Logging While Drilling

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The engineering of well logging sensors into drill collars is stimulating a revolution in logging and drilling. It gives the driller more comprehensive real-time information, and gives the geologist a look at the formations while invasion is taking place.

This technology will affect logging hardware, interpretation methodology, ecnomics of drilling and logging, and the roles played by drillers, geologists, petrophysicists and log analysts. It is expected to afford savings for oil companies by increasing the efficiency and effectiveness of their drilling programs.

This article introduces the Prospector logging-while-drilling (LWD) system, which provides measurements of resistivity, neutron, density and spectral gamma ray from new tools built into special drill collars. It can be run simultaneously with Anadrill's measurements-while-drilling (MWD) systems and can access Anadrill's mud-pulse telemetry and the Advisor† surface system.*

We explain how the LWD system is engineered, how it integrates real-time drilling and logging information, and its complementarity with wireline measurements. The Prospector system is a rapidly evolving technology. This article appears as the system enters commercialization. Further developments will respond to industry demands and the perennial drive of research and engineering.

Real-time logging-while-drilling presents a typical engineering challenge: Take an existing technology—well logging—and adapt it to do the same job under much harsher conditions. A tough task on several counts.

Survivability: A wireline logging tool has to endure the occasional jolt when tripping in and out of the hole, but only intermittently while making its measurements. Logging-while-drilling tools have to give their best performance under the most adverse conditions of sudden, brief shocks: up to 1,000 g-milliseconds [g-ms][1] vertically, laterally and torsionally for the life of the bit run—maybe more than 100 hours. In one well, logging-while-drilling tools may work for as many hours as a wireline tool does in two years. They must survive and give good data even when the bottom-hole assembly is in resonance, that is, when it vibrates and bends like a drive shaft out of balance. Additionally, they must survive the erosive effects of mud laden with cuttings and sand.

Telemetry: A wireline tool communicates through a cable that easily conveys all the information. Life is more complicated for the LWD tool. Real-time data can only be sent by mud-pulse telemetry, which has a much lower bandwidth and bit rate than cable telemetry—about 3 bits per second for Anadrill's MWD-XL3† system[2], compared to 100 kilobits per second for wireline. This limits the real-time transmission capacity, so nonessential data are stored in a downhole memory that is read when the LWD tools reach the surface. The oil company therefore must decide, before logging, which data it needs in real time.

Sampling: The wireline engineer logs at the optimal sampling rate for the tool suite and borehole conditions—data are sampled incrementally versus depth every 1.2, 2 or 6 inches. Logging-while-drilling tools sample data at regular time intervals: the rate is set

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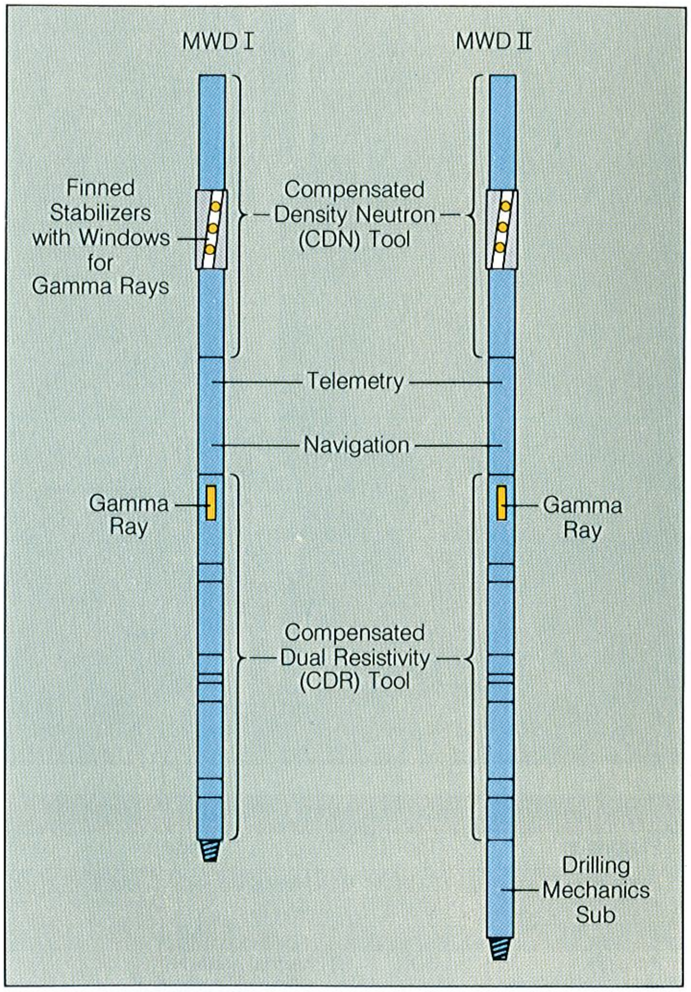
*Mark of Schlumberger
†Mark of Anadrill



□*Configurations for the bottomhole assembly including the Prospector LWD system, Anadrill's MWD XL-3 and second-generation MWD II systems. The tools are powered by the MWD mud turbine. Batteries are used for backup and for logging when the turbine is not operating, for example, during tripping. MWDII differs from MWDI in that it has a new drilling mechanics sub that measures bending moment, side force at bit, pressure differential across bit, and triaxial vibration; it also has a modular design, which permits more options in tool makeup. The first LWD Prospector system has 6½- and 8-inch collars. In its introductory form, it will consist of the Compensated Dual Resistivity (CDR*) tool with the MWDI system and the CDR and Compensated Density Neutron (CDN*) tools mated with MWDII.*

at the surface and can be changed only when the tools return to the surface. The sampling rate versus depth is the ratio of the time sampling interval and drill bit rate of penetration (ROP), or, in a wiper trip, of the speed the drill string is lowered or raised in the hole. LWD tools, therefore, need a way to accommodate changes in survey speed (see *page 12* for how LWD tools do this). Furthermore, real-time information sampling rate is limited by the mud telemetry.

Packaging: A wireline tool operates alone in the borehole, accommodating only to the borehole diameter, deviation and mud properties. Logging-while-drilling tools have to fit inside a drill collar, permit relatively uniform fluid flow, and be designed so that wear points can be quickly and cheaply replaced. They must be versatile enough to function in a variety of bottom-hole assemblies and make-up combinations.

To meet these challenges, Schlumberger assembled a team of engineers in Sugar Land, Texas from its Wireline and Anadrill divisions. In two years, they developed two new logging tools[3,4] that are combinable with Anadrill's MWD system[5,6] (*left*). In a single output, the drilling engineer and well site geologist can have all MWD data plus six new formation measurements from two new tools, the Compensated Dual Resistivity (CDR) and the Compensated Density

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1. Shock has two components: amplitude, the magnitude of acceleration measured in g's, and duration, measured in milliseconds (ms). A shock of 500 g's lasting 1 ms has the same magnitude as a shock of 250 g's lasting 2 ms. An acceleration of 500 g's is roughly achieved by dropping a tool from a height of several feet onto a hard surface.
2. For basics of mud-pulse telemetry:
   Desbrandes R: "Status Report: MWD Technology Part 2–Data Transmission," *Petroleum Engineer International* 60, no. 10 (October 1988): 48-54.
3. Clark B, Allen D, Best D, Bonner S, Jundt J, Lüling M and Ross M: "Electromagnetic Propagation Logging While Drilling: Theory and Experiment," paper SPE 18117, presented at the 63rd SPE Annual Technical Conference and Exhibition, Houston, October 2-5, 1988.

   Clark B, Lüling M, Jundt J, Ross M and Best D: "A Dual Depth Resistivity Measurement for FEWD," *Transactions of the Twenty-Ninth Annual SPWLA Symposium,*" San Antonio, Texas, June 5-8, 1988, paper A.
4. Evans M, Wraight P, Marienbach E, Rhein-Knudsen E and Best D: "Formation Porosity Measurement While Drilling," *Transactions of the Twenty-Ninth Annual SPWLA Symposium,*" San Antonio, Texas, June 5-8, 1988, paper C.
5. For details of Anadrill's second-generation MWD system:
   Westlake W and Boyle B: "MWDII Anadrill's Second Generation Measurement While Drilling Tool," *Drilling and Pumping Journal* 7 (December 1988): 23-28.

   Pidcock G and Daudey J: "Gulf Canada Improves Drilling With MWD Techniques," *Petroleum Engineer International* 60, no. 9 (September 1988): 16-24.

   For a description of Anadrill's MWDI system:
   Bates TR Jr and Martin CA: "Multisensor Measurements-While-Drilling Tool Improves Drilling Economics," *Oil & Gas Journal* 82, no. 12 (March 19, 1984): 119-137.
6. For an overview of MWD technology:
   Desbrandes R: "Status Report: MWD Technology Part 1–Data Acquisition and Downhole Recording and Processing," *Petroleum Engineer International* 60, no. 9 (September 1988): 27-33.

   Desbrandes R, reference 2.

   Desbrandes R: "Status Report: MWD Technology Part 3–Processing, Display, and Applications," *Petroleum Engineer International* 60, no. 11 (November 1988): 42-51.

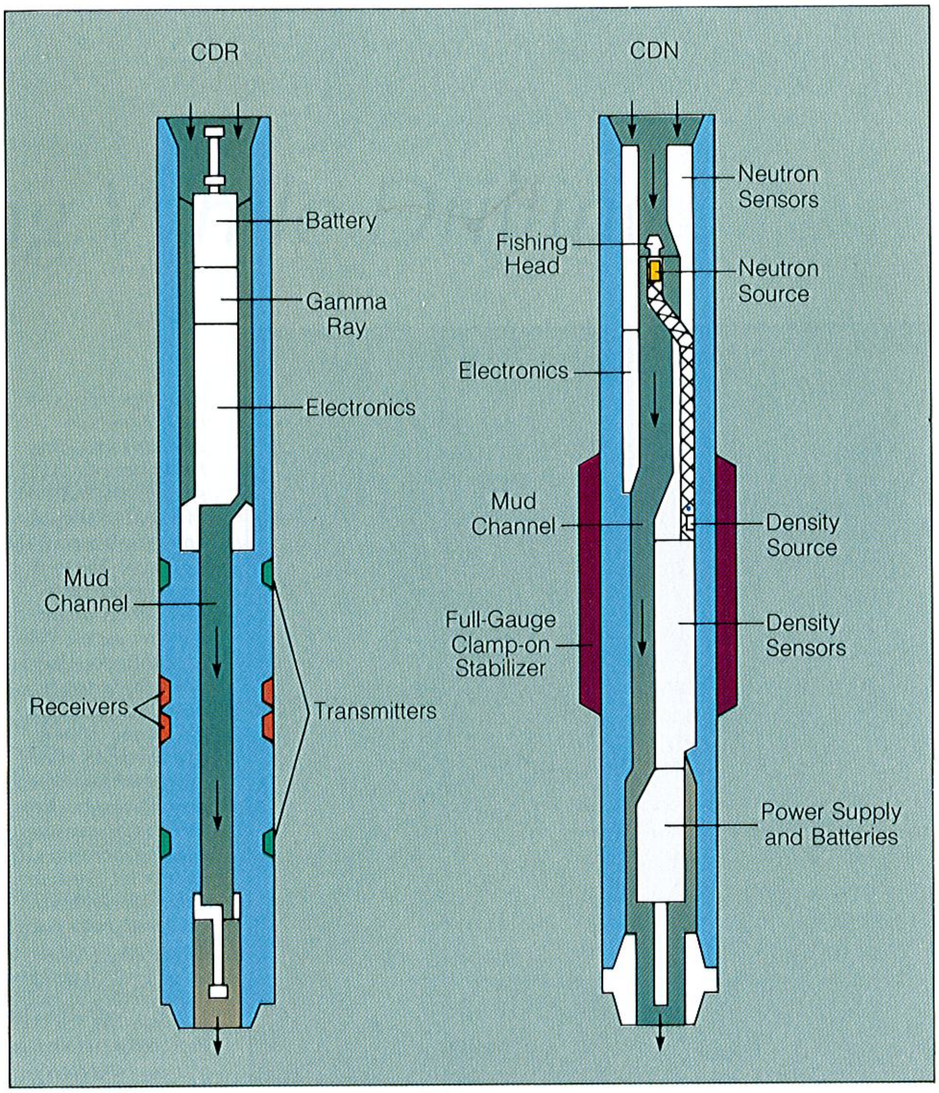
Neutron (CDN) tools (*right*). These data can be interpreted to provide a reliable lithology log[7], an estimate of formation pore pressure, and rock mechanical properties (see "Formation Parameters from the CDR and CDN Tools," *below right*).

Drilling data provided by the MWD system system include real-time downhole weight-on-bit (DWOB[†]), downhole torque at bit (DTOR[†]), borehole direction and inclination, tool face orientation, mud temperature and flow rate. Second-generation hardware, scheduled for release this year, includes a new drilling mechanics sub just above the bit that measures triaxial vibration. This tells whether the drill collars are in resonance, and gives the bending moment, side force at bit and pressure differential across the MWD hardware, including pressure drop across the bit.

The CDR tool, as its name implies, makes a borehole-compensated electromagnetic propagation measurement with two depths of investigation, 35 to 65 inches [89 to 165 cm], and 20 to 45 inches [51 to 114 cm], depending on true resistivity, R_t.[3] (See "LWD Tool Specifications and Uses," *page 9*; and "LWD Tool Physics," *page 8*.) The two depths of investigation are essential for deriving R_t in invaded formations. The measurement behaves similarly to an induction measurement—with the same limitations in salty muds—and given an optimal resistivity contrast and a slow ROP, it can detect beds as thin as 6 inches [15 cm] (*opposite, left*). The CDR tool also makes a spectral gamma ray measurement yielding relative proportions of thorium, uranium and potassium.

The CDN tool gives apparent epithermal neutron porosity, formation bulk density, and photoelectric factor, P_e.[4] This measurement is sensitive mainly to atomic number and helps distinguish lithologic changes from gas effect in hard rock formations. Vertical resolution of the compensated density measurement and neutron porosity is about 24 inches [61 cm], given an ROP of 50 feet [15 meters] per hour. The near-detector density measurement, used alone in good borehole conditions and a slow ROP, may detect 6-inch [15-cm] beds. The radioactive sources are safely contained within the collar and are connected to each other by a steel cable so they can be easily fished by slickline if the drill collars get stuck.

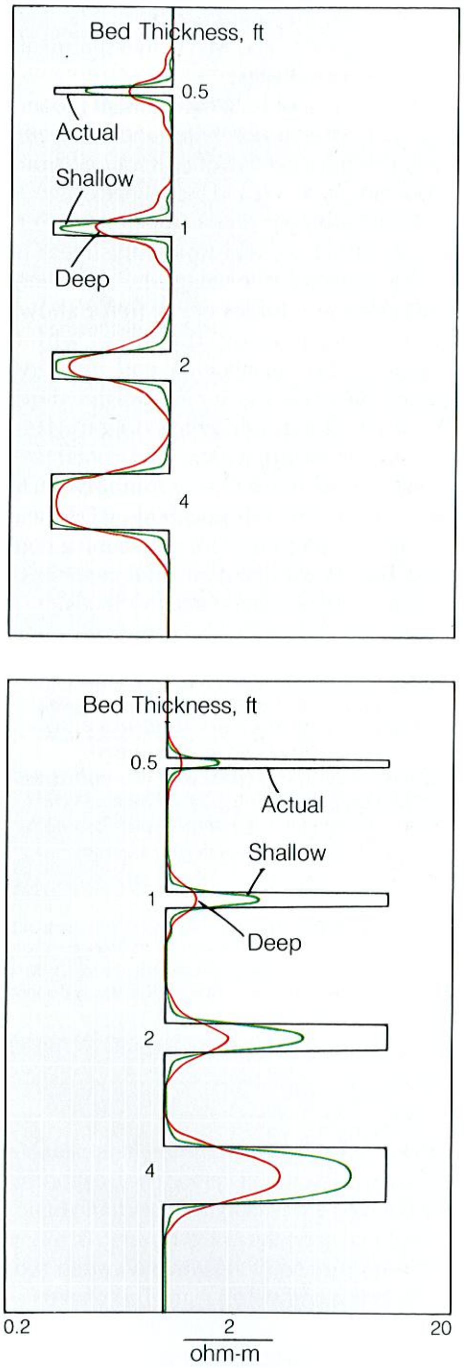
With this system, the CDN tool must be positioned on top to permit fishing of the nuclear sources. The makeup of the bottom-



□*CDR and CDN tools of the Prospector system. The CDR tool makes a compensated resistivity measurement with two depths of investigation. Compensation eliminates error caused by hole rugosity, and differences in receiver tuning enhances vertical response and log quality. Two depths of investigation allow calculation of true resistivity, detection of invasion and location of permeable zones and oil-water contacts. The CDR tool also makes a spectral gamma ray log similar to the Natural Gamma Spectrometry (NGS*) log. The CDN tool measures compensated density, neutron porosity and photoelectric factor,* P_e.

Formation Parameters from CDR and CDN tools

Parameter	Tool	Data
Correlation	CDR	Dual resistivities (R_{ps} and R_{ad}) Gamma ray (total API)
Porosity	CDN	Epithermal neutron Compensated spectral gamma-gamma density
R_t R_{xo} Thin beds Invasion Permeability index	CDR	Dual resistivities
Shale volume	CDR	Spectral gamma ray (total API and Th, U, K) Computed gamma ray
Lithology	CDN	Density-neutron crossplot P_e



☐*Theoretical modeling results of CDR response in thin conductive beds (top) and in thin resistive beds. Opposite conductive beds, resistivity is lowered so the vertical resolution is enhanced.* R_t *can be read in a 1-foot [30-cm] bed with the shallow phase shift measurement, and in a 4-foot [120-cm] bed with the deep attenuation measurement. Opposite resistive beds, vertical resolution is degraded and* R_t *cannot be read even in a 4-foot [120-cm] bed.*

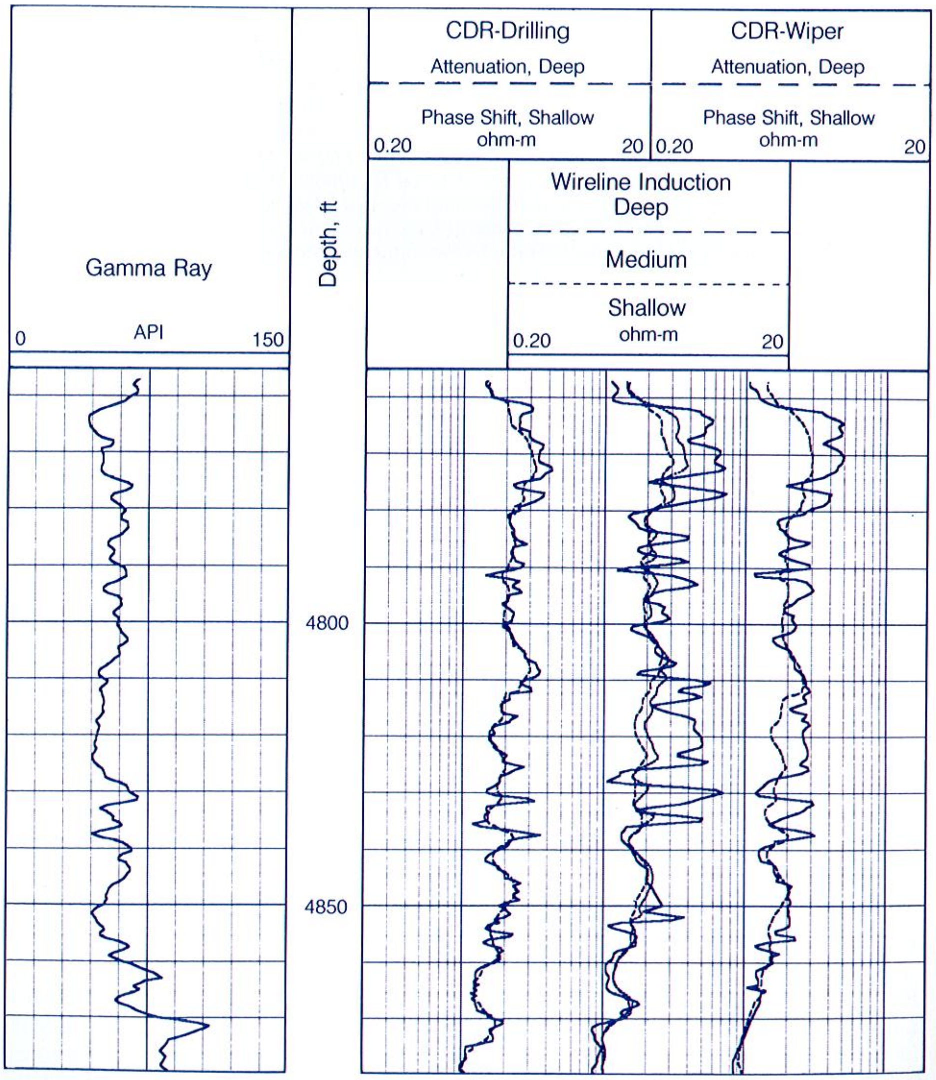
hole assembly dictates the lag between CDN and CDR data. The lag—the time between the bit passing the formation and the LWD sensors recording a measurement—may be several minutes to hours, depending on the rate of penetration. Invasion may already be deep after such delay. The two CDR resistivity measurements are therefore a must for a reliable estimate of formation resistivity.

The full consequences of logging while drilling are still to be realized, but the benefits of LWD come from real-time log measurements, from helping the drilling process and from helping formation evaluation.

Logging in Real Time

Benefits of real-time logging, whether data are telemetered through the mud or stored downhole, include:

- "Insurance" logging. Guaranteed data recovery, even if the well is lost or cannot be logged by wireline.
- Real-time location of casing and coring points. Saves drilling past the interval to be cased or cored, or tripping too early before setting casing. Also reduces guessing about potential bad hole conditions.
- Precise location of seismic reflectors during drilling. Reduces unnecessary drilling and enhances stratigraphic mapping and well-to-well correlation, which assists depth control and location of target depths.
- Early reconnaissance of potential pay, particularly gas zones.
- R_t determination while invasion is taking place—in effect, a dynamic R_t (*below*).
- Improved statistical accuracy of nuclear measurements when ROP is 50 feet [15 meters] per hour or less.



☐*Resistivity logs from a South Texas well, made with the CDR tool during drilling (track 1), about 1 week later with wireline (track 2), and with the CDR tool following borehole conditioning about 1 day after the wireline trip. Although drilling was fairly quick, the log made while drilling shows some invasion at, for example, 4770 feet. The sand around 4820 feet, however, does not invade during drilling but does later. Resistivity measured during drilling agrees well with deep measurements made later, both by wireline logs and by LWD during the wiper trip, and therefore is close to* R_t.

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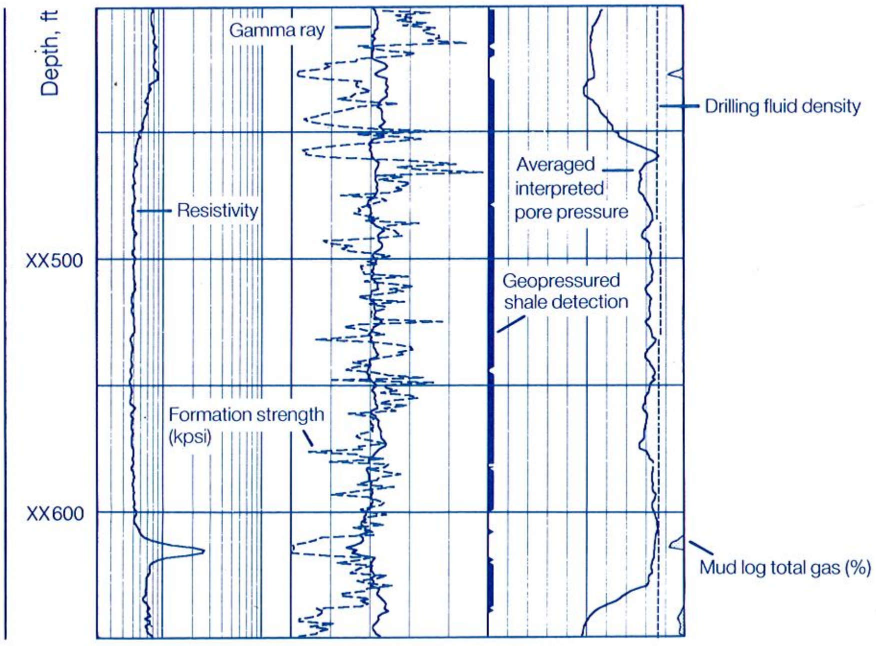
7. Principles and feasibility of computing lithology from MWD data and cuttings:
Tannenbaum E, Sutcliffe B and Franks A: "A Composite Lithology Log While Drilling," *AAPG Bulletin* 72 (February 1988): 253 (abstract).



*A real-time pore pressure log, **averaged interpreted pore pressure**, from offshore Louisiana, which allows the driller to safely use the lowest mud weight possible, thereby reducing the chance of sticking and formation damage. The pore pressure is calculated from excess effective porosity in overpressured shales using a compaction model. Inputs are formation strength (calculated from drilling parameters given in the Mechanical Efficiency Log [MEL†] service), CDN measurements and CDR gamma ray and resistivity (shale resistivity decreases with increasing pore pressure in some areas).*

This well was a sidetrack drilled after the original well kicked (at XX,330 feet) and the bottomhole assembly was lost. The original well was drilled with 13.2-lb/gal [1.58 g/cm³] mud when it kicked and required 16.5-lb/gal [1.98 g/cm³] mud for control. In this sidetrack, the driller increased mud weight slightly at XX,480 feet, in response to the pore pressure log. The large increase in pore pressure from XX,435 to XX,460 feet was interpreted as caused by penetration of a geopressured fault block. Geologists have suspected that geopressured shales act as lubricants for fault blocks and permit a greater degree of faulting than would be expected from tectonic stresses alone. Pore pressure logs confirmed this.

Helping the Drilling Process

Combining LWD and MWD measurements yields several benefits:

- Assessment of rock mechanical properties, hence better boreholes and more efficient drilling because of correct decisions about drilling speed and bit changes.
- Improved pore pressure estimates. Permits continuous, real-time adjustment of mud weight and identifying why and where mud gains and losses occur (*left*); allows minimizing mud overbalance, which improves rate of penetration, core recovery[8] and mud economics. At mud weights above about 12 pounds per gallon (lb/gal) [1.44 g/cm³], increasing weight by 1 lb/gal [0.1 g/cm³]can increase costs prohibitively. In wells drilled with oil-base muds, CDR measurements are essential for determining pore pressure, since short-normal resistivity devices work only in conductive muds.

continued on page 10

LWD Tool Physics

Compensated Dual Resistivity (CDR) tool

The CDR tool is an electromagnetic propagation tool built into a drill collar. It is designed for standard induction measurement applications in areas such as the US Gulf Coast and the North Sea. It has several similarities with the Dual Induction (DIL*) tool: 1) it responds to conductivity rather than resistivity; 2) it operates in water- and oil-base muds; 3) it provides two depths of investigation; and 4) it has shoulder bed effects. The CDR tool has a better vertical resolution but a shallower depth of investigation than the DIL tool.

The CDR tool broadcasts a 2-MHz electromagnetic wave and measures the phase shift and the attenuation of the wave between two receivers. These quantities are transformed into two independent resistivities that provide the two depths of investigation. The phase shift is transformed into a shallow resistivity (R_{ps}*, for resistivity from phase shift–shallow); the attenuation is transformed into a deep resistivity (R_{ad}*, for resistivity from attenuation–deep). In a 1-ohm-m formation, the 50-percent diameter of investigation is 30 inches [76 cm] for R_{ps} and 50 inches [127 cm] for R_{ad}. Two depths of investigation are essential when invasion occurs while drilling, a not uncommon occurrence. A tool with two depths of investigation can be used to locate permeable zones, and to provide a better measurement of the true formation resistivity (R_t) with and without invasion.

The CDR tool has upper and lower transmitters that are fired separately. The phase shifts and attenuations for the upward and downward propagating waves are averaged to provide a borehole compensated measurement, similar to that of the borehole compensated sonic tool. Borehole compensation reduces borehole effects in rugose holes, improves the vertical response, increases measurement accuracy, and provides log quality control.

The CDR tool can detect 6-inch [15-cm] beds. However, R_{ps} and R_{ad} may read too low in a thin, resistive bed with conductive shoulder beds. A relatively small bed thickness correction is required to obtain R_t in this case. A major advantage of the CDR tool is its ability to measure R_t in thin beds before invasion occurs. Once thin beds have been invaded, there is no known method for obtaining R_t.

Compensated Density Neutron (CDN) tool

The physics of measurements made by the CDN tool is very similar to that of the corresponding wireline services. For the neutron porosity measurement, fast neutrons are emitted from a 7.5-curie americium-beryllium source. The rate at which the neutrons slow

LWD Tool Specifications and Uses

CDN TOOL

Measurement	Range	Accuracy	Statistical Repeatability	Log Vertical Resolution
Compensated epithermal neutron porosity	0 to 100 limestone p.u.	Depends on lithology & porosity	In 30-p.u. formation: 1 p.u. @ 50 ft/hr [15 meters/hr]; 2 p.u. @ 200 ft/hr [60 meters/hr]	24" [61 cm]
Formation bulk density from compensated spectral gamma-gamma density	1 to 3.5 g/cm^3	±0.02 g/cm^3 over 2 to 2.7 g/cm^3 in good borehole	± 0.01 g/cm^3 @ 50 ft/hr [15 meters/hr] @ 2.4 g/cm^3 density	24" [61 cm]
Photoelectric factor (P_e)	1.3 to 5.1 units	± 0.2	±0.1 at 50 ft/hr [15 meters/hr] in limestone	24" [61 cm]

CDR TOOL

Measurement	Range	Accuracy	Statistical Repeatability	Log Vertical Resolution
Deep resistivity (35" to 65" [89 to 165 cm] depending on R_t)	0.2 to 50 ohm-m	2 millisiemens/meter	Does not apply	Qualitatively 6" [15 cm]; quantitatively, depends on R_t and shoulder bed resistivities.
Shallow resistivity (20" to 45" [51 to 114 cm] depending on R_t)	0.2 to 200 ohm-m	0.5 millisiemens/meter	Does not apply	Qualitatively 6" [15 cm]; quantitatively, depends on R_t and shoulder bed resistivities.
Natural gamma ray scintillation spectroscopy [Th, U, K]	0 to 250 API	Not determined	± 1.3 API @ 50 ft/hr [15 meters/hr] @ 100 API mean value and a 24" [61-cm] depth average.	24" [61 cm]; 8" [20 cm] by averaging data less and accepting higher statistical variation.

Six-and-a-half-inch LWD tools can accommodate mud flow of 12 barrels/min [1,900 liters/min]; 8-inch tools can accommodate 24 barrels/min [3,800 liters/min]. Temperature limits are 300°F [149°C] for circulating fluid, 320°F [160°C] for static fluid. The limit of borehole curvature is 4½ degrees/100 feet [30 meters]. The CDN and CDR batteries last about 200 hours in stand-alone downhole recording mode.

down to thermal and epithermal energies is related primarily to the quantity of hydrogen in the formation in the form of water- or oil-filled porosity. Neutrons and capture gamma rays are detected in near- and far-spacing detectors so that ratio processing can be used for borehole compensation. The energy of the detected neutrons is predominantly epithermal because a high percentage of the incoming thermal neutron flux is absorbed as it passes through the 1-inch [25-mm] steel wall of the drill collar. Also, a wrap of cadmium under the detector banks shields them from thermal neutrons arriving from the inner mud channel. This mainly epithermal detection practically eliminates adverse effects caused by thermal absorbers in the borehole or formation.

The tool has three banks of near and far ^{3}helium detectors and one bank of Geiger-Mueller detectors, since the emphasis is on the measurement of neutrons directly, not on capture gamma rays. The ability to detect capture gamma rays is retained to take advantage of the high salinity sensitivity of the measurement to provide information on formation salinity.

The density section of the tool uses a 1.7-curie ^{137}cesium gamma ray source in conjunction with two gain-stabilized scintillation detectors to provide a high-quality, borehole compensated density measurement, and a measurement of the photoelectric factor, P_e, for lithology identification. Physically, the measurement is of gamma ray attenuation, which takes place mainly by Compton scattering. The received gamma ray flux is inversely proportional to the electron density index, ρ_e, of the formation. Electron density relates to bulk density, ρ_b, by:

$$\rho_e = 2\left(\frac{Z}{A}\right)\rho_b ,$$

in which Z/A is the average value of the ratio of the atomic number to the atomic weight of the formation.

Three mechanical features of the density measurement are noteworthy: 1) the inner mud channel is eccentered to permit substantial shielding of the detectors, essentially eliminating direct gamma ray leakage inside the tool between the source and detectors; 2) mud standoff between the exterior of the drill collar and the borehole wall is practically eliminated in good boreholes through use of a full-gauge clamp-on stabilizer, with three full-coverage helical blades; 3) one blade is modified to include three small rubber-filled holes to minimize attenuation of gamma rays as they pass from the source, into the formation and to the detectors. These "windows" permit measurement of P_e.

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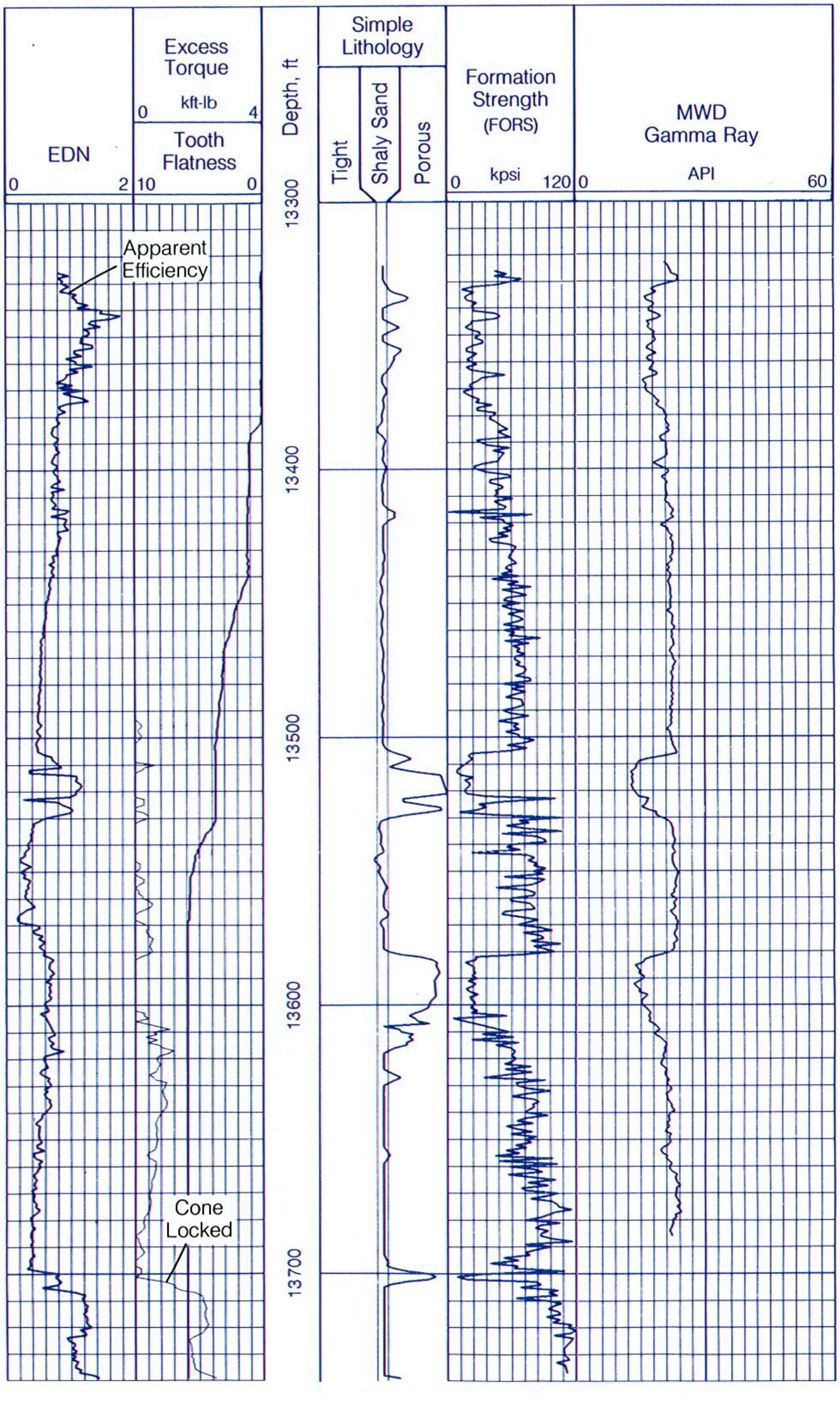
[8] Bradburn FR and Cheatham CA: "Improved Core Recovery in Laminated Sand and Shale Sequences," *Journal of Petroleum Technology* 40 (1988): 1544-1546.

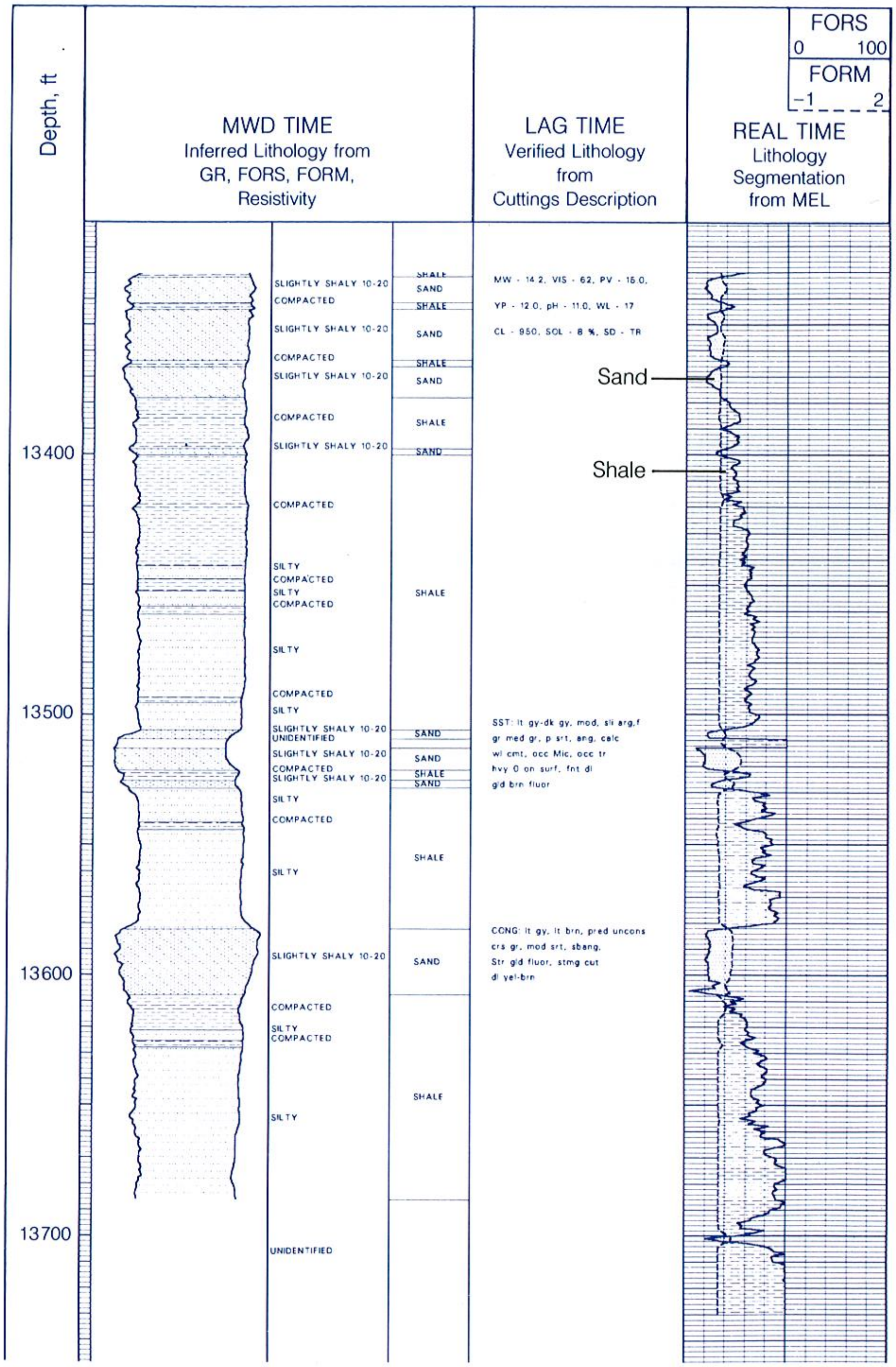
- Better assessment of gas shows.
- LWD lithology indicators help improve Mechanical Efficiency Log (MEL) data that indicate drilling incidents such as losing a bit cone (*left*). They also help improve Sticking Pipe Indicator (SPIN†) data that indicate when the bottomhole assembly is about to stick—the LWD measurements may identify where and why.[9]
- Helps assess borehole stability, enhances mud engineering and bit selection; helps determine optimal pump rate and selection of casing points.
- Lithology identification. Aids well-to-well correlation and identification of facies boundaries.
- Integration of mud log, cuttings and CDR and CDN data on a single data base and log presentation (*right*).



☐*Anadrill's Mechanical Efficiency (MEL) log, which is not presented directly in the LWD output but is used in computation of pore pressure and composite lithology (see log at right). This example is from the Beaufort Sea, Alaska. The MEL log provides real-time information about bit wear in shale-type formations, and indicates abnormal torque losses below MWD hardware due to, for example, cone locking or stabilizer gouging; it also gives lithologic information based on the formation's shear-compressive strength ratio. The MEL service yields this information based on measurements of penetration rate, torque, weight-on-bit and rotary speed.*

From left, ***apparent efficiency*** *(**EDN** in header) is normalized efficiency downhole, in which 1 is the efficiency of a new bit in shale, normalized for changes in downhole weight on bit.* ***Excess torque*** *shows when torque goes above or below the level expected for a given weight-on-bit in shale. Increases indicate possible stabilizer gouging or cone locking; steady decreases show bit wear, and sharp drops indicate a low porosity, tight formation or "bit balling" in which clay clogs the bit.* ***Tooth flatness*** *indicates bit wear. Bit teeth are measured in 1/8-tooth-height increments, so a tooth flatness of 1 means 1/8 of tooth height is gone. A flatness of 8 means teeth are worn away completely.*

Skipping one column, ***formation strength*** *is based on normalized rate of penetration. In the US Gulf Coast, for which the formation strength model was developed, strength decreases with increasing clay, porosity and geopressure. Porous rock has lowest strength, then wet clays and silty shales; low porosity, clean rocks have highest strength. Formation strength is used like a tool input in a pore pressure log, taken in terms of clay volume, porosity and pressure.* ***Simple lithology*** *indicates porous or tight formation based on formation strength and apparent drilling efficiency (acquired once per foot) minus efficiency averaged over 5 to 6 feet [150 to 180 cm]. The curve deflects toward "porous" when there is excess torque and formation strength is low. It moves toward "tight" when torque is low and rock strength is high.*



□*The composite lithology component of the LWD output. The left column is framed on the left by the gamma ray and on the right by a shallow resistivity log. The cuttings description has a lag time depending on well depth, hole diameter and pump rate. The right track shows logs of apparent formation strength* (FORS) *and drilling efficiency* (FORM). FORS *is*

$$\text{FORS} = \frac{\text{WOB RPM } 40\ A_1\ E_d}{\text{ROP BDIAM}}$$

in which WOB *is weight-on-bit,* RPM *is revolutions per minute,* A_1 *is gouging component of bit torque (from a crossplot),* E_d *is efficiency of bit based on tooth wear and* WOB, ROP *is rate of penetration and* BDIAM *is bit diameter.*

FORM *is related to the ratio of drilling efficiency (torque divided by weight-on-bit) to the drilling efficiency in shale. These efficiencies are a function of a rock's shear-to-compressive strength ratio. In shaly sands,* FORM *will read 0, in porous and permeable formations greater than 0 (usually greater than 1) and in tight formations less than 0. Because* FORM *anticorrelates with* FORS, *plotting the two on one track provides a quick-look sand/shale discriminator. LWD measurements of neutron porosity, bulk density and* P_e *allow discrimination of complex lithologies and an estimation of porosity.*

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9. For details on SPIN and MEL data:
Reference 5, Pidcock and Daudey.

Burgess TM and Lesso Jr WG: "Measuring the Wear of Milled Tooth Bits Using MWD Torque and Weight-on-Bit," Paper SPE/IADC 13475, *Proceedings of the 1985 IADC/SPE Drilling Conference*, New Orleans, March 5-8: 453-462.

Falconer IG, Burgess TM and Sheppard MC: "Separating Bit and Lithology Effects from Drilling Mechanics Data," paper SPE/IADC 17191, Proceedings of the *1988 IADC/SPE Drilling Conference*, Dallas, February 28-March 2, 1988.

Lesage M, Falconer IG and Wick CJ: "Evaluating Drilling Practice in Deviated Wells with Torque and Weight Data," paper SPE/IADC 16114, *Proceedings of the IADC/SPE 1987 Drilling Conference*, New Orleans, March 15-18: 555-566; *SPE Drilling Engineering* 3 (September 1988): 248-252.

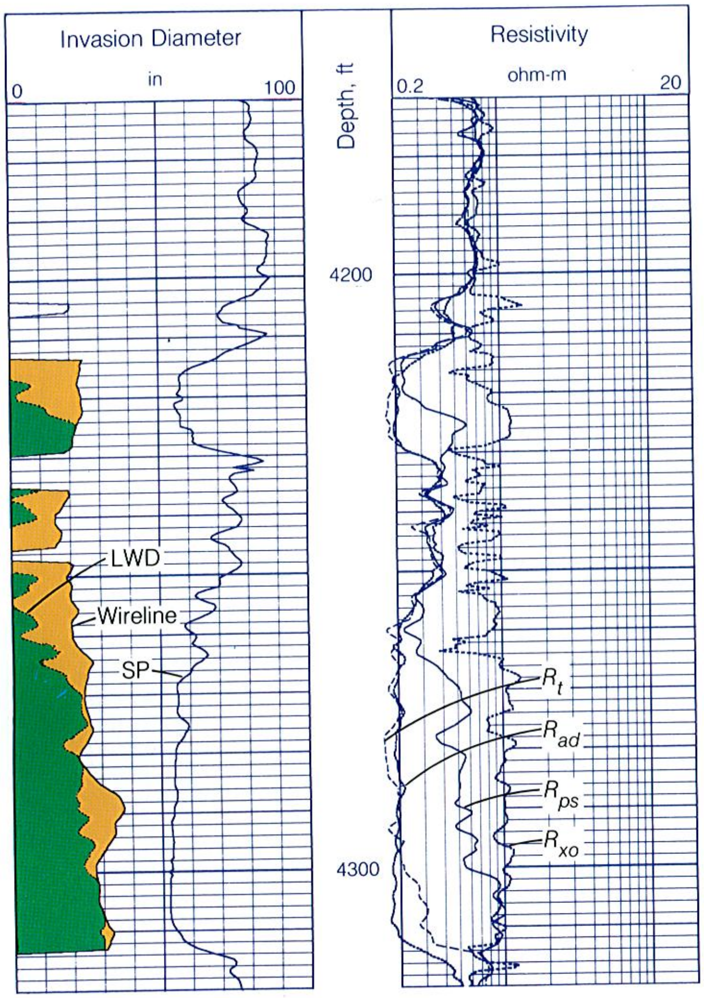
Helping Formation Evaluation

- "Transient" logging. Comparing multiple passes over time from LWD and wireline logs can show changes in resistivity that indicate how invasion evolves with time (*right; page 7, lower right*). Various rates of invasion may be tied to grain size variation (*far right; below*).
- Reduces the cost of making the go/no-go decision on setting casing and sidewall coring and in choosing offset direction and depth.
- Evaluation of LWD measurements leads to optimizing the design of wireline logging programs to more fully characterize potential pay zones.
- Evolution of shale hydration as seen on density time-lapse logs.

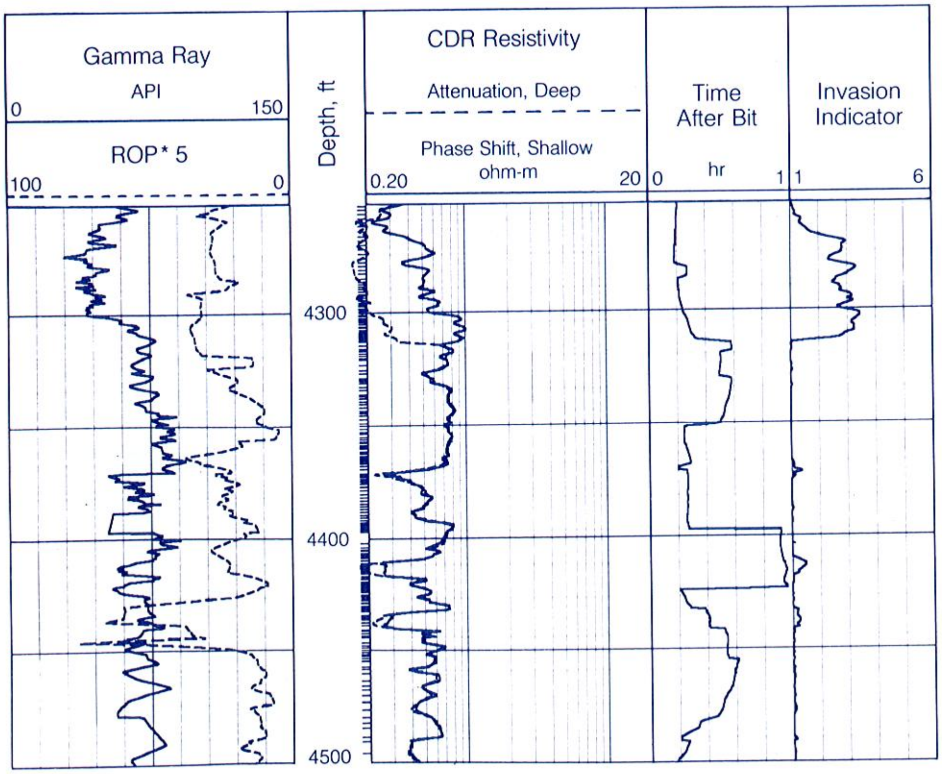
LWD Experience to Date

Despite the difficulties of logging while drilling, field tests to date show that LWD tools have an average "efficiency" of 95 percent for delivery of data for CDR and CDN measurements (efficiency is the ratio of footage logged to footage drilled).

A chief concern in tool design is survivability. This begins with the backbone of the hardware, the drill collars. They must not only endure the vibration modes encountered in drilling but also resist stress corrosion cracking that induces collar failure. Because the inner diameter of the collar is



☐ *Resistivity logged while drilling with the CDR tool and with the wireline Dual Induction tool shows relative differences in sand permeabilities that are masked by invasion by wireline time. From the bottom of track 1 to 4270 feet, the invasion diameters from wireline logging and logging-while-drilling (LWD) are about the same, indicating that all the invasion that took place did so nearly immediately. Interpreters consider this rapid invasion as indicating high permeability. Above 4270 feet, wireline and LWD invasions are very different (except at 4224 to 4230 feet).*

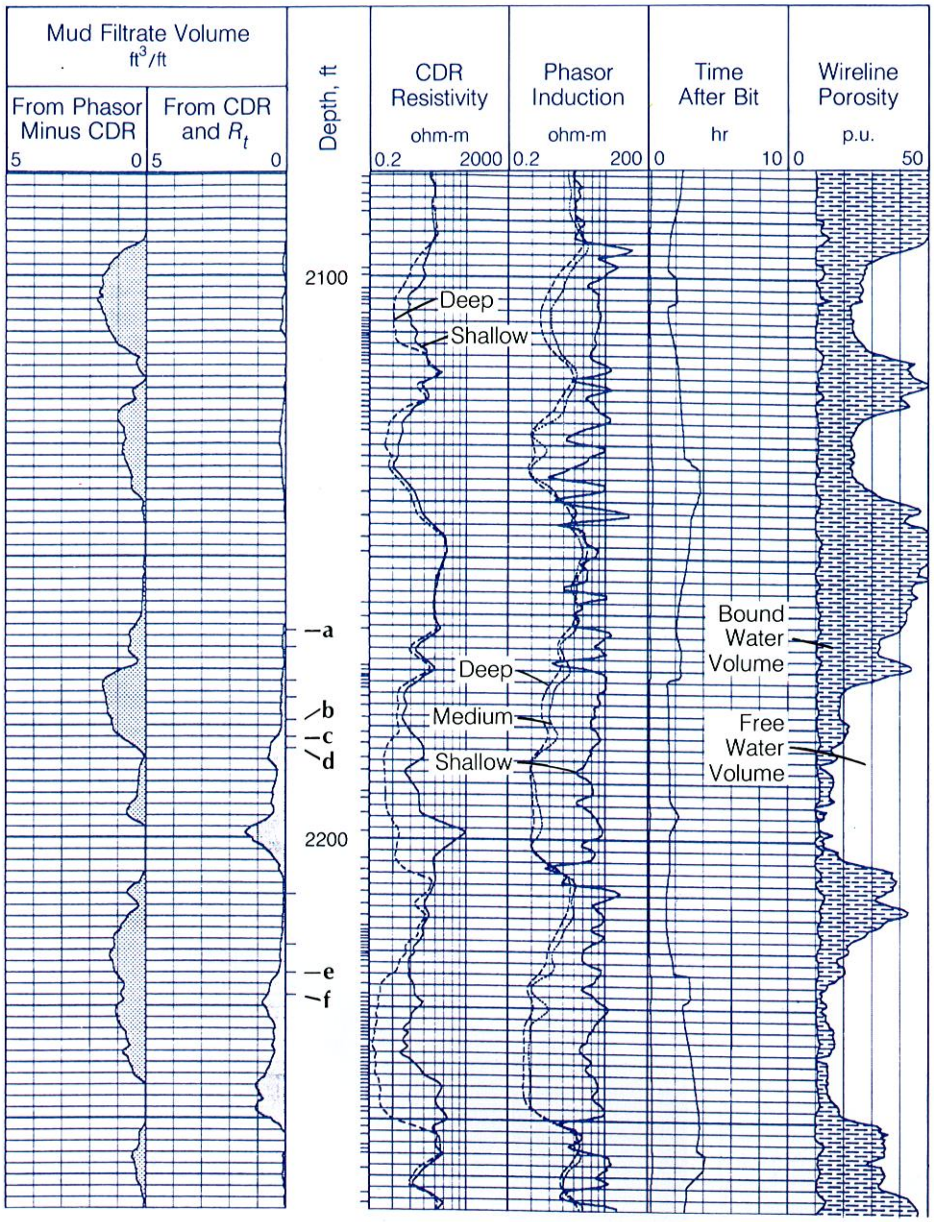


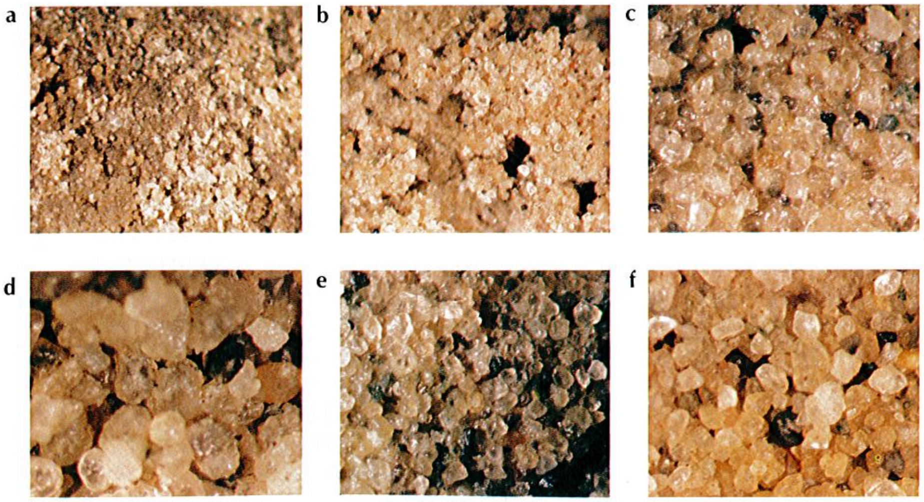
☐ *This log shows the same principles of invasion as the log to the right but includes two other parameters of interest to drillers: rate of penetration averaged over the last 5 feet [150 cm] (**ROP*5**) and **time after bit.***

Pips, or tick marks, along the depth track indicate where a data sample was taken. Since the sample rate is fixed, the slower the ROP, the closer the pips and the higher the log resolution; the faster the ROP, the farther apart the pips and the lower the log resolution. Pips are an indicator of log quality.

*In this well, rapid rate of penetration (greater than 1,000 feet/hr [305 meters/hr]) produces flat spots in the gamma ray curve, indicating that the tool is moving too fast for precise sampling. In the **time after bit** curve, step-like features (such as at 4400 feet) indicate a halt in ROP, because the driller paused to circulate or to install a new stand of pipe. The step at 4425 feet indicates the tools were about 60 minutes behind the bit, probably when the driller stopped to circulate.*

Coupling resistivity and drilling data can tell something of the formation's permeability. At 4410 feet, for example, the sand shows little invasion on the invasion indicator curve, even though the CDR tool reached it almost an hour after the drill bit. Likewise, a small degree of invasion is indicated at 4375 feet, although the CDR tool was only about 12 minutes behind the bit. The zone at 4375 feet is possibly more permeable than that at 4410 feet. Even more permeable perhaps than either of these zones is that around 4300 feet, which shows a large invasion indication. The CDR tool was about 10 minutes behind the drill bit in places.





☐*Relationship between grain size and various formation evaluation parameters, computed from CDR and wireline data for a US Gulf Coast well. Core sample photographs are all at the same magnification. (The photos are of cores taken from depths marked by lettered pips on the right margin of the second track.)*

The left-most log of ***mud filtrate volume*** *is the difference in filtrate volume calculated from the Phasor* Induction and the CDR measurements. (The CDR measurement was 5 to 15 minutes behind the bit; the Phasor Induction measurement was 4 days later.) The log second from left is computed from the ratio of the deep attenuation and shallow phase shift CDR measurements and* R_t *from the deep induction (for shallow to moderate invasion, the diameter of invasion is proportional to the ratio of the deep attenuation and shallow phase shift resistivities at a given* R_t*). The* ***time after bit*** *track shows how long the formation was open before it was logged by the CDR tool. The left margin of the* ***wireline porosity*** *log is total porosity from the wireline sonic log; the right margin is effective porosity (volume of total porosity minus bound water volume).*

Volume of invasion and porosity increases dramatically with grain size. Likewise, separation of deep attenuation and shallow phase shift CDR measurements tends to increase with grain size and invasion and decrease with bound water volume. Even though it was recorded within minutes of drilling, the shallow phase shift CDR measurement is not close to R_t*—reading almost as high as the Spherically Focused (SFL*) log in places. The deep attenuation CDR measurement is closer. The wireline induction log indicates deeper invasion in some places (2240 to 2250 feet). But at 2210 to 2220 feet, the CDR log shows little initial invasion, and the induction log indicates most invasion took place later. Early time invasion from CDR measurements appears to have potential as an indicator of formation permeability.*

reamed to accommodate logging components, extra strong collar material is used.

Testing during development of the LWD system showed that nearly all failures were of electrical connections, induced by large mechanical shocks. As a consequence, new mounting and packaging techniques were developed and extensively qualified in house.

To ensure that each tool meets specifications, it undergoes a series of torture tests that simulate downhole conditions: temperatures up to 300°F [149°C], spinning in resonance for several days, and three kinds of shocks up to 1,000 g-ms: axial, torsional and lateral. Axial shock occurs when the bit bounces. Torsional shock is caused by variation in rotational speed when the downhole assembly grabs or chatters. Transverse shock is perpendicular to the drill collar and occurs each time the drill string bangs against the borehole wall. In one test well, the system functioned during 300 transverse shocks per second above 200 g's.

During an early field test, the CDR tool was subjected to seven days of continuous axial shock during a fishing job with hydraulic jars. The forces of the fishing job were modeled to be at least 550 g's. The tool emerged intact and functional.

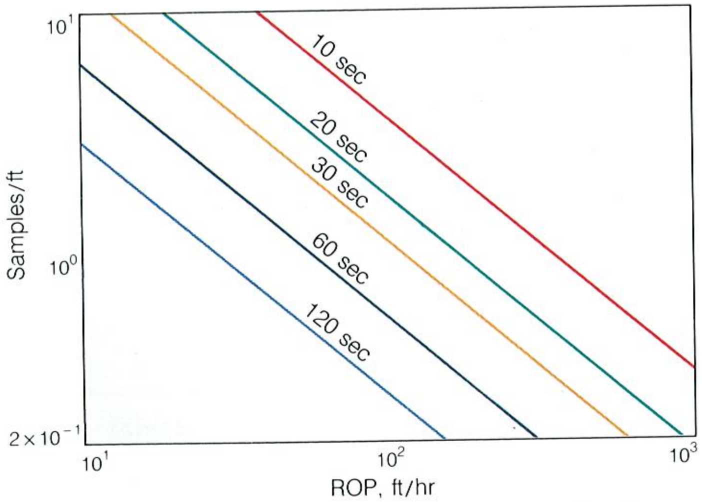
Another challenge was accommodating high mud flow rates while resisting erosion by heavy sand content. The tools have been designed for, and comprehensively tested in, flow conditions harsher than typically encountered in the field. Flow channels have been streamlined to ease flow and minimize resistance.

Perhaps the most distinctive feature of the LWD system is that users decide which data to transmit uphole in real time. All raw data are stored downhole for retrieval and refined analysis when the tools reach the surface.

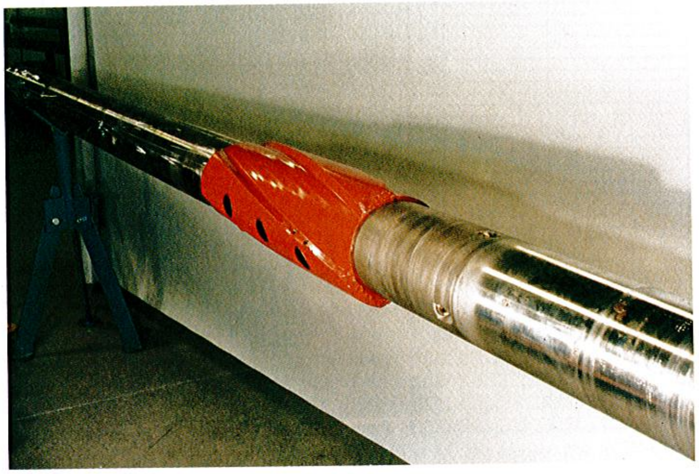
A chief advantage of real-time telemetry is that it gives instant access to data that affect drilling decisions. However, a limited number of measurements can be conveyed due to data rate constraints.

The main advantage of putting data in memory is that it permits a much higher sample rate. However, because the sample rate for each interval is fixed at the surface before each run in the well, the rate should be optimized for the measurements and the expected ROP (*below left*). The optimal rate is set by knowing the approximate depth and thickness of formations of interest, and estimating how long the drill bit will take to reach and traverse them. With these inputs, the logging engineer can program the tool sample rates at the surface for specific drilling interval, so the rates will automatically change downhole at the appropriate depths.

An initial concern with the compensated density measurement was that poor contact with the borehole wall would mean poor quality logs. This was overcome by imbedding the detectors in stabilizer fins, which reduce standoff and wipe mudcake away to reduce borehole effect (*below*). Field tests indicate that the tool can tolerate standoff up to 1/2 inch [1.3 cm]. Washouts of 1 inch [2.5 cm] diameter or more will result in undercorrected measurements, the degree



☐*Relationship between LWD tool sampling rate and rate of penetration (ROP) of the drill bit. By obtaining an estimated ROP from the driller, the logging engineer can determine the appropriate tool sampling rate to optimize sample density. In the US Gulf coast, a bit run averages 40 hours, with a typical penetration rate of 10 feet/hr [3 meters/hr].*

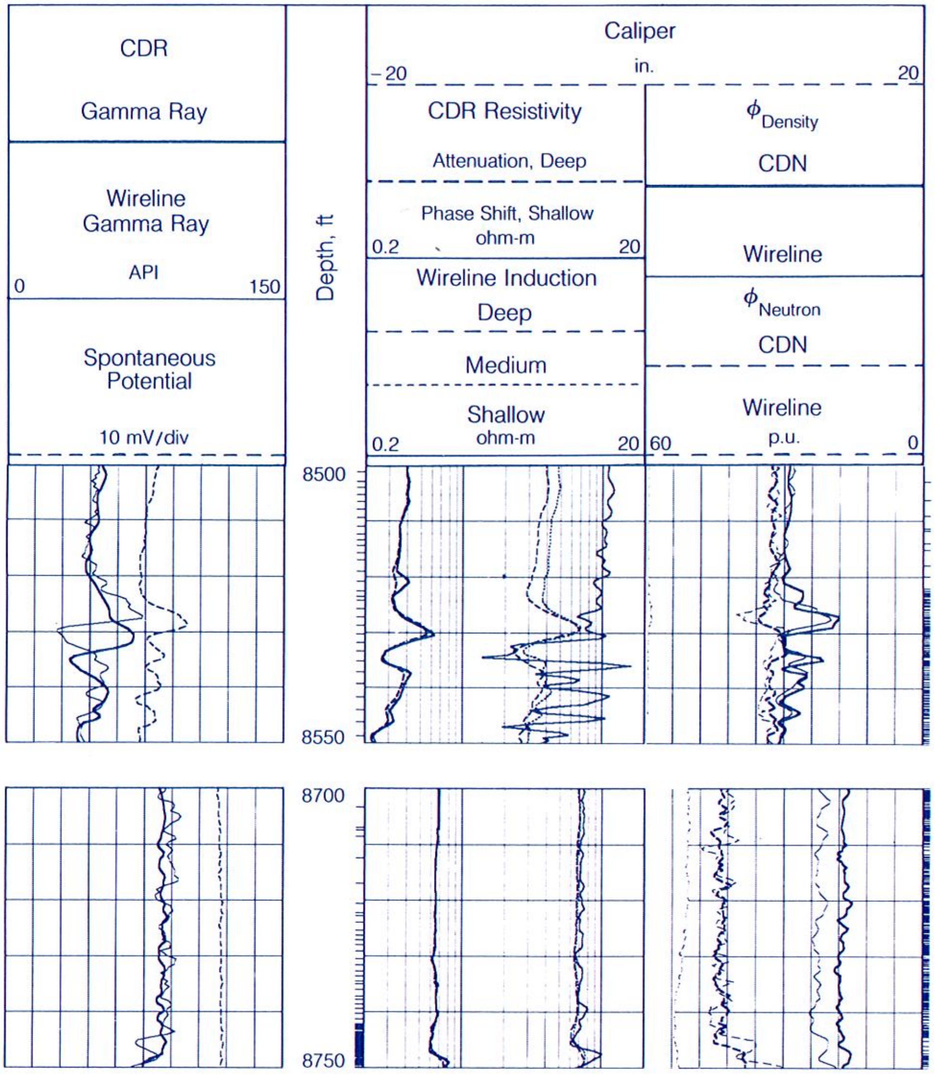


☐*CDN tool showing the full-gauge clamp-on stabilizer with rubber plugs covering windows for the gamma ray measurements.*

of undercorrection depending on mud weight. Most CDN logs compare well with wireline logs made in good borehole conditions (*right*).

A chief advantage of CDR measurements is that they can be handled much like induction measurements. Similar charts are used to correct for shoulder and thin-bed effects.[10] As with the nuclear measurement, comparison of the compensated and uncompensated measurements can be used as a log quality check.

MWD companies have offered various measurements and interpretations to infer pore pressure changes near the bit in real time. None of these worked all the time, usually due to changing parameters downhole. Anadrill's pore pressure program uses resistivity, gamma ray, lithology from density-neutron, downhole weight-on-bit, and downhole torque to perform a volumetric analysis of the formations penetrated. The outputs of the program are effective porosity (hydrocarbon and free water), overpressure porosity (volume of shale water causing overpressure), clay volume (bound water and dry clay), and matrix volumes. By simultaneous solutions of four equations, the program solves for these unknowns and converts overpressure porosity to pore pressure using a conventional compaction porosity-effective stress model. This pore pressure and other data are presented in log format. The program is designed for undercompacted, overpressured shales, where abnormal pressure is associated with excess porosity. Techniques for analyzing areas with more complex pressure mechanisms, such as the North Sea, are being studied.



□*Comparison of LWD and wireline density logs, made about 1 week apart. From 8500 to 8550 feet the CDN and wireline densities track close together, and the wireline caliper indicates the hole is near bit size. The pips indicate fairly rapid ROP. The CDR log shows almost no invasion at LWD time, whereas invasion is deep by wireline induction time. Farther down the well, at 8700 to 8740 feet, the pips show ROP slowing with depth. Both CDR and wireline resistivities show no invasion. The wireline and CDN densities separate by 4 to 6 porosity units (p.u.). This is interpreted as due to swelling and sloughing of shales by wireline time.*

How Do Wireline & LWD Data Compare?

Field tests show the complementarity of the two techniques. LWD logs can provide essential information on the formation crossed by the drill bit. They cannot provide the accuracy and high resolution of wireline measurements. Their value, in addition to helping the drilling process, is particularly important in exploration where it is necessary to ensure a minimum amount of data as soon as the bit has been given access to the formation. This is also true in highly deviated and horizontal wells. In late development wells, LWD logs may replace some intermediate logs for correlation purposes.

Wireline measurements complement LWD measurements several ways:

- Wireline measurements provide a high resolution description of the formation. They are used to quantify rock and fluid volumes and to establish a detailed description of the reservoir's static and dynamic properties. These measurements include Phasor Induction, Dual Laterolog (DLL*), high-resolution Litho-Density* and Compensated Neutron Log (CNL*) tools, Formation MicroScanner* images, dipmeter surveys, sonic logs, and pressure testing and fluid sampling with the Repeat Formation Tester (RFT*) tool.
- Resistivity measurements where invasion is quick and deep are beyond the range of the CDR tool, but still within range of wire-

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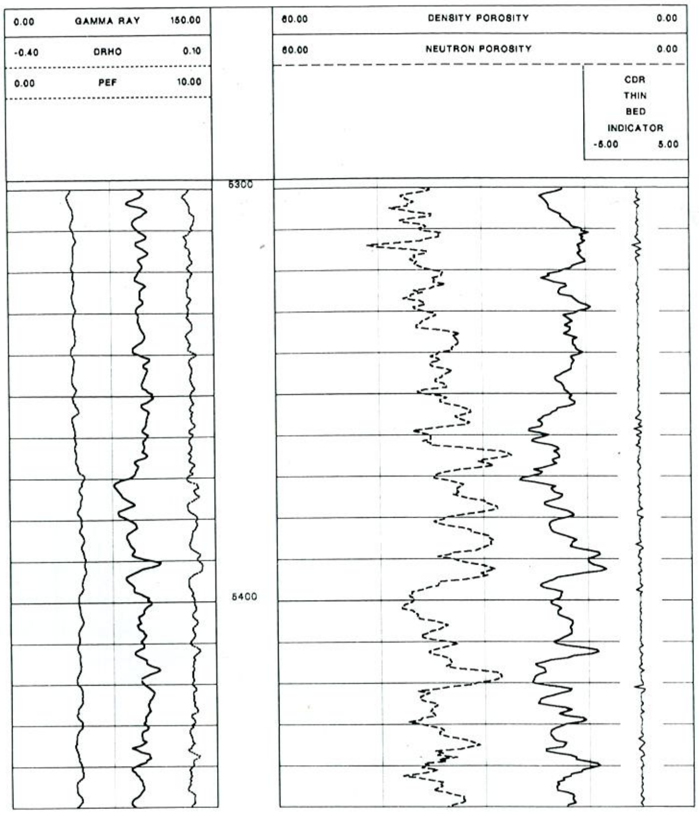
[10] *Schlumberger Log Interpretation Charts.* Houston: Schlumberger Educational Services, 1989. See charts **Rcor-11**, **Rcor-12**, **Rcor-13**, pages 109-111.

line induction and laterolog tools, which investigate up to 120 inches [3 meters] and are enhanced with an invaded resistivity, R_{xo}, log.

- Wireline measurements can complete a formation description begun with LWD techniques (*left*). For instance, in thinly bedded formations, the Electromagnetic Propagation (EPT) and the Formation Micro-Scanner tools can complete the description of the formation.
- Resistivity of rocks of 50 to more than 1,000 ohm-m can be measured only with wireline tools, which have a wider dynamic range than the CDR tool. The CDR tool is designed primarily for sand-shale environments, with moderate formation/mud resistivity contrasts. The range of the shallow phase shift measurement is 0.2 to 200 ohm-m, and of the deep attenuation 0.2 ohm-m to 50 ohm-m.
- Wireline logging runs usually include a mechanical caliper, which is used for estimating cement volume—best determined at wireline time, immediately before casing is set. Wireline calipers are also important for log correction and log quality. Wireline runs also routinely include a spontaneous potential log, crucial for estimating water resistivity (R_w) and identifying sands.

Likewise, LWD measurements complement wireline measurements:

- The chief value of resistivity measurements made while drilling is that they give early-time resistivity measurements for transient invasion determination.
- By wireline time, deep invasion some-



☐ *Experimental thin-bed indicators from the CDR tool. Indicators like this can flag intervals where high-resolution wireline logs, such provided by the Electromagnetic Propagation (EPT*) and Formation MicroScanner tools, are needed to provide more detailed formation evaluation. The CDR thin-bed indicator makes use of the tool's two receivers and two transmitters. When the upper and lower receivers straddle a bed, the up and down signals will be asymmetric because of a resistivity variation across the bed boundary. This thin-bed curve indicates the difference between the upper and lower measurements. Each wiggle indicates a change in resistivity caused by a bed at least 3 inches [75 mm] thick. Where there are no wiggles (5320 to 5350 feet) the formation is interpreted as homogeneous.*

Acronyms and Abbreviations

Advisor: The MWD logging and interpretation output that integrates downhole and surface measurements to obtain qualitative and quantitative analysis of the drilling process.

CDN: Compensated Density Neutron tool, a logging-while-drilling tool that makes neutron and density measurements within the Prospector logging system.

CDR: Compensated Dual Resistivity tool, a logging-while-drilling tool that makes gamma ray and deep and shallow resistivity measurements within the Prospector logging system.

CNL: Compensated Neutron Log, a wireline device providing neutron porosity.

DIL: Dual Induction Spherically Focused Resistivity, a wireline induction tool.

DLL: Dual Laterolog, a wireline resistivity tool.

DTOR: Real-time downhole torque measurement, made with MWD equipment, and integrated and correlated with other downhole and surface data in the Advisor system.

DWOB: Real-time downhole weight-on-bit measurement, made with MWD equipment, and integrated and correlated with other downhole and surface data in the Advisor system.

EPT: Electromagnetic Propagation Tool, a wireline dielectric tool.

Formation MicroScanner: A wireline tool that makes a microresistivity image of the borehole wall from pad-mounted electrodes.

Litho-Density: A wireline tool that measures bulk density and photoelectric factor, P_e.

LWD: Logging-while-drilling, technology that makes formation measurements from sensors built into special drill collars.

MEL: Mechanical Efficiency Log, an Anadrill service that differentiates lithology changes from bit wear, cone locking and stabilizer gouging, based on measurements of penetration rate, torque, weight-on-bit and rotary speed.

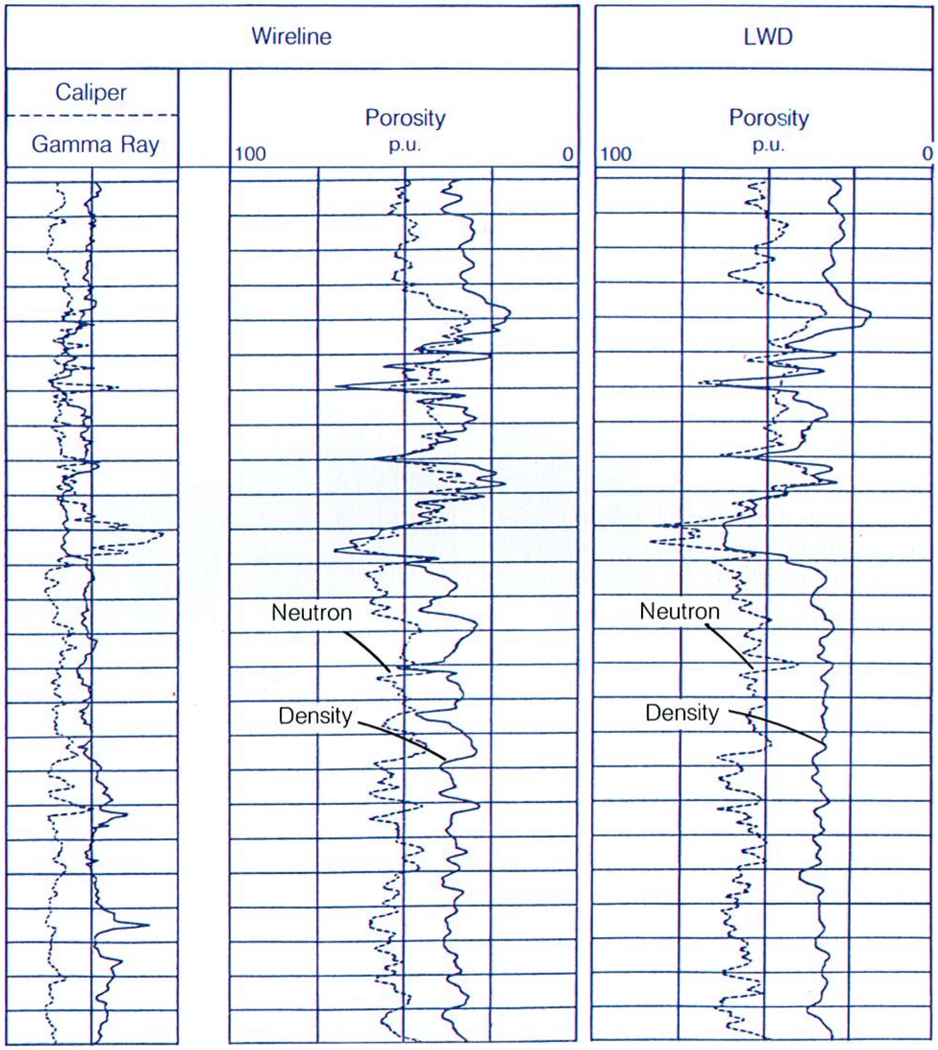
times masks neutron-density crossover, hiding gas shows. These crossovers may be detected early on LWD logs providing increased safety while drilling.

- Because the CDN tool sees the formation before extensive damage, it gives a better porosity measurement than comparable wireline measurements in severe washouts (*right;* log *page 15*). Comparison of real-time neutron porosity and the wireline value uncorrected for caliper can be a qualitative indicator of borehole condition.

The Future

LWD services are more expensive than comparable wireline services, but will contribute to overall cost effectiveness of drilling and well completion.

Major design and engineering challenges facing the new LWD system have been met. The system records logs that in certain conditions meet wireline standards while surviving the rigors of drilling. Now it faces trial by full-scale commercialization to see how and where it fits in the scheme of things. In the US Gulf Coast, several oil companies have already begun long-range comparative studies using a full suite of wireline and LWD services in the same well. If recent field tests are a reliable indicator, operators will find that the higher initial cost of LWD services is offset by the money it saves in preventing loss of wells and blowouts, loss of circulation and cement, in keeping mud weight to a minimum, and in reducing the need for side tracking. —JMK



□*Comparison of wireline and LWD porosity logs, showing a smoother, slightly lower density porosity at drilling time, probably due to better borehole conditions.*

MWD: Measurements-while-drilling, typically refers to drilling parameters and directional information.

MWDI: Anadrill's hardware used in conjunction with MWD and LWD

MWDII: Anadrill's second-generation hardware used for MWD and LWD measurements. It differs from MWDI in that it is modular, permitting greater flexibility in bottomhole assembly design, and has a drilling mechanics sub that provides additional information about forces acting on the drill bit.

MWD-XL3: The accelerated telemetry system (3 bits per second), used on both MWD I and MWDII.

NGS: Natural Gamma Ray Spectrometry tool, a wireline spectral gamma ray tool.

Phasor Induction: Enhanced resolution wireline induction tool.

Prospector: The set of measurements made by LWD technology. The Prospector log can combine data from the CDR and CDN tools with drilling measurements and cuttings analysis. The Prospector log provides a real-time first look at formations crossed in the well. It is used by the drilling engineer and well site geologist to optimize drilling decisions.

R_{ad}: Resistivity attenuation, the deep measurement of the CDR tool.

RFT: Repeat Formation Tester tool, a wireline device for sampling reservoir fluids and measuring formation pressure.

ROP: Rate of penetration of the drill bit.

R_{ps}: Resistivity phase shift, the shallow measurement of the CDR tool.

SFL: Spherically focussed log, a wireline device that makes a measurement of shallow resistivity

SPIN: Sticking Pipe Indicator log, an Anadrill service that predicts when drill collars might stick, based on measurements of friction anomalies between MWD hardware and the surface.