NEW AZIMUTHAL RESISTIVITY AND HIGH-RESOLUTION IMAGER FACILITATES FORMATION EVALUATION AND WELL PLACEMENT OF HORIZONTAL SLIM BOREHOLES

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ABSTRACT

A new logging-while-drilling (LWD) device provides laterolog resistivity logs and borehole images in 6-in. holes drilled with water-based mud. On a single drill collar, the tool combines classical laterolog measurements and azimuthal imaging capabilities.

The tool uses two monitored button electrodes and five toroidal antennas to produce focused laterolog resistivity measurements with azimuthal sensitivity. The measurements are made at four different depths of investigation but with similar vertical resolution. In addition, two deeper (non-azimuthal) and a bit resistivity measurements can be acquired by the toroidal array.

A parametric inversion combines the data, delivering an estimation of true formation resistivity in invaded formations. A new measurement configuration within the button electrodes provides the downhole mud resistivity, which can be used to detect salinity changes in the borehole and to improve the correction of measurements influenced by salinity.

A high-resolution imager, consisting of an array of button electrodes on a removable stabilizer, will provide the high resolution of a wireline imager with the full borehole coverage of an LWD device. A dedicated data-compression algorithm allows real-time transmission of the resistivity images, enabling applications such as well placement and fracture evaluation while drilling.

Several field examples illustrate the application of this slim-hole device in horizontal wells for formation evaluation, fracture system characterization, and structural analysis.

INTRODUCTION

Highly deviated wells have become an essential aspect of the energy industry. A successful horizontal well is an extremely valuable asset for any operator. Accurate placement of the borehole within the reservoir, correct evaluation of formation fluids, and identification of features impacting producibility are key elements for success. LWD technology has been used to steer and evaluate deviated wells for several years. Yet, it is only recently that the measurements offered in 6-in. boreholes have become comparable to those available in larger diameters. The development of a slim LWD laterolog imaging tool is a significant addition to that offer.

A laterolog measurement offers many advantages in highly deviated wells. Galvanic devices are far less affected by shoulder-bed effects than induction tools, facilitating the qualitative and quantitative interpretation of thin resistivity events. By manipulating the current paths, it is possible to estimate drilling fluid conductivity and borehole shape. The device can also use the entire metal body of the lower drilling assembly as return electrode, to provide an estimate of the formation conductivity changes at bit depth.

The measurement current can be focused to achieve azimuthal sensitivity and better thin-bed resolution, which are used to produce high-quality borehole images. These images serve to infer bedding orientation and extrapolate the geological setting in real time, with the possibility of adjusting the borehole trajectory.

LWD images are acquired by rotating sensors that sweep the entire borehole circumference, providing full borehole coverage. This makes them particularly suited for fracture analysis. Orientation and trace lengths can
be reliably extracted without extrapolation, and used to characterize the reservoir fracture networks.

**TOOL LAYOUT AND FEATURES**

The laterolog measurement is based on the same physics employed by equivalent devices developed for larger hole sizes (Bonner et al., 1994), but with a new sensor arrangement (Figure 1).

An array of five toroidal transmitters, distributed along the tool axis, send a radial current out of the collar through the conductive mud, and into the formation (Allouche et al., 2010). Two button electrodes measure the current which, once corrected for borehole effect, is a function of formation conductivity. A unique feature is the axial co-location of the two buttons, which are mounted at 180° on the collar. This ensures full borehole coverage for about any combination of rate of penetration (ROP) and collar rotational speed (RPM).

As the investigation volume depends upon the transmitter-receiver spacing, it is possible to acquire four resistivity measurements with increasing depth of investigation (DOI\(^1\)), conventionally termed “shallow”, “medium”, “deep”, and “extra deep”. A laterolog DOI also depends on the ratio of formation true (Rt) and invaded (Rxo) resistivity. Table 1 summarizes the DOI of each spacing for an Rt/Rxo=10.

<table>
<thead>
<tr>
<th>Sensor spacing</th>
<th>DOI (in.)</th>
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<tbody>
<tr>
<td>Shallow</td>
<td>1.5</td>
</tr>
<tr>
<td>Medium</td>
<td>3</td>
</tr>
<tr>
<td>Deep</td>
<td>5</td>
</tr>
<tr>
<td>Extra deep</td>
<td>6</td>
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This method assumes axially symmetric current paths. In a simple transmitter-receiver configuration, formation layering and changes in the electrodes’ contact impedance can potentially distort the paths, leading to errors in the resistivity estimation. For a robust measurement, the tool uses a cylindrical focusing technique: it superimposes electric field potentials from transmitter pairs, located above and below the button electrodes (Figure 2).

The buttons themselves are monitored to keep the collar and the electrode at the same potential when investigating the formation (Figure 2, top). It is also possible to apply a potential difference across the monitors, forcing a current flow between the button and the collar (Figure 2, bottom), to estimate the mud conductivity. Mud conductivity is related to salinity, which is an important parameter for the correction of other measurements.

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\(^1\) Radial distance from the tool surface at which the cumulative signal is 50% of total

Fig 1 – *Layout and measurement configuration. The collar size is 4.75 in. and suitable for boreholes diameters ranging from 5-7/8 to 6-1/2 in.*

Fig 2 – *Cylindrical focusing (left), and monitored buttons (right). The buttons can be operated to acquire both formation and borehole conductivity.*
Figure 3 shows the modeled button in the Oklahoma formation. The focusing almost completely eliminates shoulder-bed effects.

![Figure 3](image)

**Fig 3** – Modeled button response in Oklahoma formation.

The focusing technique offers as additional benefit almost identical response function to bed thickness (Figure 4) for the different spacings. Therefore, the quantitative vertical resolution\(^2\) is about 0.4 in. for the shallow, medium, deep, and extra deep resistivity measurements.

![Figure 4](image)

**Fig 4** – Modeled button response for varying bed thickness, assuming shoulder and bed resistivity of 10 ohm.m and 1 ohm.m respectively.

A laterolog measurement is relatively immune to shoulder bed and anisotropy effects. However, its interpretation may be complicated by the presence of invasion. Figure 5 shows the cumulative response for conductive and resistive invasion.

![Figure 5](image)

**Fig 5** – Button response to conductive (left) and resistive invasion (right) for button shallow (BS), medium (BM), deep (BD), and extra deep (BX).

The shallow button response is dominated by the flushed zone even when invasion is relatively modest, while the extra-deep button still has more than 50% of its total response in the virgin zone for 6-in. invasion radius. The different sensitivity can be used in an inversion (Li et al., 1999) to estimate formation Rt.

All toroidal antennas can alternatively operate as transmitters and receivers, thus it is possible to derive two resistivity measurements without the buttons. These measurements (from now on referred to as “toroid resistivity”) are axially focused, but have no azimuthal sensitivity and a larger vertical resolution (15 in.) than the buttons. As such, they are used to acquire resistivity when the buttons cannot sweep the borehole circumference (drilling without rotation).

Figure 6 shows a comparison between wireline and LWD laterolog logs, acquired in a vertical well. The toroid resistivity is almost identical to wireline. The buttons exhibit a much better resolution, identical for all spacings.

\(^2\) Minimum bed thickness for which the center-bed measurement is within 10% of the true value.
Fig 6 – Comparison between wireline (left track), and LWD laterolog (middle track). In the right track is an overlay of toroid and wireline resistivity.

An “at the bit” resistivity measurement is performed with the bottom two coils (using one as transmitter, and the other as monitor). This measurement is not focused and thus cannot be used quantitatively, but it serves to detect formation conductivity changes as soon as they are penetrated by the drilling bit. An azimuthal gamma ray and an inclination sensor complete the measurement package.

The button measurements are acquired in independent azimuthal bins, which are referenced to the natural earth magnetic field to orient the borehole resistivity images. Thin conductive features can be clearly identified, enabling applications such as structural analysis (Lovell et al., 1995), or fracture characterization. The images cover the full borehole circumference; therefore fracture length can be accurately measured. The images are in calibrated resistivity; they may serve for fracture porosity and opening computations, as re-scaling is not necessary.

The tool is designed to accommodate a sleeve-mounted micro-button array (currently under development), that can provide images at even higher resolution for detailed structural and textural analysis. Figure 7 shows an example of a comparison between the button and the micro-button images. An innovative algorithm cross-correlates the response of each array electrode to detect depth increments at the smallest scale (normally missed by surface-based depth tracking systems), preserving the native resolution.

Fig 7 – Borehole electrical images from deep button (left) and array imager (right).

The resistivity images can be compressed and transmitted up-hole in real time via mud pulse telemetry for well placement applications.

The next sections discuss field examples using the button resistivities and images that further illustrate the device capabilities and their applications.
RESISTIVITY IN HORIZONTAL WELL

Figure 8 shows an example of resistivity interpretation in a horizontal borehole. This drain was drilled through a turbiditic sequence. The formation is laminated, and highly anisotropic. LWD propagation and laterolog tools were both included in bottom hole assembly. In the target sand, anisotropy increases the apparent phase resistivity, with an effect monotonically increasing with measurement spacing (the deepest curve is the most affected).

The laterolog data also shows separation with a similar pattern. However, in this case, the separation was due to conductive invasion (anisotropy barely affects galvanic measurements). The data were inverted to estimate formation Rt, that closely approximate the phase-shift shortest spacing (the least affected by anisotropy). The laterolog-inverted Rt is also unaffected by the polarization horn that develop on propagation curves at the bed exit (marked by a series of faults at about X560 ft measured depth). The dip information extracted from images and the inverted Rt were used to build a resistivity model (Figure 9). The modeled phase-shift and attenuation closely match the measured values.

Fig 8 – Comparison of laterolog (left) and propagation (right) in a horizontal well. The Rt curve is inverted from laterolog data.

Fig 9 – Formation model (bottom panel) constructed using dips from images (top panel) and Rt from laterolog inverted data. The modeled phase-shift and attenuation curves closely match the real logs (middle panel).
WELL PLACEMENT

Prior to drilling this shale oil horizontal well, a wireline high resolution imaging log was acquired in a nearby vertical well to identify the best horizontal target interval, confirm presence of natural fractures and maximum horizontal stress orientation. Using this information, the direction of the horizontal well was selected to maximize the intersections of these natural fractures and enhance development of complex fracture network during well stimulation.

Subtle structural fold and minor faulting were observed in the vertical well providing the first indication of potential structural variation from what was initially assumed a flat structure, with less than one degree dip change along the planned lateral. While drilling, the steering of this horizontal well has proven to be a lot more challenging than anticipated. Real-time LWD images showed the lateral was crossing multiple faults with severe structural deformation along each fault plane as shown in Fig 10.

Using the real-time images along with other LWD and mud gas data, the well placement engineer managed to correlate and confirm the position of the borehole relative to the target formation. Using this information, the structural model was constantly updated while trying to keep the well trajectory within the desired interval. However, after crossing a fault plane with significant fault throw, the last quarter of the lateral was placed below the target formation. With only few hundred feet left from planned lateral length, the operator has decided to sidetrack to improve the reservoir exposure.

Steering the second lateral has proven to be less demanding after incorporating the new structural understanding derived from previous image interpretation. The real-time image data also revealed less structural change in the second half of this lateral. With constant update of the model, this well was successfully placed within the predefined target interval as shown in Fig 11.

Fig 10 – Final interpreted model from first lateral showing well trajectory cutting through numerous fault blocks.

Fig 11 – Real-time images and structural information learn from previous lateral were used to effectively keep the lateral within the predefined target formation.
In the second example, the LWD real-time images along with azimuthal gamma ray allowed to keep the trajectory within the target window over 3000 ft. lateral while maximizing reservoir contact in a highly fractured shale play.

The Niobrara formation in the Denver-Julesburg basin comprises up to four laterally continuous chalk benches with intervening marls. Both permeability and porosity in the Niobrara chalk are relatively low and production is expected to be enhanced by natural fractures.

Real-time images were transmitted to surface where structural dips were picked and reflected in the real-time model while keeping the well trajectory within the target window. In addition to reservoir navigation, the high quality real-time button resistivity image also confirming abundance of natural fractures (Fig 12) along the lateral, consistent with those observed in the vertical wells.

The final structural interpretation using the images is in Fig 13. Fracture evaluation and characterization were performed classifying open and close fractures on the images. The information was used to help optimizing the stage designs for hydraulic fracturing in the lateral.

**Fig 12** – Comparison of real-time (left) and memory (right) deep button resistivity images in a horizontal well. Several healed fractured (cyan) are visible on both.

**Fig 13** – Dip information extracted from real-time images, were used effectively to keep the 3,000 ft lateral within the predefined target window.
STRUCTURAL ANALYSIS

In this horizontal well, the trajectory was designed to maximize the intersections of the natural fractures of the Niobrara formation. Initial interpretations of the seismic data predicted a relatively benign geologic section. Analysis of the LWD image data identified numerous fractures both open and healed, five significant faults with missing section and numerous micro-faults with minimal throw (Figure 14).

The interpreted bedding and fault dip correlations (Figure 15) were used to generate the structural cross-section of Figure 18, which is aligned parallel to the path of the wellbore. The facies presented are based upon a neural net cluster modeling of the LWD natural gamma ray and resistivity logs. The cross-section revealed the presence of structural deformation associated with fault block rotation and ramp/relays. The cross-section includes initial fracture strike rosettes respective of the structural and facies domains.

The structural curvature events are used to predict local stress variations that are differential to the traditional far field orientation and magnitude. Using the concepts of structural deformation (Ramsey, 1967), the computation of local strain along the wellbore path provides an insight to the variation of stress for the completion design.

The fracture locations, types (conductive or resistive), and orientations respect to stress are critical in making decisions on the stimulation strategy (Tollefsen et al., 2010). Image examples of natural fractures, faults and bedding are presented in Figures 16 and 17.

In cemented and perforated completions, ideal staging can be performed with selective perforation positioning. For wells with packer isolated completions, the use of short joints is imperative for optimized positioning. The completion program of openhole packers in the example used the consideration of likeness.

Within a staged interval, this includes formation facies type, faults, fractures both conductive and resistive, how the natural fractures are oriented to far field stress, borehole shape, and local structural curvature. As the formations properties change, so does the completion staging. For instance, if the fault has locally deformed beds, the packer spacing should be decreased to effectively isolate the interval.

A visual analysis of the modeled structure, the calculation of the local curvature changes that occur along the wellbore path and the recognition of their differential stress provides insight to idealized staging size and location.

Fig 14 – Identified in this section were one open/conductive fracture (blue), numerous healed/resistive (cyan) fractures, two faults (magenta), and structurally deformed bedding (green).
Fig 15 – Fault image data in bi-dimensional and tri-dimensional wrap presentation. Deformed bedding and missing section are clearly visible.

Fig 16 – Mineralized fractures and bedding image data presented in bi-dimensional and tri-dimensional wrap format.
Fig 17 – Mineralized fractures with bedding and micro-fault.

Fig 18 – Structural cross-section, based on image and log data, with fracture/fault rosettes by geologic interval.
CONCLUSIONS

A new laterolog LWD tool in 4.75 in. collar size provides laterolog resistivity and images. The resistivity is acquired at multiple spacings, using cylindrical focusing and monitored buttons. The vertical resolution allows quantitatively resolving beds less than a half-inch thick. The button data is binned azimuthally and oriented with respect to the earth’s magnetic field, to provide borehole resistivity images. A second mode of the button monitoring system allows measuring borehole fluid conductivity. The device also acquires two ring-type resistivities (“toroids”), useful for quality control and in sliding-mode situations, where the drill string cannot be rotated.

The laterolog measurement is much easier to interpret than propagation in horizontal wells. In presence of invasion, the multiple spacings can be inverted to derive an estimation of true resistivity. The borehole resistivity images are usable for structural and sedimentary analysis. Images can also be compressed and transmitted uphole in real-time for optimized well placement. The collar is designed to host a sleeve-mounted imager array (currently in development phase) with even higher resolution. An azimuthal natural gamma ray and an inclinometer complete the current measurement suite.

Field examples have confirmed that the device can deliver a quantitative resistivity and quality images in diverse and challenging environments. The benefits of a full laterolog imaging device were particularly evident in horizontal boreholes, where interpretation of propagation resistivity data is problematic, and wireline imaging devices are difficult to deploy.

REFERENCES


ABOUT THE AUTHORS

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