Understanding of Reservoir Compartmentalization and its Impact on Flow Behaviour in Fractured Basement in Mumbai High South field.

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Summary
Fractured Basement reservoir is unconventional hydrocarbon reservoir where hydrocarbon storage and conductivity are provided by fracture system associated with faults. The average porosity of fractured reservoir is small, about 2-3% while the permeability is distributed in relatively wide range. Fracture system divides reservoir into compartments and creates high heterogeneity of permeability and porosity distribution. Flow in fractured basement reservoir is unpredictable and requires in-depth study for reservoir characterization.

Compartment identification is an important factor in the exploration and exploitation of oil and gas reservoirs and may have a significant impact on the estimation of in-place and/or recoverable reserves, as well as the placement of exploration, development and production wells.

Present study discusses the causes of compartmentalization at structural level, from reservoir pressure data, fluid properties and anomalies in Static model i.e. Discrete Fracture Network for different wells of prospective up dip part of Mumbai High South. Compartmentalization can be caused by lateral flow barriers, such as faults, reservoir pinch-out, or it may be caused by simple structural closure along the top or base seal surface. Study considers analysis of pressure production data at basement level, fluid characteristics, seismic data, geochemical data and well logs FMI data. This study has led to better understanding of unconventional reservoir and its flow behaviour. The analysis has been useful in deciding the optimum placement of new wells and relocation of poor producers.

Introduction
Mumbai High is a giant multilayered field situated in the western offshore of India. The field is producing hydrocarbons primarily from multilayered lower Miocene carbonate reservoirs and the fractured Basement and Basal Clastics as secondary reservoirs. Although commercial accumulation of hydrocarbons from naturally fractured Basement and Basal Clastics have been established quiet early. After over three decades of establishing hydrocarbon in Basal Clastic and Basement, focused efforts to exploit the full potential of this unconventional reservoir have taken pace in last five years through exploratory and development drilling. The study area is indicated in location map of Western Offshore Basin as shown in Fig. 1.

Geological Setting
Mumbai high field is a large doubly plunging anticline (paleo-high), bounded towards east by NNW-SSE trending basement controlled fault and towards west, it grades into monoclinal deeper continental shelf. The entire shelf is split into longitudinal strips by a number of Basement controlled faults, which resulted in horsts and grabens (Fig. 2).

The field is giant paleo-high of the Precambrian granitic rocks overlain by Deccan Traps at some part and clastics and carbonates over the greater part of the area. Tertiary sedimentary sequences of Early Oligocene to recent overlying the Basal Clastics were deposited in response to various transgressive and regressive events registered during geologic past. Eastern boundary fault is a major zone of deformation comprising several faults which are offset by minor ENE-WSW cross faults. The drilled well data indicates the basement rocks of varied lithology consisting of granite gneiss, biotite schist, phyllites and basalts. The major carbonate reservoirs of Mumbai high were deposited during upper part of Early Miocene (Bombay formation) and Middle Miocene (Bandra Formation). In between these two major carbonate reservoirs, a thin sheet like sand/silt body is deposited, which is designated as Mahim formation.
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Fig 2: Major Tectonic Trends in Mumbai High

The Mumbai High remained exposed till Oligocene times. The weathering due to longer exposures, alterations of mineral constituents, faulting and fracturing by tectonic processes, might be some of the reasons for the development of secondary porosity and permeability, and thereby creating the reservoir.

Objectives

Basement reservoir of Mumbai High exhibits wide variation in production rates; wells drilled away from fault zones are devoid of hydrocarbons whereas some wells drilled over the structures or close to faults produced hydrocarbons in the range of 1500 to 2500 bopd. Structurally shallower wells found dry, produced oil with high water cut and structurally deeper wells found cleaner oil. Pressure transient analysis also indicated that very less dissipation of pressure and depletion is around the well bore. Phase behaviour studies also indicated the variation in fluid characteristics in the basement wells. The seismic data and formation micro imaging data analysis indicated that the faults and fractures are associated with anomalies in static model DFN studies. Hence, integrated approach of analyzing available G&G data with pressure and production history of wells is essential for evolving a working strategy to realize the potential of Basement.

Area of Study

The large size and complex reservoir characteristics of the field have necessitated the acquisition of information, initially on a strategy to drill widely spaced exploratory wells to the Basement for determining the geological and reservoir heterogeneities, areal extent, fluid properties and the initial oil and gas volumes. Later, vertical well of most of the platforms were drilled to the Basement during the late eighties for better understanding of the reservoir. Initial oil in place is estimated mainly in four areas A, B, C and D as shown in Fig. 3.

Fig 3: Established Hydrocarbon areas in Basement

The present work is based on analysis of geoscientific data of Area B in MHS. The area B is considered because of availability of pressure and production data.

Exploitation status of Area - B in MHS

The area separated by a structural low which is bounded by prominent extensional cross faults trending nearly east west. The area is bounded to the east by the Mumbai High main extensional fault with over 600 m throw towards east. In the year 1989 with the drilling of exploratory well-AC real breakthrough was achieved with higher oil production around 2500-4000 bopd in Basement (Fig.4). During 1990 to 2000 two development wells produced oil in this area. Well-AB produced oil around 750 bopd during initial
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testing and cumulative oil production was 0.058 MMt. The well was transferred to upper L-III due to low influx. Other well-AE was completed towards mid 90’s and produced oil over 600 bopd with around 60% water cut. Well has cumulatively produced 0.011 MMt and it has also been transferred to upper L-III due to high water cut.

For further development of this area, one appraisal cum development location AD for Basement was drilled to Basement in 2009 as a directional well. The well encountered near vertical fractures with very less aperture and some are filled with pyrite & quartz. The Basement section produced only water and no influx was observed from Basal Clastics even after stimulation job.

In order to exploit the oil reserves of Basal clastics and Basement from the known Block of well-AC area, the well-AD as ADz was planned and drilled to a depth of over 4000m (100m tvd in Basement). Well-ADz was drilled during 2011-12, about 630m south of well-AC and put on production in April 2012. The well-ADz was completed in Basal clastics and Basement and produced around 1800 bopd of clean oil on self flow with ½” choke and is currently producing oil around 800 bopd with ¾” choke with 28% water cut. One subsea well AC-SS has been drilled and put on production in mid of 2014. Well AC-SS is producing @1400 bopd with no water cut. Completion of well-ADz & AC-SS added the oil production of over 3300 bopd in this area and presently the area is contributing around 2200 bopd with 15% water cut.

Methodology

The common goal is to characterize reservoir properties with sufficient resolution so that fluid flow pathways are “mapped”, production behavior predicted, and hydrocarbon production maximized. Accurate characterization of the connectivity and compartmentalization of permeable reservoir (reservoir flow-unit architecture) is required. For the last several decades it has been widely held that the use of sedimentary-process and sequence-stratigraphic analysis would help resolve reservoirs architecture. However, the impact of these techniques in unconventional reservoir has been limited because they are based on non-dynamic depositional facies models and an incomplete understanding of the range of possible reservoir architectures.

Initial reservoir pressures obtained from Pressure Transient analysis and Reservoir Formation testing indicates anomalous pressure points such as reservoir depletion, inadequate build up periods and sub-seismic reservoir compartmentalization. Low permeability/porosity reservoir rocks, dramatic lateral changes in structural geometries, and large distances between wells generally produce reservoir compartmentalization and can be ascertained as given below.

1. Structural Compartments effecting production potential
2. Pressure Compartments
3. Fluid properties anomalies
4. Basement characterization by DFN showing discontinuities

Results

1. Structural top and production potential

In Area B structurally shallower wells like AD produced water and well AE produced oil with high water cut and structurally deeper wells like AC, ACSS & ADz produced good amount of oil around 1500 to 2500 bopd as shown in Fig. 5.
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Wells in Area B exhibit wide variation in production rates and at shallower level produced water or oil with high water cut which indicates that compartments may exist within the well and area which is affecting production from basement. Data is shown in structure map and Table 1.

<table>
<thead>
<tr>
<th>Well</th>
<th>Year</th>
<th>Basement top tvd msl</th>
<th>Ql bpd</th>
<th>Qo bpd</th>
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<tr>
<td>AB</td>
<td>1990</td>
<td>1881</td>
<td>746</td>
<td>746</td>
</tr>
<tr>
<td>AC</td>
<td>1989</td>
<td>1899.5</td>
<td>2575</td>
<td>2575</td>
</tr>
<tr>
<td>ACSS</td>
<td>2014</td>
<td>1956.5</td>
<td>1532</td>
<td>1532</td>
</tr>
<tr>
<td>AD</td>
<td>2009</td>
<td>1868</td>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Adz</td>
<td>2012</td>
<td>1885</td>
<td>1861</td>
<td>1861</td>
</tr>
<tr>
<td>AE</td>
<td>1994</td>
<td>1864</td>
<td>1700</td>
<td>665</td>
</tr>
</tbody>
</table>

Table 1: Basement top and testing results

Production performance of different wells in Area B indicates the wide variation in oil rate. Well ACSS and Adz started producing with 1500 to 1800 bopd. Wells AB and AE initially produced with around 650 to 750 bopd and later ceased due to high water cut indicated in Fig. 6.

2. Pressure compartments

Pressure-depth plots are powerful methods to visualize the wide array of pressure data and aid interpretation for safety, drilling, and exploration purpose and compartment analysis. Pressure compartmentalization of reservoirs involves restricted fluid movements over geological time. Initial reservoir pressure of wells in Area A indicates that wells were drilled at different time from 1989 to 2015 but initial reservoir pressure recorded was around 2950 psi though in between wells have produced oil from Basement.

<table>
<thead>
<tr>
<th>Well</th>
<th>Formation</th>
<th>Date of study</th>
<th>SBHP psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>Basal Clastics, Basement</td>
<td>October-92</td>
<td>2938</td>
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<tr>
<td>AC</td>
<td>Basement</td>
<td>March-89</td>
<td>2931</td>
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<tr>
<td>ACSS</td>
<td>Basal Clastics, Basement</td>
<td>January-15</td>
<td>2935</td>
</tr>
<tr>
<td>AD</td>
<td>Basement</td>
<td>July-05</td>
<td>2947</td>
</tr>
<tr>
<td>Adz</td>
<td>Basal Clastics, Basement</td>
<td>April-12</td>
<td>2947</td>
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<tr>
<td>AE</td>
<td>Basal Clastics, Basement</td>
<td>September-95</td>
<td>2938</td>
</tr>
</tbody>
</table>

Table 2: Initial Reservoir Pressure of wells

Multiwell P-T plots permit recognition of pressure compartments in the subsurface. Wells where the same magnitude of pressure is found at a common reservoir-level are likely to be located in a shared pressure compartment (Fig. 7). Different amounts of pressure in the same reservoir in multiple wells indicate either the reservoir is compartmentalized by barriers (largely static) or the fluids are flowing from a higher overpressure region (dynamic system). A hydrodynamic system can be recognized where pressures systematically change without the presence of barriers. Recorded pressure in producing wells is plotted with time and cumulative oil production showing that each well is behaving like separate unit.

![Fig 6: Production Performance of wells in Basement](image)

![Fig 7: P-T Plots with cumulative oil](image)
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Basal Clastics reservoirs in the area and between wells. These compartments respond in different ways to pressure/stress changes, and on flow behaviour which becomes a great challenge.

Phase behaviour studies of wells in Areas A, B, C and D show (Fig. 9) that saturation pressure of wells is ranging from 36 to 123 kg/cm² and GOR values are also in wide variation from 50 to 81 v/v. Bottom hole temperature is also varying from 109°C to 135°C. It is indicating that fluid properties of wells are varying from area to area.

4. Basement characterization by DFN showing discontinuities

The understanding of the network of fractures is one of the major challenges in unconventional basement reservoirs. The strategy of exploitation and the development of field is determined by the spatial distribution of these fractures. The zones with strong density of fractures, the knowledge of their connectivity, orientation, inter fracture spacing and their elongations are the essential elements.

There are many situations where compartmentalization unexpectedly impacts development; we still have some way to go before we have work flows and practices that enable consistent prediction of the impact of faults, fractures, stress and other reservoir heterogeneities ahead of the drilling.

The fracture properties, viz. fracture length, fracture width, and fracture density were up-scaled into the 3D geological model to create the Discrete Fracture Network (DFN) Model which captured the spatial distribution of fractures and associated heterogeneities. DFN model helps to show more clearly the intensity of the fracturing around the wells.
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(Fig. 10). Static model of this area is prepared with the acquisitions of well data by the imaging techniques and seismic data, which is reflecting the discontinuities.

Conclusions

The goal is to derive a general strategy to improve profits through a better understanding of reservoir size, compartmentalization, and orientation as well as reservoir flow characteristics. Understanding the nature and distribution of reservoir compartments, and using effective reservoir management strategies, can significantly improve recovery efficiencies from Basement reservoir of Mumbai High field. The approach involves an integrated geologic, geophysical, and engineering approach devised to identify heterogeneities in the subsurface that might lead to reduction of uncertainties. The approach involves the following key steps:

1. Impact of structural complexity as seen from table-1 (that shallower wells produced water); on reservoir fluid flow to guide further exploration and exploitation. This happens when wells failed to intersect connected, conductive fractures. It requires pre-drilling description of the effective fracture network.

2. Investigated trends of reservoir pressure in table-2 clearly indicate that wells near to each other do not communicate and fractures are working as barriers which may create reservoir compartment.

3. Basement reservoir in which fault & fracture networks control on production, characterization of fracture networks is a vital task in optimizing the flow. DFN model is one of the best ways to characterize a basement reservoir. It accurately accounts for the heterogeneity and orientation of fracture set. Thus it is vital to characterize reservoir compartmentalization as early as possible in field life, ideally during appraisal.

As more wells are drilled, it has become possible to better correlate and map the producing horizons with the proper understanding of compartmentalization of the fractured reservoir and study can also be extended to other producing areas of the field. This clearly allows better planning of the location of future wells, and the thickness of the basement section which needs to be penetrated, for optimizing field economics.

References

2. Well Completion and Formation Evaluaton, PVT reports, and pressure build up study of various wells from Mumbai High field-unpublished reports of ONGC.

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