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## **Optimizing Production in Jurassic Tight Carbonate Reservoirs by Strategically Positioning Wells Within Prime Carbonate Reservoir Facies Through Integration of Source-Less NMR While Drilling and Deep Azimuthal Resistivity Tools**

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### **Abstract**

The Jurassic Marrat formation in West Kuwait is characterized as a dense and varied carbonate reservoir, where its petrophysical traits hinder accurate predictions of reservoir properties. Drilling a new well presents operational risks; thus, the use of LWD triple combo is avoided to prevent environmental concerns and manage costs. In its place, the combination of LWD-NMR and Deep Azimuthal Resistivity tools is identified as the ideal approach for assessing the formation and optimizing well placement to target the highest quality reservoir.

The advanced While Drilling nuclear Magnetic Resonance tool is employed for precise porosity measurements due to its independence from lithology. The T2 distribution serves as a direct indicator of both porosity and permeability. The DAR is an azimuthal propagation resistivity tool that significantly minimizes the risk of misplacing the wellbore during the drilling of extended reach and complex 3D horizontal wells. Although the Marrat reservoir typically exhibits high resistivity, its porosity levels are not always optimal. This creates additional challenges for geosteering operations when relying solely on gamma and resistivity logs. By integrating LWD-NMR with DAR, operators can enhance reservoir contact and optimize production from the highest quality reservoir zones.

The drilling plan was adjusted in real-time to ensure a successful landing within the target zone; After successfully landing the well at a 90-degree inclination based on the NMR and DAR signatures, we continued to increase the inclination angle to 90.5 degrees to carefully slice stratigraphically through the section and access the optimal reservoir zone, before gradually tapering off to 89.3 degrees based on the NMR and DAR signatures to keep the well within the most favorable reservoir facies. During geosteering in the F-11 zone, we observed a decline in porosity from 16 pu to 2 pu as detected by the NMR. In response, we made real-time adjustments to navigate away from the tighter area and direct the well toward the sweet spot within the F-11 zone. The effective integration of NMR and DAR tools led to a successful well landing in the F-11 zone, which shows strong hydrocarbon potential. The production data thus far demonstrate very promising results compared to the offset data.

## Introduction

The Jurassic Marrat formation in West Kuwait is characterized as a dense and varied carbonate reservoir, where its petrophysical traits hinder accurate predictions of reservoir properties. Drilling a new well presents operational risks; thus, the use of LWD triple combo is avoided to prevent environmental concerns and manage costs. In its place, the combination of LWD-NMR and Deep Azimuthal Resistivity tools is identified as the ideal approach for assessing the formation and optimizing well placement to target the highest quality reservoir.

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Through the effective integration of while drilling nuclear magnetic resonance and deep azimuthal resistivity, we have successfully addressed the difficulties of well placement in a highly heterogeneous environment, while also eliminating the need for radioactive-based porosity logging tools in this well profile. This approach has led to substantial CAPEX savings for drilling and logging operations, while also enhancing production in the Umm Gudair field.

## Geological Background

Umm Gudair field is located approximately 10 km west of the Greater Burgan Field, the Umm Gudair Field is a significant oil producer in Kuwait, covering roughly 250 sq km ([Figure 1](#)) and in continuous operation since 1962. The primary Jurassic reservoir within this field is the Marrat Formation, a conventional reservoir ranging from 800 to 1000 ft thick ([Figure 2](#)). This formation primarily consists of limestone, dolomitic limestone, and argillaceous limestone, with minor shale and anhydrite.



Figure 1—Location map of Umm Gudair Field (west of Kuwait)

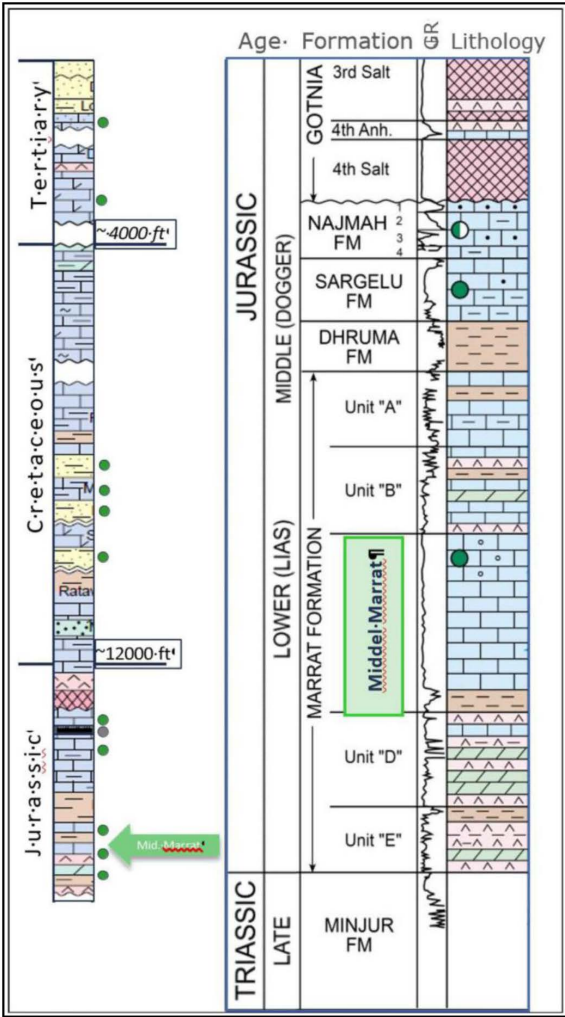


Figure 2—Stratigraphic columnar section of the rocks sequence in Kuwait including the Middle Marrat carbonate reservoir and its geological age.

While Cretaceous formations have historically been the focus of Kuwaiti oil development, increased production demands have led to the exploitation of the Jurassic sequence over the past two decades. The Jurassic sequence, starting around 12,000 ft, is characterized by high pressure, high temperature (HPHT) conditions, and natural fractures.

The bottom of the Jurassic section in this area is marked by the Dharuma formation, which consists of calcareous shaly limestone. Above this is the Najmah-Sargelu formation, consisting of source rock and tight, fractured limestone reservoirs. Above these are the Gotnia and Hith formations, which are thick sequences of salt and anhydrite. The Hith formation spans about 300 ft and has a pressure gradient that increases from 13 ppg at the top to 17 ppg at the base. The Gotnia formation's thickness varies from 500 to 1500 ft depending on location.

The Marrat sequence, a series of limestone reservoirs, is a key target for horizontal and deviated wells. It is divided into three sub-sequences within the Umm Gudair Field:

Upper Marrat: Primarily calcareous shale and argillaceous limestone with anhydrite streaks.

Middle Marrat: Consists of limestone, shale, anhydrite deposited in outer ramp to shoal water environments, peritidal subkha evaporites, and occasional dolomites. It is further divided into sub-reservoirs based on porosity development

Lower Marrat: Largely argillaceous limestone and shale, especially in the upper section, with some evaporite layers.

The Marrat Jurassic reservoir in Umm Gudair is a deep and tight carbonate limestone reservoir that is difficult to produce from with vertical wells due to unfavorable reservoir properties and pressure depletion. To improve production from the Middle Marrat reservoir, horizontal drilling has become common. The goal is to place the lateral section within the most porous and productive zone of the reservoir, thereby maximizing reservoir exposure.

Drilling horizontal wells in these deep (over 12,000 ft TVD) Jurassic reservoirs presents significant challenges. These include high torque and drag, poor weight transfer, and inadequate hole cleaning. Geologically, the high formation dip (5-7 degrees upward) complicates landing and geosteering the lateral section. It is difficult to accurately maximize the wellbore's exposure to the high porosity zones, requiring precise navigation through the complex geological stratigraphy to optimize production

## Tool Selection and Methodology

Deep-reading azimuthal resistivity (DAR) tools are now standard in drilling, allowing for near-real-time formation evaluation up to 5 meters away from the borehole. These measurements are crucial for accurate well placement (geosteering) and for characterizing reservoir properties like saturation, dip, and anisotropy. These tools rely on complex multi-spacing, multi-component, and multi-frequency induction measurements. However, fundamental questions remain about what these measurements truly reflect and how sensitive they are to different formation features. Key parameters like depth of investigation (DOI) and directional sensitivity are often poorly understood, and the proprietary "black box" interpretation methods used by service companies obscure the underlying tool response. As we strive for even deeper penetration with these frequency-based measurements, the increasing complexity and heterogeneity of the geology exacerbate these uncertainties.

The rise of horizontal drilling in the late 1990s made LWD resistivity a vital measurement for applications like well placement, geosteering, and reservoir navigation (terms often used interchangeably, though "well placement" frequently refers to deviated sections, while "geosteering" and "reservoir navigation" are more common for horizontal ones [Skillings 2001]). LWD resistivity tools, boasting a significantly larger depth of investigation (DOI) compared to other LWD tools (e.g., gamma ray, nuclear, acoustic, NMR), became highly desirable. As illustrated in [Figure 3](#), even with placement further back from the drill bit, the greater DOI of these tools allows for early detection of approaching beds, helping to avoid drilling out of the

reservoir. This pseudo look-ahead capability depends on the tool's DOI (or Depth of Detection, DOD, which will be defined later) and the angle between the drill path and the upcoming geological layer, assuming a consistent and linear bed boundary.

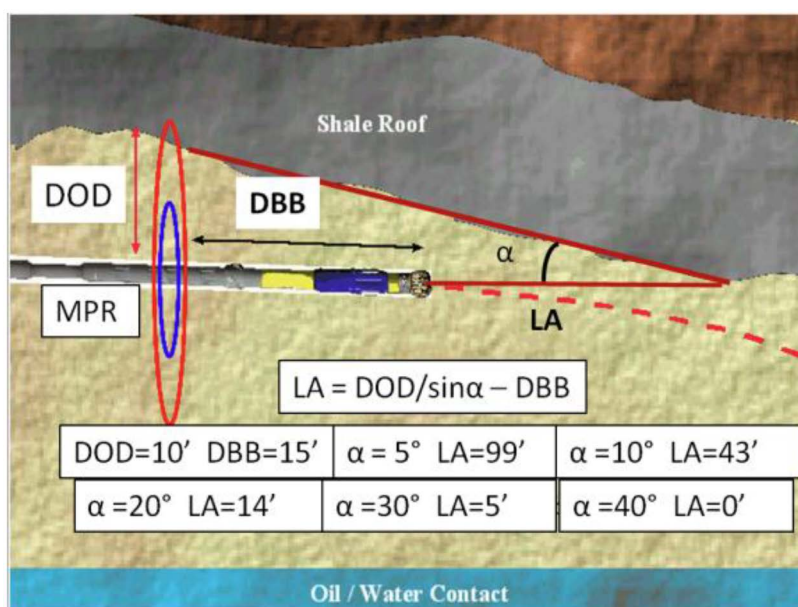


Figure 3—illustrates the use of LWD resistivity tools in geosteering. These tools provide early bed detection, mitigating the risk of drilling out of the reservoir. Key parameters include depth of detection (DOD), distance behind bit (DBB), and look-ahead distance (LA)

The Deep Azimuthal Resistivity (DAR) tool uses electromagnetic fields at 400 kHz and 2 MHz, measuring multiple magnetic field components with both short and long receiver-transmitter spacing at each frequency. It determines the apparent resistivity of the surrounding formation by analyzing the attenuation and phase shift of omnidirectional magnetic field components. Crucially, the tool also employs azimuthally sensitive cross-components, derived from orthogonal coils, to detect conductivity variations around the borehole. This allows for the identification of nearby boundaries and their direction and distance, ultimately aiding in proactive drilling decisions to address specific reservoir challenges.

Tool specifications are detailed in the LWD Tools Survey available on the Society of Professional Well Log Analysts (SPWLA) website (Zhou, 2016). Further information on the tool's underlying physics and measurement system can be found in publications like Bell et al. (2006) and the recent Standardization of Deep Azimuthal Resistivity Services (SDAR) paper from the SPWLA Houston Chapter work group (Baker Hughes, 2019).

For simple geosteering scenarios with DAR tools, where the tool's detection range involves just one or two boundaries, a visual assessment is usually sufficient for qualitative analysis and decision-making.

Bed boundary proximity can be detected by analyzing changes in omnidirectional and azimuthal resistivity measurements. Specifically, attenuations, phase shifts, separation of apparent resistivity values, and variations in azimuthal signal strength all provide clues about the approaching or retreating of bed boundaries. The direction to a more conductive layer is determined using a "target angle" azimuthal measurement. Quantitative analysis, such as the D2B calculation method (Wang et al., 2007), complements visual interpretation to estimate the distance to the nearest boundary.

To optimize the placement of the planned lateral wells and meet our geological and geosteering goals, using a Deep Azimuthal Resistivity (DAR) tool in the bottom hole assembly is highly recommended. This tool's combination of directional sensors, gamma-ray imaging, multiple propagation resistivity, and deep-

azimuthal propagation resistivity provides a wide detection range, enabling proactive steering for accurate wellbore positioning.

On the other hand, the Logging While Drilling NMR tool (Fig. 5) used in this study, as described by Borghi et al. (2005), employed a symmetrical arrangement of powerful permanent magnets mounted on a drill collar. These magnets generated a strong static magnetic field ( $B_0$ ) to pre-polarize the surrounding formation and fluids, much like a standard wireline NMR tool. A coil antenna acted as both a radio-frequency (RF) transmitter and receiver. As the bottom hole assembly (BHA) drilled downward, the hydrogen atoms' magnetic spins aligned with the  $B_0$  field due to this pre-polarization process.

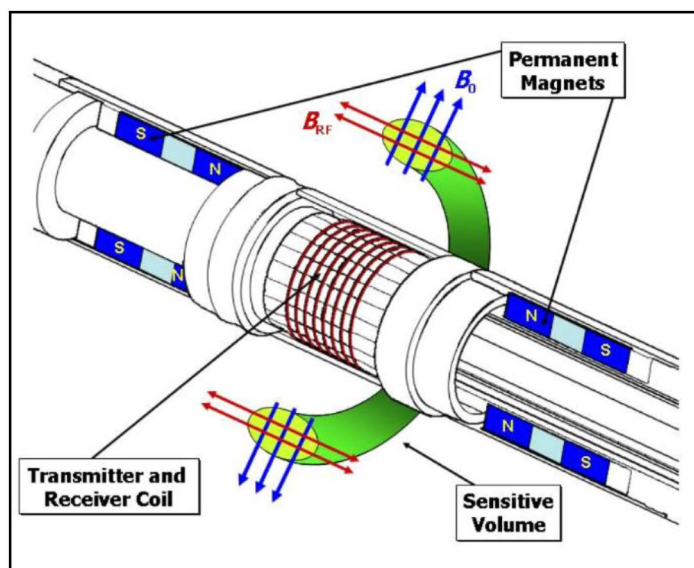


Figure 5—Diagram of the Logging-While-Drilling NMR Tool Design

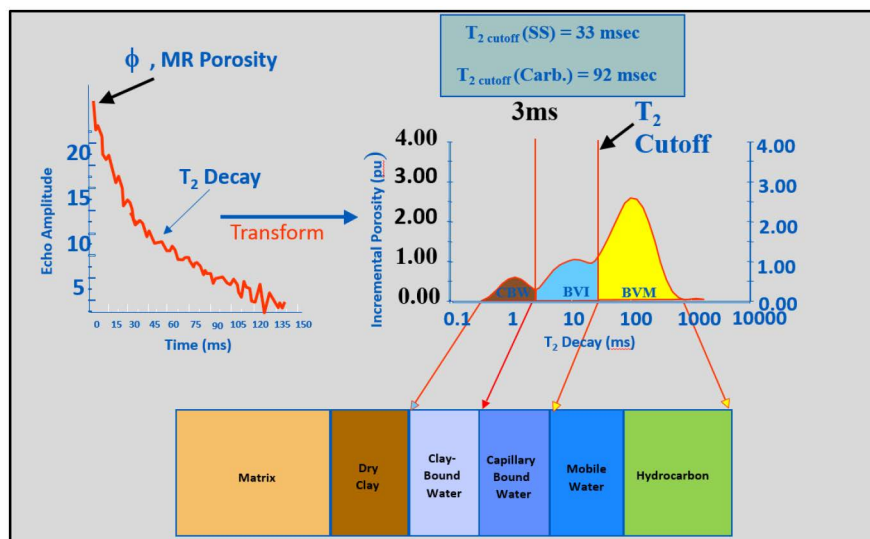


Figure 5—Overview of NMR Measurement Logic

The process of pre-polarization was initiated by the Wait Time ( $T_w$ ) and RF antenna, which emitted radio-frequency pulses (Echo Spacing  $T_e$ ) of BRF magnetic field. These pulses caused the magnetic spins of hydrogen atoms to tilt at a 90° angle and undergo precession in an attempt to realign. The RF antenna then detected this signal, and the series of measurable pulses that were detected, known as  $T_2$  decay, generated a  $T_2$  distribution for each depth (Figure 5).

In addition to being the most reliable method for measuring porosity regardless of lithology, NMR offers several other valuable outputs that are often overlooked (Figure 6). These outputs include the measurement of Clay Bound Water (CBW) volume, Irreducible Fluid (BVI) volume, Movable Fluid (BVM) volume, T2 distribution, Permeability Index, as well as qualitative assessments of Hydrocarbon Saturation and Fluid Indication. These outputs provide crucial information of high significance in various applications.

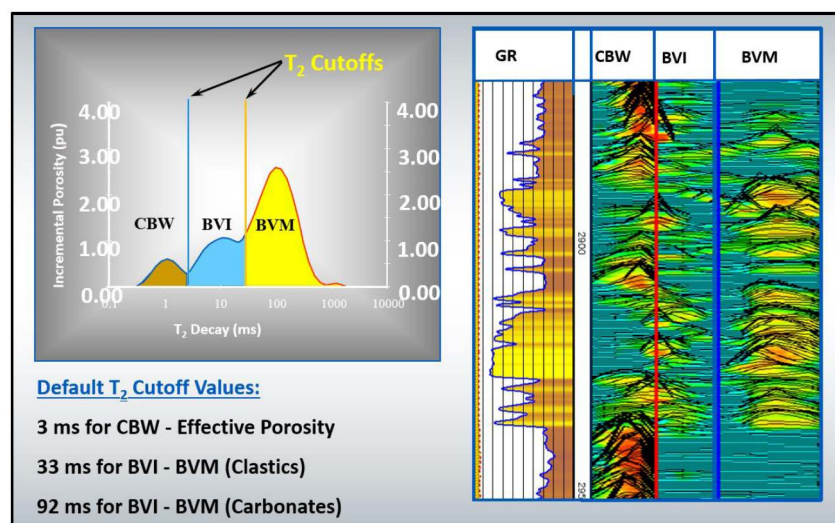


Figure 6—Presents a representative NMR log, illustrating data acquired in a real application

In essence, the primary advantage of utilizing the LWD Magnetic Resonance Tool during drilling is its capacity to provide highly beneficial formation evaluation data in real-time. This data is vital for making immediate decisions concerning completion, especially in complex situations such as drilling deep Jurassic wells in Kuwait. Traditional density-neutron tools that use chemical radioactive sources are often avoided or canceled in these wells due to challenging drilling conditions and frequent problems, which can lead to serious issues like stuck pipes. These complications can result in substantial additional costs and environmental risks, making the real-time data provided by the LWD Magnetic Resonance Tool even more valuable.

Unlike conventional wireline NMR tools, which operate in stable conditions, logging-while-drilling (LWD) NMR tools require robust designs to withstand the harsh drilling environment. This environment subjects the tool to significant shocks and both axial and lateral vibrations. To overcome these challenges and maintain accurate T2 measurements for real-time formation evaluation (M. Borghi et al., 2005), the LWD NMR tool incorporates the following key features:

1. A carefully shaped static magnetic field, generated by permanent magnets, provides a highly uniform gradient within the investigation zone.
2. Advanced electronic circuitry minimizes the echo spacing (TE) to a rapid 0.6 milliseconds, enabling faster and more precise measurements.
3. Specialized stabilizers are integrated around the tool to minimize friction-induced rotation or "whirl" arising from contact with the borehole wall, thereby ensuring reliable data acquisition.

## Aim of the Study

This study presents an analysis of two wells where an integrated Logging While Drilling (LWD) strategy, combining Nuclear Magnetic Resonance (NMR) and Deep Azimuthal Resistivity (DAR) measurements, was employed. The primary objective was to optimize well placement, completion, and production in the complex Marrat reservoir. While both wells utilized NMR for lithology-independent porosity determination

(Well A for formation evaluation only), Well B uniquely leveraged LWD-NMR as a real-time geosteering tool. The integration of LWD-NMR and DAR addressed the challenges posed by the reservoir's variable porosity-resistivity relationship, enabling accurate porosity and permeability estimation (via T2 distribution) and minimizing the risk of wellbore misplacement during the drilling of extended reach, horizontal sections. The ultimate goal was to maximize reservoir contact and ensure production from the most productive intervals.

## Pre-Job Planning

Both wells utilized the same Bottom Hole Assembly (BHA). However, the key difference lies in the application of Nuclear Magnetic Resonance (NMR) logging. In Well A, NMR was run after drilling, in washdown mode, as a source-less porosity tool for formation evaluation. Conversely, Well B was planned to use NMR *before* drilling the horizontal section. The intended purpose was to guide the wellbore placement within the optimal porosity zone of the Middle Marrat (MRW-F11) sublayer. Well B targeted a 1500-foot horizontal reach, guided by formation dip. Both seismic data and log correlations suggested the absence of faults within the target area."

## Planning and Preparation

A comprehensive pre-well study, incorporating data from nearby wells, was performed to pinpoint high-porosity, high-resistivity zones. Multiple geosteering scenarios were developed and communicated to all teams. Proprietary geosteering software, utilizing pre-well resistivity modeling, was employed to optimize reservoir contact. Well placement was carefully planned, taking into account the area's structural geology and offset well petrophysics.

## BHA and LWD Suite

The bottom hole assembly (BHA), depicted in [Figure 7](#), was designed without chemical radioactive sources. It featured a push-the-bit rotary steerable system (RSS) and a suite of logging-while-drilling (LWD) sensors. This suite included real-time azimuthal deep propagation resistivity, azimuthal Laterolog high-resolution resistivity imaging, nuclear magnetic resonance (NMR), and gamma ray.

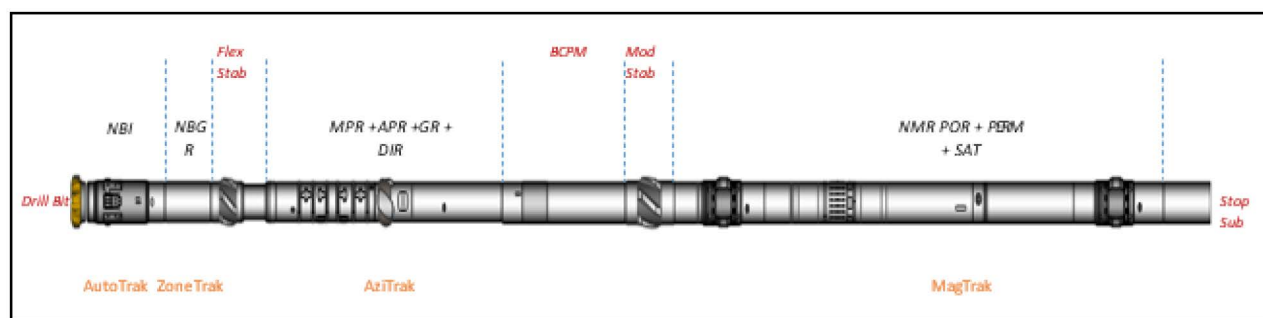


Figure 7—BHA configuration.

## Geosteering Strategy

Azimuthal deep propagation resistivity and azimuthal Laterolog high-resolution resistivity imaging were the primary tools for geosteering within the reservoir sub-units. NMR provided porosity and permeability data. The geosteering strategy was adaptable, contingent on the actual formation structure and any deviations from the predicted formation dip. If reservoir properties differed significantly from expectations or faulting was encountered, the geosteering plan would be re-evaluated and adjusted.

Geosteering Workflow and Rationale

Offset well data was loaded into the geosteering software for rigorous data quality control. The resulting True Vertical Depth (TVD) logs were analyzed to confirm the positional accuracy within the target zone. Formation evaluation revealed significant resistivity contrasts between the upper and lower boundaries of the reservoir, and also between its sublayers, providing valuable insights into boundary proximity.

Pre-well modeling of azimuthal propagation resistivity yielded promising results [Figure 8 & 9](#)). After consulting with all stakeholders, it was decided to implement sourceless BHA solutions for geosteering in Well B. This strategy will utilize azimuthal deep propagation resistivity, azimuthal Laterolog high-resolution resistivity imaging, and gamma ray sensors. Additionally, real-time formation porosity and permeability data will be obtained using NMR.

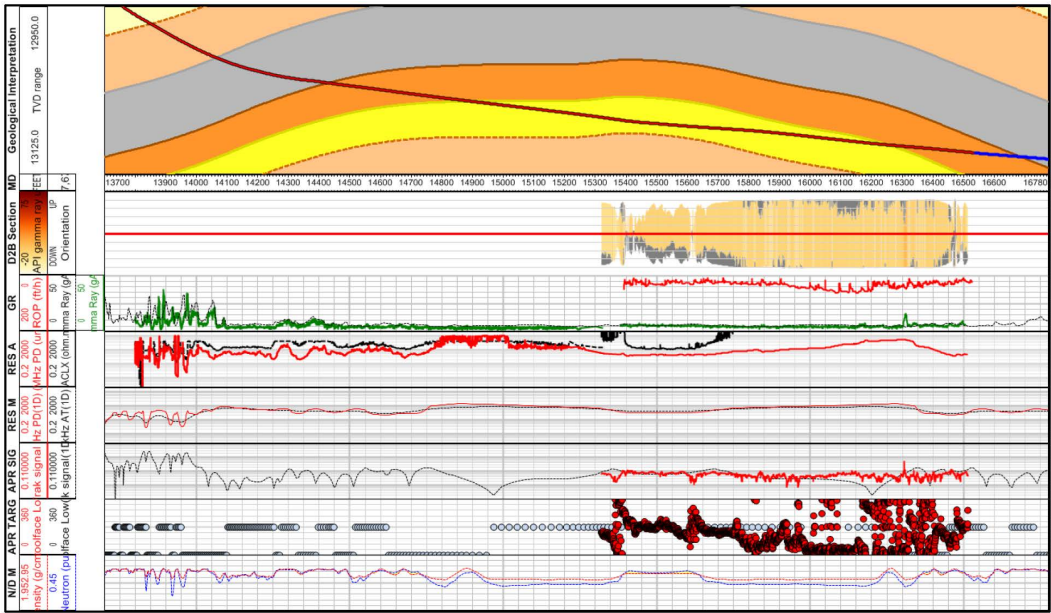


Figure 8—Well A curtain Section based on the offset wells.

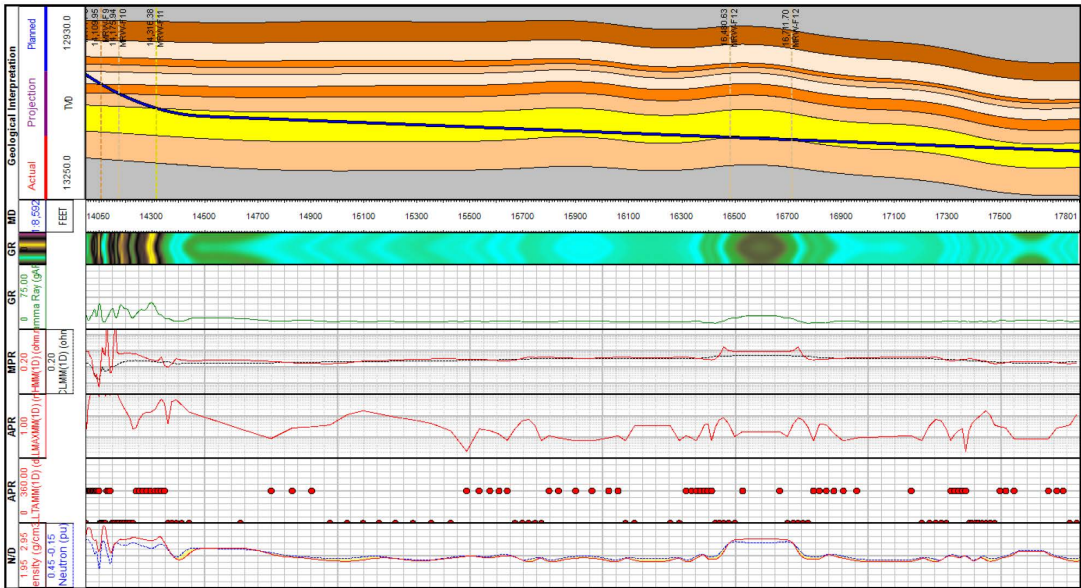


Figure 8—Well B curtain Section based on the affset wells.

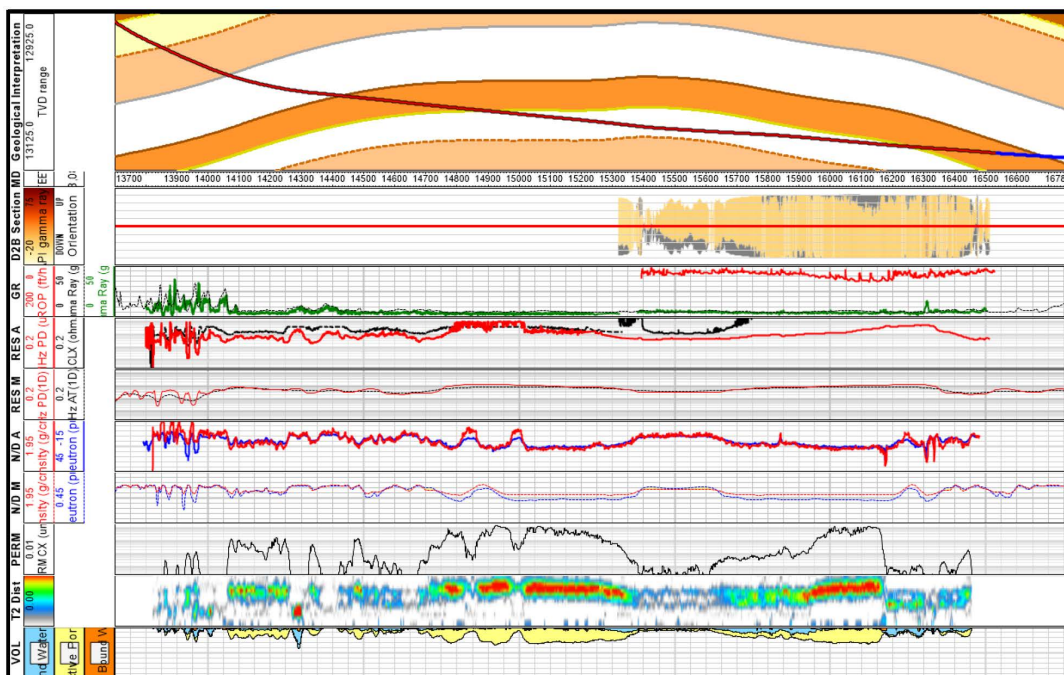


Figure 9—Curtain Section: final model based on Offset Well

## Well A – Geosteering Operation Summary

Initial lateral drilling in the lower MRW-F13 reservoir commenced at an 87.5° inclination. Real-time logging, particularly the Azitrak™ signal, revealed upward stratigraphic movement, prompting adjustments. The inclination angle was increased to 89°.

The original plan was to maintain this 89° inclination until resistivity reached 200 ohmm. However, the AziTrak™ tool detected a conductive body upslope, requiring a reduction in inclination to 88.0° to compensate for the reservoir's dip and prevent further upward movement.

Resistivity subsequently increased to approximately 400 ohmm, indicating good quality reservoir rock and proximity to the F13/F12 boundary. The wellbore successfully exited MRW-F13 and entered MRW-F12 as planned.

Drilling continued at 88.0° inclination, guided by the Azitrak™ signal, until reaching total depth (TD). The wellbore remained within the target reservoir zone throughout the lateral section, as designed.

Figure 9 presents the final well model based on offset well data. NMR data, logged after washdown, confirms that the well was successfully placed 100% within the target layer. However, the NMR porosity data (shown as the first track in yellow) indicates that the reservoir quality in this location is not optimal.

## Well B Geosteering Summary (NMR While Drilling)

The well was landed and the lateral section geosteered within the MRW-F11 reservoir utilizing AutoTrak, AziTrak, and MagTrak BHAs for geo-correlation, guided by a resistivity forward model and formation top picks based on offset wells.

The initial landing and lateral drilling proceeded as planned. However, formation tops, starting with MRW-F8 (5 ft TVD shallower), were encountered at shallower depths than predicted. Following consultation, the team approved increasing the dog leg severity (DLS) to 4.65 deg to adjust for the shallower anticipated MRW-F11 entry. The top of the MRW-F11 reservoir was ultimately encountered 24 ft TVD shallower than planned.

Geosteering adjustments were then implemented. Initially, inclination was increased to 90.7 deg based on AziTrak data (suggesting improved facies 2 ft TVD above the well). The well was then leveled to 90 deg and

subsequently gradually dropped to 89.3 deg, guided by AziTrak and MagTrak (porosity and permeability index) data, to optimize placement within the middle section of the F11 reservoir.

Drilling continued to section TD, maintaining the wellbore within the targeted zone of the F11 reservoir.

Figure 10 illustrates the finalized well model, developed using offset well data. NMR data was instrumental in geosteering the well to target and remain within the highest-quality reservoir facies.

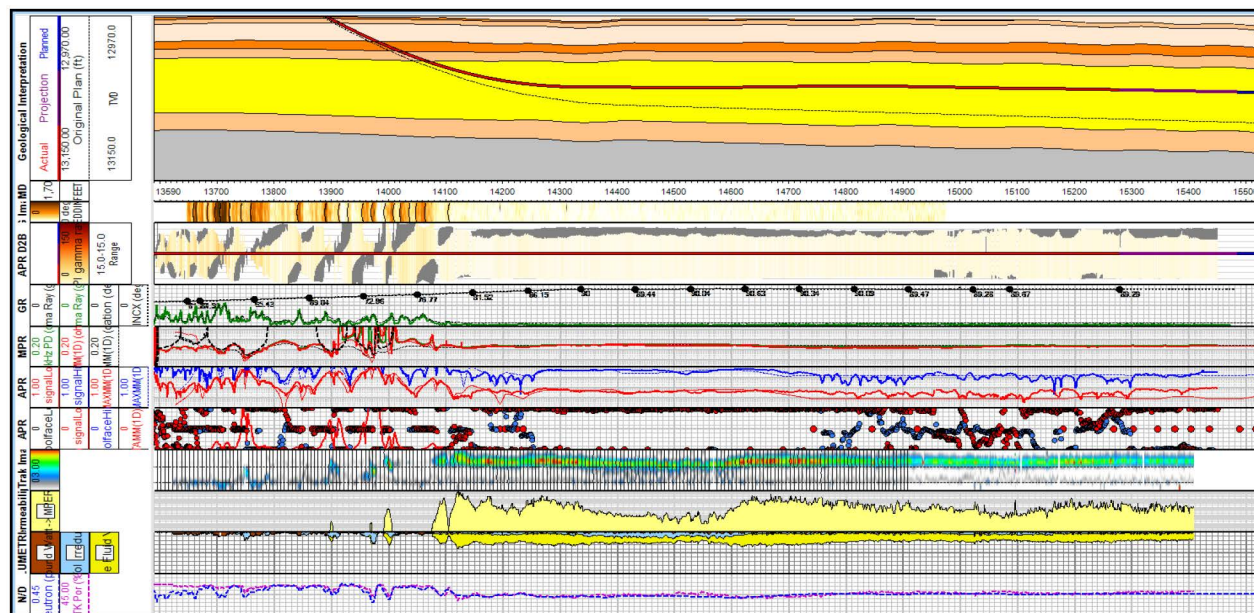


**Figure 10—Curtain Section: final model based on Offset Well**

## Completion and production optimization

In completion design for tight lateral sections, source-less NMR porosity offers a significant advantage over density-neutron porosity measurements. Density-neutron logs often overestimate effective porosity in tight formations because they include capillary-bound water within their total porosity calculation. Source-less NMR, however, excels at distinguishing between free and bound fluids, effectively mapping the capillary-bound porosity. By accurately identifying the fraction of porosity that contributes to fluid flow (free porosity), NMR enables a more precise assessment of reservoir potential, allowing for optimized completion strategies that target intervals with higher permeability and avoid stimulation of sections dominated by unproductive, capillary-bound water, thus maximizing production from the lateral section.

In the challenging tight carbonate formations of West Kuwait, production optimization using While Drilling Nuclear Magnetic Resonance (WD-NMR) offers a powerful approach. WD-NMR logging provides real-time, high-resolution measurements of crucial petrophysical properties like porosity, permeability, and fluid typing, allowing for immediate adjustments to drilling parameters and well placement. This real-time data enables geosteering within the most productive zones, maximizing reservoir contact and minimizing formation damage, crucial for enhancing well productivity in tight carbonate reservoirs with limited natural permeability. Furthermore, the ability to identify bypassed pay zones during drilling with WD-NMR opens possibilities for strategic wellbore stimulation or recompletion, ultimately boosting overall field production in these geologically complex and economically significant reservoirs.

Figure 11 illustrates the value of LWD NMR technology in optimizing perforation strategies in Well A. The final formation evaluation compares perforation intervals suggested by conventional density-neutron porosity logs (yellow) with intervals identified using post-drilling LWD NMR data (green). The NMR analysis proved crucial in recognizing and bypassing zones with critically low effective porosity and near-zero permeability, thereby improving the likelihood of a successful completion.

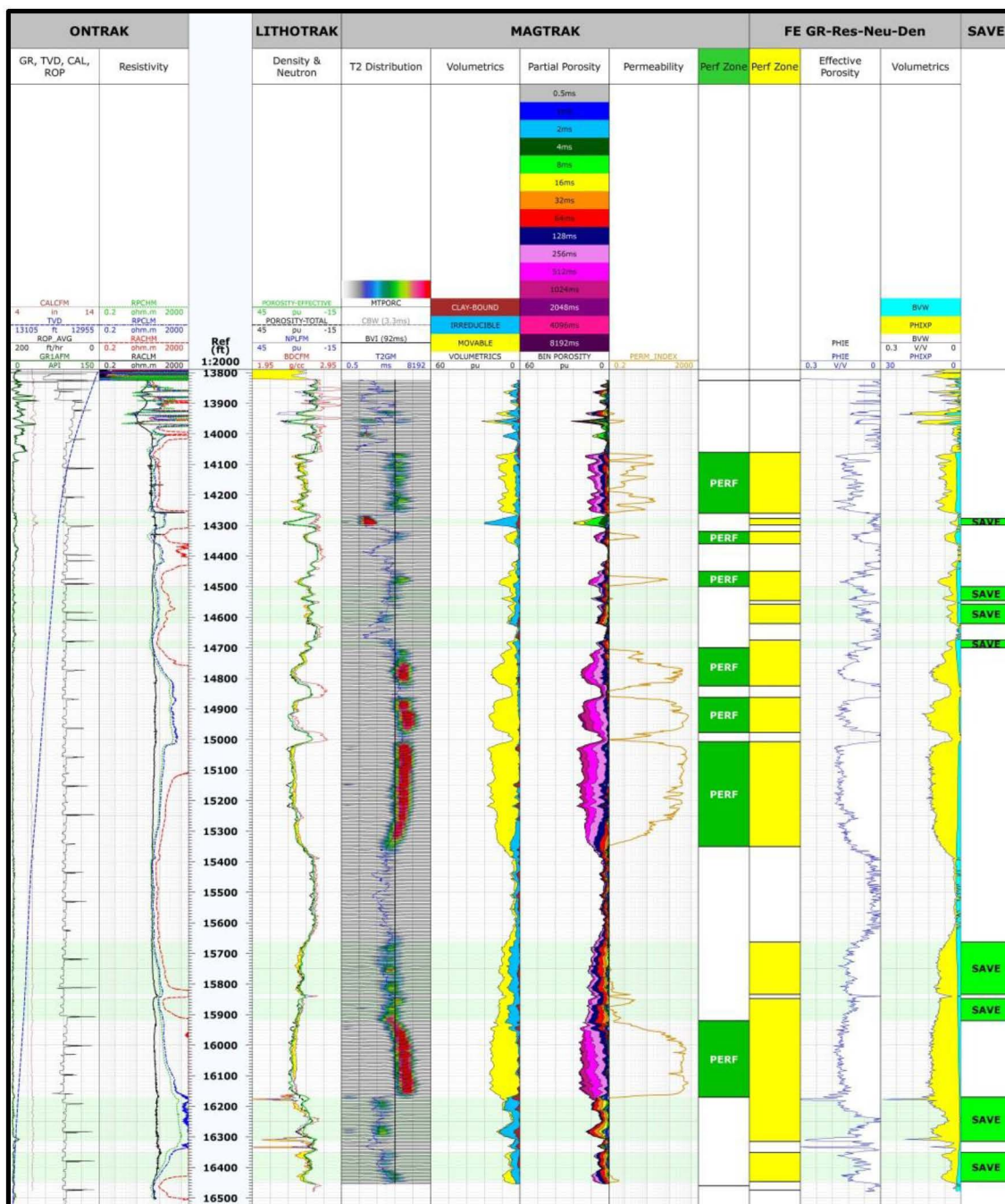


Figure 11—Well A final formation evaluation with perforation intervals as suggested from density Neutron porosity (Yellow color) and perforation intervals as suggested from after drilling LWD NMR results (green color).

Figure 12 highlights a key difference between Well A and Well B. Well B, using WD-NMR, revealed a previously unrecognized zone with substantial hydrocarbon saturation. This data allows for future stimulation aimed at increasing production from this bypassed zone. In contrast, Well A, lacking WD-NMR analysis, offers no such insight, potentially leaving valuable hydrocarbons unrecovered.

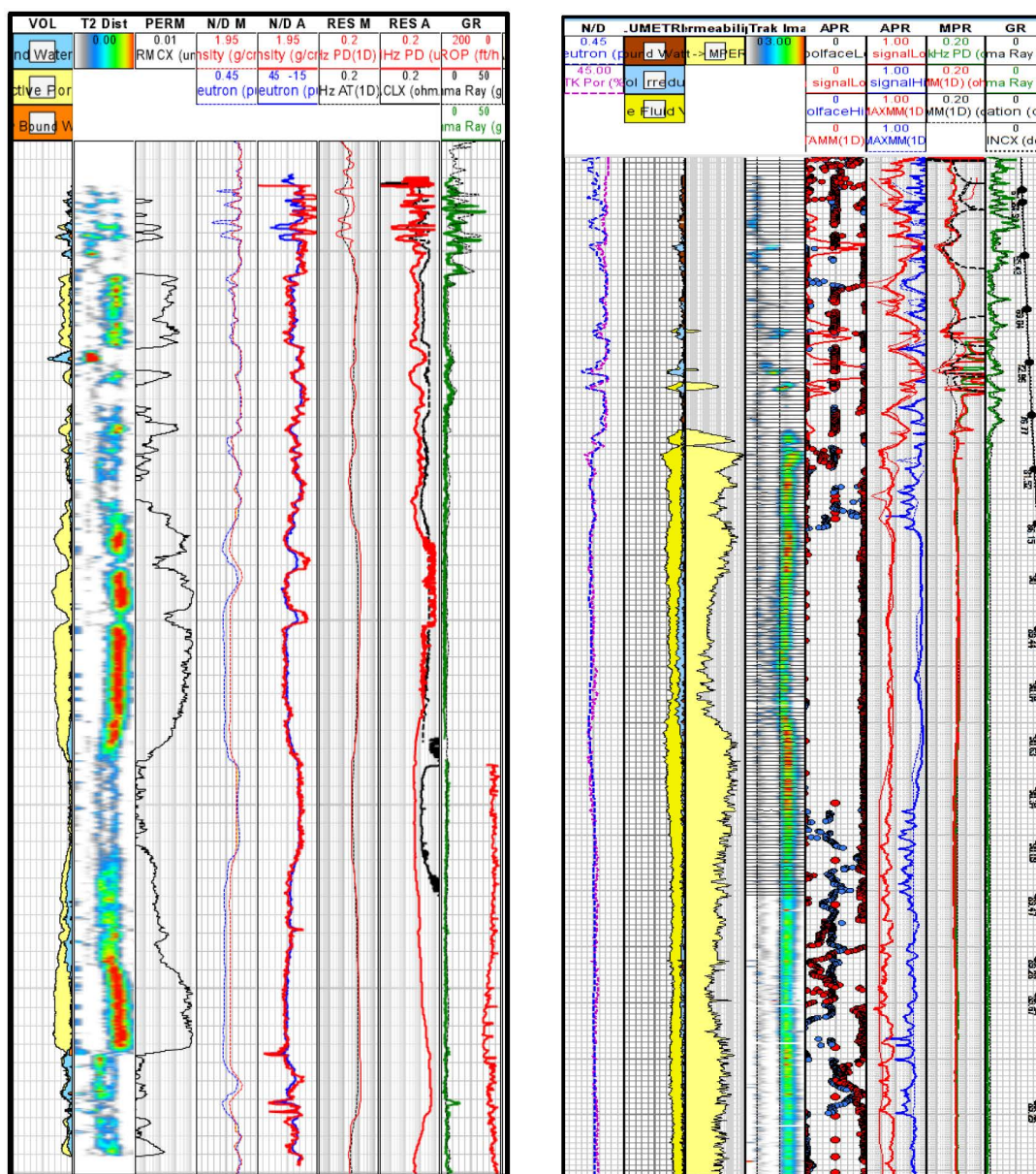


Figure 12—log comparison: Well: A Well: B

The advantage of WD-NMR is clearly demonstrated when comparing wells drilled with and without this technology. For example, in Well A, where NMR data was not recorded while drilling, the well's production potential was inherently limited by the lack of real-time reservoir understanding. However, in Well B, where WD-NMR was utilized, the real-time data revealed a ~1000 ft additional interval of high permeability containing movable fluid. This discovery allowed for immediate geosteering to stay within this highly productive zone.

This targeted geosteering, guided by WD-NMR, leads to significantly increased reservoir contact and minimizes formation damage. Furthermore, the ability to identify bypassed pay zones during drilling with WD-NMR opens possibilities for strategic wellbore stimulation or recompletion. The expected outcome from strategically drilling in these sweet-spots will boost overall field production. Such enhancements are projected to increase production by ~3000 bopd or higher in geologically complex and economically significant reservoirs.

## Conclusion

By effectively implementing an integrated approach that combines while drilling nuclear magnetic resonance (NMR) and deep azimuthal resistivity (DAR), we have successfully addressed the difficulties associated with well placement in a highly heterogeneous environment. This approach has allowed us to circumvent the need for radioactive-based porosity logging tools in this particular well profile. As a result, the project has not only achieved substantial cost savings in terms of drilling and logging operations but has also significantly increased production in the Umm Gudair field.

While drilling NMR technology offers an invaluable advantage in tight carbonate formations, enabling real-time decision-making, optimized well placement, and increased production. The substantial production increase demonstrated by scenarios like Well B clearly showcases the potent economic benefits of implementing WD-NMR as a standard practice in West Kuwait operations.

## Acknowledgement

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## Abbreviations

|        |   |                                                        |
|--------|---|--------------------------------------------------------|
| (BHA)  | – | Bottom hole assembly                                   |
| CAPEX  | – | Capital expenditures                                   |
| (CBW)  | – | Clay Bound Water                                       |
| DAR    | – | Deep Azimuthal Resistivity                             |
| D2B    | – | Distance to Bed                                        |
| ft     | – | Feet                                                   |
| Fig.   | – | Figure                                                 |
| DLS    | – | Dog Leg Severity                                       |
| BVI    | – | Irreducible Fluid                                      |
| KOC    | – | Kuwait Oil Company                                     |
| kHz    | – | kilohertz                                              |
| KM     | – | Square kilometre                                       |
| LWD    | – | Logging While Drilling                                 |
| (BVM)  | – | Movable Fluid                                          |
| NMR    | – | Nuclear Magnetic Resonance                             |
| RF     | – | Radio-frequency                                        |
| RSS    | – | rotary steerable system                                |
| SDAR   | – | Standardization of Deep Azimuthal Resistivity Services |
| pu     | – | Porosity Unit                                          |
| ppg    | – | Pounds per gallon                                      |
| TVD    | – | True vertical depth                                    |
| 3D     | – | Three Diminutions                                      |
| WK     | – | West Kuwait                                            |
| Tw     | – | Wait Time                                              |
| WD-NMR | – | While Drilling Nuclear Magnetic Resonance              |

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