Real-Time LWD: Logging for Drilling

Third-generation logging-while-drilling tools are adding a new dimension to ongoing industry efforts targeting more efficient and cost-effective well construction. Capability enhancements offer lower risk and more accurate well placement. As a result, real-time logging-for-drilling is fast becoming a reality.

Pushed to keep pace with changing economics and rapid advances in drilling innovations, logging-while-drilling (LWD) technology has matured into its third generation in just over a decade (next page). The first tools, introduced in the late 1980s, provided basic directional and formation-evaluation measurements, and served as insurance logs in vertical and deviated wells. At that time, the primary applications were stratigraphic and structural correlation with nearby wells and basic formation evaluation. Logging while drilling ensured acquisition of basic data needed to determine productivity and commerciality and mitigate drilling risk.

As more and more reservoirs have been successfully exploited, the exploration and production (E&P) industry has undertaken development of more difficult and marginal reservoirs—smaller, thinner, fractured and of lower quality—which previously had often been poorly rated and bypassed. Today, technically and economically challenging well designs that were rare or nonexistent only five years ago—deepwater, extended reach, horizontal and multilateral—are routinely utilized to maximize reservoir production and reserves. To hit these smaller, tighter and harder-to-reach reservoir targets, well construction evolved from geometrical designs to wells steered by geological information.

The second phase in LWD development, throughout the mid-1990s, reflected this evolution with the introduction of azimuthal measurements, borehole images, instrumented steerable motors and forward-modeling programs to achieve evaluation and logging, IMPulse, INFORM (Integrated Forward Modeling), InterACT, InterACT Web Witness, ISONIC (IDEAL sonic-while-drilling tool), IWOB (Integrated Weight on Bit), KickAlert, M3, MACH-1 (Seismic Guided Drilling), MEL (Mechanical Efficiency Log), PERFORM, PERT (Pressure Evaluation in Real Time), Platform Express, PowerDrilling, PowerPulse, RAB (Resistivity-at-the-Bit tool), RWOB (Receiver, Weight on Bit and Torque tool), SHARP, Slim 1, SlimPulse, SPIN (Sticking Pipe Indicator program), UBI (Ultrasoundic Borehole Imager), VIFER, VISION, VISION First Look, VISION475, VISION675 and VISION825 are marks of Schlumberger.
accurate well placement through geosteering. Initially, real-time steering used rate of penetration (ROP), then resistivity to “bounce” off sand-shale bed boundaries. Drillers now use real-time azimuthal measurements, including borehole images, formation dips and density to find and stay within the reservoir sweet spot. These advances have resulted in a higher percentage of successful wells, especially highly deviated, extended-reach and horizontal boreholes.

Today, drilling efficiency, risk management and accurate well placement are the keys to lower exploration and development costs. Drilling efficiency means minimizing lost or non-productive time by avoiding problems such as drillstring failure, stuck pipe and fluid influx or loss, and also managing the risks inherent in the drilling process, such as wellbore instability. Mechanical earth models (MEM) are used to integrate all available data. Logging for drilling provides the data needed to define the geologic environment and drilling process and the real-time information essential for confirming or updating the predicted MEM during drilling.

Inconsistencies between prediction and reality may indicate the need for preventive or remedial action. Accurate well placement means steering wells to an optimal position in the target reservoir to maximize production. At the same time, today’s economic constraints related to the high cost of reaching reservoirs often dictate that a well access multiple targets, typically over long horizontal segments. Failure to correct rapidly for unforeseen variations in geology and structure, such as fault offset or changes in dip, can result in a low-value deviated or horizontal hole.


Introduction history for logging-while-drilling (LWD) and measurements-while-drilling (MWD) technologies.

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Near-bit inclination and azimuthal data, especially borehole images, offer the best means for reaching the desired target with fewer correction runs, less tortuosity, and more of the borehole within the reservoir. Current tools routinely achieve absolute vertical depth tolerances of less than 2 m [6 ft] and relative depth tolerances of less than 0.35 m [1 ft]. This allows wells not only to stay within narrow pay zones but also avoid collisions with other wells draining the same zone. In total, enhanced well placement produces safer, more efficient and more accurate drilling, and more productive wells, resulting in significant cost savings.

To accomplish these objectives, data must be available and delivered to decision-makers within the relevant time frame required for making operational choices. “Relevant” real time may vary from seconds to 12 hours, depending on the type of problem that is anticipated or has been encountered, and the type and speed of response required. Rapid advances in communications technology, particularly Internet-based solutions, make possible in-time data delivery to asset teams anywhere in the world.

Real-time LWD products now include enhanced resistivity, porosity, acoustic transit time, borehole images, dips, annular pressure, leakoff and formation integrity tests. This article discusses recent advances in LWD technology, focusing on the application of real-time at-bit inclination data and images for enhanced well placement and drilling efficiency.

**Enhancing Well Placement**

Continuous inclination saves rig time by reducing the need for stationary measurements. Combining continuous wellbore surveys from the new AIM At-Bit Inclination Measurement module with VISION modules optimizes drilling control and efficiency (above).

Direct measurement of inclination change during slide drilling optimizes steering and results in reduced tortuosity and minimal undulations in horizontal wells. Resulting reductions in torque and drag on the drillstring enable greater rates of penetration and enhance the ability to drill extended-reach wells with longer lateral sections while reducing the chances of getting stuck. AIM technology lowers costs by saving rig.
time and improving drilling efficiency, and increases productivity by maximizing pay-zone footage and mitigating borehole undulations that can result in restricted oil flow.

A West African horizontal well project called for a target window that was only 4 m [13 ft] below the gas-oil contact and 12 m [39 ft] above an aquifer. One deviated and six horizontal wells were drilled to create the horizontal drains. Maximum reservoir drainage required a tight vertical depth tolerance of ±1 m [±3 ft] to prevent water coning and gas production. In the first two wells, A and B, the operator used conventional steerable-motor bottomhole assemblies (BHA) and the vertical depth variation exceeded 2 m [6.5 ft], resulting in gas production (previous page, bottom). The next three drainholes were drilled with the GeoSteering tool, an instrumented motor with an inclination sensor positioned 2.5 m [8 ft] behind the bit. The average vertical tolerance improved to ± 0.7 m [± 2.2 ft]. The last well was landed in a 8½-in. hole from which a 5-in. lateral was drilled. A steerable motor equipped with AIM capability was used, and the average vertical tolerance achieved was ±0.3 m [± 0.9 ft]. The drainhole section was completed three days ahead of schedule because of reduced tortuosity and better BHA control. In the last four wells, the use of near-bit sensors providing continuous directional control, together with steerable motors, achieved the necessary depth tolerance to avoid gas production.10

**Multidepth Vision**

The VISION system represents the latest generation of LWD multidepth measurements, including induction-type, or electromagnetic propagation, resistivity, azimuthal density-neutron, and conventional and azimuthal laterolog services (above right). The VISION propagation resistivity and azimuthal density-neutron tools, redesigned based on the earlier RAB Resistivity-at-the-Bit and ADN Azimuthal Density Neutron tools, are equipped with increased downhole memory and all-digital electronics that provide more accurate and reliable measurements equal in quality to the wireline Platform Express system. Real-time APWD Annual Pressure While Drilling measurements contribute to improved steering performance, drilling efficiency and rig safety.11

Fullbore images for use in structural interpretation, geosteering, formation evaluation and borehole-failure analysis can be obtained with the VISION system in all mud conditions. In conductive muds, GeoVISION azimuthal resistivity provides additional imaging capability. Sixteen-channel density images and 56-channel resistivity images are available in real time or from memory data. In highly deviated or horizontal wells drilled with oil-base or synthetic muds, VISION tools often provide the only option for borehole images. For enhanced interpretation, both tools can be combined on the same BHA.

Initially introduced in a 4½-in. tool collar size, VISION modules are now available for 6-in. BHAs. The VISION475 tool is designed for boreholes smaller than 6½-in. diameter, while the new VISION675 tool is used for 8- to 9½-in. holes.12 The forthcoming VISION825 system is designed for 12¼-in. boreholes. VISION services are combinable with optional AIM measurements, GeoVISION, GeoSteering tool, IWWB (Integrated Weight on Bit), ISONIC IDEAL sonic-while-drilling, and MVC (multiple axis vibration) services.

High-resolution azimuthal image logs are extremely valuable in highly deviated wells, but sometimes the deviation itself makes the measurement difficult to acquire. VISION azimuthal density-neutron (VADN) technology advances the azimuthal technology introduced with the previous ADN tool.13 Density and Pe photoelectric factor measurements with 6-in. vertical resolution are now sampled in 16 azimuthal sectors for more detailed imaging—compared with only four quadrants in the older ADN tool—and simultaneously in four quadrants for improved real-time geosteering decisions and petrophysical analysis. The availability of quadrant data ensures that

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reliable density is obtained in highly deviated boreholes. This is especially important when tools are run slick without stabilizers. Viewing the density image or analyzing quadrant data indicates which sectors are actually in contact with the borehole, thus providing an accurate density measurement (above).

In the case of enlarged wellbores, reliable and accurate data can be extracted manually from different sectors for different intervals. Furthermore, as long as the BHA rotates, the azimuthal sensors continue to acquire measurements for each sector. Because the tool can be ecentered within the borehole, these data may represent varying amounts of mud and formation. Under these circumstances, density images still provide valuable information about borehole geology, such as dips and concretions, and conditions, such as spiraling. Although structural data, such as absolute image-derived dips and azimuth obtained from a slick tool are not reliable, relative changes will still be significant.

For optimum drilling efficiency and accuracy, high-resolution resistivity images can reveal subtle stratigraphic features, formation bedding and near-borehole dip to enable drillers to keep boreholes parallel to bedding, thereby reducing uncertainty in geosteering. Resistivity images also provide valuable information about fractures and borehole failure that reflect the geomechanical state of the borehole. Recognizing and understanding the modes and mechanisms of borehole failure allows drillers to take remedial actions that improve drilling efficiency.

GeoVISION tools add important laterolog resistivity measurements to the VISION system for 6-1/4-in. BHAs. Measurements include at-bit resistivity, high-resolution ring resistivity, and an option for near-bit high-resolution, and multi-depth, azimuthal resistivity. GeoVISION technology is based on earlier RAB technology, but the new design and technical improvements provide more accurate measurements in high-resistivity zones—even in the most conductive muds. The resolution of GeoVISION recorded-mode images has improved by increasing the maximum scan rate from once every 10 to once every 5 seconds. Built-in, downhole processing, first introduced with RAB measurements, allows real-time calculation of structural dip. GeoVISION technology now includes the transmission and viewing of 56-sector azimuthal resistivity fullbore images in real time (next page, left).

When sufficient density contrast exists, formation heterogeneity, thin beds and large-scale stratigraphic features can be identified on density images, as well as on higher resolution GeoVISION resistivity images.

Conventional image processing and analysis, including normalization, and dip-extraction techniques are applied to LWD density and resistivity images. GeoVISION images have the highest LWD resolution, but this is still lower than wireline FMI fullbore Formation MicroImager resolution by a factor of five (next page, right). LWD images can be acquired only during drilling rotation.

Image quality is affected by a number of factors that must be considered during image interpretation. The first is the relative location of the sensors used to make the images. Resistivity images are generated from data obtained by near-bit sensors, while density images are generated from data obtained by sensors 60 to 130 ft [18 to 40 m] behind the bit. Features apparent on density images but not on resistivity images may be drilling-induced and signal the need to make corrections in the drilling process. Second, discrimination of structural and stratigraphic features on density images requires a contrast in density greater than 0.1 g/cm³. Third, borehole shape and size and BHA position within the hole may prevent sensors from contacting the borehole wall, resulting in a lower quality image. Fourth, image resolution suffers when rotation speed is low (less than 30 rpm) or the rate of penetration is high (greater than 200 ft/hr [61 m/hr]) since this affects the number of data points per foot.

Defining geologic structure while drilling is often crucial to accurate geosteering. Structural dips computed in real time or “relevant” real time—using images created from memory data retrieved during bit runs—from VISION systems are used to update the INFORM Integrated Forward Modeling model. This reduces uncertainty in the structural model and helps improve interpretation. The results are more efficient drilling and lower cost to reach the desired target or to stay within the pay zone. Detailed post-drilling dip interpretations using density and resistivity images are valuable for updating geologic maps and planning subsequent well trajectories. Dip determination from density images is similar to the process used by traditional microresistivity interpretation.

The complex geology of the Cook Inlet, Alaska, USA, presents many technical challenges for drilling and evaluation. Targets include tight, steeply dipping anticlinal structures. Successful drilling and completion require the acquisition of precise structural and stratigraphic dips to update predrilling seismic models and to geosteer wells for optimal placement. In one recent well, the...
Anadarko Petroleum Corporation Lone Creek No. 1, wireline FMI dips were acquired in the upper portion of the well, but drilling difficulties prevented FMI logging in the lower and reservoir portions. A measurements-after-drilling pass with an LWD BHA acquired GeoVISION images over a zone previously logged with the FMI tool. Comparison of wireline- and LWD-derived dips in the overlap zone demonstrated that GeoVISION images could provide accurate dip measurements sufficient for geosteering wells (left). As drilling progressed, steeper dips and a tighter fold geometry than predicted by the predrilling data were encountered, and GeoVISION dips allowed the well to be steered close to the anticlinal crest to adequately test the structure.15

Image-derived dips are available in real time or can be handpicked off images generated from memory during bit runs (below left). In contrast to conventional dipmeter processing, which is most accurate when bedding planes are nearly normal to the borehole, real-time dip determination is most accurate when bedding planes are nearly parallel to the borehole.16 At high relative angles, beds normally too thin—less than 6 in. [15 cm]—to be quantitatively resolved by the VISION density measurement will have an apparent thickness that allows them to be resolved. For example, at an apparent dip of 85°, a 1-in. [2.5-cm] thick layer has an apparent thickness of 1 ft [30 cm]. Handpicking dips using a workstation helps to remove low-quality dips and supplement intervals where automated dips are not computed, thereby emphasizing subtle trends that may otherwise be masked (next page).


In eastern Venezuela, an operator is using lateral drainholes to develop the Faja, a shallow, heavy-oil reservoir. The reservoir comprises stacked, high-permeability, well-sorted, unconsolidated channel sands that are typically 20 to 40 ft [6 to 12 m] thick. These stacked channel sands are discontinuous sand bodies separated by silty laminations, creating a complex and challenging environment for lateral drilling and optimal well placement. GeoVISION azimuthal measurements are used to differentiate between nonproductive laminated siltstones, homogeneous pay sands and mudstone reservoir boundaries. These measurements also provide the relative orientation of these geological features with respect to the well trajectory, allowing stratigraphic features to be recognized and their influence on production studied.

A series of lateral wellbores averaging 4000 ft [1220 m] in length was drilled from vertical stratigraphic wells. Three-dimensional (3D) seismic data were used to predict the most likely position of the channel sands away from the vertical wells. Reservoir studies indicate that resistivity of the best pay sands exceeds 500 ohm-m, while resistivity of the layered, non-productive silts is generally less than 50 ohm-m. The percent of total measured-depth footage within the higher resistivity range is used to gauge the well’s success. To date, an average of more than 75% of the sections drilled are in pay sand.

^ Revealing subtle trends. Structural trend is difficult to see in GeoVISION real-time dips (right) but is readily apparent in the handpicked data (left). Real-time images would greatly enhance this drilling program but were not available at that time.
Measurements and images from another well demonstrate how azimuthal measurements can be used for proper well placement (top). The separation of the azimuthal and bit resistivities shows the borehole approaching, then dropping away from a low-resistivity layer along the top of the wellbore. This is more readily seen in the resistivity image. The low-resistivity layer, the dark color along the left and right sides, represents the top of the borehole. Resistivity increases from 3530 to 3560 ft, indicating that the wellbore is going in the correct direction to regain its position in the high-resistivity sand.

A 3D view of the same azimuthal image presents the wellbore with respect to local geology (above). A 50-ft [15-m] measured depth interval is shown for the 8½-in. diameter borehole. Lithology boundaries, shown by the green lines, are used to compute the true dip of the layers. This presentation shows the wellbore coming up through a transition from high-resistivity sand (light colors at the bottom of the wellbore on the left) to a low-resistivity, nonreservoir layer (dark colors at the top of the wellbore on the right).

In this case, the use of conventional, nonazimuthal measurements alone would have resulted in an incorrect interpretation. If the omnidirectional bit-resistivity measurement is used for geosteering, the 40 ohm-m reading between...
3545 ft and 3560 ft suggests that the wellbore is in a low-resistivity, nonproductive silt layer. In contrast, the azimuthal data, particularly in the structurally oriented image, indicate that only a few inches of the low-resistivity layer have been penetrated. Azimuthal measurements combined with true dip provide the correct interpretation.

Geologic information derived from borehole images can influence real-time decisions for optimizing well placement and completion. A North Sea subhorizontal production well was originally predicted to penetrate two reservoir sections within separate west- to northwest-titled fault blocks. Structural dips manually picked on images generated from VISION density data confirmed that the actual structure was quite different and more complex. In fact, the well trajectory crossed two fault zones oriented approximately NE to SW. These faults defined three fault blocks containing three different...
reservoir sections. The dominant structural attitude of these reservoirs is 13 to 35° NNW. Bedding drag and fault-damaged zones adjacent to the fault affected the reservoir intervals. A low-angle unconformity is present at the base of stratigraphic marker B. Dip information was integrated with other LWD petrophysical measurements and formation tops correlated with nearby wells. The resulting geologic cross section contained more detail and higher reliability than seismic information combined with only well tops, and provides an excellent representation of the reservoir. VISION density images confirmed three separate reservoirs, rather than two, as originally predicted.

Prejob modeling and planning reduce drilling uncertainty through evaluation of expected LWD response. VISION azimuthal data and images allow predrilling structural and petrophysical reservoir models to be updated in real time during drilling. Real-time interpretation, based on observed changes in the reservoir, enables corrective geosteering action to adjust the borehole trajectory for optimized well placement and improved well productivity.

In a southern North Sea gas development well, geosteering based on predictive real-time modeling has successfully reduced uncertainty in well positioning. Prejob modeling and planning reduce drilling uncertainty through evaluation of expected LWD response. VISION azimuthal data and images allow predrilling structural and petrophysical reservoir models to be updated in real time during drilling. Real-time interpretation, based on observed changes in the reservoir, enables corrective geosteering action to adjust the borehole trajectory for optimized well placement and improved well productivity.

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In the model for Scenario 2, the reservoir dip is 0.75° and the well is approaching the top of the reservoir.

In the model for Scenario 3, formation dip is -1° with the well essentially parallel to bedding. A variation in dip as small as 3.5°, between Models 2 and 3, could have resulted in the well exiting the reservoir.
During this same bit trip, density images were generated from memory data, and dip interpretation was conducted by the office-based asset team (left).

Image-derived dip information established the correct structural model and provided the operator with an unequivocal interpretation of the relative position of the well in the formation prior to resumption of drilling. Once the position was known, the decision was made to steer down to penetrate the lower portion of the reservoir and ensure drainage from these lower layers (next page).

The density images also yielded important facies-related information. The reservoir is predominantly a fluvial sequence containing dune apron and dune slip-face facies. The dune slip-face facies, characterized by 20 to 30° dips evident at 4275 to 4350 ft, usually provides the best permeability. The southwest dip direction indicates a paleotransport direction consistent with other field data.

**Drilling Efficiency Through Integrated Solutions**

Downhole drilling mechanics processes are too complex to be characterized by any single measurement. Experience shows that combining downhole measurements results in a synergy that allows better understanding of how the drilling process can affect the borehole and influence LWD measurements.

LWD borehole images, especially higher resolution resistivity images, provide a means to directly evaluate downhole geological facies,
structure and borehole failure, such as fractures and breakouts. The addition of real-time images to conventional LWD data can dramatically and significantly alter log interpretation and help select the best remedial operations to optimize drilling operations.

The drilling process causes the wellbore to undergo changes with time. Drilling-induced changes range from formation invasion to mechanical failure of the borehole wall, such as fractures and sloughing. During drilling, it is important to distinguish natural features from those induced by the drilling process so that the drilling program can be modified to minimize its impact and ensure accurate petrophysical evaluation. Borehole images are essential for diagnosing drilling-induced changes.

With only conventional LWD data or a single logging pass, these changes may go unnoticed. Time-lapse data, obtained during drilling or washdown, are particularly important in monitoring dynamic processes affecting the borehole.

In many sand-shale environments, separation of deep- and shallow-reading resistivity curves occurs because of conductive invasion and is an indication of formation permeability. However, curve separation also may result from resistivity anisotropy with high apparent formation dip, close proximity of tight streaks, permeability variations in carbonate reservoirs, or formation fracturing by heavy mud or high equivalent circulating density (ECD). In the latter case, curve separation may serve as an early indicator that
An unanticipated problem is occurring in the reservoir (above).

The GeoVISION tool uses three button sensors to provide azimuthal resistivity measurements with different depths of investigation. These data typically are used for invasion analysis in formation evaluation. However, borehole images generated for each depth of investigation can provide additional information regarding the influence of drilling on the borehole and on petrophysical measurements (left). In this case, the shallow resistivity is strongly affected by the conductive mud that fills features near the borehole wall. Unlike natural features, induced features may seem to disappear with increasing depth of investigation.

![GeoVISION time-lapse data illustrating how invasion and the increase of borehole failures (breakouts) with time affect LWD resistivity measurements (right). Washdown images were acquired two days after the drilling pass. Resistivity curve separation occurs at two intervals—between X080 and X090 ft, and X100 and X110 ft—where the images show conductive invasion.](image)

![GeoVISION borehole images generated from 56-sector resistivity data measured by the shallow- (Track 1), medium- (Track 2), and deep-reading buttons (Track 3). The borehole breakouts (dark color) seen in the shallow image (Track 1) appear to gradually disappear in the medium- and deep-reading images. Shallow, near-borehole features like these are commonly drilling-induced rather than naturally occurring.](image)
Misidentifying zones as permeable or overlooking tight streaks can lead to overly optimistic predictions of productivity, while failure to recognize formation breakdown can result in costly remedial operations. Real-time resistivity and density images provide the additional information necessary for making correct interpretations.

In this example, borehole breakouts filled with conductive mud caused curve separation (above). Real-time annular pressure provides additional information that further indicates whether breakouts are natural or drilling-induced.

Annular-pressure-while-drilling data can help calibrate formation strength and stress parameters. Integrating resistivity images with APWD measurements allows geologists and engineers to study dynamic processes, like cuttings buildup and the evolution of the geomechanical condition of the borehole. These data can help distinguish not only drilling-induced changes—along with depth, azimuth and extent of failure—but also the mechanism of borehole failure. The recognition of drilling-induced fractures and knowledge of their influence on logging measurements greatly improves geological and petrophysical interpretation. Furthermore, correct diagnosis is essential to identifying problems and implementing proper remedial actions needed to optimize the drilling operation. In many extended-reach and horizontal wells with a narrow margin between pore pressure and fracture gradient, such as in deep water, borehole instability is unavoidable. In these cases, drilling optimization focuses on monitoring and managing, that is minimizing, instability through mud weight and circulation pressure.

The recognition of drilling-induced fractures in a horizontal well leads to decisions to reduce tripping speeds to ensure that swab and surge pressures are kept to a minimum and that correct hole-cleaning procedures are utilized to prevent unmanageable formation breakdown.

A North Sea operator was drilling a horizontal well in chalk in search of natural fractures. In this case, as in many wells, successful drilling required that the pressure exerted by the drilling fluid stay within a tight mud-weight window.
defined by the pressure limits for wellbore stability: the upper limit being the formation fracture gradient and the lower limit, the formation pore pressure (above). Increasing water depth reduces the margin between the mud weight required to balance formation pore pressures to avoid wellbore collapse and the mud weight that will result in formation breakdown.

GeoVISION resistivity images made in the horizontal portion of the well show a relatively continuous vertical fracture running for approximately 1100 ft [335 m] (right).

Normally, the image data presented on a log are the data recorded the first time the sensor passes a depth. However, time-lapse data are also available, showing changes in the same interval as a function of time (next page). The deep-button sensor was positioned 53 ft [16 m] above the bit. The gray curve superimposed on the image shows the depth of the deep-button sensor as a function of time. The green curve is the ECD that was computed from a downhole pressure measurement in the annulus.

A typical pressure window for a deepwater well. The overburden pressure (purple) is the fracture gradient and defines the upper limit of the pressure window. The predrill seismic pore-pressure estimate (black) defines the pressure window lower limit. The closeness of the two curves indicates a tight pressure window. The actual, resistivity-derived pore pressure is shown in red. The actual mud-weight profile plotted as APWD-derived ECD is shown in blue. Overall, the drilling program succeeded in staying within the narrow pressure window. However, at two depths where mud weight dropped below the lower pressure limit, the well took kicks.
During the first 1 3⁄4 hours of this time sequence, the well was drilled from X1933 ft to X2017 ft (horizontal white line) and imaged from X1880 ft to X1964 ft. The drilling image was acquired within an hour of the bit penetrating the formation and shows a faint axial fracture. During the next six hours, the BHA was raised and lowered numerous times to help clean out the drill cuttings. At about eight hours, drilling continued, and the interval drilled seven hours earlier (X1965 to X2017 ft) was finally imaged while drilling. A dramatic change was noted in the later image that shows a wide induced fracture in addition to the sought-after natural fractures, which appear as low-angle sinusoids. This difference is explained by analysis of the drilling records.

Memory data recorded between 1 3⁄4 and 8 hours, while the pipe was being worked, were used to extract the center image. This time-lapse image clearly shows that a fracture was enlarged soon after drilling. Although the image acquired between 7 3⁄4 and 8 1⁄4 hours was generated while drilling, the borehole interval between X1964 and X2040 ft was open six hours longer than that above and below these depths.

The downhole annular pressure was recorded during a bit run, and the ECD was derived from that measurement. There was a distinct buildup in ECD during the drilling of the top interval. During the period the pipe was being worked to clear debris, the ECD varied between 13.5 and 15.5 lbm/gal (1.62 and 1.86 g/cm³), and the highest reading occurred approximately 1 1⁄2 hours after drilling was stopped. Severe losses occurred in this interval every time the flow rate increased above a certain level.

Cuttings removal is a major problem in the drilling of horizontal wells. However, in fields like this one where the tolerance between pore and fracture gradient pressures is small, high flow rates and surge pressures that occurred during hole-cleaning operations led to high ECD and, ultimately, to hydraulic fractures.

Without the ECD information provided by APWD measurements, interpretations based on borehole images alone might have indicated the need to increase mud weight to handle the apparent borehole breakouts seen in the image. This would have been the incorrect response. The addition of the time-lapse pressure profile provided the evidence (spiking of the ECD) that, in fact, it was the drilling process itself that induced the borehole failure.

This combination of information provides guidance to drillers about where, when and how to improve processes to avoid damaging the borehole. LWD measurements show how geology, geophysics and drilling process come together to make the correct interpretation. The GeoVISION image shows not only the geologic environment, but also the consequences of the drilling process.
Images and Geomechanics

The state of stress around the wellbore has a direct influence on drilling efficiency and wellbore stability. Recognizing borehole failure and instability and understanding how and why failure occurs are vital to successful drilling. Proper management of borehole stability minimizes nonproductive time and is central to drilling optimization.

Borehole failure results from stresses around the borehole. The Earth’s far-field stresses (maximum horizontal, minimum horizontal and vertical) are converted into wellbore stresses (radial, axial and tangential) at the borehole wall (below).

When these stresses exceed the formation strength, irreversible shear and tensile deformations occur in the near-wellbore formation. The mud weight is used to control borehole stresses.

Most geological forces acting on the borehole are compressive and produce shear failure. Other structural forces act to pull rock grains apart, resulting in tensile failure. Shear failure is initiated by two orthogonal stresses with different magnitudes, whereas tensile failure is initiated by a single tensile stress. Shear and tensile failure mechanisms can, and most often do, act independently. Understanding the relationship between stresses affecting the borehole provides information about formation strength, information that is especially important for drilling highly deviated and horizontal boreholes.

Many failure mechanisms have specific associated fracture signatures that are apparent on borehole images, and each failure mode has a unique pressure regime of high or low mud weight or ECD. GeoVISION images, coupled with VISION APWD measurements, allow immediate, real-time identification of potential failure modes and provide early warning of borehole stability problems (above). Based on a diagnosis of the associated issues, the driller can take appropriate remedial actions for managing borehole instability.

The application of geomechanical models that incorporate image and pressure data has a direct and immediate impact on drilling optimization and completion. Results from these models
Recognizing and Preventing Problems

Information obtained from density images can result in remedial action to minimize and prevent borehole damage. Borehole enlargement may result from the drilling process: too fast, too much weight on bit, or too high a circulating pressure. The VISION density measurement is extremely sensitive to the tool standoff that increases with borehole enlargement. Tool standoff is easy to recognize on density images: dark color indicates high density and good borehole contact, light color indicates the presence of lower density mud.

An operator drilled through a massive, poorly consolidated sandstone reservoir. The density image shows low-density standoff (light color) extending from the top of the hole past the right and left side of the hole in the intervals X480 to X512 ft and X542 to X562 ft (right).

The density variations, both radially and vertically, are the result of the drilling process. The low-density features reflect borehole enlargement that was produced by a bent steering sub during BHA rotation. During BHA sliding, the borehole is closer to gauge, the density image quality is good around the complete borehole interval from X512 to X542 ft, and all four density curves stack. Furthermore, density variations within the intervals of BHA rotation are directly related to the rate of penetration. In these poorly consolidated sandstones, slow rates of penetration result in high rates of borehole washout from X492 to X502 ft. These images indicate that increasing the rate of penetration and operating in sliding mode would improve borehole quality and drilling efficiency.
The information derived from these images also benefited the petrophysical interpretation. Generally, the bottom-quadrant density provides the best density value in highly deviated and horizontal wells because gravity causes the BHA to rest on the bottom of the borehole. Occasionally, the tool may climb to the side of the borehole, such as when the smaller diameter VISION475 tool is run slick. In these instances, the bottom density measurement may not have the lowest delta Rho, and a different quadrant density is most representative. An example of this phenomenon occurs in the interval X502 to X513 ft where the BHA climbs the right side of the borehole and the right bulk density measurement is the best value.

Cyclic density is often an indication of a threaded borehole (right). A recent North Sea well shows a spiral borehole that developed through movement of the BHA during the first bit run. Drilling engineers were alerted to the problem and added a near-bit stabilizer to the BHA with the next bit run. This action prevented the spiraling and resulted in a smooth borehole. This image was generated from the memory data played back during the bit run, and the interpretation and correction action were taken in time to successfully drill the next interval. Recognizing drilling-induced features on images allows corrections in the drilling process that lower cost through more efficient drilling.

**Real-Time Images**

The examples presented in this article, with one exception, used images generated from downhole memory data. Retrieval of stored downhole data requires pulling the BHA during or between bit trips. Interrupting the drilling for data retrieval and interpretation may result in added rig time and higher well costs. Recently introduced data-compression techniques now make real-time transmission of VISION azimuthal density and GeoVISION resistivity images possible.

Resolution of GeoVISION real-time images is the same as that for the earlier RAB recorded-mode images. A compressed data frame consists of sixteen 10-sec time scans that each have 56-channel azimuthal scans. Data are compressed in both the azimuthal and time dimensions by a ratio of 50:1. The high compression rate means that a relatively low bandwidth, approximately 1.5 bits per second (bps), is required for transmitting real-time image data. This figure is well within the capabilities of the PowerPulse MWD tool that achieves an uphole data rate that is commonly 6 bps and reaches 12 bps under favorable conditions. These data rates, combined with VISION downhole preprocessing of data, including data compression, mean that an operator can obtain real-time images in addition to other real-time data needed for geosteering decisions.

In this article, we’ve discussed how real-time azimuthal measurements can significantly enhance well placement and drilling efficiency—and, in the process, reduce E&P costs. Geologic information and structural dips derived from borehole images remove much of the guesswork in geosteering, and thereby improve the success rate of extended-reach and horizontal wells. Information on borehole condition provided by images during drilling allows monitoring of drilling operations in real time. VISION azimuthal measurements are just one element of the new generation of LWD technology that is transforming while-drilling measurements into Logging-for-Drilling. Integration of these images with other real-time measurements provides an effective means for enhancing drilling efficiency. —SP