Operators are gaining an accurate, at-the-wellsite first look at pay zones, thanks to new technology that incorporates logging measurements environmentally corrected in real time, fast forward modeling and inversion techniques. At the heart of this technology are good science and innovative engineering.

To maximize asset value, oil and gas operators continually strive to characterize the location and extent of recoverable reserves. Traditionally, open-hole logs generated with “triple-combo” tool strings have provided key information: porosity from neutron-density measurements and saturation from resistivity measurements. The introduction of an advanced logging system in 1995, based on a platform of integrated sensors, has resulted in a quantum change in data acquisition capability, reliability and efficiency. The shorter, lighter, operator-friendly tool string is capable of faster rig-up at the wellsite and better access to deviated holes. Flexible mechanical design and short tool length enable the operator to drill shallower wellbores while retaining the ability to log important pay zones at the bottom of the well. Array-resistivity measurements, microresistivity and three-detector density tools are improving accuracy in difficult environments without sacrificing logging speed.

But there is more to the story than more flexible operations, reduced rig time and improved accuracy of standard measurements. Using the latest technology, new-generation tools provide more complete reservoir characterization right at the wellsite—opening up a wealth of opportunities for locating and tapping additional reserves. Improved tool response in thin beds, better pad application in poor holes, greater accuracy in high-weight muds and real-time corrected formation evaluation—all presented in clear, easy-to-understand formats—aid decision-making. New tools, calibration methods and processing techniques, combined with a comprehensive log quality-control (LQC) system, allow engineers to monitor tool measurements and environmental conditions—validating data acquisition and ensuring that high-quality analysis can be performed over the entire logged zone. In many wells, this saves valuable time by eliminating the need for repeat passes for log verification. Faster wellsite calibrations, real-time environmental corrections, quality control, depth matching and a complete wellsite quick-look contribute to wellsite efficiency and put formation evaluation data into the operator’s hands more quickly.

In this article, we look at three aspects of new platform logging technology and illustrate the simultaneous improvement in operational efficiency that can be achieved while accurately determining formation characteristics under increasingly difficult environmental conditions.
First, we discuss the foundations supporting real-time environmental corrections, including speed and depth, as a vital first step toward the use of forward models and inversion techniques for making real-time environmental corrections to basic logging measurements. Model-based inversions—along with new measurements, such as those from mud resistivity sensors, microresistivity measurements, array tools with multiple-depth measurements and density backscatter detectors—contribute to a clearer picture of the borehole and formation.

Second, the latest developments in openhole logging are highlighted, including the new HRLA High-Resolution Laterolog Array tool with multiple depths of investigation, a tool capable of resolving the effects of shoulder beds, invasion and dipping formations, thereby providing better resistivity evaluation in complex environments with saline mud. Post-log processing techniques, to interpret logs in extreme environments, are discussed along with a new maximum-entropy-based inversion technique developed to quantitatively interpret induction logs from highly deviated wells or with large shoulder-bed contrasts.

Finally, we look at two important benefits of real-time environmentally corrected logging data—complete wellsite log interpretation and log quality control. We illustrate how LQC is enhanced by real-time environmental information.

Real-Time Corrections
Every logging tool suffers from environmental effects of one sort or another. Real-time corrections are essential to get accurate logging information into the hands of the operator efficiently. As a first step, every tool raw sensor measurement requires a speed-derived depth correction. Next, forward models are used to predict each measurement response for a given set of borehole and formation properties. Finally, by comparing predicted sensor responses with logging measurements—a process called inversion—the environmentally corrected formation properties are determined. This sequence of steps is performed during data acquisition and applied to openhole logging measurements made with the Platform Express tool system first reviewed in the Oilfield Review three years ago.1

It may seem surprising that real-time depth correction is such an important issue. After all, most log analysts can shift logs at the computing center simply by “eye” or with automatic mathematical correlation algorithms. The depth of the logging tool is traditionally determined from the length of unwound cable with an approximate adjustment for cable stretch. However, one of the greatest uncertainties in wireline logging has been the assignment of petrophysical data to the correct depth of the subsurface.

As the tool is pulled up the wellbore, changing wellbore conditions such as caves or frictional drag will cause the tool speed to change erratically, and even to stick and slip, while the cable speed measured at surface remains constant. Thus each sensor’s motion across the formation may not correlate with the motion of the cable at the surface. The high tool speed—up to five times the normal logging speed—occurring after a stuck zone often results in lost data. Speed-derived depth corrections are essential at two basic stages.

First, at the measurement stage, some logging measurements depend on integrating raw data from multiple sensors located at different locations along the tool string. Irregular or nonuniform tool motion during the measurement cycle will invalidate the assumption that all the data come from the same volume of the formation. Log processing will produce an incorrect or unstable result, especially visible at layer boundaries.

Some tool designs, such as neutron and density tools, have multiple asymmetrically positioned sources and detectors and unequal source-detector spacings, and their measurements—based on comparing the count rates in each detector—can be affected by nonuniform tool motion. An example from the North Sea illustrates the effects of speed-corrected density measurements (above).

Likewise, the AIT-H Array Induction Imager tool filter-based processing algorithm assumes that the data from the eight asymmetrical arrays are regularly sampled every 3 in. Irregular tool motion can give rise to artifacts on the logs. Caliper measurements and auxiliary mud resistivity measurements must be correctly depth aligned with the AIT array measurements to derive AIT borehole corrections.

At the second stage, depth corrections are equally important when integrating logging data from different tools to perform petrophysical interpretations. For example, log analysts frequently look for gas by comparing density and neutron porosity logs. For the characteristic crossover to be meaningful, the spectral count rates of each gamma ray detector in the density tool must change in phase with the count rates in each neutron detector in the neutron porosity tool as each passes the gas-saturated bed in the formation.

In addition to speed-based depth corrections, resolution matching is equally important. Since the neutron measurement samples a slightly thicker region in the formation than does the density measurement, these measurements must be matched volumetrically. This resolution-matching process is important in all high-resolution interpretations, because it ensures that the sensors of each tool used in a combined measurement see exactly the same formation thickness.

Finally, measurements with high vertical resolution can have errors amplified by irregular tool motion because the acquisition system obtains data at sampling rates that vary as a function of the required bed resolution. When tool speed differs substantially from the recommended, then over- or under-sampling results. Rapid acceleration following a stuck-tool episode can result in lost data. Tool-speed-based depth corrections are a prerequisite to good high-resolution measurements.

Obtaining properly depth-matched high-resolution measurements is critical for Ocean Energy's efforts to evaluate thinly bedded reservoirs in the Gulf of Mexico (next page). In one well, high-resolution invaded-zone resistivity, \(R_{ce}\), measurements from the MicroCylindrically Focused Log (MCFL) tool in combination with density logs clearly show the many thin beds—some less than 1-ft thick (0.3 m)—throughout the reservoir. Comparison with the FMI Fullbore Formation MicroImager images confirms the presence of thin beds, and the real-time porosity derived from the high-resolution density log enables accurate reserve calculations.

Crucial depth corrections are implemented in the Platform Express system during acquisition using a built-in tool-axis accelerometer. This device measures instantaneous tool acceleration to determine tool velocity and the true depth at which all the other tool measurements were recorded. Stability of the depth-correction algorithm is maintained by the use of a Kalman filter-based optimization. This optimization minimizes

detecting thin beds in the Gulf of Mexico. The FMI Fullbore Formation MicroImager tool image shown in track 1 confirms the presence of many beds less than 1-ft thick detected by the high-resolution Micro-Cylindrically Focused Log (MCFL) $R_{xo}$ log shown in track 2. The high-resolution (black) and very high-resolution (blue) density logs are shown in track 3. The high-resolution density logs are quantitative in beds over 8-in. thick. The high-resolution, deep induction log shown in track 2 detects many of the thin beds and can be used quantitatively in beds 1 ft or thicker. Track 4 compares all the density logs with the neutron porosity log.

the overall error in the depth correction by solving a system of simultaneous equations linking the exact moment each sensor measurement was made with the true tool position—derived from the instantaneous accelerometer measurement. Cable depth is used as a constraint to help stabilize the solution. All raw sensor measurements and optimization solutions are performed in the time domain. This allows them to be easily converted to true depth or cable depth, whichever is required. Time-domain processing also helps to overcome limitations encountered in high-frequency depth sampling during high-resolution logging operations.

Forward Modeling for Environmental Corrections

In the language of log analysts, the phrase forward modeling refers to computing a logging sensor response in the presence of the environment surrounding the logging tool. Almost any tool response can be linked to formation properties through the physics of the sensor measurement and its interaction with the materials of the formation and borehole environment. Compton scattering and photoelectric absorption govern the interaction of low-energy gamma rays used to measure formation density. The physical principles embodied in Maxwell’s equations are well understood, and with enough knowledge of a resistivity tool design and its environment, the voltages and currents that make up the tool responses are predictable.

Forward modeling is important because it allows prediction of tool response under any given conditions. These predictions can then be compared with observed measurements, in a process known as inversion—described later in this article—to understand the real conditions under which the measurements were made. In this article, unless otherwise specified, tool or sensor response means the raw measurement, such as count rate in a nuclear detector, or voltage and current measured on an electrode or induction tool antenna coil.
Density forward models—The three-detector density tool in the Platform Express tool string uses a gamma ray source that emits 662-keV photons from a source capsule located in the logging pad (above). Although density measurements are sensitive to a relatively small volume of the environment between the source and detector, the increasing source-to-detector spacing of each detector enables each to see progressively deeper into the mudcake and formation.

Gamma rays from the source enter the mudcake and formation and typically scatter several times before being detected by each detector in the logging pad. Each Compton scattering encounter causes the incident gamma ray to lose energy and change direction, eventually bending many gamma rays back towards the detector aperture in the tool. The comined effect of energy-degraded photons from multiple Compton scattering and photoelectric absorption contribute to an overall continuous gamma ray spectrum seen in the formation by each of the three detectors.

Typically, increasing density causes an increase in the gamma ray flux near the source because there are more scattering targets in a higher density material. This increases the observed backscatter detector count rate. On the other hand, increasing density tends to cause a decrease in the observed count rates in the two detectors spaced farther from the source because of the long attenuating path to these detectors. Also, changes in formation lithology can be detected by variations in the low-energy window count rates due to photoelectric absorption. These count rates are also strongly affected by barite in the mudcake, and its presence can make the photoelectric effect measurement intractable.

A forward model is used in Platform Express real-time density analysis to calculate each window count rate as a function of formation and mudcake properties. The formation model geometry consists of a homogeneous formation and mudcake corresponding to a one-dimensional (1D) radial step profile varying in density and photoelectric properties. Within this framework, the different detector count-rate responses depend on only five environmental

Density calibration database. The density forward-model database was recorded in the Environmental Effects Calibration Facility in Houston, Texas, USA, which was built for the characterization of nuclear logging tools. This database covers the range of environments to which the tool will be exposed. The facility manager, John Spallone, is shown lowering the Platform Express density tool into one of the calibration blocks. Since the Platform Express tool first became available, a continuous effort has been under way to enhance the density measurement capability in heavy mud environments.
parameters—formation density and photoelectric factor; mudcake density and photoelectric factor; and mudcake thickness.

An ideal implementation of the gamma ray physics in this formation forward model would be given by an exact solution to the Boltzmann equation for gamma ray transport. Unfortunately, the Boltzmann equation has no simple analytic form for this environment. Instead, a proxy for the exact sensor response physics parameterizes the detector window count rates as exponential functions in terms of formation and mudcake properties. Each window count-rate response function contains empirical coefficients, which account for source strength, detector collimation, average gamma ray track length for each particular source-detector spacing, and energy-dependent Compton scattering and photoelectric absorption cross sections. These coefficients form the calibration for this nonlinear parametric forward model, and are determined by a weighted least-squares fit to a database of laboratory measurements.

The database measurements were obtained in a laboratory with a calibrated density tool in known formations and mudcake conditions (previous page, right). Today, over 1130 calibrations in boreholes with barite mudcake and 420 calibrations with nonbarite mudcake have been made, and recent calibrations for the density forward model have extended the operating range of the density tool to mud weights of up to 17 lbm/gal [2.04 g/cm³].

Resistivity forward models—In contrast to nuclear measurements with their small volume of investigation, all deep-resistivity responses, whether from induction or laterolog tools, are influenced by the resistivity distribution in a large volume surrounding the logging instrument. Correct interpretation requires corrections for borehole, invasion and other large-scale environmental or geometrical effects such as shoulder effects.

The response of a laterolog, such as the High-Resolution Azimuthal Laterolog Sonde (HALS) measurement, is computed by solving Laplace’s equation for the electrostatic potential in the borehole and formation environment. Laplace’s equation follows from Maxwell’s equations in the low-frequency limit and dictates conservation of current everywhere in the environmental domain. Knowing the voltage and currents everywhere along the tool allows prediction of the apparent resistivity reading. Unfortunately, analytical solutions exist for only a limited number of problems with simple geometries. In practice, the solution requires the use of numerical methods. The two methods most frequently employed are the Finite Element Method (FEM) and the Finite Difference Method (FDM). Development of forward modeling techniques using FEM and FDM for resistivity measurements was discussed two years ago in the Oilfield Review.

Both FDM and FEM divide the environmental domain into grid cells and solve for the potential in each cell. The interactions between neighboring cells are controlled by Laplace’s equation. Combining all the cell interactions together with the boundary conditions yields a large system of linear equations, which is solved by the computer to find the electric potential at the vertices of each cell. Depending on the complexity and dimension of the formation model, either two-dimensional (2D) or three-dimensional (3D) solutions of the electromagnetic field are needed (right).

Multidimensional forward modeling techniques have been successful in rapidly and accurately predicting the tool response of resistivity tools. The models are used to optimize tool designs, characterize their response and provide the basis for inversion procedures designed to find formation characteristics. Although modeling speed has increased considerably in recent years, it is frequently too slow to allow real-time inversion of measurements while logging, especially when a 3D model is needed. When the number of formation parameters is limited, it is often more practical to create a database of the tool response to variations in parameters and interpolate from this database to build the numerical forward model used during the inversion.

Formation model dimensions. In HALS laterolog resistivity modeling, a 1D radial formation model is concerned only with the influences of the radial invasion profile (A). It assumes that the reading is being taken in an infinitely thick formation bed. At other times, a 1D layered formation is used to model the effects of thick and thin shoulder beds with resistivity contrasts (B). A 2D model assumes that the formation is composed of homogeneous layers perpendicular to the borehole (C). In this model, both the invasion of each layer and the shoulder-bed effect of adjacent layers are taken into account, resulting in a more accurate Rᵣ calculation in beds where significant shoulder-bed effects exist. A 2D model is defined by the values of Rᵣ, R₀, the invasion radii and thicknesses of the formation layers. The 2D model can be taken one step further by incorporating the formation dip relative to the axis of the borehole. This results in a 3D-formation model (D). This scenario could be due to structural formation dip, deviated borehole or both. More complicated 3D formation models can be constructed in various ways. One way is to partition the layers into azimuthal sectors (E). This model takes into account azimuthal anisotropy, shoulder-bed effects and invasion as well as variations in layer thickness with distance from the wellbore.
The HALS tool uses two such FEM-derived databases for processing its measurements. The first database is used to correct apparent resistivities for borehole effects. It models the tool response in an uninvaded formation as a function of formation-to-mud-resistivity contrast, borehole size and the tool eccentricity. The borehole forward model is based on solutions to Maxwell’s equations in a cylindrical borehole with resistivity \( R_m \) surrounded by a homogeneous formation of resistivity \( R_f \). The tool can be located with a standoff anywhere in the borehole, but is assumed to be parallel to the borehole axis. In this model, the signal in any given AIT array is predicted as a function of four environmental parameters—\( R_m, R_f, \) borehole size and tool standoff. This model is used to develop a database of tool responses that provides calibration for the fitted forward model used in real time to predict tool responses in any borehole environment.

**From Forward Models to Inversions**

Given a forward model with a system of equations governing tool responses, one simply enters the formation and borehole parameters into the model and, after computation, the desired tool measurements are predicted. The prediction is a set of tool responses that would be observed if a physical experiment were performed in the given formation and borehole environment. When the governing equations are linear, the process is reversible—or invertible in one step. Iteration is not needed. Given the tool response, the model parameters can be estimated by multiplying the vector of observed tool responses by the generalized inverse of the same matrix used in the corresponding forward problem.

Unfortunately, nature does not always pose linear problems. Density and resistivity tool responses are not linear with respect to formation properties. For these responses, a more versatile technique is to find a solution by iteratively solving the forward problem. Inversion is the process of creating a model, mathematically modeling the physical response to that model, and then varying the parameters in the model until the modeled response matches the one seen by the logging tool. There are two ways to perform this task, manually and automatically. A log analyst often uses manual inversion, adjusting model parameters based on previous experience or knowledge, with advanced post-logging processing programs at a computing center.

Automatic inversion is performed by an algorithm that computes the response to a model, then follows certain rules to modify the model to converge to a solution. Common algorithms minimize the difference between the observed response and the modeled synthetic response by adjusting the model parameters to reduce the differences at each step. Real-time environmental borehole corrections in the Platform Express system all depend on automatic inversion techniques.

**Density Inversion**

Density inversion is based on a maximum likelihood method that uses the nonlinear parametric forward model discussed above to link the depth-corrected observed count rates in each of the detector count-rate windows to the formation parameters. At every depth, the inversion predicts the count rates in each detector window and compares them with those measured by the tool. Minimizing a cost function containing three terms optimizes the solution.

The first term in the cost function is based on the best fit of all the observed window count rates. This is done by minimizing the “reconstruction error,” which is a term proportional to the average squared difference between all the measured and modeled count rates in each detector energy window—each weighted by the expected error based on counting statistics and model uncertainty.

The second term in the cost function measures the difference between the current model-predicted environmental parameters and those at the previous logging depth. This term, called the smoothness condition, helps ensure compatibility between sampling rate and measurement of vertical resolution.

The final cost term helps control the stability of the solution when formation and mudcake parameter estimates are far from the database range, which can happen when large standoffs occur. This term vanishes when the solution is within the limits of the database.

A powerful example of density inversion robustness can be seen when comparing density measurements derived during extreme conditions (down logging) with normal measurements taken while logging uphole (next page). Occasionally, for precautionary reasons, logging
measurements are taken while going into the borehole. The caliper arm and pad are closed to prevent getting stuck against the borehole wall while going down the borehole. This results in a large standoff with excessive mud and mudcake between the density pad and formation. Under such large standoff conditions, two-detector density measurements based on a graphical spine and ribs algorithm cannot account for these extreme standoff conditions. The different radial sensitivity of each of the three density detectors helps the inversion algorithm provide a final environmentally corrected density log that compensates for the extra standoff. This corrected log agrees well with the density log obtained under normal logging conditions.

The use of a parametric forward-model-based inversion for density measurements has several advantages. It makes the most efficient use of all the sensor measurements while simultaneously obtaining formation and mudcake properties. For example, all density, photoelectric and standoff information contained in the entire spectrum from each gamma ray detector is automatically taken into account in the inversion algorithm, providing a strong degree of redundancy in the information available from the density tool. Both statistical uncertainties and forward model errors are considered in the inversion calculation, and provide realistic output uncertainties. These take into account count-rate statistics, calibration errors and model errors, and establish reliable confidence limits for LQC and subsequent petrophysical analysis.

Resistivity inversion—Inversion is central to the borehole correction algorithm in the processing chain for AIT logs. It uses the AIT polynomial forward model to correct the eight depth-corrected raw array measurements for tool effects in a nonstandard borehole environment. The parameters for the inversion are the four components of the database—borehole radius, tool standoff, mud resistivity and formation resistivity. The inversion is an optimization that finds the set of borehole parameters that best reproduces the four shortest arrays (6-, 9-, 12- and 15-in. measurements). However, since these measurements overlap considerably in their investigation range, their information content is not sufficient to solve for all borehole parameters simultaneously.

In practice, the inversion process reliably determines only two of the four parameters. The other two parameters are always measured or fixed. Since formation resistivity is always an unknown, there is only one additional free parameter for the inversion to determine. Accordingly, there are three modes of borehole correction—depending on which parameter is sought. If an accurate hole diameter from the density caliper and mud resistivity from the auxiliary mud resistivity, \( R_{m} \), sensor are used, then the borehole correction inversion determines tool standoff. Mud resistivity needs to be measured within 5% of its true value, which can be met with the AIT mud sensor. By solving for formation resistivity and standoff, the borehole correction problem can be solved with no intervention from the engineer. Likewise, hole diameter can be computed with an accurate standoff and mud-resistivity measurement, or else the mud resistivity can be computed from accurate hole size and standoff information.

\[ ^{\text{Using inversion to obtain the correct answer under extreme conditions. When a density tool is lowered into the borehole, the caliper is kept closed to prevent getting stuck in the hole. Under these conditions, the density pad is not pushed firmly against the borehole wall, resulting in a large standoff (black dashed) derived from the inversion algorithm shown in the depth track. All three detectors (blue curves) see low density in track 2 because of extra mud and mudcake encountered in this configuration. However, the inversion algorithm is still capable of accounting for the extra mud and standoff in this environment. It produces a density curve (blue) in track 3 that agrees with the density reading (red) obtained under normal conditions—logging up the borehole with the caliper open and pad pushed against the formation.} \]
Invasion profiles. Typically, radial inversion is another 1D four-parameter optimization that uses a monotonic-conductivity invasion profile model to produce logs of $R_{xo}$, $R_t$, and the limits of a transition zone (left).

Real-time wellsite processing for laterologs also involves borehole corrections followed by a 1D inversion for $R_t$. For example, HALS borehole corrections adjust for the presence of the borehole, taking into account the borehole size and the ratio of apparent resistivity to mud resistivity $R_a/R_m$. It also includes an eccentricity correction that allows for the eccentric position of the tool in the borehole. The mud resistivity needed in the correction can be derived from the tool itself or from an external mud-resistivity measurement. Following borehole correction, an inversion based on a 1D three-parameter step-profile invasion model is used to determine the formation parameters—$R_t$ and the invaded-zone radius—that best describe the borehole-corrected deep and shallow measurements. Since only two formation parameters can be determined from the two measurements (shallow and deep resistivity), the value of $R_{xo}$ must be supplied to the inversion. It is obtained from the MCFL tool, which gives a resolution-matched microresistivity measurement.

After all the raw array measurements have been corrected for nonstandard borehole effects, they are processed by the usual AIT log-forming techniques. This involves generating the standard depth (10-, 20-, 30-, 60- and 90-in.) and simultaneously resolution-matched (1-, 2- and 4-ft) logs by convolving the corrected raw array measurements with the Born-approximation-based weighting functions. Subsequently, real-time interpretations are based on inverting these processed measurements radially to obtain an estimate of $R_t$. This radial processing also gives a quantitative estimate of invasion geometry as well as an accurate estimate of $R_t$ in complex formations.

Resistivity invasion models. The simple piston-invasion, or step, profile, and the ramp profile require three parameters; the slope profile is a four-parameter model; the annulus profile is a five-parameter model. A step profile is used for real-time HALS and HRLA radial inverse invasion modeling, and the slope profile is used for real-time AIT radial invasion inversion.

Eliminating the Groningen effect. The DLL Dual Laterolog Resistivity deep-resistivity (red) and shallow-resistivity (blue dashed) curves in track 3 show a large separation (yellow shaded) caused by the Groningen effect. The HRLA curves in track 2 are not affected by the Groningen effect because all the currents return to the tool string itself, rather than the surface. The fact that all five HRLA curves are reading the same resistivity over this interval also establishes that the formation is uninvaded.
A similar $R_t$ inversion technique is used for the new HRLA High-Resolution Laterolog Array tool discussed below. For this tool, there is enough information in the five array measurements to allow an accurate estimate of $R_t$, and determine the invasion profile—indeed of an external $R_w$ under most conditions. However, if an additional $R_w$ measurement is used, it helps constrain the inversion processing and improve the derived $R_t$. In the HRLA inversion, weights are assigned to each measurement based on the magnitude of its borehole correction. The measurement with the smallest borehole correction is given the highest weight in the inversion algorithm.

### New High-Resolution Resistivity Technology

Although the concept of an array laterolog tool has existed since the 1950s, Shell was first to recognize that an array-resistivity tool could improve thin-bed saturation evaluation, and proposed a point-electrode array tool called the Multi-Electrode Resistivity Tool (MERT). Their tool design is similar to a multiple-spaced “normal” measurement to which lateral and second-difference voltage measurements are added. Recently, Baker Atlas commercialized their HDOLL High-Definition Lateral Log service, which is an implementation of the MERT architecture.

In response to this need, Schlumberger developed a new HRLA High-Resolution Laterolog Array tool that can be used with the Platform Express system. This tool achieves multiple depths of investigation through a segmented array of six simultaneous, symmetrical and actively focused laterolog measurements. This design gives a coherent set of high-resolution resistivity measurements that can be inverted to correct the deepest measurements for the environmental influences of invasion and shoulder beds. By having all the laterolog currents return to the tool body, the HRLA tool minimizes the two most unwanted laterolog parasitic distortions—reference effects and shoulder-bed effects. In addition, the surface current return and insulating bridle are no longer needed—reducing cost and risk.

Reference effects—Traditionally, laterolog tools operate in a deep mode with currents returning to a reference electrode at the surface. This requires isolating the logging cable from the tool by use of a long insulating bridle. A systematic shift in the resistivity measurement, called the Groningen effect, arises when high-resistivity formation layers above the tool force returning currents—following the path of least resistance—into the borehole. This leads to a potential drop along the cable, and subsequently the voltage reference of the tool can no longer be considered to be infinitely far away. As a result, formation resistivity computed using this reference reads artificially high.

Long tool strings and drillpipe have a similar effect—artificially increasing the measured formation resistivity.

Shoulder-bed effects—Shoulder beds with large resistivity contrasts have a strong influence on most laterolog measurements. The measurement and focusing currents from the laterolog tool tend to flow along zones of least resistance. A distortion in the focusing current distribution allows the measurement current to flow diffusely across intervals with significant resistivity variations. This defocusing introduces a coupling between the vertical and radial response characteristics of the resistivity measurement.

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The HRLA tool addresses these problems with multiple modes of tightly focused array measurements. Multifrequency operation of the segmented electrodes enables the simultaneous resistivity measurement modes to be distinguished. Software focusing by linear superposition of each mode is used to provide active focusing. The shallowest mode is the most sensitive to the borehole and is used to estimate mud resistivity, $R_m$. The deepest mode has a response comparable to the deep-resistivity measurement of the HALS tool. The spacing of the other arrays is such that they have response characteristics that optimize the information content of their measurements with respect to the invasion profile.

The addition of shallower curves improves the radial sensitivity to resistivity change, which results in greater log curve separation in the presence of invasion. This is especially helpful in thin beds, where deeper measurements tend to lose both depth of investigation and vertical resolution because of antisqueeze effects. In addition, with reference effects gone and shoulder-bed effects reduced, the separation between the deep and shallow measurements caused by these effects is also reduced. The improved invasion discrimination in thinly bedded formations leads to better vertical resolution and more accurate inversion processing for formation resistivity.


Current distributions for HRLA focusing modes. By increasing the number of central electrodes that are kept at the same potential, the tool current return in the formation is moved farther away, and the depth of investigation is increased. Six modes with increasing depth of investigation are used. In Mode-0, current flows directly from the central electrode to the nearest array electrodes. This mode is sensitive to the mud column environment and is used to estimate mud resistivity and borehole diameters. The deepest mode, Mode-5, sends current out from all but the outermost electrodes. The spacing of the array has been designed to optimize the information content of the measurement data with respect to the invasion profile.

Radial response of resistivity tools. The borehole-corrected HALS deep-resistivity radial response compares well with the Mode-5 response from the HRLA array measurement, while the HALS shallow-resistivity response is intermediate between the Mode-2 and Mode-3 HRLA responses. The additional HRLA resistivity measurements provide improved definition of radial resistivity changes, which helps evaluate invasion profiles.
An inversion for the HRLA tool based on a 2D-formation model with a piston-invasion profile is currently being developed for the GeoFrame log interpretation system. The inversion processing proceeds by detecting bed boundaries and segmenting the log into discrete beds with average thickness of 1 to 2 ft [0.3 to 0.6 m]. The inversion will iteratively refine formation parameters until the forward model accurately reproduces the input logs. Because the formation model includes the borehole shape and mud resistivity, the input logs do not need to be borehole-corrected.

More accurate representations of the formation environment lead to more accurate estimates of $R_t$, especially in thinly bedded formations. When the reservoir and water layer thickness are on the order of 2 to 5 ft [0.6 to 1.5 m], it is not unusual to see differences of 50 to 100% between the 1D- and 2D-inversion resistivity estimates (right). Usually the 1D-inversion estimates are too pessimistic. An obvious extension of these models includes dipping layers with 3D models.

> Improved $R_t$ estimate with 2D inversion. The 2D inverted formation resistivity $R_t$ (wide red) and invasion resistivity $R_{so}$ (green) are shown in track 3 along with the raw HRLA curves. The shading between $R_{so}$ and $R_t$ indicates where the invasion is normal ($R_{so} < R_t$) or reversed ($R_{so} > R_t$). In track 4, the 2D inverted resistivities $R_t$ (red) and $R_{so}$ (green) are compared with the 1D inverted formation resistivity $R_t$ (magenta) and the $R_{so}$ (black) from the MCFL tool. The 2D inversion shows a significant increase in $R_t$ obtained in thin beds—such as those between XX30 and XX70 ft—over the 1D-inversion results. A good match between the 2D inversion-derived $R_{so}$ and the one independently obtained from the MCFL measurement—adds confidence to the inversion results. The EPT Electromagnetic Propagation Tool dielectric attenuation and propagation time curves, confirming the presence of thin beds in track 1, were used to constrain the inversion for the uninvaded formation model in the shales.
Optimal array focusing is enhanced by the symmetric tool design, ensuring that all the signals are measured at exactly the same time and at the same logging tool position. This helps avoid horns and oscillations produced by irregular tool motion, and ensures that the measurements are exactly depth aligned. The coherent nature of the focused, depth-aligned, resolution-matched measurements from the HRLA tool produces a more intuitive LQC, as the curves separate following the invasion resistivity profile. At the wellsite, operational safety and efficiency are improved by the elimination of the bridle and surface current system.

**Tackling Difficult Environments**

Model-based inversion processing is a delicate balancing act. Two conflicting factors need to be considered. On one hand, the accuracy of the result depends on how much additional information can be built into the model. On the other, the speed with which the result is delivered increases with the complexity of the model. Fast 1D-inversion models are needed for real-time environmental corrections to help the operator process, interpret and evaluate logs quickly at the wellsite. However, sometimes the wellsite answer isn’t enough. For example, various parasitic effects on resistivity measurements—shoulder beds, spiral boreholes and dipping formation beds with invasion—can continue to cause errors when computing \( R_t \). For these, post-processing techniques available at the computing center can help.

**Shoulder beds**—The presence of shoulder beds can lead to overestimating \( R_t \) in the “squeeze” case and underestimating it in the “antisqueeze” case. Consequently, in both cases, water saturation, \( S_w \), estimation will be affected.

For example, a log analyst will estimate the water-filled resistivity, \( R_w \), from a water-saturated bed (squeeze case), and estimate \( R_t \) in the pay zone (antisqueeze) using Archie’s equation. Errors in both resistivities contribute to overestimating water saturation in the pay zone, which can lead to overlooked hydrocarbons.

How to tackle this problem? The 1D radial inversions used in real time are for simpler cases and do not address the fact that nearby adjacent high-contrast beds may influence the resistivity reading. Improved methods involve the combination of 1D shoulder-bed corrections followed by a 1D radial inversion, but they do not address the fact that the radial and vertical responses are coupled, leading to significant errors in resistivity determination. It has been long recognized that resistivity estimation can be improved by the use of inversion techniques that take into account true 2D or 3D formation structure (see “Getting More Pay from Resistivity Logs,” *previous page*). Application of 2D formation models to the inversion technique can double the calculated reserves, particularly in thinly bedded formations.

**Spiral boreholes**—Some drilling practices produce a borehole with a 3D shape that has a spiral groove on top of the bit-sized hole. Such boreholes produce a quasi-periodic character in the logs, and are variously referred to as “corkscrew” or “threaded hole.” These have been associated with downhole drill motors and high-angle wells. Displaced stabilizers can produce the same effect in vertical wells. The effect is seen as a periodic oscillation on the caliper log. The effect on other logging tools depends on the physics of the measurement. The impact of spiral boreholes on induction measurements has been extensively studied by BP Amoco Exploration.

Recently, filter techniques have been developed to reduce the effects of spiral borehole rugosity on logging tool measurements (see “Dealing with Spiral Boreholes,” *next page*). For density tools, the effect of the spiral-grooved hole is to produce a cyclic mudcake effect.

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Dealing with Spiral Boreholes

For the AIT tool, saline mud combined with spiral or corkscrew boreholes can produce a strong signal and completely smear an array induction tool log (below). The origin of the induction tool response distortion is likely due to changes in standoff. Practical experience shows that the effect is worst in 6-in. holes where the standoff distance is limited. As the tool moves along the borehole, the standoff ribs on the tool tend to fall into the grooves, allowing the induction sonde to approach the borehole wall—periodically reducing tool standoff. Using the fact that the spiral borehole introduces a periodic effect or distortion to the log, several signal-processing techniques effectively cancel the unwanted periodic signal.

There are three main steps: automatically detecting the primary signal and its harmonics, estimation of their frequency, and subsequent removal of all unwanted components. For AIT measurements, the method involves frequency spectrum estimation and peak identification over short logging segments, in which each array data segment is replaced by a parametric autoregressive model. The advantage of this approach is automatic detection and frequency estimation of the dominant periodic components in each segment. Typically, up to three sinusoidal harmonics are detected in AIT logs. Once the harmonic components are determined, the task is to filter them out. For each array data segment, a notch filter is designed with the appropriate transfer and phase characteristics to remove—without phase distortion—all harmonics from the spiral borehole (bottom). The filter is applied to the raw signal just after borehole correction. Similar methods have been proposed for handling the effects of corkscrew rugosity on nuclear logs.

1. Barber et al, reference 21, main text.

![Frequency spectrum and notch filter. A power spectrum of the logging data shows several peaks (arrows) caused by cyclic standoff variations in tool standoff. A frequency response shows the attenuation (top right) and phase-shift (bottom right) characteristics of a three-frequency notch filter designed to remove periodic noise found in logging data.]

![Induction logs in a spiral borehole. On the left is a Platform Express induction log from a Canadian well with a severe spiral borehole (left). Filtering the data from the spiral borehole well has removed unwanted harmonic borehole noise, and now the environmental flags indicate that the 2-ft resolution logs are valid (right). Chart-based C, bad hole B and magnetic mud M log quality-control (LQC) flags are shown to the left of each log. The color of the chart-based and bad hole flag shows the recommended resistivity bed resolution. The color of the magnetic mud flag indicates either magnetic mud (red) or nonmagnetic mud (yellow).]
Handling dip — The large volume of investigation of induction tools complicates the interpretation of their logs. Modern induction devices such as the AIT tool are designed for use in vertical wells, and are carefully focused to limit their response to a relatively thin formation layer perpendicular to the borehole. However, in wells at high relative dip, the response cuts across several beds, and the measurement is no longer focused in an isolated single layer. The effect of high relative dip is to blur the log response and to introduce horns at the bed boundaries.

Traditional dip-correction algorithms for induction logs are limited in practice to angles less than 50° because of an increasing nonlinear response to dip and adjacent bed-boundary contrasts. As a result, interpreting resistivity from induction logs at apparent dip angles over 50° has been limited to iterative inversion using 1D forward models. The presence of invasion has added additional complexity to the geometry, requiring processing based on 3D inversion codes. Even with fast computers, the processing has been excessively time-consuming for long log sections or when many thin beds are encountered. Recently, a new algorithm based on a maximum-entropy inversion of raw, borehole-corrected array data through a fast 1D forward model has dramatically improved the speed and ability to interpret multiarray induction logs in invaded formations at high relative dip angles (see “Interpreting Induction Logs in High Dip Angle Formations with Invasion,” page 54).

**Density LQC logs.** In a well drilled with nonbarite mud in the North Sea, the density inversion processing reconstruction errors (left) for all detectors are seen to be nearly zero—closely tracking the center of each track, as expected. The density curve (yellow) from this interval is superimposed to highlight the large change in densities computed across this interval. The global cost function log is low throughout the entire interval indicating good reconstruction and high confidence in the inversion results. Statistical analysis of the reconstruction errors shows that every energy window is below its maximum bias level. The hardware LQC logs (right) from this well show stable tool operation. As expected, the backscatter total count rates (black) in track 1 anticorrelate in Zones A and B with those of the from the short-spacing detector (black) in track 2 and long-spacing detector (black) in track 3. No detector hardware error flags were displayed in the green columns shown at the left side of each track.
Active Log Quality Control

Many questions arise when logs appear strange. Raw data may be fine, but the computed formation parameter, such as density, may look abnormal. This leads to questions: Is the tool in an unusual formation? Is the software correct? Is the tool working properly? Good log quality control (LQC) resolves these issues, and with the addition of real-time environmental corrections provides insight during acquisition into both the effects of the logging environment on every tool measurement and the way these measurements are being processed.

Numerous LQC analyses, logs and flags are available in the Platform Express system to ensure quality measurements and processing. These literally form a log quality-control hierarchy from the top level of environmental processing down to the bottom level of tool-specific sensor performance and calibration. Following are some examples showing how LQC actively works to provide better logging answers both at the wellsite and afterwards.

Density LQC—Window count-rate reconstruction errors from the density inversion algorithm are a measure of the “health” of the inversion process (previous page). They pinpoint significant differences between modeled window count rates and those measured for each detector. A large systematic bias in the observed reconstruction error log for more than one energy window indicates a problem in calibration, excessive pad wear or tool standoff. High intermittent values in the reconstruction errors indicate an abnormal noise level on the measurement (hardware problems), or instabilities in the inversion process that may be associated with bad borehole conditions.

A typical example of significantly high reconstruction errors occurs when the logging engineer selects the wrong mud-type-processing option—Barite or No-Barite. These two modes correspond to different tool-response models as well as specific inversion schemes, and the choice has to be made according to the importance of photoelectric absorption in the mud, which is linked to the barite content. If the engineer does not have exact knowledge of the mud composition, the wrong option might be selected, resulting in poor estimation of density and \( P_e \). However, the raw count rates are always recorded, and since processing is applied on the raw counts, it is always possible to recompute correct results regardless of the acquisition mode.

Recently, a new “switchless” mud-density algorithm was designed to eliminate problems with incorrect mud-algorithm selection. Currently being field-tested, the algorithm uses a unique tool-response model, valid for all mud properties, and a generalized inversion scheme based on a barite indicator. The barite indicator provides an estimation of the amount of barite in the mud at each depth, and is based on low- and high-energy window count-rate ratios in the backscatter detector.

Another example of how LQC provides active control of the log acquisition process is the automatic offset recalibration for high-resolution density logging measurements. The robust low-resolution window count-rate reconstruction error helps identify slowly varying count-rate offset errors on the backscatter and short-spacing detector measurements—used primarily for the high-resolution density logs. Any offset count-rate error detected in these measurements is corrected before being used in the inversion algorithm to estimate the high-resolution formation parameters. Whenever LQC detects extreme rugosity or bad borehole, the more robust low-resolution density logs are recommended.
An example from the North Sea shows how LQC helps build confidence in the tool measurements when the unexpected happens in unusual borehole conditions (previous page). Each of the three detectors in the Platform Express density tool sees progressively farther into the formation. Like the invasion profile produced by an array-resistivity tool, array density measurements produce density profiles. These profiles depend on the mud weight used. In wells drilled with light nonbarite mud, the density profile tends to increase from low to higher density, as the detectors look deeper into the formation. Typically, in wells drilled with high-density barite mud, the density profile will be from high to low as each detector looks farther into the formation.

When first seen in boreholes, unexpected apparent density profiles were thought to be due to hardware problems. However, LQC quickly verified that the tool was functioning correctly. Further examination revealed the answer: In deviated wells, where pipe grooves frequently occur, the borehole is scraped clean of mudcake, giving an unpredicted density response. Now that the phenomenon is well understood, the inversion algorithms are designed to accommodate this effect.

Environmental LQC for resistivity—The operational limits of the AIT induction measurement have been incorporated into a “fuzzy-logic” algorithm that uses real-time inputs of caliper and mud-resistivity measurements to determine the best resolution logging output consistent with the environment (above). The output of the logic has four possible states—1-ft valid, 2-ft valid, 4-ft valid or “Out of Range.” The last state is flagged when environmental parameters are completely outside the range of the least restrictive induction tool measurement. This means laterolog tools would provide better resistivity measurements.

However, the chart-based induction tool LQC algorithm is based on smooth boreholes, and does not always detect when the environment is unfavorable for induction measurements. In wells where the borehole is very rough or when standoff is inadequate, spurious spikes and other anomalies might render high-resolution logs unusable. Research has shown that high-frequency induction array signals come from near the borehole, confirmed by the extremely sharp spikes near the tool axis seen on the shortest array Born-response tool sensitivity function. In these cases, a ruggedness-detection algorithm combines high-pass-filtered, short-array data with mud-resistivity information to make certain that ruggedness detection is dominant. The default wellsite presentation is the most appropriate composite-resolution log, which varies smoothly between the 1-ft to 4-ft resolution log—based on the combination of the chart and hole-ruggedness logic. In all cases, the three basic-resolution and composite-resolution logs are always recorded.

Remote witnessing—Recently, BP Amoco Exploration initiated a program of remote witnessing on their wells in the Andrew field in the North Sea by combining the capabilities of Platform Express real-time LQC and interpretation with the InterACT communications system. The InterACT system provides the capability for real-time transmission of log data and wellsite graphics to distant locations. This allows direct and immediate communication and interaction between the offshore wellsite and consultants in Aberdeen and London during log acquisition for better and more timely decision-making.

For example, in one well, a wireline logging tool was unable to reach target depth due to wellbore deviation. The situation was confirmed while logging. An immediate decision was made to pull out of hole and go straight to a drillpipe-conveyed logging option. In other cases, irregularities in borehole dimensions shown on the caliper were witnessed during logging and a quick decision was taken to pull out of the hole and rig down—eliminating the possibility of a stuck tool. In all cases, real-time LQC provided confidence in the tool measurements during logging, enabling operators to make appropriate decisions based on environmental constraints, and not on limitations in the tool performance.

Remote witnessing has also decreased costs and improved safety by reducing personnel and transportation requirements at the wellsite. Logs and evaluations are immediately available to the experts who need them, and real-time LQC ensures that logging measurements are valid and can be trusted. If problems occur, expert opinions are available to help with contingency plans and decisions.

A new algorithm based on maximum-entropy inversion of borehole-corrected multiarray induction data through a fast 1D forward model has been developed and tailored for highly deviated wells. This algorithm provides the same interpretation for invasion that has previously been available only for vertical wells. The key to maximum-entropy inversion is a fast forward model. For this model, an analytical solution is used to compute the response of the AIT tool in a layered formation with dip. The response of each array is computed by finding exact solutions to Maxwell’s equations for the beds at a given dip angle. In implementation, it is desirable to have the layer thickness less than the resolution of the sensors—typically layers 6- to 12-in. [15- to 30-cm] thick.

The inversion is formulated on finding the unknown formation conductivity that minimizes a cost function. Like the other inversions used in the Platform Express system, the first term in this cost function is a measure of how well the forward model predicts each array raw measurement—weighted by the expected error or noise in each measurement. For example, if the model predicts array voltages that agree well with those observed on each AIT receiver coil, then its contribution to the cost function is low. The second term is one proportional to the total entropy in the resistivity log. This term adds stability to the solution. Finally, there is an empirical smoothing term included in the cost function. The smoothing term also helps add stability to the solution, but is used sparingly because it tends to decrease vertical resolution.

The concept of entropy as applied to log data is not intuitive. In physics, entropy is a measure of the degree of disorder in a system, and the second law of thermodynamics states that the total entropy of a system can never decrease during a change. Applied to log data, entropy is a measure of the departure of log values from locally averaged values. For example, by setting up a simple least-squares inversion of the thinly layered model—done by including only the first term in the cost function—the results can have many high-frequency “wiggles” (below). Including the entropy term in the cost function helps smooth out all the extraneous high-frequency information content—meaningless information below the resolution capability of the tool.

The implementation of maximum-entropy inversion processing is more robust when pairs of arrays are inverted at the same time to obtain formation resistivity. As a result, rational sets of array pairs are inverted together, with the surprising property that the depth of investigation of each pair is the same as that of the deeper-reading array. This means that radial response functions for the arrays can be used to define the radial response of the inverted logs. Furthermore, by weighting the results of inverting the array pairs, the inverted logs can be focused radially to give logs with standard AIT depths of investigation.

The combination of maximum-entropy processing, resolution-matched inverted formation resistivities and radial focusing is called Maximum Entropy Resistivity Log Inversion (MERLIN). This processing works on AIT data at all dip angles from 0º to approximately 80º (next page, top). In principle, it will work up to 90º, but in practice, the parameterization requires that the wellbore cut all beds of interest. MERLIN processing replaces the Born-response function filter-based standard AIT processing. The resulting logs can be inverted for invasion parameters as if they were in a vertical well, but at any dip angle. In addition, although maximum-entropy inversion was developed to remove the effects of high dip, the exact solution forward model at the heart of the method works at any dip angle, including zero.

![Maximum-entropy solution. A simple least-squares inversion of the thinly layered model results in a log with a high noise component (left). In the high-entropy solution (right), the dotted curve indicates the increased entropy found in the maximum-entropy solution.](image-url)
For example, formations with high shoulder conductivity and with shoulder-bed contrasts can be modeled correctly with the exact-solution-based MERLIN processing. In a vertical well drilled with oil-base mud, anomalies are seen on the bottom and top of the reservoir section in the real-time AIT logs (right). The high contrast between the reservoir resistivity (100 ohm-m) and that of the conductive clay shoulder beds (less than 1 ohm-m) causes the standard logs to overshoot in the resistive reservoir. This happens because standard AIT processing—based on Born-based response functions—includes contributions from many depth intervals around the tool. Although these functions are accurate models of the induction response in low-to-moderate-contrast environments, when the shoulder-bed contrast approaches 500:1, the Born-based approximation for the tool response is poor. The MERLIN logs are well-behaved in these difficult induction-logging environments.


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Real-Time Interpretations

Wellsite interpretation during log acquisition is another benefit of real-time environmental corrections. Platform Express interpretations feature integrated petrophysical computations and graphic presentations that help operators make timely decisions about the reserves in their field during the logging run. These include a complete formation volume and lithology evaluation, fluid saturation analysis, invaded-zone gas saturation and a special horizontal well presentation.

For example, formation porosity is derived from the traditional crossplot of tool-measured bulk density, $\rho_B$, and the thermal neutron porosity. Comparing neutron response with that of the density measurement, a lithology-corrected formation porosity is determined. With these results, porosity-corrected formation grain density, $\rho_{maa}$, and volumetric matrix photoelectric factor, $U_{maa}$, are computed, to provide inputs needed for a standard $\rho_{maa}$-$U_{maa}$ crossplot-based mineral interpretation. By its nature, this crossplot method is independent of porosity. Finally, clay volume, $V_{cl}$, derived from gamma ray or spontaneous potential (SP) measurements, provides a third dimension to the standard mineralogy crossplot (below).

Formation lithology analysis. The $\rho_{maa}$-$U_{maa}$ crossplot, derived from neutron and density tool measurements, forms the basis for a standard mineralogy interpretation (right). Porosity is effectively removed from these inputs, resulting in a crossplot that is a function only of the mineralogy in the formation. End-points for pure anhydrite, sandstone (quartz), dolomite and limestone (calcite) are shown. The lithology column color change depends on clay volume, $V_{cl}$, and is derived from the SP or gamma ray measurement. Colors assigned to the plot are derived from a color cube with the corners of yellow, green, cyan and white on one face, which represents zero $V_{cl}$, and corners of red, black, blue and magenta on the opposite face, which represents 100% $V_{cl}$. The Platform Express lithology column shows significant lithology changes in the lower section of the BP Amoco Catoosa test well (above).
The clay volume and the mineralogy crossplot drive the real-time lithology column profile. The color change depends on $V_c$ and the position of each point on the $\rho_{mav}$ $U_{mav}$ crossplot. This lithology image provides a valuable method to observe lithology changes in the formation. Although not intended to provide a volumetric interpretation of the mineralogy of the formation, it can be used effectively for well-to-well correlation.

Next, porosity and resistivity measurements are coupled with Archie’s equation to determine water saturation. An optional invaded-zone gas or steam saturation—computed from the density-neutron crossover separation—is used to compute a gas-corrected neutron-density porosity.

Finally, a special wellsite Platform Express presentation has been developed for highly deviated and horizontal wellbores [above]. A real-time true vertical depth (TVD) computation—based on the deviation derived from the built-in tool-axis accelerometer—is used to plot a wellbore shape versus cable depth using the lithology image as an area fill in the wellbore trajectory curve. The availability of a real-time well deviation and lithology profile at the well helps to explain unexpected logging results often encountered when crossing beds and fault zones in highly deviated wells.

The Road Ahead

More than two-thirds of the “triple-combo” logging operations performed by Schlumberger in 1998 were done with the new-generation platform logging technology. Real-time depth and environmental corrections provide the key to getting accurate formation information into the hands of the operator when and where it does the most good—at the wellsite. Real-time, speed-based corrections are being implemented on every tool platform that contains a built-in accelerometer, such as the Xtreme quad-combo tool string designed for high-pressure and high-temperature environments and the SlimAccess quad-combo tool string designed for the slim and complex-geometry borehole environment. New technology, such as the HRLA tool, addresses the traditional problems encountered in conductive boreholes and promises to bring more accurate results in a wider range of environments.

Improved 2D and 3D forward models are helping to clarify increasingly more difficult logging environments. Breakthroughs in computing speed will eventually lead to their increased application. Advanced processing, such as MERLIN and HRLA 2D processing are available in computing centers and may be available someday for real-time operation. These developments promise an exciting time for geologists, reservoir engineers and petrophysicists who use openhole-logging measurements.

—RH