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New Technology High Temperature and High Pressure MWD & LWD System

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ABSTRACT

This paper discusses the development of two *completely new* measurement-while-drilling systems. The first system is the Hostile Environment Logging (HEL™) MWD system that comprises directional and gamma ray tools, with options for downhole pressure, vibration, and temperature sensors. The second system is the PrecisionLWD™ system that uses all components of the HEL MWD system, but adds resistivity, neutron, and density tools to the tool string. Combining the two systems provides a triple combo logging suite of gamma ray, resistivity, and neutron/density sensors. The primary focus of this paper is the PrecisionLWD triple combo.

The systems use technology specifically designed to meet the needs of difficult drilling operations. The main design objective for the MWD/LWD system was to develop the industry's most reliable and most accurate measurement service.

The capabilities of these new systems provide the following improvements over competitive LWD/MWD systems:

High temperature capability. The HEL MWD system is rated to a maximum operating temperature of 180 ºC (356 ºF) and survival to 200 ºC (392 ºF).

Fastest logging speed with wireline accuracy for LWD triple combo. Newly designed gamma ray, resistivity, density, and neutron porosity tools achieve accuracy equivalent to wireline tools, even at high drilling rates up to 400 ft/hr (122 m/hr). This is a significant improvement over the industry average for LWD tools of 200 ft/hr (61 m/hr) maximum ROP (or logging speed) for similar accuracy specifications.

Greater reliability. The environmental qualifications for both systems are believed to be the most demanding in the industry. The environmental specifications were defined to meet the needs of today's aggressive drilling practices. Testing includes combinations of thermal cycling, vibration, flow-loop and pressure testing. This is expected to result in higher reliability compared to competitive MWD and LWD systems.

Highest flow rate capability. Superior erosion resistance, high-strength materials, and larger bore diameter permit using continuous flow rates that meet or exceed the maximum capability for competitive systems.

Highest bottomhole pressure rating of 30,000 psi (207 MPa) is 20% higher than the highest rated competitive system.[1] This pressure rating allows drilling 32,000-ft (9,754 m) MD wells with mud weights as high as 18 ppg (2.16 sg).

Laboratory tests, theoretical calculations, and field data are presented to demonstrate these capabilities.

1. DRILLING TRENDS

Most LWD systems were originally designed approximately twenty years ago when drilling conditions were more benign than today. Naturally the systems that were designed then were intended to serve the drilling conditions common at that time. Therefore, as operators have subsequently ventured into deeper water depths, higher temperatures and higher pressures, these "mature" LWD systems have been pushed beyond original design limits.

Today, operators are drilling in ultra-deepwater (water depths exceeding 6,000 feet [1,829 m]) and challenging environments like hot geothermal wells. The following trends related to drilling in ultra-deepwater have placed greater demands on LWD systems:

Higher rig rates

Higher temperatures

Higher flow rates

Higher bottomhole pressures

1.1 Higher Rig Rates

In ultra-deepwater, rig rates can exceed U.S.$10,000 per hour. Therefore, every minute is valuable; even more valuable than when mature LWD systems were designed in the 1980's. Thus, development of new LWD systems that reduce rig time could help operators reduce drilling costs in ultra-deepwater.

1.2 Higher Flow Rates

Frequently, it is possible to drill very fast in deepwater, with ROP so high that it is deliberately throttled back to avoid overloading the hole with drilled cuttings. If the hole cannot be kept clean of cuttings while drilling ahead, then it may be necessary to stop drilling and circulate cuttings out of the hole. Also, more frequent wiper trips may be required to ensure the hole is clean. Both practices require extra rig time and are therefore costly to the operator.

According to Offshore Magazine[1], the maximum flow rate for mature LWD systems for 4-3/4 in. (121 mm) systems is 400 gpm (1,514 l/min); 800 gpm (3,028 l/min) for 6-3/4 in. (171 mm) systems, and quite varied for larger systems, although 1400 (5,300) to 1600 gpm (6,057 l/min) represents the highest specifications for triple combo capability. Operators have expressed the need for flow rates higher than the current limits imposed by mature LWD tools. Often the limiting factor in obtaining higher flow rates is erosion of mature LWD tools. Erosion of LWD tools is often worse than standard drill collars because the LWD tools have a smaller flow area that results in higher velocities than the rest of the BHA. Higher velocities cause higher erosion rates.

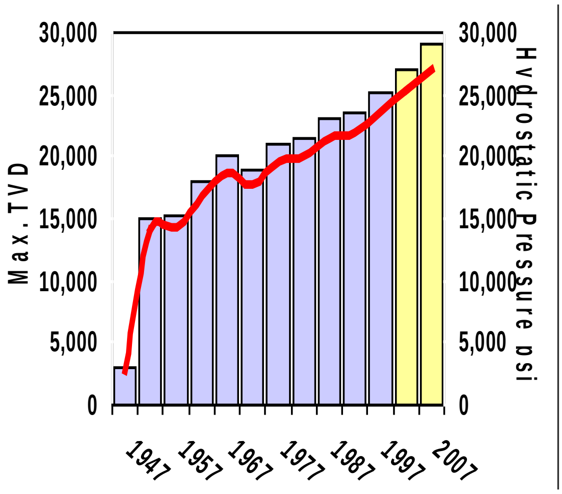

Figure 1. Data From MMS OCS 2000-2001 Report

Certainly, it is possible to pump flow rates through LWD tools higher than their maximum design specification. In fact, this is the only solution routinely available for mature LWD systems operated beyond design limits. However, continuous circulation above the maximum flow rate rating can result in significant erosion of LWD tools. This can cause downhole failures, thereby reducing reliability and costing rig time. In addition, erosion can require costly repairs or, in extreme cases, even scrapping the LWD collar.

1.3 Higher Pressures

The maximum pressure rating for mature LWD systems is typically 20,000 psi (138 MPa). [1] Some tools are rated to 25,000 psi (172 MPa). [1]

As operators drill wells in increasingly deeper water depths, there is a clear trend for an increase in the maximum hydrostatic pressure at TD (Figure 1). [2] These data show that the maximum bottomhole pressure will approach 30,000 psi (207 MPa) by 2007, which will significantly exceed the capabilities of mature LWD systems.

1.4 Higher temperatures

The Hostile Environment Logging (HEL™) MWD system is rated to a maximum operating temperature of 180 ºC (356 ºF) and survival to 200 ºC (392 ºF).

2. OPPORTUNITIES FOR LWD SYSTEMS TO REDUCE DRILLING COST FOR OPERATORS

As a result of these drilling trends in challenging geothermal wells and increasing water depths, several important opportunities were identified for a new generation of LWD systems to help operators reduce drilling costs in ultra-deepwater.

2.1 Reducing Downhole Failures.

A failure that requires a round trip in ultra-deepwater can easily cost the operator U.S.$100,000 (or more) in rig time.

Therefore, greater reliability of LWD systems would reduce drilling cost for operators.

2.2 Increasing Maximum Logging Speed.

To replace wireline with LWD logs, the accuracy must be equivalent. In some cases, ROP must be throttled back to accommodate the maximum LWD logging speed that achieves the desired accuracy. Another option is to wipe back through sections drilled too fast to obtain an accurate LWD log. Either way, the extra time increases drilling cost.

Therefore, faster logging speed of LWD systems while drilling could reduce drilling cost if wireline accuracy were maintained.

2.3 Improving Hole Cleaning.

Mature LWD systems sometimes cannot achieve the flow rate to keep the hole clean of drilled cuttings at the desired ROP. If the LWD system results in a reduction in flow rate while drilling, then extra time could be needed to maintain a clean hole.

Therefore, higher flow rate capability for LWD systems could reduce drilling cost.

2.4 Providing Higher Pressure Capability.

If wells are drilled with hydrostatic bottomhole pressure exceeding 25,000 psi (172 MPa), as expected, then the maximum pressure ratings of mature LWD system cannot provide the needed capability.

As the MMS data shows, the industry needs LWD systems designed to meet the higher pressure demands of tomorrow's ultra-deepwater drilling needs.

2.5 Providing Higher Temperature Capability.

Exploration and development wells are now seeking reservoirs and energy sources, such as geothermal, where directional drilling is a required technology.

Therefore, a reliable, accurate Directional/Gamma Ray service is required to enable the exploitation of these resources.

3. PRECISIONLWD™: A NEW GENERATION OF LWD TOOLS

Computalog Drilling Services, a division of Precision Drilling Corporation, has developed two completely new measurement-while-drilling systems. Both systems are rated to 30,000 psi (207 MPa) hydrostatic pressure for tool sizes 6-3/4 in. (171 mm) and smaller.

The first system is the Hostile Environment Logging (HEL™) MWD system. The HEL MWD system is rated to a maximum operating temperature of 180 ºC (356 ºF) and survival to 200 ºC (392 ºF). The following sensors comprise the high-temperature HEL system:

High-temperature Azimuthal Gamma Ray (HAGR™) tool

Integrated Directional Sonde (IDS™) tool

Pressure while drilling sensor for both bore and annulus (BAP™)

Vibration and temperature using the Environmental Severity Measurement (ESM™) sensor

The second system is the PrecisionLWD™ system that uses all components of the HEL MWD system, but adds the following tools:

Multi-Frequency Resistivity (MFR™) tool

Thermal Neutron Porosity (TNP™) tool

Azimuthal Density (AZD™) tool

The LWD triple combo system is rated to a maximum operating temperature of 150 ºC (302 ºF) and survival up to 165 ºC (329 ºF). The primary focus of this paper is the LWD triple combo.

4. ADVANTAGE R&D

Computalog Drilling Services, through its Advantage Research and Development Group, has hired some of the best and most experienced LWD R&D staff in the industry. In addition, a large capital investment was made in a new facility to design, test, and build the industry's first completely new LWD system to meet the needs of more aggressive drilling practices described earlier. State-of-the-art design techniques are used, such as the CAD shown in Figure 2.

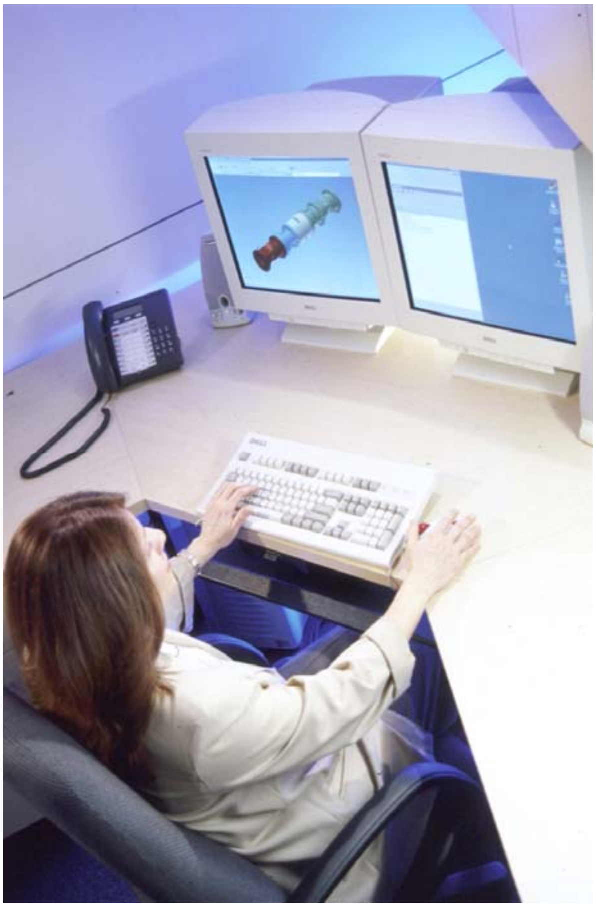

Figure 2. CAD Operator

Sensors in the PrecisionLWD system were designed using an advanced collective computer array. The array has the computing power equivalent to several Cray mainframe super-computers at a fraction of the cost. The advanced modeling using this technique significantly reduces both time-to-market and development costs. One example of the benefits of such modeling is that it allows for improvements in accuracy and performance before sensors are machined.

5.DESIGN OBJECTIVES

The main design objective was to develop the industry's most reliable and most accurate LWD system for challenging drilling environments. The system was designed to be as transparent as possible to the drilling operations. The capabilities of the new system provide the following improvements over mature LWD systems:

Fastest logging speed while drilling for LWD triple combo with wireline accuracy:

Greater reliability

Highest flow rate

Highest pressure rating

High temperature

5.1 Fastest Logging Speed While Drilling For LWD Triple Combo With Wireline Accuracy

The design goal was to achieve the industry's highest accuracy in triple combo – that is, gamma ray, resistivity, and neutron/density sensors. It was also a goal to achieve this accuracy at logging speeds much faster than the current industry's maximum capability. To achieve this, a logging speed of 400 ft/hr (122 m/hr) was selected as the design specification, which is twice as fast as the generally accepted upper limit for mature triple combo LWD systems.

5.2 Gamma Ray

The design for the High-temperature Azimuthal Gamma Ray (HAGR) [3] uses multiple two-detector banks of Geiger Muller Tubes. Five banks are used in the 4-3/4 in. (121 mm) tool and eight banks are used in the 6-3/4 in. (171 mm) and 8 in. (210 mm) tools. The tubes are arranged symmetrically to provide azimuthal measurements while rotating and/or sliding. This design feature is essential for geosteering capabilities.

5.3 Resistivity

The MFR operates at both 2 MHz and 400 kHz at antenna-receiver spacings of 20, 30 and 46 inches (508, 762, and 1168 mm). [4] All antenna arrays are fully compensated and integrated into the drill collar to increase reliability and simplify maintenance. The compensated antenna design and dual operating frequency were chosen specifically to address challenging deepwater logging environments such as high conductive formations drilled using oil-base mud. The tool diagram of the MFR is shown in Figure 3.

New, low-noise digital electronics use state-of-the-art components and design to increase measurement accuracy. Digital signal processors (DSP) are used to measure phase and attenuation at each transmitter-receiver pair, resulting in 48 measurements. These 48 measurements are combined to produce 12 fully compensated resistivity measurements at unique radial distances from the borehole. The fully compensated antenna design and DSP electronics result in both phase and attenuation accuracy specifications of +/-.25 mmhos and +/-.5 mmhos respectively.

The 400 kHz attenuation measurement made at the 46 inch (1,168 mm) antenna-receiver spacing has a diameter of investigation of 197 inches (5,004 mm) at 20 ohm-m, which is deeper than what is currently available in the industry today. [4] Making resistivity measurements accurately, deeper and at varying radial distances from the borehole enhance existing applications such as geosteering and inversion modeling.

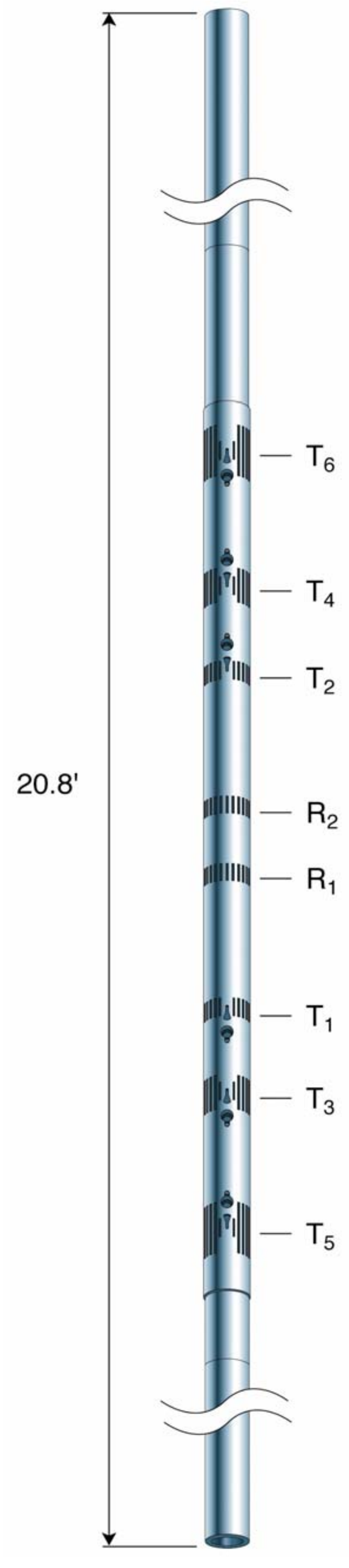

Figure 3. MFR Tool Diagram

5.4 NEUTRON DENSITY

Density and neutron porosity measurements are provided at penetration rates up to 400 feet per hour (122 m/hr) with the precision and accuracy of an equivalent wireline tool logging at 30 ft/min (9.1 m/hr). [5] The sensors are designed to reduce standoff effects on the density measurement and correct the neutron and density measurements for the effects of standoff and borehole size while drilling. The main novelty in the design of the density tool is the outward placement of the detectors under the stabilizer blades. This design creates more space to use a large, long-spaced detector and use more shielding. The novel detector allows moving the detector further from the source to reduce standoff effects while maintaining good statistical precision. The increased shielding also reduces borehole effects on the measurement accuracy.

6. GREATER RELIABILITY

The environmental qualifications for the system are believed to be the most demanding in the industry. The system's environmental specifications were defined to meet the needs of today's more aggressive drilling practices. Testing includes combinations of thermal cycling, vibration, flow-loop and pressure testing.

All sensors are qualified for all three axes to 30 g's RMS from 5 to 500 Hz, which is believed to be the highest vibration qualification level in the industry. Several "shake" (vibration) tables are used, including the one shown in Figure 4 that is capable of testing to 35 g's at 200 deg C, using 200 hp (149 kW), 40,000 lbf (17,792 daN) actuators. The result is superior capability to withstand shock and vibration that is expected to contribute to higher reliability compared to mature LWD systems.

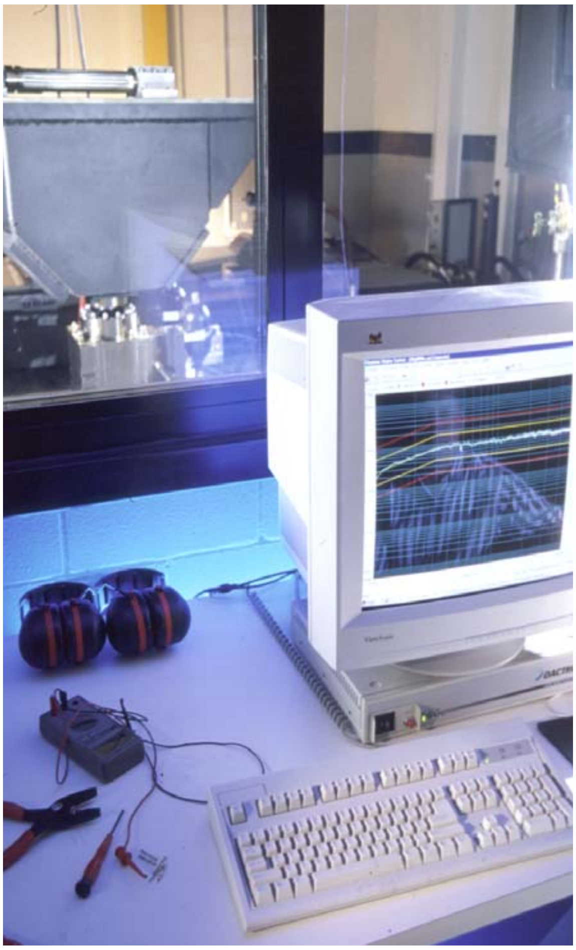

Figure 4a. Control Room View of Shake Table Test Facility

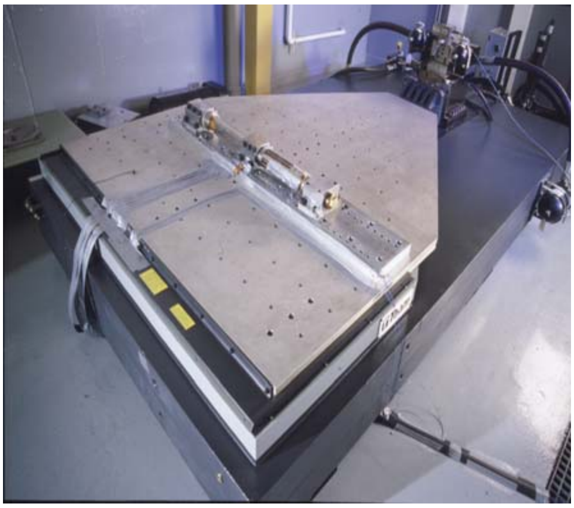

Figure 4b. Close Up of Horizontal Vibration Table Capable of 35gs

The first version of the ESM sensor incorporates a single lateral accelerometer to measure tool shock and vibration. An ESM sensor is installed in every pulser and various tools to improve reliability. Real-time vibration data, triggered after exceeding pre-set thresholds, will alert the driller that changes are needed to drilling practices to reduce or eliminate harmful downhole vibration. The vibration data from ESM will also be used for preventive maintenance and for improved ruggedizing of sensors to further improve reliability. Future version of ESM data will include tri-axial vibration sensors that will allow real-time interpretation of the source of downhole vibration to assist drilling optimization.

Another method used to improve reliability has been extensive flow-loop testing using two systems: (1) 200-foot (61-m) loop for erosion testing, and (2) 6,000-foot (1,829-m) loop used for pulse testing and pulse detection.

Significant emphasis is placed on training of all personnel since it is recognized that human error is a detrimental factor in the overall LWD system reliability. Our industry experience suggests that typically one-fourth to one-third of all LWD failures is caused by human error. Human error can occur either during tool assembly or during field use. By providing as much attention to training as to sensor engineering and development, the overall system reliability should increase.

7. HIGHEST FLOW RATE CAPABILITY

The design specification is to meet or exceed the current industry capability for mature LWD systems for all hole sizes. The specifications for maximum continuous flow rate for the new LWD system are as follows:

• 400 gpm for 4-3/4 in. system (1,514 l/min for 121 mm system)

•1000 gpm for 6-3/4 in. system (3,785 l/min for 171 mm system)

•1800 gpm for 8-1/4 in. system (6,814 l/min for 210 mm system)

The higher flow rate capability is achieved using higher strength material and large bore diameters compared to mature LWD tools. The inner diameter of PrecisionLWD tools is 2.00 in. (51 mm) for 4 3/4 in. (121 mm) and 6-3/4 in. (171 mm) tool, compared to 1.92 in. (48 mm) for mature LWD systems. For larger diameter tools, the PrecisionLWD tools have an inner diameter of 2.75 in. (69.9 mm) compared to 2.3875 in. (60.6 mm) for mature tools. Another advantage is that the new-technology PrecisionLWD system was designed using state-of-the-art electronics that are smaller than those used in mature LWD tools. This also allows larger inner diameters of tools.

8. HIGHEST PRESSURE CAPABILITY

The new LWD system is designed with the industry's highest pressure rating. The design provides a hydrostatic pressure rating of 30,000 psi (207 MPa), which is 20 % higher than the highest rated competitive system and 50 % higher than most standard competitive system. [1] For example, this would enable drilling a 32,000-foot (9,754-m) MD well with mud weight as high as 18 ppg (2.16 sg). As stated earlier, the higher pressure capability is achieved using higher strength material. The MFR sensor and other components have been successfully pressure tested to 30,000 psi (207 MPa) at Advantage R&D.

9. HIGH-TEMPERATURE CAPABILITY

The high-temperature HEL system is designed to operate reliably at temperatures up to 180 ºC (356 ºF) and to survive up to 200 ºC (392 ºF).

9.1 Field Results

Most of the new-technology LWD system is commercial. Additional developments are continuing. To date, field use has concentrated primarily on field-testing and the first commercial jobs that have been conducted on land. Consequently, the highest flow rates and pressures encountered have not tested the maximum design specifications. Several high temperature jobs with dynamic downhole temperatures up to 172 °C (342 °F) have been successfully conducted using the HEL system on- and offshore in North America, Far East and Europe. The highest observed downhole pressure was slightly above 20.000 psi (1.380 bar).

The HAGR and MFR have been successfully field-tested and are in commercial use. These LWD sensors are compared with wireline logs from the Burgos Basin in Mexico in Figures 5 and 6.

Figure 5 shows the response of the 4-3/4 in. (121 mm) HAGR tool in a shaly-sand sequence drilled using a 6.125 in. (156 mm) bit in 12.6 ppg (1.51 sg) mud. [3] The LWD gamma ray log is compared to wireline logs from the same well. The two measurements agree within ± 1 to 3 API units, which is well within the statistical precision of the LWD and wireline tools.

In Figure 6, an MFR log is compared to a wireline induction log in the Wilcox Formation. The 6.125 in. (156 mm) vertical hole was drilled using oil-base mud. [4] The depth scale is in meters and the resistivity scale is linear. Gamma ray is shown in Track 1, wireline ILD and ILM in Track 2, MFR phase resistivity in Track 3 at 2MHz frequency, and MFR in Track 4 at 400 KHz. This example shows the good vertical resolution of the MFR resistivity and excellent comparison with the wireline log.

While it is premature to quote reliability statistics due to insufficient hours on the tools, the results to date are encouraging.

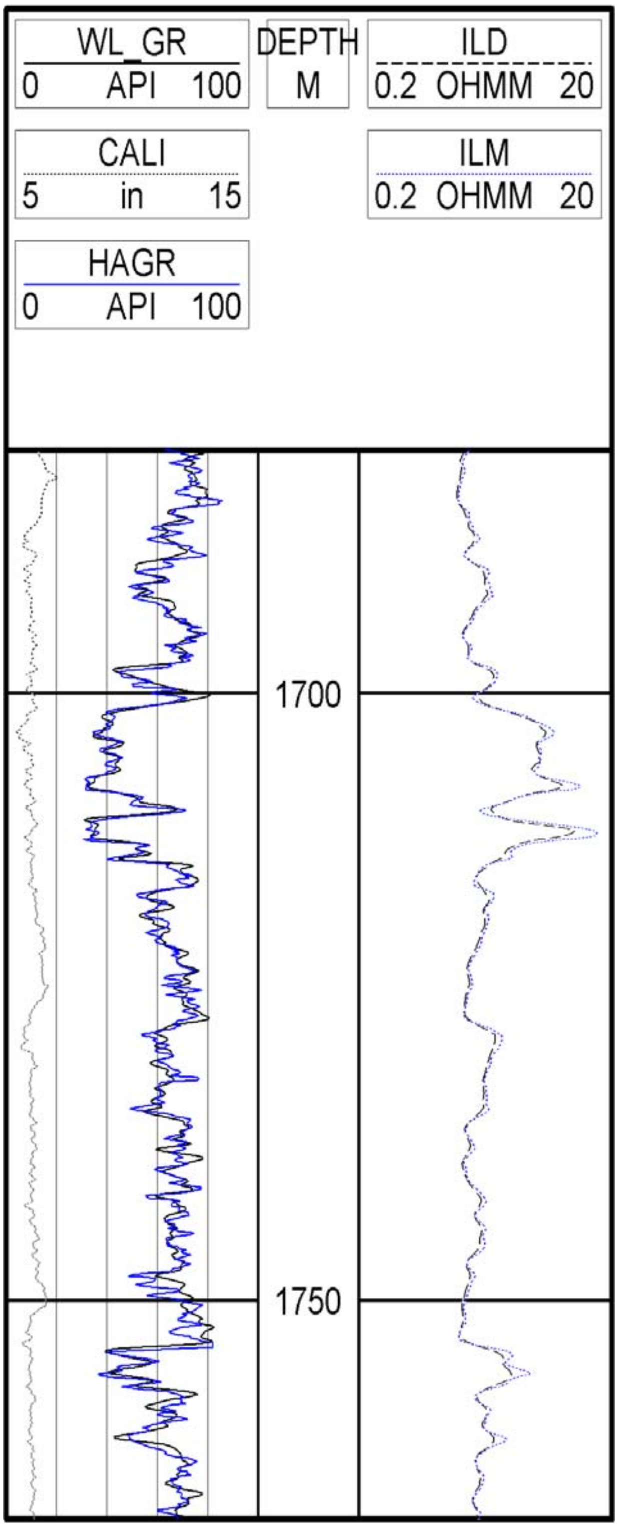

Figure 5. Field Example 1: 4.75” HAGR Tool, 6.125” Borehole, 12.6 ppg Mud

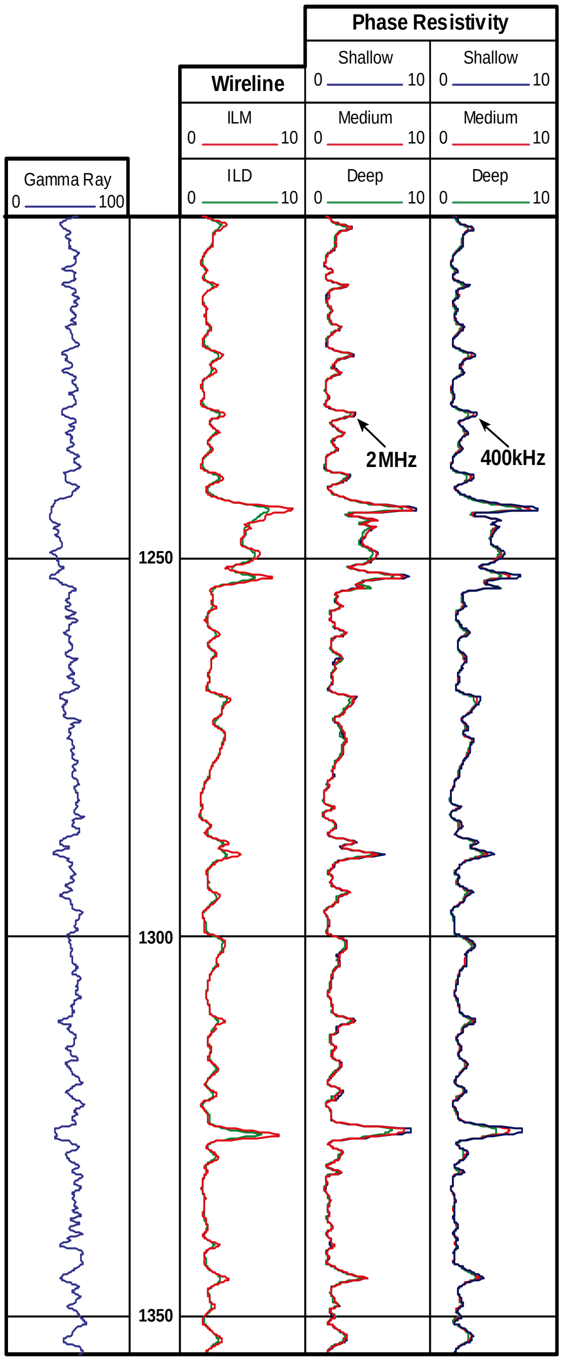

Figure 6. MFR log example from the Burgos Basin, Mexico. The well was drilled vertically with OBM. The resistivity scale is linear and the depth scale is metric.

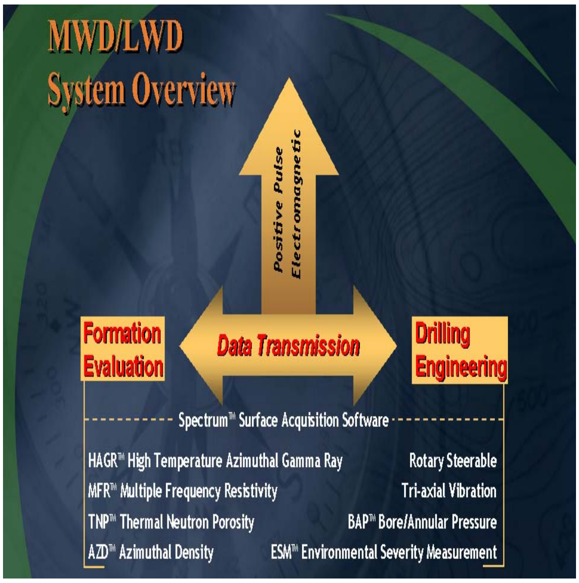

Figure 7. MWD/LWD System Overview

10. LWD SYSTEM COMPATIBILITY WITH ELECTROMAGNETIC TRANSMISSION

As shown in Figure 7, the LWD formation evaluation sensors are available with high flexibility of data transmission methods. While mature LWD systems are limited to data transmission using mud-pulse telemetry, the PrecisionLWD system is designed to be compatible with not only mud-pulse but also the EMpulse ™ electromagnetic MWD system. The significant advantage of this flexibility is that EM is the transmission method of choice for underbalanced drilling. Therefore, all PrecisionLWD tools and sensors will be available in conventional overbalanced drilling as well as underbalanced drilling.

CONCLUSIONS

Today, operators are drilling in very challenging environments that place demands on MWD and LWD systems that were did not exist when most LWD systems were designed over twenty years ago. Major trends in these environments that affect LWD systems are high temperature, higher rig rates, higher flow rates while drilling, and higher hydrostatic pressures at TD.

The PrecisionLWD system is designed specifically to meet these challenging needs of drilling operations. Compared to LWD systems designed over twenty years ago, the new system is designed to provide the high temperature operations with the fastest logging speeds while maintaining wireline equivalent accuracy, greater reliability, the highest flow rate capability, and the highest hydrostatic pressure rating.

ACKNOWLEDGMENTS

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NOMENCLATURE

BHA … bottom-hole assembly

C … Celsius

daN … decanewton

deg … degrees

F … Fahrenheit

ft … feet

ft/hr … feet per hour

g … gravity force, a unit of force measurement

gpm … gallons per minute

hp … horsepower

ILD … deep induction wireline resistivity log

ILM … medium induction wireline resistivity log

in. … inch

kHz … 1000 Hz

kW … kilowatt

l … liter

lbf … pounds force

LWD … logging-while-drilling

m … meter

MD … measured depth

MHz … 1 million Hz

min … minute

mm … millimeter

mmhos …conductivity, the inverse of resistivity

MPa … megapascals, or 1000 kilopascals

ohm/m …ohms per meter, measurement of resistivity

psi … pounds per square inch

ppg … pounds per gallon

ROP … rate of penetration

sg … specific gravity

TD … total depth of the well

TVD … true vertical depth

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