Pushing the Limits of Formation Evaluation While Drilling

Through a few case studies this article demonstrates how new logging-while-drilling measurements are being used to open frontiers and evaluate formations as soon as they are encountered.

Logging-while-drilling (LWD) technology became available a mere ten years ago. At that time, the tools fulfilled the primary purpose of their design, which was to aid in correlation. Within a couple of years, the industry had found six main applications for these tools—applications that remain key today:

- **Formation evaluation**—Real-time correlation and evaluation allow coring and casing point selection. Logging before extensive invasion occurs may reveal hydrocarbon zones that can be saturated with borehole fluid by the time wireline logs are run.
- **Multiple-pass logging**—Comparison logs made at different times can help distinguish pay from water zones, locate fluid contacts and identify true formation resistivity (Rf). Permeable zones may be identified from time-lapse filtrate movement.
- **Insurance logging**—Logs obtained while drilling provide contingency data in case the well is lost or when conditions create boreholes that yield poor-quality wireline logs.
- **Cost reduction**—Running wireline tools in high-deviation wells requires conveyance by drillpipe. In some cases, these wells can be logged with LWD tools, either while or immediately after drilling, saving rig time offshore or in wells otherwise needing the TLC Tough Logging Conditions system.

**Enhancing drilling safety and efficiency**—Measurements while drilling provide real-time data on drillstring mechanics, fluid dynamics and petrophysics for assessing pore pressure and wellbore stability and for drilling program and completion strategies (see “Using Downhole Annular Pressure Measurements to Improve Drilling Performance,” page 40).

**Geosteering**—By comparing real-time log responses to an expected model, the wellbore trajectory is modified, thereby placing the well in the most productive portion of a pay zone.

As the real-time nature of LWD information began to be fully exploited, the early emphasis on correlation in the late 1980s gave way to dominance by geosteering and well-placement applications. Availability of LWD data permitted safe and efficient drilling of exotic trajectories and extended-reach and multilateral wells that were unimaginable ten years ago (see “Key Issues in Multilateral Technology,” page 14). These wells frequently make headlines in industry journals when technological advances contribute to breaking existing directional drilling records.¹

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Many of the LWD innovations that have helped directional drillers master the art and science of geosteering are also advancing the cause of assessing reservoir quality while drilling. Forward modeling routines have been developed that allow real-time comparison between predicted and observed logs, helping drillers stay in the pay. This modeling capability also lets interpreters evaluate LWD data for petrophysical and fluid properties and for geologic structure.

Oil company interpreters are becoming more familiar with while-drilling measurements, understanding their departure from wireline-style logs, and trusting them. Operators are also demanding more measurements for more hole sizes, and as a result, a broader range of services is being offered. The more comprehensive reservoir assessment that is now possible makes LWD formation evaluation results valuable not only for wellsite decisions, but also for longer term reservoir planning and development—as wireline logging results have been all along.

Ten years ago, the available LWD measurements were gamma ray, neutron porosity, lithodensity, photoelectric effect and phase-shift and attenuation resistivities. In the interim, technological advancements have vastly improved and enhanced these basic measurements and even added new formation evaluation measurements not previously available in the logging industry. First came azimuthal or quadrant measurements such as the quadrant density and photoelectric factor (Pe) on the ADN Azimuthal Density Neutron tool and the quadrant gamma ray and real-time resistivities on the RAB Resistivity-at-the-Bit tool. Then came quantitative images with multiple-depth resistivity images from the RAB tool and density images from the VISION system. The addition of multiple depths of investigation to the azimuthal data has created new opportunities to complete the formation evaluation picture.

The comprehensive Schlumberger VISION system (the nominal outer diameter of the tool is 4.75 inches) encompasses the enhanced technology to provide formation evaluation and drilling measurements in 5¼- to 6¼-in. holes. In addition to direction, inclination and toolface, the VISION tool makes a neutron porosity measurement, azimuthal readings of lithodensity, Pe and gamma ray, and records 2-MHz phase-shift and attenuation resistivities at up to ten depths of investigation.

Deciphering phase-shift measurements with multiple depths of investigation for resistivity interpretation has become common practice in the industry. However, the inclusion of attenuation resistivity measurements with multiple depths of investigation has brought additional value to the petrophysicist. Although acquired with the same transmitter-receiver spacing, the attenuation measurement has a greater depth of investigation than the corresponding phase-shift measurement. These complementary measurements offer an opportunity to understand more about the fluid and resistivity characteristics of the formation. For example, comparison of atten-

> Possible oil-water contact on phase-shift resistivity. The gamma ray (GR) in track 1 shows sand from 7740 to 8020 ft, and the phase-shift resistivity in track 2 indicates the zone above 7920 has high resistivity—a possible pay zone above the oil-water contact. Attenuation resistivity in track 3 shows the possible oil layer to be a zone of resistive invasion, and not worth completing.
ulation and phase-shift resistivities provides a diagnostic method for differentiating between borehole fluid invasion and formation anisotropy, a technique discussed later in this article.

In one case from a Forest Oil well in the Gulf of Mexico, the while-drilling gamma ray (GR) indicated a sand from 7740 to 8020 ft and the phase-shift resistivities identified a possible oil-water contact at 7920 ft (previous page). The five phase-shift resistivities, each with a different depth of investigation, have very little separation, which indicates little to no invasion. A simple resistivity index calculation yields 38% water saturation, making the potential oil layer a candidate for testing.

However, the attenuation resistivities that are simultaneously recorded by the VISION475 tool appear to contain evidence to the contrary. These deeper reading resistivities show significant separation, with the deepest measurement—an approximately 30-in. (75-cm) depth of investigation from the 34-in. receiver-transmitter spacing—recording the lowest resistivity of about 0.4 ohm-m. This profile indicates resistive invasion, which might be expected for wells drilled with oil-base mud, but this was water-base mud with a resistivity, $R_m$, of 0.1 ohm-m. However, formation water resistivity, $R_w$, in this zone is approximately 0.03 ohm-m, causing the resistive invasion profile. When formation resistivity is computed by inversion processing that takes invasion into account, the zone shows 100% water saturation. If this zone had been completed, a significant investment would have produced only water. The extra information brought by the deeper reading attenuation measurements avoided the cost of an unnecessary completion.

Extracting meaningful information from the two-receiver, five-transmitter tool configuration to probe five depths of investigation each for phase-shift and attenuation resistivity requires careful borehole compensation and borehole correction of the measurements. Without borehole correction, washouts together with conductive mud can masquerade as invaded or anisotropic zones. Borehole rugosity can cause spikes, or resistivity horns that may be misinterpreted as laminated formations (above). Borehole compensation is necessary because it significantly reduces the effects of borehole rugosity and precisely cancels measurement errors caused by gain and phase-shift differences in the receivers’ electronics, which typically vary with temperature.

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A series of logs from a Shell deep-water project in the Gulf of Mexico demonstrates the impact of adding still more LWD measurements to the interpretation. In this highly deviated well, the standard GR, rate of penetration (ROP), phase-shift resistivity and average density and neutron data indicate a homogeneous formation in this potential pay zone (above). The well was drilled with high-salinity drill-in fluid, and phase-shift curves exhibit a conductive invasion profile with the deepest spacing at 34-in. measuring the highest resistivity, about 4 ohm-m. Resistivity processing to compensate for the invasion effects would correct $R_t$ to above 4 ohm-m.

This is the limit of information available from a conventional “triple combo” be it LWD or a wireline system, and it appears to give a respectable interpretation of the reservoir, but the VISION475 system provides more information and sheds new light on the reservoir interval.

If this were truly a conductive invasion profile, as the phase-shift measurement indicates, the deepest attenuation curves would show higher resistivity than the deepest phase-shift curves. However, all the attenuation outputs read a lower resistivity than even the shallowest phase-shift curve. This is an example of resistivity anisotropy—a difference in resistivity value depending on the direction in which the mea-
surement is made (see the first case study from 7700 to 7740 ft for another example of anisotropy, page 30).4

In vertical wells penetrating horizontal layers with no invasion, 2-MHz tools measure horizontal resistivity, $R_h$. This is taken as equivalent to $R_t$, the resistivity input to most formulae derived to predict fluid saturation, and so serves as the reference, or threshold, by which formations are judged to contain pay or not. At other angles, for example, in highly deviated and horizontal wells passing through horizontal layers, 2-MHz tools respond to some combination of vertical and horizontal resistivities. Vertical resistivity ($R_v$), or resistivity perpendicular to bedding, is always at least as much as, and usually more than, horizontal resistivity—sometimes reaching a 10 to 1 ratio (see “Anisotropy and Invasion,” next page).

In the case at hand, the phase-shift curves are each reading a different combination of horizontal and vertical resistivity, depending on the transmitter-receiver spacing. Formation resistivity, $R_f$, is not greater than 4 ohm-m, as would have been calculated by a radial-invasion resistivity inversion program. An anisotropy inversion program can be used to calculate $R_h$ and $R_v$, and then $R_h$ is used in water saturation calculations to derive $S_w$.

Density curves from the VISION$^\text{475}$ log also provide more information than previous-generation LWD density tools, which combine weighted averages of density from all around the borehole. The density and Pe measurements of the VISION$^\text{475}$ tool are recorded in 16 oriented sectors. These can be displayed either as an image, or presented as four quadrants—top, bottom, right and left—as the drillstring rotates (below).

For a first view, the bottom and average densities can be compared for consistency (previous page). This log was recorded in a highly deviated well, so the bottom-quadrant density, in closer contact with the borehole, should give the best quantitative data. In this interval, not only does the bottom-quadrant density disagree with the average density, but it also occasionally measures a lower bulk density. This appears strange because assuming the bottom of the tool is in contact with the formation also implies that the top of the tool is not. When that occurs, the mud density, which here is less than that of the formation, should influence the top-quadrant reading and as a result, the average density would tend to be lower.

Taking the next step in evaluating this well, all four quadrant densities are presented with photoelectric factor and bulk density correction for each quadrant (left). The right and left density quadrants agree well throughout the entire interval. The top and bottom quadrant densities not only disagree, but cross each other. A threaded borehole, borehole breakout, or a combination of heavy mud and hole conditions could explain this unusual response. The response could also be due to a position change of the borehole assembly in

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Anisotropy and Invasion

Many resistivity logs exhibit a combination of anisotropy, invasion and shoulder (adjacent) bed effects, and each effect must be taken into account to deduce true formation resistivity.

Resistivity anisotropy can be caused by layering, lithology or fluid content. It is typically expressed as the ratio of vertical to horizontal resistivity, $R_v/R_h$, and its effects on tool response can be understood by modeling. The standard response of 2-MHz tools in vertical wells penetrating horizontal layers with no invasion is taken as the reference, and tool response to layers at other relative angles can be computed (below left).

In this model the formation consists of a sand interbedded with an equal amount of shale for an anisotropy ratio $R_v/R_h$ of 6.7. As the relative angle increases, the apparent resistivity measured by both phase-shift and attenuation increases. Above 45 degrees, the effect is greater on the longer spacings; for example, the phase-shift 34-in. curve measures a higher apparent resistivity than the phase-shift 28-in. curve. The curve order resembles a conductive invasion profile, and therefore may be misinterpreted. Anisotropy can cause resistivities measured in high-angle wells to be deceptively high.

Two keys are used to distinguish conductive invasion from anisotropy. The first is comparison of phase-shift to attenuation measurements: although phase-shift resistivities indicate a conductive invasion profile, corresponding attenuation outputs measure lower resistivity. If conductive invasion were causing the phase-shift curve separation, the deeper reading attenuation outputs would measure a higher apparent resistivity than the phase-shift curves. This is an important use of attenuation measurements. The second key is revealed in the modeled example—the curves are uniformly separated when viewed on a logarithmic scale. Uniform separation is less common with invasion.

If anisotropy can be identified in sands, it is usually an indication of hydrocarbons. However, in anisotropic formations that are hydrocarbon-bearing, deep invasion could hide the anisotropic response if $R_{mf}$ and $R_w$ are similar. To understand the effect of invasion on an anisotropic formation, a state-of-the-art 3D finite-difference code was developed that computes phase-shift and attenuation responses with increasing diameter of invasion.1

Resistivity responses were modeled for an anisotropic formation whose anisotropy changes with invasion (below right). The virgin formation anisotropy ratio, $R_v/R_h$ is 6.8, but once invaded, the anisotropy ratio falls to 1.25—nearly isotropic. This change will have different effects on the phase-shift and attenuation resistivity responses, depending on their depth of investigation. For invasion diameters less than 15 in., the anisotropy effect dominates.

Anisotropy is recognizable by separated phase-shift curves reading higher than attenuation curves. At invasion diameters greater than 50 inches, the effects of invasion rule curve separation. Measuring phase-shift and attenuation resistivities before extensive invasion is therefore crucial when anisotropy is present.


^ Effects of anisotropy on phase-shift and attenuation resistivities. Anisotropy becomes evident as the relative angle between bedding and tool axis increases. The curves resemble those seen in a conductive invasion profile except that with anisotropy, phase-shift curves read more resistive than attenuation.

^ Effect of invasion on an anisotropic response. In this formation, which is anisotropic before invasion, but less so after, modeling shows that for invasion diameters less than 15 in., the anisotropy is still interpretable from phase-shift and attenuation resistivity curves. After invasion diameters surpass 50 in., the effects of invasion mask the anisotropy of the virgin formation.
the wellbore caused by changes in wellbore inclination. But no interpretation guesses are necessary because the **VISION475** system clearly provides the answer with density image data.

The density images reveal the detail of reservoir configuration—a series of thin sands and shales dipping at varying angles relative to the borehole (below left). These **VISION475** images provide an easy and efficient means of interpreting complex data. The first track image is color-scaled to represent measured quantitative density variations, while in the second track the variations have been enhanced by changing the color scale to bring out detail.

Throughout this interval, the azimuthal density imaging was the only measurement to flag the subtle sand-shale layering. The lessons learned are twofold: first, the standard suite of GR, resistivity, neutron and average density measurements may not always be sufficient for complete formation evaluation. In this case, all the standard measurements pointed to a homogeneous zone. Clearly the revelation of a laminated sand-shale sequence can have an impact on the appraisal of reservoir quality and its subsequent drainage. Second, techniques that assume maximum density to be the correct density would greatly underestimate porosity and distort the true reservoir character. This new information is valuable not only to drillers in real time, but also to well planners who may need to change future drilling trajectories, to completion engineers for effecting more efficient completions, to reservoir engineers for modeling and simulating production and to geologists for calculating structural dip.

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**Invasion, Dip and Gas**

The previous examples show how LWD logs improve formation evaluation in deviated oil wells with invaded zones, anisotropic layers and thin dipping beds. Determining accurate values of porosity and water saturation in gas wells under these conditions, however, has been a special problem that only recently is seeing some resolution.

In vertical wells, depth of invasion of mud filtrate into a formation depends on many factors, including mud properties and lithology, porosity and absolute and relative permeability of the formation. In the simplest case of a vertical hole in a homogeneous permeable formation, the invasion profile is radially symmetric. But when impermeable or dipping layers, or both, are encountered, the volume invaded by borehole fluid takes on a new shape (below right).

The invasion front becomes even more distorted in a gas zone, because the borehole fluid is so much heavier than the formation gas. Invasion begins radially, but with time the heavier phase...

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slumps in the down-dip direction. The rate of slumping depends on the vertical permeability of each zone: the higher the vertical permeability, the more rapid the slumping. In addition, permeability anisotropy will distort slump geometry. In formations with permeability on the order of one darcy, strong azimuthal variations in invasion have been observed less than an hour after the bit penetrates the formation.

In gas zones, such variations can make quantitative porosity interpretation from nuclear tools an even greater challenge than usual. Porosity determination from nuclear tools requires that the effects of gas be removed. For this, knowledge of the gas volume and both radial and azimuthal location is needed. Further complicating the problem, the neutron and density measurements respond differently to the radial and azimuthal location of gas. The neutron tool reads deeper and is sensitive to any gas near the borehole, relatively independent of the azimuthal location of the gas. The density tool reads shallower and is sensitive only to the gas in front of its detectors.

What is needed is a way to quantify the volume of gas radially and azimuthally over the same region of formation that the density and neutron logs investigate. Then those volumes are used to apply appropriate gas corrections to the nuclear tools for final computation of porosity.

Radial and azimuthal gas quantification is accomplished by analyzing while-drilling quadrant resistivity data acquired as the RAB tool rotates in the borehole. The RAB tool investigates a region similar to that probed by nuclear tools, and has five depths of investigation.

\[\text{Depth, ft} \quad \begin{array}{llll}
0.1 & 100 & 40 & 0 \\
X050 & X100 & X150 & X200
\end{array}\]

\[\text{ohm-m} \quad \text{p.u.} \quad \text{ohm-m} \]

\[\text{RAB Resistivity} \quad \text{Porosity} \quad \text{RAB Resistivity} \quad \text{VISION Density}\]

\[\text{Shallow Button Down} \quad \text{Density Up} \quad \text{Top} \quad \text{Bottom} \]

\[\text{Shallow Button Up} \quad \text{Density Down} \quad \text{Top} \quad \text{Bottom}\]

\[\text{Deep Button Up} \quad \text{Neutron} \quad \text{Top} \quad \text{Bottom} \]

\[\text{CDR} \quad \text{CDR}\]

\[\text{Track 1 displays resistivities: three from the RAB tool and attenuation resistivity from the CDR Compensated Dual Resistivity tool. Additional filtrate detected by the resistivity in the down direction compared to the up direction is shaded. Similarly for the porosity curves in track 2, the left curves are from the up and down quadrants of the density tool and the right curve is from the neutron tool. Track 3 contains the RAB image, with white most resistive, and track 4 shows the density image with dark as the most dense, and lighter colors as less dense.}

\[\text{Images of invasion slump. Density and RAB images show filtrate slumping, but not always down. Track 1 displays resistivities: three from the RAB tool and attenuation resistivity from the CDR Compensated Dual Resistivity tool. Additional filtrate detected by the resistivity in the down direction compared to the up direction is shaded. Similarly for the porosity curves in track 2, the left curves are from the up and down quadrants of the density tool and the right curve is from the neutron tool. Track 3 contains the RAB image, with white most resistive, and track 4 shows the density image with dark as the most dense, and lighter colors as less dense.}\]
using readings from all around the borehole, three of those depths of measurement can be partitioned azimuthally into 56 segments. From these three measurements, three quantities can be solved for—the diameter of invasion, \( DI \); invaded zone resistivity, \( R_{xo} \); and true formation resistivity, \( R_t \)—in any or all of the 56 azimuthal segments. \( R_{xo} \) and \( R_t \) are assumed to be constant around the hole; only \( DI \) varies. The determination of \( R_t \) is most robust from the direction with minimum \( DI \), and \( R_{xo} \) is most robust from the direction with maximum \( DI \).

Correcting the LWD density and neutron tools requires an appropriate radial response function and appropriate \( DI \); both are different for each tool. The qualitative response of density and neutron tools has long been understood.\(^7\) The radial response function of the density tool has been quantified and is relatively independent of the fluids involved. The neutron radial response function has been elusive, but Ellis and Chiaramonte of Schlumberger-Doll Research, Ridgefield, Connecticut, USA have recently completed a modeling code to allow the response to be calculated under all conditions. Their modeling shows that the neutron responds to the gas closest to the borehole. Therefore the \( DI \) needed to correct the neutron is the minimum \( DI \) computed around the wellbore. In the typical slumping-filtrate case, the closest gas usually is at the top of the hole or possibly on the sides, but definitely not at the bottom. The \( DI \) for the density correction is the one computed in the direction the density sensor is pointing.

Finally \( R_{xo} \), \( R_t \), invasion factors for density and neutron, bulk density, neutron porosity, plus appropriate parameters are entered in ELAN Elemental Log Analysis software to solve for porosity and water saturation.

This method was tested by partners ARCO and Enterprise on a North Sea gas well deviated about 40° encountering formations with 70° apparent dip. Images from the ADN and RAB tools plot the location of the higher density, lower resistivity mud filtrate, which did not always slump straight down (previous page). The diameter of invasion is plotted, and the computed porosity displayed for comparison with core measurements.

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\(^7\) Sherman H and Locke S: “Depth of Investigation of Neutron and Density Sondes for 35-Percent-Porosity Sand,” Transactions of the SPWLA 16th Annual Logging Symposium, New Orleans, Louisiana, USA, 1975, paper Q.
Getting a First Look

High-quality images provide valuable input to the interpretation process. Geological information, such as laminations, location of the wellbore with respect to bed boundaries and the apparent dip magnitude and direction of bedding planes, is essential for interpreting log responses in highly deviated wells. Images quickly reveal whether the bit is drilling down into or up through bedding planes—critical for geosteering a well and refining geological interpretations.

The VISION First Look display is a wellsite answer product that combines images with the complete VISION dataset to provide a format for quickly interpreting logs in highly deviated wells and making drilling decisions. In this real-time interpretation for the Shell deep-water Ram Powell field in the Gulf of Mexico, the horizontal wellbore is drilled in a clean sand sheet deposit nearly parallel to bedding. During drilling, several tight or hard features were encountered unexpectedly (above). Rate of penetration (track 1) dropped significantly each time, and resistivity increased (track 2).

These tight streaks were of concern, as they might influence production, perhaps necessitating a change in wellbore trajectory. They first were assumed to be depositional features lying parallel to bedding. However, careful examination of the signature of the events on the density and neutron curves reveals that these are vertical interfaces. If the hard streaks were parallel to bedding planes, the tool would encounter the boundary more gradually and the measurement transition from reservoir to tight streak would occur over some distance. These transitions are quite abrupt, indicating a high-angle boundary.
This interpretation of vertical boundaries raised new concerns for the operator: Was the reservoir compartmentalized? Were these streaks mineralized fault planes? What is the vertical extent of these features? Should the wellbore trajectory be changed? The VISION First Look log, played back with recorded mode data, was able to answer these questions (above).

The density images displayed on the VISION First Look log reveal the true nature of the "tight streaks." The boundaries of the features are not planar, but rather calcite-cemented nodules. The features are not continuous vertical planar events and will not have a large-scale impact on production.

The deeper reading attenuation resistivity measurement confirms this interpretation. The attenuation measurements are not influenced by the high-resistivity hard streaks to the degree that phase-shift measurements are, and there are no polarization humps, which indicates that these events do not extend far from the wellbore.

**The Future Vision**

The ability to achieve better reservoir quality assessments in real time has satisfied some, but not all, formation evaluation while-drilling needs. Already operators are asking for these LWD measurements in more hole sizes, and this demand is being met with the imminent introduction of the VISION675 and GeoVISION675 systems for 8- to 12-in. holes. The VISION675 system will encompass the ARC675 Array Resistivity Compensated measurement, an enhanced PowerPulse MWD tool with the new VISION Telemetry Compensated measurement, and a new 6.75-in. VISION675 density-neutron tool. The VISION675 density-neutron tool extends the capabilities of the existing 6.75-in. ADN tool by adding multiscalar density, Pe and caliper images for both oil-base and water-base mud. A related tool for geological imaging while drilling will appear in the GeoVISION675 system, which will contain a new-generation laterolog imaging tool in place of the ARC675 module.

Other measurements are making their way to the 4.75-in. format, including downhole annular pressure and bit inclination for precision trajectory control.

To keep pace with the introduction of new measurements, interpretation experts are devising new techniques for getting the most from the new data. Programs for interpreting measurements in layers that are anisotropic, invaded, thin, dipping, or all of the above, are finding new challenges when applied to time-lapse LWD data—LWD logs acquired before and after bit changes or other delays in drilling. Researchers are developing methods for faster modeling and inversion of tool responses in more complex geometries and more realistic formations. These efforts will enhance our ability to perform formation evaluation while drilling, and also will improve all other LWD applications. —LS