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Role of tectonics in development of fractured basement reservoir in Mumbai High Field, Western Offshore Basin, India

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Summary

Mumbai High structure is a giant hydrocarbon field with Miocene carbonate as primary reservoirs and the fractured basement and basal clastics as secondary reservoirs. Mumbai High has witnessed four major tectonic episodes which have given rise to extensive fractured basement reservoirs which have been established as commercial producers.

The present study has integrated the 3D seismic data with the well and production data and brought out the detailed Basemen fault pattern of Mumbai High field and the probable locales of fractured basement reservoir prospectivity.

The two major factors influencing the development of fracture systems viz; 1) the tectonic history and 2) the Basement composition have been analyzed in detail.

The NS trending Mumbai High East fault is the major tectonic trend along which the higher fracture density is inferred.

Predictability of fracture trends and thereby the identification of favorable locales for basement exploration can be rated as moderate to high in Granitic and metamorphic basements. However, in Basaltic basement the predictability remains poor

Keyword*: Tectonics, Fractured basement reservoirs*

Introduction

Mumbai High situated in the western offshore of India, is a giant field producing hydrocarbons primarily from multilayered Middle Miocene carbonate reservoirs (Fig-1). Although commercial accumulation of hydrocarbons from naturally fractured Basement reservoirs have been established in the Mumbai High Field quite early in the field history, focused efforts to exploit the full potential of this play have begun only recently.

Globally, though many fractured Basement fields have been discovered by serendipity, but over the years there has been a concerted effort by the Geoscientific community to understand the origin, occurrence, distribution and commercial potential of basement oil, which has lead to a comprehensive understanding of the various aspects of the Petroleum system of Basement oil.

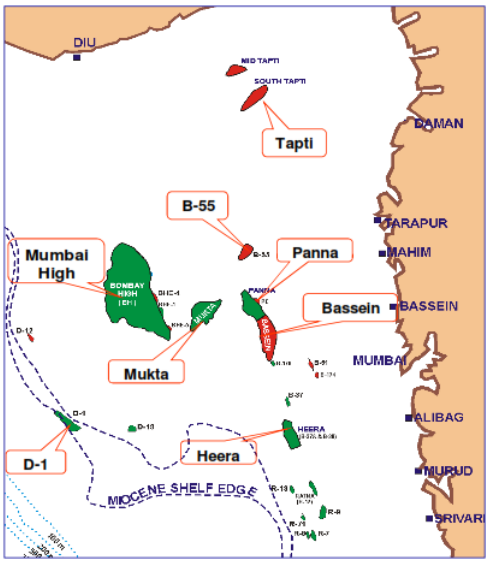

Figure 1: Index Map of Mumbai High Field

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In this paper, we attempt to synthesize all the data available in the Mumbai High Field on Basement reservoirs with special focus on the seismic identification of natural fractures and their origin and relationships to fault systems and the tectonic, lithologic and stratigraphic variables that control their distribution in order to evolve a working strategy to realize the potential of Basement oil exploration.

Tectonic set up, structural fabric and fault reactivation

The basic structural fabric of Mumbai High is characterized by the imprints of the four major tectonic episodes witnessed by the basin viz:

1. NW-SE trending Dharwar rift phase,
2. NS to NNE- SSW Aravalli Trend,
3. ENE-WSW fault set corresponding to Narmada trend
   and
4. NNE-SSW fault sets reactivated during the Tertiary strike slip regime that resulted during the northward plight and the attendant anticlockwise movement of Indian Plate (Biswas, 1982, Verma.N.K. etal 2001).

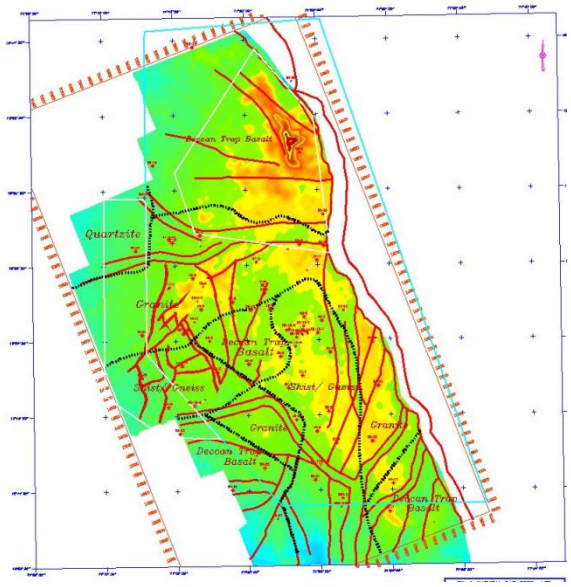

Figure 2: Structure map on top of Basement depicting different fault sets

Fault Pattern Analysis

In the present study the reprocessed PSTM 3D seismic data was analyzed to bring out the detailed fault pattern of the Mumbai High field. Several window and surface attributes were generated and studied to map all the major fault sets that would have significant bearing on the development, augmentation and preservation of fracture systems.

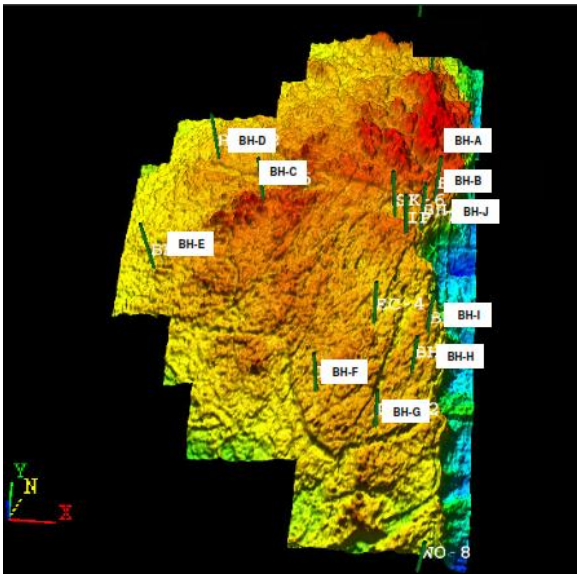

Figure 3: Perspective view of Basement top.

The above figure (Figure.3.) depicts the perspective view of the basement top with the key wells that have yielded hydrocarbons from fractured basement. The dark red patches in the north and northwestern part of the map correspond to the Basaltic country and exhibit the highest structural relief in Mumbai High. In general the intensity and spread of faulting is seen to be higher in the southern part which is dominated by Granitic and metamorphic rocks.

The RMS magnitude Map of a 20 msec window below Basement top (Figure.4) brings out lineaments other than those seen on the perspective view probably indicating the fracture sets developed in the window appearing as amplitude smear patches in the vicinity of major fault trends.

The structure cube attribute (Figure 5) and time slice @ 1700msec extracted from structure cube have more

precisely brought out the fault sets. It can be observed that the MH East Fault is not a single fault but a set of enechelon faults that exhibit sinistral side stepping and dilatational jogs and inter connected by short relay cross faults.

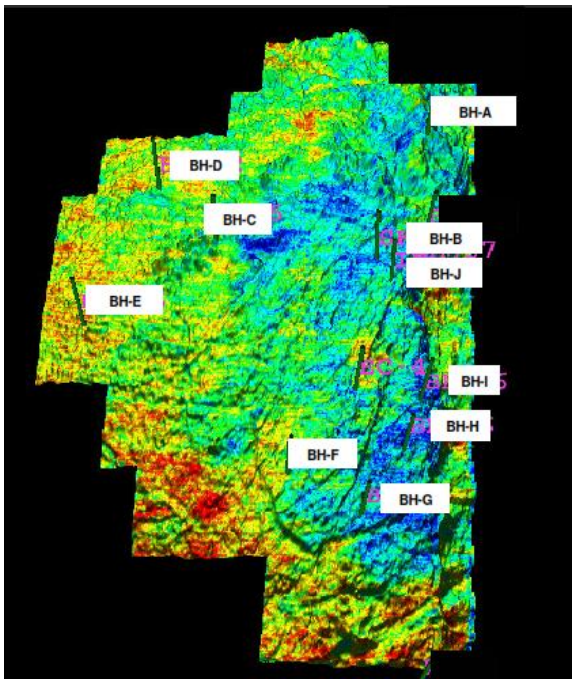

Figure.4: RMS Amplitude map of a 20msec window below Basement top depicting the fault pattern

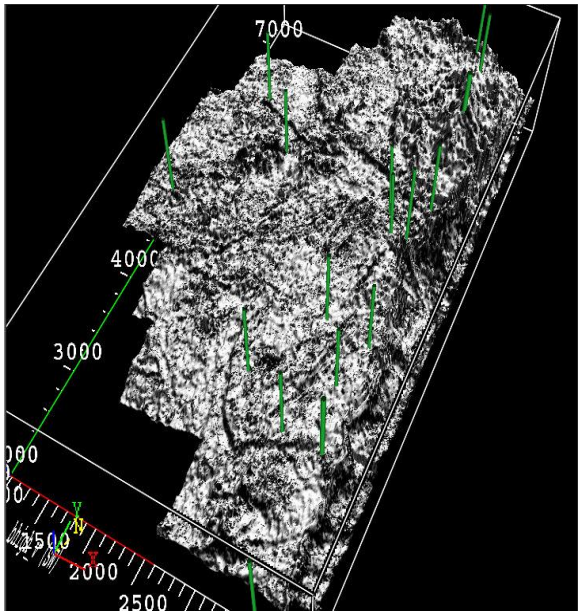

Figure 5: Structure cube attribute map on top of Basement depicting the Fault pattern.

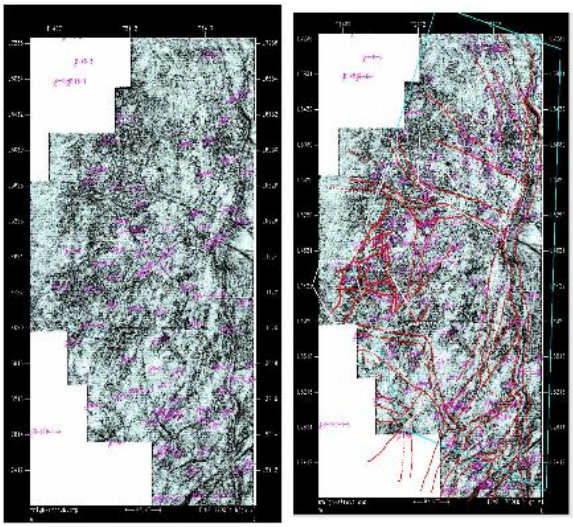

Figure 6: Structure cube slice @ 1700ms showing fault trends at Basement level

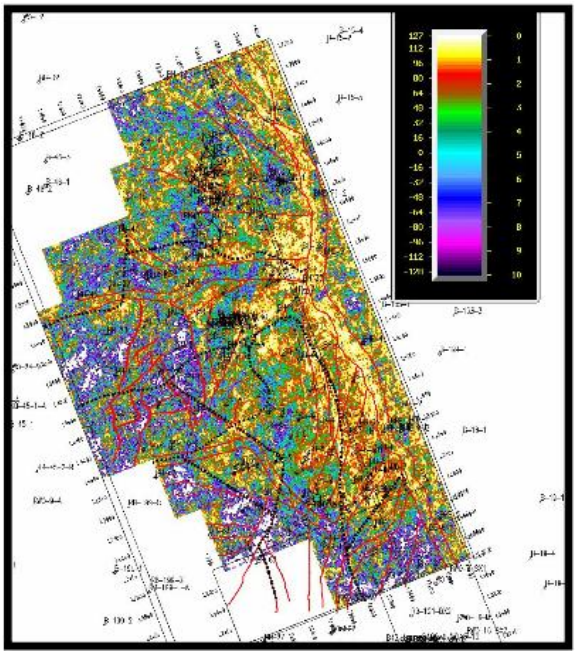

Figure 7: Amplitude variance Cube extract of 0 to 20 msec window below Basement top indicating probable development of fracture porosity along major fault zones.

The amplitude Variance Cube extract (Figure. 8) depicts clearly the areas of low variance located in the vicinity of MH East fault and the associated fault sets indicating probable fracture development. The Mumbai High East fault which acted as a fulcrum for all the tectonic disturbances the areas witnessed is the single most

prominent trend bounding the Mumbai High along its eastern boundary. It is a major zone of deformation comprising several en echelon faults which are offset by minor ENE-WSW cross faults. It can be well appreciated that the Variance cube has the potential to bring out areas of higher fracture density which are represented by the low variance trends.

In addition such low variance is exhibited by areas close to the major E-W fault trend. Occurrence of HC in Basal clastics also in such corridors point to these being effective migration fairways

Factors influencing Fractured reservoir development in Basement rocks

1. Tectonic History: High levels of deformation associated with fault propagation tend to induce higher fracture density. Therefore proximity to major fault zones is the key influence for better reservoir quality.
   However, cataclastic and thermochemical processes generally affect the porosity and permeability along active fault surfaces.
2. Basement Composition: Granitic rocks which in general are more blocky and homogeneous are affected by fracture systems which are long and interconnected as compared to the layered metamorphic rocks which tend to have disjointed fracture system.
3. Episodic fault reactivation: Identifying and mapping the youngest episode is the key to understand the open fracture sets that will provide the best reservoir system.
4. Mineralization: Periodic fluid migration along preexisting open fracture system, tend to seal major part of the fracture thus resulting in disjoint and reduction in void space as wells as effective permeability. Conversely the same process may result in dissolution of mineral phases in the fractures and in the matrix thereby enhancing reservoir quality.
5. Present day in-situ stresses: High stress anisotropy at the present day is likely to cause critical shear selectively along particular set of fractures.

However, the first two factors play a major role in determining the reservoir quality and extent in Mumbai High area and are discussed in detail in the following paragraphs.

Role of Tectonics in Fractured Reservoir development and fluid distribution

- Faulting is an expression of the interaction between rock rheology, kinematic boundary conditions, and associated stress fields.
- The structure and rheology of faults vary with depth, such that pressure-dependent frictional behavior predominating in the upper, brittle part of the crust
- In general, the longer the time and length scales of faulting episode, the greater the potential influence of the kinematic and thermal history on the rheology of the fault system.
- In Basement rocks fluid redistribution is influenced by hydraulic gradient and structural permeability developed under the prevailing stress field.
- Field evidence suggests that mesh structures, comprising faults interlinked with extensional-shear and purely extensional vein-fractures, form important conduits for large volume flow of hydrocarbon fluids.
- Meshes may be ‘self-generated’ by the infiltration of pressurised fluids into a stressed heterogeneous rock mass with varying material properties, developing best where bulk coaxial strain is symmetric with existing layering
- Within mesh structures, strong directional permeability may develop in the direction parallel to fault-fracture intersections and orthogonal to fault slip vectors.
- Mesh activation requires the condition $P_f \tilde{} \sigma_3$ to be maintained for the structures to remain high permeability conduits, requiring fluid overpressuring at other than shallow depths in extensional-transtensional regimes.
- Favoured localities for mesh development include linkage structures along large-displacement fault zones such as dilatational jogs, lateral ramps, and transfer faults (Figure.8)

Figure.8: Major Fault sets at Basement top: Mumbai High field. Note the presence of dilatational jogs, lateral ramps and transfer faults

In Figure 8 note the cluster of fault sets at acute angle emanating from MH East Fault These are the favorable locales for development of fracture permeability

The major EW cross fault dividing MHN & MHS would have facilitated long distance migration to the west but in a very narrow corridor towards south of the fault.

Role of Basement composition in fracture development

Basement country rock in Mumbai High area comprises of a milieu of composition ranging from Archaean Granite, Phyllite schist / Gneiss, Quartzite and Deccan Basalt (Figure.9). It is observed that the topography and fault pattern at Basement level is strongly influenced by the litological composition. In the northern part the distinct topographic high is represented by Basalt country whereas in the southern part the predominantly Granitic / metamorphic terrain reflects the older rift related topography of linear ridges and grooves. As can be seen from the figure the intensity of faulting is higher in the Granite/ Metamorphic terrain as compared to the younger Basaltic flow. Also the hydrocarbon presence in the basement reservoirs clearly depict the influence of fracture induced porosity in the granitic / metamorphic terrain as opposed to the Basaltic country where the role of weathering is more dominant at the basement top surface. In well – A drilled in the northern part of Mumbai High in Basalt country , interpretation of Array Sonic Log has indicated presence of three fracture zones within the drilled section of 135 m. All the three fracture zones are= developed well below the basement top, the shallowest fracture zone being 55m below the top. It was further observed that the hydrocarbon bearing zone was 10m thick and occurs 85m below the top.

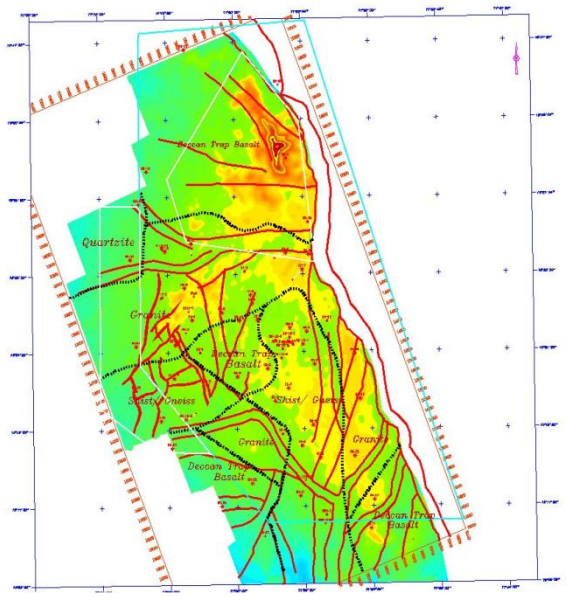

Figure. 9 : Basement composition Map

Based on the analysis of the Mumbai high data the following key observations are made:

1. In granitic / metamorphic terrains the intensity of fracturing is high and fractures mostly occurs close to top of basement.
2. As the older granitic terrain has suffered at least 4 major tectonic episodes the density of network of fractures is higher and this significantly enhances the total and

effective permeability.

3. In Basaltic country, the top part reservoir development is largely due weathering. However, tectonically induced porosity and permeability is expected in the area in close vicinity to the MH east fault.
4. In addition the development of fracture zones can be expected at deeper levels in the basalt country mainly due to differential cooling. Such fracture mesh has been encountered in Well-A which has yielded commercial quantity of oil from this zone.
5. Towards west the intensity of fracture mesh development is envisaged to be low and therefore the area in general presents low prospectivity expect for the corridor along the major EW fault trend that divides the MH North from the MH South area.

Exploration Focus

Prospects close to major fault sets - MH east fault and the associated conjugate fault sets are required to be identified Prospects should be ideally located close to kitchen area to the east and south. Towards west prospects should be located on or near the EW transverse fault trend

It is of paramount importance to determine the migration and tectonic history with particular emphasis on recent episode as the maximum fluid migration would have been facilitated along the fault set that remained active during the peak migration period.

The associated mineralization history of the different tectonic episodes need to be unraveled in order to locate fracture sets relatively unsealed.

Present day insitu stress distribution plays a major role in redistribution of hydrodymamic regime and hence understanding the same will help identify faults most susceptible to present day dilation.

The following key criteria should be observed in formulating a strategy for Basement exploration: (Fig.10)

i. Prospect should be located very close to major regional faults.
ii. Prospects oriented parallel / sub parallel to the direction of maximum stress are favorable compared to those oriented parallel to direction of minimum stress.
iii. Prospects associated with longer structures are more favorable than those associated with short structures.
iv. Prospects with multiple fault sets enhance the connectivity and hence are more favorable.
v. Prospects associated with reactivated structures are more favorable because they increase the storage capacity and enhance the effective permeability.
vi. Prospects are more likely hold hydrocarbons in the top window of the basement as compared to the deeper zones. However, preferential increase in storage capacity and permeability may exist depending on the compositional banding of the basement rock.

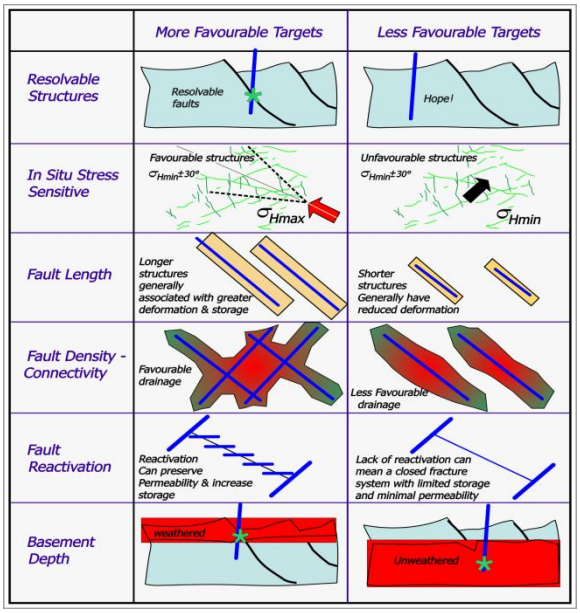

Figure10: Schematic depiction of tectonically favorable locales for Basement exploration

Conclusions

- Mumbai High structure initially evolved in an extensional regime modified by later transtensional stress regime during the anticlockwise rotation of Indian Plate resulting in extensive development of fractured basement reservoir and accentuated by subunconformity weathering presents an ideal Basement play. It can be compared to Bach Ho field, Vietnam.
- Predictability of fracture trends and thereby the identification of favorable locales for basement exploration can be rated as moderate to high in

Granitic and metamorphic basements. However, in Basaltic basement the predictability remains poor.

- Wells should be targeted in the maximum damage zone in the MH east Fault
- Steps and Jog zones along the MH East fault are probable locales of high stress concentration and therefore will have higher fracture densities.
- Wells are to be targeted in more homogenous rock especially Granitic terrain where more fracture permeability is expected.
- Along the EW corridors wells may be located within the major fault zone.
- Further in order to exploit the full potential of Basement reservoirs, drilling of high-tech wells and completion need to be looked into by a MDT for proper planning of the wells.

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