Logging While Drilling – Surmounting the Limitations to Acquiring Wireline Quality Formation Evaluation Data

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Abstract

The demand for high quality formation evaluation data has never been greater: precise reservoir description and ultimately high value business decisions depend upon accurate and complete data sets being available.

The instrumentation necessary to obtain this high quality data has historically been restricted to the domain of wireline and it is only comparatively recently that technology has permitted the migration of this instrumentation to the drilling environment. Having set the standards for quality, wireline provides the benchmark by which these new sensors are judged.

In contrast to the relatively controlled wireline logging environment, where instruments can be positioned in the borehole for optimal response, Logging While Drilling (LWD) measurements are made in a constantly changing and dynamic environment where variable tool standoff and borehole size must be modeled and corrected for. Despite the challenges associated with taking measurements in this tough environment, the demand and justification for acquiring high quality data remains.

This paper examines many of the improvements to the ever increasing number of LWD measurements being made available. Examples and comparisons between wireline and LWD are provided. The improvement and robustness of today's tools provide accurate and reliable data for real-time decision making, and when combined with wireline and/or offset LWD data permits "prediction ahead of the well" and enables techniques such as reservoir navigation (geosteering). Net-to-gross can also be quantitatively evaluated while drilling. The measurements discussed include resistivity, nuclear, acoustic, formation and annular pressure as well as formation imaging technology.

Introduction

It is perhaps instructive to take a look at the development of wireline and logging while drilling technologies from a historical perspective to gain an understanding of initial limitations to LWD originated versus wireline advancements. Although the first electric log run was accomplished in 1927 (Schlumberger, Pechelbronn, France), it was not long thereafter that the first attempt at continuous logging of resistivity during a drilling operation was made. This LWD acquisition was performed in the early 1930's by J.C. Karcher of Geophysical Surveys, Inc. as a geophysical operation using insulated conducting rods in the drill pipe (Karcher, J. C., 1935). Another early design by Amerada Geophysical Research Corp. employed electrical cable inside drill pipe to provide the means of communication. By the 1940's and 1950's the patent literature exposed the possibility of using electromagnetic or radio waves through the earth, acoustic telemetry methods, relay stations in the drillpipe and tracers in the mudflow, but none were fully succesful. Meanwhile, wireline measurements by the early to mid 1950's included resistivity in water or oil-based muds with a variety of spacings and depths of investigation, nuclear (gamma ray, neutron, and density gamma-gamma counts), acoustic, wireline coring, formation pressure, borehole caliper, temperature and formation dip. Clearly one of the major impediments to development of logging instruments while drilling was the telemetry problem – getting data to surface in an easy, reliable and quick enough manner to obtain useful data. At that time quality was not the issue, but certainly data transmission was.

Progress was finally made in the late 1950's with the advent of the ARPs Corps. mud pressure pulse telemetry system (Arps et al., 1964). This method allowed the pressure pulse to travel at the speed of sound in mud, or between 4,000 and 5,000 ft/sec, which carried the log information in a pulse-coded format to surface where it was transferred into an analog voltage. By the early 1960's, resistivity and gamma ray measurements could be made using this system while continuously drilling.

Once this initial telemetry limitation was met, new logging devices and quality improvement became the important next step, for which the industry began meeting the challenge.

Limitations to Logging While Drilling Quality

Drilling dynamics affect the life of downhole tools as well as cause spiky log behavior through torque shocks, axial and lateral vibrations, bit bounce, stick-slip, and torsional oscillation. See Figure 1 for the definitions of the 3 vibration modes. Lateral vibrations are responsible for most measurement-while-drilling tool failures during drilling operations (Jogi et al., 1999).

The ability to monitor drilling dynamics provides a powerful tool for optimizing the drilling process. Real-time measurement of stick-slip and vibration allows rate of penetration and reliability to be optimized. Drilling parameters are measured and adjusted so as to reduce the forces that induce mechanical and electrical failure.

These measurements include *X* and *Y* BHA bending moments, axial acceleration, dynamic weight-on-bit, dynamic torque, and *X* and *Y* axis magnetometers. In addition to providing a diagnostic tool that can help explain erroneous tool response, these measurements greatly increase the probability of obtaining full data sets. Figure 2 illustrates the destructive effects lateral vibration resulting in tool failure.

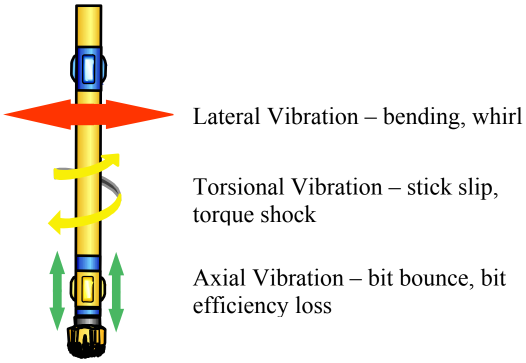

Figure 1 The three vibrational modes in drilling.

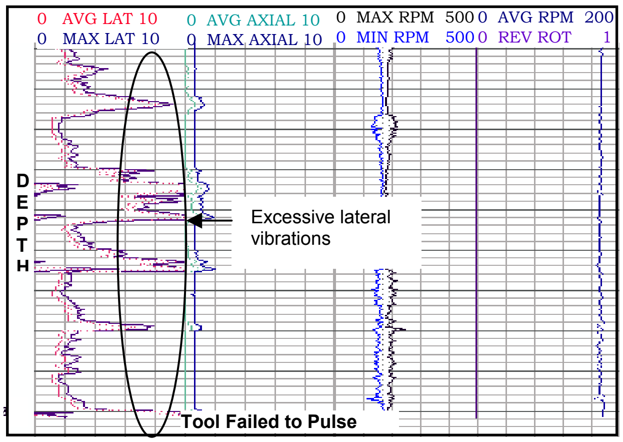

Figure 2 Destructive lateral vibration – the last few hours of an LWD tool's life.

It should be recognized that frequently LWD data is acquired in high angle and horizontal wells, and the true vertical thickness of the formation may be expanded over a long section of log measured depth. This produces a much different appearance than that in a vertical well, subject log data to potential anisotropic effects and potentially generates resistivity polarization horns.

Tool wear due to drillstring rotation can have a direct impact on data quality. Rotating tools are subject to wear, which can alter the standoff between sensors and borehole wall.

Hole enlargement and washout is usually asymmetric, and thus measurement in azimuthally different directions will encounter varying amounts of standoff and consequently the need for varying amounts of measurement corrections. This may be counteracted by making sliding passes of the drill string, but this is time consuming, although sliding passes are very useful when measurements during drilling are in question or affected by sticking and slipping.

Advantages

There are some advantages to log quality and environmental effects resulting from LWD acquisition. The most notable is the chance for less drilling fluid invasion in the formation as the formations are exposed to the borehole environment for a shorter period of time before logging as compared to wireline acquired logs. This can make hydrocarbon, and in particular, gas detection easier to observe on neutron and density logs. Figure 3 examines the differences in LWD density and neutron logs versus wireline logs obtained in the same well separated by a few days.

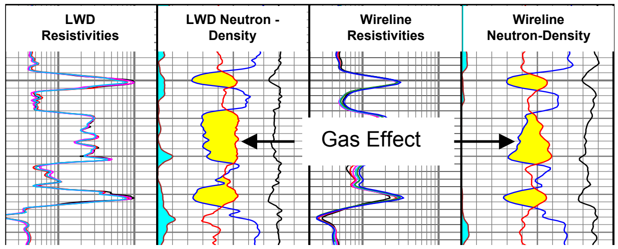

Figure 3 Gas crossover on the LWD density-neutron shows little invasion while the wireline crossover is reduced at the top due to invasion.

Shale/clay hydration from the interaction of borehole fluids with the rock matrix can lead to slower compressional velocities which are more likely to influence wireline acoustic measurements, for which in fact the long-spaced acoustic log was developed. The LWD acoustic is less influenced by this hydration-caused formation alteration, and less time for hole degradation has occurred.

Considering the frequent need to have data at hand for reservoir navigation purposes, quick decision-making or insurance logging in high risk areas, the real-time abilities of LWD can be indispensable, another important advantage. LWD logs also give an early view to the quality of the borehole, so that changes can be made in the drilling parameters producing a more in-gauge borehole with fewer undulations, making casing and liner placement easier.

Resistivity

Most LWD resistivity tools use higher frequency electromagnetic propagation methods and different spacings than induction based wireline tools (Meyer, 1995). Resistivity measurements are based upon phase shift and attenuation and as a result are subject to environmental effects and response characteristics that are different to those encountered for wireline. Some devices are fully borehole compensated by nature of their transmitter-receiver configurations, while others are compensated using post-processing methods. LWD resistivity measurements are frequently used for reservoir navigation (also termed geosteering) where the trajectory of the well path is altered in real-time so as to precisely position the well for optimum production and drainage.

The environmental factors that influence the accuracy of LWD propagation measurements are very similar to those that affect wireline induction and galvanic measurements, namely, borehole size, formation and mud resistivity contrasts, dielectric effects, anisotropy, relative dip, filtrate invasion, sensor response functions, and thin beds.

Propagation based LWD tools can provide quality measurements in a wide range of resistivities although, in some cases, the high frequency electromagnetic signal can magnify eccentricity effects in enlarged holes.

One major advantage of LWD resistivity measurements over wireline is that typically acquisition takes place prior to any significant mud filtrate invasion, and as a result, the shallow and deep reading curves may not require significant or any invasion corrections to be applied.

Some environmental effects can be accentuated by drilling through formations with large apparent dip (highly deviated or horizontal wellbores opposite low angle or horizontal bedding planes). For example, high relative dip in an anisotropic formation, which is frequently observed in high angle and horizontal wells, can cause separation in the resistivity curves. With appropriate processing this phenomenon can be used to extract more accurate vertical and horizontal resistivity values for improved an improved estimate of reserves in place.

In formations with high apparent dip, deep reading curves may be influenced by adjacent formations to the formation of interest and forward modeling becomes important in ascertaining the correct values of resistivity. The use of forward modeling is particularly encouraged when drilling horizontal wells, and offset data is frequently used to predict tool response for various scenarios that may be encountered. Should differences be observed while drilling, the well can be steered to adjust the well's path to the subsurface geology using 3-D earth models (Coghill et al., 2001). Polarization horns can often be observed at the bed boundaries of formations with high apparent dip providing tell-tale information for geosteering.

Real-time data can provide water saturation analysis and net-to-gross accumulation to help steer the well for optimizing economic value (Coghill et al., 2001). Data is frequently transmitted real-time to a shore-based computing center for analysis.

Inversion and resolution matching of the raw data can permit bed resolutions down to 6 inches which compares favorably with wireline resistivity resolution (Figure 4). In cases of anisotropic reservoirs, LWD measurements are complimented with wireline 3-D induction logs to avoid missing hidden pay (Kriegshauser et al., 2001).

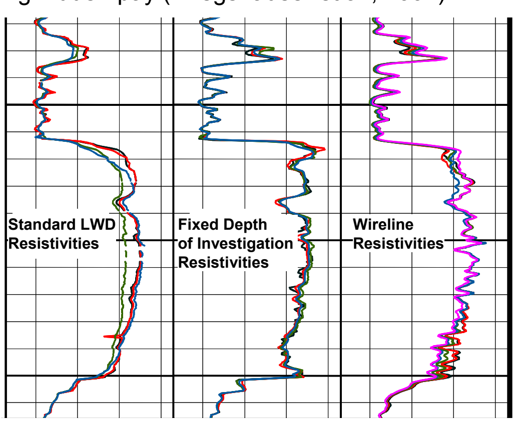

Figure 4 Fixed Depth of Investigation processing results yielding nearly identical bed resolution to the wireline log without invasion effects.

Acoustic

The evolution of LWD acoustic instruments occurred in various stages, with the first tools having the capability of recording only compressional data (Aron et al., 1994 and Minear et al., 1995). Dipole LWD instruments were later introduced (Varsamis et al., 1999), and finally quadrupole shear LWD tools for slow formations (shear velocity lower than fluid velocity) were introduced in the new millennium (Joyce et al., 2001 and Tang et al., 2002).

There are numerous applications for acoustics in the wellbore, and real-time acquisition of compressional, shear and Stoneley waves using LWD instruments provides an opportunity to resolve more complex information including: Pore pressure prediction, acoustic-derived porosity, rock mechanics, acoustic-derived hydrocarbon indicators, surface seismic ties, inputs to AVO processing. Stoneley wave attenuation-based permeability prediction, thin bed detection, gas detection, Vp/Vs lithology and overpressure determination, and even acoustic anisotropy all come into the realm of possibility, and indeed many of these are being accomplished today.

LWD acoustic measurements are particularly susceptible to the inherent noise of the drilling environment. Tool wave arrivals in the collar, tool eccentering and vibration induced acoustic signal deterioration have to be overcome. Isolation between the transmitters and receivers is important in any downhole acoustic logging instrument, but is even more critical in an LWD device considering the amount of tool occupancy in the hole and tool rigidity. Newly designed isolators can efficiently attenuate the direct source-receiver signal.

Variations in drilling environment noise are caused by the type of bit and whether circulating or drilling, examples of which may be seen in Figures 5 and 6. Complex receiver arrays and waveform stacking are used to enhance signal to noise ratios and techniques such as advanced semblance processing are performed downhole in order to isolate and extract the information required.

With the current low data transmission rate capability of LWD compared to that of wireline (bits per second versus kilo bits per second), full waveform data cannot be transmitted to surface. When large intervals of log data are acquired a significant volume of data must be stored in downhole memory.

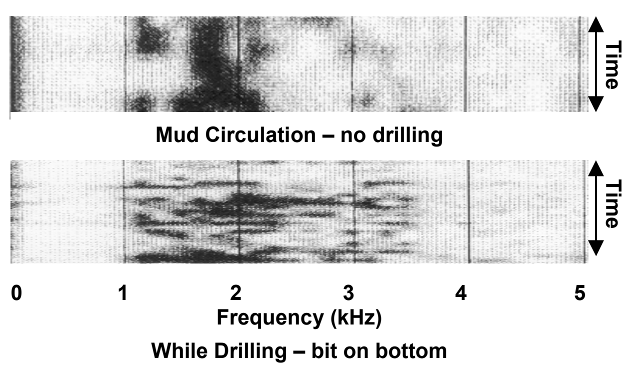

Figure 5 Drilling noise generated by mud circulation and drilling.

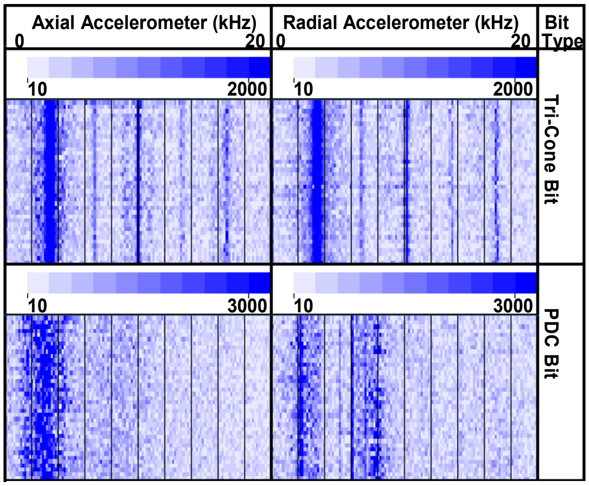

Figure 6 Axial and radial vibration frequency spectrum for different types of bits, indicating the need for excellent noise rejection in the acoustic while drilling environment.

Acoustic sources and isolators have been designed to optimize signal-to-noise ratios while still initiating the proper modes of acoustic excitation. High-powered and omni-directional segmented transmitters now provide:

- High frequency monopole for compressonal and low frequency monopole for Stonely
- High and low frequency quadrupole modes for slow and fast formation shear measurements
- Low frequency dipole for flexural wave evaluation in the LWD environment

The importance of exciting the correct mode for shear measurements is demonstrated in Figure 7. The quadrupole omni-directional transmitter allows shear arrivals to be recorded prior to any tool arrivals. The arrivals do not require any dispersion corrections for fast formations in the 5 to 12 kHz frequency range, however low frequency excitation is required in slow formations.

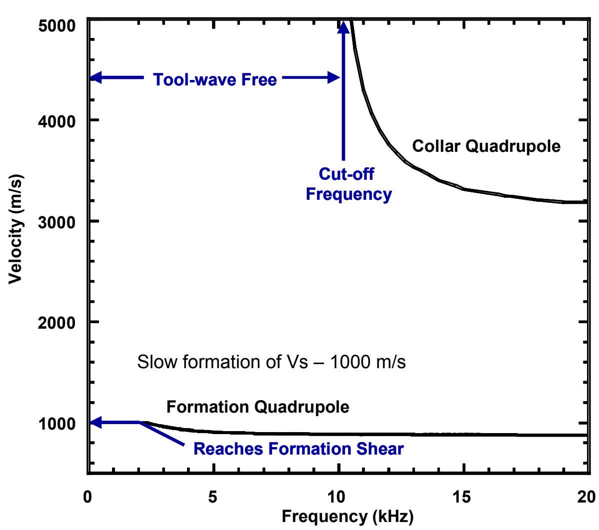

Figure 7 Quadrupole in a slow formation approaches shear velocity and avoids tool arrivals

Although shear waves can be acquired in slow formations using quadrupole excitation, they are in reality guided interface waves that require dispersion corrections to be applied, the magnitude of which increase with increasing frequency. These corrections are now characterized based on the frequency range and the properties of the drilling fluid (Tang et al., 2003), and are much less than those for dipole data. Drilling in vertical versus horizontal attitudes, especially in soft sediments in deep water reservoirs where shales can be highly anisotropic may produce shear slownesses significantly different to those in the vertical and horizontal directions. Numerical modeling is required to understand the propagation of the shear wave in these cases, but fast and slow shear arrivals can now be recorded to solve the problem (Tang et al., 2003) in highly transverse isotropic formations.

Figure 8 exemplifies high quality compressional and shear data (track 4) in a well with severe stick-slip conditions (rapid downhole RPM variations in track 1).

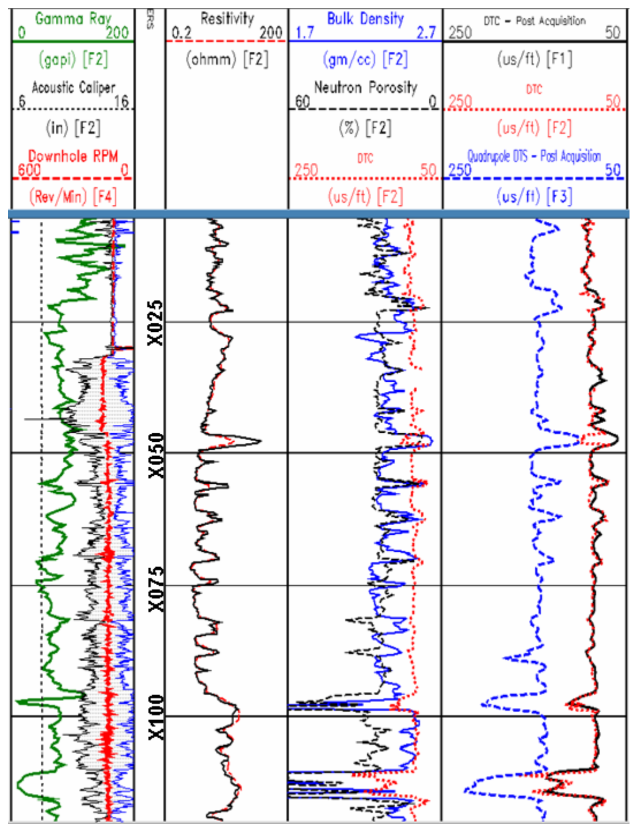

Figure 8 Real-time compressional and shear with severe stick-slip (high variations in downhole rpm). Good response is seen over the wide range of formation types (tight limestones though high porosity coals) except the zone at X047 where the real-time compressional picked the refracted shear, later verified by quadrupole post-processing.

Nuclear

Density

Density measurements are particularly sensitive to the effects of tool standoff and in the rotary acquisition mode tool body wear becomes a concern. Any change in tool geometry can have significant impact on measurement accuracy, but designing an LWD density instrument to operate within an envelope of controlled wear and managed standoff can result in data quality equal to that of wireline. The mass of the tool housing helps to shield detectors from borehole effects.

For wireline tools in a deviated wellbore, the density pad is generally oriented toward the low side of the borehole, with the pad maintained +/- 45 degrees from low side in order to avoid cuttings or drillpipe induced formation damage. By combining magnetometer and caliper sensors into the tool design and acquiring data in the rotary drilling mode the LWD density instrument can acquire density information from the entire circumference of the borehole. Low side quadrant density or more complex methodologies such as weighted algorithms that match measured density to instantaneous tool standoff optimize measurements for the effects of standoff and borehole washout.

Long and short space detectors are used to correct for mud in the annular space between the tool and borehole wall. Wireline density tools, on the other hand, use the long and short space detectors to correct for mudcake since the tool is positioned against the borehole wall.

Further applications of azimuthal density measurements include the generation of borehole density images. By combining sectored density data and orientation data from a navigation sensor, images can be correctly oriented and structural dip in the vicinity of the borehole derived (Figure 9). This is an invaluable tool for reservoir navigation in formations with contrasting densities.

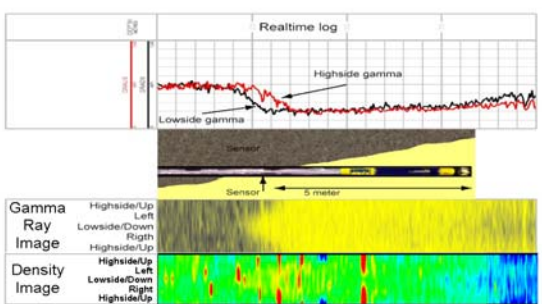

Figure 9 Horizontal well images in a sandstone with a well defined bed contrast on the GR image from high radioactivity from mica, but not easily discernable on the density image.

Neutron

Extensive mathematical modeling and precise borehole caliper information permits accurate corrections resulting in LWD measurements that match those of wireline. This modeling has provided excellent response transforms that are linear over a wide range of porosities.

LWD neutron measurements are prone to the same effects as wireline and require correction for the effects of hydrocarbon, temperature and pressure, shale and salinity. However, with greater tool occupancy, LWD neutron measurements generally require less borehole correction than their wireline counterpart. Precision caliper information and comprehensive response modeling allow precise borehole corrections to be applied.

However, it should be noted that it is not uncommon to observe differences between LWD and wireline neutron porosity logs in gas zones. Typically, the LWD tool shows a more pronounced gas effect (i.e. drop in porosity) than the wireline tool, because the LWD tool logs the formation before significant mud invasion has occurred – both near and far detectors are seeing more of the gas. The gas effect for wireline tools can be masked depending on the depth of invasion and sweeping effect of the mud filtrate (See Figure 3).

Gamma Ray

Wireline tools provide a measurement of natural formation gamma ray activity in calibrated API units. Unlike wireline gamma detectors that are contained within relatively thin walled tool housings, LWD gamma detectors are mounted within heavy walled steel collars and are prone to a phenomenon known as spectral biasing.

Natural gamma rays have a wide spectrum of energies and the lower energy gamma rays have their energies further reduced by the steel surrounding the LWD gamma detector. The attenuation of the measured gamma radiation increases as the collar thickness increases and is greater for low energy gamma radiation. This spectral biasing has the effect of enhancing potassium radiation (1.46 MeV). Without correct modeling an LWD sensor can exhibit over sensitivity to potassium. Accounting for drill collar thickness in response modeling and tool calibration permits derivation of a true API gamma measurement.

Additionally, reducing the mass of steel between the detector and the formation reduces the effect of spectral biasing. New generation gamma detectors are being positioned closer to the surface of the tool body, beneath hatch covers that more closely mimic the wireline tool configuration.

As with wireline, LWD gamma measurements must be corrected for mud weight, borehole size and mud potassium content. To allow quantitative comparisons between different borehole sizes and tool sizes, the measured gamma response must be corrected to a standard set of conditions.

New developments include the ability to generate natural gamma ray images of the borehole. Count rate and speed of drillstring rotation ultimately determine resolution and usefulness of this technique, although quadrant measurements (left, right, up, down) are frequently made for the purposes of geosteering (See Figure 9).

The example log in figure 10 illustrates the excellent agreement that can be obtained between wireline and LWD density, neutron and gamma ray data.

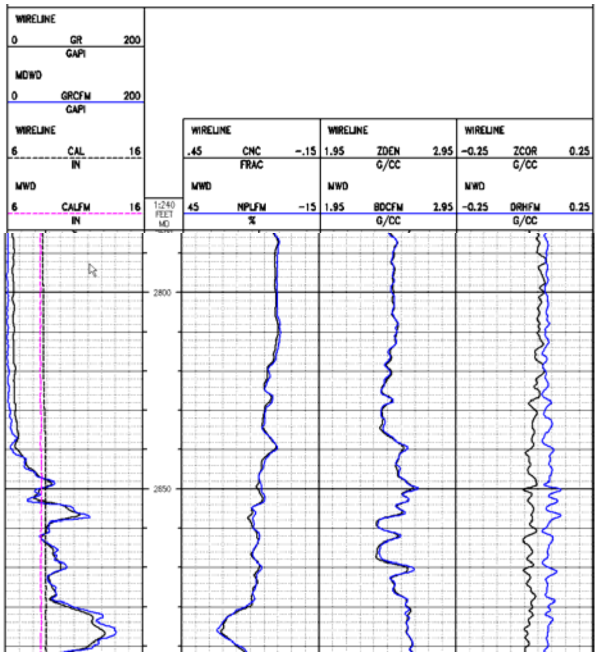

Figure 10 Wireline vs. LWD gamma ray, density and neutron logs.

Formation Testing

LWD formation pressure testers provide real-time stationary measurements of in-situ pore pressure and formation fluid mobility. Gradient information can be used to determine fluid type and fluid contacts. Formation pressure information can also be used as an aid in geosteering by maintaining the well path within specific pressure regimes. Optimization of equivalent circulating density (ECD) can be achieved by monitoring annular pressure while drilling.

Various tool designs exist, one of which is based on the wireline principle where a sealing pad is extended against the borehole wall with sufficient force to isolate the formation from the borehole hydrostatic pressure. Formation fluid is drawn into the instrument while pressure and temperature are recorded. Up to three draw down and build up sequences can be obtained at each depth to confirm hydraulic isolation between the formation and the borehole.

Current designs minimize measurement cycle times. Test results are computed downhole and sent to the surface. Additional data is stored in memory for later retrieval.

To maximize measurement accuracy while minimizing the duration of the stationary operation, techniques such as Formation Rate Analysis (FRA) can be employed to optimize control draw down rate and volume.

Conclusions

Judicious design of LWD instrumentation and proper consideration of drilling dynamics, environmental effects, and the application of appropriate environmental corrections has produced LWD measurements of accuracy and reliability that are consistent with the quality associated with wireline measurements.

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