Petroleum Systems of the Mumbai Offshore Basin, India*

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Abstract

Mumbai Offshore Basin, a pericratonic rift basin in the western continental shelf of India, covers about 148,000 km^2 from coast to 200 m isobath. The basin is divided into six tectonic blocks (Tapti-Daman, Diu, Heera-Panna-Bassein, Mumbai high-Deep Continental Shelf [DCS], Ratnagiri, and Shelf Margin), and the sedimentary fill ranges from 1100-5000 m. Several large oil and gas fields have been discovered in this basin, and the presence of hydrocarbons has been established in the multiple pay zones belonging to L-III limestone reservoir of Miocene age (only in Mumbai high), Mukta (early Oligocene), Bassein (middle Eocene), Panna (Paleocene to early Eocene) reservoirs, and Daman (early Miocene-late Oligocene) and Mahuva (early Oligocene) formations in Tapti Daman block. This work presents the detailed geochemical evaluation on more than 200 rock extracts and 250 oil samples and maturity modeling in key generative depressions of all the tectonic blocks of the basin.

Studies indicate that Paleocene to early Eocene Panna Formation has good to excellent source-rock characteristics in the basinal part of every block in the entire basin. The middle of Panna Formation attained the maturity of 0.6% VRo equivalent at about 12-20 Ma. The Panna source rocks have predominantly Type III kerogen in lower layers and Type II and III mixed kerogen in upper layers. However, few source-rock layers in Mahim graben and Deep Continental Shelf (DCS) area contain Type I kerogen. Based on the variations in organofacies, the oils have been placed into two groups. The first group oils, having only terrestrial source input, correlate with the source-rock extracts of lower layers, whereas the second group oils, with terrestrial and marine mixed input, correlate with the source-rock extracts of upper layers of the Panna Formation. Based on the reservoir and source combinations, major petroleum systems in the basin are: Panna-L-III, Panna-Mukta, Panna-Bassein, and Panna-Panna.

Introduction

Mumbai offshore basin accounts for nearly two-thirds of the annual petroleum production of India. The mature source rocks are present in the lower Eocene-Paleocene Panna Formation. Further, marginally mature potential source rocks within Oligocene in Tapti-Daman area and within Neogene in DCS and deeper part of the basin also exist. Hydrocarbons have been discovered in multiple reservoirs in this basin, ranging from fractured basement to middle Miocene. The Mumbai offshore basin has three major depressions: Surat and its southward extension to Ratnagiri in the east, Saurashtra low in the northwest, and Murud and Rajpur lows in the southwest. Due to multiplicity of depressions, source rocks, and reservoirs, oil-source genetic relationship is a challenge. The understanding of genetic correlation amongst oils and source rocks is a prerequisite to model hydrocarbon generation, expulsion, and entrapment. The prime objectives of this study are:

- To geochemically characterize the source rocks and oils through conventional biomarkers, non-biomarkers, and stable carbon isotopic composition.
- To carry-out 1D-thermal maturity modeling in key generative depressions.
- To provide geochemical inputs for petroleum system modeling.

Geological Setting and Stratigraphy

Mumbai offshore basin, a divergent passive continental margin basin, is located on the continental shelf off the west coast of India. The basin is bounded by the western coastline of India in the east, Saurashtra arch in the north, Vengurla arch in the south, and west margin basement arch in the west (Figures 1 and 2). The basin was formed due to extensional tectonics at the time of rifting of the Indian plate from Madagascar during Late Jurassic-Early Cretaceous period. Large-scale volcanic eruptions, which covered most of the basin, followed this episode. As the rifting continued, the immature sediments deposited at the toe of faults as alluvial fans, filled the initial morphotectonic depressions during Paleocene. This was followed by the first marine incursion towards the close of Paleocene and beginning of early Eocene. Thus, early Eocene marks a widespread transgression. Sediments were deposited in deltaic to restricted marine to shallow marine environments. Sedimentation during this period caused some adjustments in the basin. The early Oligocene transgression covered most parts of the basinal area and inundated parts of Mumbai high. A major unconformity is noted at the top of lower Oligocene. Sea level rise during early Miocene submerged large areas of the basin and terminated the . Oligocene delta progradation. The middle Miocene transgression marks the last phase of the widespread carbonate sedimentation in the Mumbai high–DCS area (Basu et al., 1982; Zutshi et al., 1993).

The basin has a NW-SE-trending horst-graben geometry. The grabens are bounded by normal faults, and the horsts/ridges are dissected by NE-SW-trending cross faults. On the basis of its structural configuration and its nature, as well as the type of sediment fill, the basin is divided into six tectonic blocks: Tapti-Daman, Diu, Heera-Panna-Bassein, Bombay high-DCS, Ratnagiri, and Shelf Margin blocks.

The main Mumbai high block is surrounded by three depressions:

- Surat depression (Daman, Purna and Navsari lows) and its southward extension through Mahim depression in the east.
- Saurashtra low in the northwest.
- Southern paleosink and Murad depression in the southwest.

The Shelf Margin block bounded on its west by Kori-Comorin ridge and east by Paleogene hinge and its northern part includes Saurashtra offshore (Figure 2). Surat depression and its southward extension through Mahim depression to Vijaydurg depression in Ratnagiri block are the prime depocenter of the clastic sediments of early Eocene to Paleocene age. Murud depression and Saurashtra low had relatively more open marine environment due to minor shielding provided by the west basement arch compared to Surat-Mahim depression.

The main reservoir rocks in the basin are the limestones ranging in age from Eocene to middle Miocene. Clastic sequence of Paleogene also hosts the hydrocarbons. The extensive post-Miocene shale acts as a regional cap rock in the basin. The local shale interbeds within limestones act as a local cap rocks for different pay zones. However, in Ratnagiri block, compact and tight limestones may also act as cap rocks for hydrocarbon accumulations in fractured limestone reservoirs.

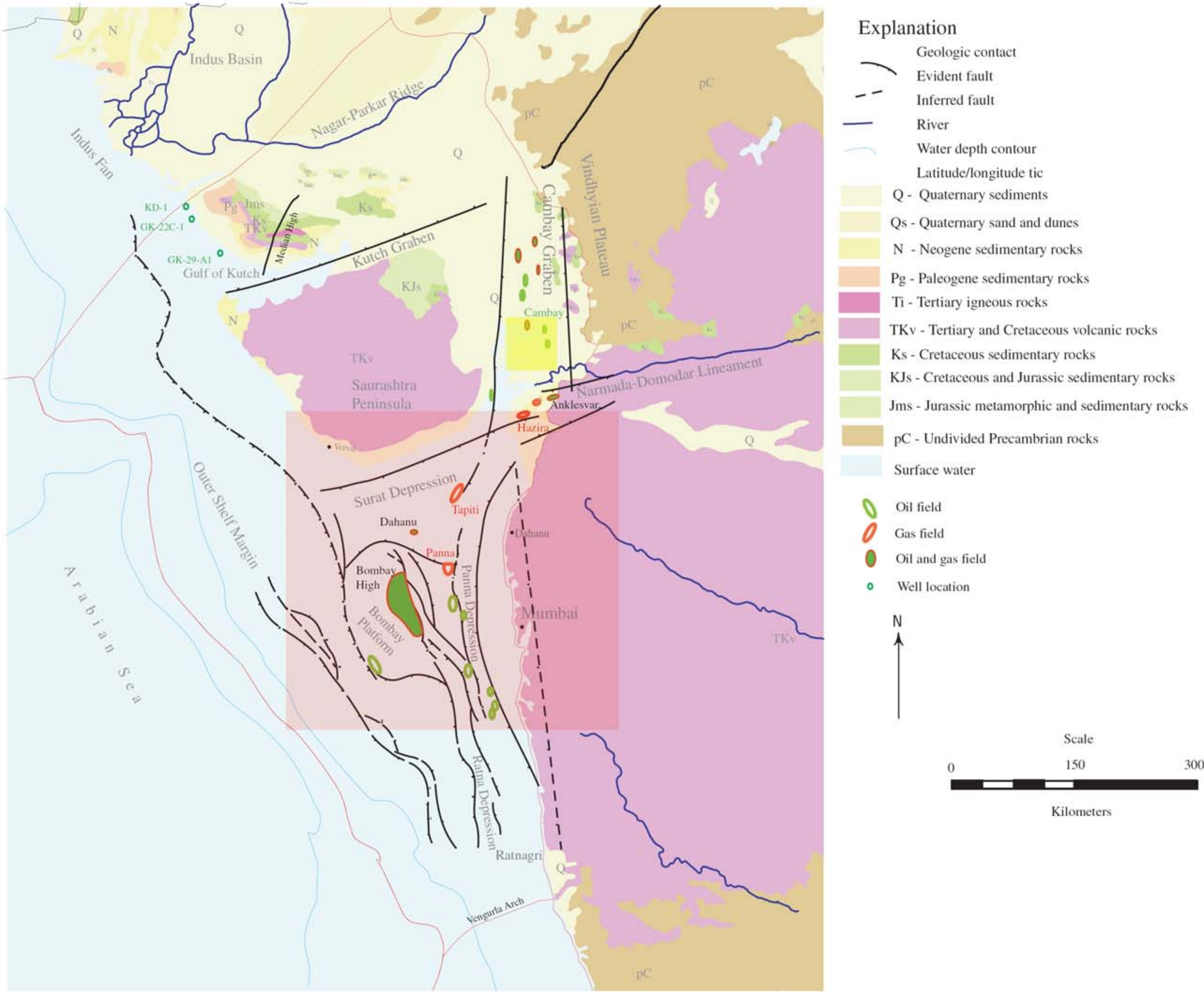

Figure 1. Regional structure and selected oil and gas fields of Bombay geologic province (from Wandrey, 2004), with general area of study (larger, pink polygon) and area of study (smaller, yellow polygon) for article by Saxena et al. (Search and Discovery Article #40266 (2007)).

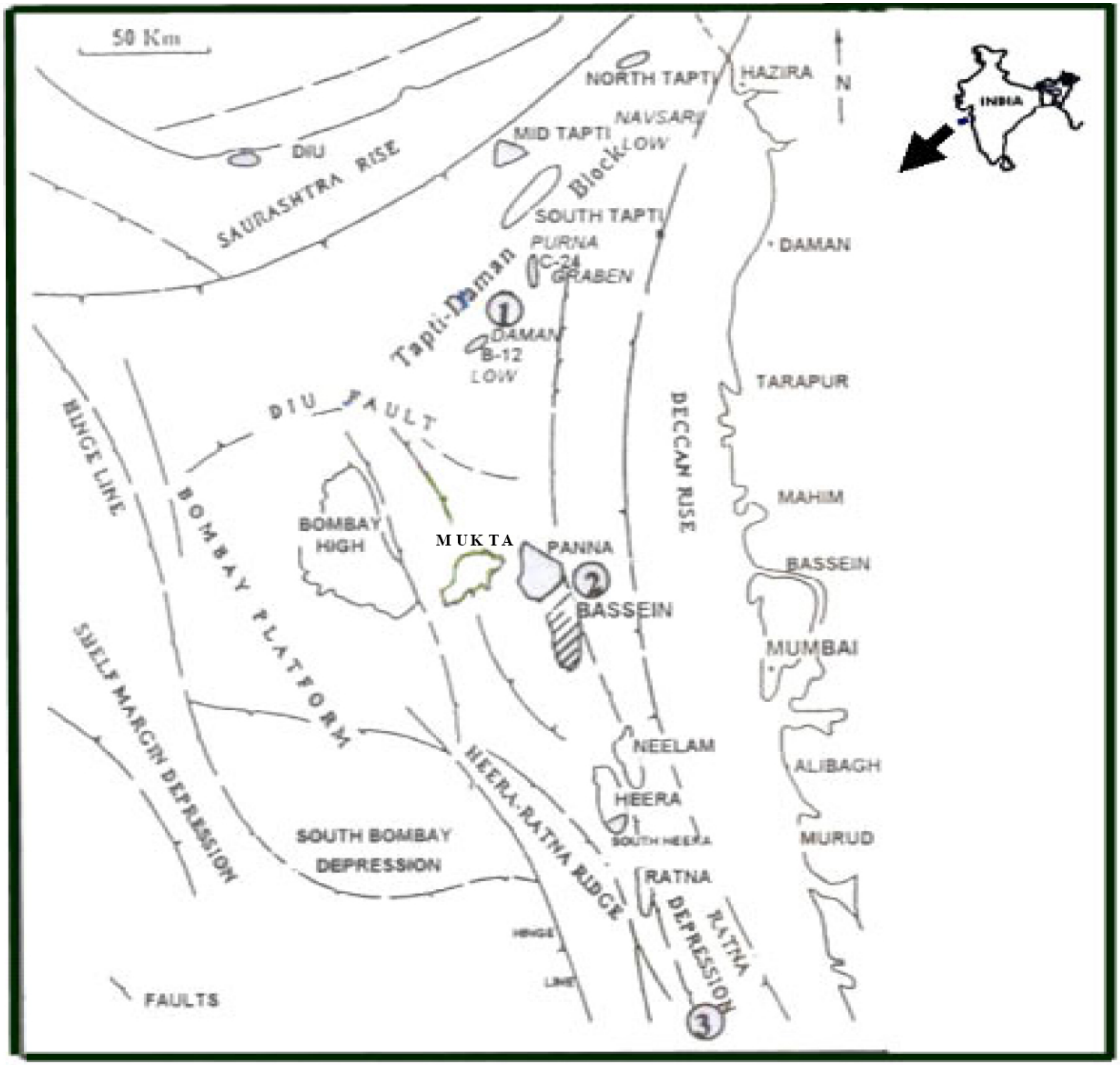

Figure 2. Structural and tectonic elements, with selected fields, of Mumbai offshore basin.

Hydrocarbon Occurrences

Oils mainly occur in the limestone horizons of lower Miocene age (L-III) in major hydrocarbon fields; viz., Mumbai high, Panna, S. Bassein, Heera and Ratna, Mahuva and Daman pay (Oligocene) in Tapti area, Bassein pay (middle Eocene to upper Eocene) in Panna-Bassein-Heera and Ratna areas and Ratna pay (mid Eocene to lower Eocene) in Ratnagiri area. With the recent oil occurrences in the sands of Panna Formation in Vasai East, the Panna pay is emerging as a commercial pay zone. Few oils also occur in clastic / fractured basement reservoirs and middle Miocene L-II and S1 pays. The majority of these oils show moderate API gravity (25-40°), high pour point (27-33°C), significant wax (7-20%), and low sulphur (0.1-0.3%) contents. These oils are predominantly aliphatic, having high saturate/aromatic ratio (>1.5) and saturate content (>40%). Only a few oils and mostly condensates were found in the Tapti Daman block.

Source Rocks

The clastic sediments in the lower Eocene to Paleocene sedimentary sequences (Panna Formation) are the principal source rocks across the basin. Thickness of the source rock varies from 30 m to 1000 m depending on location. The excellent source rocks of restricted marine to lagoonal deposits within the Panna Formation in the Central graben and adjoining area are the principal source of hydrocarbon accumulation in the basin. In the Mahim graben, a 400-m-thick sequence in the Panna Formation contains very good/excellent oil-prone effective source-rock facies, which account for the commercial petroleum reservoirs within Bassein, Mukta and Heera formations in the east of Panna and Bassein fields (average TOC=2.3- 15.4%; average S2=3.5-50.1 mg HC/g rock; average HI=112-277 mg HC/g TOC). Organic-rich mature source-rock sequences in the Panna Formation occur in depressions across the DCS area and west-southwest of Mumbai high (average TOC=1.5-5.6%; average S2=2.6-11.6 mg HC/g rock; average HI=94-270 mg HC/g TOC). Source-rock data from the deepest exploratory well in the Vijaydurg graben of Ratna depression show good, mature source-rock section in the lowermost unit of the Panna Formation and thin coal and coaly shale layers with very good source-rock quality at the top of Panna Formation. In the Tapti-Daman area, two exploratory wells, located in the eastern flank of Navsari low, contain about 70-m-thick oil and gas prone source-rock layers (average TOC=2.3-5.4%; average S2=2.5-8.3 mg HC/g rock; average HI=91-154 mg HC/g TOC), and better source rocks are more likely to occur in distal environments in the Purna graben and west Daman low corresponding to these layers. The sedimentary column in Shelf Margin areas is dominated by clastics, except in middle Eocene, which has carbonates. Source-rock potential of the Paleogene sediments is moderate, but some good organic carbon-rich source-rock layers are present in Neogene sediments.

Maturity Modeling

1D-thermal maturity modeling, using Genex 1D-basin modeling software, indicates that the sedimentary sequences of the Panna Formation from a well near the Mahim graben have generated substantial oil. These source-rock sequences started expelling oil from late Oligocene (30Ma) with peak expulsion spreading from 12 Ma to present day along the flank of graben (Figure 3).

These source-rock layers distributed in Mahim graben area are overmature, generating gas in the center of the depression, as the maturation level is high (Ro =1.3-2.0%). Thus, the entire section appears to be the major gas source for the giant Bassein gas field adjacent to this hydrocarbon kitchen. Maturity modeling of a well from the low of Bassein platform also shows significant generation, which began 20 Ma, and peak expulsion started taking place from 6 Ma and continues to present day. Approximately 120-m-thick dominantly marine organic-rich source-rock section from a well near the depocenter of DCS area is predicted to have begun significant generation 12 Ma, with peak expulsion occurring from 5 Ma and continuing to present day. In Ratna depression, thick lowermost source-rock section began significant generation 18 Ma.

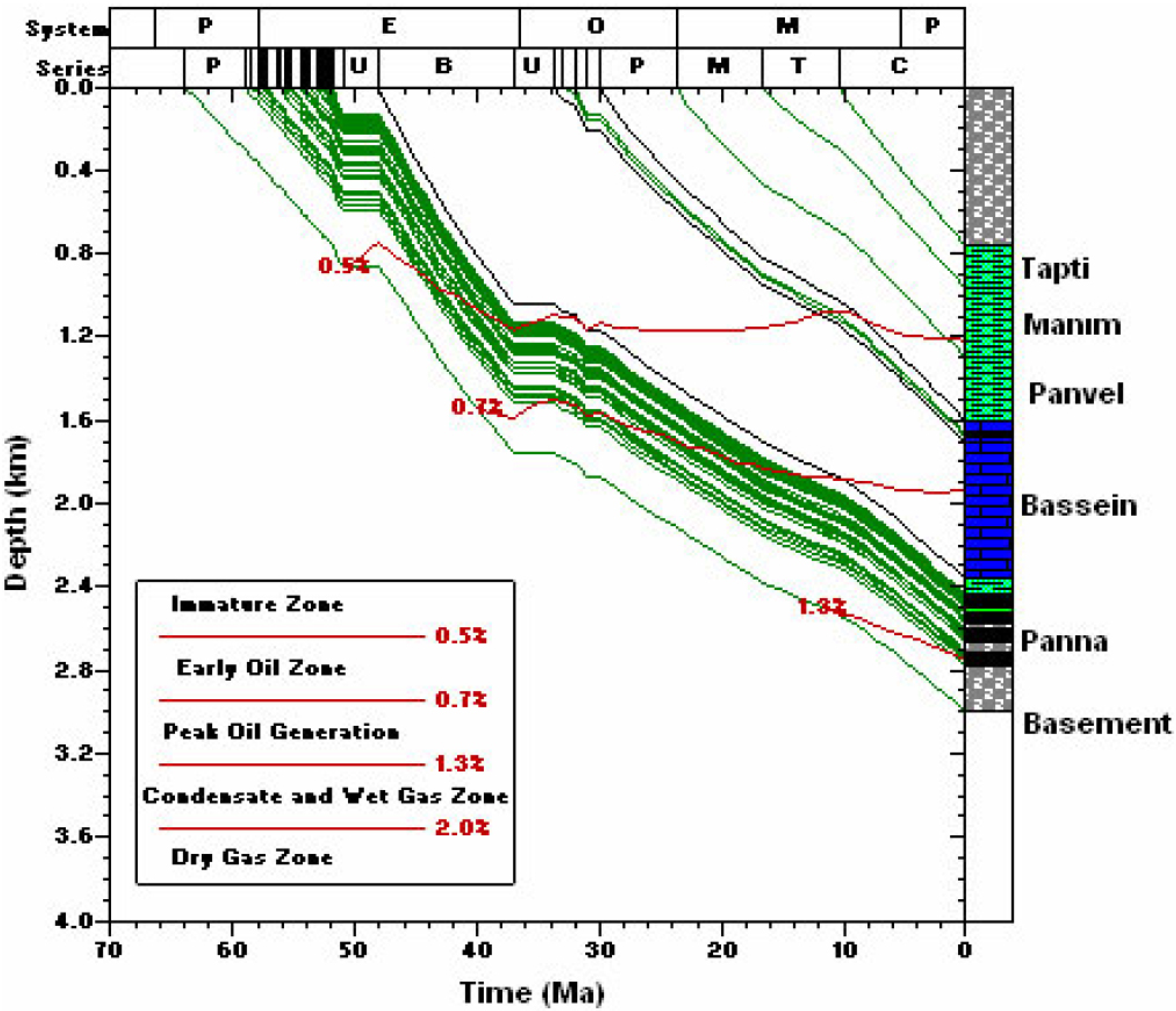

Figure 3. 1D-Thermal maturity modeling of a well near Mahim graben.

Correlation Studies

Based on several bulk parameters, conventional biomarkers, and stable carbon isotopic composition, oils of the Mumbai Offshore Basin, irrespective of their pay zones, can be broadly categorized in two groups with some overlaps. Group I oils show high values of Pr/Ph ratio (> 3.0), high canonical variables (C.V. > 0.47), relatively low abundances of bicadinanes, oleanane, oleanoid triterpanes, tricyclic terpanes, predominance of C_{29} over C_{27}, and C_{28} regular steranes, and presence of diasteranes. However, the group II oils have low Pr/Ph (<3.0), low Pr/nC_{17} (<1) ratios, low values of C.V. (<0.47), relatively high abundances of bicadinanes, oleanane, oleanoid triterpanes, presence of C_{30} steranes (both 24-n-propyl cholestane and 4-methyl steranes), and are isotopically heavier than the group I oils. The occurrences of these genetically dissimilar oils are not following any distinct pattern and are present in all the blocks in different pay zones. Group I oils are generated from predominantly type III organic matter and deposited under fluvial conditions whereas the group II oils are derived from mixed organic matter input with significant marine organic matter contribution and deposited under marginal marine conditions. However, all these oils have been generated at similar maturity levels.

Studies also indicate that source-rock extracts of the lower Eocene-Paleocene sediments from the peripheral part of the various lows in different blocks contain mainly terrestrial organic matter deposited in fluctuating fluvial/fluvio-deltaic to marginal marine environments. These source rocks are adequately mature to generate hydrocarbons and are genetically correlatable with the group I oils. Several thin streaks in the upper layers of the lower Eocene-Paleocene sediments in the central part of these depressions also show marine organic matter and these source rocks are genetically correlatable with the group II oils. The difference in the relative abundance of the several biomarkers; i.e., bicadinanes, oleanane, pr/ph ratio, etc., in two different group oils seems to be controlled mainly by the change in the depositional environment from the basinal part (more anoxic) towards the peripheral area (less anoxic). These two groups of oils and their probable source rocks are clearly differentiated by a plot of bicadinanes/C_{30} hopane versus oleanane/C_{30} hopane ratios (Figure 4A) and stable carbon isotopic composition (Figure 4B). Though some lacustrine facies were also present in a few wells in Mahim graben and DCS low, no oil with dominant lacustrine biomarker characteristics was found in the basin so far. This may be due to charging of reservoirs from the multiple source rocks. Results also show that the studied oils and the potential source rocks have been generated at similar maturity level (moderate to peak oil window). Presence of oleanoid triterpanes in both oils and source-rock extracts and also the carbazoles distribution in oils support the conclusion that, except for the oils of Mumbai high, most of the oils in different blocks are locally generated and have not experienced a long distance migration.

Petroleum Systems

Based on the reservoirs and the source combinations, the various petroleum systems in the basin are: the Panna-Daman, Panna-Mahuva (only in Tapti Daman block) and Panna-L-III, Panna-Mukta, Panna-Bassein, and Panna-Panna.

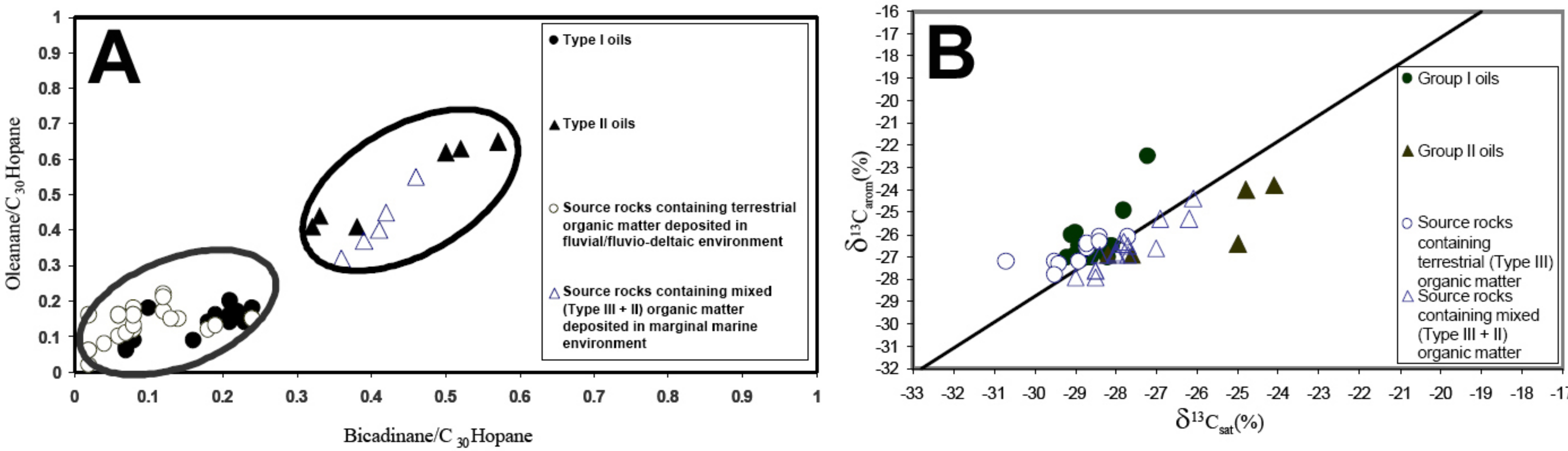

Figure 4. A. Cross-plot of bicadinanes/C_{30} hopane. B. Cross-plot of isotopic composition of the saturates and aromatics. These two cross-plots for the oils and source rocks of Mumbai offshore basin show the existence of two distinct oil-source families in the basin.

Conclusions

- Lower Eocene-Paleocene sediments have very good source-rock characteristics and good hydrocarbon generation potential throughout the basin, but quality and quantity of the organic matter deteriorated towards the peripheral area from the basinal lows. The organic matter is dominated by input from terrigenous higher land plants. However, two potential source sequences are identified in the lower Eocene-Paleocene sediments. Specific biomarkers, particularly the relative contribution from resinous plants, flowering plants, carbon isotopic composition and marine organic matter diagnostic biomarkers, indicate that these sediments exhibit intervals with different organofacies.
- Oils of the Mumbai Offshore Basin can be broadly categorized into two groups based on their biomarkers distribution and stable isotopic composition.
- Group I oils containing only terrestrial organic matter from fluvial/fluvio-deltaic depositional environment generally correlate with the lower Eocene-Paleocene source-rock extracts from the wells located in the peripheral area of the lows in each block. On the other hand, group II oils, which contain mixed type organic matter deposited in marginal marine conditions, correlate with the upper layers of the lower Eocene-Paleocene source sequences in the wells located in the central parts of the lows in each block.
- All oils in the field are at approximately the same level of thermal maturity and were expelled from sources that still retain significant generative potential. These oils are generated locally and have not undergone long distance migration.
- Maturity modeling of vitrinite indicates that in general the sedimentary sequences of the Panna Formation started oil expulsion 18-30 Ma and peak oil expulsion 12 Ma and continues to present day.

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