World Oil®

Originally appeared in
World Oil, April 2024.
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FORMATION EVALUATION

Reservoir mapping advances optimize well placement with 3D views of reservoir architecture

New reservoir mapping services reduce uncertainties by collecting pure signals with appropriate confidence analysis. The assessment identifies potential in-fill targets and opportunities for de-risking projects and maximizing recovery by mapping lithological and fluid contacts while drilling. Thus, operators gain insight into reservoir distribution and quality for improved field development planning/execution.

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Optimizing production and recovery from reservoirs drives an industry need for while-drilling reservoir navigation and mapping advances that clearly, and accurately, map reservoir distribution and quality. Such insights are critical to reducing uncertainty and de-risking challenging drilling projects by ensuring that the well lands, as required, in the target production zone—and stays in the best position to help increase ultimate reservoir recovery, prevent early water breakthrough, and improve long-term reservoir management.

A clearer understanding of reservoir structure and fluid contacts vastly improves reservoir navigation and well placement. To date, most reservoir mapping technologies, based on ultra-deep azimuthal resistivity (UDAR) measurements, deliver maps that detect potential fluid and lithological boundaries up to hundreds of feet away from the wellbore. However, these maps are not typically or adequately accompanied by detailed confidence analysis performed on the inversion results.

The quality and accuracy of UDAR measurements are critical when investigating large volumes in the sub-surface. As a result, antenna design is a key consideration and a research focus within the industry.[1] Some antenna configurations may be sub-optimal, due to the challenge of effectively extracting actual signal measurements from mixed signals or noise.

A lack of collocation of UDAR measurements can lead to excessive corrections and further uncertainty. When these measurements are not quantified with appropriate confidence analysis, the resulting inversion maps can be misinterpreted by the operational team, leading to reduced drilling efficiencies, non-ideal well placement, ambiguous reservoir volumetrics and lower overall production and recovery rates for the asset's life.

New service delivering sharper subsurface insights for more confident well placement. The TRU-ARMS advanced reservoir mapping services from Baker Hughes were developed to reduce these uncertainties by collecting pure signals with the appropriate confidence analysis. The resulting geomaps improve appraisals of field production and recovery potential by identifying, as an example, potential in-fill targets and opportunities for prevention of early water breakthrough through the lithological and fluid contacts mapped while drilling.

As a result, operators gain sharper insights into reservoir distribution and quality for improved field development planning and execution. Such insights can identify cost-savings enabled by drilling fewer but better-placed wells than may have been planned initially. The services capture deeper insights from the UDAR measurements through three differentiating components, as follows:

- **Enhanced data quantity with multi-application transceiver modules.** The services employ the industry's first transceiver modules capable of transmitting or receiving data. The modules operate at multiple frequencies ranging from 1 kHz to 2 MHz when combined with both shallow and deep azimuthal resistivity services. This range of frequencies, components and spacings allows for improved definition of both shallow and ultra-deep environments, leading to superior inversion outputs. The transceiver modules add significant flexibility by matching the bottomhole assembly (BHA) design to the specific mapping objectives. Multiple configurations become available to support landing, geostopping, geosteering, geomapping and formation evaluation objectives. Transceiver assignments can be programmed and configured while drilling to provide real-time data transmission that supports simultaneous reservoir navigation objectives and larger-scale geomapping objectives looking deeper into the reservoir.

- **Enhanced data quality with new antenna design.** The services include the industry's first 3-component collocated and orthogonal antennas that measure pure x, y, and z magnetic field components. The new design incorporates a highly efficient antenna that yields a higher signal-to-noise output, compared to other UDAR antenna configurations. The system has been designed for optimal electronic performance that efficiently utilizes available downhole power without needing to boost any specific frequency. The resulting UDAR dataset, obtained from pure signals with a high signal-to-noise ratio, provides greater sensitivity for more accurate insights into the reservoir's geometry, properties, and distribution.
- **Enhanced data integrity with multi-dimensional inversions and embedded confidence analysis.** The advanced reservoir mapping services unlock a depth of detection up to 300 ft (91 m) into the reservoir, which represents a step change, compared to other UDAR geosteering systems. The resulting UDAR inversion outputs are accompanied by quantitative confidence analysis on the mapped structural boundaries and fluid contacts. This, in turn, supports improved volume estimations based on quantifiable confidence ranges.

The advanced UDAR inversions and their associated confidence analyses can be combined with a full range of logging-while-drilling (LWD) measurements and seismic data to enhance reservoir understanding. Broadly, a range of techniques is proposed to add deeper quality control, confidence, and understanding of the inversion results. Linear confidence analysis is subdivided into boundary and resistivity confidence analysis. Further multiple statistical analyses, such as P10, P50, and P90, are provided, along with associated visualization in the form of curtain sections. A dynamic depth of detection (DoD) estimation adds further critical insights at the extremities of the detection envelope around the wellbore.

As **FIGURE 1** illustrates, the confidence of the range of occurrence of a particular surface may be displayed for given inversion intervals. From a reservoir modeling perspective, the geo-modeler can extract greater value by appraising the minimum and maximum volumetric uncertainties from the boundary confidence analysis. In real-time, the boundary confidence analysis quantifies the detectability of boundaries, thus enabling better-informed and more timely decision-making to maintain wellbore inclination and/or azimuth versus making a proactive decision to adjust the wellbore trajectory to meet objectives.

Resistivity confidence analysis resolves beds, based on resistivity and anisotropy, **FIG. 2.** These may be visualized as a tool-relative resistivity profile (Rt-profile) and for anisotropy as vertical resistivity (Rv) or anisotropy factor. Using this confidence analysis, operational teams can evaluate the resistivity variation and sharpness of contrasts in the stratigraphic column, i.e., true stratigraphic depth (TSD).

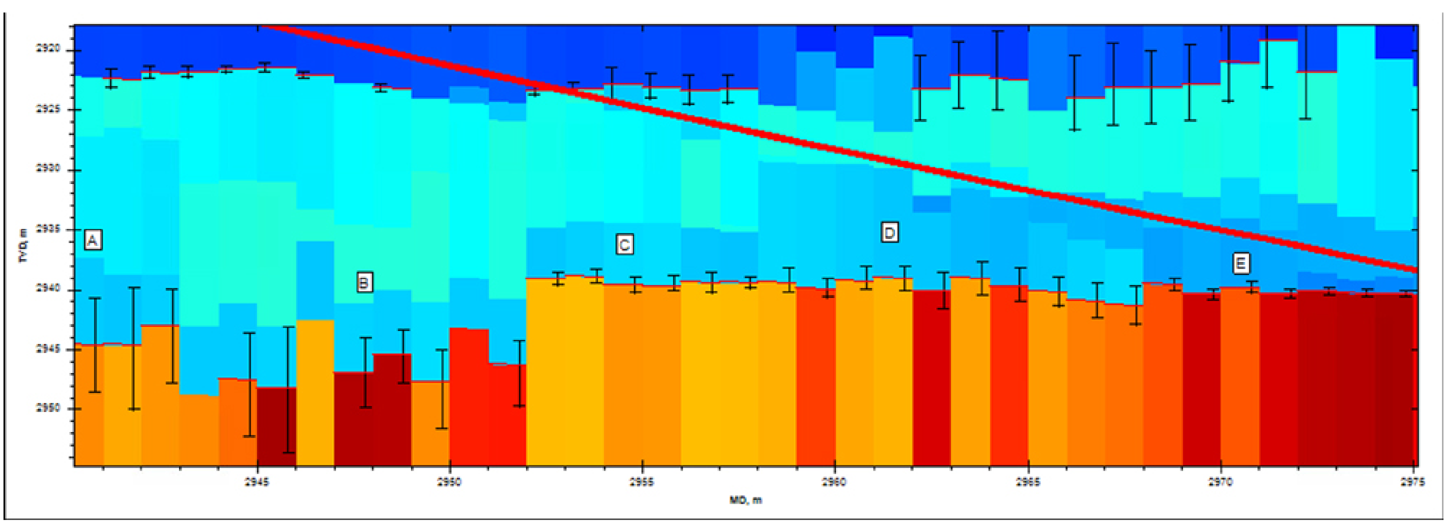

FIG. 1. Boundary confidence analysis. Error bars indicate the shallowest and deepest possible positions of a corresponding boundary.

Statistical analysis is necessary to evaluate the global uniqueness of mapping results, **FIG. 3.** Several possible scenarios are used to test different hypotheses about the inversion model and study parameter sensitivity (resistivity, anisotropy, boundary positions, relative dip). The variance of boundary position and resistivity/anisotropy translates into confidence about volumetrics and reservoir fluids distribution, respectively. Operational needs (real-time reservoir navigation) usually focus on interval-by-interval analysis, and larger-scale analysis is based on statistical curtain sections.

Dynamic depth of detection is vital to understanding the sensitivity to a remote boundary. Data inversion, linear confidence and statistical confidence analysis provide the best possible explanation of the measured data and quantify related uncertainties within the tool sensitivity range. DOD evaluation, in turn, focuses on the remote targets and evaluates the edge of tool sensitivity to produce a dynamic envelope for inversion models, **FIG. 4.**

The advanced reservoir mapping services support the recently introduced advanced borehole exchange data format, which automatically ties multiple data sets from both wireline and LWD domains to the wellbore, regardless of data type. These data sets will automatically move if updated wellbore surveys are calculated, based on in-field referencing updates that may alter the wellbore's x, y, and z positions. Linking the data to the wellbore also improves the efficiency and accuracy of geomodels by avoiding any mismatch between the original data logging location and the final location after the updated survey is run.

The enhanced data quality, quantity and integrity afforded by the advanced mapping services help operators achieve their reservoir navigation and geomapping objectives to maximize return on investment from their fields. The real-time insights help optimize real-time well deliverability for improved production and overall asset recovery. Field development costs and risks are also reduced by ensuring more sustainable field developments with fewer drilled wells. The detailed inversion maps generated by the mapping services also improve collaboration between an operator's well engineering, subsurface, and production teams.

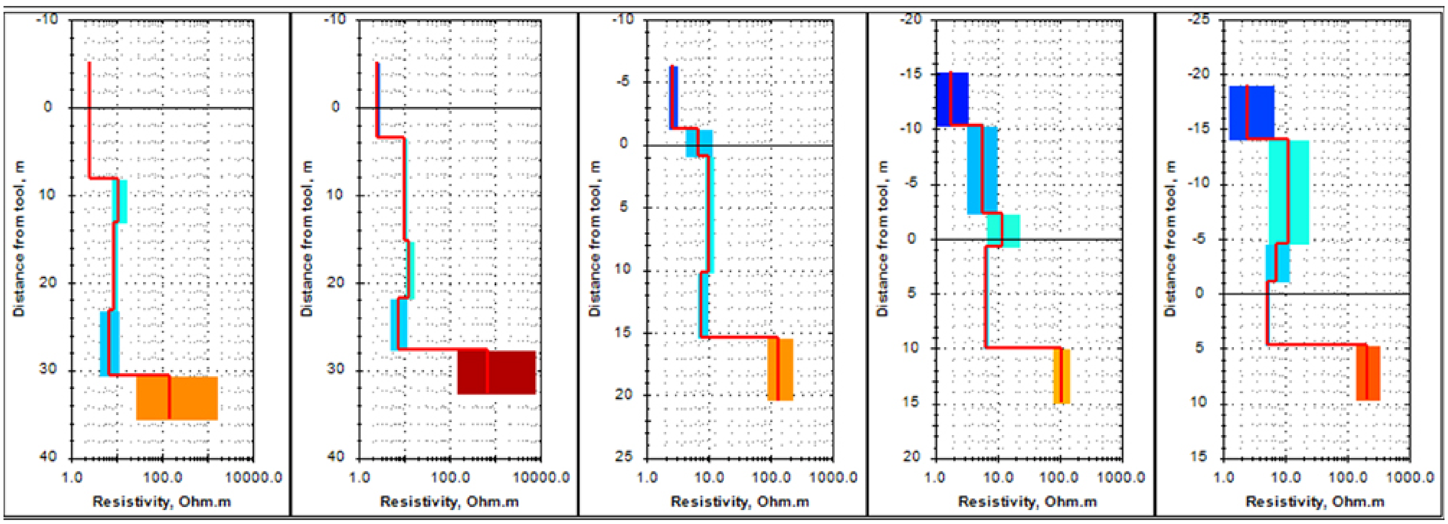

FIG. 2. Resistivity confidence analysis. For each layer, a confidence range is visualized as a rectangle with a corresponding width. The color is consistent with the curtain section palette and corresponds to the layer resistivity value.

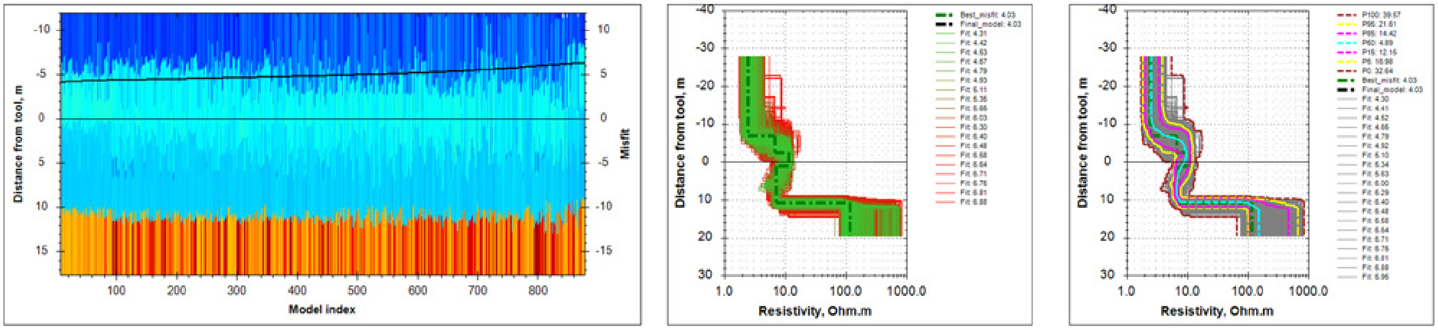

FIG. 3. Statistical analysis. Intermediate inversion models are visualized in three ways (from left to right): As a model sorted by data match, Rt-profiles with color-coding based on data match, and Rt-profiles with percentile envelopes.

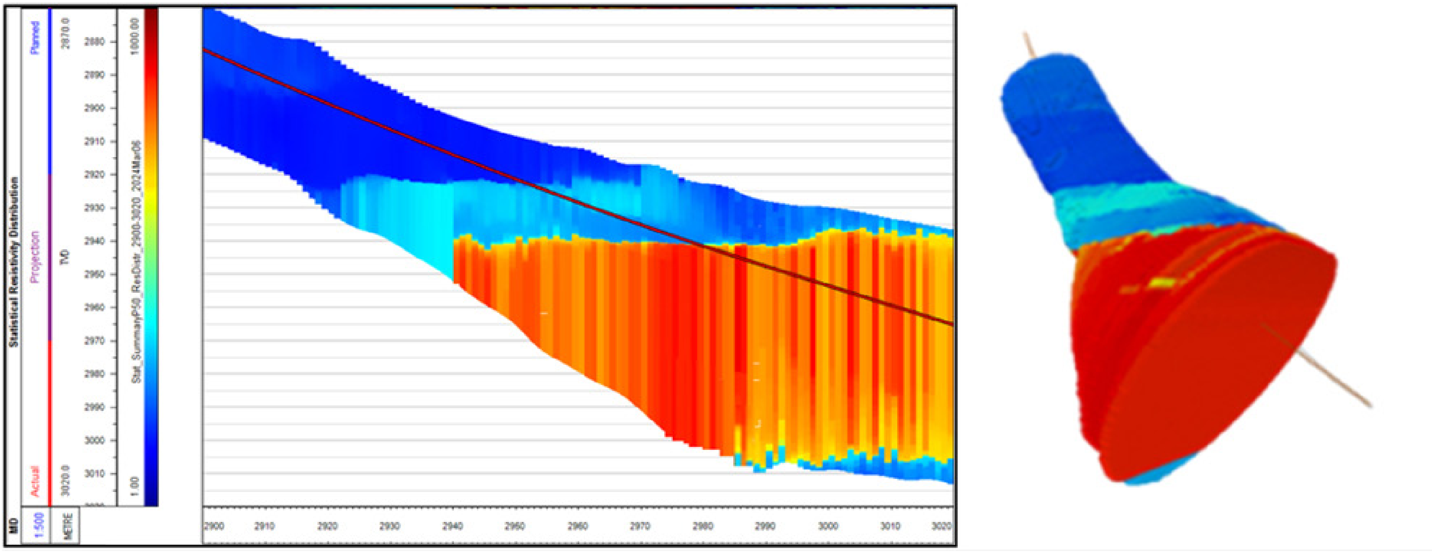

FIG. 4. Dynamically cropped inversion output and 3D visualization of advanced borehole exchange format cropped as a DOD tube.

Putting the pieces together. Development and testing of the advanced reservoir mapping services drew upon the company's 30-year history of developing technologies in the reservoir navigation and mapping services domain. As with previous tools, the development process for the new mapping services began with a sound understanding of the well placement challenges and field appraisal needs of operators drilling in challenging reservoirs. After detailed data gathering and discussions with several operators, upfront modeling and design work were performed to translate operator needs into technical requirements for the new mapping services.

The components of the services were designed and manufactured in the company's Celle Technology Center (CTC) in Germany. An interdisciplinary team of mechanical, firmware, and electrical engineers, as well as experts in signal processing and reservoir evaluation, worked together with supply chain teams to deliver all components. A detailed qualification and testing process was followed to ensure the services met all technical requirements. This included laboratory-scale flow loop testing, as well as evaluation in the company's dedicated test drilling rig near the CTC.

During the test rig deployment, tools were tested under actual downhole conditions to ensure they met the required measurement and drilling performance metrics. After testing, the tools were returned to the technology center for inspection and evaluation. Any modifications or improvements to the tools' design were made quickly and verified rapidly at the test rig. This iterative process significantly reduced development time and lowered project risks by ensuring that the tool worked reliably as designed before deployment to the field.

Optimizing well placement and field appraisal in challenging offshore reservoirs. Major operators have deployed the new reservoir mapping services to help achieve their reservoir navigation and geomapping objectives during an extensive field-testing program. The services were deployed with LWD and directional technologies in different configurations, depending on each well's measurement KPIs: a standard two-module configuration and a three-module configuration with varying frequencies and components for different spacings.

Members of the Baker Hughes reservoir technical services and drilling services teams collaborated with the operators to develop the optimal reservoir mapping services configuration for their fields. The best combinations of spacing, frequencies and components were determined through an iterative and comprehensive pre-well modeling and feasibility process. Consideration was also given to the BHA's power consumption, vibration mitigation, and drilling engineering to ensure that the deployment of such complex BHAs would meet all well objectives.

In one scenario, the operator's geosteering objectives included drilling production intervals no more than 2 m from the reservoir roof to maximize the well's productive life by minimizing attic oil. Other scenarios called for mapping the top and bottom of the reservoir, along with the associated confidence analyses, which the operator would use to update volume estimates within the subsurface model. The services accurately mapped the reservoir thickness and geometry to improve the operator's volume estimations. The precise well placement also allowed for optimal well performance and potentially increased recovery. Around 4,877 m were geosteered and mapped, with no interruption to the planned operations.

Meeting today's drilling demands with room for growth. In a growing number of complex drilling operations, the TRU-ARMS advanced reservoir mapping services are demonstrating an unprecedented ability to optimize wellbore placement and de-risk future field development. By combining industry-first transceivers, full-tensor collocated and orthogonal antennas, and detailed UDAR inversion maps with built-in confidence analyses, the services bridge the gap between wellbore-centric and seismic-scale measurements hundreds of feet into the reservoir.

Near-wellbore data support an operator's geosteering efforts by enabling real-time decision-making to maximize reservoir contact during the drilling operation. At the same time, data from deeper in the reservoir enables clear geomaps of lithological and fluid boundaries, providing deeper insights into the extent and architecture of the reservoir to de-risk planned future production or injection wells and reduce field development costs.

The application of advanced reservoir mapping services clearly supports the drive towards the goal of cleaner energy by driving efficient field development through a step change in optimal well placement. This, in turn, leads to a reduction of the carbon footprint during hydrocarbon production and recovery operations. As the advanced reservoir mapping services are deployed in more wells and applications, Baker Hughes is capturing the field data and lessons learned. With this information as a guide, the company is committed to further advancing the field of ultra-deep azimuthal resistivity technology and driving greater value for operators in more challenging drilling environments. **WO**

REFERENCE

[1] Li, H., and J. Zhou, "Distance of detection for LWD deep and ultra-deep azimuthal resistivity tools," SPWLA paper 2017-PPPP, presented at the SPWLA 58th Annual Logging Symposium, Oklahoma City, Okla., June 17-21, 2017.

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