Reducing Reservoir Model Uncertainties with Real-Time Fluid Contact Mapping Using Extra-Deep Azimuthal Resistivity - Case Study From a Mature Oilfield, Offshore China

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Abstract

Oil field A is currently operated by CNOOC in Shenzhen area, southeastern China. Up to the present date, there are over 30 directional and horizontal wells drilled with conventional tools for sustaining production, which has been on-going for over 13 years. Early 2022, production reached approximately 45% recovery, and 95% average water cut. After a multi-disciplinary study of by-passed oil distribution, the residual oil is believed to be located as a very thin oil column at the structure top or trapped within thin beds of the highly heterogeneous formation. As the field becomes more mature, it is essential to accurately identify the dynamic oil-water interface, optimizing the stand-off and maintaining the wellbore position within 1-2 m of the roof of the reservoir.

Previous wells utilized deep azimuthal resistivity technology that supported accurate and informed reservoir navigation decisions. The real-time decision-making process in these wells greatly depended on the quantification of distance between the wellbore and nearby layers based on the resistivity contrast. With the presence of intra-shale layers, the interpretation is limited to the mapping of the reservoir top and the intra-shale layer. Aiming to solve these challenges, the extra-deep azimuthal resistivity technology, associated with automated inversion processing, was introduced to the latest planned horizontal well in the field.

The deployment of this technology was a significant milestone for the A field. Using the new approach, CNOOC accomplished all reservoir navigation objectives. During real-time operations, an instantaneous distance-to-boundary calculation, using shallow and deep resistivity measurements, was provided with detection ranging up to 4.5 mTVD. Based on which, timely steering decisions were made to maintain the well within a 1-meter-thick sand lobe. Also, the automated inversion processing used all shallow, deep, and extra-deep resistivity measurements to delineate resistivity-based earth models along the wellbore up to 20 mTVD around the wellbore. This supported seamless mapping of the reservoir top, a near-by intra-shale layer, and the oil-water contact, approximately 10 mTVD below the wellbore. The interpretation of all reservoir layers, including the remote fluid contact was further assessed with real-time statistical uncertainty analysis. The inversion results, being displayed with its confidence range.

As the first deployment of extra-deep resistivity technology in the field, this success brought more insights to help CNOOC calibrate their understanding of the reservoir heterogeneity, as well as the dynamic oil-water contact. Eventually, uncertainties in reservoir model can be further reduced to optimize the planning of future wells within the field.

Introduction

The A field is a mature oilfield located in the South China Sea, Shenzhen area (Figure 1). The target block is located in the western side of Huizhou depression, Pearl River Mouth basin, which was discovered in 2003 and is one of the major oil and gas projects that has been developed since 2008. The field is commercially operated CCLS Operation Group, China Offshore Oil Company. In early 2022, the field production reached approximately 45% recovery, and 95% average water cut. Therefore, it is crucial to understand the dynamic oil water contact (OWC) within the reservoir while maintaining the production wells at the upper most reservoir layer with thickness ranging from 1.2 to 2.6m. The presence of several intra-shale layers added significant challenges to the mapping of fluid contact at approximately 10m below the well bore.

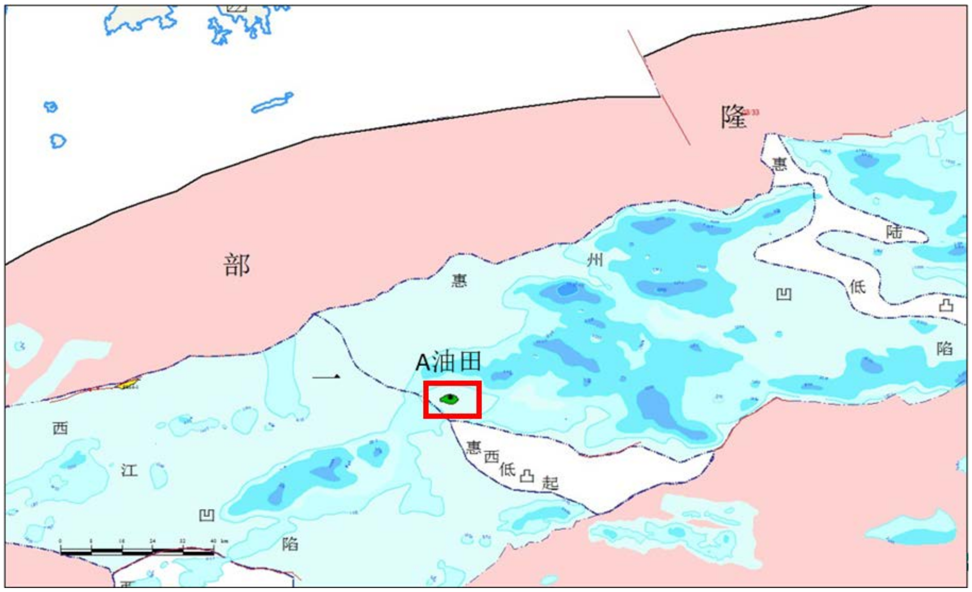

Figure 1 – The A field, located in Pearl River Mouth basin, China.

Well Background, Objectives and Challenges

Well Background

In order to increase well life and optimize the oil production, the horizontal production well was planned to drill within the upper most layer of the target formation. The reservoir is a relatively clean sand with gross thickness ranges from 30m to 40m. As the field has been producing for over 13 years, the oil-water-contact has moved significantly within the sand, leaving a thin oil column of approximately 10m. While the most part of the formation represent clean sand characteristics, the upper interval where the remaining oil is trapped shows a relatively heterogeneous behavior. From the offset well data, there are a tight layer with inconsistent resistivity signature, and 1 or 2 intra-shale layers of 0.5m – 1m thickness.

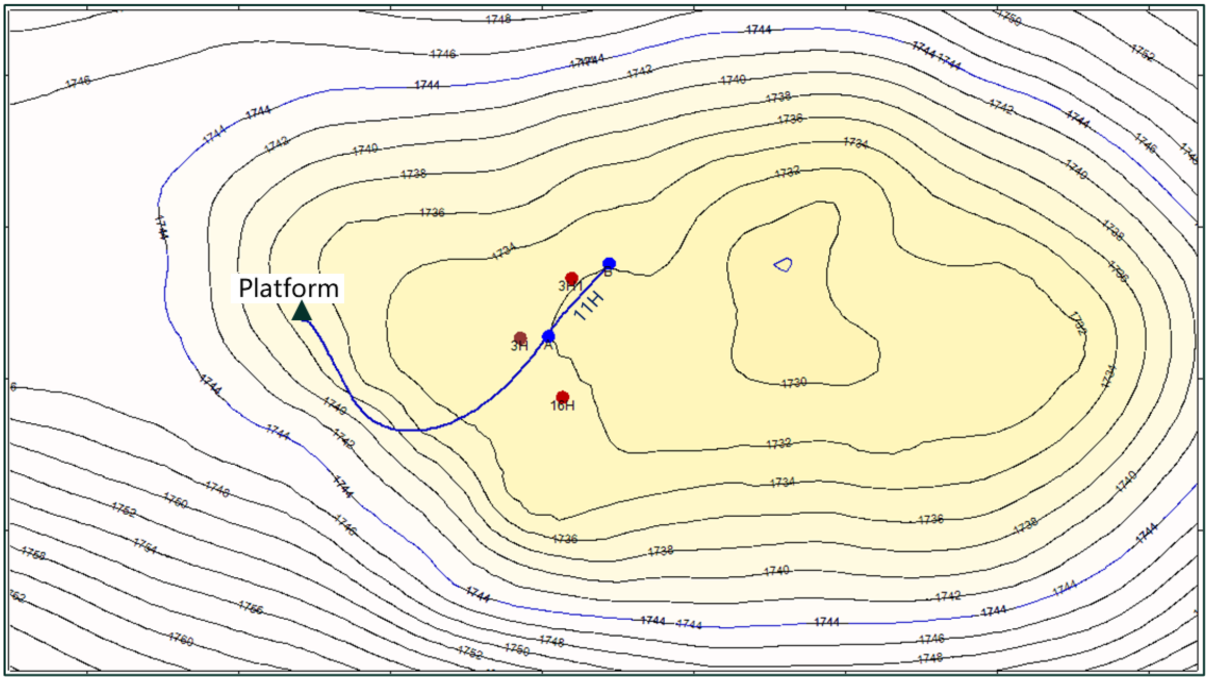

Figure 2– This horizontal oil producer is proposed as a bottom water reservoir, the average oil column thickness is about 6.8~12m in a heterogeneous formation.

The well was planned to drill 8.5" lateral section with 280m drainage hole near to the reservoir top (Figure 2). The intra-shale layers seem to be varying from one offset well to another, in both thickness and resistivity contrast. The average resistivity value across the thin shales is approximately 6 Ohmm, while the sand resistivity is measured from 12 to 26 Ohmm. This represents a relatively low sand/shale resistivity contrast ratio between 2:1 and 4:1, which is marginal to the detection limit of any extra-deep resistivity tool.

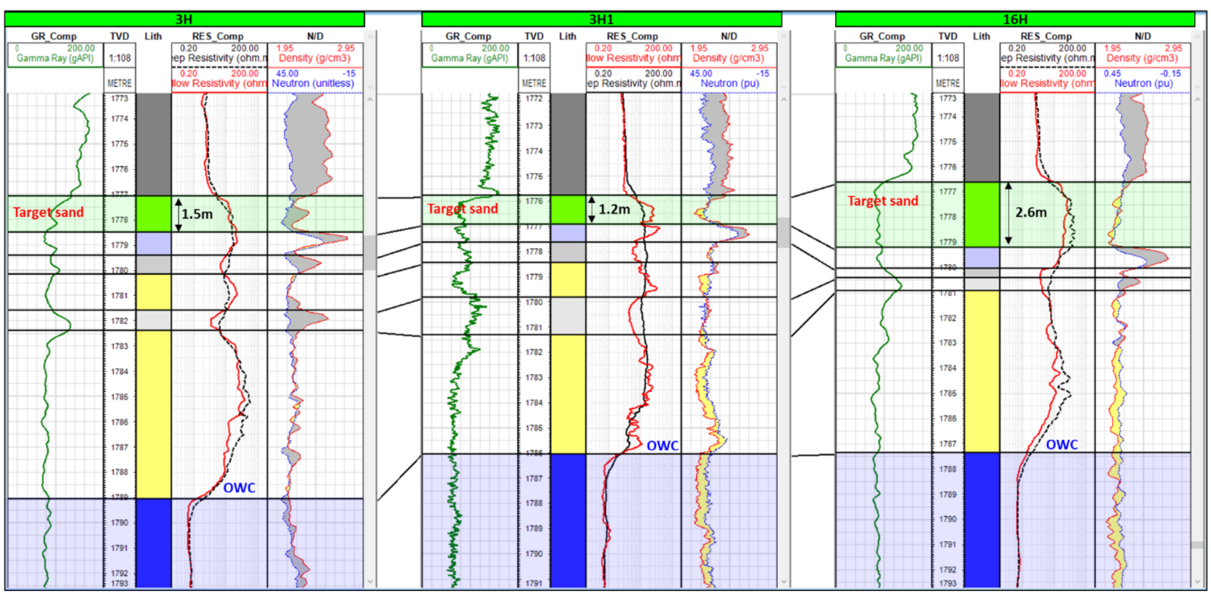

Figure 3 – Offset well correlations. From left to right of each well: GR (green), deep (black) & shallow (red) resistivity, density (red) and neutron (blue). The correlation shows target sand layer thickness ranges from 1.2 to 2.6m.

Objectives and Challenges

From the thorough geological assessment, CNOOC sub-surface team has identified the 3 main challenges to overcome and the key factors to ensure the well objectives are met:

- The placement of the horizontal section in the upper most sand layer of 1.2m – 2.6m thickness without exiting through the roof is essential to achieve sufficient sand exposure, save operation time, and maximize reserve recovery.
- Offset data indicates inconsistent presence of intra-shale layers near to the top of the reservoir. The geometry and petrophysical properties of these layers may vary laterally. It is important to be able to map the position of these layers along the well path to understand the local reservoir characteristics.
- The OWC is predicted to be approximately 10m away from the planned well position. The contact might not be consistently flat throughout and its actual depth can vary. A conventional logging-while-drilling (LWD) suite is unable to provide information on the remote fluid contact. Therefore, a more advanced tool with deeper depth of detection is needed to provide more insights, solving the fluid contact uncertainty problem.

Methodology

Prior to drilling the well, the service provider carried out a detailed reservoir navigation feasibility, using the latest reservoir model. This aims to provide a clear visualization of how the well would be drilled, and how the reservoir navigation tools could help to overcome the challenges and achieve the ultimate well objectives. From the results, it was apparent that the extra-deep azimuthal resistivity (EDAR) logging-while-drilling technology is suitable to provide mapping of the remote OWC. EDAR technology is not new to the industry, the explanation of downhole measurement system and examples of its applications can be found in earlier studies (Hartmann et al. (2014), Sviridov et al., (2019), Nguyen et al. (2022)). The EDAR service is combined with advanced multi-layer inversion processing to deliver a resistivity-based geological model along the well path, enhancing subsurface understanding (Fig. 4 EDAR, resistivity boundary detection tool). Within the tool's detection range, resistivity boundaries with sufficient contrast can be detected and mapped by the inversion. These boundaries can be oil-water-contact, reservoir top/bottom, or reservoir intra-layers.

A high-performance bottom-hole-assembly would not be completed without an advanced rotary steerable drilling system (RSS). RSS is an essential factor in oil and gas exploitation and the technology is constantly upgraded over the years (Li et al., 2020). In this project, the selected RSS has 3 precision-controlled pads to maintain a continuous proportional steering vector. This allows a high build-up rate up to 12^0 / 30.5 m, which can handle the most complex 3D well trajectories while ensuring optimal borehole quality and directional control. The tool's orientation is checked every millisecond, and steer forces are automatically adjusted, enabling precise control of well path within the ultra-thin reservoir target.

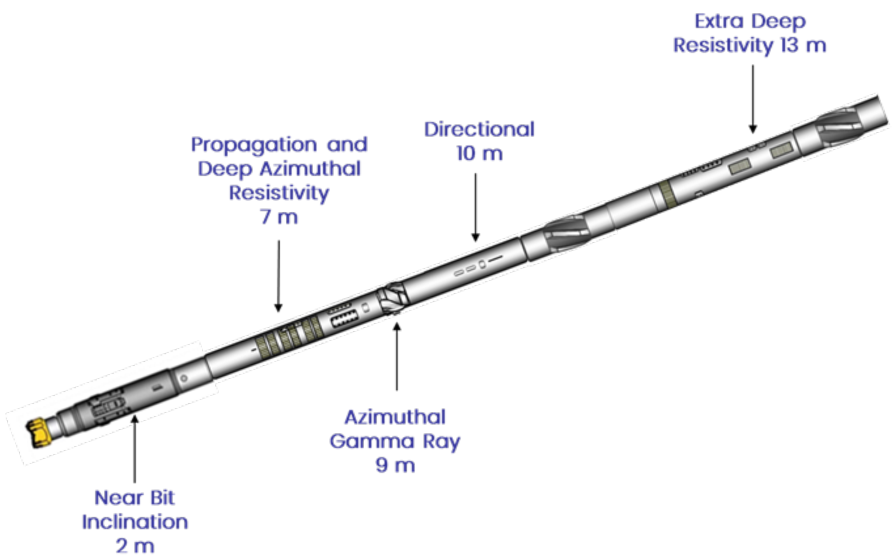

Figure 4 – Extra-deep resistivity boundary detection tool and measurements offset.

Automated Multi-Layer Resistivity Inversion

As the fit-for-purpose tool selection plays an essential role in collecting comprehensive petrophysical data, the processing and interpretation of the data is no less important. With the EDAR tool's depth of detection reaching up to tens of meters away from the wellbore, there are many details of the formation structure to be recorded. The combination of shallow and deep measurements is commonly too complex to be deciphered by human. This leads to the deployment of the real-time advanced data inversion processing to provide insights behind the logs. There are different approaches on inversion processing technique. In this case study, the data have been processed in real-time using a gradient-based local search approach.

The real-time reservoir navigation software, with built-in inversion processing module, allows a wide range of input parameters settings to be set (Sviridov et al., 2019). As there are various reservoir types with greatly different geometrical and petrophysical properties, such approach aims to provide the engineer flexibility in customizing the inversion workflows inputs for better efficiency. One of the important advantages of such approach is the ability to test out multiple geological scenarios and quicker processing time compared to a stochastic approach.

Flexible implementation of the software allows running several inversion workflows with different strategies. A common processing setup includes a combination of 2 inversion workflow groups: light-processing with constrained input parameters, and heavy-processing with wide range of input parameters (Figure 5). The goal of a gradient-based inversion approach is to search for the model that delivers the lowest data misfit. Most of the inversion workflows were developed with the algorithm to reduce the number of layers to find the simplest model with acceptable data match. The option to remove simplification process in inversion is available in the heavy-processing workflows to efficiently resolve and maintain the small details of complicated geological scenarios.

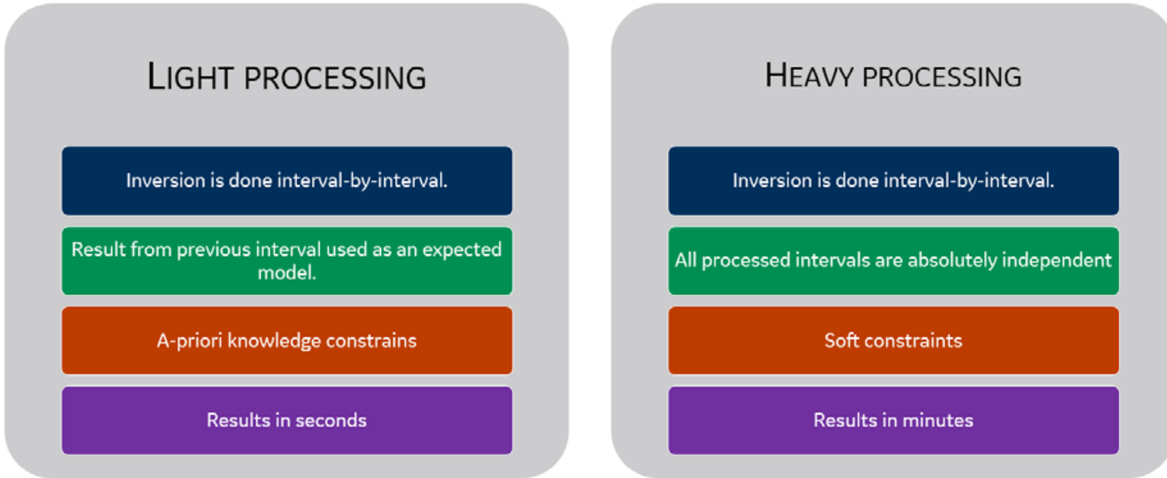

Figure 5 – Deterministic inversion workflows are divided into two main groups.

As the well was planned to be drilled within the upper most layer, the tool's measurements would be traveling through the possible intra-shale layers before reaching the OWC at 10m away. A heavy-processing workflow without model simplification process was set up to efficiently resolve the thin shale layer while mapping both the reservoir top and water zone. Inversion interval was set at 1m with data overlap of 4m ahead and behind. This means that, in total 9m of data is taken into the processing at a time and the resulted model is displayed at 1m interval.

The primary method to evaluate the inversion model is to look at Misfit level. Misfit represents the degree of matching between the inversion result (or earth model) and the log data over a specific interval (Figure 6). High misfit means a poor match and the inversion result might not reflect the true geological scenario. Since misfit is a mathematical calculation, it depends greatly on the real-time log quality, and there can be more than 1 result with same misfit value, equivalence. It is not uncommon that an inversion result with misfit of 0.5 does not deliver a sensible geological interpretation, whereas another result with misfit of 2 matches better with the understanding of the geology. This happens when both of the results are not the true solution, but the one with higher misfit value is closer to true. The one with lower misfit in this example can be referred to as an equivalent model to the true solution. In case of poor real-time log quality, it can be challenging to obtain a good match across all the curves, resulting in higher overall misfit.

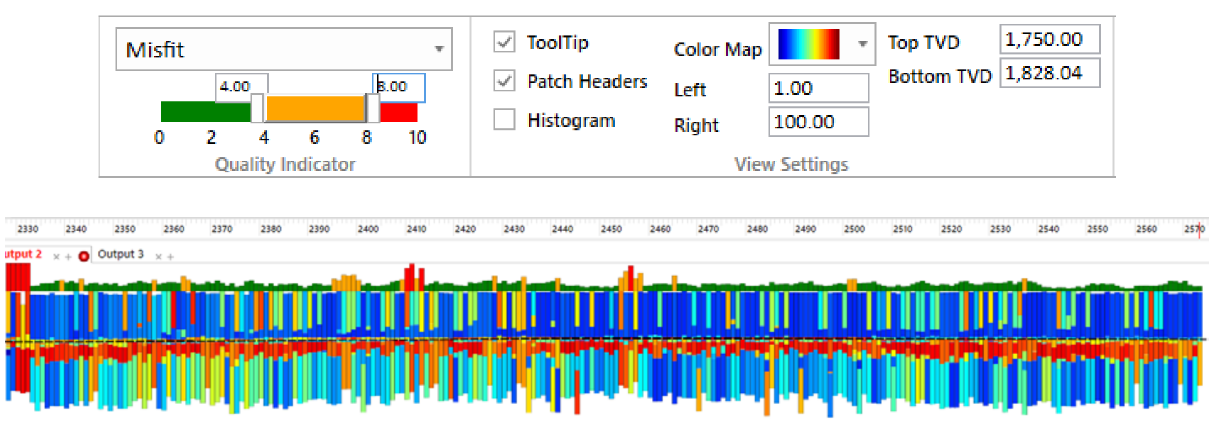

Figure 6 – Color-coded misfit & inversion results. On the top left is the misfit color setting: green = good fit, orange = moderate, red = poor fit; on the top right is the inversion color palette and TVD range. Misfit of each inversion result is shown above the inversion output.

In real-time, the conventional triple combo was used, incorporated with the deep azimuthal resistivity (DAR) measurements to provide highly accurate proactive steering decisions, maintaining the well within the ultra-thin target sand layer. A total of 11 decisions were made along the 280 mMD section, achieving optimal reservoir exposure. Close to TD, the well entered the shale roof due to the decision to hold well inclination at 89.70 and maintain TVD for better production. Inversion mapped the varying sand thickness between 0.8 m to 2.2 m along the well path. The inversion results also indicate a 4.5 Ohmm intra-shale layer below the well with average thickness of 1 m. The entire oil column from reservoir top down to OWC was mapped by inversion from the beginning of the section until well TD. It was clear from inversion that the OWC is not a perfectly flat layer. The distance of the water zone to well bore varies along the well path. Furthest distance is up to 12 m away, observed at the section's heel and toe. In the middle part of the well, OWC is likely to be shallower, as close as 6 m below the well bore. All the objectives of the well have been met, thanks to the thorough pre-well study and the right selection of tool suite.

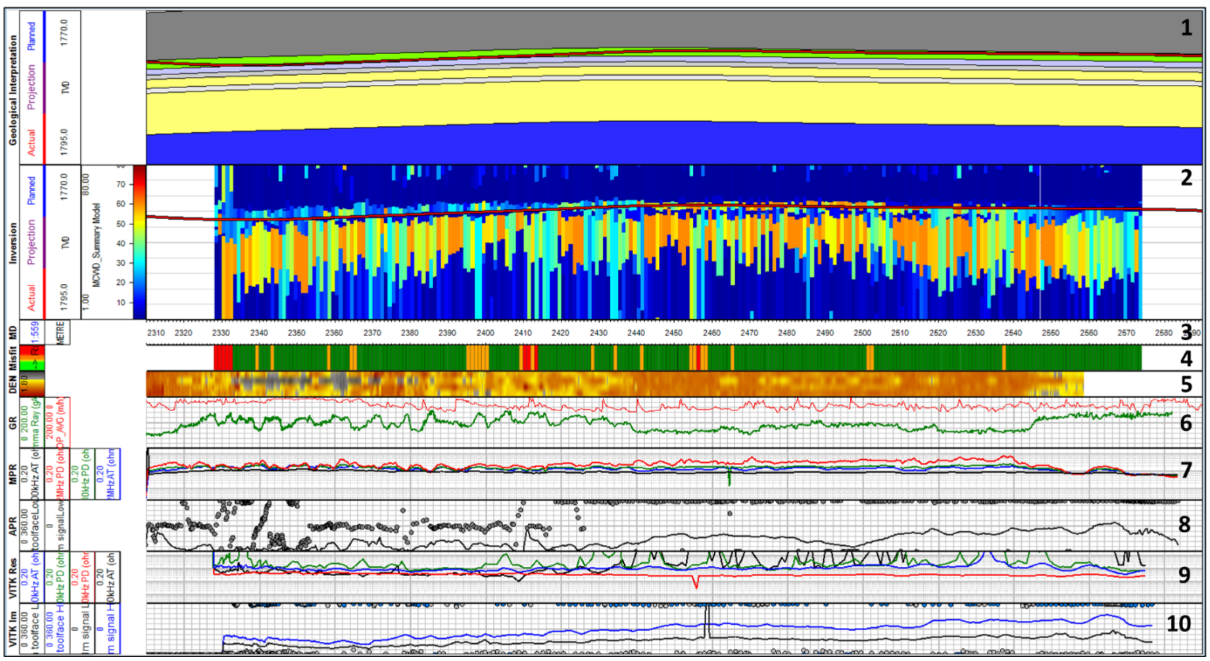

Figure 7 – Real-time reservoir navigation display. Log tracks description: 1. Geological Interpretation track showing actual well path (red) position within the target formation, 2. Inversion output clearly maps the target thin layer, an intra-shale below and the dynamic bottom water, 3. Measured depth track, 4. Inversion quality QC – misfit, 5. Density quadrant image, 6. GR and ROP, 7. Multi-propagation resistivity curves, 8. Deep azimuthal signal strength and target direction from DAR tool. 9. Bulk resistivity from EDAR tool, 10. Extra-deep azimuthal signal strength and target direction from EDAR tool.

Real-time Depth of Detection and Confidence Analysis

For real-time evaluation of inversion results, apart from the misfit indication, the estimation of the EDAR tool's depth of detection (DOD) is as important to understand the confidence level of near and far boundaries being mapped. With the BHA design in this case study, the measurements available for inversion processing are:

1. Multipropagation bulk resistivity: 2MHz phase and attenuation resistivity, 400kHz phase and attenuation resistivity.
2. Deep azimuthal signal: 2MHz signal strength and target direction, 400kHz signal strength and target direction.

3. Extra-deep bulk resistivity: 50kHz phase and attenuation resistivity, 20kHz phase and attenuation resistivity.
4. Extra-deep azimuthal signal: 50kHz signal strength and target direction, 20kHz signal strength and target direction.

Variable DOD range can be estimated using different subsets of the measurements mentioned above. The confidence of boundaries resolved from inversion generally decreases with increasing DOD. This is due to the fact that the near-wellbore boundaries can be sensed by more measurements compared to the far ones. The table below outlined 3 different DOD delivered by the software and the measurements used for each of them.

	Name	Measurement used for DOD calculation
DOD curve 1 (Black)	Optimistic/Far	20kHz phase and attenuation extra-deep bulk resistivity
DOD curve 2 (Red)	Intermediate/Mid	All measurements from EDAR
DOD curve 3 (Green)	Realistic/Near	All the resistivity measurements

Table 1-DOD curves nomenclature.

Based on the 3 basic range of EDAR DOD, an additional statistical confidence analysis was run on the real-time deterministic inversion results. The analysis takes into account a preset number of intermediate inversion models, for example: 1000, 2000, 5000 models, etc. The main goal is to compliment the deterministic inversion result, which displays only the model with lowest misfit, with the understanding of other models being processed. As a result, a P50 visualization is delivered, providing insights on the most popular geological scenarios, some of which might not be shown in the deterministic results (Track 2, Figure 8). The DOD calculation clearly shows that the OWC is within the tool realistic detection range, which means high confidence level can be applied to this interpretation.

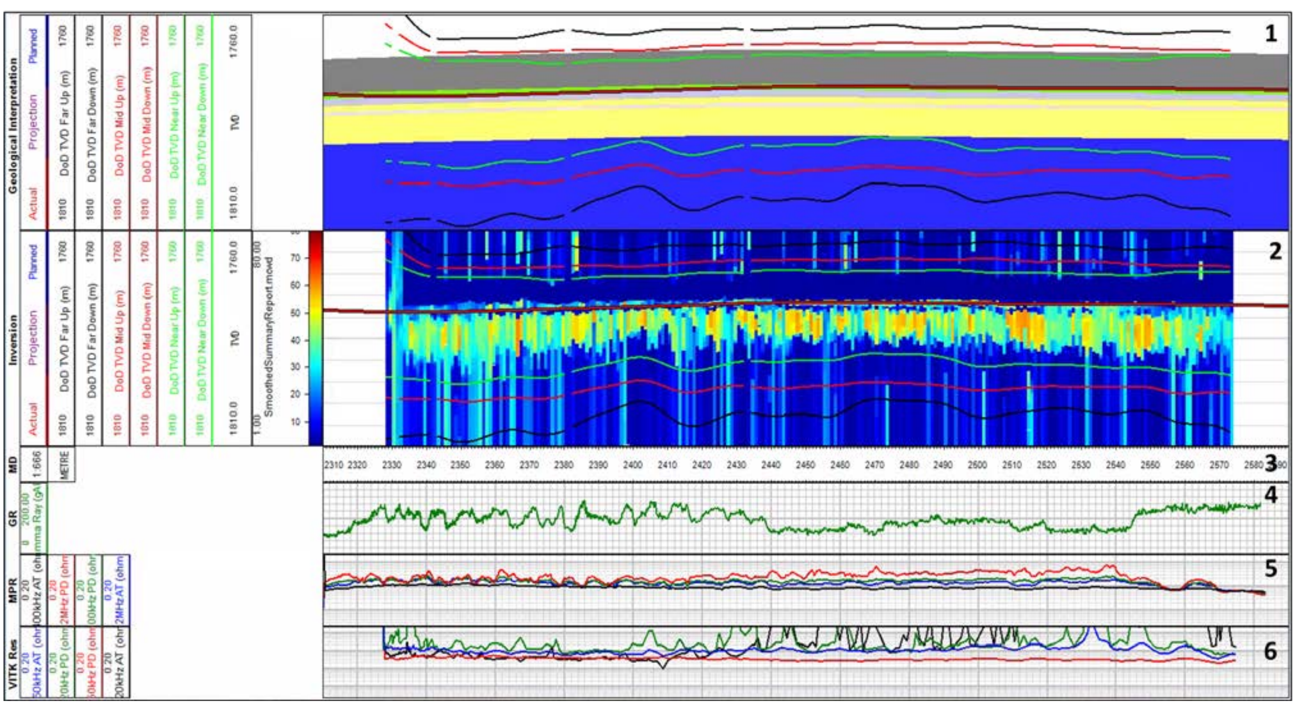

Figure 8 – Reservoir navigation display with EDAR variable DOD estimation and statistical uncertainty analysis. Log tracks description: 1. Geological Interpretation track showing actual well path (red) position within the target formation and variable EDAR DOD, 2. Inversion output after statistical uncertainty analysis 3. Measured depth track, 4. GR and ROP, 5. Multi-propagation resistivity curves, 6. Bulk resistivity from EDAR tool.

Conclusion

The deployment of this technology was a significant milestone for the A field. Using the new approach, CNOOC accomplished all reservoir navigation objectives. During real-time operations, an instantaneous distance-to-boundary calculation, using shallow and deep resistivity measurements, was provided with detection ranging up to 4.5 mTVD. Based on which, timely steering decisions were made to maintain the well within a 1-meter-thick sand lobe. Additionally, the automated inversion processing used all shallow, deep, and extra-deep resistivity measurements to delineate resistivity-based earth models along the wellbore up to 20 mTVD around the wellbore. This provided a seamless mapping of the reservoir top, a near-by intra-shale layer, and the oil-water contact at approximately 10 mTVD below the wellbore. The interpretation of all reservoir layers, including the remote fluid contact, was further assessed with real-time statistical confidence analysis. The multiple depth of tool's detection range provided a better understanding of the boundaries being resolved from inversion and their confidence level.

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