

## Hydrocarbon Fairway Template vis a vis Tectonic Framework of Mumbai Offshore Basin

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Play fairway, Fault categorization, Accumulation trend

### Summary

The tectonic history of the Mumbai Offshore Basin from the time of Madagascar separation to the present day has shaped the structural configuration, sedimentation pattern, as well as migration and entrapment of hydrocarbons in the Basin. This paper analyses the imprint of the tectonic history through faults mapped on latest 3D seismic data spanning 13 volumes covering 32,000 sq.km. The faults have been categorized into four types according to their genesis and timing of evolution. Subsequent to that, the study integrates oil to source data with the mapped fault trends to establish most likely play fairways and finally, it analyses the hydrocarbon accumulation trends to identify probable dry and wet corridors.

### Introduction

The Mumbai Offshore Basin which is a part of the extended shelf, off the coast of Mumbai, traces its existence during the separation of Madagascar from the Indian Subcontinent during 83 Ma (Late Cretaceous). The break up initiated rifting along the NNW-SSE trending Dharwar grain and gave rise to the Mumbai High east fault trend which is the most prominent architecture to have emerged during this period. Traverse of the Indian plate over the Reunion hotspot (65-69 Ma) resulted in doming associated with mantle plume, which changed stresses in the Bombay Platform area. This enhanced the already established horst-graben structures, possibly by reactivation of older faults and new rifts were initiated. As India moved off the hotspot, lithospheric cooling was accompanied by subsidence which formed locales for later sedimentation. Post eruption, sea floor spreading along Carlsberg ridge (62 Ma) resulted in breakup of Seychelles from the Indian plate, further reactivating faults and creating accommodation, which in turn accumulated the sediment pile constituting source pods. The next stages of modifying tectonics were those of the

Himalayan Orogenic movements, each stage of the orogeny leaving a profound impact on the sedimentation of the Basin. Briefly put, the first stage (48 Ma) decelerated the movement of the Indian Plate resulting in development of the Bassein carbonate platform. During the second phase (Siwalik Phase, 20-15 Ma) several small structures were formed due to development of major strike slip trends predominantly in a NE-SW direction. The third and fourth phases of Himalayan Orogeny were very active from the Late Pliocene to Middle Pleistocene period. The rise of Himalaya was at its maximum position which has facilitated transportation of colossal amount of fine sediments into the Basin. The enormous supply of clastics, filled the Basin with preferential channeling of sediments through the South Bombay Low and imparted to the Basin, its present day structural configuration. The basal dip further steepened to the west during this time. The resultant structural entities are known from east to west as Eastern Homocline, Central Graben, Vijaydurg Graben, Heera Panna Bassein Platform, Mumbai High and its extended shelf, beyond which lies the Deep Continental shelf.

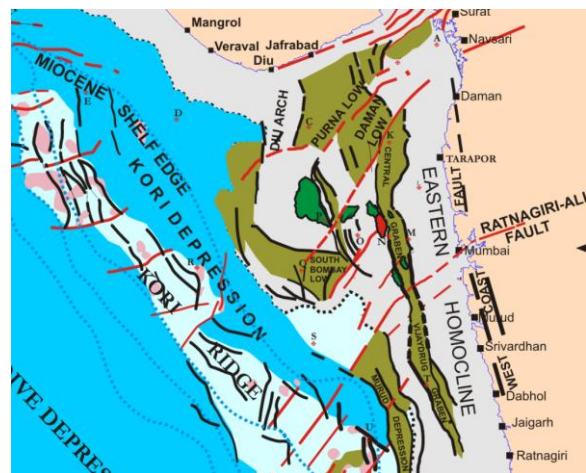


Figure 1: Tectonic Framework of the Mumbai Offshore Basin

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To the north and south lie the Dahanu and South Bombay lows which house the source rocks. (Figure.1)

### Methodology

Historically, seismic data gathered for over five decades, beginning with analog to digital 2D vintages and graduating to 3D seismic and more recently the new Broadband 3D surveys have helped in depiction of the tectonic framework, more precisely.

In, the present study, 3D seismic data of the 13 latest vintages including 5 Broadband 3D data were used for the analysis. The Multiple fault attributes like that of discontinuity, fault likelihood, structure cube were used in conjunction with various time thickness maps to bring out a cohesive fault pattern. A number of iterations for parameter optimization across multiple datasets had to be done to arrive at the best quality slices on such a regional scale. Thus the new Broadband 3D datasets has been a valuable aid in mapping of the strike slip faults in addition to those of normal/ reverse faults.

**Fault Mapping:** Fault network for 32,000 sq.km of the Mumbai Offshore Basin has been interpreted primarily for the economic Basement known as H5, comprising predominantly of flood basalts,

interspersed with Precambrian inliers. To have a broad understanding of the disposition of the Basement at key stages of geological time, Time thickness maps of the Early Eocene sequence (depicting Basement at that time) and Middle Miocene plus all older sequences (depicting Basement at Middle Miocene) were also analyzed.

The expanse of the Basin is such that the occurrence of Basement varies from having sediment cover of a thin veneer of less than 250m in the Eastern Homocline (beyond the mapped area) to over four and a half kilometers (drilled so far) in the Central Graben. That brings the range of Basement depths from 1280 m to 4500 m in the study area. The corresponding time values vary from 1370 ms to 3500 ms. Depiction of these disparate depths required different time slices to be analysed over the different tectonic blocks suiting the Basement depth over the area. The discontinuity map therefore is a collage of slices corresponding to Basement for that particular area with each slice corresponding to a different time (Figure. 2).

An analysis of the faults mapped on this data, throws up some obvious points. The three major trends are those of the NNW-SSE Dharwar trend, NE-SW

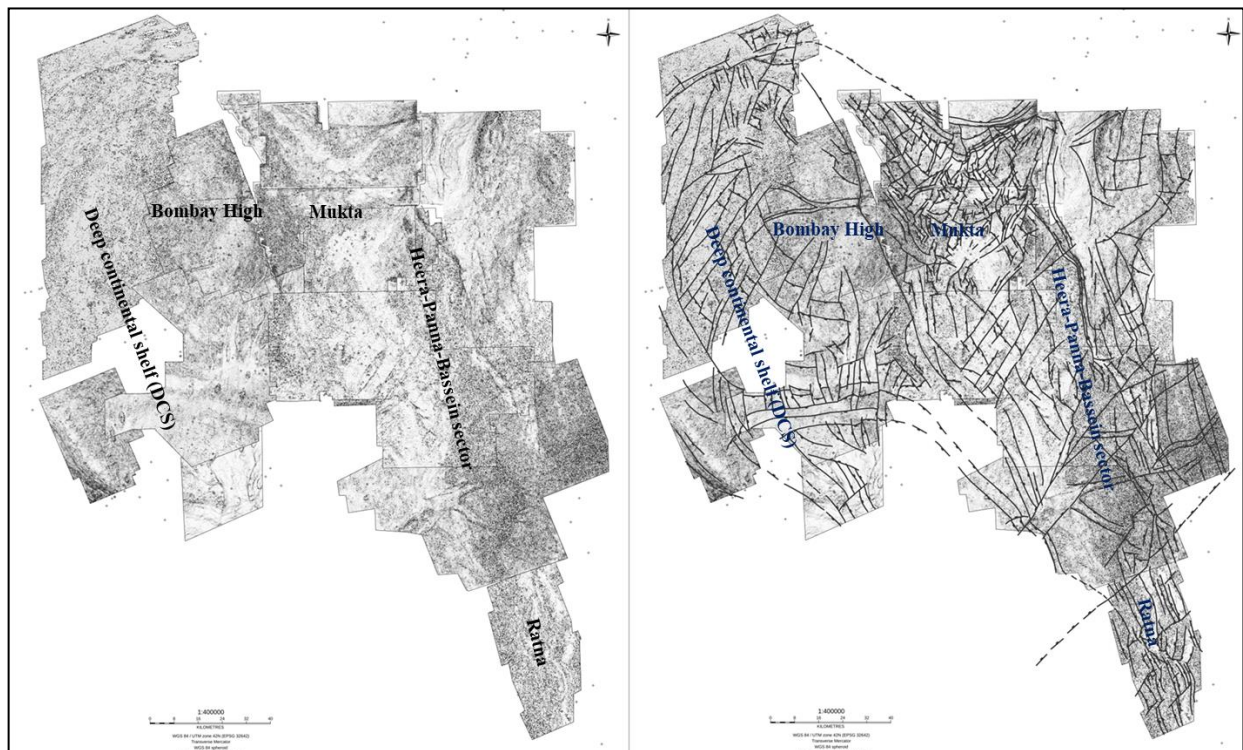


Figure 2: Fault pattern derived from various fault attributes

## Hydrocarbon Fairway Template vis a vis Tectonic Framework of Mumbai Offshore Basin

Aravalli trend and the ENE-WSW Satpura trend. Interplay of these three major trends defines the structural configuration of the Basin. The Basin forming and accommodating faults (Central Graben, Vijaydurg Graben) evolved during the rifting phases (Madagascar rifting, Deccan Volcanic and Seychelles rifting) and are oriented NNW-SSE. The Bombay high east fault which defines the Bombay high structure developed during rifting of Madagascar from Indian Subcontinent in Late Cretaceous. The other major Lows i.e. Dahanu and South Bombay are associated with the cooling and sag phase and these lows typically occur as arcuate sediment sinks controlled by down to basin faults. The influence of the Dharwarian trend is seen in the segmentation of the Heera Panna Bassein Platform, where most of the smaller structures are bound by faults trending in the same direction. A second set of faults in the NE-SW Aravalli trend are the later strike slip faults which appear in the post collision phase and displaces the dominant structural grain.

**Fault Categorization:** The faults have been categorized into four different types based on their genesis and link to the dominant tectonics of related geological time. The four sets are those of (i) Basin forming faults, (ii) Paleo-High bounding faults, (iii) Strike slip faults / Riedel shears and (iv) Compression related Inversion faults. (Figure 3)

✓ **Basin Forming Faults:** In the post rift phase of Late-Paleocene -Early Eocene, the Basin forming faults (Coloured Pink) were instrumental in accommodating copious sediment thicknesses as seen in Central and Vijaydurg Graben, Dahanu and South Bombay Lows. The fault bounding the western flank of the Central Graben known as the Panna-Bassein fault has a Paleocene-Early Eocene sediment thickness of more than 1500m juxtaposed against it. A similar pattern is seen in all the sinks though in case of the South Bombay low the role of faults for sedimentation is less pronounced compared to the original structural configuration because the area is a part of paleo-depression. These sedimentation locales are the effective source pods for hydrocarbon generation in Bombay Offshore Block.

✓ **Paleohigh Bounding faults:** A set of faults which define the pre-existing Basement highs and are co-eval to the basin forming faults (Coloured Blue) came into being during the different rift phases. These faults trend principally NW-SE, east of the Mumbai High structure, and NE-SW as one moves to

the west of Mumbai High. Reactivation of these faults during Late-Oligocene-Miocene period modified structures as well as aided in migration.

✓ **Strike slip faults:** The strike slip component in the Basin introduces itself at a later Post collisional stage in a dominant NE-SW direction in the Aravalli trend (Coloured Green). These faults displaced the earlier generation of faults and are responsible for creation of the subtler nosal structures. A case in point is the North of Mukta area which has numerous nosal structures, developed due to an interplay of two sets of faults. Some of the strike slip faults can be traced on a regional scale to have emanated from the Laxmi Ridge and Calsberg Ridge and extending onland (Eg. Alibaug fault).

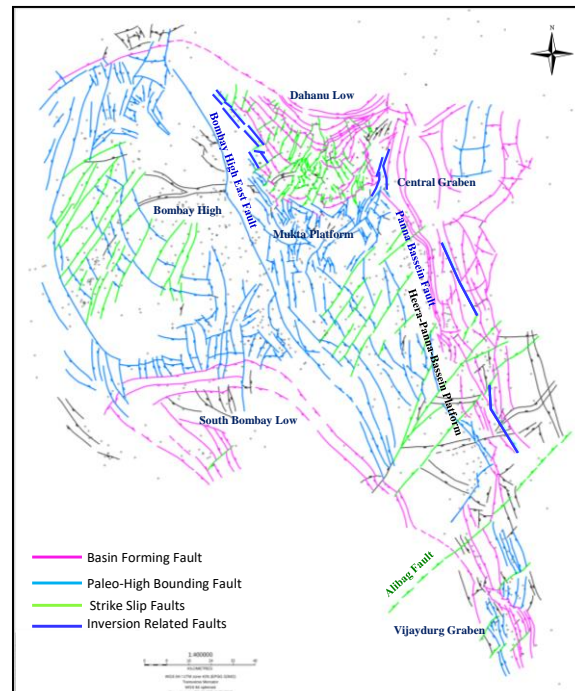


Figure 3: Fault categorization in Mumbai Offshore Block

✓ **Inversion related faults:** The main accommodation faults, especially those bounding the narrowest sections of the Central and Vijaydurg Graben reversed their movement during some time in Middle to Late Eocene, due to paucity in accommodation space and gave rise to a series of inverted structures along the length of the graben (Coloured Dark Blue). These faults get younger from south to north.



## Hydrocarbon Fairway Template vis a vis Tectonic Framework of Mumbai Offshore Basin

**Faults as Fairways:** To understand the role of faults on hydrocarbon accumulation over the Bombay offshore area, the established pools and source rock data have been integrated in the present study. (Figure 4)

The four prominent lows Central Graben, Vijaydurg Graben, Dahanu Low and South Bombay Low host the source pods which have fed the prolific hydrocarbon bearing structures of Mumbai Offshore. The source rock belongs to Paleocene-Early Eocene age and reaches thicknesses greater than 1000m. Detailed source rock study suggests a unique kerogen type for each source pod which suggest a different environment of deposition for each. Central Graben has Oleanane and Biscadinane biomarker in the lower part which indicate terrestrial origin of organic matter where as the upper part has Oleanane and Methyl Sterane indicate Lacustrine/Marine origin of organic matter. Oil to source correlation suggests that, all the structures in Bassein, Vasai East, Neelam, West of Bassein, Panna are fed by this low, chiefly by the faults in the aforementioned Panna-Bassein fault trend.

Vijaydurg Graben is a narrow elongated low towards the extreme south of Bombay Offshore Basin and hosts mixed organic matter which are less mature as compared to the Central Graben and Dahanu Low. The Heera Field and R-Series structures bear the fingerprints of the Vijaydurg Graben source rock and are distinct from the northern fields of the Panna Bassein trend in the fact that, these are not saturated reservoirs, unlike those in the north.

In the Dahanu Low, organic matter was deposited in lacustrine restricted conditions which underwent maturation yielding gas to the northern Inversion structures of Tapti Daman. Southwards, it fed the Northern Mumbai High, Structures in North of Mukta area and the Mukta Field. Northwest extension of the Mumbai High massif is dissected into a number of smaller structures wherein some of the oils are correlated with the oils of structures fed by Dahanu Low (North of Mukta area) which suggest migration of hydrocarbon from the same low.

The South Bombay low holds two effective source pods, namely that of D-33 and DRA Lows, distinguished by their unique kerogen type. D-33 low has Bisnorhopane and Gammacerane biomarker whereas DRA Low has Methyl sterane and has not reached gas generation window. Oil to source correlations show that pools bearing the Methyl

sterane fingerprint occur around the south western part of the Bombay Platform. It is interpreted that the large arcuate fault running parallel to the shelf is the main migration pathway which filled the structures through the NW-SE trending reactivated faults. The uniqueness of these oils is their low GOR, at most times staying within single digits. The structures fed by D-33 Low, lie all along the southern periphery of Mumbai High and the Mumbai High South as well.

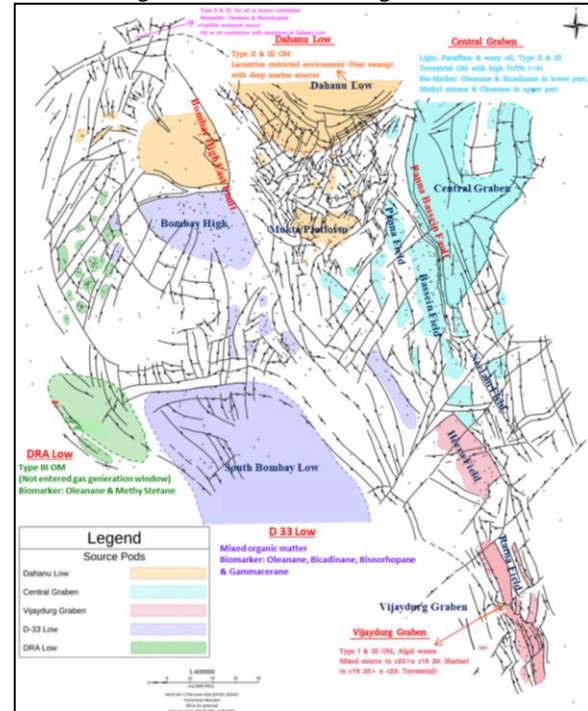


Figure 4: Oil to Source correlation over Mumbai Offshore Block

**Hydrocarbon Accumulation Pattern & Role of Faults:** Categorizing the fault pattern and examining the details of each source pod and oil to source correlation led to analyzing the role of the different set of faults in migration and entrapment of hydrocarbons. To this end, the fault pattern was overlain with available structures in the Mumbai Offshore Basin and the status of each structure was plotted to understand the hydrocarbon distribution clearly. The pools are seen to largely follow the three identified fault trends, i) Accumulation on the paleo-high trend, ii) Accumulation along strike slip fault trend & iii) Accumulation along Inversion trend (Figure 5).

## Hydrocarbon Fairway Template vis a vis Tectonic Framework of Mumbai Offshore Basin

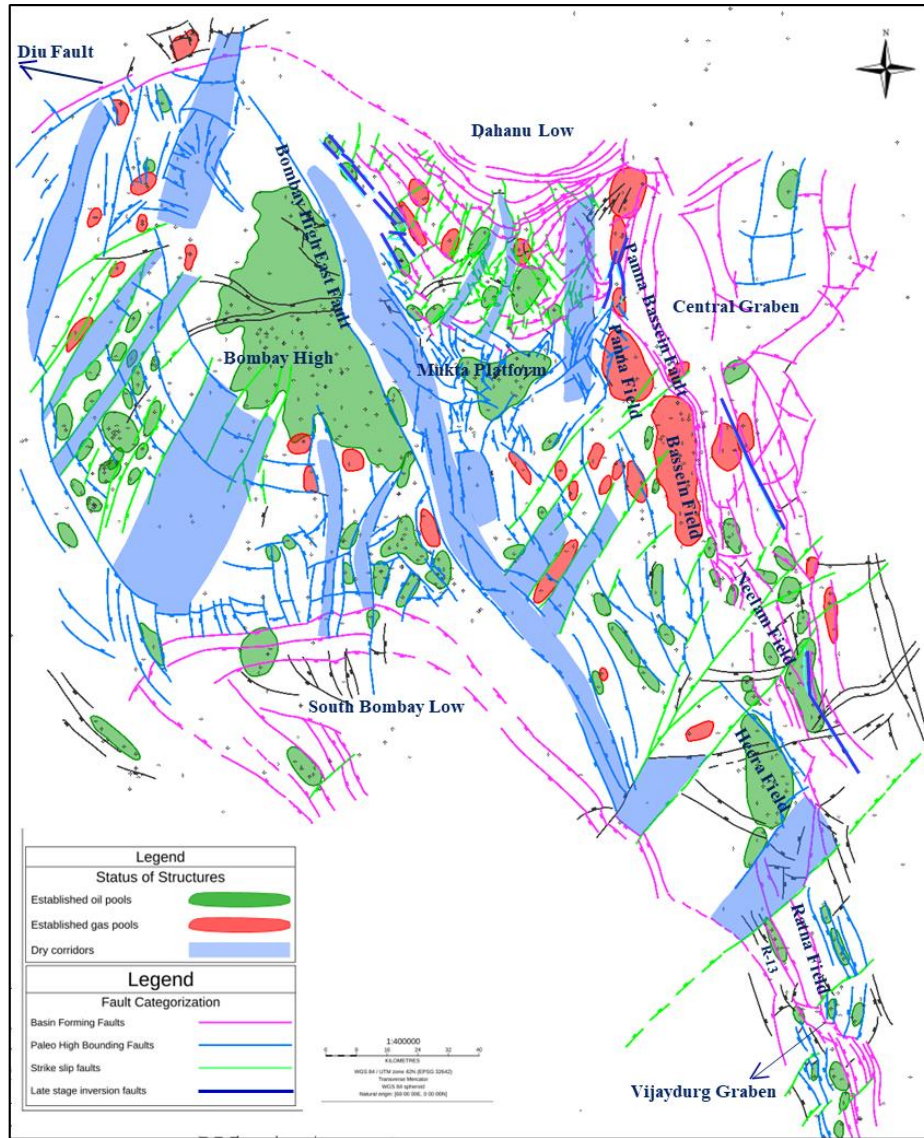


Figure 5: Fault fairway map of Mumbai Offshore Block

i) *Accumulation in the paleo-high trend:* All major fields of the basin belong to this trend, inevitably bound by east trending “paleo-high bound / sedimentation faults”, which are both entrapment and migration faults (Bombay High, Bassein, Heera & Panna). The smaller Basement highs have been charged through this group of faults (Mukta, West of Bassein, Ratna, SW of Bombay High) which appear to have been reactivated during the Late-Oligocene to Miocene times.

(ii) *Accumulation in the strike slip trend:* In this case, the structures formed by the interplay of rift trends and strike slip movements are the locales for hydrocarbon accumulations, where the faults linked to these structures act as charging faults. This scenario best fits in North of Mukta area, where all entrapments are in fault bound north high trends which formed as a response to the strike slip movement. A similar scenario occurs in the northern rising flank of the South Bombay Low. The fields located on the southwest extension of the Mumbai

## Hydrocarbon Fairway Template vis a vis Tectonic Framework of Mumbai Offshore Basin

High massifs are also oriented in the NE-SW strike slip trend.

(iii) *Accumulation in the inversion trend:* Compressional forces which acted in the Central and Vijaydurg Grabens resulted in inversion structures which are oil and gas bearing, eg Vasai East, Neelam & R-13. This set of structures though are older (Middle to Late Eocene) to the ones formed in the North of Mukta, which are late formed and related to the last phase of compressional tectonics, linked to the Himalayan Orogeny.

Juxtaposition of the hydrocarbon pools and the fault network helped in segregating the hydrocarbon bearing areas from those that are dry (Figure 5). Once represented on a map, it can be seen that there are distinct areas of non-accumulation.

Most of the dry trends tend to occur between strike slip faults, at times coinciding with faults which bound strong low trends. Such trends to the west, south and SW of Mumbai High appear as dry corridors. Towards the northwest of the Mumbai High field, most of the structures are dry/water bearing probably due to the presence of faults which were quiescent through time. Reactivation thus becomes a necessary component for entrapment. A second reason may be absence of large regional faults establishing connection to the source pod.

In the platform area (Heera-Panna-Bassein Platform), similar low trends flanked by strike slip faults appear to be dry. A linear belt, east of the Bombay High fault, looks to have been bypassed by the migrating hydrocarbons, remaining as a shadow zone for hydrocarbon accumulation.

Though the identified “dry corridors” are associated with particular fault types, the absence of oil and gas in an area is a manifestation of other factors as well, namely reservoir presence.

### Conclusions

✓ A fault network map has been prepared based on the interpretation of 32,000sq.km of the latest 3D data.

✓ The faults were then categorized, based on their genetic link with the movement of the Indian Plate, their role in sedimentation and later entrapment.

✓ Available oil to source correlations have been integrated into the study and the maps thus derived indicate the faults which are most likely to have acted as migration conduits.

✓ The next stage of integration by way of

classifying the hydrocarbon accumulation pattern and its association with the identified fault categories brought out the wet and dry “corridors”.

✓ The study has thus helped to prepare a “fairway template” for the Mumbai Offshore Basin, for future reference.

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