True 3D measurements for enhanced reservoir quantification

Rt Scanner
Rt Scanner* triaxial induction service calculates both vertical and horizontal resistivity ($R_v$ and $R_h$, respectively) from direct induction measurements while simultaneously solving for formation dip at any well deviation. Making measurements at multiple DOIs in three dimensions ensures that the derived resistivities are true 3D measurements. The enhanced hydrocarbon and water saturation estimates computed from these measurements result in more accurate reservoir models and reserves estimates, especially for formations with laminations, anisotropy, or faults.

The compact, one-piece Rt Scanner tool has multiple triaxial arrays for making true 3D measurements.

Rt Scanner measurements in three dimensions at multiple depths of investigation (DOIs) quantify even low-resistivity laminated pay zones to reduce uncertainty and refine your reservoir model.

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The compact, one-piece Rt Scanner tool has multiple triaxial arrays, each containing three collocated coils measuring at various depths into the formation. $R_v$ and $R_h$ are calculated at each of the triaxial spacings. A unique electrode sleeve with short single-axis and collocated triaxial receivers is used to fully characterize the borehole signal and remove the borehole effect.
The collocated transmitter and one of the several collocated receivers (left) of the Rt Scanner tool independently obtain tensor resistivity measurements (right) that yield valuable information, especially in laminated formations.

In addition to advanced resistivity measurements, formation dip and azimuth are available for structural interpretation. The Rt Scanner tool also delivers standard AIT* array induction imager tool measurements for correlation with existing field logs. The tool’s innovative single-piece design requires the addition of only a caliper and the GPIT* general purpose inclinometry tool to the toolstring to operate. Rt Scanner service is also fully combinable with most openhole services and the Platform Express* platform—adding only 7 ft [2 m] to the length of a Platform Express triple-combo when replacing the AIT resistivity tool.

COLLOCATED COILS
The key to the unique measurement capabilities of Rt Scanner service is proprietary collocated coil technology. Inducing currents horizontally and vertically into the formation from one depth point and then receiving them at another mutual depth point provides measurement of the formation properties in true 3D. The multiple collocated receivers also measure at progressively deeper radial depths. The resulting 3D information contains structural dip, azimuth, and resistivity anisotropy information, which provides critical contrast in low-resistivity laminated pay and other challenging environments.

**APPLICATIONS**
- Quantification of laminated or low-resistivity formations
- Corrected resistivity for shoulder beds at any angle
- Determination of water saturation, $S_w$
- Geometric reservoir modeling
- Structural analysis
- Completion design and facilities optimization

The collocated transmitter and one of the several collocated receivers (left) of the Rt Scanner tool independently obtain tensor resistivity measurements (right) that yield valuable information, especially in laminated formations.
**ACCURATE QUANTIFICATION OF LAMINATED SANDS**

Conventional wireline induction tools measure mainly $R_h$. However, this measurement bias results in low-resistivity readings in anisotropic resistivity sequences, such as thinly laminated sands and shales. The conductive shales dominate the resistivity, neutron, and several other logs, masking pay zones in the sands and producing pessimistic interpretations of hydrocarbon volume.

Rt Scanner service extends the basic AIT induction logs to include $R_v$ and $R_h$. These additional measurements in combination with structural dip and azimuth obtained by the tool provide valuable insight to the resistivity of the sand portion ($R_{sand}$) of laminated formations. A 1D inversion algorithm is used to determine $R_{so}$, $R_{vp}$, and the bed boundaries and dip azimuth. The dip-corrected measurements are used to populate a reservoir model that can incorporate a shale anisotropy factor to account for the intervening shales. The enhanced saturation estimates computed with the model account for the geometry of the layers.

The 1D inversion of the Rt Scanner measurements obtained by the collocated coils produces both dip and resistivity information. $R_h$ runs parallel to the bedding plane, $R_v$ is orthogonal to $R_h$.

The butterfly overlay on the crossplot of $R_v$ and $R_h$ (right) includes input for the shale content (left track). Data corresponding to shales, water zones, and pay zones are shown in green, cyan, and magenta, respectively. As the horizontal bar is moved in the $S_w$ track, the cumulative sand volume ($\sum F_{sand}$), hydrocarbon volume from $R_v$ and $R_h$ ($\sum V_h R_v R_h$), and hydrocarbon volume from $R_h$ ($\sum V_h R_h$) are displayed. The volume fraction of shale $F_{shale}$ in the left log track is a good match to core from the interval at 850 to 950 ft (left).
Low-resistivity laminated pay cannot be accurately logged with conventional tools. To the right of the log, a 20-ft [6-m] section of FMI* fullbore formation micro-imager images shows the 60° relative dip and highly laminated formations in this US Northern Gulf Coast well. The neutron log (Track 2) is so severely influenced by the shale laminations that there is no density-neutron crossover. Resistivity is similarly dominated, with depressed measurements in Track 3. However, laminated sand analysis based on Rt Scanner measurements accurately quantifies the hydrocarbon in place, including otherwise unidentified pay (Track 4). In addition, the combination of dip measurements in Track 5 from Rt Scanner and imaging tools enhances structural understanding throughout the well.
Both the Rt Scanner and OBMI dip measurements show a distinct change in dip at X,580 ft, indicating an unconformity. The change in dip is also reflected in the shift of the classic AIT resistivity logs—they overlie the Rt Scanner \( R_t \) curve in the low-dip interval above the change, but are between the Rt Scanner \( R_t \) and \( R_v \) curves in the underlying interval of higher dip. The overlay of \( R_v \) and \( R_t \) in the wet sands also provides a quicklook of the fluid type in this case.

Layer dip is computed over 10- to 50-ft [3- to 15-m] intervals. Although at a lower vertical resolution than dip from an imaging tool or dipmeter, these measurements are sufficiently robust to provide critical structural information and detect major events, such as bed boundaries and unconformities or faults crossing the borehole. Additional stratigraphic insight can be achieved from pairing Rt Scanner dip measurements with OBMI* oil-base microimager data.

Stick plots of Rt Scanner triaxial dip measurements can also be used to scale up from continuous structural content at a single-well scale to the borehole or surface seismic section. Bridging the gap between image logs and the seismic section with dip measurements greatly enhances geometric understanding of the reservoir.
CASE STUDIES

ESTIMATING HYDROCARBON VOLUME IN THINLY LAMINATED SANDS

Formation evaluation of conventional induction logs from a thinly laminated gas-bearing sand calculated high values of $S_w$. These classic logs were essentially measuring a bulk value of $R_t$ for the interbedded sands, shales, and mudstones, which range from almost a meter to less than a centimeter in thickness, with most of the layer thicknesses in the centimeter range, well below the vertical resolution of the classic induction tool. The low resistivity resulting from the low-conductivity anisotropic shale layers in turn depressed the hydrocarbon volume interpretation.

To calculate correct $S_w$ values, the dip-corrected Rt Scanner $R_p$ and $R_v$ measurements were used in a laminated sand-shale model that incorporated a shale anisotropy factor determined from the massive underlying shale. Instead of the nearly 100% $S_w$ values obtained from classic induction resistivity measurements, the Rt Scanner model calculated $S_w$ between 20% and 50%.

The Rt Scanner saturation values were a good match to nuclear magnetic resonance (NMR) logging and core measurements. Subsequent formation tester sampling downhole confirmed the presence of hydrocarbon, and producibility was demonstrated with a drillstem test. Without the revised $S_w$ values possible with Rt Scanner 3D measurements, the potential of this complex reservoir would have gone unrecognized.

Compared with the analysis of classic induction logs, the Rt Scanner resistivity anisotropy measurements for the laminated sand indicate the presence of hydrocarbon that otherwise would have been overlooked (Tracks 6 and 7 are the pay flags for the classic and Rt Scanner anisotropic interpretations, respectively). Gas is indicated by the crossover between density and neutron at X,150–X,155 ft, X,188–X,192 ft, and X,268–X,271 ft.
RESOLVING BED BOUNDARY EFFECTS IN HIGH-DIP, LOW-RESISTIVITY PAY

Induction logs are prone to bed boundary effects in thin-bedded sands. To better understand low-resistivity pay in a channel complex at a relative dip of 60°, an operator ran Rt Scanner triaxial induction service. The Rt Scanner measurements identified the low-resistivity pay in the lower half of the well and resolved the bed boundary effects shown as horns in the AIT 10-in [25-cm] resistivity at X,990 and Y,040 ft. The correctly identified true resistivity ($R_t$) for the channel sands is greater by a factor of 4 than the AIT 90-in [229-cm] resistivity value. If only conventional logs had been used, the effects of the surrounding shale beds would have resulted in an inaccurately low estimate of oil saturation and consequently of reserves.

In Zone A, the conventional AIT 90-in resistivity reads low in the thicker channel sands because of the surrounding dipping shale beds. The AIT 10-in resistivity also exhibits significant shoulder-bed horns. The Rt Scanner $R_v$ and $R_h$ measurements correct for the dipping shale beds in Zone A. In Zone B, the Rt Scanner measurements correctly identify a low-resistivity pay zone that otherwise would have been overlooked.
**USING DIP INFORMATION TO FOLLOW TURBIDITE CHANNELS**

An operator wanted to place additional wells in a productive turbidite sand in Mexico, but seismic information was lacking for following the sinuous channel body. However, Rt Scanner dip measurements were obtained during the logging run. Stratigraphic interpretation of the Rt Scanner dip information in combination with imaging tool data assumed a channel geometry with fine accretionary overbank deposits resulting from the lateral and downstream migration of relatively sinuous and confined subaqueous channels. In this scenario, the strike of the bedding in the argillaceous channel base indicates the direction the channel followed.

With the channel direction revealed, the next well could be located northeast of the original well. The well trajectory was planned using the dip information, and the same good-quality sands of the turbidite channel were intersected.

**DRILLING A SUCCESSFUL DEEPWATER SIDETRACK IN THIN-BEDDED SANDS**

Low-resistivity thin-bedded sands intercalated with shale layers were insufficiently characterized by conventional logs for placing a sidetrack in turbidite deposits offshore West Africa. Additional complications were the possible deformation of bedding by nearby salt deposits and that the seismic data was often doubtful because of the depth and seismic resolution.

To better understand this challenging situation, Schlumberger recommended dip angle measurements at multiple DOIs around the borehole well. The OBM12* integrated dual oil-base microimagers and Rt Scanner triaxial induction service were run because they can obtain accurate images and measurements of low-resistivity formations drilled with oil-base mud. The OBM12 tool recorded dip data around the borehole wall at a DOI of approximately 3.5 in [8.9 cm], and the Rt Scanner tool obtained far-field, radially variant dip measurements at DOIs of 39, 54, and 72 in [0.99, 13.7, and 1.8 m]. The Rt Scanner 3D dip measurement was also insensitive to any borehole irregularities, which were expected in this heterogeneous depositional environment.

Schlumberger Data & Consulting Services (DCS) introduced an improved approach to structural dip computation that integrated the two dip measurements. The first step was determining the level of confidence for the Rt Scanner dips with respect to borehole resistivity image dips from a known formation. The structural dip values were also compared with the vertical seismic profile to improve the view away from the borehole and better display large-scale variations in the deposits. The conventional averaging method was also used to compute another set of dip values for comparison.

The DCS analysis found that as the DOI increases, the average dip decreases. The same bedding nature was also observed in the VSP data. Averaging the four sets of dip data achieved a more realistic structural dip value that could be used to improve reservoir modeling. With this information, the operator was able to drill a successful sidetrack.

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<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>( R_v, R_h, ) AIT logs, spontaneous potential, dip, azimuth</td>
</tr>
<tr>
<td>Max. logging speed</td>
<td>3,800 ft/h [1,097 m/h]</td>
</tr>
<tr>
<td>Combinability</td>
<td>Platform Express platform and most openhole services</td>
</tr>
<tr>
<td>Max. temperature</td>
<td>302 degF [150 degC]</td>
</tr>
<tr>
<td>Max. pressure</td>
<td>20,000 psi [137,895 kPa]</td>
</tr>
<tr>
<td>Bore hole size—min</td>
<td>6 in [15.24 cm]</td>
</tr>
<tr>
<td>Borehole size—max.</td>
<td>20 in [50.8 cm]</td>
</tr>
<tr>
<td>Outside diameter</td>
<td>3.875 in [9.84 cm]</td>
</tr>
<tr>
<td>Length(^2)</td>
<td>19.6 ft [5.97 m]</td>
</tr>
<tr>
<td>Weight</td>
<td>404 lbm [183 kg]</td>
</tr>
<tr>
<td>Max. tension(^2)</td>
<td>25,000 lbf [111,205 N]</td>
</tr>
<tr>
<td>Max. compression(^3)</td>
<td>6,000 lbf [26,689 N]</td>
</tr>
</tbody>
</table>

\(^1\) A standoff is mandatory with this service
\(^2\) GPIT tool is required to be run in combination
\(^3\) Limits derived at 302 degF and 0 psi