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Advantages and Challenges of Using Logging-While-Drilling Data in Rock Mechanical Log Analysis and Wellbore Stability Modeling

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Abstract

A full Logging-While-Drilling (LWD) suite - gamma ray, resisitivity, density/neutron/caliper, sonic, borehole pressure and formation tester tools - provides all the logging data that are typically used in rock mechanical log analysis. Numerous comparisons with equivalent wireline log data have proven the validity of the LWD measurements and have also highlighted differences between the two types of log data – differences that indicate both advantages and present challenges in rock mechanical analysis and wellbore stability modeling.

These differences largely stem from the relative time-of-measurement of the logs. A number of challenges result from the short time of recording LWD data behind the drill bit and the real-time availability of these data. The while-drilling-data typically are less affected by borehole and invasion effects. Mud cake either may not have been built or does not form an impermeable barrier which governs the selection of a near-wellbore stress model.

The availability of the data in real-time presents an advantage because the analysis can be done while drilling. Drilling parameters can be modified when required before borehole damage occurs. At the same time, the slow LWD telemetry provides only limited data sets in real-time which would require the use of simplified algorithms (for example linear-elastic instead of poro-elasto-plastic models). Equivalent Circulating Density (ECD) data from downhole pressure measurements are used in wellbore stability analysis to reflect the real flowing borehole pressures. These pressures can easily exceed the mud-weight computed ECDs by more than a pound per gallon - enough to cause borehole failure. Swab and surge pressures can have the same effect. Caliper measurements are made while drilling. These can be used to evaluate borehole failure in real-time. Probably even more important are time-lapse calliper measurements as borehole break-out does not necessarily happen at the drill bit. Oriented caliper images aid in determining breakout direction and hence stress field orientation.

Introduction

Rock mechanical log analysis in the wireline industry originated with the advent of full waveform sonic tools. The availability of compressional and shear slowness facilitated the computation of the formation's elastic moduli (Poisson's Ratio, Young's Modulus)[1]. Later, borehole images (resistivity and ultrasonic) provided information on actual borehole failure (fractures and break-out) and hence calibration of geomechanical and failure models[2]. More complicated models have been added to the original linear-elastic ones with the introduction of plasticity, visco-elasticity, temperature and finite element modeling among others. The Mohr-Coulomb failure criterion is still a favorite in rock mechanical analysis but quite a number of other failure criteria are widely used.

The Logging-While-Drilling (LWD) industry is catching up quickly with wireline technology. Gamma ray, resisitivity, density/neutron/caliper, sonic, and borehole pressure tools form a standard LWD tool suite. LWD borehole imaging has become available [3] and the first slow shear sonic tools are on the market [4,5]. Add to that an LWD formation tester tool [6] and the LWD industry provides all the data that are typically used in rock mechanical log analysis.

LWD logs can be quite different from wireline logs due to the comparatively early time of recording the LWD data behind the bit and the changing borehole environment between the time of LWD and wireline logging. Also, LWD data are transmitted to the surface in real-time while drilling. These factors present at the same time a number of advantages and a series of challenges to rock mechanical analysis and wellbore stability modeling based on LWD data.

Logging-While-Drilling Data Quality

Numerous comparisons with equivalent wireline log data have proven the validity of the LWD measurements [7,8]. Comparative studies [9] have also highlighted differences between the two types of log data, differences that largely stem from the relative time-of-measurement of the logs. LWD data are recorded shortly after the bit penetrates the formation, whereas wireline logs are run days to even weeks after drilling. A number of processes continuously change the borehole environment with time during and after drilling. These processes include shale hydration, mud filtrate invasion in permeable zones and borehole damage (break-out, wash-out, mechanical damage). Thus the logging environment can change quite considerably in the time between the LWD data recording and wireline runs. Time-lapse logging may be used to capture the change and the rate of change of the logging environment.

LWD Data Advantages: Real-time Data

The obvious advantage of having log data available while drilling is that drilling decisions can be made immediately when necessary. The use of a downhole pressure measurement is a prime example of such real-time drilling-decision making. These tools measure the mud pressure inside the tool and the flowing pressure in the annulus between the tool and the borehole wall. These pressure measurements are then used to compute the Equivalent Circulation Density (ECD) of the mud at downhole conditions. This ECD represents a more realistic image of the downhole conditions than when surface mud weight values are used. It is the parameter that should be used for mud weight in the rock mechanical analysis.

Real-time Equivalent Circulation Density Example

Figure 1 shows an example of an LWD log that includes a downhole pressure measurement. Track 1 contains the gamma ray curve and the Rate-Of-Penetration (ROP) data. Track 2 shows the resistivity curves. Track 3 shows the mud weight data. The curve at the left side of the track is the mud weight measured at surface. The curve to the right of it is the downhole equivalent circulation density computed from the surface mud weight (ECD_{MW}). The third curve, highlighted in green, is the ECD computed from the downhole pressure measurement (ECD_P). ECD_P reads just under .5 ppg higher than ECD_{MW} above 9710 ft. Below this depth there is an increasing difference between the two values. This change coincides with a negative trend on the resistivity log. Such a negative trend indicates increasing pore pressure. This increasing pore pressure also coincides with a increase in ROP. An increase in ROP without an increase in mud flow results in cutting loading of the mud. This cutting loading is reflected in the increased ECD_P. Without the downhole-measured pressure, the estimated ECD would be about 1 PPG below the real value. Such a difference could well be large enough to cause wellbore damage. The increased ECD was recognized and the sharp drop in ECD_P at the bottom shows that the driller reacted to the problem and cleaned out the borehole

LWD Data Advantages: Environmental Effects

The advantage of LWD data over wireline log data is that environmental effects are typically smaller in the LWD logs. Invasion is a timed process; it continues until an impermeable mud cake has formed. Borehole wash-out does not happen necessarily at the bit. Borehole break-out due to stress relief typically does not happen at the bit and can continue for a long time after drilling. The LWD data represent a better picture of the true formation properties. The following examples illustrate environmental effects using LWD sonic and caliper logs.

Sonic Log Example

The wellbore stability plot in **Figure 3** (Tracks 1, 2 and 3) was computed using a linear-elastic geomechanical model and LWD sonic and density logs in a near horizontal well in the North Sea. Track 1 shows the compressional (DTP) and shear slowness (DTS) and track 2 contains Poisson's Ratio. The stability analysis is presented in track 3. The shaded area represents the range of borehole pressures in megaPascal for mechanically stable borehole conditions between the Mohr-Coulomb shear failure curve in black and the tensile failure curve in red. The analysis is very similar to the rock mechanical analysis proposed in reference 1 of this paper, but adapted to handle deviated wells [10]. A mud pressure curve is added to indicate that at a number of levels, the mud pressure approaches or slightly exceeds the tensile failure pressure. This would indicate that borehole failure in the form of drilling induced fractures may occur. As stated earlier it is imperative to use the downhole measured mud weight (ECD) to evaluate failure.

It has been shown that alteration can change the measured compressional slowness with time by up to 10 microseconds per foot in shales and to a lesser extend in sandstones [9]. **Figure 2** shows the effect of a 3 µsec/ft increase in compressional slowness in a sandstone on the computed Poisson's Ratio. Tracks 4, 5 and 6 of **Figure 3** show the effect of such a change on the wellbore stability analysis. Tracks 4, 5 and 6 are equivalent to tracks 3, 2 and 1. The intervals in track 4 shaded red indicate where the altered dataset predicts the onset of wellbore failure that is not observed on the LWD data.

Caliper Example

A stand-off transducer is included in the density-neutron tool to be able to improve the density measurement and to correct the neutron porosity for a measured stand-off. These corrections are crucial for density-neutron measurements in an LWD environment because of the ever changing position of the tools within the borehole. By incorporating three of these ultrasonic stand-off measurements at a 120 degree spacing around the tool, a borehole caliper can be computed [11]. **Figure 4** shows a caliper log from the North Sea, with the gamma ray curve in track 1, mirror caliper images in track 2, borehole volume (BHV) and annular volume (AHV) tick marks in track 3, and the three ultrasonic stand-off curves in track 4. This log shows that the shale section from x060 ft to x290 ft was washing out, contrary to what was expected by the operator. Changing the mud properties was the obvious answer to prevent further well bore deterioration.

LWD Data Challenges: Real-time Data Density

The real-time nature of the LWD data presents an advantage over the use of wireline log data as discussed earlier, but at the same time, the low data density presents quite a challenge to the real-time utilization of the LWD data. Although it is the author's belief that LWD telemetry rates will drastically improve in the not too distant future, the present optimistic 20 bits per second present a major challenge to geomechanical LWD log analysis. **Figure 5** shows a plot of data rate versus Rate-of-Penetration (ROP). This data rate is for a 'quad combo' tool (resistivity, density-neutron-caliper and sonic). Pulse width is the time in seconds of the telemetry systems pulse, the shorter the pulse width, the faster the data transmission. This figure indicates that at ROPs of over 100 ft/hr the real-time sampling rate drops to below the 1 to 2 samples per foot that are typically required for log analysis.

LWD Data Challenges: Shear Sonic

Shear slowness is a very important parameter in the geomechanical analysis. The dynamic elastic moduli of the rock are computed from the sonic velocity ratio Vp/Vs. The availability of a depth based Poisson's ratio is one of the most important reasons for using sonic log data in geomechanical analysis. Current LWD sonic tools only provide real-time shear in hard rock where the refracted shear arrives at the receivers before the fluid arrivals (typically 189 μsec/ft in a water based mud to as high as 220 μsec/ft in a synthetic oil based mud). Slow shear is defined as a shear wave that travels slower than the direct sonic wave in the borehole fluid.

Real-time slow shear computed from a flexural wave is not currently available from LWD tools. It is a major challenge for the LWD companies to provide a real-time slow shear service. Two possible options are to improve the downhole computations or increase the data transmission rate so that waveforms can be transmitted to surface and processed in the logging unit like it is done in wireline dipole logs.

LWD Data Challenges: Wellsite Interpretation and Model Selection

The continuous stream of log data, albeit at a relatively slow transmission rate, ideally requires geomechanical models to be updated every time a new data point arrives at the surface logging system. Complex models that require substantial user input are not suited for such analysis. Automated rock mechanical programs are available to use the real-time log data stream, but they generally use the basic linear-elastic theory and a Mohr-Coulomb failure envelope, much like the originally published rock mechanical models for wireline application.

The while-drilling log data are typically less affected by borehole and invasion effects. Mud cake either may not have been built or does not form an impermeable barrier. This has an important effect on the selection of a near-wellbore stress model and its parameters. Existing models assume either an underbalanced or an overbalanced wellbore to formation pressure condition. The overbalanced case typically assumes the presence of an impermeable mud cake. When such a mud cake is not fully developed, an overbalanced condition with fluid flow into the formation must be considered.

Conclusions

LWD data provide quality data in real-time to perform geomechanical log analysis. A number of advantages of the use of LWD log data for geomechanical have been described. At the same time the use of these data presents a number of challenges to the analyst.

LWD Data Challenges

The low data telemetry rate for real-time LWD data typically reduces the data density (samples per foot) as compared to memory data or wireline data. This can compromise the continuity of geomechanical analysis at high speed drilling rates and for that matter the quality of any other real-time log interpretation.

Shear sonic is one of the crucial log measurements in rock mechanical log analysis. In slow formations, this measurement is not available in real-time in the LWD industry at the time of publication of this paper. Slow shear tools are being commercialized but the data have to be processed at the surface. Solutions to real-time slow shear will undoubtedly appear soon.

Current geomechanical models may not be entirely suitable to take full advantage of the real-time availability of the LWD data. Existing models may be too complex to update continuously when data arrive while drilling, even at the relatively slow rate of the mud pulse telemetry. Also models may not take the LWD environment and its effect on the data fully in consideration. Again, undoubtedly, more LWD geomechanical analysis experience will solve these problems in the foreseeable future.

LWD Data Advantages

Two major advantages of the use of LWD in log analysis stem from their real-time measurement nature. First of all, the data are available in real-time while drilling, at the

wellsite and in any office with satellite and/or internet connections. This provides the opportunity to make drilling decisions while drilling and before major problems may occur.
Secondly, the early measurement time of the LWD data behind the bit provides a less invasive and damaged borehole environment. The LWD data better reflect the virgin formation conditions.

Given the advantages of LWD data, their increasing range and reliability of measurement and real-time availability, it is the author's final conclusion and recommendation that it is up to the geomechanical community to start making full use of this information and to explore its new – real-time – applications.

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Nomenclature
Vp = compressional wave velocity
Vs = shear wave velocity

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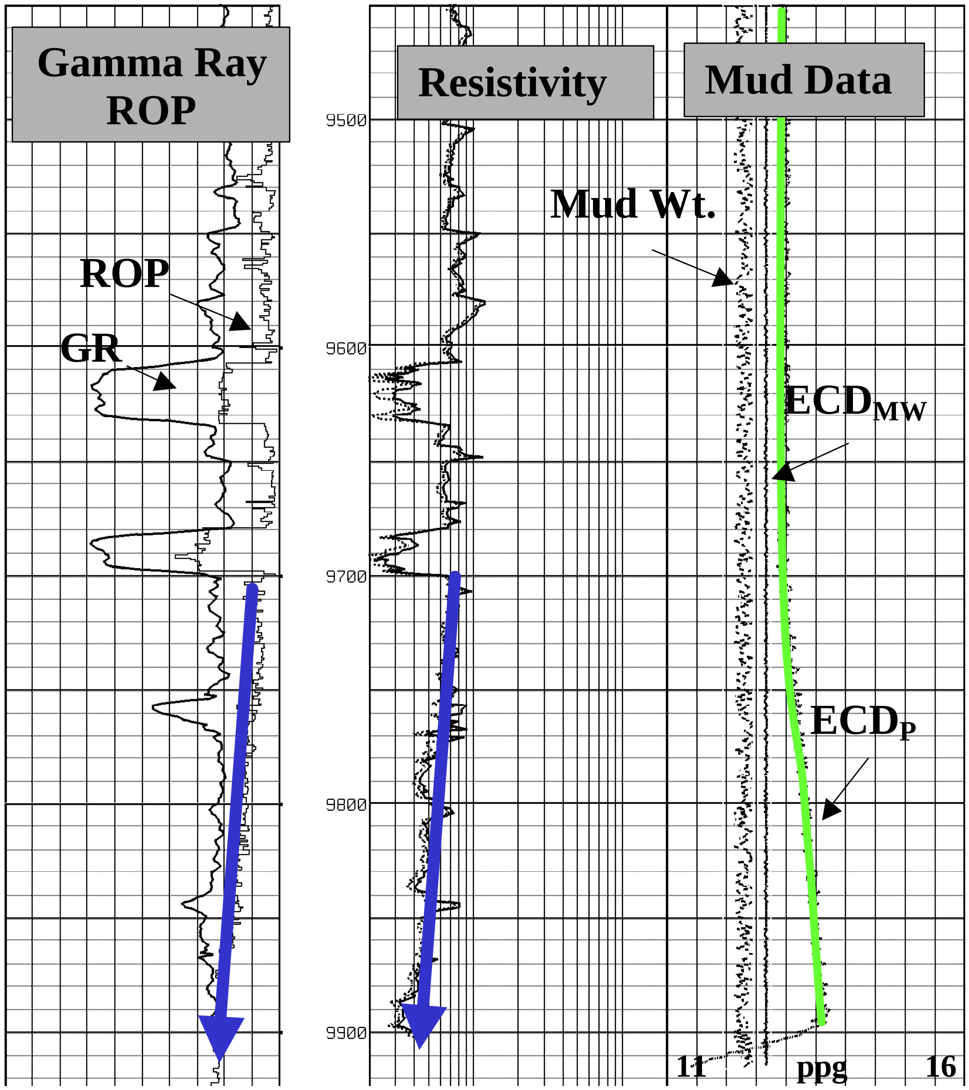

Figure 1 – LWD Log with Gamma Ray, Resistivity and Downhole Pressure (ECD) Measurements.

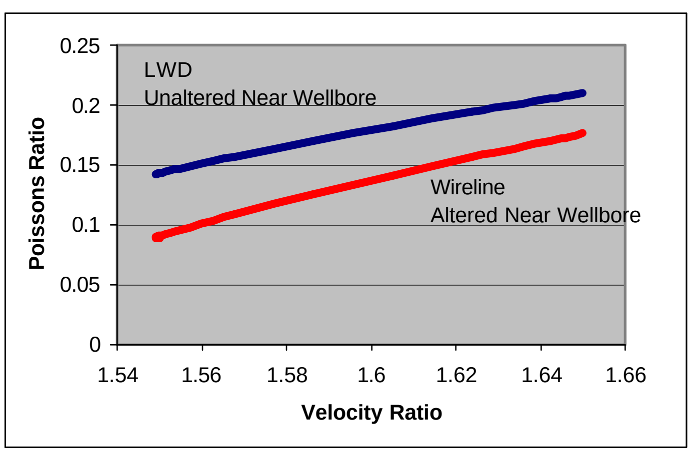

Figure 2 - Change in Poisson's Ratio with Changing Velocity Ratio due to Alteration.

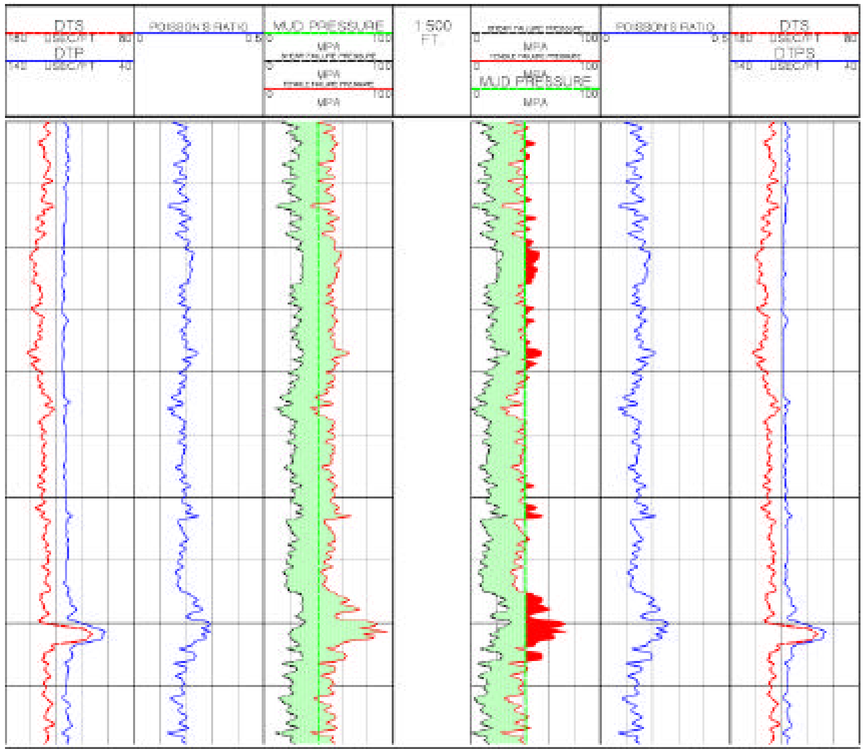

Figure 3 – Wellbore Stability Plot Using Measured LWD data in Tracks 1, 2 and 3 and Altered Compressional Slowness in Track 4,5 and 6

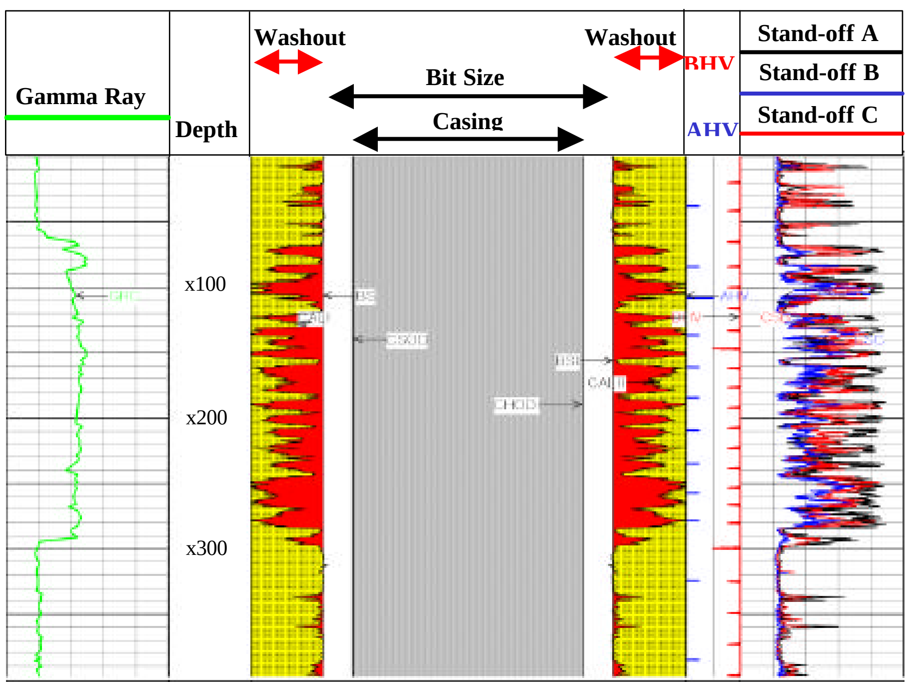

Figure 4 – LWD Caliper Log

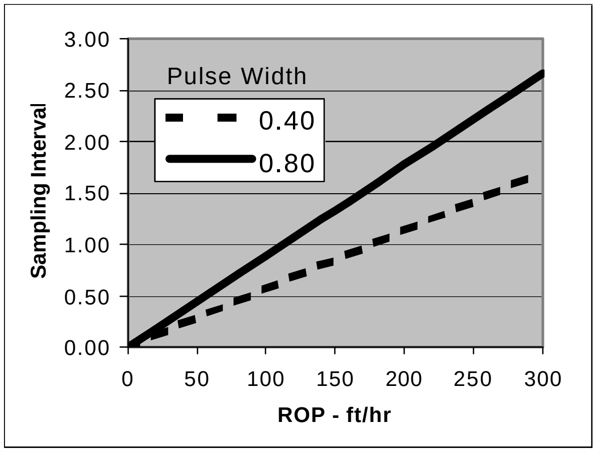

Figure 5 – LWD Data Sampling Interval related