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Analysis Behind Casing: A door to improved oil recovery from a carbonate reservoir in India.

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Summary

Drilling new / side track wells into a depleted reservoir is a challenge. Many times, total mud losses are encountered and this combined with shale swelling makes the well bore extremely unstable and prone to failure. Such operational problems warrant the immediate lowering of casing liners with out recording open hole logs. This is the case with Mumbai High carbonate reservoir which is one of the biggest Middle Miocene hydrocarbon reservoirs in India. The Mumbai High field which is on production since 1976 has been producing oil from this multi-layered reservoir. Each layer of the limestone is encapsulated in shale/Marl. Logging after casing lowering brings the possibilities of evaluating the formation with out jeopardizing the stability of the well bore.

In this paper, we present the results and validity of logging through casing run in 3 different wells completed in the limestone reservoirs in the Mumbai High field. All the wells experienced losses while drilling and logging after casing lowering was done. The objectives of the logging behind casing were different in different wells.

*The first well was drilled in 2005 and traditional open hole logs could not be recorded due to adverse hole conditions and bore hole environment. The tool was used for **primary formation evaluation**. The objective was to identify which zones could be perforated to maximize oil production while minimizing water production.*

*The second example is about a long time producing well and highlights the importance of ABC(Analysis Behind Casing) tools which provide an excellent means of **identifying bypassed hydrocarbons** and subsequent placement of horizontal drain holes in the un-drained pay zones to improve production performance.*

*The third example illustrates the ability of these tools to evaluate the level of depletion of the producing intervals which is vital for **reservoir monitoring.** A CHFR depletion index curve identifying depletion was generated.*

A basic petrophysical evaluation was performed incorporating the data from through casing logs in each of these wells. Based on the analysis of cased hole formation evaluation, the un-depleted intervals were exploited both conventionally and by drilling horizontal drain holes.

In this paper we describe the interpretation procedure and results from individual wells. We also outline the data validation procedures used to check the data quality.

Introduction

The Mumbai High field **(Fig. 1)** is located 160 km W-NW offshore from Mumbai in western coastal shelf of India at a water depth of 75 m. It contributes about 70% of India's total oil production. The field was discovered in 1974 by ONGC and put on production in 1976. The field was

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divided into Mumbai High North and Mumbai High South by a narrow east-west graben (**Fig. 2**). L-II is the second

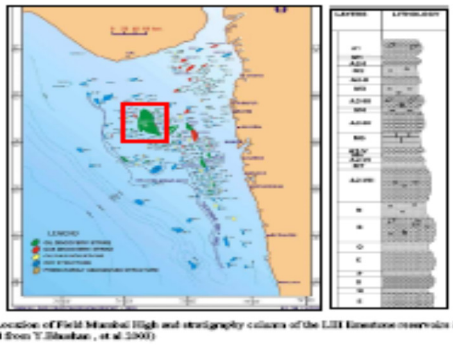

Fig. 1 The Mumbai High Field

biggest reservoir (after L-III limestone sequence) and is hydrocarbon bearing only in Mumbai High North. In this article we discuss three case studies, one in L-II reservoir and two in L-III reservoir of Mumbai High North field.

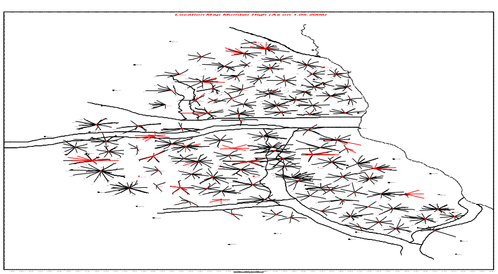

Fig. 2 MH field divided into North and South by east-West graben.

Producing oil from a matured field especially when it is thin, heterogeneous and multi-layered is a challenge. Drilling of new / side track wells and exploitation of by-passed oil pockets in old wells are some of the most efficient ways to improve productivity, extend field life and reverse the declining trend. Drilling through L-II and L-III reservoirs is often associated with total mud losses warranting the immediate lowering of casing liners which precluded the recording of open hole logs. Lack of open hole measurements does not provide formation evaluation information which is a prerequisite to know the hydrocarbon potential of different layers of the reservoir for successful completion of the well. There is, therefore, a need for saturation evaluation to provide comprehensive formation evaluation behind the casing.

An efficient reservoir management system requires formation evaluation in older reservoirs. As the field matures, the development strategy and approach have been focused on bypassed hydrocarbon pays and depletion levels in producing intervals. The acquisition of logging data behind casing made it possible not only to identify bypassed hydrocarbons but also to track changes in saturation and detect movement of reservoir fluid contacts.

In this paper, we demonstrated three case studies and explained the merits of measurements behind casing. In each of these wells, the comprehensive suite of Analysis Behind Casing services (ABC) was run for detailed formation evaluation. The basic services Cased Hole Formation Restivity (CHFR*)[2,5,6], Cased Hole Formation Density(CHFD*)[8] and Cased Hole Formation Porosity(CHFP*)[4] were recorded and the interpretation results were utilized in completing the wells as conventional, horizontal and multi-laterals.

Geological overview and reservoir description

Mumbai High is a prominent basement uplift in the continental shelf and is located in the western coastal shelf of India. It is a doubly plunging assy-metrical anti-clinal structure with a gentle western limb. The eastern limb of this structure is affected by a set of major down-to basin faults. The limestone deposition over Mumbai High started from early Oligocene and continued up to middle Miocene with a few major marine cycles. These have led to deposition of thin alternating bands of shale layers and lime stones in one hand and thick shale layers on the other.

The L-III reservoir of Mumbai High field is a heterogeneous, multi-layered, carbonate reservoir inter-bedded by thin shale bands and tight lime-stones (**Fig. 1).** It is interpreted to have been deposited as a shallow marine, low relief carbonate platform whose growth was controlled by the lateral and vertical build up of carbonate facies during period of minimum clastic input. Carbonate deposition is occasionally disrupted by the sudden influx of terrigenous clastics across the platform resulting in the cessation of carbonate sedimentation and the deposition of shales. This cyclic deposition of carbonates and shales has resulted in the layered L-III reservoir seen in Mumbai High field. The L-II reservoir consists of mid Miocene limestone facies and are characterized as cyclic deposits indicating frequent sea level fluctuations. Accumulation of hydrocarbon is structure controlled.

Cased hole logs and log responses

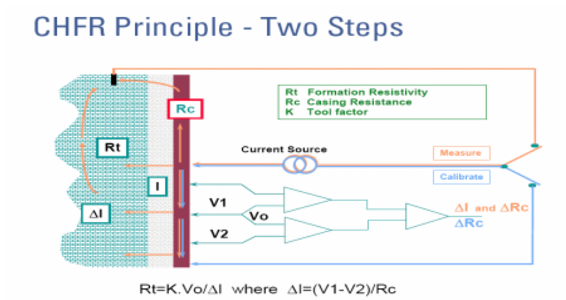

Fig.3 CHFR Principle

The cased Hole Formation Resistivity tool makes direct deep-reading formation resistivity measurements through casing and cement (**Fig. 3).** current into the casing. There is a reduction in current flux as it travels along the casing due to the leakage of a small amount of current into the formation. This leakage current is proportional to the formation conductivity and allows the potential calculation of resistivity.

The formation resistivity behind the casing is not an absolute measurement and needs to be calibrated in a zone of known resistivity. This calibration is generally performed by comparing CHFR reading to open hole data of known formation resistivity, such as a shale. This is because the resistivity of the shale is not expected to change over the time period of the reservoir. The resistivity multiplier (K-factor) is suitably adjusted to make the cased hole resistivity overlay on the open hole reference log.

The Cased Hole Formation porosity service makes accurate porosity and sigma measurements in cased holes. This measurement uses an epithermal pulsed electronic neutron source instead of a chemical source. The Accelerator Porosity Sonde (APS) and the well site log is fully corrected. The APS tool has four sets of detectors in an array with a down hole neutron accelerator for measuring the formation neutron response. The detectors are eccentered to minimize the effects of borehole environments, casing stand off and formation characteristics such as lithology and formation salinity. Unlike the unfocussed nature of the CNL log, the APS tool uses shielding and focusing for minimal environmental corrections.

The Cased Hole Formation density service makes accurate formation density measurements behind the casing. The tool uses a chemical gamma ray source and three detector measurement system to make measurements in a wide range of casing and bore hole sizes. The response of the three detector cased hole density tool was experimentally measured in density blocks and in controlled test tank conditions for variety of formation, casing and cement parameters[8]. Several feasibility studies have indicated that under favorable casing-cement conditions, density measurements are sufficiently sensitive to the formation density in cased holes[1]. The photo-electric effect (Pe) log can not be used for lithology identification, but serves to estimate the casing thickness. The three detector system makes a density measurement corrected for casing and cement thickness.

Validation of cased hole measurements

The best way of validating logging measurements is by a comparison of logs with cores. No conventional cores were taken in each of the study well. So, it is not possible to make a comparison of logging and core measurements. The other way to validate the logging measurements is to compare the cased and open hole log responses. This is reasonable because, most of the completion decisions are considered on the basis of log responses and they are treated as representative measurements of formation parameters.

Open hole logs could not be recorded in study well-A and study well-B due to hostile bore hole conditions. Hence, it is not possible to compare and validate log responses in these wells. Although open hole resistivity and nuclear logs are available in study well-C, only CHFR log was recorded in this well. Hence, a comparison is made between the open hole deep resistivity and cased hole resistivity logs. The cased hole resistivity is a station measurement and the station values have been interpolated to provide a continuous looking resistivity curve for a decent comparison. There is a perfect match between CHFR and open hole resistivity in the shallower gas bearing layers in the interval 1667 – 1718 m. The expected depletion levels have been observed across the perforated intervals 1727 – 1734 m and 1747 – 1750 m, justifying the validity of the cased hole measurement. However, the much higher value of cased hole resistivity observed across the interval 1750 – 1756 m as compared to the open hole resistivity value is a cause for concern and needs an explanation.

Case study A

In this case study, an attempt has been made to explain the importance of ABC services for primary formation evaluation in cased holes, when adverse hole conditions prevented the recording of open hole logs. This is the example of a new well drilled in the

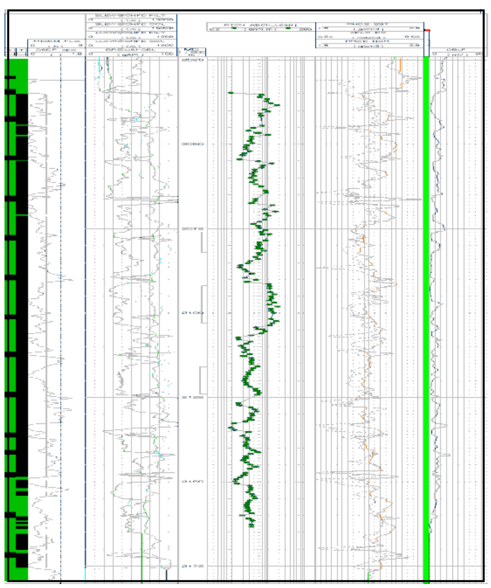

Fig.4 Cased hole logs of study well-A

lime stone reservoir of Mumbai High North field. The reservoir has experienced declining production for several years and extensive redevelopment plans have been initiated in an attempt to reduce and reverse the declining trend. There is however, a significant problem of high water cut that affects oil production and recovery in this field. The plan was designed to accomplish two objectives. The first was to take production in the initial phase from the various sub-layers of the L-III reservoir till the water cut reaches the limiting value, and the second objective was to convert it later into a water injector to provide adequate pressure support to the nearby producers in the area.

The study well was drilled in partial and total mud loss conditions through out the drilled section. The well also experienced severe wash outs while drilling .this reservoir section. A number of LCM pills were placed at different depths but the loss could not be controlled. The alternative was to cement plug and side track the well to acquire necessary well log data in the zone of interest. This is however, an expensive and time-intensive endeavor and there was no guarantee that the hole condition would improve while drilling the side track. It was therefore decided to drill the prognosticated reservoir section, case the well by lowering 7" liner in the 8 ½" hole

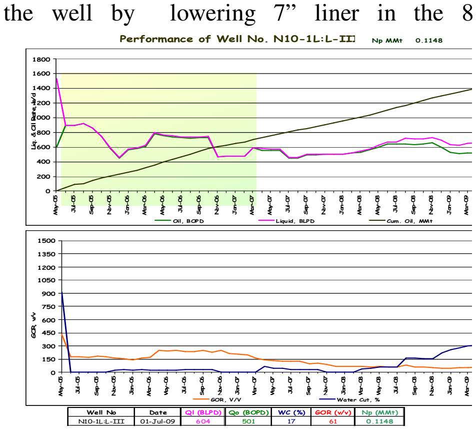

Fig.6 Performance Graph of Study well-A

immediately after drilling, record ABC suite of services and complete the well in potential hydrocarbon layers. The hostile bore hole conditions prevented from recording the open hole logs which is a prerequisite for primary formation evaluation and subsequent completion of the well

Accordingly, cased hole logs were recorded in the interval 2035-2164 m in the year 2005 and the acquired data were used for petrophysical evaluation **(Fig. 5).** A cement bond log was also acquired to aid in the interpretation.

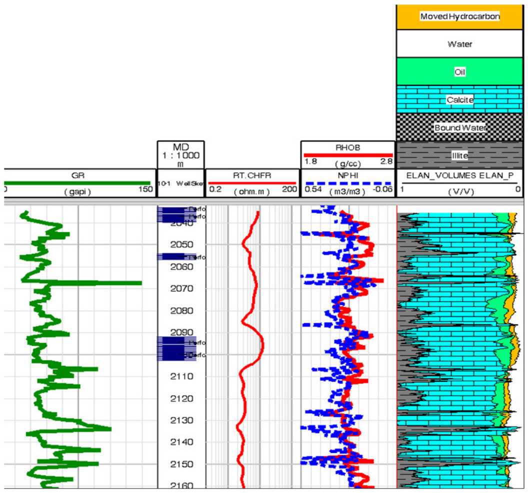

Fig.5 petrophysical evaluation of study well-A

Using the interpretation results, the well was completed as a dual producer with layers A2-VII(2092-2103 m) in LS(Long String) and the layers A2-II(2054 – 2057 m) and A1(2033 – 2040 m) in SS(Short String). The cased hole logs (**Fig.4**) clearly indicated other layers as oil bearing and can be exploited in future. After perforation, the well started producing oil approximately at the rate of 1500 bopd with 10% water cut from both the strings together. The well has cumulatively produced approximately 650790 barrels of oil after perforation. The performance graph is shown in **(Fig. 6)**. The other layers in different intervals have yet to be tested and will be added to the completion when production from the existing layers declines.

Case study B

This example illustrates the ability of the cased hole logs to detect and evaluate bypassed hydrocarbons that existed in the old well. This case study demonstrates the production behavior of an old well drilled in a mature carbonate

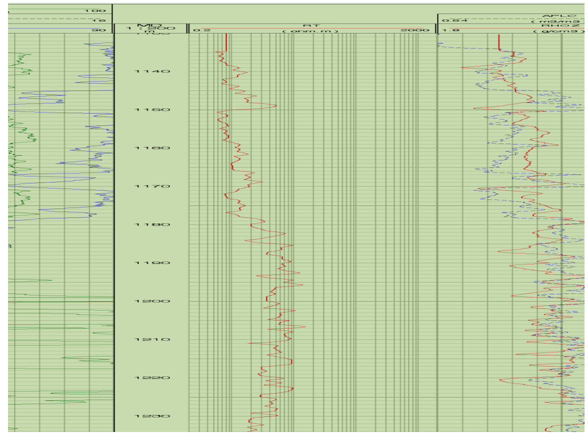

Fig. 7 triple-combo equivalent data acquired through casing in study well-B

reservoir of Mumbai High North field in western offshore, India. The reservoir has a gas cap in the crestal part and a water table in the down flank. The reservoir is divided into six sub-layers and each of these litho units is separated by thin shale bands ranging between 0.5 to 2 m in thickness.

The study well was drilled in the year 1993 on one of the fault blocks in central part of the Mumbai High North field. The structural picture around the well depicts an easterly dipping flank of the main anti-clinal structure, which is dissected by NE-SW and NNW-SSE trending faults. The well falls in gas cap area. The layers falling below the regional GOC are oil bearing. The study well falls in the block from which the production till date corresponds to only 12.04% recovery. This area is having best structural position; pay thickness varies from 30 to 33 m, porosity development more than 25%, and oil saturation 55 to 46%. Reservoir in this part has experienced karsting effect (solution channels and vugs providing conduit for water movement). As a result, some of the producers in the area are flooded with injection water. There is every possibility of bypassed oil in this sector due to preferential movement of water. The water injection wells in this block are taking care of voidage compensation and pressure maintenance. As the study well is inclined and conventionally completed in oil bearing sub-layers, horizontal drain hole drilling is possible in these layers which will improve the production performance of the well.

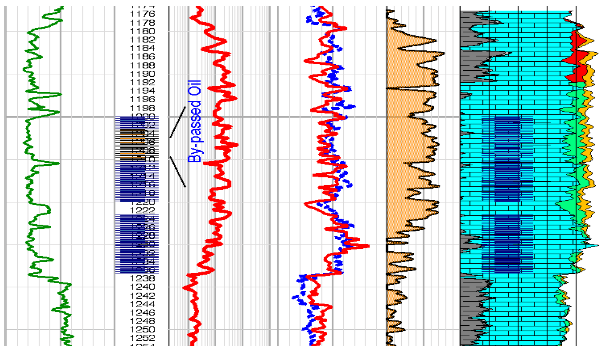

Fig.8 petro physical analysis of CH logs of study well-B

Due to severe mud losses and hostile borehole conditions open hole logs could not be recorded in this well. The well was completed on the basis of cased hole CNL and the open hole logs of nearby wells. To evaluate the potential of various sub-layers of the reservoir, it was decided to acquire log information through casing.

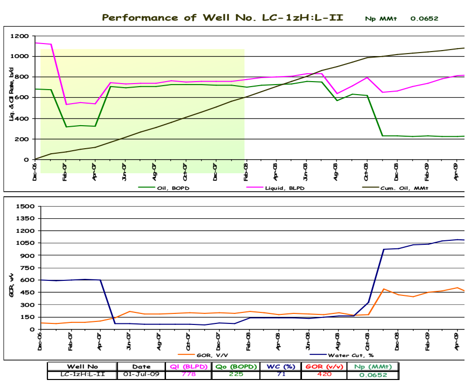

Fig. 9 Performance Graph of study well-B before WOJ

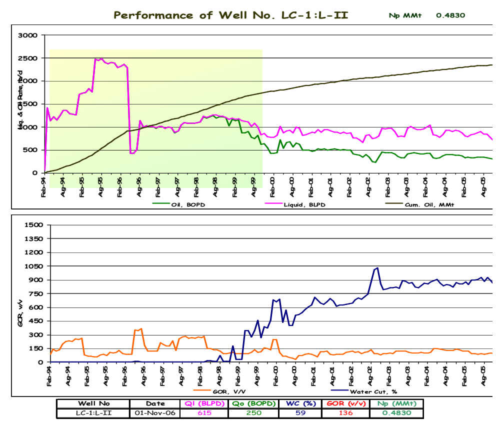

Fig. 10 Performance Graph of study well-B after WOJ

A CHFR log was recorded over the interval 1135 – 1256m to make deep reading formation resistivity through casing and cement. In addition to resistivity, gamma ray, epithermal neutron porosity and cased hole formation density were also recorded in the same interval to provide a means for determining lithology and effective porosity. A cement bond log was also acquired to aid in the interpretation. A basic petro physical analysis was done with this data as shown in (**fig. 8**). **Fig. 7 i**s a plot of the basic triple-combo equivalent data acquired through casing.

The ABC results reveals additional hydrocarbon zones in the interval 1203-1210m which were subsequently exploited by drilling horizontal drain holes using advanced SRDH (Short Radius Drain Hole) technology. Before the work over job, the well was producing oil at the rate of 266 bopd with 62% water cut. The well produced oil at the rate of 706 bopd with 42% water cut after adding the bypassed oil pocket. This attempt has given an impetus to record cased hole logs in other wells with similar results. The performance graphs are shown in **(Fig. 9 & 10)** before and after work over job.

Case study C

This example describes the utility of the cased hole logs to gauge the level of depletion of the producing layers in old well and track changes in saturation, which can greatly assist in efficient monitoring of the reservoir. This case study illustrates the performance

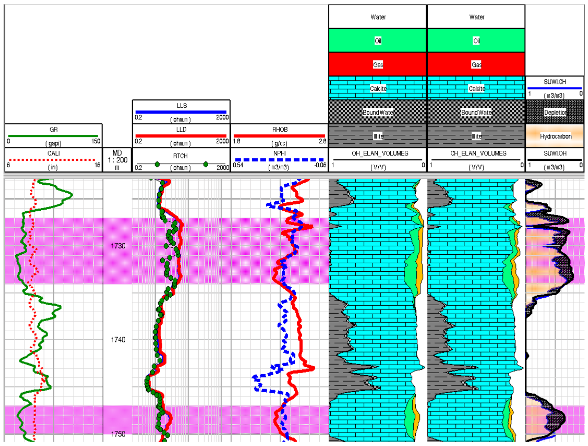

Fig.12 Petro physical analysis of CH logs of study well-C

history of a long time producing well drilled in the L-III reservoir of Mumbai High North field in the year 1994 and completed by lowering 7" liner in 8 ½" hole. The well is located in a structurally high position with most of the upper layers falling in gas cap area and a few lower layers below GOC being oil bearing. The oil bearing zones were conventionally perforated in the

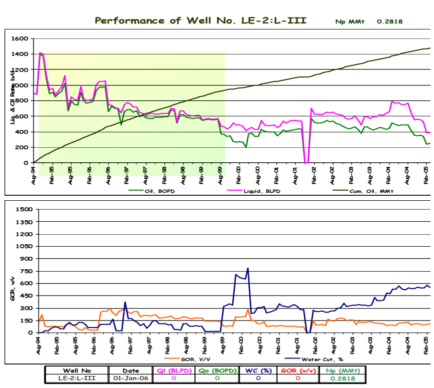

Fig. 13 Performance Graph of study well-C before WOJ

layers C(1727-1734 m) and D(1747 – 1750 m) of L-III reservoir and put on production as a single completion with GLV. Initially, the well flowed oil at the rate of 1230 bopd with 10% water cut and continued to flow with out any change in water cut for a pretty good time. The liquid rate gradually declined to 300 blpd and the water cut increased from 10% to around 40% . In order to improve the production performance of the well it was decided to drill horizontal drain holes in the existing oil bearing layers.

Before drilling the drain holes it was imperative to know the resistivity of the producing zones and to estimate the current water saturation after long period of production and subsequently place the well path in the relatively un-drained part of the producing layers.

Accordingly, the ABC survey was conducted in the interval 1660 – 1760 m. The overlay of the CHFR log with the existing open hole resistivity log has clearly shown that majority of the producible hydrocarbons had not been recovered across the perforated intervals C-layer(1727 – 1734 m) and D-layer(1747 – 1750 m). The perfect match **(Fig. 11)** between the open and cased hole logs in the gas bearing layers above the GOC in the interval 1667 – 1718 m has aided in providing the necessary confidence for the interpretation of the depleted producing pay zones. The analysis of open and cased hole logs has shown slight depletion in C-layer(1727 – 1734 m) and D-layer(1747-1750 m). The shallower gas bearing layers are at their original saturation. The results of the interpretation are shown in F**ig 12**

A basic petrophysical evaluation was performed using the cased hole log data to estimate oil saturation. After detailed analysis of the open and cased hole

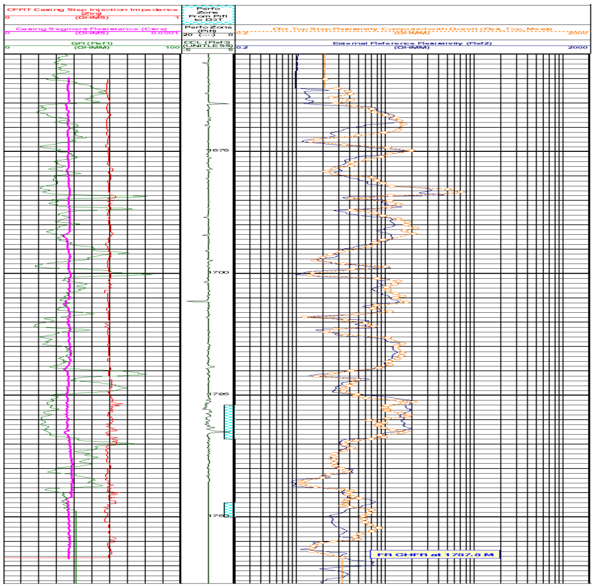

Fig. 11 triple-combo equivalent data acquired through casing in study well-C

logs, a horizontal drain hole of length 209 meters was drilled in D-layer and another drain hole of length 180 meters was drilled in C-layer of the reservoir by using the advanced SRDH technology.

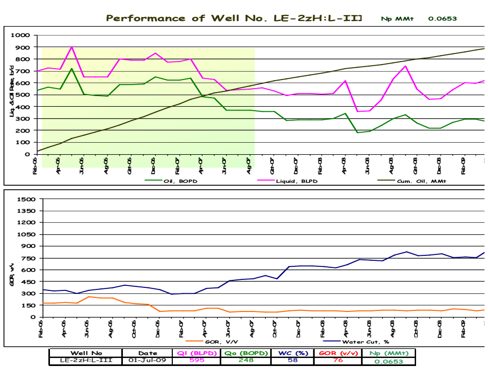

Fig. 14 Performance Graph of study well-C after WOJ

The well was put on production in 2006 and started producing oil at the rate of 630 bopd with 20% water cut. Before work over job, the well was producing oil at the rate of 180 bopd with 40% water cut.

A quick look depletion indicator was developed using CHFR measurement. This indicator is based on Archie's water saturation equation:

$$S_w = \sqrt{\frac{a R_w}{\O^m R_t}}$$

Assuming the formation water salinity remains constant and the only change to the factors in Archie's equation with depletion are S_w and R_t, the CHFR depletion indicator can be computed as follows:

$$CHFR\_Depletion = \sqrt{\frac{R_{CHFR}}{R_{OH}}} = \frac{Sw_{OH}}{Sw_{CHFR}}$$

As depletion occurs, the CHFR depletion indicator should be less than 1. With respect to undisturbed zone, a depleted zone will be identified by a deflection of the depleted indicator curve to the left (towards lower values).

Conclusions

Adverse hole conditions precluded the recording of open hole logs in study well-A. The ABC services provided the needed cased hole data for primary formation evaluation and subsequent completion of the well in potential zones of interest. Analysis Behind Casing provided an excellent means and successfully identified the bypassed hydrocarbons in the study well-B. Data acquisition through casing has provided greater understanding of the depletion level of producing layers and successful exploitation of the un-depleted layers through drilling of horizontal drain holes.in study well-C. It was observed from the analysis of the cased hole data that majority of the producible hydrocarbons had not been recovered across the perforated intervals. Reliable formation evaluation in cased holes helped in significant savings by deciding not to drill side track wells. Petro physical evaluation using cased hole data has helped to make completion decisions on the basis of hydrocarbon saturation for both new and existing wells. The successful completion of study wells in Mumbai High field has prompted to acquire cased hole data in many wells with similar results.

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