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Mapping Uncertain Water Contact by High-Definition Reservoir Mapping Technology: A Novel Methodology for Pilot Removal, Umm Ghudair Field in Kuwait

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Abstract

Umm Ghudair Field, Kuwait, is a significant oil-producing area. The Lower Cretaceous Minagish Oolite Formation developed in 1962, and since then, over 200 wells have been drilled to extract oil. The formation consists of three units: Lower, Middle, and Upper. The lower and upper units are not reservoirs, while the middle is. However, due to continuous production over the last five decades, the field has experienced a fluctuating increase in its oil water contact (OWC). This uncertain rise in OWC has affected the planning and production of newly wells. Several drilled wells exhibited water breakthrough much sooner than anticipated.

In an effort to proactively anticipate the current OWC depth in upcoming wells, Kuwait Oil Company (KOC) has decided to experiment with the new High-Definition Reservoir-Mapping-While-Drilling (HD-RMWD) technology in one of their horizontal wells, and the goal is to evaluate the technology's capability to identify and map the current OWC while positioning the well in the desired location. With its detection range of over 200 ft, the technology allows for early proactive adjustments to the landing point to accommodate any unforeseen OWC depth changes in the field.

Morevover, this work is considered a road map for mapping the uncertain OWC for any field and demonstrates the success of its techniques for mapping out the orientation, thickness and geometry of the sand channels. Deep resistivity images offer information able to fill the gaps among conventional logging and seismic data and add more critical information to the reservoir characterization dilemma.

Introduction

On May 19, 2014, Schlumberger established the GeoSphere* reservoir mapping-while-drilling service. This innovative approach allows for the identification of characteristics in underground layers and liquid interfaces at the reservoir level, enhancing well landing processes, steering capabilities, and mapping of various boundaries through advanced deep-directional resistivity measurements utilizing exclusive real-time clarification methods [**Error! Reference source not found.**].

Reservoir maps depicting petroleum reservoir properties in a plan view projection are utilized to facilitate the optimal development of the field. The maps play a crucial role in determining well placement, calculating reserves, and monitoring reservoir performance. Mapping is an integral component of reservoir characterization, and its outcomes heavily rely on the expertise of professionals in applied geologic models.

Recognizing reservoir fluid properties is an important task in order to have a positive field development, specifically as wells have become gradually complex with more deviated and extended-reach trajectories. To meet these challenges, workers are looking for smart downhole fluid analysis methods that provide a precise, complete picture of fluid distribution at all stages of the lifetime of the reservoir -in real time while drilling-to improve completions and meet production objectives [**Error! Reference source not found.**].

In recent years, there has been a notable advancement in resistivity measurement technology, allowing for directional resistivity to be measured on a larger scale compared to traditional logging tools. The most recent progress in this field enables the identification of resistivity differences within tens of meters around the wellbore [**Error! Reference source not found.**].

Reservoir Mapping Technology

Statoil is now known as Equinor ASA, (a Norwegian state-owned multinational energy company headquartered in Stavanger, Norway) tested deep look around resistivity logs and verified several data for more than 10 wells in Norwegian Continental Shelf, Visund and Asgard fields. They demonstrated how the devices were used in a range of different applications in geosteering operations. These applications include detection of the reservoir boundary up to 20-meter True Vertical Depth (TVD) away, and recognition of Gas Oil Contacts (GOC), and Oil Water Contact (OWC) to 20-meter TVD away [**Error! Reference source not found.**].

Saleh Komies - Abdulaziz Alshaya [**Error! Reference source not found.**] discussed several Electromagnetic technology designs for reservoir mapping. Moreover, they addressed the issues and crucial factors essential for carrying out a successful survey, such as precision of measurement, spacing between wells, depth, signal-to-noise ratio, operational expenses and time, types of completion, and the most effective frequency range. Ultimately, they showed the outcome that renders electromagnetism a captivating concept that is emerging in the domain of reservoir monitoring. We will compare and contrast various EM survey methodologies to underscore the optimal approach and its potential impact on field expansion.

The oil and gas industry offers various tools and services for mapping bed boundaries to define the reservoir during drilling, but their reach is limited. The most advanced systems can only map up to 15 to 20 feet (4.6 to 6.1 meters) from the wellbore. These limitations have created challenges in enhancing directional drilling in narrow pay zones or complex reservoirs with faults, unconformities, injected sands, or channel sands. Consequently, wellbore positioning may not be optimal, leading to less efficient drilling operations [**Error! Reference source not found.**].

Several papers were presented to describe the problem of production from Umm Gudair field due to the reservoir heterogeneity [**Error! Reference source not found.**-**Error! Reference source not found.**]. From example, as a result of increase of water cut from 50% to 80% in a number of well in Umm Gudai field. The case history presented by Al-Muairi et. al showcased successful applications of a deep penetrating polymer system. This system was utilized to establish an impermeable gel barrier in the reservoir surrounding the well bore, leading to long-term water shutoff results in South Umm Gudair (SUG) wells. The success of these treatments and the management of uncertainties were attributed to a comprehensive understanding of the reservoir, geology, fluid flow mechanism, and a systematic treatment design with proper placement techniques. The system was implemented in multiple SUG wells, resulting in excellent water shutoff outcomes in all cases. Notably, the first well experienced a reduction in water cut from 71% to less than 1% (0.9%), while another well saw the water cut decrease from 72% to 3.4%. These interventions led to a significant increase in oil production across all the wells [**Error! Reference source not found.**].

The accurate depiction of the reservoir and precise establishment of trajectory in the upper part of the target are essential for the development team. The BZ-X field, although marginal, holds significant potential for achieving a higher recovery ratio. Wu et al [8] documented this scenario during the execution of the second phase "Phase II" of the horizontal well campaign designed to extract trapped oil in this field. The successful experiences in the complex fluvial system in Bohai Bay motivated the operator to utilize ultra-high-definition multilayer mapping-while-drilling technology and ultra-deep reservoir mapping technology to enhance wellbore location and gain a better understanding of this area after years of production [**Error! Reference source not found.**].

To recover the oil that has been left behind and meet production targets, multi-dimensional reservoir mapping during service drilling is essential. The reason for this is the limited understanding of the dynamics of reservoir fluids. Following a 20-year production halt at the YME field in the southern Norwegian sector of the North Sea, the field is being redeveloped using advanced Ultra Deep Azimuthal Resistivity (UDAR) technologies for reservoir mapping while drilling. These technologies are aimed at aiding horizontal well placement and enhancing comprehension of the reservoir. An essential challenge is the distribution of fluids during the past two decades of production. To address these uncertainties, it is crucial to employ multi-dimensional 3D UDAR reservoir mapping, which transforms ultra-deep electromagnetic measurements into a volumetric resistivity distribution around the wellbore. The primary objectives of this mapping are to geosteer for optimal exposure to high-quality reservoir and to map reservoir heterogeneity, thereby contributing to a better understanding of the production impacts from existing wells [**Error! Reference source not found.**].

In their research, Wang et. al. [**Error! Reference source not found.**] introduced an innovative method for mapping reservoirs using advanced ultra deep azimuthal resistivity measurement. Their approach involves generating a real-time 3D reservoir map from multiple transverse 2D inversion slices, allowing for the timely adjustment of the reservoir model as drilling progresses, enabling operators to make well-informed decisions. This new technology has been implemented in various locations worldwide and across different geological settings. The authors of the paper analyze the outcomes of deployment and operation to showcase the technology, covering the entire process from preparation to real-time execution, and concluding with the updating of the model after the job is completed.

The high-definition reservoir mapping-while-drilling allows for internal layer delineation within heterogeneous reservoirs and enhanced reservoir mapping. The use of both technologies gives a capability of recognition up to 40 m, addressing scenarios making accurate fluid contact mapping and assisting landing in heterogeneous reservoirs [**Error! Reference source not found.**]. The system used acquires an extensive array of electromagnetic measurements. These measurements undergo conversion into 3D resistivity volumes after the data of an advanced cloud-based 2D-transversal inversion technique. In Marlim Field, the focus is on presenting a comprehensive azimuthal characterization of the reservoir to achieve insights into its intricate structure. The ability to map the geological layers in all directions creates the prospect of azimuthal geosteering [**Error! Reference source not found.**].

In their study, Mohamed et al. [**Error! Reference source not found.**] introduced a proactive geosteering technique for stacked channels using Ultra-Deep Azimuthal Resistivity (UDAR) 360 technology. This method enabled comprehensive reservoir quality mapping in 360 and facilitated optimal azimuthal steering decisions for maximizing exposure. They proposed three innovative approaches: firstly, the utilization of high-resolution 1D reservoir mapping with Deterministic Parametric inversion (DPI); secondly, the implementation of 2D Transverse inversions in real-time; and thirdly, the real-time delineation of channel sand structure using (mapped/inverted) resistivity volumes. The integration of these novel methods allowed for a complete set of Ultra-Deep Azimuthal Resistivity (UDAR) inversions, which were instrumental in making real-time azimuthal geosteering decisions in the field.

In their study, He et al. [**Error! Reference source not found.**] explored the Ultradeep reservoir mapping service and highlighted that the successful implementation of this service and the resulting modeling outcomes led decision makers to adopt the ultradeep reservoir mapping service (UDRMS) for efficient redevelopment at a lower cost. By utilizing a depth-of-investigation (DOI) of up to 30 m from the borehole, UDRMS could employ resistivity inversion to remotely identify multiple boundaries and accurately map the specific reservoir's properties, such as the reservoir top, boundaries of local interbeds, oil water contact (OWC), and the complex layering of contrasting resistivity within the reservoir.

Geological Background

Umm Ghudair oil field is the main oil fields in Kuwait discovered around 10 km west of the giant Greater Burgan Field. The field covers a surface area of around 250 KM2 (Figure 1). The field has been producing continuously since the year 1962 from the highly porous and permeable Lower Cretaceous Minagish Oolite Limestone reservoir. The reservoir is characterized by a water derive system in which the aquifer is expanding and helping to sustain production (P. Dutta et al. 2011[**Error! Reference source not found.**]). The formation is overlaid by Ratawi limestone and underlaid by Makhul carbonate Formations. Petrophysically, the average permeability and the porosity of the Ooilte pay are 245 md and 23% respectively (T. Al-Mutairi et al. 2003 [**Error! Reference source not found.**]). Due to the continues production, the water contact kept rising variably in the field which resulted in having issue planning new horizontal wells properly. To accommodate this issue, KOC must drill pilot holes to define the exact water depth, then they plan the horizontal sections accordingly. However, drilling pilot holes is considered an extra unnecessary cost which should be avoided. To eliminate the need for these pilot holes and hence the extra unnecessary cost, KOC decided to try the new HD-RMWD technology due to its ultra-deep boundary detection range. To make sure the approach fits the need, it was tried in a horizontal well with a pilot hole and checked if the technology could really eliminate the drilled pilot hole. A pilot hole with 45 deg inclination was drilled and intersected the water contact to define its exact depth. After this pilot was plugged back and the horizontal section was drilled with the HD-RMWD tool in the drilling bottom hole assembly (BHA). The tool could detect the water contact around 90 ft TVD below the well before reaching the landing point. Having such deep detection (i.e. 90 ft TVD) confirmed that drilling the pilot hole could have been eliminated as the landing point could be adjusted smoothly away from the water contact before reaching the landing point. The well was landed at the upper most part of the 20 ft TVD thick target (5 ft TVD from its top) which would guarantee minimizing the attic oil left behind in this water derive system. The well was steered for around 1257 ft MD in the sweetest spot of the reservoir while mapping multiple layers above and below including the water contact. While steering, the water contact was continuously mapped below the well at around 87 ft TVD.

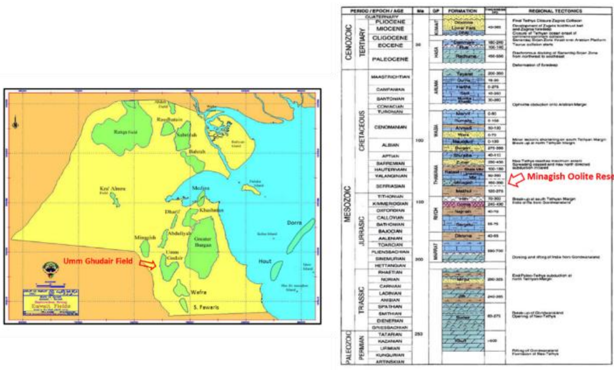


Figure 1 Location map indicates the location of Umm Ghudair Field to the West of Kuwait, and its lithology column with the age of Oolite Reservoir Minagish.

The pilot hole as well was drilled with the HD-RMWD tool in the BHA but that was to serve another objective which is going to be discussed in a different paper.

Methodology

Different LWD tools were used while drilling the well under study. Below is a general overview of each of the tools used.

1. High-Definition Reservoir Mapping Tool (HD-RMWD); this is a modular electromagnetic propagation tool with one transmitter and up to 3 receivers. The HD-RMWD transmitter and receiver sub sketches showing tool dimensions. Both the receiver and transmitter antennas are tilted to increase the tool directional sensitivity. The subs are separate to allow placing them anywhere in the BHA and based on the required depth of investigation as shown in (Figure 2). In this case study, two receivers were used. The transmitter is tilted to improve the directional sensitivity of the measurement. It operates with 6 frequencies ranging from low to high to ensure multiple depths of investigations as per the logged environment. The receivers are also tilted and are placed strategically in the drilling BHA to ensure the deepest detection range possible. Pre-job modeling is performed on data from the offset wells in the field to decide the transmitter to receiver spacing as well as the frequencies to be used. The tool can be placed anywhere in the BHA as it is compatible with all the other drilling components.

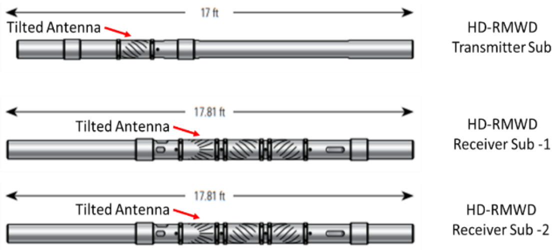


Figure 2 HD-RMWD transmitter and receiver sub sketches showing tool dimensions[**Error! Reference source not found.**].

The tool was used in this case study to map the reservoir boundaries and water contact to be able to steer the well to the optimum place of the reservoir. The data acquired by the tool is inverted in real-time by a proprietary inversion algorithm using a special geosteering software so that the answer product can be used to make the required real-time decisions.

2. Electromagnetic Resistivity Tool: this tool provides the formation resistivity and natural gamma ray measurements. The tool is made of a set of electromagnetic transmitters and receivers (Figure 3). The transmitters send electromagnetic waves at different frequencies which are then received at the receivers. The receivers provide information on the level of attenuation and phase shift happened to the transmitted electromagnetic wave. Such attenuation and phase shift are transformed to attenuation and phase shift resistivity. The tool was used in this case study to provide the gamma ray and resistivity data for formation evaluation purposes like water saturation and shale volume computations. In addition, the resistivity measurements are an input to the proprietary inversion algorithm used for the HD-RMWD service.

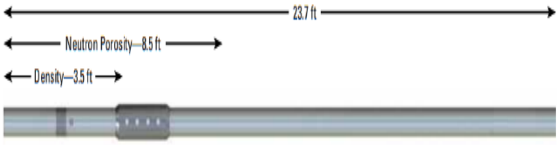


Figure 3 Sketch of the azimuthal LWD density-neutron tool used in drilling the well under study. The tool is 23.7 ft long and is designed to allow source fishing in case of stuck pipe [**Error! Reference source not found.**].

The tool has also two tilted directional sensors that give it directional sensitivity for geosteering purposes. However, it was used mainly in this BHA to provide the conventional resistivity values needed by the HD-RMWD inversion algorithm to compute the distance to the different formation boundaries.

3. Density/Neutron Porosity Tool; This tool is made of a drill color that can provide petrophysical data like azimuthal density, thermal neutron porosity, photoelectric factor and density caliper measurements (Figure 4). This tool is made of 5 axial transmitters and two axial receivers used to measure the formation resistivity. The tool is also capable of measuring directional measurements that can be used in steering using its two directional sensors. However, in this well it was mainly to provide the HD-RMWD inversion algorithm with the conventional resistivity measurements needed. The tool operates with two chemical sources: Americium Beryllium for neutrons and Cisume-137 for gamma rays. The tool is designed in way to have these sources fished using Wireline in case of pipe stuck.

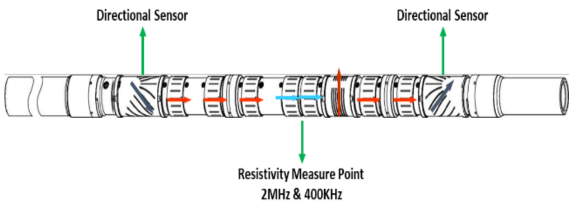


Figure 4 Diagram of the electromagnetic resistivity-GR tool used in drilling this well [**Error! Reference source not found.**].

The technology was used in this well to provide the real-time data required for the formation evaluation analysis such as lithology and porosity computations. It was also used to provide the density images used by the geosteering specialists to estimate the formation dip for geosteering purposes.

4. Short Radiuses Hybrid Rotary Steerable System: This RSS provides complex 3D well shapes while maintaining high Rate of Penetration and wellbore quality (Figure 5). The tool uses both the point and push the bit mechanisms to achieve high DLS values up to 17 deg/100 ft. The tool used in this well allows landing the well smoothly in target as depicted in Figure 5. It decreases shape limitation and improves the kick angle in troublesome formations. The tool was used to allow achieving high directional drilling performance while building the angle to landing the well in Target. This tool can achieve dog leg severity (DLS) up to 17 deg/100 ft.

Figure 5 Diagram of the hybrid rotary steerable tool[**Error! Reference source not found.**].

Planning and Execution

The planning for this trial job started with building a predrill geosteering model using Petrel*. Afterword, the layers of the model were populated with resistivity values acquired in the pilot hole as it represents the closest offset well to the drilled horizontal well. This predrill geosteering model was used to model the HD-RMWD tool responses to be able to plan the best BHA design as well as the firing frequency configuration to be used in this specific formation environment. As a result, the modeling showed that the tool could detect the current OWC up to 95 ft TVD (Figure 6) below the well which is more than the set success criteria in this trial (i.e. 70 ft TVD). The inversion canvas shows the predrill modeling of the HD-RMWD using data from the drilled pilot hole. The OWC is estimated to be mapped at around 95 ft TVD below the well before reaching the landing point. In addition, all the reservoir layers above and below the well could be mapped clearly which would allow taking high confidence geosteering decisions during the drilling operation.

Having such a deep detection range for the OWC in this environment, proved the concept that the HD-RMWD could be used to eliminate the need for drilling the pilot hole. This is because the landing point could be adjusted smoothly to accommodate the uncertainty in the depth of the actual OWC. The BHA design was made of a combination of each of; the high radius rotary steerable system (RSS), HD-RMWD Transmitter Sub, Resistivity-Gamma ray tool, HD-RMWD First Receiver Sub, High Power Telemetry Tool, HD-RMWD Second Receiver Sub and Density/Neutron tool. The dimensions of the BHA used are shown in Figure 7. The BHA design also took into consideration the drilling parameters in this well. BHA modeling was done to eliminate the possible shocks and vibrations that might happen while drilling. To ensure a high build up rate while rotating and during landing the well in target, a hybrid RSS tool was used. This tool uses the two industry-known mechanisms (i.e. Push the Bit and Point The bit) to achieve high DLS values up to 17 deg/100 ft. The well landed smoothly in target and continued steering the lateral section until well TD.

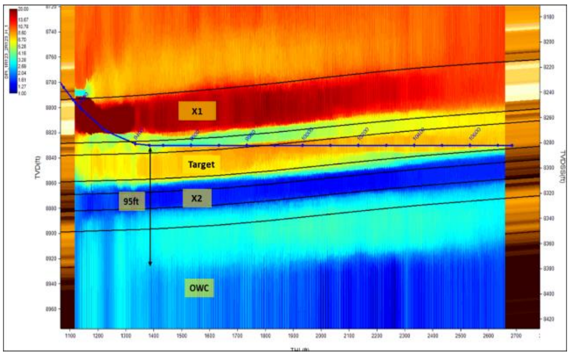
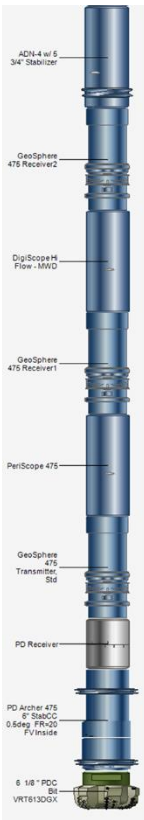


Figure 6 Cross section along the planned trajectory.



Sensor Offset from Bit (ft)	
Gamma Ray	8.11
D&I	9.01
Mid-point of Tx Antenna	28.00
PeriScope Res	50.25
PeriScope APWD	59.19
PeriScope GR	59.97
Mid-point of Tx Antenna	75.16
DVD4T Gamma Ray	96.28
D&I	100.79
Mid-point of Tx Antenna	126.72
Density	143.27
Neutron	146.91

Stabilizer Summary		
Blade Mid-Pt to Bit (ft)	Blade OD (in)	Blade Length (ft)
1.860	6.000	0.650
12.270	6.000	0.670
142.060	5.700	2.700

Bend Summary	
Bend Angle (deg)	Bend to Bit (ft)
0.500	1.490

Figure 7 BHA design showing all the components used in drilling the well under study. The Transmitter and Receiver subs of the HD-RMWD tool were placed strategically based on the predrill modeling so that the tool can provide

the deepest depth of investigation possible [**Error! Reference source not found.**].

After doing the planning stage, the tools were programed based on the predrill modeling study. The section started with 77o inclination at the casing shoe and was targeting the landing point at 90 deg after 425 ft MD. As the HD-RMWD went out of casing, the OWC started to be mapped at around 90 ft TVD which matched what was seen during the predrill modeling (Figure 8). In addition, the depth of the mapped OWC matched the one intersected physically in the pilot hole. The tool mapped the different layers in the reservoir which gave high confidence in the decision of the landing point. Another objective was to land the well at the upper most part of the target (i.e. 5 ft TVD) to minimize the attic oil. Being able to map all the layer boundaries allowed achieving this objective smoothly. At the landing point, the OWC contact was at around 87 ft TVD below the well which could provide a clear idea on how much hydrocarbon volume is there to produce before the water breaks through.

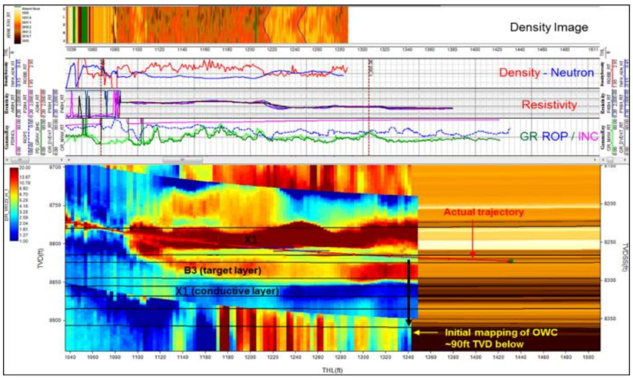


Figure 8 HD-RMWD inversion canvas close to the landing point. While landing the well in target the tool could map all the reservoir layers including the OWC at around 90ft TVD below the well.

After landing, the inversion results of the HD-RMWD showed the structure is gently up dipping by around 0.5 deg in the direction of drilling. To accommodate this, a geosteering decision was taken to build up the angle from 90 to 90.5 deg to stay in the sweetest spot of the target. While drilling the lateral section, the tool kept mapping the different formation layers above and below including the water contact. Gentle undulations were seen in the formation dip which were accommodated by either nudging the well angle up or down (Figure 9). The well was TD'ed after drilling 1257 ft MD in the upper most part of the reservoir with average reservoir properties in the range of; GR: 15-25 API unit, Resistivity: 8-10 Ω.m, Density: 2.35 -2.45 g/cc and Neutron: 19-23 %.

The inversion was able to detect all the layers above and below in addition to mapping the water contact all the way. The conductive layer (micrite layer) was also mapped all the way below the target layer and above the water contact, as shown in Figure 9.

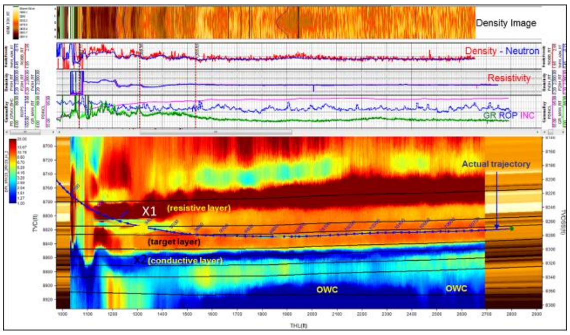


Figure 9 HD-RMWD inversion canvas shows the interval logged interval.

The well trajectory was following the plan and deviating from it only if changes in the structural dip are seen. Figure 10 shows the plan and cross-sectional view of the well with both the actual and planned trajectories super imposed on each other. The pilot hole was also plotted for reference purposes.

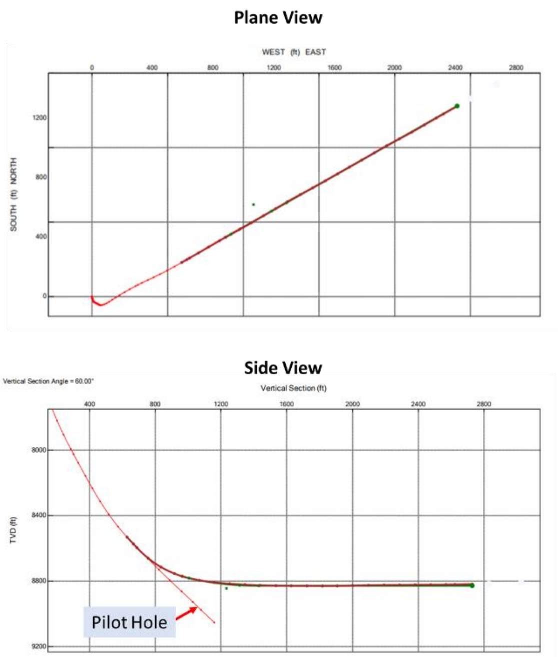


Figure 10 Plots showing plane and cross section views of the drilled well.

As shown in Figure 10, the dark red trajectory is actual well while the green is the planned one. The figure also shows the pilot hole drilled through the water contact to confirm its position before using the HD-RMWD tool in the horizontal section.

Deep resistivity images offer data and information able to fill the gaps among conventional logging and seismic data and add more critical information to the reservoir characterization dilemma.

Conclusions

After conducting this new trial of work, several conclusions have been achieved:

- Combined with other drilling technologies, HD-RMWD tool is a capable technology to map the OWC in Umm Ghudair Field and optimize the well position far above it.
- The results showed that the technology could detect the OWC 90-ft TVD below the well which would allow maneuvering the well trajectory to land the well safely away from it.
- The High-Definition Reservoir Mapping Tool (HD-RMWD) was the first HD job in the whole Middle East, and the success of this trial should open new opportunities towards advanced strategies such as the elimination of drilling unnecessary costly pilot holes.
- Successfully achieving the detection and mapping of the current OWC while landing the well in the target demonstrates the potential of the technology.

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Conflicts of Interest

There are no conflicts to declare.

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