RESERVOIR NAVIGATION – FOR ENHANCING RESERVES AND BOOSTING HYDROCARBON PRODUCTION AS A PART OF BROWN FIELD DEVELOPMENT

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ABSTRACT

Shrinking reserves and the increasing complexity of remaining reservoirs has made optimal well positioning more challenging than ever. For brown fields, changes in water saturation, pressure depletion, oil-water contacts (OWC), reservoir drives, gas cap pressure depletion and the proximity of nearby wells make it crucial to place the well in the correct target. Measurements acquired while drilling and the real-time interpretation of these measurements can assist in refining geological models and optimal well positioning, resulting in maximum recovery.

In the process of drilling a borehole,reservoir navigation adjusts the borehole position so it can reach one or more geological targets. The introduction of technology capable of real-time measurements of the distance from the wellbore centre to the formation boundary and the direction usingdeep electromagnetic azimuthal propagation measurements has enabled operators to guide drill bits through longer and more complex well paths. A formation tester in the bottomhole assembly while drilling gives additional advantages of identifying pressure regimes and reservoir connectivity, calibrating the formation pressure gradient and updating the reservoir model.

In the Indian sub-continent this technology could be a key player for exploiting maximum hydrocarbon production from smaller and thin-bed reservoirs, depleted zones and leftover parts of the brown fields such as Mumbai High.

In this paper we present a methodology that integrates data from openhole logs from offset wells, seismic data, and directional data of existing wells to generate a 2D/3D model that can be updated in real time for accurate well placement. In addition, we discuss case histories to show how this approach resulted in improved recovery from brown fields in other parts of the world.

INTRODUCTION

According to the terminology used in the petroleum industry, a brown field is a field where it is difficult to sustain the production with the continued implementation of technologies thatwere available during development of the field. Brownfields frequently are aging fields that have been in production for more than 30 years. Brownfields are still very important as two-thirds of the global oil production comes from these fields (Egypt conference Sep 9 –Sep 10, 2011)Keep in mind that fields beginning productionnow will become brownfieldsin the future.

A few years agobrownfields were considered dying assets, but now with recently available technologies, these fields can become economical and can give good returns on investment to oil companies. With the increase in oil prices and energy demands, it is now a necessity to develop brownfields to sustaineconomic growth. The main challenge is to first identify the potential of the brown field and then quantify it as accurately as possible. In this paper we will concentrate on the mature Mumbai High field (both North and South) and discuss the application of reservoir navigation in this field to exploit the remaining commercial oil-in-place.

MUMBAI HIGH FIELD

Exploration in the Mumbai High field started in the nineteen sixties, and the first oil discovery was made in a limestone reservoir in 1974. Further exploration activities resulted in significant discoveries including oil and gas fields like Heera, Panna, Neelam, Mukta, Ratna, Tapti, etc. In addition, many small or satellite fields have been put on production in the last decade. The Mumbai High field is situated about 165 kmwest-northwest of Mumbai and coversan area of about 1200 square kilometers. Refer to **Figure 1**.

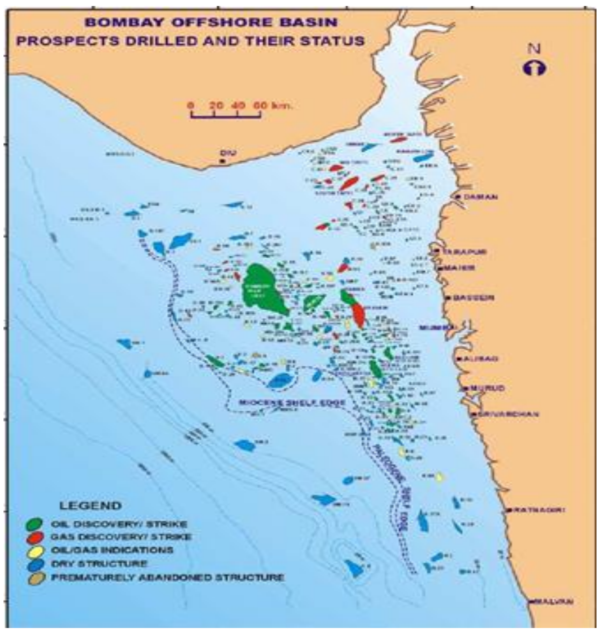


Fig.1. Location map of Mumbai Offshore basin (http://www.scribd.com/doc/36422643/1/GENERAL GEOLOGY OF MUMBAI OFFSHORE)

The structure is a doubly plunging anticline with gently dipping limbs on three sides and a fault on the east side. The fault divides the structure into two parts known as Mumbai High North and Mumbai High South, which are hydrodynamically separated from each other. Oil and gas have been discovered in many reservoirs, of which L2 and L3 are two main lower Miocene limestone reservoirs. The estimated initial oil-in-place (OIIP) in Mumbai High North and South is approximately 1659 MMt. The L3 reservoir is multilayer reservoir with a limestone/shale sequence and holdsalmost 94% of the initial oil-in-place of the entire Mumbai High field. Other hydrocarbon-producing reservoirs are L-I, L-II and S1.The L3 reservoir consists of sixmain reservoir sub-layers named A,B,C,D,E,F and G. The A layer is further subdivided into 10 layers. The average depth of L-III top is about 1350 m below mean sea level. A log showing the L-III layers is seenin**Figure 2**.

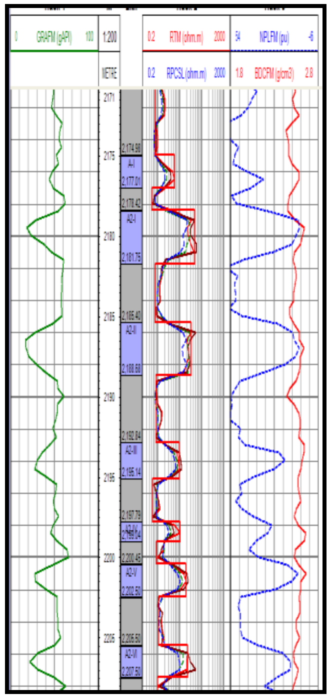


Fig.2. Distribution of L-III layers

The complexity of the sub-layers makes the field a good candidate for reservoir navigation. Over the entire field some shale layers are very thin or pinched out, making it more challenging for effective reservoir navigation to enhance oil production. According to data released by DGH-India and the Ministry of Petroleum and Natural gas, government of India (www.dghindia.org), the oil production was 395,000 bbl per day during 1984-1985 and maintained until theyear 2000. Recently,productionhas dropped to less than 185,000 bbl per day with high GOR and water cut. The Mumbai High re-development programme was launched by ONGC, and a few ERD horizontal and multilateral wells were drilled, initially increasing the oil production. In this paper we will discuss advanced reservoir navigation techniques that can be used for boosting oil production. The well log data used for making the models is not from this field, but a similar field for illustrative purposes only.

RESERVOIR NAVIGATION AND AVAILABLE TECHNOLOGY

All horizontal and/or multilateral well drilling requires proper well planning and room to adjust the path, if required, due to geological or structural uncertainties. The drilling, when incorporated with real-time optimized well placement, becomes reservoir navigation. Reservoir navigationcan be passive, reactive or proactive (as defined at SPE, ATW, St Maxime France,2001). In pro-active or level 3 reservoir navigation, the well path is changed in real time, based on data acquired while drilling, and correlating the data with the model and look-ahead capability for predictingthe formation or formation properties yet to be drilled. There are many case histories, procedures and best practices available in the literature that are published or presented in SPE / SPWLA and other conferences, but this paper will discuss those parts (latest available tools, software modifications) thatare considered to be the most beneficial for L-III reservoir in Mumbai High. In general, reservoir navigation is performedby developing a resistivity model using offset well data, determining the bed boundaries according to resistivity changes including the planned well path and generating a modeled resistivity curve to use in real time. The main problem with this method is thatvariations in the model resistivities are frequently considered to be an indication that the wellbore is approaching an oil-water contact (OWC) or shale roof. This is not always true,especially in the case of the L-III reservoir, because of injection water flooding, porosity/permeability variations and pinch out of L-III sub-layers.

Using thedata available from more than 700 wells, in this paper we suggest use of the latest available techniques for effective reservoir navigation. First, with available petrophysical data we generate a 3D model of the field. We also incorporate core analysis data, permeability andporosity data, dip information and geomechanical model data. With this technique we identify the most productive portions (sweet spots). **Figures 3a and 3b** show respectively the 3D model generated using data from nearby wells in the same field and crosssection along the planned well path incorporating petrophysical data.

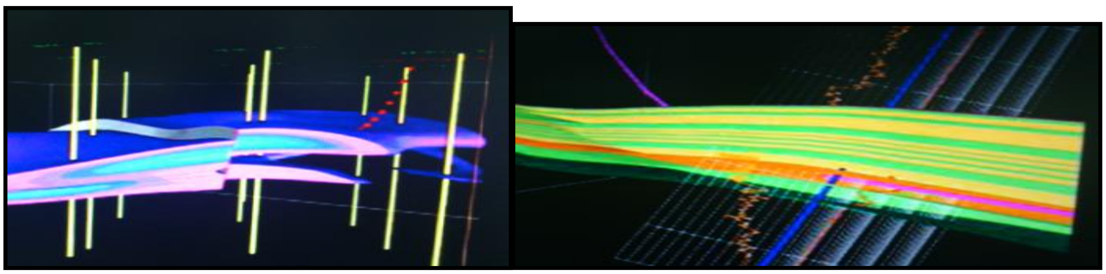


Fig. 3a and 3b. Snapshots of the 3D model and cross section along the planned well path

Next, along with resistivity, gamma, neutron and density tools while drillingwe add modeling of an azimuthal resistivity tool. **Figure 4** shows a 2D plot of a reservoir navigation software model using only propagation resistivity data and the density image for real-time dip picking and integration into the model. Using conventional curves for reservoir navigation has its own limitations. Changes in parameters with respect to depth can be accounted for, but changes along with direction are difficult to capture. It then becomes necessary to have a tool thatcan tell us the direction-to-bedchanges.

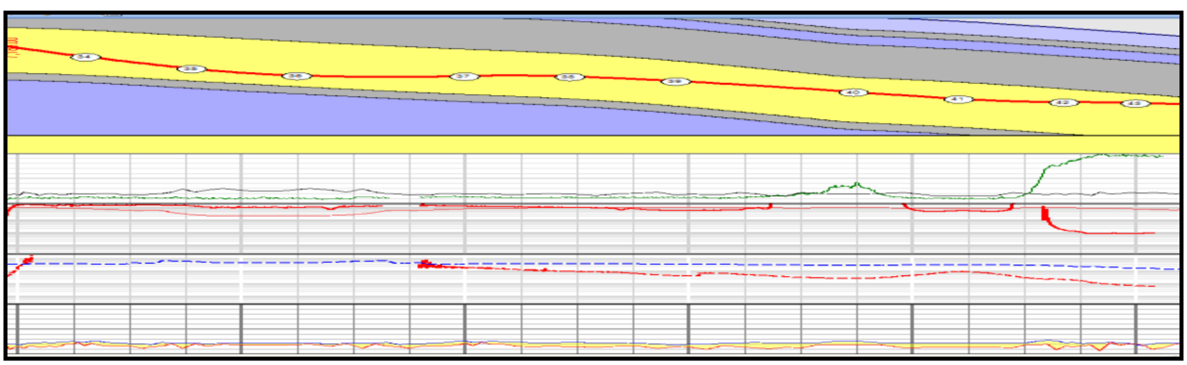


Fig. 4. Example of a 2D crosssection of a reservoir navigation model

The top part of this figure shows the layered, cake-model crosssection of the beds. The next track is for the gamma ray for correlation,and the next two tracks are for modeled and actual resistivity curves. The final track is the density/neutron for reference.

The advantage of using azimuthal resistivity data is it can detect approaching bed direction, and when properly calibrated can give the distance to the bed boundary. This is helpful in the planning stage as well as during drilling. **Figures 5a and 5b** show two scenarios of the well path entering the reservoir and exiting the reservoir.

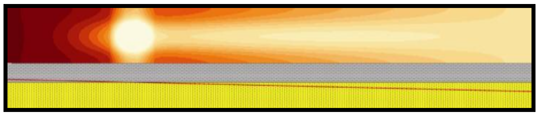


Fig. 5 a. The scenario of a well path entering the reservoir

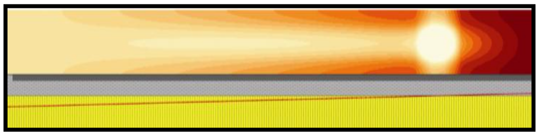


Fig. 5 b. The scenario of a well path exiting the reservoir

Both figures are illustrations showing the advantages of having azimuthal resistivity data available for reservoir navigation. Looking at the images and the patterns enables an understanding of the well path downhole and its relation to the formations. For more information on these images (themes and motifs), refer to the paper titled ‘Geosteering using deep resistivity images from Azimuthal and multiple propagation resistivity’, by W.David Kennedy, Bill Corley, Stephen Painchaud, Giorgio Nardi, Eric Hart, presented in SPWLA, 50th Annual Logging Symposium, June 21 – 24, 2009.Asthe L-III reservoir has many thin limestone shale sequences, this technology will be very useful indeterminingthe distance to the bed boundary, whether approaching a bed or OWC and the azimuth to the beds or contacts to ensure placement in the “sweet spot”.

Finally, theuse of formation testing while drilling is recommended. Formation pressure data in real time can detect if any L-III layers are connected with other layers having the same pressure regime or whether they are dynamically connected. As the Mumbai High field is under water injection, analysis of the pressure data and gradient data can determineif there is any differential sweeping. In addition,the real-time mobility values help indesign and placement of completion equipment.

SUGGESTED METHODOLOGY

Following are steps suggested for the redevelopment of the Mumbai High field in the L-III layer.

Collect the seismic, vertical seismic profile (VSP) and acoustic data from wells in the Mumbai High field and,along with other data,generate the geomechanical model of the entire field. The benefits of this study include drilling optimization, improved drilling BHA design, pore pressure analysis, mud system design, etc.

Update the reservoir model with the latest information related to petrophysical logs, saturations, pressure depletion, expected OWC, production data, water cut, and identify “sweet spots” considering porosity, permeability and saturation.

Integratethe 3D model into well planning and during real-timereservoir navigation. This will clearly define the targets, give better visualization of the planned well path, reduce geological uncertainties, reduce drilling limitations such as dog leg severity and enable planning for contingency well paths.

The recommended drilling BHA would have the following minimum LWD toolsuite: propagation resistivity, gamma ray, neutron, density and caliper. In addition, for distance-to-bed and directional guidance the azimuthal resistivity tool would be highly recommended as discussed previously. Also recommended area resistivity imaging service for detailed formation dip information, a formation tester while-drilling tool for formation connectivity and dynamic pressure effects, an acoustic while-drilling tool if there are seismic uncertainties in upper hole sections requiring synthetic seismic ties,and modeling software capable of real-time dip picking, distance-to-bed boundary calculation and anisotropy modeling.

The completion equipment and placement according to the well path can be optimally planned with this information.

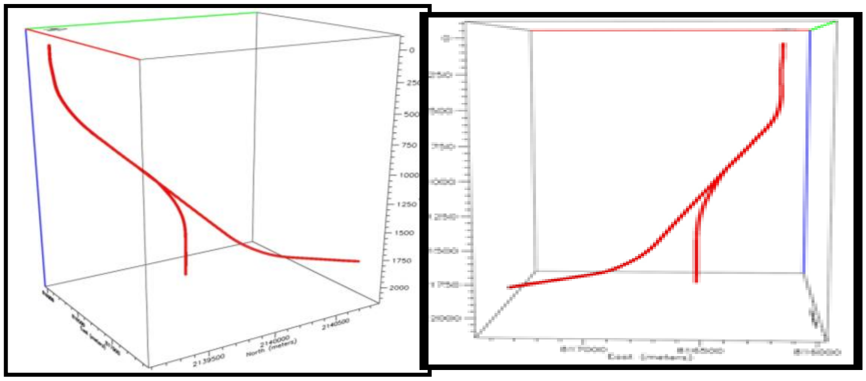
For drilling horizontal or lateral sections, it is also recommended to use automated rotary closed-loop drilling systems. This system has a proven record in India for drilling horizontal and lateral wells in demanding environments with high performance in terms of precision/ efficiency/ TVD control/ reliability and tortuosity.

The closed-loop system permits well path changes on the fly without interrupting the drilling process. It also helps to keep the borehole smooth with minimum tortuosity.

CASE STUDY

Offset Well

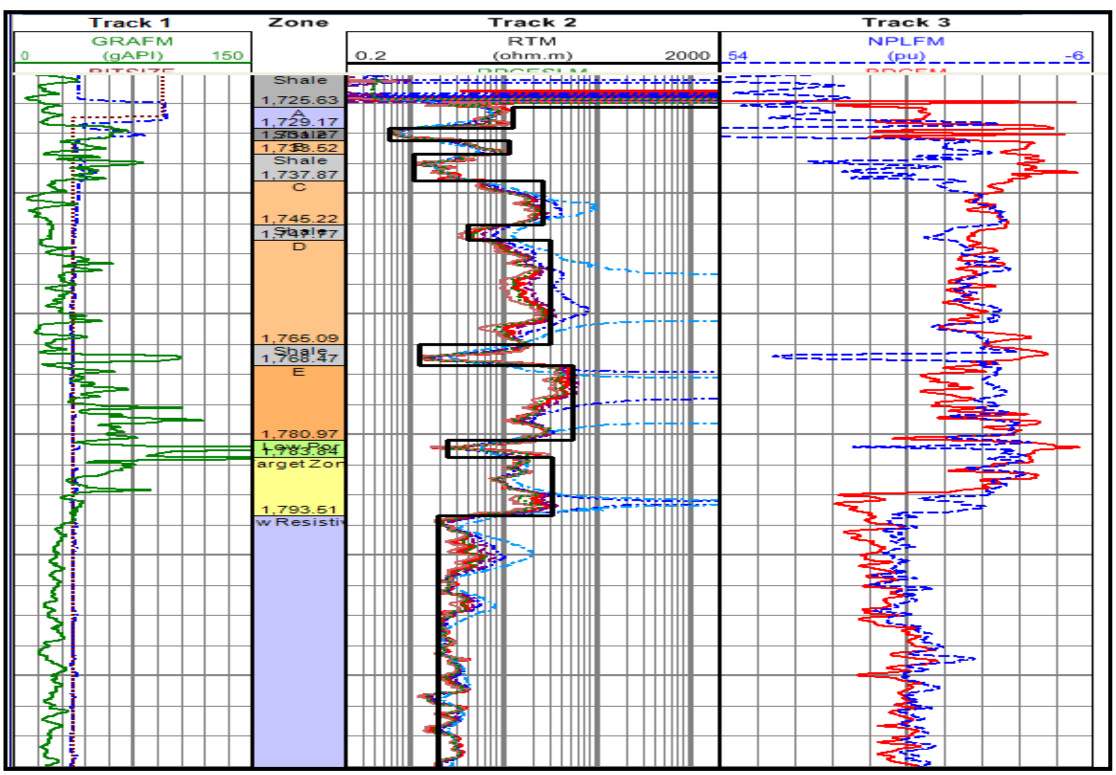
The well selected for a case study is in an area thathas similar formations to Mumbai High. The selected reservoir has a thin oil column overlain by a large gas cap and underlain by a large aquifer. This results in the reservoir beingconing dominated by gas and water. Because of this structure, the best option is to increase the drainage area of the oil by drilling horizontal and/or multilateral wells.The selected reservoir is divided into two zones: X and Y. Zone X has porosity ranging from 6 to 20 percent and zone Y has porosity ranging from20 to 25 percent. The zones are separated by a tight limestone and shale section, which separates zone X from zone Y. The predominant interest is in zone Y, which has a 5 to 15m thick gas cap. The oil thickness is about 5 to 10m with an oil-water contact below. The plan was to drill a 17½-in. hole section with a standard motor BHA, then drill a 12¼-in.hole section with a rotary steerable BHA as a pilot hole and land a 9⅝-in. casing on top of zone X. Then an 8½-in. pilot hole would be drilled vertically covering both zones X and Yuntil reaching the top of the basement. After drilling the formations and logging to obtain the exact depths of the zones, the well would be abandoned and the 9⅝-in. casing retrieved. The well would then be sidetracked just below the 13⅜-in. casing shoe and the 12¼-in.hole section drilled until encountering the top of zone X. Then land the well in the 8½-in.holesection 5m below the gas-oil contact in zone Y. Zone Y would be drilled with a rotary steerable assembly with gamma-resistivity-density-neutron LWD tools in the BHA. The planned horizontal section is about 500m. **Figures 6a** and **6b** show the planned well paths for the pilot well and horizontal well.



Figs. 6a and Fig 6b. Well path plans for the pilot and horizontal wells

The Work Flow

First,all log and survey data of the pilot holewere collected. This pilot hole data was used as an offset well to build the geological and reservoir navigation model. The resistivity from the pilot hole was used to generate a squared resistivity curve, mark the different beds or zones and to generate a resistivity profile.**Figure 7**shows the pilot hole (offset well) beds and resistivity curves across those beds. The gamma ray and neutron/density log data are plotted for reference.



F**ig: 7.** Log of offset well with bed markers

With available survey data, relative dips and planned survey data, model resistivity curves were generated across the planned well path. This model was then sent to the Geology &Geophysics (G&G) group for feedback. A second model was made including structural data from the seismic database. The resultant model for reservoir navigation is shown in **Figure 8.**

Fig. 8. Crosssection of the model in 2D

The planned well path and crosssection of beds is seen in the top part. The second track is the gamma ray from the offset well, the third track shows the forward-modeled resistivity curves and the density/neutron logs are seen in the fourth track for reference.

A well was drilled according to this plan. The first correlation was performedat the top of the first zone, and it indicated the planned well path was shallow by 1.5 m in true vertical depth (TVD) to the target zone. The parameters were changed and a downlink was sent to the rotary steerable tool to land the well in the target zone. Once the depths and correlation were confirmed after landing the well, drilling continued until the expected 500m of horizontal section was completed. The model was updated at every stand of drillpipe and the distance-to-bed boundary was monitored. Continued drilling and were able to drill 300m more than what was planned, client decided to stop drilling due to hole-cleaning issues.

Figure 9 shows the reservoir navigation working window approaching the target zone. The top part of the model is cross section and well path. Below that, two tracks of azimuthal gamma ray and density images are added. Out of these two images, the azimuthal gamma ray image shows better bed boundaries and is used for dip calculation to enter into the model. The dips from these images were entered into the model from time to time.

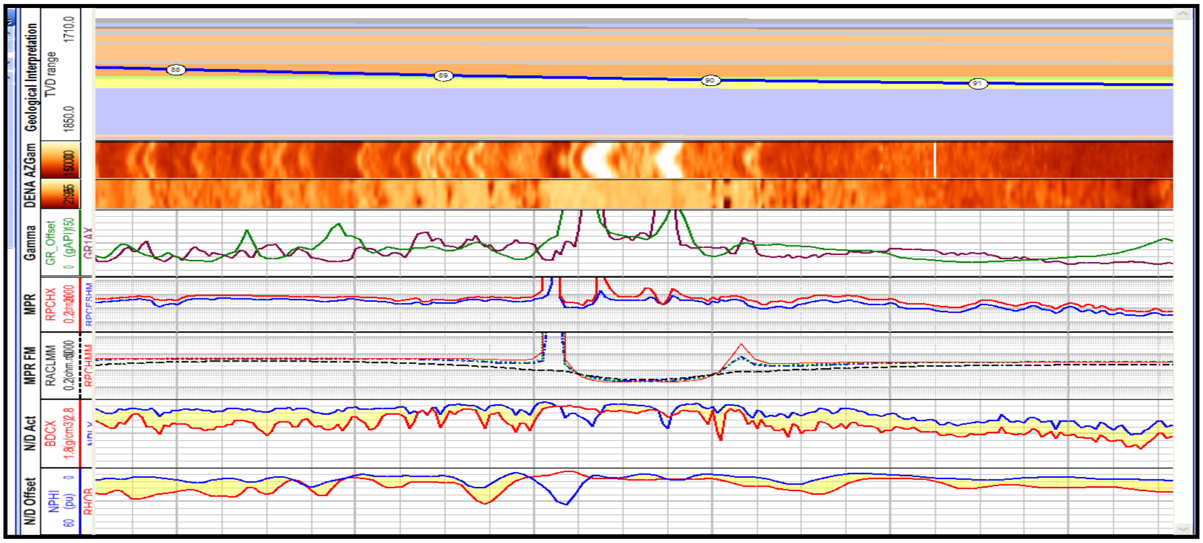


Fig. 9. The figure shows the details of the reservoir navigation working model for the reference well

The data were updated with every stand. Gamma ray and resistivity, tracks show the comparison and correlation of modeled curves and actual curves. The bottom two tracks of actual and modeled density – neutron are added for cross reference. The gamma ray image has given better understanding of the interaction of well path at the top of target zone, giving two bright zones that confirm the accuracy of the model and give confidence for landing the well.

Figure 10 shows the same working model after landing the well near the planned horizontal target depth. Good correlation is found between the modeled and actual curves. The client decided to continue drilling. Gamma ray and density images helped to confirm that we are drilling in the planned TVD tolerance keeping the well always in the sweet zone. After drilling 300m further the model was reviewed and found to be well, but due to hole-cleaning issues and proximity of nearby wells, the client decided to stop drilling.

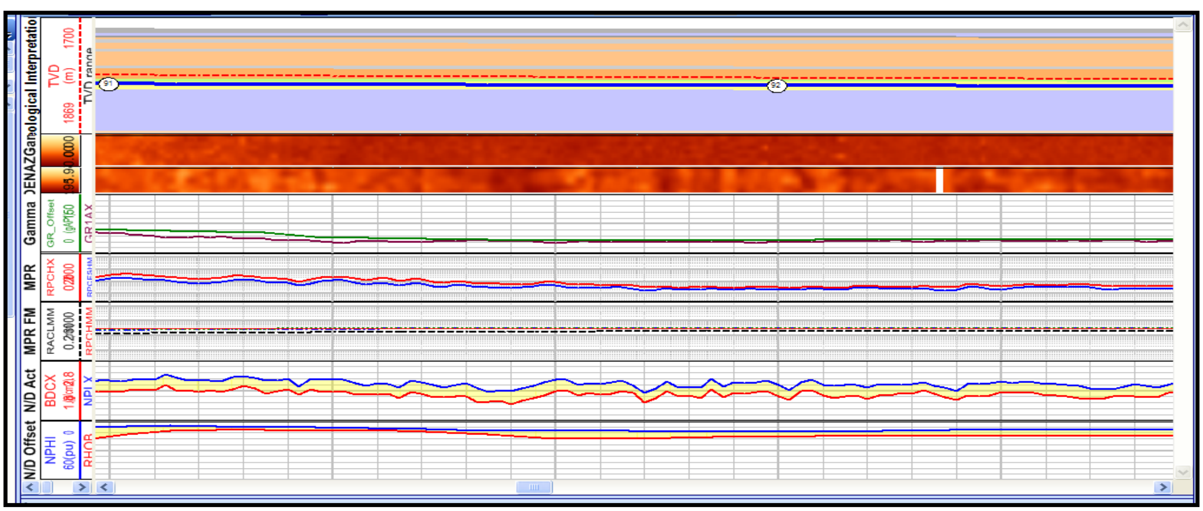


Fig.10. The details of the horizontal section.

RECOMMENDATIONS

Use a rotary steerable drilling system to drill smooth wellbores when drilling horizontal or lateral wells.

Ensure good communications between the reservoir navigation crew, the G&G group, the drilling crew and the LWD/MWD engineers to collaborativelydrill the well in the target zone and obtainmaximum reservoir exposure.

If the azimuthal resistivity tool is not used, then obtain maximum benefits from azimuthal density and azimuthal gamma ray images for detecting bed boundaries and calculating dips.

Though the resistivity tool gives a warning about approaching bed boundaries, it does not provide information regarding the direction.Therefore, it is beneficial to use the azimuthal resistivity tool in the BHA for this purpose. It should be placed as close to the bit as possible for the maximum directional and distance-to-bed benefit.

Make use of more than one offset well if data areavailable for the modeling, planning and real-time structural validation.

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