ID-2011160

Exploitation of hydrocarbons from unconventional fractured Basement/ Basal Clastic reservoirs underlying the offshore giant Mumbai High Field.

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Abstract

Fractured basement reservoir, where the oil and gas in place may be held within an extensive interconnected fracture network rather than within the matrix of the formation. Mumbai High is a multilayered oil field having major reservoirs are Fractured Basement, Basal Clastics, L-V, L-IV, L-III, S1 & L-I . The field is on commercial production of oil and gas since 1976. Hydrocarbon was established in the Basal Clastics/Basement rocks in 1981. However, the focus remained on development of the multilayered prolific producing L-III reservoir. A few vertical development wells were drilled from platforms to Basement & Basal Clastics during the late eighties in different parts of the field. After over two decades of establishing hydrocarbon in Basal Clastic and Basement, an attempt was made to exploit oil from deeper unconventional Basement prospects in addition to the main L-III reservoir.

Basement is unconventional in the context of reservoir nature and, hence, complex to characterize and isolate the locales of interest. Due to challenges of geology, it is essential to have successful operations as well as reducing uncertainties and improving the efficiency of unconventional field management.

An attempt has been made in this paper to understand the hydrocarbon production from Basement and Basal Clastics of Mumbai High field. The present work outlines the drilling, completion, production performance and stimulation jobs in the recent placement of new/ sidetrack wells in favorable locales in Basal Clastics/ Basement based on detailed analysis of geoscientific data. These wells resulted in almost five fold in increase in oil production, giving a boost to oil production and recovery from these unconventional reservoirs. The present production rate is over 3500 bopd from Basal Clastics and Basement. The analysis of performance behaviour of these wells would help in fine-tuning the development of Basal Clastic/ Basement in Mumbai High.

Introduction

Mumbai High is the giant offshore oil field discovered in 1974 and located about 160 km west-north-west of Mumbai city in the Arabian sea (Fig.1). It is the largest and most prolific oil field in India. The field area extends to about 1500 Sq Km. On the basis of an E-W trending shale channel in L-III reservoir, the field is divided into two blocks: Mumbai High North (MHN) and Mumbai High South (MHS) (Fig.2). Oil and gas have been discovered in a number of reservoirs, viz., Fractured Basement, Basal Clastics, L-V, L-IV, L-III, L-II, S1 & L-I (Fig.3). Out of these, LII and LIII are the two main

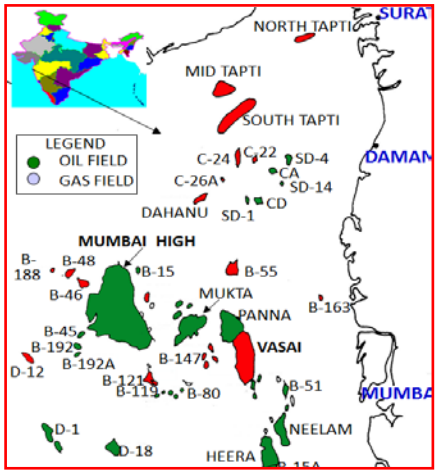

Fig. 1: Location Map of WOB

limestone oil reservoirs of Miocene age. L-III reservoir is multilayered limestone reservoir with a gas cap and partial water drive occurring at about 1300 m depth and holds about 94% of the total initial oil in place. Mumbai High is one of the most complex fields in terms of reservoir heterogeneity. Development of L-III layer has been carried out since 1976 in phases.

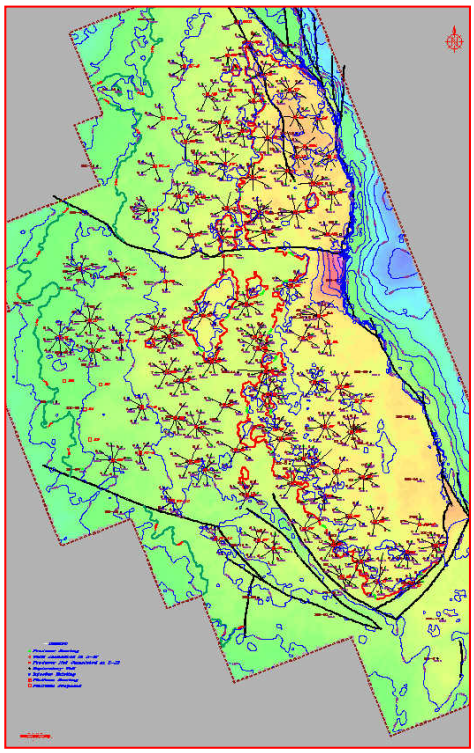

Fig. 2: Mumbai High field

The field was put on production in May'1976 and developed through the implementation of development schemes. The bypassed oil in the major reservoir is being exploited through two phases of redevelopment. A philosophy of phase-wise efforts is being followed to improve recovery of the hydrocarbon reserves. Five year re-development plans were adopted since 2000, starting with Phase-I to improve field performance and recovery factor. Based on the success of the redevelopment Phase-I, redevelopment Phase-II was launched and expected to be completed in 2013-14. The recovery improvement strategy incorporated reduction of inter-well spacing through infill drilling and improvement in water injection to enhance areal sweep.

The Phase-III scheme of Mumbai High targets minor reservoir viz Basal Clastics and Basement for incremental oil gain along with the major reservoir of L-III. The present study has indicated the exploratory and development wells drilled so far to Basement, initial testing results, Production performance, pressure data, prospective areas, analysis of data generated in recent wells and their results. The placement of the wells based on detailed analysis of available geoscientific data of nearby area yielded mixed results, as confirmed by the performance of the conventional inclined wells drilled during 2012-13. The data generated from these wells would help in selecting appropriate locale for drilling and completion of the future wells as a sub-sea well, through available slots in the existing platform and sidetracking of poor producers of L-III to Basement and help in further enhancing the production of the field.

Geological Setting

The western continental margin of India is marked by three dominant tectonic trends, the NNW-SSE Dharwar trend; the NE-SW Aravalli trend and ENE-WNW Satpura trend. The area has undergone extensional tectonics, giving rise to rifting and fault block movements along NNW-SSE trending normal faults, creating a series of horst graben structures. Mumbai High, Bassein and Heera are prominent basement highs which are flanked by the aforementioned faults.

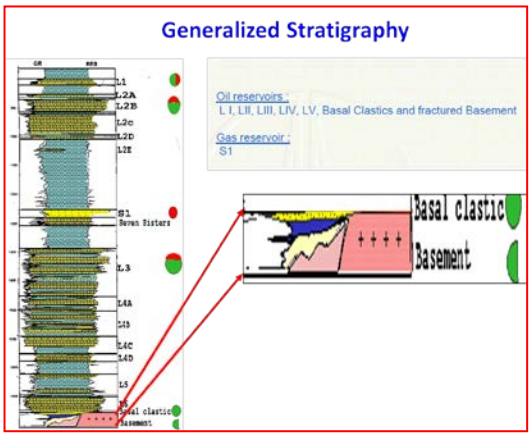

Fig 3: Stratigraphic Sequence in Mumbai High

It is likely that these highs were covered by Deccan Traps, part of which might have been stripped off due to long exposure to elements. In case of Mumbai high, the northern, western and southern peripheries have the Deccan Basalts forming a veneer over the Archaean basement. The Eastern limit of Mumbai High is a large displacement normal fault, about

70 Km in length and having throw of about 400m in the central part, towards the east. The magnitude of throw decreases in the Northern and Southern part. The constant reactivation of fault as inferred above is of significance in basement hydrocarbon exploration as zone of intense fracturing would be generated for HC accumulation.

In addition to the main NNE-SSW fault defining the eastern limit of the Mumbai High, there are a number of NE-SW and NNE-SSW trending fault sets. Intersection of these fault sets is likely to give rise to intensely fractured zones in the form of fracture swarms in basement. Storage volumes of intensely fractured zones can be significant.

The Basal Clastics unit directly overlies basement in Mumbai High South. It is considered to be of Paleocene/Early Eocene age. The unit has proved to be hydrocarbon bearing in a number of wells. The sand in Basal Clastics unit is postulated to be derivatives of weathered products of basement rocks from positive areas.

Reservoir Characterization

Thin clastics sequence forms the base for upper Tertiary sediments distributed mainly over the southern part of the field and overlying the predominately crystalline Basement. The Basement reservoirs are usually characterized by rock having irregular and low matrix porosity and permeability and production relies on fractures, which are irregularly distributed and give significant variations in well productivities. The Basement rocks are very tight, brittle and when subjected to geo stresses. Mud loss usually occurs through fractures while drilling. Production is dependent on hydrodynamic communication of the well bore with network of fracture system. Well logging and PLT analyses show multiple fractured pay intervals. With the available data average net reservoir thickness is 200m. The intensity, of fracturing tends to increases in the vicinity of faults. The fractures are categorized on image logs as continuous, discontinuous, boundary and vuggy. In the instant case, the image logs indicates that fracture orientations are multidirectional in the central block, but elsewhere are NE-SW and contain numerous fractures of inclined nature. The inclined fractures dip at an angle of 45° to 80°. In the well-AC, fractures in the core are observed to be filled with calcite, chlorite, secondary silica and some disseminated pyrite. Pyrite as dissemination is also observed on the surface of the rock type. The fractured Basement and Basal clastics have been proved to be potential pay zones with the production performance from few completed wells in the past. The oil with API gravity of 35-36 is highly under saturated with saturation pressure ranging from 36 to 83 kg/cm2 and low GOR of 50 to 58 v/v in Basement. Initial reservoir pressure ranges from 194 to 206 kg/cm2 with temperature ranging from 109 to 126°C. Current reservoir pressure is around 176 kg/cm2.

Production History

The Mumbai High field was put on production in 1976 and by Aug 1981, Basal/ Basement production was started through well AP with oil rate of 1100 bopd with nil water cut. The cumulative oil production from Basal clastic/Basement is 2.54MMt, which amounts to about 2.4 % of inplace oil. The average daily rate of production during 1981-82 was about 4,000 bopd. In the next few years, the field production was 3000 bopd and then maintained to 2000 bopd with average water cut of 50 % from 1992 to 2001 on account of drilling and completion of development wells. During 2002 to 2012 decline in oil rate and increase in water-cut occurred

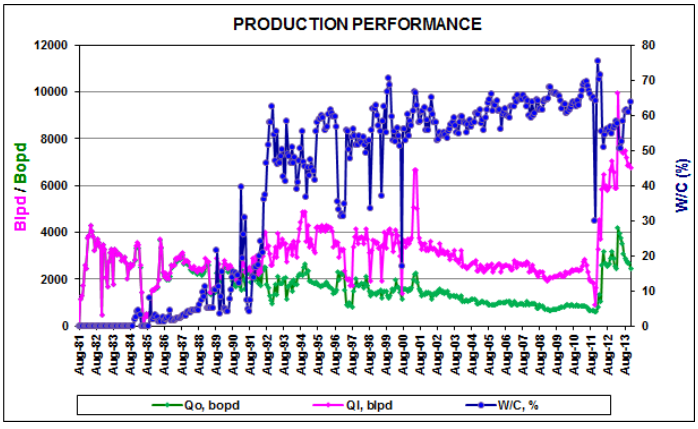

Fig 4: Production Performance of Basal Clastics/Basement

and average oil rate was 1000 bopd with water cut of 70%. The decline in oil production is attributed to drop in productivity due to high water cut. During 2012-13 six wells were added with mixed results. The current oil rate is 3778 bopd with 52% water cut (Fig.4).

Exploitation Strategy

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 Basement for determining the geological and reservoir heterogeneities, areal extent, fluid properties, the initial oil and gas volumes and drive mechanism. Later vertical well of most of the platforms (development wells drilled to produce the upper prolific reservoir L-III) were drilled to Basement during the late eighties for better understanding of the reservoir (Fig.5). In the development scenarios, knowledge of these parameters is utilized in the placement of infill wells. Drilling of infill and sidetrack wells is a proven incremental recovery option and to recover more oil in unconventional reservoirs. This is likely to increase the amount of recoverable reserves. The Basal Clastics unit directly overlying basement in Mumbai high south, thought to be of Oligocene age, has proved to be hydrocarbon bearing in a number of wells. Except a few wells, all other wells in Mumbai high drilled to basement have been tested together in basement and Basal Clastics making it difficult to assess true potential of these discrete units. First attempt to bring out a geological model on Basal Clastics on Mumbai High was made in 2010-11 and locations were drilled based on the model with mixed success.

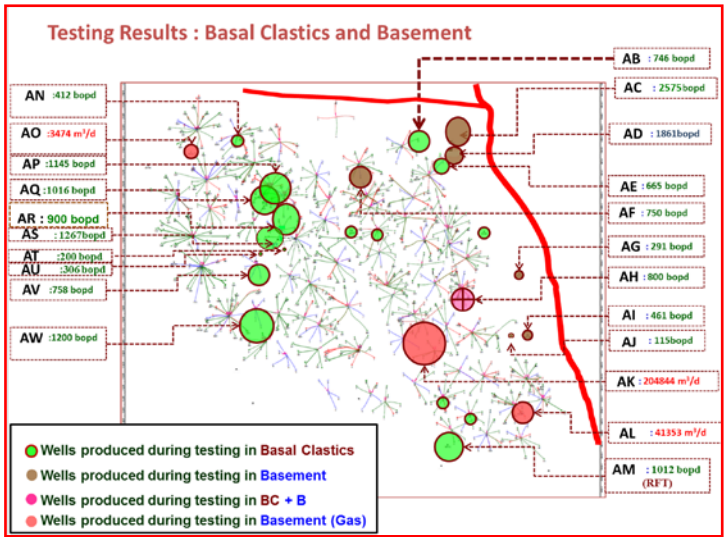

Fig 5: Initial testing of wells tested in Basal/Basement

Overlying prolific producing reservoir L-III and other HC bearing horizons L-V & L-VI are encountered in the upper sections. Due to production from upper prolific L-III layers, the pore pressures of these reservoirs have dropped substantially. Thus, there is a situation where a sub hydrostatic layer is in between normal pressured shales and underlain by normal pressured limestones L-V & L-VI leading to challenges in drilling the wells for basal clastic/basement.

The basement rocks at Mumbai high are tight and production relies on fractures, which are irregularly distributed and give significant variations in well productivities. More fractured zones have been identified along the maximum damage zone near the eastern boundary fault. Well logging and PLT analyses show multiple fractured pay intervals. The average net reservoir thickness is 30 to 40 m. The intensity of fracturing in the basement tends to decrease with depth but increase in the vicinity of faults.

Presently more than 1000 wells completed in MH field, around 80 penetrated basal clastics and basement, covering length and breadth of the field. Out of 80 wells, nearly 50% of the wells were reasonably tested and reserves were established. Of the wells drilled upto basement, 50% of the wells penetrated less than 50m of basement, 35% penetrated upto 100m and 15% wells penetrated more than 100m of basement section. As the well penetration was restricted to shallower part of basement, its true potential is yet to be assessed. Thirteen of the tested wells have been put on sustained production at different interval of time and have cumulatively produced 2.726 MMt of oil

till Mar'2013, which is only 2.55% of estimates. Most of the earlier wells are drilled as vertical but recently most of the wells have been drilled as inclined wells.

The area around the eastern boundary fault of Mumbai High field with fractured Archean Basement is known to be potential area for hydrocarbon prospect. This has been proved with the drilling of exploratory wells AI, AG and AC close to main fault during 1987-1989. Real breakthrough with higher oil potential @ 2575-4400 bopd was achieved with the drilling of exploratory well AC, which is situated on the North-eastern part of the Mumbai High South, was drilled in the year 1989. The basement is fractured and oil-bearing. In the subsequent years, focus was on development of multilayered prolific L-III reservoir occurring at shallow depth. After a gap of more than two decades, to enhance the oil production from field an attempt was made to exploit oil from deepar prospects.

Basement exploitation programme has started with the drilling of development wells during 2012-2013 through sidetracks and available slots near the existing potential area proved during initial testing and production performance of wells completed in Basal clastics/Basement.

Significant reserves and limited production encouraged to drill more wells to exploit the unconventional reservoir. To enhance the oil production from field an attempt was made to expoit oil from deeper prospects. Four prospective areas for exploitation of Basal clastics and Basement have been identified.

1. Area - A in Mumbai High North

2. Area - B in Mumbai High South

3. Area - C in Mumbai High South

4. Area - D in western part of central Mumbai High South

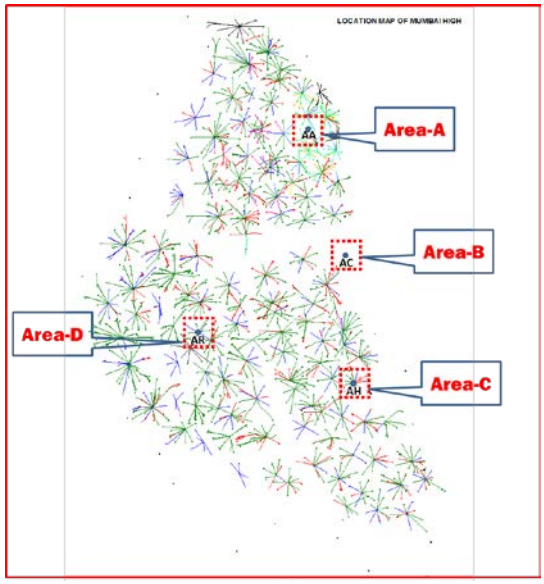

Fig 6: Prospective areas of Basal and Basement

Area - A in Mumbai High North

The area is structurally highest at basement level and the exploratory well-AA drilled 133 m in Basement had produced oil @ 1056 bopd during initial testing. The production of oil from basement at well-AA is indicative of fractured basement and accumulation of oil within fractures. The area around well-AA at the basement level forms a north-south elongated high and is considered favorable for accumulation of oil in fractured basement. At present there is no oil production from Basement in MHN and it needs to be exploited by drilling of deeper sections of basement.

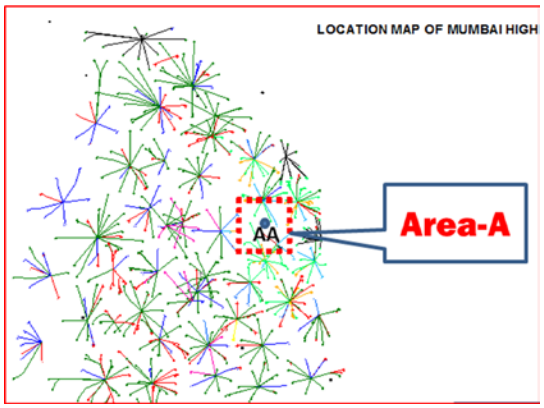

Fig7: Well AA in Mumbai High North

Area - B in Mumbai High South

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 @ 2575-4400 bopd in Basement (Fig.8). During 1990 to 2000 two development wells produced oil in this area. Well-AB produced oil 746 bopd during initial 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 in Mar'94 and produced oil @ 665 bopd with 63% water cut. Well has cumulatively produced 0.011 MMt and it has also been transferred to upper L-III due to High water cut.

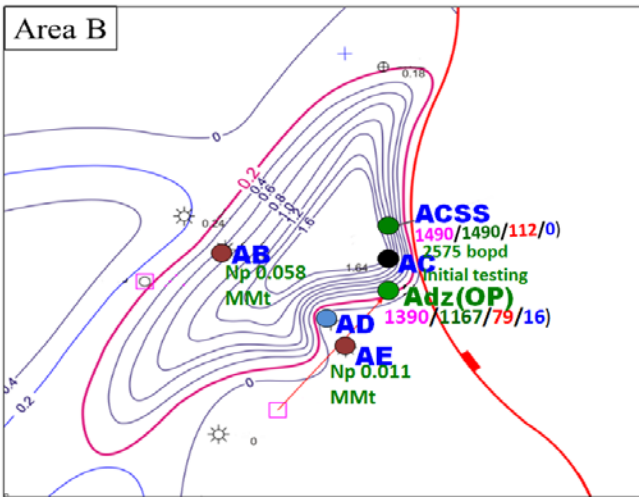

Fig 8: Exploitation status of wells in Area-B

For further development of this area, one appraisal cum development location AD for Basement was drilled to Basement in May 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 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 4310m with a drift of 3366m in 40°N. Well-ADz was drilled as a part of field development during 2011-12, about 630m south of well-AC and put on production in April 2012. The well-ADz completed in Basal clastics and Basement and produced @ 1860 bopd of clean oil on self flow with ½" choke, the highest per-well production in the current scenario in Mumbai High field. Well is currently producing oil @ 1167 bopd with ¾" choke with 16% water cut (Fig.9). One subsea well AC-SS has been drilled and put on production in June2014. Well AC-SS is producing @1490 bopd with no water cut. Completion of well-Adz & AC-SS added the oil production of over 3300 bopd in this area and presently contributing @ 2612 bopd with 16% water cut.

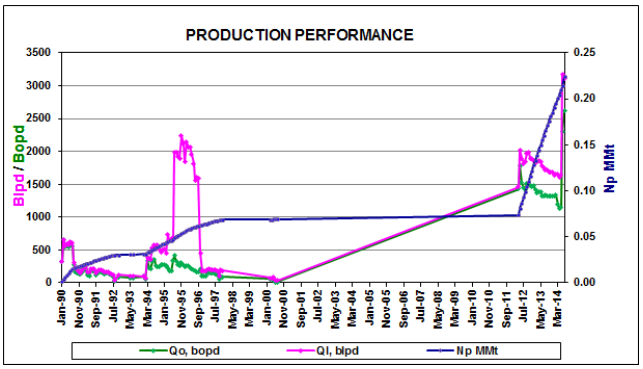

Fig 9: Production Performance of wells in Area-B

Area - C in Mumbai High South

In the southern part of Mumbai High structure a series of narrow grabens, bounded by two prominent parallel extension faults, are present. In Dec'92 one development well-AH completed in Basal clastic and still producing with oil rate of 417 bopd with 84% water cut (Fig.10). Well-BA was completed as conventional inclined well in Basal Clastics. After pumping in acid, well was flown back and it produced 182 bbl liquid, 5 bbl oil with 98% water cut having salinity 57037 ppm and GOR of around 12750 v/v. After stimulation job,

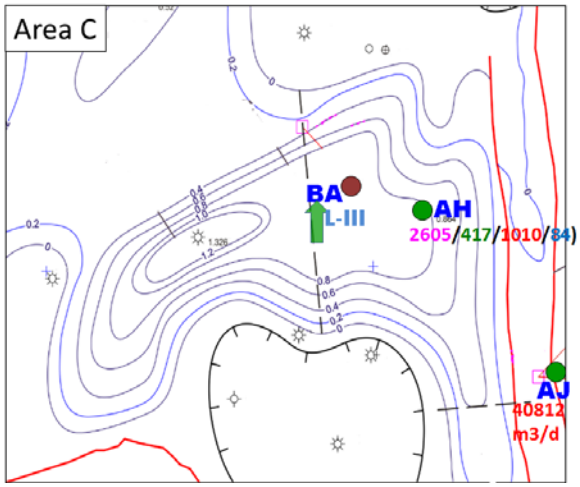

Fig 10: Exploitation status of wells in Area-C

observed improvement in production with liquid @ 164 bbl, oil @ 127 bbl, water cut of 22% and GOR of 315 v/v. Last testing before well ceased to flow indicated salinity is of the order of 33000 ppm whereas the salinity of formation water in Basal clastics and basement is in the range of 10000 to 15000 ppm. Additional perforation was done in Basal, no gain was observed. Due to no activity well has been transferred to L-III for oil production. Second development well-AJ drilled to exploit Basement, could drill only 45 m against 124 m in MD due to total mud loss at 3100 m in Basement section. Repeated attempts were made to control mud loss without success. Basal Clastics was perforated and produced gas. At present well is producing gas @40812 m3/d. During 2012-2013 two development wells completed for enhancement of production from Basal clastics/Basement. Completion of two wells-AJ & BA and WOJ of well-AH enhanced the oil production from around 280 bopd to around 1000 bopd from Basal clastics/Basement in this area (Fig.11). At present flowing with@ 581 bopd with 80% water cut.

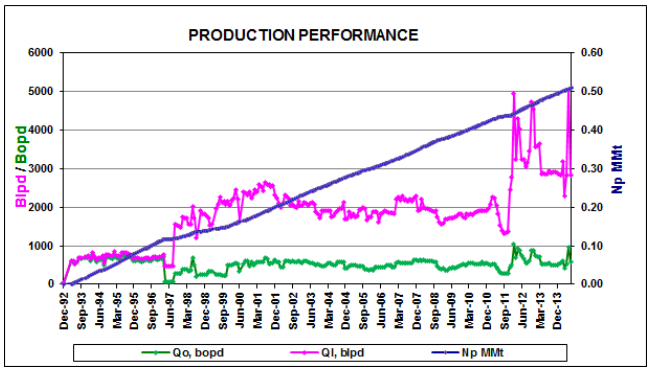

Fig 11: Production Performance of wells in Area-C

Area - D in western part of central MHS

The area lies in the west of the central Mumbai High field around wells AR and AP. It is bounded to the north by the east-west trending cross faults and forms a structurally high area. Initial testing results of this area indicated that area is highly fractured and prospective. First well AP started producing from this area is from Aug'81 with oil rate of 1100 bopd and cumulatively produced 0.829 MMt. In 2004 well transferred to upper L-III reservoir because of poor influx from Basal. Second well AR completed in Basal with oil rate of 800 bopd in June'82 and still producing with oil @ 200 bopd with water cut of 32%. Cumulative production from the well is 0.716 MMt. Third well AQ was completed in Basal and Basement with initial production @1016 bopd in Feb'91. Well transferred to upper L-III in Dec'2003 due to poor influx. Cumulative oil production from Basal and Basement was 0.231 MMt.

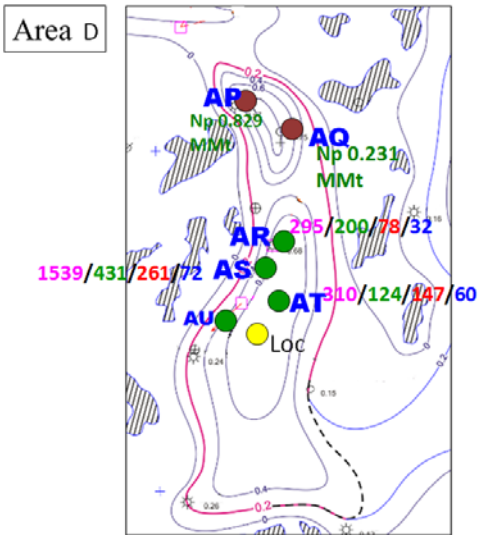

Fig 12: Exploitation status of wells in Area-D

During 2012 to 2013 three more wells AU, AT and AS completed in this area for enhancement of production. Well AU was tested in 23 m of Basement section, poor influx then tested in Basal clastics, produced @ 306 bopd with 6% of water cut during initial testing. The well was completed with mono-bore segmented completion. Stimulation job was carried out in June'12, after the job well produced @ 200 bopd with 53% water cut. At present well is closed. Well was tested in L-V, L-VI gave poor influx and transferred to L-III. Two wells AS and AT completed in Basal clastics and Basement. Well AS completed as conventional inclined well, produced oil @ 1267 bpd with 34% water cut. Water cut has increased to 60% within six months. PLT was carried out to know the

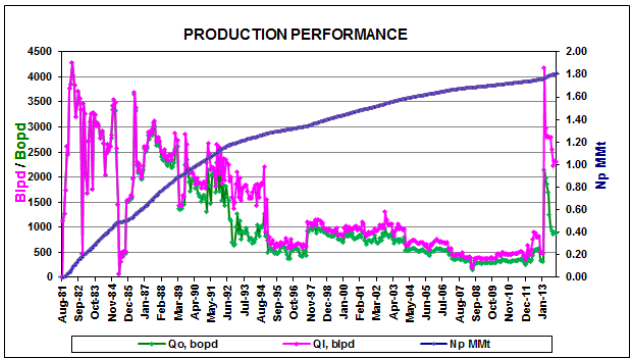

Fig 13: Production Performance of wells in Area-D

source of water indicated that water contribution is from Basal clastics. At present well is producing @ 431 bopd with 72% water cut. Well AT completed as a conventional inclined well. During initial testing produced @ 100 bopd with 46% water cut. After stimulation job oil rate has enhanced to around 300 bopd with 50% water cut. Presently producing @ 124 bopd with 60% water cut. Two wells produced in the past from this area and three wells are presently producing oil @ 661 bpd with 65% water cut from this area. During 2012 to 2013 three wells have been completed in Basal and Basement, that's boost up the oil production from 300 to 1200 bopd (Fig.13).

A total of six wells have been drilled during 2012 & 2013 to enhance production and recovery from the unconventional reservoir. Induction of various techniques and technologies put the field production on an ascending trend(Fig.14).

Recent drilled wells have been a mixed results, with less geological surprises and more drilling and completion problems associated with basal clastic/basement reservoir. Problems of suboptimal casing/liner size for completion, and difficulty in separating contribution from Basal clastics and Basement is essential for the assessment of its true potential.

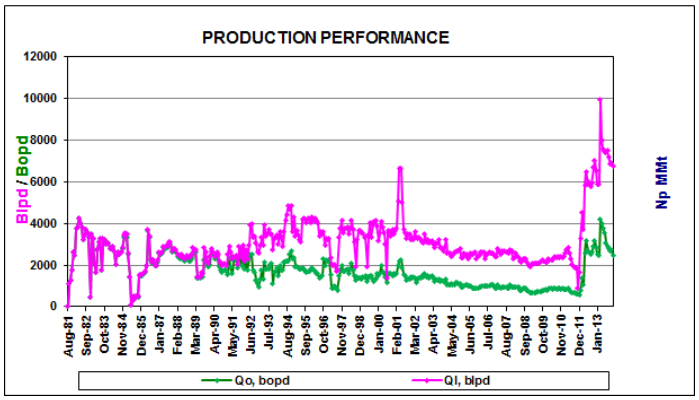

Fig 14: Production Enhancement in Basal /Basement

Placement of future locations requires a detailed integrated study to achieve a realistic production forecast. It is considered necessary to critically examine the data of surrounding wells and also take into account the rapid variation in the thickness of lenticular sandstone beds within the Basal Clastic sequence. There are cases of rapid thinning of such beds due their fluvial environment of deposition. In the area where nearby wells had been put on production from Basal clastics/Basement earlier and later ceased, producing with high water cut needs to be examined for ascertaining the reasons for decline in production.

Various kinds of acidizing treatments including hydrochloric acid, mud acid, acid fracturing nitrified acid and hydrofracturing jobs have been applied in the basement reservoir since 1981. Improvement was noticed in oil production rate through nitrified acid, acid fracturing and hydrofracturing jobs. For further improvement it has been observed that 46% fracture infilling matter (26% Calcium, 5% Magnesium and 15% Iron salts) is soluble in 15% HCL

Thus the main strategy so evolved for the exploitation of oil has been targeting the proved reserves areas with more number of wells and simultaneously wells need to be planned in probable and possible category reserves areas for upgradation of reserves. Under the existing development strategy drilling of more wells have been planned for targeting the undrained oil with suitably placed wells through available spare platform slots/new platforms/subsea completion/low potential wells of upper layer through sidetrack. Further, refinement on the basis of production performance of all the well contributing to oil production, PLT survey data and pressure data will help in exploitation of undrained oil through high angle inclined wells and increase of oil production from the area.

Conclusions

Basal Clastics and Basement has been developed over the years as an exploratory and development target. Exploitation of oil from the complex, unconventional reservoir and drilling through sub-hydrostatic depleted L-III is a real challenge. The current redevelopment plan Phase-III focus with an aim to enhance the oil production and improve the recovery factor of Basal clastic/Basement as one component. Drilling of recent wells based on updated geological model have been initiated which resulted in quantum jump in hydrocarbon production. The plan also

envisages for the development which includes drilling of additional wells from available slots as well as installation of an additional well platform and sub-sea locations.

The development of Basal clastics / Basement is on track but there has been a mixed response from the recent drilling activities in existing platform areas. The lower liquid rate and rise of water cut are matter of concerns. Stimulation job and PLT is planned in wells to know the potential and source of water. Upcoming locations will likely to throw light on the potential of deeper section of the field.

Acknowledgements

The author wishes to express her sincere thanks to Director (Exploration) for encouragement to prepare this paper. Thanks are due to Geo-scientists of sub-surface team of MH-Asset and CoD Basement team for providing the data. Thanks are also extended to various authors of the reports consulted during the preparation of this paper.

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