Nuclear Magnetic Resonance Logging While Drilling

Innovative drilling and measurements technologies now provide increasingly comprehensive borehole and formation-evaluation data in real time. Recent developments in nuclear magnetic resonance logging while drilling are helping operators make more informed drilling and completions decisions, reduce risk and nonproductive time and optimize wellbore placement and productivity.

Nuclear magnetic resonance (NMR) logging while drilling (LWD) represents a significant advancement in geosteering and formation-evaluation technology, bringing the benefits of wireline NMR to real-time drilling operations. Critical petrophysical parameters, such as permeability and producibility estimates, can now be obtained while drilling, providing information that helps petrophysicists, geologists and drillers achieve optimal wellbore placement within a reservoir.

Real-time while-drilling measurements are especially important in high-cost and time-sensitive drilling environments. With rig costs running as high as USD 175,000 per day, errors in well placement, formation evaluation or well-completion design can result in significant additional well costs or the drilling of expensive sidetracks.\(^1\)

In this article, we review basic NMR concepts, introduce developments in NMR logging while drilling and discuss how operators are using this technology for wellbore placement and formation evaluation in real time.

Development of Wireline NMR

In the decade that NMR logs have been available, they have undergone continual improvement.\(^2\)

The CMR Combinable Magnetic Resonance tool family, beginning with the introduction of the CMR-A service in 1995, provided measurements of effective porosity, bound-fluid volume (BFV), permeability and \(T_2\) distributions, a concept described later in this article. The CMR-200 Combinable Magnetic Resonance tool introduced advances in electronics that provide an increased signal-to-noise ratio (S/N) while shorter echo...

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spacing, on the order of 200 µs, improved petrophysical measurement quality, including total porosity. Further improvements led to the CMR-Plus logging tool with high-speed capability to acquire data at logging rates up to 2400 ft/hr [730 m/hr] for full porosity logging and 3600 ft/hr [1100 m/hr] for bound-fluid logging, rates three to five times faster than the CMR-200 tool.3

To date, more than 7000 CMR logging jobs have been performed. For many applications, NMR measurements are superior to other logging techniques and can provide critical answers to questions concerning the presence, type and producibility of reservoir fluids. For many operators, NMR logging has become a routine service in typical logging programs.

**Dance of the Protons**

NMR logging measures the magnetic moment of hydrogen nuclei (protons) in water and hydrocarbons. Protons have an electrical charge and their spin creates a weak magnetic moment. NMR logging tools use large permanent magnets to create a strong, static, magnetic-polarizing field inside the formation. The longitudinal-relaxation time, $T_1$, describes how quickly the nuclei align, or polarize, in the static magnetic field. Full polarization of the protons in pore fluids takes up to several seconds and can be
done while the logging tool is moving, but the nuclei must remain exposed to the magnetic field for the duration of the measurement. The relationship between $T_1$ and increasing pore size is direct, yet inverse, to formation fluid viscosity.

A series of timed radio-frequency (rf) pulses from the logging-tool antenna can be used to manipulate proton alignment. The aligned protons are tilted into a plane perpendicular to the static magnetic field. These tilted protons precess around the direction of the strong induced magnetic field. The precessing protons create oscillating magnetic fields, which generate a weak but measurable radio signal. However, since this signal decays rapidly, it has to be regenerated by repeatedly applying a sequence of radio-frequency pulses. The precessing protons in turn generate a series of radio-signal pulses or peaks known as spin echoes. The rate at which the proton precession decays, or loses its alignment, is called the transverse-relaxation time, $T_2$.

$T_1$ and $T_2$ processes are affected predominantly by interaction between pore-fluid molecules, or bulk-relaxation characteristics, and from pore-fluid interactions with the grain surfaces of the rock matrix, also known as surface-relaxation characteristics. In addition, in the presence of a significant magnetic-field gradient within the resonant zone, there is relaxation by molecular diffusion that influences only $T_2$ processes.¹

### NMR While Drilling

Following the widespread acceptance of wireline NMR, development and field-testing of LWD NMR tools began in the late 1990s.³ Research and development efforts and lessons learned from wireline-conveyed NMR logging ultimately led to the introduction of the proVISION real-time reservoir steering service in 2001, capable of providing precise high-resolution NMR measurements under the harsh conditions typically encountered while drilling.

Similar to the CMR tool, the proVISION LWD tool delivers measurements that include mineralogy-independent porosity, bound-fluid volume (BFV), free-fluid volume (FFV), permeability, hydrocarbon detection and $T_2$ distributions.

Flexible design allows engineers at the wellsite to modify the measurement sequence and operational characteristics of the tool for one of three drilling modes: rotating, sliding or stationary. The tool can be programmed manually or set to switch automatically based on drilling conditions (below). Engineers can program the tool to measure $T_1$, $T_2$, or both simultaneously. Although both measurements can generate NMR formation-evaluation data, the proVISION system relies primarily on $T_2$ measurements, which produce higher statistical repeatability and vertical resolution.

Both $T_1$ and $T_2$ measurements sample an exponential time evolution process. $T_1$ measurements sample an exponential buildup and $T_2$ measurements, an exponential decay. The $T_1$ measurement consists of a few samples on this buildup, each of which requires an additional wait time depending on the point measured. The $T_2$ measurement, on the other hand, captures the complete decay within a single Carr-Purcell-Meiboom-Gill (CPMG) measurement after only one wait time, resulting in a greater number of echoes per measurement. Thus the $T_2$ measurement can be taken more quickly leading to either a higher sample rate or to more averaging and, therefore, enhanced data quality.

For LWD NMR measurements to be available in real time, they must be transmitted to the surface by mud-pulse telemetry. From the raw measurements performed by the tool, an optimal signal-processing algorithm is implemented downhole to perform the critical $T_2$ inversion process. As a result of this inversion, important petrophysical measurements can be derived in real time, namely: lithology-independent porosity, $T_2$ spectral distributions, bound- and free-fluid volumes, permeability and information about fluid saturations and characteristics. However, because of telemetry bandwidth limitations, real-time data transmission is limited to magnetic resonance-derived porosities, BFV, FFV, motion-dependent quality control parameters and $T_2$-LM, or logarithmic mean of the $T_2$ distribution. These are used in conjunction with the standard formation evaluation and survey measurements to optimize wellbore placement within the reservoir.

Transmission of $T_2$-LM, BFV or FFV and porosity allows calculation of permeability using the Schlumberger Doll Research (SDR) or Timur-Coates equations.⁴ Although $T_2$ distributions themselves can be provided in real time, telemetry bandwidth limitations require prioritization of data; less critical information is stored in memory for later processing.

Data are transmitted to surface in real time by the PowerPulse MWD telemetry system. As with other VISION Formation Evaluation and Imaging While Drilling LWD tools, maximum environmental conditions for the proVISION tool are 300°F [150°C], 20,000 psi [138 MPa], and dogleg severity of 8°/100 ft [8°/30 m] while rotating and 16°/100 ft [16°/30 m] while sliding.

The proVISION opposing-dipole magnet design produces a symmetric magnetic field. The vertically oriented tubular samarium-cobalt permanent magnets are stable within the operating temperature range of the tool. A predictable and repeatable NMR measurement is produced (next page, top).

The interaction of the rf field and static magnetic field produces a resonant region, or shell, with a diameter of 14 in. [36 cm] and height of 6 in. [15 cm] (next page, bottom). Magnetic-field strength within the shell is approximately 60 gauss, with a field gradient of about 3 gauss per centimeter. The width of the measurement shell allows formation measurement in slightly enlarged or deviated wellbores and when the tool is eccentered. The formation depth of investigation (DOI) varies with borehole diameter. For example, in an 8¾-in. diameter borehole, the DOI is 2¾ in. [7 cm]. At a drilling rate of 50 ft/hr [15 m/hr], vertical resolution is 3 to 4 ft [0.9 to 1.2 m] after data stacking.
For geosteering purposes, field engineers can place the tool directly behind the downhole motor or PowerDrive rotary steerable system or directly above the bit sub. To further enhance geosteering capabilities, the proVISION antenna section, which contains the permanent magnets, is located at the bottom of the tool, placing the measurement point as close to the bit as possible.

The existence of powerful magnets within the bottomhole assembly (BHA) has the potential to adversely affect azimuthal magnetic-survey instruments used for determining spatial coordinates of the borehole. However, Schlumberger engineers have demonstrated through modeling and experimentation that the axially symmetric magnetic field of the proVISION tool has little influence on azimuthal magnetic measurement. Since the magnitude of magnetic-field interference is small and directly proportional to the intensity of the magnetic field produced by the proVISION tool, errors are significant only when the proVISION tool is placed directly above the survey instrument. Based on numerical models and physical measurements, Schlumberger engineers have developed survey correction algorithms for NMR magnetic interference. These algorithms are included in the IDEAL Integrated Drilling Evaluation and Logging well-site software.


$^\dagger$ The proVISION tool design. Housed within a 37 ft [11.3 m] long, 6.75-in. [17.1-cm] diameter drill collar, the tool’s outside diameter is 7.75 in. [19.7 cm]. When configured with no external upsets and with wearbands in place, the tool can be run in boreholes ranging from 8.5 in. up to 10.5 in. diameter. On-site field engineers may attach a screw-on stabilizer to reduce lateral motion and centralize the tool in a borehole. Telemetry connections on both ends of the tool assembly allow configuration to any section of a bottomhole assembly (BHA). The tool is turbine-powered, rather than battery-powered, and can accommodate flow rates ranging from 300 to 800 gal/min [1136 to 3028 L/min].

$^\ddagger$ Cross sections of the proVISION tool. The axial section through the antenna (left) illustrates the symmetric tool design. The dark blue bars are hollow cylindrical magnets. Lines of constant field strength (blue) indicate a gradient magnetic field that decays away from the tool. The section through the coaxial wound antenna coil is shown in black. The interaction of the antenna and the magnets produces a cylindrical resonant shell (red stripes) that is 6 in. [15 cm] long, 0.4 in. [10 mm] thick, with a 14-in. [36-cm] diameter of investigation. The transverse section through the coaxial wound antenna coil (right) illustrates the axisymmetric resonant shell (red). The resonant shell is the only place the measurement is made—no measurement is made between the tool and the resonant shell or from the resonant shell farther into the formation. The formation depth of investigation (DOI) in an 8.5-in. [21.5-cm] diameter borehole is 2.75 in. [7 cm].
Making Measurements

The proVISION tool operates in a cyclic mode rather than a continuous mode. The operating cycle consists of an initial polarization wait time followed by the transmission of the high-frequency rf pulse and then the reception of the coherent echo signal, or echo train. The cycle of pulsing and echo reception is repeated in succession until the programmed number of echoes has been collected. Typically, the acquisition is defined by the Carr-Purcell-Meiboom-Gill (CPMG) sequence. An initial 90° pulse followed by a long series of timed 180° pulses characterizes the CPMG sequence. The time interval between the successive 180° pulses is the echo spacing and is generally on the order of hundreds of microseconds.

To cancel the intrinsic noise in a CPMG sequence, the CPMGs are collected in pairs. The first of the pair is a signal with positive phase. The second of the pair is collected with an 180° phase shift, also known as the negative phase. The two CPMG sequences are then combined to give a phase-alternated pair. Compared with the individual CPMG sequence, the combined or stacked CPMG sequence has an improved S/N.

Measurements of $T_1$ and $T_2$ and their distributions are key elements of NMR logging. The primary $T_1$ quantity measured is signal amplitude as a function of polarization recovery time. The primary $T_2$ quantities measured are echo-signal amplitudes and their decay. Pulse parameters such as echo spacing, wait times and the NMR measurement cycle define all aspects of the NMR measurement and are completely programmable in the proVISION tool.

Drillstring Dynamics and NMR Measurements

NMR measurements are not instantaneous. Tool movement may cause the resonant or excited region to move during data acquisition (above left). The proVISION tool is equipped with sensors that measure the amplitude and velocity of lateral motion, and instantaneous revolutions per minute (rpm).

Tool movement can affect both $T_1$ and $T_2$ measurements. Motion-induced decay primarily affects long $T_2$ values, resulting in faster echo decays that may reduce the accuracy of NMR measurement, particularly in light hydrocarbon and carbonate formations. These motion effects are most severe when the measurement shell is thin in relation to the tool displacement, often resulting in movement of the resonant shell out of the region of investigation, even for small tool movements. A high-gradient static magnetic field...
Since lateral motion can potentially shorten $T_2$ decay rates, understanding this motion is critical for developing data quality-control techniques. To assess motion-induced effects, engineers must know the frequency, amplitude, trajectory and timing of the motion. Rapid-sampling accelerometer and magnetometer systems measure real-time drillstring motion (previous page, bottom). Motion data are processed in 20-sec snapshots. Raw snapshot data are compressed and can be stored in memory, while the processed results are recorded continuously to provide an uninterrupted log of lateral motion. The theoretical maximum $T_2$ value resolvable during motion is calculated and a flag indicating NMR data quality is transmitted with the real-time data set.

Motion data obtained with the proVISION tool have broad independent utility. These data can alert the driller to excessive lateral motion, an unfavorable resonant mode or excessive shocks allowing corrective action to be taken to reduce potential BHA or drill-bit damage and to optimize drilling rates, improving drilling efficiency. Timely response to excessive drillstring motion can also minimize borehole enlargement (above right).

**Optimizing Well Productivity**

Proper well placement and completion design are key to optimizing productivity. To accomplish this, drillers must place wellbores in the most productive part of a target reservoir, and engineers must design completions to maximize oil production and recovery while simultaneously limiting water production. Real-time LWD NMR logging provides the data necessary for informed decision-making.

Determining which intervals of a reservoir should be completed requires an estimate of a well’s productivity index (PI). Traditionally, this question has been addressed after completion of drilling, wireline logging and production testing. The PI is based on a permeability profile, which is the product of reservoir permeability and vertical thickness. These measurements are obtained from well logs, formation tests, or both.

For more than a decade, operators have sought real-time estimates of permeability and PI. In 1994, BP engineers successfully experimented with real-time PI determination methods at their Wytch Farm project located in the south of England. Geological studies of the Sherwood sandstone oil reservoir established that reservoir productivity is a function of permeability, and that permeability is controlled by grain size and porosity. Core data were used to create permeability bulk-density transforms for each grain-size class and these, in turn, were used to estimate PI. As drilling progressed, a permeability log was generated in real time using grain size obtained from sieve analysis of drill cuttings and combining porosity measurements from a litho-density-neutron logging tool. Petrophysicists then calibrated the model against offset wells.

Engineering and petrophysical teams used these early real-time permeability-productivity estimates to model and optimize a well’s economic potential in several ways. Decisions to adjust well trajectory were based on real-time productivity predictions. By optimizing perforation intervals, the team maximized production and minimized the potential for water break-through. These data were used to estimate reserves remaining in wells where intervals had been plugged back for water shutoff.

At Wytch Farm, BP’s method was relatively simple to implement. The Sherwood sandstone is not highly cemented and grain size, porosity and permeability have a clearly defined relationship. Also, well cores were available for model calibration. In many other reservoirs, the petrophysical characteristics are less straightforward. While similar processes might provide comparable results while drilling in more complex reservoirs, the petrophysical community wanted a more accurate and complete formation-evaluation solution. NMR in real time can provide this information and help in optimizing wellbore placement and completion design.

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NMR in Real Time

Modern NMR logs measure mineralogy-independent porosity and provide an estimate of permeability and bound-fluid volumes. They can also detect the presence of hydrocarbons. When combined with other LWD measurements, NMR data can be used to generate potential production estimates in real time.

In 2002, BP engineers applied the proVISION system on a deepwater project in the Gulf of Mexico, USA (right). During drilling with oil-base mud, real-time NMR logs were obtained in three separate 8 1⁄2-in. diameter wells. The proVISION pulse sequence consisted of a single wait time and burst sequence. A relatively long wait time of 12 sec was used to ensure adequate polarization of the light hydrocarbons that were expected in this reservoir. Six hundred echoes were collected after the long wait time. The burst sequence consisted of 20 echoes following a 0.08-sec wait time. Echoes were collected with spacing of 0.8 and 1.2 msec. The overall NMR cycle time was about 30 sec at a drilling rate of approximately 70 ft [21 m] per hour. This combination of cycle time and rate of penetration (ROP) gave a depth sample rate of about 0.75 ft [0.23 m] per phase-alternated pair.

To determine BFV, a $T_2$ cutoff of 90 msec was chosen. This $T_2$ cutoff value was based on experience with wireline NMR measurements in this field. Evaluation by the petrophysical team indicated that neutron, density and NMR porosity were in agreement through the sandstone, which has a porosity of about 28 p.u. In addition to NMR data, the proVISION data set provided the operator with drilling performance, lateral motion and downhole RPM logs to detect erratic drilling conditions, such as stick-slip motion, and allowed the driller to take corrective actions, potentially extending the life of the bottomhole assembly and optimizing ROP.

The Quest for Carbonate Evaluation

Hydrocarbons in the Al Shaheen field, offshore Qatar, are currently produced from three Cretaceous formations, the Kharaib, Shuaiba and Nahr Umr. The Kharaib and Shuaiba reservoirs are carbonate, while the Nahr Umr comprises thin sandstones (next page, top).

Maersk Oil operating the Al Shaheen field in cooperation with Qatar Petroleum is developing these complex formations with extended-reach horizontal wells that occasionally exceed 30,000 ft [9144 m] measured depth (MD) while only 3000 ft [914 m] in true vertical depth. In such wells, drillpipe cannot be rotated in the hole with logging cable attached. Frictional effects eventually prohibit sliding beyond about 13,000 ft [3962 m]. Thus, wireline-conveyed logging tools are typically unable to reach the farthest part of a horizontal section. LWD tools are conveyed over the entire length of the borehole while providing data for geosteering and primary formation evaluation.

NMR techniques can help determine reservoir fluid flow and permeability characteristics. These characteristics may vary significantly with changes in geologic facies. Detection of facies variation is critical to reservoir understanding and optimal wellbore placement. Often, particularly in carbonate reservoirs, the lack of consistent relationships between porosity and permeability on a reservoir scale limits LWD...
petrophysical characterization using porosity logs. Conventional wireline-conveyed NMR logging has improved the characterization of geologic facies and other petrophysical carbonate properties such as permeability (bottom).

Drilling extended-reach wells in the Al Shaheen field is challenging. Rotary steerable BHAs are typically used for directional control in the drilling of the long horizontal sections. The petrophysical team was concerned about diminished LWD NMR data quality due to motion-dependent $T_2$ decay resulting from the typically high levels of BHA shock, stick-slip and lateral tool motion during drillstring rotation. With ROPs occasionally in excess of 500 ft/hr [152 m/hr], further data-quality loss was expected.

Carbonate rocks typically have lower surface-relaxation times, which leads to extended $T_2$ times. Since much of the important petrophysical information is contained in the later echoes, acquisition sequences in carbonates typically require a longer wait time and a greater number of echoes than in clastic formations. It was unknown whether the late $T_2$ components typically seen in the Al Shaheen carbonate rocks would be detected under the expected difficult drilling conditions.

Engineers attempted to alleviate as many variables as possible during prejob planning. To improve the S/N, raw echo stacking was also planned. Since facies changes typically occur over tens or hundreds of feet in extended-reach wells, and the detection of small-scale variations was not the main objective, a loss of resolution in exchange for improved S/N was acceptable.

The world's first proVISION deployment in a carbonate reservoir was in an extended-reach, 81/2-in. diameter horizontal well, drilled to more than 24,000 ft [7315 m] MD with water-base mud. A rotary steerable assembly controlled trajectory while LWD NMR data were obtained in real time along the entire borehole length.

Limited amounts of core material were available from this particular section of the Shuaiba reservoir. Historically, carbonate facies identification and interpretation were based on a combination of drill cuttings, thin sections and log data. Today, advanced logging tools, such as NMR, provide valuable information on fluid distributions and reservoir properties.


^Identifying changes in the Shuaiba limestone reservoir with wireline NMR data. The NMR data show a large decrease in free fluid, an increase in bound fluid (Track 3, shown shaded yellow) and a decrease in NMR permeability (Track 2) from a depth of XN010 to XN070. It would be difficult, if not impossible, to identify these changes with standard porosity (Track 3, neutron porosity in blue and bulk density in red) and gamma ray logs (Track 1, solid green curve).

^Location of the Al Shaheen field operated by Maersk Oil Qatar AS in cooperation with Qatar Petroleum.
The borehole was expected to penetrate multiple carbonate facies with varying permeabilities and producibility characteristics. Maersk Oil hoped to gain significant reservoir information in real time from the proVISION tool, including differentiating various carbonate facies along the wellbore path and comparing LWD NMR log quality with that of selected intervals of wireline-conveyed NMR logs.

As expected, a high level of downhole shock and stick-slip occurred. ROP was variable, sometimes exceeding 500 ft/hr. Because of tool motion and fast ROP, NMR LWD data had a moderate degree of noise compared with a wireline-
conveyed NMR log. However, data stacking improved the S/N. Results from multiple MDT Modular Formation Dynamics Tester runs provided data to estimate fluid mobility and adjust the constants in NMR permeability equations.

Analysis based on NMR permeabilities, porosities, T2LM, bound-fluid volumes and free-fluid volumes discerned three distinct porosity systems. The team used changes in T2 character to map facies variation along the borehole (previous page). A low bound-fluid volume and a high ratio of free to bound fluid typify Facies 1 (above). Facies 2 has moderate bound-fluid volume and a lower bound- to free-fluid ratio. The average T2 of Facies 2 is shorter than that of

Facies 1 from LWD NMR. The LWD data shown indicate an interval of clean carbonate where the T2 (transverse relation time) distribution (Track 4) contains a significant percentage of late T2 values. The solid blue line is an empirically determined T2 cutoff that is used to partition the T2 distribution into a fast component representing bound fluids and a slow component indicating the free fluids. The red trace represents the T2LM distribution. The T2LM is generally well above the T2 cutoff value, indicating that most of the fluid in the pore space is free fluid. The total porosity computed from the NMR data, shown as a dashed black line in Track 3, is in agreement with the conventional limestone matrix neutron porosity in blue, and with the formation bulk density displayed in red. The yellow area represents the bound-fluid volume, while light green indicates the portion of the total porosity that is filled with free fluids, or the effective porosity. The longest T2 times indicate the largest pores, while the shortest are attributed to the smallest pore sizes. Large pores appear to make up a significant portion of the total porosity, with only a small percentage comprising small and very small pores.
Facies 1 and the complete data spectrum is shifted to shorter $T_2$ values. Facies 3 is typified by high bound-fluid volume and a low ratio of free to bound fluid. In Facies 3, the $T_2$ spectrum is shifted farther toward shorter values. Thin sections made from cuttings confirmed the facies significance of the LWD NMR $T_2$ response.

LWD NMR porosity agreed with density porosity in Facies 1 and 2 with an average 3 p.u. deficit in Facies 3 believed to be due to a percentage of faster-decaying $T_2$ signals. LWD NMR data indicate different $T_2$ decay rates for each of the three facies, allowing clear differentiation; this would not have been possible with neutron-porosity measurements alone (left).

To improve confidence that the LWD NMR data were identifying petrophysical changes in the carbonate facies, the team had to rule out the possibility that the interpreted $T_2$ response was being dominated by motion-induced $T_2$ decay. Measured lateral velocity data were used to confirm that the $T_2$ data were accurate and correctly indicating changes in the carbonate facies (next page, top left). This particular data set shows a large amount of $T_2$ data acquired even at elevated lateral velocities. The current proVISION design does not directly allow compensation for downhole tool motion in the $T_2$ decay measurement. However, highlighting intervals of increased tool motion can be used as a log-quality indicator.

To examine the effects of downhole tool motion on LWD NMR data, wireline CMR measurements acquired after drilling were compared with real-time proVISION data. Porosity, FFV, BFV, NMR permeabilities all compare favorably (next page, right). The CMR data were acquired over limited intervals for comparison, primarily in the proximal part of the well that had been open to invasion the longest. Some CMR logged intervals displayed a small decrease in $T_2$LM values consistent with the additional filtrate invasion time prior to wireline logging. None of the LWD NMR intervals indicated any identifiable motion-induced $T_2$ decay. The favorable comparison of the late $T_2$ components indicates that downhole lateral tool motion is not a dominant $T_2$ decay mechanism in this data set.

The proVISION system was configured to transmit porosity, $T_2$LM and FFV in real time to allow use of measurements for geological characterization and to aid geosteering. Although further evaluation will be required to completely understand the NMR $T_2$ response in carbonate rocks, the team working in the Al Shaheen field demonstrated that carefully interpreted LWD NMR data can be used to help detect variation in carbonate facies and their petrophysical characteristics.

Contrasting NMR data with resistivity images. An LWD resistivity image log is shown in Track 5. The image is scaled such that conductive formations are dark and more resistive formations are light with no absolute scale. The resistivity image shows a significant change in the formation resistivity while the porosity remains more or less constant, implying a possible textural change. The NMR log over the interval identified as Facies 2 indicates some large pores. The $T_2$LM is above the cutoff value, but with a broad distribution of pore sizes resulting in a significant percentage of the total porosity being occupied by bound fluid. The estimated permeability of Facies 2 is lower than that of Facies 1 (see figure, page 49). The NMR log over the interval identified as Facies 3 indicates few, if any, large pores. The $T_2$LM is below the cutoff value, and most of the total porosity is occupied by bound fluid. The estimated permeability of Facies 3 is lower than that of Facies 1 or 2.
The Next Generation

The proVISION system has demonstrated its ability to acquire real-time logs in both clastic and carbonate reservoirs, potentially identifying less obvious or otherwise undetected facies changes. Even for longer $T_2$ components in carbonate formations drilled at elevated ROP, the tool delivers sufficient data resolution for facies determination and for permeability and bound- to free-fluid volume calculations. The LWD proVISION tool provides essential real-time reservoir information and data useful for making geosteering decisions in complex reservoir settings.

Severe stick-slip and BHA shock are often associated with drilling long horizontal sections. Bottomhole shock, combined with high ROP, may increase noise in the data sets. However, field data demonstrate that the proVISION tool is sufficiently robust to handle these conditions and provide reliable $T_2$ data.

Future generations of NMR tools hold great promise. The industry can look forward to the continued evolution of LWD NMR technology, which is expected to provide drilling engineers and petrophysical teams with significant advancements in real-time formation evaluation for geosteering and productivity optimization.

—DW, SP

^ Lack of motion-induced decay. The data acquired in this field show no apparent reduction in $T_2$ values associated with the lateral velocity of the LWD NMR tool, implying that in this well, tool motion does not affect $T_2$ decay.

^ Agreement of wireline CMR and proVISION data. The wireline NMR porosity is seen to follow the same trend as the LWD NMR porosity with a small systematic shift to lower porosity (Track 1). This difference in total porosity is influenced by the differing depth of investigation of the tools and the difference in mud-filtrate invasion related to the formation exposure time. Computed bound-fluid volumes are in agreement (Track 1). The vertical, or spatial, resolution of the LWD NMR tool is reduced because of the high level of stacking utilized to increase the S/N. Likewise, the physics of measurement imposes a temporal, or time, resolution limit on the LWD tool relative to that seen with the wireline sensor. The overall effect is a smoothing of the $T_2$ distribution over time and depth. The $T_{2,LM}$ of the LWD NMR is shown overlaid on the CMR data (Track 2). Considering the difference in tool design, acquisition parameters, environmental conditions, and the time lapse between drilling and drillpipe-conveyed wireline logging, the comparison is excellent.