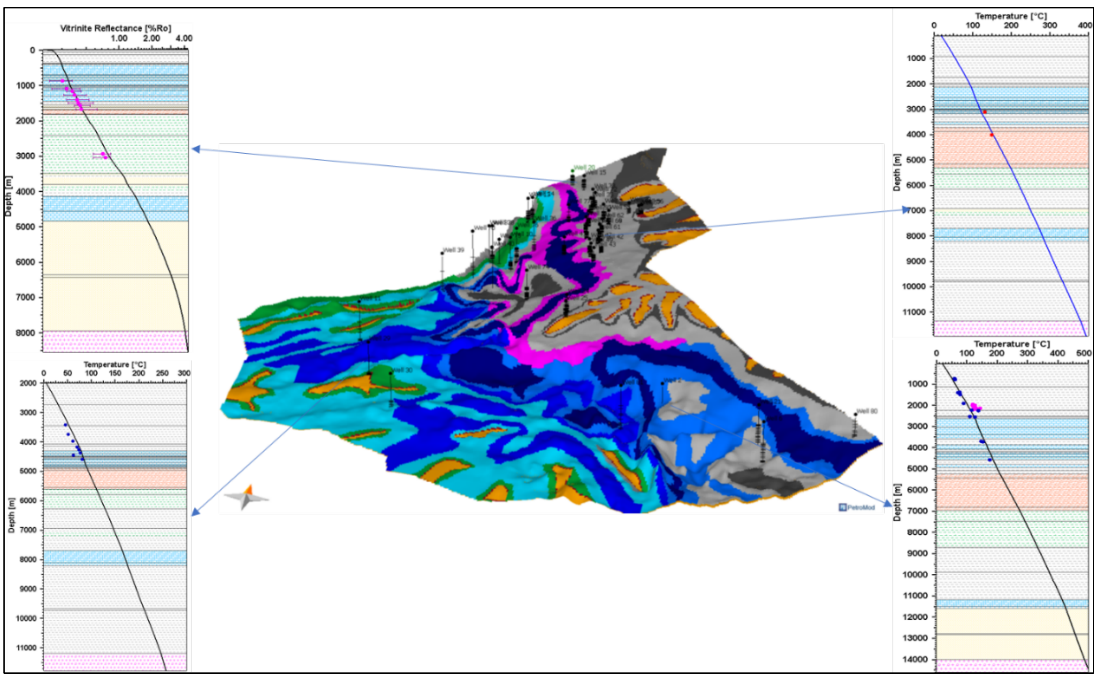

Fig. 4: Temperature calibration was performed with all key wells having porosity data and pressure data from various sources (MDT, Testing).

Based on the burial history and thermal maturity outcomes from 3D petroleum system model, some of the deeper areas in Kutch and Saurashtra are found to be prospective kitchens from where the hydrocarbons are being sourced to the various discoveries in the basin (Ex. GK-29A and GK-28-2, GK-22C-1).

In the shallow offshore areas of Kutch Basin modeling predicts that the thermal maturity evolution of Early Jurassic formation was rapid with burial and entered the Early-Oil window during Middle Jurassic and Main-Oil window during Late Jurassic. With rapid burial and sedimentation, the Jurassic Formation was into Main-Oil window during Early-Cretaceous and is predicted to be in Late Oil- Wet Gas window at present day. Similarly, the shallower formations of Early Cretaceous are predicted to be in Early-Oil window during Eocene and not mature enough to generate high quantity of hydrocarbons **(Fig.5a)**.

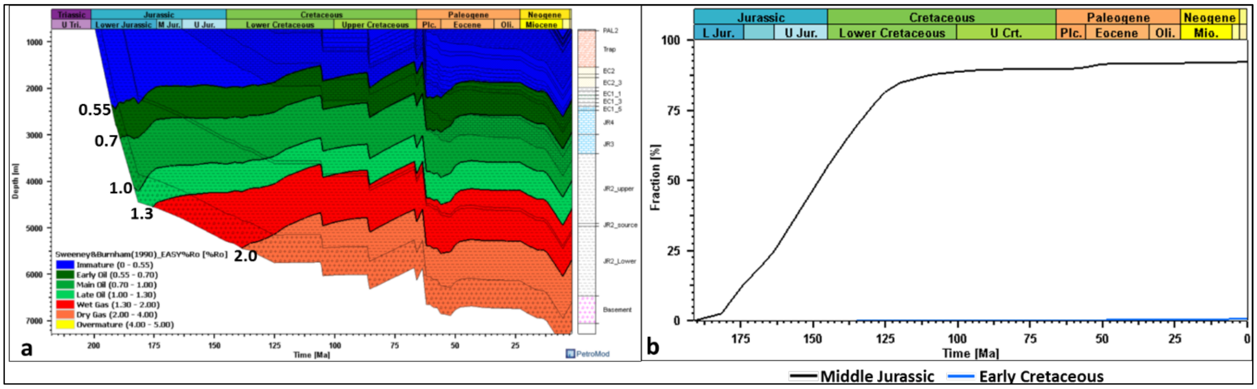

Fig.5 (a) Burial History curve showing thermal maturity and b) source rock transformation ratio for shallow offshore, Kutch Basin.

Kinetic modeling for the Mesozoic source rocks predicts that the Jurassic source rocks would have a high generation and expulsion capacity, which is supported by outcome of high transformation ratios (TR). The Tertiary formations are predicted to be immature, having a poor generation potential and thus the presence of effective source rock is not established **(Fig.5b)**.

In the deeper areas of the Kutch low deeper Formations in Mesozoic are predicted to be in Late Gas-Over mature window. The Jurassic formation moves to Early-Oil window during Early-Jurassic and with continued rapid deposition moves to Main-Oil window during Middle-Late Jurassic. It subsequently entered the Main-Oil and then to Gas window during Early Cretaceous. During Paleocene time, the Jurassic succession is predicted to be in to Over-Mature window due to deepr burial and high heat flow. Similarly, the Early Cretaceous succession is predicted to be in Early-Oil window during Early-Cretaceous, Main-Oil window during Late-Cretaceous, Late-Oil to Gas window during Paleocene and Over-Mature at present day. In Tertiary , the Paleocene is relatively less mature than the Mesozoic **(Fig.6a)**. Kinetic modeling of source rocks predicts high TR values for Mesozoic source rocks which also exhibits rapid generation and expulsion phase, thereby creating a risk of timing for the entrapment of hydrocarbons into Mesozoic reservoirs **(Fig.6b)**.

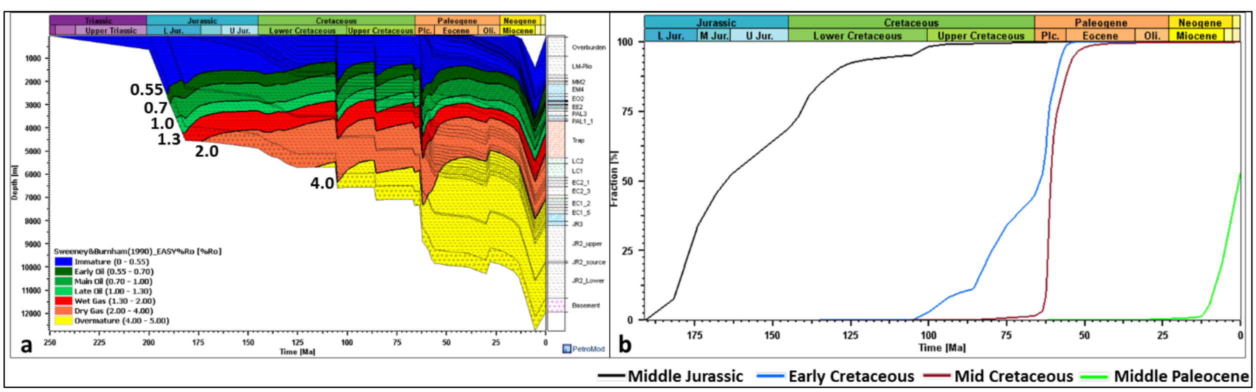

Fig.6: a) Burial History curve showing thermal maturity and b) source rock transformation ratio for deep offshore, Kutch Basin.

The burial history of kitchen in deep Saurashtra offshore has similar burial history like deep offshore Kutch Basin. The source rocks in Mesozoic like Jurassic Formation entered oil maturity window during

Early Cretaceous rapidly moved to Late Oil-Wet Gas window during Middle Cretaceous. The Late Cretaceous phase saw the Jurassic Formation moving to Dry Gas Window and subsequently was over-mature during Early Cretaceous. Similarly, the Early Cretaceous Formation was thermally mature during Middle Cretaceous and was in Late-Oil window during Late Cretaceous and in Gas window during Paleocene time. The Tertiary source rocks in Paleocene and Early Eocene were thermally mature during Early Miocene and moved rapidly to Main-Oil window during Late-Miocene with high sedimentation and rapid burial. At present day the Tertiary Formations are in the Late Oil to Gas window in deeper areas of offshore Saurashtra (Fig. 7a).

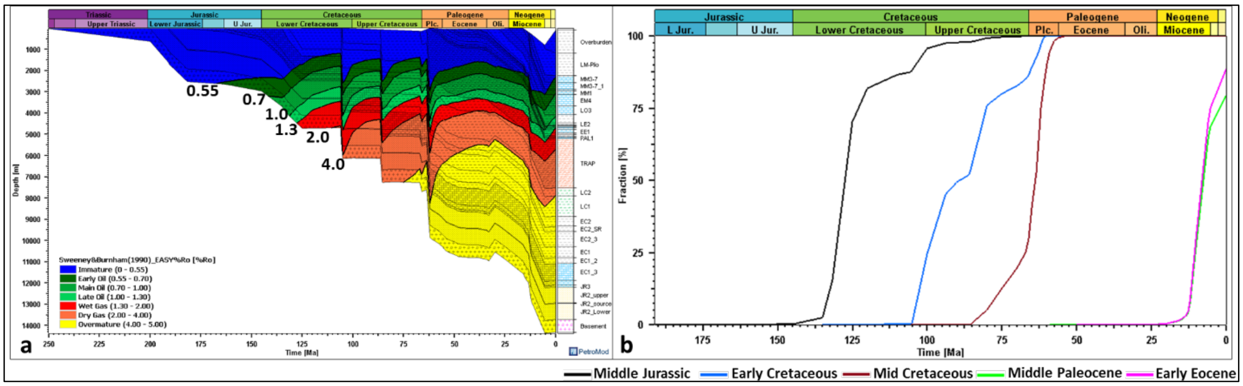

Fig.7: a) Burial History curve showing thermal maturity and b) source rock transformation ratio for deep offshore, Kutch Basin.

Kinetic modeling predicts hydrocarbon generation began from Mesozoic source rocks during Early-Late Cretaceous. The Tertiary source rocks of Paleocene started during Late-Cretaceous to Paleocene time. Good generation is also prognosed from the shallower source rocks in Early Eocene (Fig. 7b). The interpretation and modeling results presented here are subjected to the fact the complete drilling up-to basement is not yet done in shallow water region and thus basement depth or base of Jurassic is highly subjective to interpretation. The deeper areas in Kutch and Saurashtra offshore also have a similar challenge where none of the wells have been drilled to Jurassic and where, both the depth and the thickness of the deeper Mesozoic formation remains unknown.

Conclusions

3D petroleum system modeling of Kutch-Saurashtra basin was built by integrating all domain data. Burial history and thermal modeling provides a good first insight on the distribution of thermal maturity and hydrocarbon generation centers in the basin. Modeling predicts that the envisaged Mesozoic source rock in Jurassic and Cretaceous Formation are mature in the shallow and deep offshore in Kutch and Saurashtra Basins. However, the Tertiary source rocks are only predicted to be oil mature in deep offshore areas. With further exploration in Mesozoics true potential of the play would be unlocked.

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