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1. FROM OUTCROP TO RESISTIVITY RESPONSES: FIELD-BASED TRAINING FOR UNDERSTANDING SUBSURFACE FLUVIAL RESERVOIRS USING SYNTHETIC ULTRA-DEEP AZIMUTHAL RESISTIVITY (UDAR) INVERSIONS.

For decades, analogue outcrop studies have been critical for characterizing complex subsurface architecture across depositional environments. The integration of UDAR tools with Logging-While-Drilling (LWD) measurements has significantly improved horizontal well placement and maximized reservoir contact. However, accurate interpretation of UDAR inversion results demands a comprehensive understanding of both the underlying electromagnetic physics and the geological context. To address this, Equinor is developing a series of field-based training courses focused on subsurface interpretation challenges. This paper is centered on the well-exposed Olsón Member fluvial outcrop (Escanilla Formation) in the Aínsa Basin, Spanish Pyrenees. This site offers exceptional geological control for building high-resolution three-dimensional (3D) models and generating synthetic UDAR inversion outputs. This unique framework enables direct comparison between known geological features and simulated tool responses, enhancing subsurface interpretation reliability and supporting informed decision-making in reservoir characterization and geosteering operations.

To enhance the geological interpretation of UDAR data, a structured workflow was applied to reconstruct the outcrop analogue as a high-resolution geological model. Sedimentological data, including facies types, bed thickness, lateral extension and stacking patterns were collected from three detailed sections to establish a sequence stratigraphic framework. This supported the construction of a deterministic facies model capturing heterogeneities typical of fluvial reservoirs. Resistivity values were assigned to each depositional facies using analogue data from producing fluvial reservoirs in the Norwegian Continental Shelf (NCS). Subsequently, five synthetic well trajectories were incorporated into the model, intersecting a range of architectural elements. These trajectories were used to simulate UDAR responses through multilayer inversion across varying tool spacings and frequencies. The resulting synthetic datasets enable direct comparison between modeled geology and inversion outputs, offering insights into UDAR resolution limits and interpretation challenges in heterogeneous settings.

Synthetic modeling enables Bottom Hole Assembly (BHA) optimization to improve UDAR inversion sensitivity to fluvial reservoir heterogeneity, enhancing resolution of depositional architectures and stratigraphic variability. Despite these improvements, discernible challenges remain. Low resistivity contrast between architectural elements, combined with vertically stacked facies below the UDAR tools vertical resolution, hinders reliable facies discrimination. Inversion results revealed interpretational risks, mainly driven by the layered nature of the reservoir, including geometric distortion of distal boundaries where planar interfaces appear undulated and overestimation of distal layer thicknesses with inverted resistivity lower than modeled. These circumstances can lead to inaccurate volumetric estimates and misinterpretation of structural or fluid contacts critical for reservoir characterization. Additionally, signal attenuation in low-resistivity formations caused non-detection of adjacent resistive bodies, potentially hydrocarbon-filled, highlighting the difference between geophysical resolution limits and actual geological absence. These results emphasize integrating geological models with tool physics to mitigate interpretational uncertainty in complex fluvial settings.

The training framework enables participants to evaluate how BHA design parameters and frequency settings impact inversion accuracy across diverse depositional architectures. It fosters a deep technical understanding of UDAR constraints, including boundary distortion, vertical resolution limits, and resistivity contrast sensitivity. By analyzing inversion uncertainties within a controlled geological setting, geoscientists gain the ability to recognize when key features may be misinterpreted or overestimated. Although challenges remain, the consistent application of UDAR tools has demonstrated superior outcomes compared to their absence in horizontal well placement. The dual emphasis on tool optimization and interpretation complexities enhances subsurface workflows, improving well planning and geosteering operations, reservoir delineation, and volumetric estimation in fluvial systems. This initiative reinforces the integration of robust UDAR data interpretation skills within the geoscientists' expertise, strengthening technical decision-making and operational excellence.

2. HORIZONTAL LOOK-AHEAD GEOSTEERING UNLOCKED BY NOVEL TRIAXIAL AND MULTI-DEPTH AZIMUTHAL RESISTIVITY

Horizontal look-ahead-of-the-bit inversion capability has been the pursuit for decreasing reaction time, identifying or avoiding drilling risks and maximizing reservoir exposure. In recent years, the introduction of innovative UDAR technologies with near-the-bit array architecture enabled mapping of reservoir resistivity changes ahead of the bit. This paper demonstrates how a breakthrough in sensor engineering enables look-ahead resistivity inversion and an increase in accuracy of reservoir mapping capabilities. The innovation is a new integrated drilling and reservoir mapping platform with a novel array of triaxial collocated antennas that enhance 3D reservoir understanding and allows proactive geosteering decisions with its look-ahead capability.

To characterize complex reservoirs with vertical and lateral heterogeneities, multi-spacing azimuthal resistivity arrays (MSAR: ultra-deep and deep azimuthal resistivity) have been routinely deployed in tandem. However, such a combination has a lower signal-to-noise ratio and a compromised 3D sensitivity to formation changes. To overcome the systematic error associated with such architecture, a new drilling and reservoir mapping platform has been developed which combines shallow, medium, deep, ultra-deep and extra-deep measurements (MDAR: multi-depth azimuthal resistivity) with fully triaxial, collocated and calibrated antennas. This new platform provides improved signal-to-noise ratio and enhanced sensitivity to the formation's 3D resistivity changes.

The new service was run in clastic formations, representing complex channel sands with a strong meandering nature. Such a geological environment often presents features such as pinch-outs which are the manifestation of the meandering sand channel in the vertical intersection plane of the wellbore (1D inversion). The Look-ahead inversions on the subject well successfully captured one of such pinch-out features ranging as far as 70ft ahead of the bit The look-ahead sensitivity (distance) ahead of the bit and the rate of penetration (ROP) are critical factors for proactive geosteering considering the necessary time to receive the LWD measurements at surface, run the inversion and generate the resistivity map changes ahead of the bit versus the time to drill the interval ahead of the bit before intersecting the already imaged features.

This newly developed, novel multi-depth azimuthal resistivity (MDAR) platform confirmed the benefit of the new triaxial and collocated array configuration providing a robust, look-ahead reservoir mapping while drilling inversion, even within a complex, 3D channelized environment. The look-ahead inversion processing which utilizes high bit-rate mud-pulse telemetry, coupled with cloud computing resources enables inversion processing and interpretation of the results all within a in real-time context. This unlocks strategic geosteering decisions before features have been drilled by the BHA.

3. SOME COMMON PITFALLS IN THE INVERSION OF BOREHOLE UDAR MEASUREMENTS

Unlike conventional resistivity measurements acquired with logging-while-drilling (LWD) or wireline tools, Ultra-Deep Azimuthal Resistivity (UDAR) data cannot be directly interpreted without inversion. UDAR measurements are intrinsically complex, combining electromagnetic signals from various transmitter-receiver spacings, orientations, and operating frequencies. These measurements also exhibit strong nonlinear behavior with respect to spatial variations of electrical conductivity, especially in 3D, heterogeneous, and anisotropic formations, making UDAR inversion a persistent challenge. In this presentation, we discuss some potential pitfalls associated with UDAR-measurement inversion and provide recommendations to circumvent them.

We focus our study on the gradient-based inversion method with a quadratic cost function composed of data misfit and regularization terms (Occam type inversion). To address potential pitfalls, we apply this inversion method to both synthetic UDAR measurements and field data. We explore a broad range of conditions by varying the inversion's dimensionality (1D, 2D, 3D), regularization types (Tikhonov 0th-2nd order, Total Variation), and input data types (magnetic fields, voltages, apparent conductivities, geo-signals, etc.). We also vary inverted properties such as log(Rh), log(Rv), anisotropy ratio (Rv/Rh), and formation dip. Additionally, we test different formulations for data misfit (variance or standard deviation) and model uncertainty (Hessian inverse or Bayesian extrapolation). Special consideration is also given to different possibilities of prior information (none, LWD, 3D geological information), and the presence of external 3D objects offset from the well trajectory (none, conductive, resistive).

The most common pitfall is that 1D inversion results are often unreliable when the trajectory intersects a discrete 3D object such as a fault, or when a 3D object is present off-well trajectory. For these cases, higher-dimensionality inversion (2D or 3D) is needed. The commonly used Tikhonov regularization is inferior to Total Variation regularization for producing sharp inversion results. Although geo-signal data can enhance inversion sensitivity (e.g., boundary, anisotropy, dip), they also amplify noise more than other data types. We found that inverting for the anisotropy ratio rather than log (Rv) and including formation dip yield stable and accurate inversion results. Incorporating prior information from LWD data and 3D geological models helps to stabilize the inversion and mitigate non-uniqueness. The best way to calculate data misfit is with standard deviation, which correctly reflects data noise level, while model uncertainty is best calculated using Bayesian extrapolation, as it reflects tool sensitivity.

We identified several common pitfalls of UDAR inversion and offered key recommendations for more reliable interpretations. While 1D inversion is fast and widely used for real-time well geosteering applications, extreme caution is needed to interpret the corresponding results, especially when drilling into 3D environments. Relying solely on inversion results can be misleading because of non-uniqueness, hence, calculating data misfit and model uncertainty is important for the appraisal of inversion results. Where misfit and/or uncertainty is high, 1D inversion results should not be trusted along the entire well trajectory, and a higher dimensional inversion should be pursued instead. We also suggest that service providers clearly state all inversion assumptions, including regularization, data types, model parameters, and prior information, as this transparency enables improved interpretability and improvement of inversion results as additional data are being acquired during the life of a reservoir.

4. RAPID ADAPTIVE 2D/3D UDAR INVERSION: LEVERAGING A NEW BLOCK GAUSS-RADAU SOLVER AND ADJOINT SOLUTIONS

Ultra-Deep Azimuthal Resistivity (UDAR) measurements provide advanced subsurface imaging capabilities by bridging the gap between traditional well logging and seismic interpretation. However, interpreting UDAR measurements in complex, spatially heterogeneous, or anisotropic formations remains challenging. Traditional 2D/3D inversion procedures are computationally intensive and unsuitable for real-time applications. In this study, we develop and successfully verify a rapid, adaptive 2D/3D inversion for a robust and reliable interpretation of UDAR measurements. The Jacobian matrix is efficiently calculated and updated with a novel Block Gauss-Radau modeling algorithm via the adjoint method. The method is successfully validated with challenging synthetic and field measurements provided by various operating companies.

Inversion is performed using a gradient-based approach (Occam-type) and incorporates regularization to account for noise and non-uniqueness. The inversion complexity grows adaptively from 0D to 3D, based on the localized dimensionality of both measurements and spatial distribution of electrical conductivity. Modeling employs a new block Gauss-Radau solver, which is superior to the traditional Spectral Lanczos Decomposition Method (SLDM) for simulating rapid, accurate, and numerically stable UDAR measurements. This new solver adopts an interactive block method to efficiently compute multi-input multi-output (MIMO) finite-volume solution of Maxwell's equations in a single run. The Jacobian, or sensitivity matrix, is computed using mixed inner-outer products within block-Lanczos recurrences, reducing computational time by half compared to SLDM. Both modeling and inversion algorithms are designed for multi-CPU clusters and tailored for integration with local 3D geological models and arbitrary well trajectories.

We tested and verified the modeling and inversion method using challenging 2D/3D synthetic models inspired by field data, as well as actual field measurements. Figure 1 (attached) compares the Jacobian (or sensitivity) calculation for an anisotropic vertical fault model. While the conventional brute force method took over 50 days on a standard PC, the adjoint method with the new solver completed in just 20 seconds. Figure 2 compares our rapid adaptive 2D/3D inversion results with 1D inversion results. The 2D and 3D inversions show significant improvements, with inverted resistivity curtains closely matching the true 3D fault model. Furthermore, both data misfit and model uncertainty are notably reduced, particularly around the fault location. With parallel computing, the local 2D inversion runs in about 120 seconds, comparable to 1D inversion, while 3D inversion takes 600 seconds, which can be further reduced with GPU implementation.

Through successful verification using challenging synthetic models and field measurements, our rapid 2D/3D inversion method is robust and reliable for interpreting borehole UDAR measurements. Our new forward simulation method efficiently calculates the Jacobian matrix using the adjoint method, resulting in calculation times that are five orders of magnitude faster than a conventional brute-force approach. Significant improvements were found in inversion results (with low data misfit and model uncertainty), particularly in a 3D environment, when compared to traditional 1D inversion results. The current modeling algorithm is already fast but can be further accelerated with GPU implementation to achieve real-time 2D and 3D inversions.

5. A NEW INTER-INDUSTRY MODELING WORKFLOW FOR UDAR PRE-DRILL STUDIES IN 3D GEOLOGICAL ENVIRONMENTS

The Ultra-Deep Azimuthal Resistivity (UDAR) technology which was introduced about 20 years ago has fully proven itself in environments characterized by 1D "layer-cake" slow changing geology where it is now a reliable and highly valuable service. But many wells, in particular infill wells in mature fields, are often drilled in 3D environment. Operators are constantly looking for cheaper solutions with less environmental footprint by accessing multiple blocks with one horizontal well. A local 1D inversion which works well in 1D slow-changing formations, and which is a standard real-time processing for all service providers is inadequate / unreliable in well trajectory intervals with severe 2D/3D effects such as faults with significant throws.

We developed a new inter-industry workflow for UDAR modeling in 3D environments. In particular, a very efficient and accurate 3D modeling code has been developed, which is parallelized for cluster and cloud use. As we illustrate in the attached figure, a 3D model is built in the specially developed Coarse Model Editor or imported into it as XYZ file, digitized on a very fine grid and outputted into an hdf5 file along with a provided well trajectory. Then a 3D modeling job with this input file is submitted to the operating company cluster at the High-Performance Computer (HPC) center. The calculated magnetic field tensors for a vendor-specific UDAR tool configuration are then passed over to the service provider, where the realistic tool noise is added to the simulated data and then interpreted with 1D and 3D inversions.

We applied this workflow during the pre-drill study for the GoA well targeting a clastic reservoir which is heavily faulted and compartmentalized to resemble a "shattered glass". We constructed multiple realistic 2D and 3D models - all models included multiple faults with different fault dips, azimuths and fault throws. Some of the models included as many as 16 faults and some of the inversion exercises were conducted as "blind tests". With this approach we built a catalog of 2D and 3D synthetic models as well as generated real 3D models from subsurface geoscience software, studied 1D artifacts in realistic 3D models and estimated the uncertainties of 1D and 3D inversions in these models. We will describe all these results in our presentation and will discuss the novelty and accuracy of the new 3D modeling algorithm, its performance on the HPC cluster and some of the features of the developed UDAR utilities.

We developed a new inter-industry 3D UDAR modeling workflow. This workflow creates a new standard for UDAR pre-drill studies in 3D environments where a local 1D modeling-based workflow which works well for 1D slow-changing formations, and which is a standard pre-drill study approach for all service providers is inadequate. The new workflow also demonstrates technical complexity, required expertise in different areas, as well as resources and the level of inter-industry collaboration needed to robustly solve this problem.

6. NOVEL UDAR WORKFLOW COMBINING 3D RESERVOIR MAPPING WITH RESISTIVITY RANGING WHILE-DRILLING

As additional boreholes are drilled in congested oilfields, the presence of nearby wells containing metallic objects (e.g., casing or screens) can become a challenge for the successful well construction, especially for infill wells or sidetracks. Moreover, it can represent a major drilling risk due to potential collision events. Depending on the distance, such metallic objects can directly interfere with UDAR measurements causing significant impairment to the inversion results. Thus, this paper describes a novel modelling approach that can determine and measure the metal effects on the 3D EM measurements for every frequency and spacing of UDAR tool. Furthermore, motivated by such high sensitivity of UDAR measurements to nearby metallic objects, an innovative well ranging while-drilling solution was developed to provide in real-time the relative distance and the azimuthal direction of the target well, enabling all ranging applications, such as collision avoidance, well twinning, and even well interception during the drilling operation.

The traditional modelling approaches cannot be effectively deployed in the presence of metallic objects due to their geometrical shape and highly conductive property, since these solutions were designed originally for conditions related to only subsurface formation. Therefore, the novel solution consists of a 3D advanced modelling with finite-element method, where the metallic objects are considered perfect electrical conductors. Then, a complete 3D forward modelling of the UDAR measurements is performed in such advanced model to determine the effects caused by both formation and the metallic objects at any 3D spatial direction. Moreover, to leverage on this high sensitivity of UDAR to metallic features, a novel well ranging application for cases of near parallel wells was developed. It is a real-time parametric solution based on tool response table, which uses the second harmonic measurements and considers the resistivity anisotropy, to determine while-drilling the relative distance and direction of the target well.

The novel solution was deployed in a real case in offshore Brazil, where the main goal was to determine the effects on UDAR measurements caused by a metallic screen of a nearby well during drilling of a sidetrack. In the pre-job stage, the advanced modelling prognosed the safe distance from metallic interference for each spacing and frequency of the UDAR tool configuration. Then during the operation, the metallic effects on the 3D EM measurements were observed within the predicted interval defined by such novel modelling approach, and substantiated by presence of artifacts in the resistivity inversion. Moreover, the ranging workflow was deployed while-drilling to effectively determine the relative distance and azimuthal direction of the adjacent well with completion screen. Such new workflow was applied using each transmitter-receiver spacing independently with the objective of enabling a multi-depth ranging detection. The respective results of this real case are illustrated in the attachment.

This paper presents a novel approach of expanding the current modelling and answer products of the Geosteering domain by enabling simultaneously the 3D mapping of the subsurface formation together with detection of downhole metallic objects. With the ever-growing number of wells, especially in mature fields, the ability to provide beyond reservoir mapping by also determining the presence of existing boreholes in the drilling vicinity is becoming even more critical. It has great potential to optimize field revitalization by enabling the drilling in zones previously prohibited due to collision concerns driven by survey uncertainties. This real case demonstrates the full capability of the innovative approach, starting from pre-job modelling that provided a measurement interference analysis caused by metallic screen all the way to the deployment of the well ranging that determined the position and direction of the nearby well with a unique multi-depth detection thanks to UDAR configuration with different spacings.

7. CHARACTERIZATION OF INVERSION ARTEFACTS IN UDAR DATA FOR GEOSTEERING APPLICATIONS

Optimal well placement is important for exploration, appraisal, pilot and production wells. Ultra deep azimuthal resistivity (UDAR) has for more than a decade been a key tool for mapping reservoir geometry and optimizing well placement. UDAR tools have larger transmitter-receiver spacings and lower transmitting frequencies than previous electromagnetic logging tools. This gives the capability to map reservoir geometries at large distances around the wellbore, but interpreting the data can be challenging due to inversion artefacts. By artefacts we mean apparent resistivity contrasts in the inversion which do not correspond to real resistivity contrasts. In this paper we show that significant artefacts can appear even in relatively simple settings; it is enough that we have e.g. simple 2D geometries before the assumptions in the 1D inversion are not met.

To be able to distinguish commonly seen artefacts from possible real resistivity contrasts within the UDAR sensitivity range, a series of simple models have been created. The models are variations of simple geometric shapes. This facilitates a quantitative analysis of the shape, size, and magnitude of the observed artefacts. Using the service provider's cloud-based simulation and inversion tools, we have independently carried out simulation and inversion of UDAR data. These results have been compared both with results from synthetic simulation on realistic high-resolution models and with real inverted UDAR data.

Results from the simple models have been compared with real observations. We observe in the synthetic data that the truncation of resistivity contrasts causes strong artefacts in the inversion. They can be observed as resistivity contrasts dipping up or down from the edge of the truncation, or as a pull up or push down of the oil water contact or top reservoir. All these types of artefacts from synthetic data have been recognized in real data.

With the use of simple models, we have been able to recreate several artefacts typically observed on real data on the Norwegian continental shelf. Many artefacts are caused by use of 1D inversion in inherently 2D or 3D geological settings, but artefacts can also be caused by mechanisms such as e.g., inversion converging to a local minimum, unaccounted anisotropy or data windowing. By understanding the root cause of the artefacts and recognizing them in real data, we increase our confidence in the UDAR interpretation. This knowledge increases the value of information from UDAR measurements for both real time geosteering and for the final well completion. It also increases the value of UDAR data for post-well analysis as input to geomodels and further well planning.

8. ACCESSING MULTIPLE FAULT BLOCKS WITH A HORIZONTAL WELL USING UDAR TECHNOLOGY IMPROVES ECONOMICS AND REDUCES FOOTPRINT OF INFILL WELLS: A GOA CASE STUDY

Drilling sub-vertical infill wells in mature, compartmentalized fields is an economically challenging task because the resource volumes in individual fault blocks may not justify capital expenditures. In contrast, a single horizontal well can access multiple fault blocks, which may simultaneously facilitate favorable well economics and reduce overall environmental impact. In this paper, we will describe the complexities of well planning and execution of a horizontal well through several fault blocks in a deep-water turbiditic-sandstone reservoir.

Key planning and operational challenges included narrow drilling margins, risk of losses due to faults and damaged zones through differentially depleted sands, risk of wellbore stability issues, and uncertainty of lateral fault placement and dip separation. During well planning, uncertainties of the geological model were reduced based on all available seismic data (eFWI, Kirchoff, RTM), offset well data, and nearby cored reservoir. During operations the use of high resolution Ultra Deep Azimuthal Resistivity (UDAR) tools proved critical in the seismic depth calibration and in adding complexity to the geologic model. UDAR tools were utilized for Geosteering in both landing and horizontal sections. During the well execution phase, the team utilized a Real-time Collaboration and Decision Room, staffed 24/7 by a multi-disciplinary subsurface team from operator and service provider. The Collaboration Room facilitated quick, optimized geosteering decisions based on UDAR data integrated with seismic, LWD logs and imaging, and formation pressures.

We will discuss the novel application of UDAR technology in a structurally complex 3D environment, due to non-orthogonal faults, through the landing and lateral drilled sections. We will describe the challenges and highlights of the 2-year long pre-drill study, real-time execution, interpretation, decision making, and post-drill analysis associated with the UDAR application. Although UDAR tools have been in service for several years, the application has been mostly in 1D environments with slow stratigraphic changes often utilizing pilot wells. Due to uncertainties and artifacts of UDAR 1D inversion images in 3D environments and drilling without a pilot well, an LWD OBM Imaging tool and Formation Pressure tool were also incorporated to identify the faults, fault blocks, and reservoir features to assist with real-time Geosteering decisions. We present examples of real-time Geomapping through a structurally complex reservoir compared to 1D and 2D inversions from memory data and show the operational decision impacts.

We discuss the benefits and challenges of using UDAR technology in a 3D environment, with large structural changes due to the presence of multiple non-orthogonal faults. We document artifacts seen by 1D inversion in 3D environment and highlight areas of improvement in forward modeling and inversion needed for this technology in future applications. We illustrate how a collaboration of a multi-discipline team during well planning and the execution phase and integration of UDAR data with other formation evaluation tools led to a reduction in uncertainty from UDAR results and streamlined the geosteering decision making process. The paper describes the best practices and lessons learned for UDAR pre-job modelling and interpretation of real-time inversion in landing and reservoir sections. We would like to thank bp and Atlantis co-owner, Woodside Energy, for permission to publish this work.

9. WHAT DOES IT TAKE TO MAKE A ROBUST UDAR GEOSTOPPING STRATEGY? DISCUSSION BASED ON GEOSTOPPING RESULTS FROM PRODUCTION WELLS ON THE NORWEGIAN CONTINENTAL SHELF

Setting the casing at an optimal position above the reservoir has become increasingly critical in production wells as the Norwegian Continental Shelf has matured. Historically, the maximum depth limit for this section was set at twice the seismic uncertainty, exceeding 30 m TVD above the reservoir. Exposing tens of meters of unstable shale formation in the subsequent reservoir section increases the risk of formation collapse. The pressure difference between the overburden and the reservoir often complicates the selection of appropriate mud weight, potentially leading to mud loss, blowouts, or stuck pipe. Additionally, the presence of permeable, water-bearing sands above the reservoir may lead to increased water production if opened alongside reservoir sands. Traditionally, these challenges have been handled in a reactive way, but the industry is now adopting a more proactive approach using Ultra Deep Azimuthal Resistivity (UDAR) technology and robust workflows, enhancing drilling efficiency and reducing overall well cost.

UDAR technology has demonstrated the ability to detect resistivity contrasts tens of meters ahead of or below the bit in low-resistive environments, effectively bridging the seismic resolution gap mentioned above. When the top reservoir exhibits a significant resistivity contrast to the overburden shale, the UDAR tool can map this contrast, enabling a controlled drilling stop in the range of 5-10 m TVD above top reservoir. This reduction in overburden exposure has resulted in safer operations by significantly reducing drilling and wellbore stability risks. However, using UDAR for geostopping requires a different approach and mindset for decision making compared to reservoir geosteering in horizontal wells. Most importantly, the consequences of a wrong decision can be disastrous. To address these challenges, conducting extensive pre-job modelling to develop a robust decision strategy is essential for ensuring a successful geostopping operation.

In this paper, we review several UDAR geostopping jobs, focusing on the pre-job-established decision strategies to stop at a specific point above top reservoir and compare these with real-time results. Factors that influence the UDAR inversion result and interpretation include the inversion method (stochastic vs deterministic), the number of receivers, their spacing, the frequencies used, variations in resistivity levels in the shale, and the shape of the resistivity contrast around the top reservoir. Through field results and synthetic pre-job modelling examples, we illustrate the key considerations necessary for successfully planning and executing a UDAR geostopping operation given the factors mentioned above.

Realistic synthetic scenario modelling of UDAR responses in the pre-job phase of geostopping operations is essential for developing a robust decision strategy that enables stopping at a given distance above a resistivity contrast, thereby minimizing the risk of drilling too deep and encountering potentially disastrous consequences. The synthetic UDAR inversions must closely align with real-time results given the same resistivity distribution and contrasts; large differences will undermine the decision strategy for stopping at the planned position in the subsurface. Utilizing percentiles from the stochastic UDAR inversion has proven highly beneficial for geostopping decision-making. Finally, using three receivers in the UDAR inversion process secures early anticipation with large depth of investigation, while shorter receiver spacings improve the ability to resolve resistivity variations in the overburden, facilitating more precise prediction of top reservoir from the UDAR inversion results.

10. RAPID MULTI-LEVEL STOCHASTIC INVERSION OF UDAR MEASUREMENTS FOR LOOK-AHEAD IMAGING WITH UNCERTAINTY QUANTIFICATION

Look-ahead imaging of subsurface electrical resistivity is important for real-time decision-making during well geosteering and geostopping in spatially heterogeneous formations. Ultra-Deep Azimuthal Resistivity (UDAR) measurements provide sensitivity to electrically conductive formations ahead of the bit, but extracting reliable information from these measurements requires robust 2D or 3D inversion. Moreover, to support real-time decisions, inversion results must be achieved fast and accurately and need to include a measure of their uncertainty. Stochastic methods can quantify uncertainty of inversion results but come with a higher computational cost. Traditional gradient-based inversion methods are fast but rely on computing the Jacobian matrix. In contrast, stochastic inversion methods such as Adaptive Simulated Annealing do not require Jacobian calculations and can explore the solution space more freely, relying less on prior information than gradient-based approaches. This flexibility makes Simulated Annealing particularly well-suited for multi-grid 2D and 3D inversion strategies.

Our stochastic inversion strategy improves computational efficiency through several key innovations: (1) multi-dimensional inversion: we progressively add spatial complexity, starting from fast 0D and 1D stochastic inversions, followed by 2D longitudinal and lateral inversions and finally 3D inversion), (2) Multi-fidelity modeling: combining low- and high-fidelity forward models, applying high-fidelity simulations only where necessary along the well trajectory, (3) Multi-grid: inversion grid resolution (inversion pixel size) is adaptively refined during the inversion, guided by model uncertainty, (4) Sparse measurements: using only a subset of UDAR measurements that provide unique, high-resolution information, and (5) Data-driven stabilization: instead of regularization with fixed priors such as Tikhonov methods, we introduce a data-driven stabilization using spatial kriging. Pixel values are estimated via variogram models derived from the current estimation of resistivity in each pixel. Where Logging While Drilling data are available, those locations are anchored as fixed control points for kriging to enhance spatial consistency.

We successfully tested and verified the inversion method using both challenging 2D and 3D synthetic models inspired by field data, as well as actual UDAR and LWD field measurements acquired in the North Sea by various service companies. Using 2D lateral and 3D inversion, we evaluated the look-ahead capability in situations involving tilted faults and complex synthetic cases, such as when the logging point is near a thin conductive layer (see figure). We also applied the method to field data where 3D geological features were present around and ahead of the wellbore. In the synthetic test case, the fault was detected from a distance of 10 feet ahead of the bit. As the bit approached the fault (from 10 feet to 5 feet, and finally to 0 feet), the data misfit decreased from 45% to 27% and then to 19%, while the uncertainty in the estimated resistivity progressively decreased.

The above developments improved computational efficiency of our previous 2D and 3D adaptive simulated annealing inversion algorithm by a factor of 10. Additionally, the use of kriging enhanced the smoothness of the electrical resistivity images and improved the ability to capture layer resistivity contrasts. These results confirm that our stochastic inversion framework enables fast, flexible, and reliable resistivity imaging with uncertainty quantification in complex 2D and 3D environments, thereby supporting safer and more informed well geosteering and geostopping decisions.

11. APPLICATION OF HIGH-DEFINITION INVERSIONS UTILIZING ULTRA-DEEP AZIMUTHAL RESISTIVITY TO MAP VARIABLE OWC LEVEL IN THE FIRST MULTILATERAL WELL IN UMM GUDAIR FIELD

The Umm Gudair field is one of Kuwait's largest oil producing fields, in operation for since 1962. The reservoir is the Minagish Oolite of the Early Cretaceous Middle Minagish Formation. Today, water production is increasing dramatically, mainly due to water coning resulting in uncertain Oil Water Contact (OWC). Application of Ultra Deep Azimuthal Resistivity is important to map the OWC and optimize wells for long term production. Other objectives include optimizing drilling operation, reducing risk and cost saving.

The Ultra Deep Azimuthal Resistivity (UDAR) tools available presently are high-end technology which supports mapping and geo-steering in horizontal wells worldwide. It is undergoing continuous rapid development to meet the customer's objectives. In this project, a fully automated ultra-high resolution inversion workflow was used to map the variable OWC level. Improvement in the depth of acquisition was also required in the pre-well modelling, which can map the OWC from 70-90 ft away from the wellbore trajectory. The application of Casing While Drilling (CWD) in 13-3/8" section was planned to reduce drilling risk and optimize cost saving.

The high-resolution inversions from the ultra-deep azimuthal resistivity tool detected an unexpectedly shallow OWC at approximately 25 feet TVD from the trajectory at the start of the lateral section. It was then decided to optimize the stand-off of the wellbore to avoid this unexpected shallower OWC. The new target layer was established in real time to capture the shallower Minagish Oolite layer and remain within its most porous zone. The inversion results showed a possible indication of water coning at the start of the lateral. Water coning was detected and mapped from the middle of the lateral to full depth and was mapped from between 25 to 55 ft below the wellbore. Post well in-depth analysis, applying new regularization, confirmed the real time mapping of the underlying OWC, while delivering an enhanced visualization of the water-conning distribution.

The use of innovative technologies Casing While Drilling (CWD) and Ultra Deep Azimuthal Resistivity (UDAR) not only enhanced production gains but also reduced drilling risks, ensuring long-term sustainability of oil production in the Umm Gudair field. A total of 1172 feet of lateral intersection was achieved with a 100% net to gross ratio. Application of high-resolution inversion workflows for ultra-deep azimuthal resistivity delivers significant depth of detection to meet challenging objectives in mature reservoirs, supporting pro-active geo-steering that can mitigate operational risk.

12. 3D PRE-DRILL STUDY FACILITATES FAULT IDENTIFICATION IN REAL-TIME UDAR IMAGES TO ENSURE ISOLATION BEHIND CASING IN THE LANDING SECTION

In structurally complex mature fields, the challenge of optimally placing horizontal wells is amplified by seismic uncertainty—especially near faulted zones in the landing section. Traditional 1D resistivity inversion-based interpretation often falls short in resolving these complexities, risking suboptimal wellbore placement and compromised zonal isolation. This paper presents a novel integration of a 3D pre-drill study with real-time 1D & 3D Ultra Deep Azimuthal Resistivity (UDAR) inversions, which enabled the early identification and isolation of a fault during the landing of a well in the Caspian Basin. By integrating synthetic modelling, seismic interpretation, and real-time geosteering this approach not only enhanced structural understanding but also validated seismic predictions. This case study demonstrates how advanced resistivity modelling in combination with the real-time UDAR inversion images can transform landing strategies in geologically uncertain environments.

The UDAR technology with a proper multi-dimensional inversion can aid in mapping formations in structurally complex areas identifying formation dip and azimuth while approaching a target reservoir. Faults and variable local bed dips can cause the EM field to exhibit a 3D nature where a standard 1D inversion and 1D modelling no longer provide accurate solutions. Synthetic 3D pre-well modelling and real-time 1D & 3D inversions were used to ensure that an expected fault could be mapped and isolated behind casing while drilling the landing section of a well in the Caspian basin.

Pre-well seismic analysis enabled the construction of 3D synthetic resistivity modeling and UDAR response simulation. Synthetic responses with approximate tool noise were inverted using 1D/3D algorithms to predict UDAR response during landing. Combined with offset and structural data, this supported real-time UDAR imaging to guide landing strategy with increased confidence. During the execution phase both 1D and 3D real-time inversions which were constantly monitored by the geosteering and subsurface teams indicated a fault with a throw of approximately 3 to 4 meters. The 3D nature of the fault could not be revealed by the 1D inversion alone. The 3D resistivity distribution associated with the fault structure always causes distortions of the 1D inversion images, leaving doubt in the fault interpretation. Comparison of the 1D & 3D resistivity inversion results to pre-well modelling scenarios gave confirmation that the fault plane had been crossed and could be safely isolated behind the casing.

Real-time 3D UDAR inversion which is not commonly used in landing sections provided critical information for fault identification in the landing section of this well. This approach along with standard 1D inversion and in combination with pre-well synthetic 3D modelling gave confidence in the setting of section Target Depth (TD) and provided a strategy for future development well planning in similar scenarios. Additionally, it provided validation of the seismic interpretation and enhanced geological understanding of the field.

13. OPTIMIZED FIELD DEVELOPMENT IN NCS GREEN FIELD PROJECT WITH APPLICATION OF 3D UDAR TECHNOLOGY

NCS Operator is developing green field located in central part of Norwegian Continental Shelf. Development drilling commenced in 2022, and the target reservoir is Heimdal sand deposited in deep marine environment during Paleocene age. Heimdal consisted of main sand, and injectite sand above it, capped by Lista shale. Regional OWC exists within the reservoir, providing strong aquifer support. Drilling horizontal wells in deep marine–injectite reservoirs presents significant challenges. These include sharp roof-dipping changes, uncertainty in sand body distribution and high lateral heterogeneity, all driven by complex depositional environment. Achieving sufficient reservoir contact at an optimum position in this environment can be very difficult, especially with unstable shale boundaries. The Lista shale is highly reactive with continuous exposure exceeding 40m MD often leading to wellbore collapse. Without advanced planning and technologies, these challenges can lead to low productivity, for example, short producer length, low NTG and early water production.

To overcome the challenges, we have defined collaboration of technology and strategy. A key technology enabler was the use of 3D UDAR. Coupled with advanced drilling products such as Wired Drill Pipe and Dynamic Drilling Surveys, this approach improved drilling efficiency, achieving an average ROP 70 m/hr in producer wells. Faster execution reduced time-dependent risks associated with shale instability, enhancing success rate of production string installation. Tailor-fit strategy was implemented, involving horizontal pilot wells to acquire 3D reservoir mapping data. Information from the 3D UDAR reveals lateral variation, roof transverse dipping and depicts direction with better sand body development. Based on this data, control points in XYZ coordinates are selected to create the producer trajectory at the most optimal position, as close as possible to roof and maximizing distance from OWC.

Through this collaboration, NCS Operator successfully drilled over 38,000m MD of producer wells, averaging more than 1,000m MD per well with high NTG. As result of optimal producer placement and maximized distance to OWC, early production from the field in 2024 reached 60,000 bopd with very low water cut. We also share how 3D UDAR identified survey uncertainty in an extended-length well and helped to formulate solutions. We observed a discrepancy in data between pilot and producer well after drilling more than 1000m MD, where ellipse of uncertainty grew towards TD. 3D UDAR provided critical geological markers to understand the case and evaluate possible actual location for both wells.

Multi-Dimensional Reservoir Mapping has proven to be key technology for accessing hydrocarbon potential in geologically complex reservoirs, such as deep marine-injectite. This paper demonstrates how the application of 3D UDAR enabled NCS Operator to optimize field development in green field project. Through a tailor-fit strategy to acquire 3D Reservoir Mapping in horizontal pilot wells, producer wells were placed at the most optimal position to reduce attic oil, delay water breakthrough, and achieve extended reservoir contact with high NTG. Green field project provides a strong reference for similar projects in other locations on how the application of 3D UDAR enhances productivity and benefits operators in long-term cycle of the field life.

14. APPLICATION OF UDAR ADVANCED RESERVOIR MAPPING IN A LOW RESISTIVITY CONTRAST, STRUCTURAL COMPLEX, NATURALLY FRACTURED ENVIRONMENT -A NORTH SEA CASE STUDY.

The Clair field represents the largest hydrocarbon accumulation on the UK continental shelf with its reservoirs comprising low matrix-permeability, naturally fractured Devonian red-bed clastics. The initial field development strategy aimed to target the natural open fracture network to achieve economic well rates. However, this strategy faced challenges due to early water breakthrough and difficulties in the prediction of fracture location and production rate. As the field has matured, the development strategy has shifted to focus on understanding matrix properties and optimising well placement. The motivation to improve well placement led to the evaluation, modelling, field trial, and deployment of the latest generation Ultra-Deep Azimuthal Resistivity (UDAR) technology in two horizontal development wells targeting the two principal reservoirs.

The deployment of azimuthal resistivity technology in the Clair field had historically faced barriers due to low resistivity contrasts both within target sands and between the stratigraphic boundaries, and a complex structural setting with large major faults and a pervasive natural fracture network. Modern advancements in UDAR technology provide greater depth of detection, bed resolution, and multi-dimension inversion capabilities. These improvements overcome legacy technology limitations, prompting the re-evaluation of the technical feasibility. Pre-job modelling demonstrated that subtle resistivity contrasts correlating with reservoir quality could be detected at depths up to 30 meters true vertical depth (TVD) from the wellbore. This is substantially greater than previous technologies and sufficiently deep to influence geosteering decisions.

The technical feasibility scoping led to field trials in two different wells, targeting the two principal reservoir units. Results demonstrated the latest generation technology can detect resistivity contrasts with sufficient depth of detections and resolutions to influence real-time geosteering decisions. Inversion results also provided new insights into the sub-seismic reservoir architecture and heterogeneity. The field trials highlighted interpretational challenges, particularly when attempting to resolving near-wellbore parallel resistive beds and calibrate stratigraphic boundaries with no distinct resistivity markers. These challenges emphasised the critical importance of integrating UDAR data with conventional formation evaluation logs and other structural information to enable more effective geosteering decisions. Combining UDAR with deep azimuthal resistivity (DAR) inversions proved valuable to interpret across different scales and resolutions.

This work demonstrates the applicability, challenges and impact of UDAR technology in unconventional and complex geological settings. The impact of UDAR is contingent on multiple factors and must be evaluated on a well-by-well basis in the context of the geological understanding and setting. These advancements and trials have unlocked the potential of the technology for future deployment to improve reservoir characterization, well placement, and production outcomes in the maturing Clair Ridge field.

15. SUBSURFACE GEOLOGICAL UNDERSTANDING WITH ULTRA-DEEP AZIMUTHAL RESISTIVITY (UDAR)

Over the past decade, Ultra-Deep Azimuthal Resistivity (UDAR) technology has revolutionized geosteering operations. This cutting-edge technology has transformed real-time geosteering techniques by enabling reservoir mapping with detection depths of tens of meters. This has significantly altered workflows, well data integration, and expectations in the oil and gas industry. Today, UDAR information is crucial for understanding complex geological scenarios. By improving our comprehension of depositional systems and subsurface settings, UDAR technology has become indispensable, significantly enhancing our ability to update 3D geological models. Both real-time and post-drilling geological applications of UDAR technology add substantial value, making it increasingly essential for comprehensive geological assessments.

Integrating UDAR data with other geological and geophysical information, provides a comprehensive understanding of the depositional environment. This facilitates more accurate predictions of reservoir quality and areal distribution. Furthermore, the analysis of 3D post-drill inversion strengthens the comprehension of the geological model, improving the predictability of reservoir architecture and connectivity. This information is critical for updating 3D geological models, which in turn becomes crucial for planning future drilling operations and optimizing field development strategies. Finally, UDAR in complex scenarios can be planned building increasingly sophisticated synthetic models, allowing us to test and prove UDAR response capabilities and limits. This paper presents three compelling examples of the geological applications of UDAR technology:

Deltaic Environment: UDAR Real-time data was crucial for mapping sand distribution and the lateral prograding of deltaic clinoforms. Moreover, the data supported a comprehensive understanding of the depositional environment and facilitated more accurate predictions of reservoir quality and extent. Turbiditic Channel Complex: this example highlights the challenges of a turbiditic channel complex. Real-time data from UDAR was crucial for steering the well into the “sweet spot”. Moreover, UDAR data supported the validation of a conceptual sedimentological model, in areas with limited control points. The analysis of 3D post-drill inversion further strengthened the geological model's comprehension, improving the predictability of reservoir distribution and connectivity. Carbonate Platform Reservoir: This example illustrates UDAR planning to identify fracture patterns responsible for water influx in a carbonate platform reservoir by means of a complex synthetic model. Understanding the distribution and orientation of fractures is essential for managing water production and sustaining reservoir pressure

UDAR technology has transformed geosteering by providing real-time data to optimize well placement and enhance our understanding of complex geological settings. These advancements significantly contribute to the efficiency and success of drilling operations. The integration of UDAR data with other geological and geophysical information provides a comprehensive view of the subsurface, leading to improved well placement and more effective field development planning. Moreover, 3D inversion will add the multidimensional information to increase robustness in understanding of subsurface setting. Finally, for UDAR geological application a strong integration with other disciplines is mandatory in particular with sedimentology.

16. ENHANCING FIELD DEVELOPMENT IN COMPLEX DEPOSITIONAL ENVIRONMENTS USING REAL-TIME 3D RESERVOIR MAPPING WITH ULTRA-DEEP AZIMUTHAL RESISTIVITY

Clastic reservoirs can present significant development challenges due to its complex geology and heterogeneity. Multiple reservoir targets were deposited under varying geological conditions ranging from glacial and interglacial settings to post-glacial reworking, resulting in substantial variability in reservoir quality and thickness. Ultra-Deep Azimuthal Resistivity (UDAR) was integrated with multi-physics Logging While Drilling (LWD) services that enabled detailed near- and far-wellbore evaluation and interpretation. 3D reservoir mapping is crucial for efficient well placement when these variations and heterogeneities are confirmed.

UDAR 3D reservoir mapping, with both high resolution and large depth of investigation, was deployed for delivering a 3D resistivity profile around the wellbore. This information enables understanding the reservoir structure and facilitates efficient well placement and geosteering through multiple targets. The technology was deployed in two wells combined with LWD triple-combo. Nuclear Magnetic Resonance (NMR) and advanced mudlogging were deployed in the second well for real-time fluid typing.

In the first well, while drilling in the upper target, the UDAR was able to map the distance to lower target sand, helping the team to navigate quickly through the intra-shale layer and land the well in the lower target sand, after achieving sufficient footage in the upper zone. In the second well, during the landing phase, the UDAR and other LWD tools confirmed that the upper target was thin and of poor quality, whereas the lower target was thicker and of higher quality. This insight enabled the geosteering team to take decision to move to the lower target, enhancing reservoir contact and achieving better net-to-gross footage. While drilling, the 3D components of UDAR measurements were transmitted in real-time to surface, enabling 1D longitudinal and 2D transverse inversions to be run and the 3D resistivity profile around wellbore to be generated.

The multi-physics approach in these multi-laterals allowed for enhanced interpretation of this complex and heterogenous reservoir and resulted in increased reservoir contact. Lateral variations were identified confirming the viability of azimuthal geosteering in future operations. Post-job analysis of the 3D resistivity volume data from the UDAR tool revealed some interesting features such as erosional surfaces, silt inclusions and channel cuts. These insights provided valuable inputs for reservoir understanding of depositional environments and planning of future wells.

17. UPSCALING 1D AND 3D ULTRA-DEEP RESERVOIR MAPPING IN CARBONATE RESERVOIR: INSIGHTS FROM MULTIPLE WELLS, OFFSHORE ABU DHABI

Monitoring reservoir saturation and tracking waterflood progression are critical for optimizing production and injection strategies in mature fields. Traditionally, reservoir engineers have relied on techniques such as 4D seismic and electromagnetic surveys for such evaluations. However, recent advancements in Logging While Drilling technologies have introduced the ability to identify and monitor remaining oil saturation in real-time during drilling operations. This paper presents a reservoir-scale study highlighting the application of LWD reservoir mapping and borehole imaging in enhancing reservoir understanding and development.

The target field has Carbonate sedimentology and is a gentle slightly asymmetric domal anticline structure. The Field was discovered in January 1958. At present, the main crude production is from Arab reservoirs. This study examines data from recently drilled wells, each representing different geological settings across the field's crests and flanks. The primary production intervals were drilled using 6-inch horizontal boreholes, employing an advanced LWD toolset. This configuration included ultra-deep azimuthal resistivity (UDAR), high-resolution laterolog borehole imaging, density, neutron porosity, propagation resistivity, and gamma ray sensors, all integrated with a push-the-bit rotary steerable system.

The UDAR sensor enabled 1D-inversion-based reservoir mapping, utilizing deep measurements with a 75ft-DOI and shallow measurements with a 25ft-DOI. These parameters were optimized through pre-well modeling to determine appropriate spacing and electromagnetic frequencies. UDAR served as the primary far-field sensing tool, while triple combo logs and borehole imaging provided near-field validation, enabling confident real-time interpretation of both structural features and fluid distribution. Across the studied wells, UDAR helped identify key reservoir dynamics, including water influx, ongoing water flooding, and active flood fronts. On average, geosteering guided by UDAR allowed wells to be safely positioned 20–40 ft TVD above the detected water levels. Additionally, 3D-inversion of UDAR data delivered enhanced visualization of fluid distribution, revealing directional trends and dynamic movement through full 360-degree analysis. Borehole imaging further contributed by identifying geological structures. Together, the integrated dataset offered a comprehensive view of current fluid behavior and reservoir connectivity across the field.

The advanced application of Ultra-Deep Azimuthal Resistivity extends beyond geosteering and single well reservoir mapping, offering potential for reservoir-scale monitoring. It enables the identification of remaining oil saturation and tracking of water movement even before wells enter production. This innovative approach creates a vital link between reservoir-level subsurface analysis and operational decision-making. By delivering timely insights into reservoir conditions, it supports faster, more informed well planning, reduces operational risks, and ultimately improves productivity and injectivity.

18. COMBINING 3D UDAR WITH REAL-TIME PETROPHYSICS TO REDUCE UNCERTAINTY, ACCELERATE DECISION-MAKING, AND CONVERT EXPLORATION WELLS INTO PRODUCERS.

Recent horizontal drilling operation on the Kjøttkake prospect in the North Sea represents a breakthrough in Real-time interpretation of logging-while-drilling (LWD) data enabling precise geosteering, reservoir mapping, and fluid gradient analysis, leading to the deduction of a free water level and confirmation of hydrocarbon contact in an exploratory environment. Utilizing a highly advanced Bottom Hole Assembly (BHA), the project achieved the acquisition of formation fluid samples while drilling. The integration of cutting-edge technologies such as 3D UDAR, LWD FSWD, and advanced multi-function triple combo enabled precise reservoir delineation and fluid characterization, leading to zero Non-Productive Time (NPT) and a four-day reduction in rig time. This case study demonstrates the transformative potential of real-time data in optimizing horizontal exploration outcomes and accelerating the transition from appraisal to production.

The primary objective was to confirm hydrocarbon presence, delineate sand dykes and wings, and assess hydrocarbon-water contact. The sidetrack was drilled using a GM4D harsh environment rig, employing a 100-meter BHA that included a compact and advanced multifunction formation evaluation platform (GR, Res, Density, Neutron, E|CS, Sigma) steered by an 3D RSS, and guided by UDAR 3D reservoir mapping technology. The data was transmitted by high speed mud pulse telemetry which also enabled the while drilling fluid mapping and sampling while drilling. The well trajectory was J-shaped, reaching a total depth of 3341 m MD. Logging While Drilling (LWD) tools provided real-time formation evaluation, including resistivity, density, neutron, sonic and image data. The operation followed strict well control protocols and utilized an advanced OBM system to maintain wellbore stability. No wireline logging or coring was performed, and the well was permanently plugged and abandoned after the satisfactory data acquisition.

The integration of advanced LWD technologies enabled high-resolution mapping of injectite geometries and fluid gradients. The 3D UDAR successfully delineated 360 degree lateral thickness variations, while the FSWD technology acquired 12 low-contamination fluid samples in one run—setting a regional record. Real-time pressure data revealed distinct oil and water gradients, allowing for the deduction of a free water level and confirmation of hydrocarbon contact. Borehole imaging and fluid analysis matched pressure data from the mother bore, validating the results. The operation experienced zero NPT, saving four days of rig time and demonstrating the feasibility of converting exploration wells fast into producers.

The Kjøttkake sidetrack drilling program exemplifies the value of real-time petrophysical interpretation and fluid sampling in complex geological settings. The successful deployment of a sophisticated BHA and LWD suite enabled immediate decision-making, optimized well placement, and reduced operational risk. The ability to acquire high-quality formation data while drilling not only enhanced reservoir understanding but also provided a viable pathway for field development without additional appraisal wells. This case sets a precedent for future exploration strategies in similar environments, highlighting the operational and economic benefits of integrated real-time technologies.

19. THE INDUSTRY'S NEED FOR A TRUE TRIAXIAL, COLLOCATED MULTI-DEPTH AZIMUTHAL RESISTIVITY IN LWD: THE STEP CHANGE TO INCREASED SENSITIVITY AND CERTAINTY

Conventional deep azimuthal (DAR) and ultra-deep azimuthal (UDAR) tool architecture currently utilize multiple non-collocated orthogonal and/or tilted antennas (e.g. at ~45 degrees) to synthesize pseudo-triaxial responses. However, these arrangements mix the formation's electromagnetic (EM) signal with systematic errors and tilt-angle variations, making calibration challenging, leading to a reduction in the sensitivity and accuracy of a formation's horizontal resistivity (Rh) and vertical resistivity (Rv).

In contrast, wireline based collocated triaxial EM measurements with spacings up to 72 inches have demonstrated their ability to accurately determine near-wellbore Rh, Rv and dip post-drilling. Collocated triaxial measurements are inherently more robust against tool-related errors, independent of formation resistivity, and can be optimized for higher signal-to-noise ratios. Additionally, collocated triaxial antennas are more compact, allowing multiple antenna spacings to be integrated into the drill collar closer to the bit in a logging-while-drilling (LWD) context.

A novel, modular (multi-sub), LWD tool system has been developed to leverage multi-depth, collocated, calibrated triaxial EM measurements. This Multi-Depth Azimuthal Resistivity (MDAR) system delivers more accurate inverted formation resistivities and boundaries, enabling improved geosteering, enhanced petrophysical interpretation, and better subsurface model building. This paper presents the architecture and performance advantages of this novel MDAR LWD triaxial EM system, which has a significant improvement in signal-to-noise ratio and measurements accuracy when compared to the current LWD DAR and UDAR architecture deployed in the drilling industry.

The Novel MDAR architectural design, which has the smallest measurement offset to bit available in the industry, enables a considerable reduction in "Inversion Time to Bit", without compromising the measurement quality. "Inversion Time to Bit" is a function of ROP, Telemetry, Computing Power and Inversion reference point. This is achieved by utilizing an at-bit transmitter referenced inversion enabled by the innovative triaxial transmitter and receiver arrays, in parallel with the industry standard mid-point referenced inversion, where the highest measurement sensitivity is apparent. Such an approach is an industry first. This increase in measurement sensitivity, when compared to a tilted antenna architecture, will be highlighted using both synthetic and real-world examples, delivering significant improvements in distance-to-boundary detection and layer vertical resolution, also marking a step-change in reducing the vertical spatial uncertainty of the boundary depth in LWD applications.

The paper will also illustrate how the novel Multi-Depth Azimuthal Resistivity (MDAR) platform design, enabled by its triaxial and collocated antennas unlocks new geosteering techniques and additional answer products including petrophysical adjacent deliverables such as bed boundary free formation resistivity outputs (e.g. Rh and Rv) and advanced lookahead sensitivity and accuracy. This will be the first time in the industry where a wireline equivalent resistivity measurement will be made in a drilling environment, in real time.

20. ENHANCING WELL PLACEMENT IN THIN INTERBEDDED RESERVOIRS: SYNERGISTIC USE OF UDAR AND DAR MAPPING IN THE NORTH SEA

Ultra Deep Azimuthal Resistivity (UDAR) inversion is a critical technology for advanced geosteering and optimal wellbore placement. However, in thin interbedded reservoirs, its vertical resolution is constrained, leading to uncertainties in boundary definitions. This paper aims to demonstrate how the combination of UDAR and Deep Azimuthal Resistivity (DAR) services enhances vertical resolution and geological characterization, improving real-time well placement decisions in complex depositional settings of the North Sea. This study presents a case where UDAR and DAR data were integrated in real-time to refine geosteering decisions

The workflow involved the use of Logging While Drilling (LWD) Formation Evaluation (FE) logs to enhance geological interpretation, particularly lateral facies continuity and structural geometry variations. A Pre-Well Modeling (PWM) was conducted to define optimal tool settings, ensuring effective navigation through complex geological environments. Real-time data acquisition and inversion analysis were performed to evaluate the limitations and advantages of each tool in geosteering execution. A case study from a shallow-marine deltaic environment in the North Sea is presented, where FE logs revealed thickness variations between 4 - 9 meters TVD and lateral facies discontinuities.

Structural geometric changes, interpreted from seismic data, underscored the need for real-time multi-scale integration. The UDAR inversion provided a comprehensive structural geometry mapping, while the DAR inversion enhanced vertical resolution, accurately defining formation boundaries and detecting lateral heterogeneities. This dual approach facilitated precise trajectory adjustments, improving reservoir exposure and achieving planned well objectives. The post-well assessment includes the blended Inversion feature between UDAR and DAR inversions in the PWM and Memory stage, validating the importance of combining both tools in the Well placement activities in this geological environment.

The study highlights that combining these tools significantly improves decision-making confidence during well placement, ultimately optimizing reservoir contact. This paper introduces a novel methodology for integrating UDAR and Deep Resistivity mapping in thin interbedded reservoirs to improve vertical resolution and boundary definition in real-time. By leveraging both technologies as complementary solutions, this approach provides enhanced geological characterization, enabling more precise well placement strategies that can be of substantial benefit to practicing geosteering engineers and asset teams.

21. INTEGRATED UDAR ANALYSIS OF 1D/3D NEAR-BIT LOOK-AROUND AND 3D LOOK-AHEAD INVERSIONS IN A HORIZONTAL WELL IN A COMPLEX CLASTIC CHANNEL ENVIRONMENT.

UDAR technologies have an established track record for improving efficiency in Geosteering/Geomapping operations in complex sand channel reservoirs. Complex geobodies can be displayed real time and formation boundaries predicted ahead to optimize the well path. Workflow improvements allow higher rates of penetration and limit operational pauses. Efficiency of these workflows is demonstrated in an integrated analysis of 1D, 3D and 3D look ahead inversions in a horizontal well drilled with a high rate of penetration.

Comprehensive pre-job planning analysis of all nearby offset well data was performed to evaluate the primary geological scenarios and formulate a geosteering strategy prior to drilling the target well. A Bottom Hole Assembly (BHA) with triple combo and near-bit UDAR tool configuration was recommended for quicker reaction and decision making. A special customized UDAR firing file and multimode MWD download were prepared to ensure sufficient data density of all logging variables, including real-time UDAR data to accommodate the expected high rates of penetration (ROP). 1D and 3D inversions were deployed to establish a complete picture of the reservoir.

The well was drilled in one run with eighteen real-time corrections to the trajectory. Multiple layers of different resistivity and thickness were mapped at distance with high confidence. Drilling was performed at an average rate of penetration exceeding 300 feet per hour. During drilling, an abrupt and unexpected change in the formation dip of more than 12 degrees was detected. The trajectory was quickly adjusted to minimize the unproductive interval, but an exit was unavoidable. Analysis of UDAR 3D near-bit data revealed strong azimuthal variation in resistivity prior to the bit intersecting the zone with an abrupt dip change. A hypothetical corrected trajectory was designed to maximize the possible reservoir penetration. Post well a UDAR 3D look-ahead inversion analysis was also performed to identify if in future it would be possible to detect the approach to the unconformity ahead of the bit, allowing earlier well optimization.

This paper describes integrated analysis of UDAR 1D/3D look-around near-bit and 3D look-ahead of the bit inversions in a horizontal well with complex sand channels drilled in one run with high rates of penetration. Optimization of the geosteering workflows allows efficient decision making in this complex environment despite the high rate of penetration. The potential for deploying horizontal look ahead technologies is clear from the post well analysis of the data. A comparison of the effectiveness of the technologies was performed on one well including: 1D/3D Look-Around near-bit and 3D Look-Ahead inversions.

22. ELEVATING 3D RESERVOIR MAPPING WITH THE NEW FLEXIBLE INVERSION DATA FORMAT

In the constantly evolving landscape of 3D reservoir mapping and visualization, a new Advanced Borehole eXchange (ABX) data format emerges as a transformative format to redefine the way we visualize and interpret resistivity inversion datasets derived from deep and ultra-deep azimuthal resistivity (DAR and UDAR) logging while drilling technologies. The inversion algorithms utilized to interpret hundreds of measurements from DAR and UDAR tools now generate a dense dataset of resistivity values in volume around the wellbore with a radius that can be measured from ten to close to 100 hundred meters. This can now be integrated with a dynamic Depth of Detection (DOD) to enhance inversion visualization, and improve confidence in sensitivity of UDAR data to remotely mapped boundaries in complex multi-dimensions.

Integrated with visualization and analysis techniques, use has been made of established data formats including point sets, SEG-Y and Grids. This seamless incorporation ensures a smooth transition and compatibility. The ability to move between industry accepted formats allows for the application of various different techniques from 3D auto surface picking in SEG-Y format to geometry analysis utilizing grid format. This paper conducts a comprehensive comparison between traditional 2D inversion display and groundbreaking ABX 3D multi-dimensional inversion visualization, explores extensive capabilities of ABX and its profound influence on advancing 3D reservoir mapping.

Larger, and ever more complex data sets (based on 1D,2D and 3D inversions) derived from deep and ultra deep resistivity tools can be imported, processed, visualized, and analyzed in multiple ways. The outputs reveal geological and petroleum engineering insights of the subsurface. These findings contribute to the refinement of local, regional, and full-field models, enabling enhanced reservoir management. Additionally, the integration of these datasets with advanced visualization tools allows for the identification of subtle geological features and anomalies that were previously undetectable. This capability significantly enhances the accuracy of subsurface interpretations and supports the development of more effective reservoir management strategies.

While our progress has been remarkable, further work is essential to optimize methodologies, especially concerning geological uncertainties in the outputs. These are important for end users to understand upsides and risks inherent in the interpretations from the latest types of data. There is also a need to standardize on data types in use so that data exchange is facilitated, potentially through a new OSDU standard for wellbore related data. Moreover, the adoption of standardized data formats and methodologies will not only streamline multi-dimentional data exchange but also foster collaboration across the industry, enabling the development of innovative solutions to address complex geological challenges.

23. INDEPENDENT INVERSION AND INTERPRETATION OF UDAR DATA FOR ENHANCED GEOSTEERING

As ultra-deep azimuthal resistivity (UDAR) technology becomes increasingly adopted in geosteering and geomapping applications, the ability to independently process and interpret UDAR data remains limited. Currently, interpretation workflows are tightly coupled with proprietary software and expertise provided by tool vendors. This reliance creates a significant bottleneck for operators who wish to validate or conduct their own interpretations using raw or pre-processed data. Motivated by this industry need, we present the development of a vendor-independent inversion algorithm designed to enable real-time, in-house interpretation of UDAR logs.

The core of our approach lies in a parallelized modeling and inversion of electromagnetic fields framework that is computationally efficient and scalable, making it suitable for deployment in real-time geosteering operations. By leveraging multi-core processing and streamlined algorithms, the inversion engine delivers quick turnaround without sacrificing accuracy. This is essential for field environments where timely decisions directly impact drilling performance and well placement. Another key contribution of this work is the integration of advanced boundary-detection capabilities inherent in UDAR tools into a broader geosteering interpretation workflow. While UDAR provides valuable insight into formation geometry and distant boundaries, we don't consider it as a replacement of traditional methods such as log-based well correlation. Instead, we emphasize the value of a joint interpretation strategy, where conventional and advanced data sources are reconciled to produce a more reliable and geologically consistent model.

The case study presented in this work is based on a publicly released UDAR dataset, enhanced with additional measurements from the same lateral and its associated pilot well. The interpretation process begins with a comparative log analysis, followed by the creation of a correlation cross-section between the wells. UDAR data are then inverted to image formation boundaries. Finally, we demonstrate how discrepancies between the correlation-based model and the UDAR inversion can be resolved to arrive at a unified interpretation that honors both datasets. In addition to inversion, this independent software platform enables the interpreters to forward-model tool responses based on hypothesized formation geometries. This capability helps users understand the causal relationships between formation features and UDAR log signatures—an important advantage, especially given the complexity and unfamiliarity of UDAR logs for many end users.

This work presents a practical and scalable approach for independent interpretation of UDAR data, emphasizing the integration of azimuthal resistivity measurements with traditional well-correlation techniques. By combining these complementary sources, the workflow enhances geological consistency and interpretive confidence. The developed platform allows operators to make more informed geosteering decisions in real time, reducing reliance on proprietary systems. This advancement empowers users with greater autonomy, enabling flexible, accurate interpretations that improve well placement and overall drilling performance in complex subsurface environments.

24. ADVANCED UDAR MEASUREMENTS USING TRANSCEIVER CONFIGURATIONS

Measurement interpretation of Ultra Deep Azimuthal Resistivity (UDAR) has advanced significantly in recent years. Despite these improvements, the need for more data is still increasing.. Reconstructing complex geological models by inversion requires independent and diverse data. At the same time, additional sensors require space in a bottom hole assembly (BHA), pushing back traditional formation evaluation sensors. Novel ways are required to meet the demand for more data in an efficient manner. This paper introduces a novel transceiver concept that allows creation of rich datasets while optimizing BHA length.

A new, modular Logging While Drilling (LWD) UDAR system with tri-axial, collocated orthogonal antennas was designed. Each of the antennas can operate independently as transmitter or receiver. This facilitates capturing of more diverse data with different transmitter-receiver (Tx-Rx) spacings for the same BHA configuration. It also allows for the switching of transmitter and receiver positions. The system is studied and compared to a conventional transmitter-receiver system. Synthetic data in forward modeling and inversion is used to visualize and quantify the performance improvements.

In planning a UDAR BHA, modules should be positioned with a successively increased module spacing. With such a setup, switching the transmitter position achieves one additional intermediate Tx-Rx spacing. The larger data set allows for better definition of reservoir structure. This is shown by inversion of synthetic results as well as by computing the resolving power of a specific configuration. Reciprocal measurements serve as quality control for the system. When placing the TX behind, a differential measurement can be created that provides geometrical focusing. When TX and RX are operated on a single module, short-spacing geosteering measurements are generated. These provide measurements equivalent to deep azimuthal resistivity tools with a depth of detection of up to 10 m. The short modules can have flexible positions in the BHA without the need for additional antennas.

A standard three module transceiver BHA delivers a data set equivalent to a conventional four module BHA, significantly improving the ability to map the geological structure. A transceiver also allows novel applications of UDAR in a single-module-measurement. This measurement delivers shallow geosteering information without compromising the distance to bit for conventional FE measurements. This analysis shows that using a transceiver UDAR system is a key step towards the goal of efficiently creating a comprehensive data set for reservoir mapping.

25. SIMULATING COMPLEX GEOLOGICAL MODELS TO DEMONSTRATE RESPONSES FOR AUTOMATED BOUNDARY PICKING FROM UDAR DATA AND TARGET PLANNING FOR IMPROVED WELL PLACEMENT

Identifying position and dip of resistivity boundaries is standard geosteering practice. Predicting trends and projecting them ahead allows well path optimization. In complex geology, changes in boundaries need to be identified rapidly and targets set. Automating picking of multiple boundaries from UDAR inversions and automating target updates allows changes in geology to be accommodated. Simulating models prior to drilling and using pseudo real-time playback demonstrates the response of geosteering algorithms providing confidence in the technology.

UDAR mapping can detect multiple boundaries over 100ft from the wellbore. Current geosteering workflows identify these boundaries manually, assess their impact on well position and plan new targets. This process involves multiple people and takes time. Delays risk the well exiting the reservoir or requiring severe adjustments impacting completion placement. Automated boundary picking based on resistivity contrast allows formation changes to be rapidly identified and new targets generated automatically, adjusted and transmitted to the RSS while obeying constraints. Simulating variations in geology, tool spacing and sensor measure point allows testing of an algorithm prior to drilling to demonstrate its effectiveness. Contrast in resistivity associated with formation and fluid boundaries can be defined numerically with tolerances to allow for variability in the magnitude of the resistivity. The distance of this change in resistivity away from the borehole can be plotted and distance calculated using UDAR inversions.

This paper demonstrates picking boundaries above and below the wellbore simultaneously using examples of UDAR data displaying different geological scenarios: Undulating upper formation boundary to shale with a horizontal oil water contact, simultaneously dipping upper and lower formation boundaries and a pinch out scenario. In all scenarios both boundaries can be clearly defined and distance to the boundary calculated. A pseudo real-time simulator is used to show how the algorithms respond using data up to the sensor measure point and how this can be used to generate predrilling scenarios to assess algorithm effectiveness. As the well advances, changes to boundaries are rapidly plotted. As the distances to the boundaries can be calculated an optimised well path is also be calculated to either maintain distance from a single or both boundaries. The automatically calculated well path can be constrained to maintain changes to within tolerances defined for optimising the well plan.

Manual geosteering can result in decision making lag, hindering optimization of the well position. Automating boundary picking and target generation speeds the process, allowing for less tortuosity. Incorporating the ability for automated workflows to identify acute changes that would result in unacceptably major adjustments allows pausing of the automated workflow and human intervention to accommodate any identified complexities. Simulating the responses of the algorithm demonstrates its effectiveness in scenarios modelled to represent any target well.

26. REAL-TIME 1D INVERSION OF ULTRA-DEEP AZIMUTHAL RESISTIVITY DATA USING STOCHASTIC AND DETERMINISTIC ALGORITHMS

Logging-while-drilling ultra-deep azimuthal resistivity (UDAR) tools enable reservoir exploration at distances of tens of meters from the wellbore and are currently key technologies for proactive reservoir navigation in fields with complex geological structures. Due to large depth of investigation, UDAR responses typically depend on numerous formation parameters and require multi-layer formation models for interpretation. To resolve dozens of model parameters in real time, specialized fast inversion algorithms are required. This paper presents two in-house implementations of 1D inversion algorithm for UDAR data based on stochastic and deterministic approaches.

The stochastic inversion algorithm is fully data-driven allowing obtaining unbiased inversion results from the tool measurements only. However, in case of insufficient sensitivity of the tool measurements, this algorithm may encounter difficulties in resolving certain formation parameters within the tool investigation area and may lead to increased results uncertainty. The deterministic variant of inversion algorithm addresses this limitation by adaptively incorporating prior knowledge of the reservoir structure into the computational workflow. As a result, these algorithms provide an ensemble of formation models accompanied by both quality indicators and uncertainty estimates for the recovered model parameters. Both algorithms are gradient-based and demonstrate high computational efficiency along with strong resolution capabilities.

The paper describes the fundamental characteristics of the algorithms making the inversion high-performance and robust, including the data processing workflow, inversion quality indicators, parallel computing scheme, etc. Additionally, recent developments aimed at enhancing the algorithms are discussed, including: 1) an express inversion mode for rapid computations in geologically simple scenarios, 2) averaging of inversion results to produce more consistent reservoir resistivity models, 3) more reliable uncertainty estimates, and 4) first results of GPU-based parallelization. The paper demonstrates how both inversion algorithms operate on field and synthetic scenarios, compares their results, and provides general recommendations on which approach is more suitable under specific conditions. The described algorithms constitute the core of geosteering software package, that provides oilfield operators with third-party UDAR modeling and inversion capabilities. The software supports all existing UDAR tools with coaxial, tilted, or orthogonal antennas and includes a flexible interface for integrating new tools with arbitrary measurement types.

The developed inversion algorithms ensure real-time inversion results in case of multi-layer formation models, which are essential for interpreting UDAR measurements. The algorithms help to resolve structural formation uncertainties, enhance the reliability of the inversion results, and quantify their accuracy. By leveraging these algorithms, oilfield operators can facilitate the use of the UDAR services, achieve a more comprehensive understanding of full-scale reservoir structures while drilling, delineate pay zones more accurately, and improve production rates through more informed geosteering decisions.

27. APPLICATION OF ADVANCED INVERSION WORKFLOW FOR ULTRA DEEP AZIMUTHAL RESISTIVITY TO OPTIMIZE WELL-PLACEMENT IN IDENTICAL THIN RESERVOIRS ASSOCIATED WITH SUB-SEISMIC FAULTS, WITH STRICT FOOTAGE DISTRIBUTION IN EACH RESERVOIR SUBZONES—CASE HISTORY IN THE RUB AL KHALI BASIN, UAE

The primary objective of drilling more than 8,000 ft MD of lateral sections in the Rub Al Khalid Basin, UAE, was to maximize reservoir exposure across multiple thin targets while ensuring a smooth well profile. This was challenging, particularly due to the changes in formation dip and the associated sub-seismic faults. The target zones are identical with porous zones enveloped by denser layers. Displacement by a fault complicates determining their stratigraphic position, potentially compromising well objectives.

Determining fault displacement was crucial for establishing the correlation after encountering a fault. This required mapping the two reference boundaries - the overlaying shale at the top and the dense layer at the base - while drilling in the target zones. The resistivity contrast was not significant except at these boundaries. A bottom hole assembly, with near-bit gamma and density images, was positioned closest to the bit to navigate the thin target zones. An ultra-deep azimuthal resistivity (UDAR) tool was utilized to map the reference boundaries and determine the displacement in case a fault was encountered.

Integrating the ultra-deep azimuthal resistivity (UDAR) tool with advanced high-definition inversion has proven highly beneficial for determining fault displacement. Its enhanced depth of detection capability, even in low-resistivity environments, mapped fault displacement along its plane and established the stratigraphic position. The gamma-ray and density images, located approximately 11 and 16 ft from the bit, respectively, maximized reservoir exposure in thin target zones. Before utilizing UDAR technology, encountering a fault would result in being unable to determine the stratigraphic position of the well after the fault, and establishing correlation was often challenging, or sometimes impossible, due to similar properties of the target zones. This situation compromised well objectives. Implementing UDAR technology in such environments has established a method for optimizing the benefits of advanced technology. This approach has improved net-to-gross in long, complex horizontal wells that involve multiple thin targets, which are characterized by low resistivity contrasts associated with sub-seismic faults.

Integrating detailed information on structural changes and the distribution of resistivity around the wellbore can significantly enhance the existing subsurface model, providing a clearer understanding of the geological characteristics in the surrounding area. By meticulously analyzing this information, we can minimize uncertainties when planning for the development of future wells. This comprehensive approach not only fosters improved decision-making but also optimizes resource allocation and drilling strategies, ultimately leading to more effective exploration and production efforts.

POSTERS

1. A CASE STUDY FROM CLAIR RIDGE: USE OF CORRELATION-BASED GEOSTEERING PLATFORM TO INTEGRATE CONVENTIONAL LOG DATA, BOREHOLE IMAGE LOGS AND UDAR RESISTIVITY IMAGES TO ENHANCE WELL PLACEMENT.

This paper presents a comprehensive geosteering case study from a well drilled in the Clair Ridge unit V reservoir. To support economic well rates the Clair Ridge development strategy has evolved in recent years from targeting natural open fractures to better understanding the matrix character and optimising well placement. The objectives of optimising well placement were to maximise well length within the reservoir and target better reservoir properties. With the field maturing, in-fill wells are becoming increasingly more challenging and targeting areas of higher geological complexity and uncertainty. As such, geosteering is becoming an important aspect of well delivery to ensure robust well placement.

Due to generally low resistivity contrasts both between and within stratigraphic units, and complex structural geology, we cannot rely alone upon ultra-deep azimuthal resistivity images for geosteering. Integrating data across different physics and using different geosteering approaches is critical to successful decision making. In this well, we implemented an extensive and robust real-time data acquisition program. It included drilling dynamics, gas composition, mudlogging, cuttings and mineral analysis, gamma ray, density, neutron porosity, resistivity, image logs, NMR, formation pressures, and both deep and ultra-deep azimuthal resistivity logs. The data acquisition program allowed for multiple different types of geosteering approaches to be employed. A correlation based geosteering platform was used to integrate the data in one single location and build geological models that were robust to all the acquired data and geosteering approaches. The platform was a valuable tool for enabling rapid, real-time multi-disciplinary collaboration.

We successfully drilled and completed the well, with six geosteering decisions executed over a reservoir section over 1300m. Three major geosteering decisions were issued responding to unexpected faults with uncertain throws and to optimise the inclination of the latter portion of the wellbore. In some instances, UDAR data alone was ambiguous and thus understanding the subsurface positioning relied heavily on data integration Integrating structural information across different scales from image logs, deep and ultra-deep azimuthal resistivity images proved particularly valuable in constraining structural models to track the subsurface position of the well.

2. WIRED FOR CHALLENGE: DEEP AZIMUTHAL RESISTIVITY LOGGING IN THE AGE OF UBCTD

As the oil and gas industry continues to shift toward unconventional plays and more cost-efficient drilling methods, the fusion of advanced geosteering technologies with underbalanced coiled tubing drilling (UBCTD) presents both a promising opportunity and a formidable engineering challenge. The proposed tool aims to extend the depth of investigation and azimuthal sensitivity of traditional resistivity logging-while-drilling (LWD) systems, while operating under the unique mechanical, hydraulic, and electromagnetic constraints imposed by coiled tubing environments and the multiphase flow conditions typical of underbalanced drilling. Key opportunities include improved well placement accuracy, real-time reservoir characterization, and enhanced production optimization in gas reservoirs with complex heterogeneities, anisotropy, and thin-bed structures.

The article reviews recent advances in resistivity sensor technology, transmitter-receiver configurations, and high-speed telemetry systems that can potentially be miniaturized and ruggedized to fit within the coiled tubing bottomhole assembly. Particular emphasis is placed on the integration of directional deep-reading sensors capable of detecting resistivity contrasts several meters from the borehole, allowing for early detection of formation boundaries, gas-water contacts, and structural features critical for real-time geosteering. However, numerous challenges must be addressed for this tool to become viable. From an engineering standpoint, limitations in available space, power, and thermal resilience demand novel solutions in electronic packaging, downhole power generation, and heat dissipation. Additionally, maintaining electromagnetic coupling and signal integrity in the presence of underbalanced fluid flows and gas slugs complicates both measurement and interpretation.

The article also investigates deeply into the inversion challenges that arise in this context. Electromagnetic inversion under UBCTD conditions is inherently ill-posed, non-linear, and sensitive to noise, especially when gas-filled boreholes and invasion zones create strong dielectric contrasts. The reduced standoff and dynamic borehole geometry introduce further uncertainty in the forward modeling process. As such, the discussion explores the necessity for robust, real-time inversion algorithms capable of incorporating anisotropic and 3D geological models, uncertainty quantification, and machine learning-based prior conditioning. Fast forward solvers and hybrid inversion frameworks that blend deterministic and probabilistic methods are reviewed as potential pathways to overcome these obstacals

In conclusion, while the integration of deep azimuthal resistivity LWD into UBCTD for gas reservoir development holds transformative potential, it demands multidisciplinary innovation in tool design, data processing, and inversion modeling. This article sets the stage for collaborative research and development efforts by outlining the technical roadmap, current gaps, and cross-disciplinary challenges inherent to this next frontier in downhole sensing and subsurface navigation. Geosteering with limited ultra slim logging tools pose sever limitations for placing the well within the gas zones.

3. FIRST DEPLOYMENT OF HIGH-DEFINITION RESERVOIR MAPPING WHILE DRILLING IN ECUADOR: A STEP CHANGE IN HORIZONTAL WELL PLACEMENT IN THE ORIENTE BASIN

This paper presents the first deployment in Ecuador of high-definition reservoir mapping while drilling (HD-RMWD) technology, applied in both the landing section and the reservoir phase to improve wellbore placement, maximize reservoir contact, reduce drilling risks, and enhance reservoir characterization. The study describes the application of HD-RMWD in the Lower U (LU) formation of the Inchi Field, located in Ecuador's Oriente Basin. The LU formation is characterized by thin, heterogeneous sandstone bodies deposited in estuarine to tidal environments, where lateral facies variability and limited seismic resolution introduce significant uncertainty for horizontal well placement. High geological uncertainty, combined with instability in the overlying shales, has previously resulted in stuck pipe events when horizontal wells exited the reservoir sands, negatively impacting field development strategies.

To address the geological and structural complexity of the LU formation, HD-RMWD technology was integrated into the geosteering workflow. The system acquires a broad range of ultra-deep electromagnetic measurements, enabling real-time detection of formation boundaries tens of feet away from the borehole. These measurements are processed using high-resolution deterministic inversions to generate resistivity profiles around the wellbore at different depths of investigation. In the 8.5-in landing phase, HD-RMWD was combined with a rotary steerable system and resistivity and gamma ray measurements to proactively detect both the top and bottom of the LU reservoir and accurately set the casing shoe for the subsequent section. In the 6.125-in reservoir phase, HD-RMWD was combined with triple-combo logging-while-drilling measurements to maintain the wellbore within the productive sandstones. A multidisciplinary team interpreted the data in real time using specialized geosteering software, integrating reservoir mapping with complementary downhole measurements to guide horizontal well placement decisions.

The application of HD-RMWD in the Inchi Field represents a step change in horizontal well placement within the LU reservoir. In the 8.5-in landing phase, the technology enabled early detection of the top LU boundary, enhancing landing precision despite structural dip variations and limited offset well control. In the 6.125-in reservoir phase, continuous mapping of the top and bottom boundaries supported proactive geosteering decisions to keep the wellbore within the most prospective reservoir intervals. The resistivity contrast between LU sandstones and surrounding shales was sufficient for the technology to delineate reservoir boundaries in real time with high confidence. Structural dip changes and reservoir thickness variations were identified during drilling, supporting more refined drilling and completion strategies. In both case studies, the reservoir sections were extended by more than 25% relative to the initial well plans, while avoiding the operational risks associated with exiting into unstable shales.

Horizontal drilling has played a critical role in unlocking the hydrocarbon potential of Ecuador's Oriente Basin. The successful implementation HD-RMWD technology in the Inchi Field represents a significant advancement in horizontal well placement, particularly within the stratigraphically complex and laterally discontinuous LU formation. While deep azimuthal resistivity technologies have been deployed in Ecuador for almost two decades, their limited depth of detection has often constrained precise geosteering and reservoir characterization. HD-RMWD overcomes this limitation by enabling early boundary detection and more proactive geosteering decisions, thereby enhancing reservoir exposure and reducing drilling risks. The Inchi Field experience sets a precedent for broader application across the Oriente Basin and underscores the value of ultra-deep resistivity measurements. Moreover, it serves as a scalable reference for operators worldwide facing similar geosteering challenges in complex geological environments.

4. ADVANCED ULTRA-DEEP INVERSION REDUCES UNCERTAINTIES RELATED TO WATER DISTRIBUTION AND IMPROVES RESERVOIR MANAGEMENT IN A MATURE FIELD

Enhancing hydrocarbon recovery in mature fields with complex carbonate reservoirs is highly challenging due to the reservoir's inherent properties, varying waterfront conditions, and structural uncertainties. The concurrent injection of water to maintain productivity complicates the understanding of water distribution, which can significantly impact operations. This case history showcases the successful use of real time Ultra Deep inversion in a multi-lateral well to map complex water distribution, aiding in water breakthrough management and improving hydrocarbon production potential.

Geosteering with standard formation evaluation data faces limitations in such situations due to its shallow depth of investigation. To better address these challenges and understand waterfront movement, an ultra-deep resistivity mapping tool was included in the existing triple combo bottom hole assembly. To evaluate its performance in this environment, a feasibility study was performed using data from nearby offset wells and modeled water scenarios. The advanced ultra-deep inversion would identify water distribution away from the wellbore, providing crucial information for making an optimal geosteering decision to target the best zone of the reservoir.

Carbonate reservoirs are typically heterogeneous, characterized by complex geological structures with varying porosity and permeability. This complexity makes accurate mapping and prediction of water movement challenging. In this case study, integrating the advanced ultra-deep inversion in real-time enabled precise mapping of subsurface features and water distribution, thereby improving well placement accuracy in a multi-lateral well. In the lower drain, updating the ultra-deep advanced inversion in real-time allowed detection of water distribution while drilling in the upper target.

This information helped prevent moving to the unproductive second target zone and maximized reservoir exposure in the first target. In the upper drain, the ultra-deep inversion revealed structural changes, but no conductive zone was found, confirming that the waterfront has not reached this level. Mapping water distribution ensured optimal reservoir management through suitable completion design and provided insights into sweep irregularities. The inversion results demonstrate the effectiveness of this approach in enhancing hydrocarbon recovery and reducing operational risks in complex carbonate formations. Ultra-deep resistivity inversion enables the identification of both structural and resistivity changes in real-time. This allows the drilling process to proceed with maximum efficiency. The implementation of such advanced technology in geosteering significantly enhances reservoir management in complex carbonate formations.

5. A GEOMETRIC MULTIGRID METHOD FOR 2.5D FDFD OF ELECTROMAGNETIC LWD SIMULATION

With the increasing complexity of the formation in oil exploration, electromagnetic LWD is developing from near-well exploration to geological orientation and formation structure imaging. Forward simulation plays an important role in data processing and tool design. However, the 1D and 3D algorithms still face the problem of balancing forward speed and accuracy. The computational efficiency restricts the development of inversion. In 2011, Yonghua Chen et al. of the Schlumberger Doyle Research Center introduced the 2.5D method to this field for the first time, simulating the logging response of azimuth electromagnetic LWD for complex formations such as unconformity and faults. To further increase the speed of calculations. In this research, the sparse matrix linear equations are solved by geometric multigrid algorithm, which can effectively solve the problems of long iteration time and slow calculation speed of iterative solvers.

For ultra-deep EM-LWD, the tool coil is equivalent to a magnetic dipole source. Deriving Maxwell's equations yields the electric field Helmholtz equation. Then, separate the electric fields into the background and the scattering field. Represent the scattering field as a function of the background field and transform to the spectral domain. The control equations are discretized using central differencing, forming a large sparse linear equation. $\nabla\times\nabla\times\vec{E}^s-k^2\vec{E}^s=iw\mu(\sigma-\sigma_0)\vec{E}^i$ (1) This equation is solved via the multigrid method. Restriction and prolongation operators between multigrid levels are computed, and discrete system matrices are constructed. The process involves: pre-smoothing iterations on the fine grid; restricting the residual to coarser grids; solving for the error correction on the coarsest grid; prolongating the correction back to finer grids; and applying corrections. This V-cycle repeats until convergence.

A two-layer resistivity model (20 Ω.m upper layer, 10 Ω.m lower layer) was established. Geological signal measurements used a 96-inch source-receiver spacing, while resistivity signal measurements employed a 36-inch source-receiver spacing with an 8-inch coil distance. As shown in Figure 1, the GMG method for 2.5D FDFD solution demonstrates sub-1% mean relative error compared to the 1D pseudo-analytic benchmark. This validates the algorithm's accuracy for industrial applications. Convergence rates of geometric multigrid (GMG) versus alternative solvers are compared in Figure 2. GMG demonstrates superior convergence, reducing iteration counts by >50% compared to Gauss-Seidel. While BiCG and BiCGSTAB exhibit similar iteration numbers, GMG achieves the minimal count with 60% faster computation than BiCGSTAB in solving a single system of linear equations.

The GMG+2.5D FDFD method enables accurate and efficient simulation of electromagnetic logging-while-drilling. Algorithm Verification and Acceleration: Decomposition of 3D spatial field computations into multiple 2D spectral-domain calculations substantially reduces sparse matrix orders, enhancing linear system solution efficiency and enabling rapid iterative forward modeling. Validation against pseudo-analytical solutions in 1D layered models confirms the accuracy of the 2.5D forward algorithm in precisely calculating phase shift and amplitude ratio signals. Implementation of the Geometric Multigrid (GMG) method accelerates linear system solutions, slashing computation time by 30% compared to the BiCGSTAB algorithm.

6. USING A LOW CONDUCTIVITY INVERSION FOR 1D MAPPING IN HIGH RESISTIVITY RESERVOIRS

Electromagnetic propagation resistivity tools primary use in geosteering, is the precise positioning of the well in the planned target to ensure greater contact with the production zone; additionally, new technologies allow 1D mapping of the resistive properties around the trajectory, thus defining the disposition of the fluids associated with the true resistivity of the formation, allowing a better understanding of the mobility of the fluids in the field and the updating of geological models. The plan, drill horizontal wells in the Llanos basin in Colombia, characterized by continuous thick layers due to its marine depositional environment. Surface uncertainty is expected due to subseismic faults that may bring the trajectory closer to or below the oil-water contact and high resistivity zones that limit calculation of true formation resistivity (Rt).

A solution was designed including the use of electromagnetic propagation LWD resistivity tools capable of mapping around 25 ft, using the combination of a deep transmitter-receiver array, high frequencies, investigation depths and distributions, to generate the inversion best representing the distribution of fluids in the reservoir. The objective was to maintain the wellbore ~15 ft TVD from the top of the navigation layer in the Ubaque Formation, away from oil-water contact, and ensure the trajectory has low dog leg severities to allow completion. A unified multidisciplinary workflow was established between the operating and service company to address the analysis of all the information available during drilling. In four wells, azimuthal information from electromagnetic propagation LWD resistive tools was used as the primary source of information.

The tool included multiple spacings, frequencies and antennas, capable of obtaining three-dimensional components necessary to generate 1D inversions, to map resistivities of the fluids present and their disposition. Through the integration of additional information provided by this tool and azimuthal gamma ray, resistivity images and EM geosignals, it was possible to position the well trajectory in the targeted zone. We discuss the planning and execution of geosteering with dual-configuration electromagnetic propagation azimuthal resistivity LWD tools, with LCI inversion up to 25 ft investigation depth in a heavy oil field, where the reservoir has layers between 20 -50 ft TVD thick.

The implementation of this technology allowed the optimal positioning of the trajectory, in addition to the acquisition of the formation evaluation information necessary for the accurate real-time estimation of water saturation (SW) and optimization of the completion job. With the implementation of this workflow in future wells, it will be possible to integrate this information with the available seismic of the field, which will provide a clearer vision of the rock-fluid-production relationship of the field.

7. A STEPPING STOCHASTIC INVERSION METHOD FOR DEEP LOOKING-AHEAD DETECTIONS

We proposed a simulated-annealing-based stepping inversion method to invert for the formation parameters ahead of the drilling bit. As different types of measurement modes are sensitive to different formation parameters ahead of the drill bit, the ultra-deep symmetrized directional (USD) data is utilized to invert for the formation boundary depth, the ultra-deep harmonic resistivity (UHR) data to invert for the isotropic resistivity, and the ultra-deep harmonic anisotropic (UHA) data to invert for the anisotropic resistivity. And the above inversion strategies are combined to discover isotropic/anisotropic formation parameters. Moreover, each inversion process is repeated hundreds of times and the results uncertainty is obtained by investigating these inversion results to show the validity of proposed method. Both isotropic and anisotropic 3-layer-formation is utilized to test the proposed inversion method and it reveals that the proposed method could successfully discover their boundaries and isotropic/anisotropic resistivities.

The simulated annealing (SA) method is utilized to invert for various formation parameters, such as boundary depths, the layered isotropic and/or anisotropic resistivities. The frequency is 24k, 48k, and 96k Hz. For isotropic models, we first utilize the SA method and the amplitude and/or phase of USD data to invert for the formation boundary depths, and then invert for the layered bulk resistivities with the amplitude and/or the phase of UHR data. For anisotropic models, we still use the SA method and the amplitude and/or the phase of USD data to invert for the formation boundary depths, and then invert for the layered anisotropic resistivities with the amplitude and/or the phase of UHA data. Moreover, the inversion is run 100 times to investigate the uncertainty of the inversion result with a certain type of measurement data. We finally obtain the optimum inversion results under probability uncertainty 95%.

The tool located at the top of a 3-layer model to detect the formation parameters ahead of the drill bit. The inversion results for an isotropic model (Figure 1(a)) are shown in Figure 1(b-k), where b-e are about the inverse boundary depth, f-k are about the inverse resistivity of each layer. The inversion results for an anisotropic model (Figure 1(l)) are shown in Figure 1(m-r), where m-o are about the inverse horizontal resistivity, p-r are about the inverse vertical resistivity of each layer. It reveals the inverse boundary from the USD amplitude data is much closer to the synthetic model than that using the USD phase as Figure 1(b-e) and the UHR phase data enables it to reach a more accurate inverse model than the UHR amplitude data as Figure 1(f-k). Moreover, Figure 1(m-r) shows that the UHA phase data helps it to invert for an anisotropic model.

The proposed SA-based stepping inversion method utilizes the USD data and the UHR data to invert for the formation boundary and resistivity of a layered isotropic model, respectively. It also uses the USD data and the UHA data to invert for the formation boundary and anisotropic resistivity of a layered anisotropic model, respectively. The optimum inversion result and the corresponding probability uncertainty is obtained by investigating the hundreds of inversion results for a certain measurement. 2 isotropic models and 2 anisotropic models are set to verify the performances of the proposed stepping inversion method. Moreover, it reveals that the USD amplitude data, the UHR phase data and the UHA phase data enable us to obtain accurate inversion results.

8. WHERE GEOSTEERING IS HEADING BY 2035: INSIGHTS FROM AN INTERNATIONAL EXPERT PANEL AND PARTICIPANT SURVEY AT A NORWEGIAN WORKSHOP

Over the past two decades, geosteering has seen steady advancements driven by improved methodologies, enhanced collaboration, and the introduction of sophisticated tools. Today, advanced Ultra-Deep Azimuthal Resistivity (UDAR) technologies provide unprecedented volumes of subsurface data, pushing the boundaries of what is technically possible. However, as hardware capabilities plateau, the next decade will be defined not by new tools but by how effectively the industry leverages existing data, digital solutions, and human expertise. Insights from an international expert panel and a participant survey reveal a shared outlook: the future of geosteering lies in better data integration, the adoption of automation and AI-assisted workflows, and addressing challenges posed by the changing workforce. This paper examines these themes, highlighting how technology, collaboration, and competence development will guide geosteering's evolution towards 2035.

This paper summarises a topical panel discussion about the future of geosteering held at the Geosteering and Formation Evaluation Workshop by NORCE and NFES 2024. The panel consisted of experts from operating and service companies with decades of operational and technological experience. During the discussion, an interactive survey engaged a diverse audience to measure perceptions on key drivers such as technological advancements, market shifts, and education trends. By combining qualitative insights from the panel with quantitative survey data, we identified prevailing themes and concerns ranging from automation acceptance to data management challenges. They provide a grounded forecast of where geosteering will be headed over the next ten years.

The discussions and surveys revealed consensus on several points: while automation, AI, and digitalization will transform workflows, human oversight will remain essential due to persistent data quality issues and accountability concerns. The exponential growth in data per well, coupled with a declining number of geoscience professionals, highlights the urgent need for scalable, intelligent tools. Moreover, the industry must adjust to shifting business models, where operators increasingly internalize expertise while redefining collaboration with service providers. Educational gaps, standardization needs, and the challenge of effectively communicating uncertainties were also identified as critical areas for development.

According to our outlook, geosteering towards 2035 will evolve through enhanced data utilization, AI-supported advisory systems, and deeper collaboration across industry players. The path forward demands not only technological adaptation but also a cultural shift towards embracing automation where appropriate, without losing sight of human judgment. Addressing workforce challenges through interdisciplinary education and fostering open collaboration between operators, service companies, and academia will be key to sustaining progress. Ultimately, success will hinge on balancing innovation with practicality, ensuring that decision-making remains reliable, transparent, and grounded in geological understanding as the operational complexity grows.

9. RESEARCH ON DATA PROCESSING METHOD OF DIRECTIONAL ELECTROMAGNETIC WAVE LOGGING WHILE DRILLING BASED ON ACTIVITY STRATIFICATION CONSTRAINT

The orientation and distance of the formation boundary are important parameters in the high angle wells/horizontal wells, and are the key to making correct decisions in geological guidance. By using inversion and imaging techniques, the directional electromagnetic wave resistivity logging data can be converted into visualized formation parameter information. The inversion results have a high dependence on initial values. In this paper, the activity method is used to stratify the strata, and the initial values and constraints are given using the stratification results, combined with the Levenberg Marquardt algorithm to perform one-dimensional fast inversion calculations. By combining the activity stratification algorithm and inversion algorithm, the inversion is effectively reduced from falling into local minima, ensuring the global convergence of parameters. The accurate initial value reduces the number of iterative steps and improves the calculation speed. Finally, the reliability and practicality of the method were verified through actual data processing.

The activity stratification method is a type of non mathematical statistical method. This method can automatically stratify logging curves. The activity function is the theoretical basis for activity stratification. During the logging process, there are multiple curves with high dimensionality and multiple variables. In order to analyze these diverse data, it is necessary to reduce the dimensionality appropriately. In this paper, principal component analysis is used to project high-dimensional data into a low dimensional space with minimal information loss, achieving the goal of simplifying the data structure through dimensionality reduction. Mainly includes standardization, alculate the correlation coefficient matrix, eigenvalue obtain. Provide the boundary position and resistivity distribution of the formation through activity stratification, and provide an initial model for inversion.

The results of the activity stratification method can provide initial values and constraints for data inversion, reduce the ambiguity of inversion settlement, and save computation time. This article uses logging data from China Shengli Oilfield to carry out data processing of electromagnetic wave logging while drilling based on activity stratification constraints. Figure 1 (a) shows the inversion results without activity stratification constraints, while Figure 1 (b) shows the inversion results with activity stratification constraints. It can be seen that there is a significant difference between the two results in the 825m-875m section. Figure 1 (b) shows that the instrument drilled the reservoir, which is consistent with the logging records, proving the feasibility and practicality of constrained inversion of activity stratification results.

Through the processing of simulation data and measured data, it can be seen that the application of activity stratification theory can obtain the boundary position of the formation in advance, provide accurate initial values for inversion algorithms, reduce inversion falling into local minima, save inversion iteration time, and improve the accuracy of inversion results. The processing results of the measured data show that the boundary position and resistivity distribution of the formation obtained by inversion are consistent with the logging results.