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Utilizing Ultra-deep Resistivity Mapping in a Mature Oil Field of Kuwait: Eliminating Pilot Well and Achieving Effective Arrival in Sweet Formation, Case Study

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Abstract

Greater Burgan is the biggest sand-stone oil-field in the world that developed in 1930s. It consists of three fields. Traditionally, it developed using directional wells, a recent project has been started to use horizontal in upper Burgan - 3 (UB-3). Typically, a pilot well is necessary. Eliminating the pilot reduces the cost and the time. The azimuthal ultra-deep resistivity mapping technique (UDR) is recommended. Its application reduced the delivery time to 10.39 days, and saves costs of 894000 USD$, and after taking the logging modification, the saves cost is increased to 665000 USD$.

In this paper, real-time ultra-deep resistivity geo-mapping identified several slight sand lenses on top of upper Burgan 3. The OWC was found to be 35 ft TVD below the landing point. Without UDR, detecting the OWC would have been impossible. After the well landed, the lateral portion was drilled, covering a depth of 1649 feet. It includes 450 feet of depth in the upper part, 350 feet in the transition interval, and 637 feet in the lower lobe inside Burgan Unit-3. The porosity was 30%, and the saturation of water (Sw) was below 10%. Mobility measurements is about 3.4 darcy/cp.

The use of UDR shows how it changed the way lateral wells, improved reservoir understanding and reduced time and cost for drilling wells. At the end, it described the implementation, detailing the entire process including pre-modelling, execution phase as well as the overall benefits.

Introduction

Implementation of deep EM-measurement while drilling for geo-steering long horizontals has been stated early. A lot of case histories are documented and published [**Error! Reference source not found.**]. Several investigators [**Error! Reference source not found.-Error! Reference source not found.**] have demonstrated the added value from deep logging while drilling EM-measurements in the past. One of the first case has been implemented in 2002 [**Error! Reference source not found.**].

Drilling targets in deep water presents significant challenges, especially as we enhance measurement resolution to gain insights into reservoir characteristics that were previously hidden using conventional logs. This has led to geoscientists demanding high-resolution well-logs of various measurements during drilling, which were traditionally only deployed on wireline, thereby challenging new well delivery risk profiles and economics [**Error! Reference source not found.**].

Fakolujo et al. (2023) [**Error! Reference source not found.**] presented the results of a study on the optimization of reservoir contacts in an ultra-deep clastic gas reservoir through the use of high-speed, high-bandwidth unconventional wired drill pipe telemetry transmission for logging while drilling (LWD). Better placement and timely important decision-making were made possible by the real-time visualization and interpretation of images from greater bandwidth (57,600 bits per second) memory quality formation evaluation logs.

High-end drilling and logging technologies, such as resistivity, density, and gamma ray (GR) pictures that provide a timely and complete (360 deg) view of reservoir parameters, were utilized to improve well placement in a difficult environment. Well placement has been facilitated by the unambiguous stratigraphic interpretation offered by the real-time near-bit GR image. Critical reservoir vertical distribution away from the wellbore was supplied by the deep azimuthal resistivity measurement and inversion, which also guided well placement ahead of schedule. In addition to the stratigraphic data for well location, the real-time density image supplied hole shape information for mud weight modification. High-speed telemetry in conjunction with all of the previously listed measures was utilized to increase net to gross and reduce the risk involved in making crucial well location decisions [**Error! Reference source not found.**].

Reservoir Mapping Technology

Realizing the characteristics of reservoir fluid is essential for effective field development, particularly because wells have grown more complex with longer and more twisted trajectories. In order to address these issues, operators are searching for "smart" downhole fluid analysis methods that, while drilling, offer a real-time, accurate, and comprehensive view of the reservoir at every point of its life, improving completions and helping them reach production targets. Traditionally, once the well has been drilled, samples are examined in a laboratory to determine the fluid's qualities. The risk of improper well installation is not addressed by this after-the-fact method, which also takes more time.

Techniques like reservoir surveillance and fluid saturation monitoring are crucial for efficient reservoir management. Infill well placements are becoming harder to discover as formation age and water front advance. Technologies for reservoir level saturation surveillance present a fresh and exciting approach to optimizing oil recovery via improvement sets. Furthermore, it be able to assist in assessing sweep/driving efficiency and enhancing reservoir modeling. In these days, a number of well-established electromagnetic techniques, such as EM through the casing, Shallow to downhole EM (STB-EM), downhole to Surface EM (BTS-EM), and cross-well-EM (X-well-EM), are available for reservoir scale saturation monitoring [**Error! Reference source not found.**].

Komies-Alshaya (2023) [**Error! Reference source not found.**] presented a great detail about survey planning and each technology's design. Furthermore, the difficulties and essential elements for carrying out a successful survey will be covered. These elements include measurement precision, depth, signal-to-noise ratio, inter-well spacing, operational time and cost, completion types, and the ideal frequency range. Lastly, we will demonstrate the outcome that makes electromagnetic a fascinating idea that is starting to emerge the subject of reservoir surveillance. comparing the many methods used in EM surveys to identify the most effective methodology and its potential for field expansion [**Error! Reference source not found.**].

Incorporating real-time data from advanced LWD instruments, such as azimuthal thickness and azimuthal resistivity tools, into the geosteering program can enhance its effectiveness [](Pitcher 2009). The geosteering software can utilize measurements from thickness instruments to make adjustments to the geological model, especially when determining the dip angle.

Azimuthal resistivity logs can be artificially simulated and compared with real-time data to identify deviations from the wellbore's planned position, or the distances to these deviations can be calculated using inversion calculations and then plotted on the geological model [**Error! Reference source not found.**].

Geosteering with azimuthal LWD tools

Geosteering involves placing a wellbore optimally by using real-time subsurface geological and geophysical logging readings rather than relying on 3D spatial targets. Typically, the goal is to keep a deviated hole within an oil pay-zone, which is defined by its resistivity, density, or biostratigraphy [**Error! Reference source not found.**]. In developed regions, geosteering may be employed to maintain the hole within a specific reservoir limit to minimalize gas or water breakthrough and increase economic production from the well. During the drilling process, geosteering entails modifying the borehole position (inclination and azimuth angles) on the go to access one or more geological targets. These adjustments are based on geological information obtained while drilling**Error! Reference source not found.**].

Geosteering utilizes logging techniques to guide the well in a specific direction and keep it within the productive zone. It involves the continuous use of logging tools like logging while drilling (LWD) and measurement while drilling (MWD) to constantly assess and position the horizontal wellbore in the optimal position. It is a method of choice for drilling offshore and in deep water, as it maximizes efficiency due to increased reservoir exposure, increased production level and oil recovery, and helps offset the additional cost of an offshore drilling operation.

While the drilling of the borehole progresses as per the well planning, recent geological data is obtained through mud logging, measurement while drilling (MWD), and logging while drilling (LWD). Typically, the findings deviate somewhat from the anticipated modelling. The model is continuously revised based on the recent geological data (formation evaluation) and the borehole's position (well deviation survey), resulting in alterations to the geological sub-structures and potential updates to the well plan to achieve the adjusted geological targets[**Error! Reference source not found.**].

Geosteering techniques involve the real-time adjustment of wellbore placement during drilling, primarily addressing stratigraphic challenges. The goal is improving the contact and touches to the horizontal hole to targeted geological formations. Techniques may include the use of advanced logging-while-drilling (LWD) technologies and various strategies that rely on subsurface data to make informed decisions during the drilling process [**Error! Reference source not found.**].

Successful geosteering relies on obtaining accurate real-time reservoir knowledge, which is gathered from various sources throughout the well planning and drilling process. Before drilling, seismic data, offset well information, reservoir locations, core plugs, and different ways are used to obtain information about the reservoir. The well paths are then meticulously planned to position the well as precisely as possible in relation to the reservoir. However, the lack of information can often hinder this process. Drilling the well according to the proposed well path may result in it being positioned in a subpar reservoir or even outside the reservoir segment. Geosteering can avoid this by adjusting the well pathway while drilling, utilizing both the pre-drilling planning evidence and real-time data [**Error! Reference source not found.**-**Error! Reference source not found.**].

The present paper faces this challenging environment and after thorough collaboration with Drilling and Geology and Geophysics teams (G&G), it was agreed to implement a novel logging while drilling (LWD) technology described as reservoir mapping, enabling to eliminate the pilot hole phase and identifying geological boundaries and reservoir units while drilling the landing phase. Not only, this technology will allow to mitigate depositional uncertainties and adjust the trajectory while drilling to achieve the target, it will also reduce significantly costs and well delivery time of the overall project by eliminating the associated operations of the pilot hole.

Prior to implement this technology, assessment of the expected tool performance and the different parameters which affect the depth of investigation needs to be reviewed. Different scenarios are evaluated based on resistivity and thickness ranges of potential zone of interest and final configuration is decided. Eventually, the execution phase and economics of the project will be detailed and discussed.

Greater Burgan Oil Field Geology

The largest sandstone oilfield in the world is the Great Burgan reservoir, which has been under development and production since the 1930s. In the past, it was developed using directional wells, but the recent project involving horizontal holes has recently been began to extract oil from the UB-3 reservoir unit. Typically, a pilot well is necessary to determine the presence of produciing layers and the depth of the oil-water contact (OWC), which needs to be prevented in the horizontal section. Removing the need for a pilot well would reduce the time and cost of expansion and progress [**Error! Reference source not found.**].

The UDR mapping benefit has demonstrated its ability to remove the necessity for pilot wells by swiftly mapping formation boundaries and OWC, earlier than conventional methods. This enables real-time geosteering to position the well in a single drilling run within the productizing formation. Furthermore, it simplifies the process of halting drilling and installing casing above a target layer, reducing non-productive time, and aiding in optimizing prospect well planning in field development. An assessment conducted on offset wells indicated promising potential for implementing this method in the UB-3.

The Greater Burgan oil field situated in Southeastern part of Kuwait is one of the largest sandstone reservoirs in the world. The field enjoys good energy support from strong natural aquifers. Structurally, the Greater Burgan Field is divided into three different fields, Burgan, Magwa and Ahmadi. The five major reservoir sections comprising the Greater Burgan Field complex are Wara Sand (WAS), Mauddud (MAS), Burgan Sand Upper (BGSU), Burgan Sand Middle (BGSM), Burgan Sand Lower (BGSL1) & Four Sand 4S (BGSL2). Figure 1 illustrates the Greater Burgan field location and a type of log displaying the five reservoir units. BGSL2 and BGSM involves massive, stacked, fluvial channels with a strong water drive. BGSL1, BGSU2 (Burgan Upper-2) and BGSU1 (Burgan Upper-1) includes deltaic to tidally influenced delta facies at the bottom proceeded by glauconitic marine sandstones and shales at the top. [**Error! Reference source not found.**].

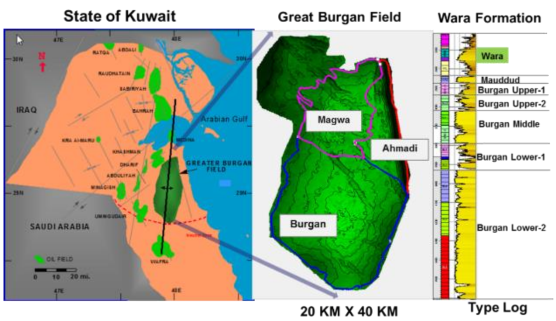

Figure 1 Greater Burgan Field, Kuwait [**Error! Reference source not found.**]

With the depletion of oil from the massive sandstones of Burgan, fairly thinner sandstone with about 10-20 ft net pay is being exploited. The target BU3 sand (as shown in Figure 2) in this case study are heterogeneously characterized by sand bodies of limited lateral as well as vertical continuity typical of tidal channel bar depositional environment. It was observed that drilling vertical or deviated wells in these sands resulted in lower production rates due to minimum reservoir exposure. Horizontal wells have proved to be a better option to reach an optimal development of this type of reservoir. With the growing demand for oil, drilling of horizontal wells has been perceived as the most appropriate way of exploiting these reservoirs. However, landing a horizontal well is often unpredictable, frequently requiring the use of Pilot hole due to heterogeneous nature of the BGSU sands. Till now drilling pilot holes has been the common practice to reduce the depositional uncertainties.

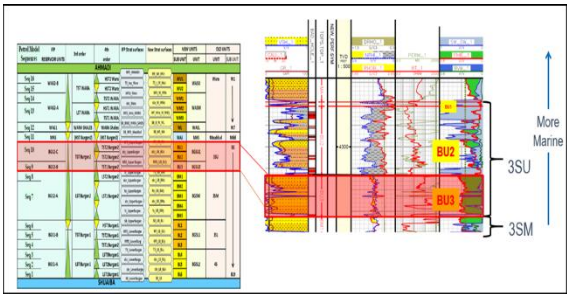

Figure 2 Greater Burgan Field Statigraphy

This study answers to how the current of state of art real time drilling methods coupled with sophisticated UDR tool helped to drill a horizontal well without drilling the Pilot hole. In well A, proactive approach in GeoSteering using UDR mapping knowledge integrated with strong collaboration and successfully overcoming geological challenges such as faults was made possible by effective communication among the multi-disciplinary team, leading to the achievement of the horizontal well objectives. The productivity of the horizontal well results was highly encouraging, thanks to the optimal placement of the horizontal well trajectory, which enabled maximum reservoir contact.

Well Plan and the main challenges (Problem)

Considering the reservoir uncertainties, the well concerned by this case study was initially planned with 70 deg inclination pilot hole in order to assess and validate the sand unit development and quality as depicted in Figure 3. Based on pilot hole logs, trajectory would be reassessed before landing and lateral section phases.

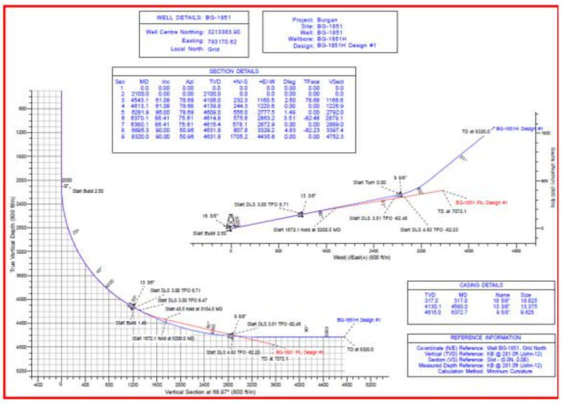

Figure 3 Original Well Plan with Pilot Hole

With the introduction of reservoir mapping technology, a more effective approach is preferred. Indeed, reservoir mapping deliverables allows the G&G teams to identify position, thickness, and quality of the sand units early enough to correct well placement and successfully land. This innovative approach allows to significantly reduce the well time and cost and therefore implies a straight-forward well plan. It is important to note that 70 deg inclination pilot hole is associated with multiple drilling issues and required in most cases a rotary steerable assembly (RSS) which adds to the cost of the overall project as depicted in Figure 4.

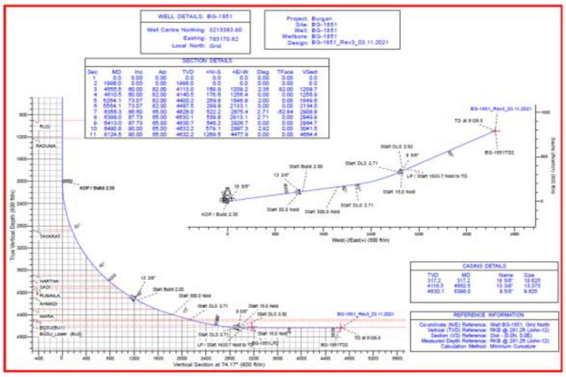

Figure 4 Well Plan After Pilot Hole Elimination

Tool Design

The ultra-deep resistivity tool [**Error! Reference source not found.**] composed of several separated collars, the transmitter collar located toward the bottom of the drilling stem is usually placed immediately above the rotary steerable assembly in order to minimize bit to sensor distance. Above this transmitter, one or two receiver collars can be implemented separated by various length of spacings depending on the Geosteering requirements and run objectives. In order to reduce the total length of the drill string, LWD sensors such as Density, Neutron or Resistivity sensors can also act as spacers. The available transmitter-to-receivers spacing range is from 25 to 125 ft as illustrated in Figure 5.

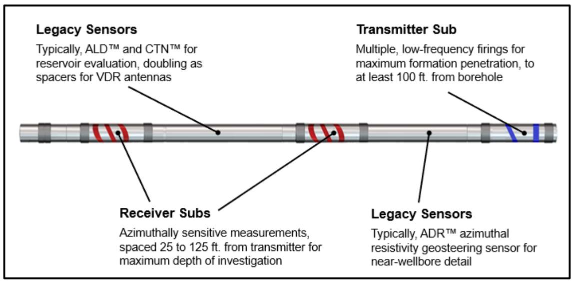

Figure 5 Diagram of The Reservoir Mapping Tool Configured with 1 Transmitter (Blue Antenna) And Two Receivers (Red Antennas), after Wu et al. 2018 [**Error! Reference source not found.**].

The transmitter collar carries two antennas, one coaxial and one 45° tilted comparative to the tool axis. Each receiver collar carries three antennas, all 45° tilted comparative to the tool axis and spaced 120° azimuthally from each other. During operation, the transmitter antennas radiate an electromagnetic wave, which is then scattered by the formation. The scattered wave containing information relating to the formation characteristics is measured by the tilted receiver antennas azimuthally around the borehole. The raw measurement comprises orthogonal components of the electromagnetic field tensor, which can be extracted using numerical techniques. These components are used to build various inversion signals, each of which is sensitive to certain characteristics of the formation, and which together can be used to construct a formation model. The primary inversion inputs are provided by the 45° tilted transmitter antenna, while the coaxial transmitter provides additional ultra-deep azimuthal geosignals and resistivities. The wide firing frequency range (1-64 kHz) and the different spacings available give an extended operating range and output in terms of depth of investigation and bed resolution

Pre-Well Study

Using data acquired in relevant offset wells, a pre-well modeling was performed to identify the optimal transmitter frequency and resistivity antenna spacing configuration for the drilling operation. A Bottom Hole Assembly (BHA) configuration including of one transmitter and two receivers with LWD tools was planned for deployment.

The modelling objectives were:

- Estimate lateral formation variations between the offset wells.
- Determine the extreme high and low cases.
- Construct a framework for mathematical modeling of the tool response.
- Forward Model (predict) the ultra-deep resistivity tool response along the planned well trajectory for different sets of transmitter-receivers spacing's & frequencies.
- Select the best tools setup for real-time application.

The candidate well is located inside a pentagone formed by the offset wells (Figure 6).

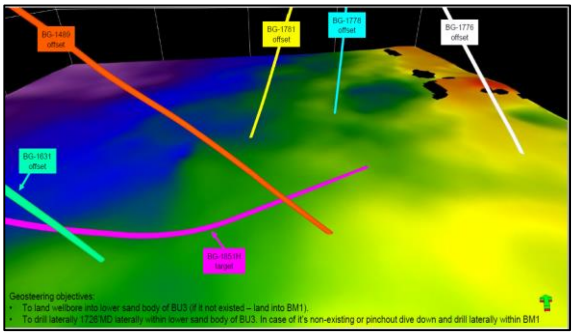

Figure 6 3D Visualization of Offset Wells

Comprehensive forward modelling was performed (with each offset dataset, focusing on the G&G team's objectives, with each scenario being evaluated (different landing target thicknesses, quality, positions) in order to identify the proper spacing and frequencies to perform successfully during the run. The zone of interest was the BU3 sand, which exhibits lateral variation among the different offset wells.

As shown in Figure 7, offset data illustrated a very heterogeneous geological deposition with noticeable lateral variation. The main target, BU3, can only be identified in 4 of the 5 offsets available, and its thickness varies from 6 to 12 feet. Therefore, it was agreed with the G&G team that if BU3 was not developed in Well A, BM1 would be selected as a backup target as it appears to be developed in all the offsets data.

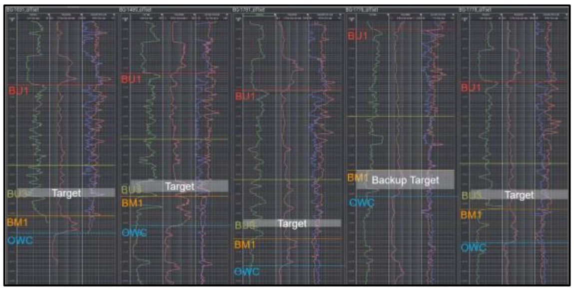

Figure 7 Offset wells logs (Gamma, Resistivity, Density and Neutron Porosity). The different markers are labeled on each offset.

Due to the observed lateral heterogeneity, pre-well modelling was performed with each individual offset data separately. The least favorable scenario is shown in the Figure 8, where the forward model predicts the response of the tool considering the minimum thickness of the target unit. Despite the 6-ft thickness, the model shows that the reservoir mapping tool could identify BU3 and BM1.

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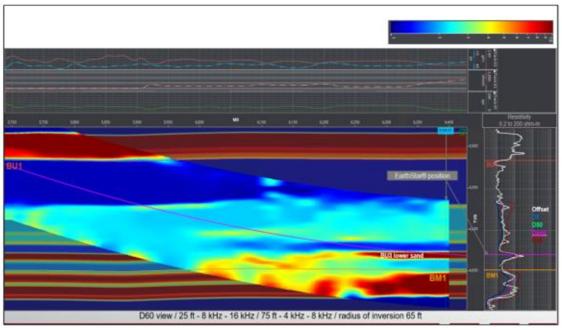

Figure 8 Pre-modelling Reservoir Mapping Inversion

After discussing the different scenario (thickness & position of the different units) with the G&G and drilling teams, spacings of 25 and 75 ft between the transmitter and receivers were selected, with real-time operation frequencies of 8-16 kHz for receiver 1 and 4-8 kHz for receiver 2. This configuration was designed to identify thin sand units with sufficient distance to real-time decision making. The BHA is illustrated in Figure 9.

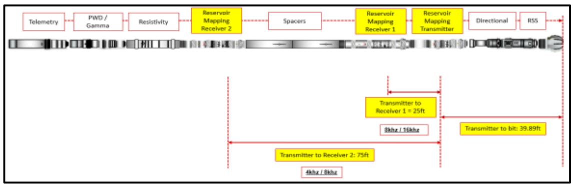

Figure 9 Bottom Hole Assembly of Landing Section with Reservoir Mapping Tool

Execution

The real-time UDR service [**Error! Reference source not found.**] officially commenced in the 12.25-in. hole at 4557 ft MD in the Ahmadi formation. The initial objective of the service was to pick the casing point in the BU3 formation with 90° inclination. The hole was drilled with the reservoir mapping tool along with RSS, gamma ray, and wave-propagation resistivity. Offset well B was used as the primary offset well for the modelling and data correlation. We can see in Figure 10 that a good correlation is observed at the start of the section.

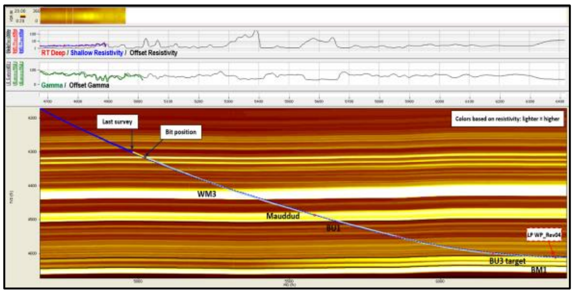

Figure 10 Correlation – Starting build section.

Figure 11 illustrates the ultra-deep resistivity inversion at the start of drilling the build section. Minor resistivity layers were successfully detected. The next mapping layers for verification of the UDR service prior to landing were Wara and Mauddud.

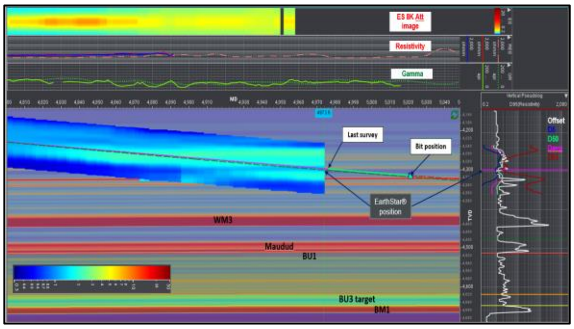

Figure 11 Reservoir Mapping Correlation - Starting Build Section

Table 1 presents the depths of formations intersected while drilling the planned trajectory.

Table 1 Formations depths.

Formation	MD, ft	TVD, ft	Difference from initial plan, ft TVD
Wara	5008	4310	1 shallower
Mauddud	5540	4471	10 shallower
Burgan BU1	5648	4501	10 shallower

Figures 12, 13 and 14 present geosteering curtain sections, TVD log correlations and ultra-deep resistivity mapping correlation while drilling the Wara and Mauddud formations.

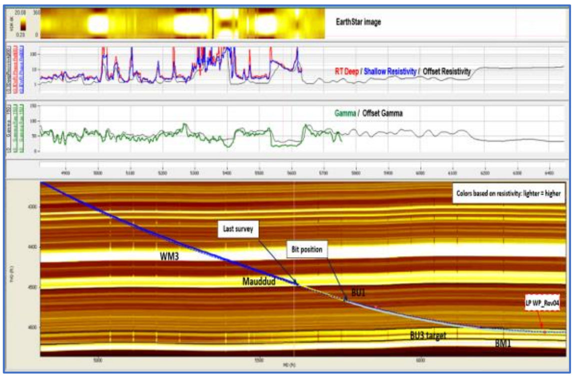

Figure 12 Correlation - Drilling through BU1 Formation

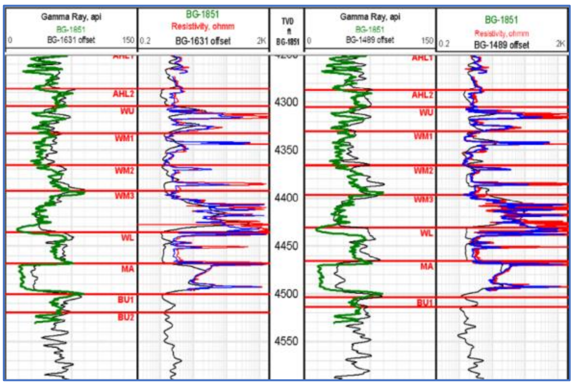

Figure 13 Correlation - TVD

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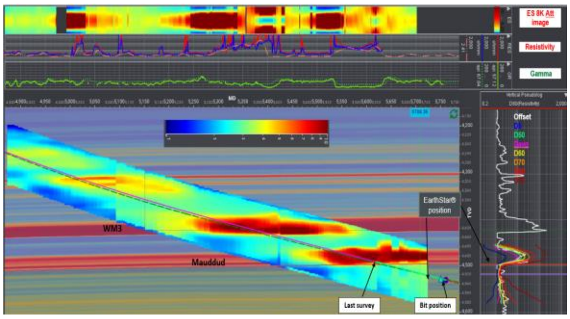

Figure 14 Reservoir Mapping Correlation - Wara / Maudud

The BU3 target zone was encountered at 6350 ft MD (4608 ft TVD), 3 ft TVD shallower than initially planned.

The landing section total depth is chosen at the clean oil saturated sand, this is at 6460 ft MD (4614.2 ft TVD, 88° inclination, 66.5° azimuth).

Although, as shown on Figures. 15-16, the conventional resistivity sensor did not enter the sand, the conclusion on saturation was reached using UDR inversion data, which showed that the wellbore was on top of a highly resistive massive body, which was a strong indicator of oil presence (Figure 17). Moreover, the UDR inversion was able to detect the oil-water contact (OWC) below this body and estimate thickness of the oil column. This data was important for planning the drilling strategy of the next lateral section – through re-calculation of hydrodynamic modelling, the maximum allowed TVDss had been established to prevent early water breakthrough during production.

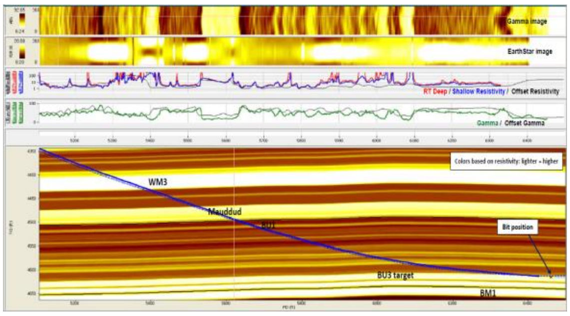

Figure 15 Correlation at Landing Phase

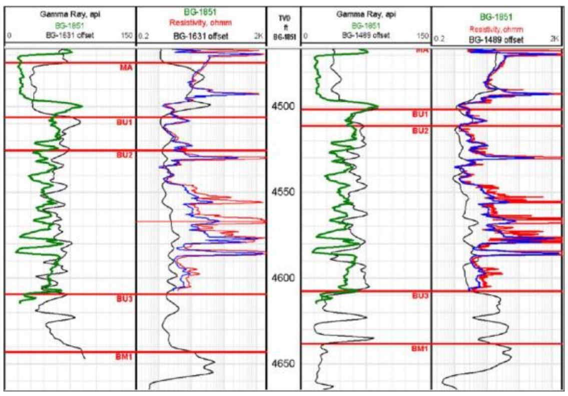

Figure 16 Offset Correlation at TD

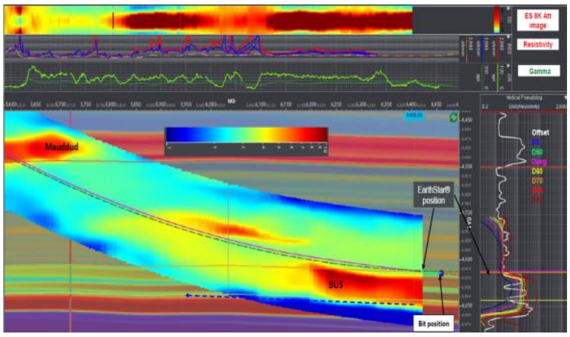

Figure 17 Reservoir mapping inversion of BU3 layer clearly shows OWC (blue dashed line below BU3).

Post Job Analysis / Lesson Learned

Once the run was completed, memory data was retrieved giving access to the entire range of frequencies fired by the tools. The first step was to perform a quality check of the datasets and verify with the same parameters the concordance of the memory and real-time resistivity inversion. The comparison of the inversion results showed good agreement between real-time and memory data which confirmed the quality of the real-time canvas, as shown in Figure 18.

Before drilling the lateral section, a thorough examination of all the data from the nearby wells was conducted to create a geo-steering plan that considers various geological scenarios. In total, several key geo-steering decisions were made in real-time to make proactive adjustments to the trajectory, resulting in the well-being positioned in the target sand with excellent reservoir exposure.

Further analysis of the memory data showed that the initial choice of frequencies was correct and alternative combinations did not add any value. These have been performed after several changes and suggest the values used in this job.

After the successful landing, the lateral portion was drilled through the upper and lower lobes of the extensive sand, covering a total distance of 1649 ft measured depth (MD) (Figure 19). This included 450 ft (Measured Depth) of the upper lobe, 350 ft (Measured Depth) of the transition zone, and 637 ft MD of the lower lobe within BU3, exhibiting a porosity of around 30 porosity units and a water saturation of below 10 percent. Pressure tests conducted on the formation indicated a mobility of up to approximately 3.4 Darcy per centipoise (D/cp) (Figure 20).

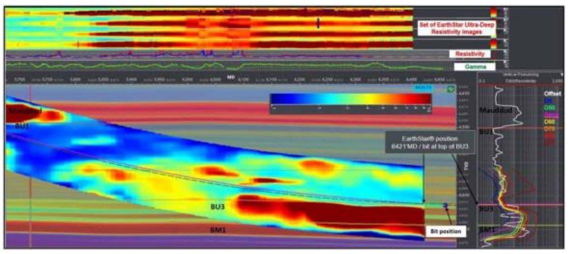

Figure 18 Memory data of ultra-deep resistivity inversion

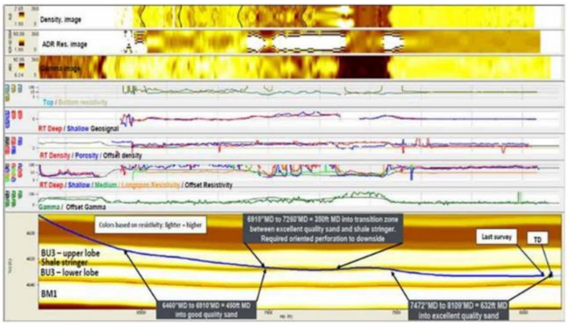

Figure 19 Lateral section final view

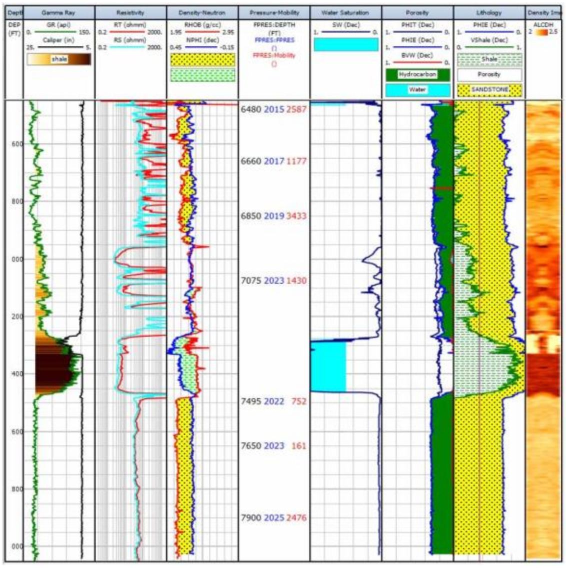

Figure 20 Composite log of lateral section

Visibility study and Economics

The decision of implementing the LWD reservoir mapping technology was taken based on tool capability and economics of the project. Below is a detailed analysis of the project economics which supported the decision.

Pilot Hole Analysis: Directional Services with RSS, LWD and MWD including service engineer:

Well Data:
8.5-in pilot hole section interval: 2479 ft
Average rate of penetration: 30 ft/hr
Drilling phase duration: 4.69 days
Total cost of this phase: $472k

Cement Phase:
After drilling, the pilot hole will be plugged back in 4 stages (cement not to exceed a 900-ft stage). Three cement plugs at 15.8 ppg and the last plug for sidetrack at 17 ppg with a total of 235 lbs of cement slurry.
Cement Phase Duration: 4.7 days
Total cost of cement phase: 40 k$

Drilling fluid:
Drilling fluid cost for the entire pilot hole phase as per drilling program requirements: 45k$

Rig Time:
Rig rate: 30k$/Day
Pilot hole drilling phase duration – rig cost: 4.69 days – 140k$
Cement plug duration – rig cost: 4.7 days – 141k$
Side tracking duration – rig cost: 1 day -30k$
Total rig cost: 312k$

Drill Bit:
Drill bit cost: 25k$

Pilot Hole Total Duration – Cost: 10.39 days – 894000 USD

The elimination of the pilot hole with the direct execution of the landing section will allow a well delivery time and cost saving of 10.39 days and 894000 USD$. After taking into account the modification of LWD requirements of the landing section, the total cost saving achieved on this well are estimated to 665000 USD$.

Conclusions

With the implementation of the reservoir mapping technology in such uncertain geological depositional environment, the G&G and Drilling teams have managed to optimize the overall drilling process of the well, several conclusions can be drawn

- Not only the tool allowed to effectively map the different sand units and place the well at the best possible location.
- It also clearly achieves a significant time and cost saving for this project and proves the viability of reservoir mapping technology in mature field development.
- The elimination of the pilot hole with the direct execution of the landing section will allow a well delivery time and cost saving of 10.39 days and 894000 USD$. After taking into account the modification of LWD requirements of the landing section, the total cost saving achieved on this well is estimated to 665000 USD$.
- This technical success represents a significant milestone in the use of ultra-deep resistivity to optimize wellbore placement and maximize the production in a mature field environment. Such applications are now considered feasible, the data and experience acquired in this project constitute a foundation for upcoming similar challenges.

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Conflicts of Interest

There are no conflicts to declare.

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Abbreviations

BGSL1	Burgan Sand Lower
BGSL2	Four Sand 4S
BGSM	Burgan Sand Middle
BGSU	Burgan Sand Upper
BGSU1	Burgan Upper-1
BGSU2	Burgan Upper-2
BHA	Bottom Hole Assembly
BTS-EM	downhole to Surface EM
EM	electromagnetic techniques
G&G	Geology and Geophysics
GR	Gamma ray
LWD	logging while drilling
MAS	Mauddud Sand
MD	Measured Depth
MWD	measurement while drilling
OWC	oil water contact
RSS	rotary steerable assembly
STB-EM	Shallow to downhole EM
TVD	True vertical depth
UB-3	upper Burgan - 3
UDR	ultra-deep resistivity mapping technique
WAS	Wara Sand

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