New Resistivity-Logging Tool Helps Resolve Problems of Anisotropy, Shoulder-Bed Effects

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Three-dimensional, colocated resistivity measurements at multiple depths of investigation (DOI) can quantify even low-resistivity, laminated pay zones to reduce uncertainty and refine reservoir models. Obtaining measurements of this type has made it possible to resolve formation anisotropy problems and shoulder-bed effects in a broad range of wells.

For decades, well-log interpretation classes began with the caveat, “Assume an isotropic, homogeneous formation.” Indeed, this was the only way a systematic approach could be developed to calculate such fundamental parameters as porosity and water saturation in reservoir rocks. Logging tools of the day lacked the spatial resolution to make precise measurements in any but the most basic formation/borehole geometries. Because most wells were vertical, or nearly so, and since many wells penetrated strata that resembled layer-cakes, tools were designed using the principle of radial symmetry. That is, they worked optimally when the borehole axis was perpendicular to the formation’s bedding planes.

Even when we knew that formation isotropy was rarely the case, we were powerless to do anything about it because of tool limitations. It could be postulated that the introduction of horizontal drilling provided the impetus to develop new tool systems that could accurately characterize formations and reservoirs regardless of formation/borehole geometry.

Today, it is possible to resolve even extremely tough interpretation problems through the application of the Rt Scanner, a triaxial-induction resistivity-logging tool that 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. By making measurements at multiple DOI in three dimensions at the same depth in the tool, true 3D resistivities result in more accurate reservoir models and reserves estimates, especially for formations with laminations, anisotropy, or faults.

**Tool Description**

The tool is typically conveyed into the borehole on wireline, but can be deployed on drillpipe, on coiled tubing, or by means of a downhole tractor for highly deviated wells. It contains multiple triaxial arrays, each consisting of colocated X, Y, and Z coils that collectively measure various depths into the formation. $R_v$ and $R_h$ are calculated at each triaxial spacing. An electrode sleeve with short-single-axis and colocated triaxial receivers can be used to fully characterize and manage borehole signals in air-filled boreholes and oil-based and water-based muds.

In addition to resistivity, formation dip and azimuth are available for structural interpretation. Standard array-induction-imaging-tool measurements are also delivered for correlation with legacy field logs. The tool can be used with most openhole services. A caliper and general-purpose inclinometry tool are also required in the tool string.

**Tough Anisotropy Issues Can Be Resolved**

Laminated sand-shale models with anisotropic shales have been discussed extensively. However, there has never existed a clear procedure to determine shale anisotropy. Today, knowledge of formation anisotropy plays an increasingly important role in deciding where to land and place lateral-completion sections of oil and gas wells, and how to design stimulation treatments.

A graphical-analysis approach has merit because it places everything in perspective. At a glance, the interpreter can see where a data point of interest falls in relation to several boundary conditions. This helps in the evaluation of the
The objectives of graphical analysis are as follows:

- Determine shale anisotropy parameters and whether it is necessary to create multiple zones.
- Define region boundaries where each analytical solution is applicable.
- Illustrate the effect of data outliers so they can be dealt with appropriately.
- Quickly perform sensitivity tests to rank quality of answers at each level.

Of course, the question is to differentiate pay and non-pay zones. The graphical solution does this very effectively, allowing a global assessment of the hydrocarbon potential of the thin-bed sections directly from the chart. In the example, thin-bed zones that once might have been impossible to interpret are interpreted, with results corroborated by imaging logs, nuclear-magnetic-resonance logs, and core data.

Graphing a complex set of equations under anisotropic conditions requires parameters that are provided by the triaxial-induction tool (Fig. 1). $R_v$ and $R_h$ are defined as resistivities normal and parallel to the bedding planes, respectively. These parameters can now reliably be measured by the tool, regardless of hole geometry or tool attitude in the borehole—results that have not been achievable previously. Typically, thin conductive shale laminae have effectively masked resistive, hydrocarbon-saturated, thin-sand laminae in the past, making their detection problematic.

### West Africa Application

A deepwater operator offshore west Africa needed to drill a successful sidetrack well using oil-based drilling fluid in a complex formation. Accurate placement of the sidetrack trajectory was critical. The formation contained turbidite deposits in thin-beded sands between shale layers. Large salt deposits were nearby, and there was no dip information.

Using the multiple-DOI features of the triaxial-induction tool, coupled with near-wellbore measurements from a dual oil-base microresistivity-imaging tool, petrophysicists were able to compute the structural dip accurately. Additional confidence in the results was obtained by comparison with vertical-seismic-profile data. The advantage of multiple colocated triaxial measurements in the tool, and advanced borehole-signal management, provided a deep reading, a more realistic structural dip, and azimuth direction that enabled drilling of a successful sidetrack.
Another turbidite channel deposit in Mexico challenged an operator who wanted to drill additional wells to exploit the discovery, but lacked seismic information. With a meandering river channel, there was a high risk of missing the pay altogether. Using the triaxial-induction tool in a single quad-combo run provided the information on structural dip that was needed to site the offset wells correctly. Layer dip was computed at 10- to 50-ft (3- to 15-m) intervals, sufficient to indicate the direction followed by the channel sand and to detect major events such as unconformities or faults crossing the borehole. The first well drilled from this dip data penetrated the channel pay sand as predicted. Although in both cases the dips were not as high in resolution as those from the microimager tools, they were sufficiently robust to yield critical structural information usable to improve drilling success.

Cracking the Anisotropy Code

Another valuable application of the triaxial-induction tool is cracking the code of anisotropy to refine hydrocarbon-saturation calculations. Because the tool discriminates resistivity in three directions and at multiple DOI, its data can be crossplotted along with sand and shale parameters to clearly identify and quantify pay. Figs. 2a through 2c illustrate how the graphical analysis descriptively called the “butterfly plot” helps unlock the anisotropy code, and demonstrates what happens if shale anisotropy is not accounted for.

Fig. 2a is the crossplot of horizontal and vertical resistivity. Fig. 2b shows the data points on the crossplot, colored to correspond to the color bars on the left margin of track 3 in the log example (Fig. 2c).

Quickly one can see that the zone from 500 to 670 m is mostly shale; the pay zone extends roughly from 730 to 1000 m; and the wet zone extends from approximately 1030 to 1130 m. $R_o$ can be established on the crossplot as the lowermost blue dot (approximately 0.3 ohm·m), and $S_w$ has been solved for (indicated by the black scale numbers along the 45° line).

On the logs (Fig. 2c), gamma ray (blue) and $F_{shale}$ (red) are found in track 1; density- (red) and neutron- (blue) porosity curves are plotted in track 2; $R_h$ (solid black), $R_v$ (solid blue), $R_{sand}$ (solid red), $R_{shale-h}$ (dashed blue), and $R_{shale-v}$ (dashed red) curves appear in track 3; Anisotropy percent (green-filled area) appears in track 4.

In track 5, $S_w$ from $R_{sand}$ (red) and from $R_h$ (black) are plotted. The yellow-filled area indicates where erroneous hydrocarbon saturation would have been plotted if anisotropy had not been considered. The presence of anisotropic shale drags down the sand resistivity to make apparent water saturation read too high in the pay zone.

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