RECENT ADVANCES IN MEASUREMENT-WHILE-DRILLING

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INTRODUCTION

MWD services have been commercially available for over ten years. The most entrenched application is that of directional services, where conventional methods such as wireline steering have all but been obsoleted. The only real advances in this application have been those influenced by software changes and data rate improvements. For example, faster tool face update rates while steering are now possible. A relatively recent sensor is one that provides weight on bit and torque in real time.[1,2] The currently intended applications are estimation of bit wear and bearing failure. A drilling model is used to estimate shear strengths of the rock, although the model currently appears to be limited to shales only. The resulting Mechanical Efficiency Log (MEL[SM])[18] is used for a variety of interpretations. An augmentation of the RLL service is now available whereby the recorded log may be retrieved on a wireline by stabbing with a "wet" connector upon demand. In the interests of brevity, neither this nor the MEL service will be discussed here. The other recent sensors/services are the EWR[R][18] and CNØ[SM],[18] both described more fully below.

DATA RATES

During the eighties, no advance has been made in information transmittal rate, measured in bits/sec. While some systems with capability of 0.25 bits/sec. have more than tripled their rates, the high rate systems have remained in the vicinity of 3 bits/sec. The probable reason is that the available suite of sensors does not demand a greater capability.[3] One frame of formation information is currently available every 25-30 seconds, about the same as it was four years ago. However, a system that records information and delivers at the end of each bit run[4] (the RLL[SM][18] service) has gone from one frame every 32 seconds to one (up to) every 2 seconds. The result is a very finely detailed log even at high penetration rates.

FORMATION EVALUATION WITH MWD

Until about four years ago, the MWD sensors available permitted formation identification rather than evaluation. This was largely due to the available resistivity sensor being a Short Normal type, which in most instances did not provide a quantitative value of formation resistivity (R_t) in pay sands.[5] On the other hand, the value in competent shales was valid and, therefore, very useful in pressure prediction. Today MWD resistivity for pressure prediction is routine, especially in areas where the pressure onset is rapid, such as in the western Gulf of Mexico. Elimination of intermediate wireline logs run for this purpose is common. However, replacement of wireline logs run for the purpose of estimating hydrocarbon saturations was not possible till the introduction of the Electromagnetic Wave Resistivity (EWR [R]) service[4,6] in 1983.

Application of EWR

EWR has a diameter of investigation of about 48 inches. Thus, in most situations, it measures beyond the invaded zone, especially if the sensor is close to the bit. The vertical resolution is 6 in. for bed delineation and 18 in. for measuring R_t. The borehole correction is negligible for normal mud resistivities.[5] The wireline logging alternative to an EWR while drilling is a combination of an induction sensor that reads deep, a medium depth tool and a shallow reading tool such as the SFL[SM(18)] for correction for the extensive invasion that can occur by the time the log is run.[7] Sometimes micro-resistivity tools are needed to define thinner beds.

The utility of the thin bed resolution of the EWR is most striking in the evaluation of thinly laminated sands and shales commonly found in the Gulf of Mexico[8], in the Kuparuk field in Alaska, and elsewhere. These are presumably storm wave deposits or turbidites. In any event, the sands are well sorted and often productive even with relatively high water saturations (S_w's). Each sand layer may be a few inches to a couple of feet thick. Anderson, in her recent paper[9], has shown theoretically that in a sand/shale stack of 1 ft. layers comprising sands of resistivity 25 ohm-meter and shales of resistivity 1 ohm-meter, the deep induction (ILD) tool will read about 2 ohm-meters, and not differentiate sands and shales (Fig. 5 in Ref 9). Greif and Koopersmith confirm this in the same issue of the Log Analyst[5]. In Fig. 1 is reproduced their data on the "B" sand in South Timbalier 300/301. The EWR is so sensitive that the values can be used to clearly demarcate oil from water (oil and water denoted in Fig. 1 by the different shades). Not shown here is their Fig. 7, demonstrating the non-responsiveness of the ILD.

While examples such as the one above are striking and obvious, thin shale laminae in an apparently thick sand body can sometimes cause the ILD to read too low in a pay sand. Fig. 2 shows such a situation, where in the upper sand, the ILD reads ~ 3 ohm-meters while the EWR reads closer to 21 ohm-meters. The EWR trace (and the GR) shows a cusp three or so feet from the bottom indicating the possibility of a thin shale layer. Fig. 3 of Anderson[9] predicts that in a 3 ft. sand layer bounded by 1 ohm-meter shale, the 25 ohm-meter sand reading would be in the neighborhood of 3 ohm-meter on an ILD. While the parallel does not hold exactly, the phenomena in Fig. 2 can be explained by the existence of shale layers too thin to be truly resolved by the gamma log, but thick enough to distort the ILD. Other factors such as dipping bed effects on ILD[9,10] probably also play a part.

Impact of Erroneous Estimates of R_t

Estimation of water saturation is done using the empirical Archie relationship.

$$S_w = \sqrt{\frac{F.R_w}{R_t}} \qquad \text{--- (1)}$$

where F is a porosity-dependent empirical property of the rock, R_t is the resistivity of the formation filled with hydrocarbon to a volume fraction S_{hc} = $1-S_w$, and R_w is the resistivity of water in the pores.

If the superscripts a and b are applied to denote the two different estimates of R_t^i, i = a,b, we have...

$$\frac{S_w^a}{S_w^b} = \frac{\sqrt{\frac{F.R_w}{R_t^a}}}{\sqrt{\frac{F.R^w}{R_t^b}}} = \sqrt{\frac{R_t^b}{R_t^a}} \qquad \text{--- (2)}$$

The approximate ratio of the ILD and EWR estimates in Fig. 2 is 7.

$$\therefore \quad \frac{S_w^a}{S_w^b} = 2.65 \qquad \text{where } a = \text{ILD}, \quad b = \text{EWR}$$

This yields, $$S_{hc}^{b} = 1 - \frac{S_w^a}{2.65} \quad . \qquad \text{--- (3)}$$

In a hypothetical case where F = 10 and $R_w = 0.05$, $S_w^a = 0.41$. The "correct" value of hydrocarbon saturation S_{hc} will be 0.84 (from eqn. 3), in comparison with 1.0 - 0.41 = 0.59. It is clear that reserves estimated using the two figures can be substantially different. In other instances, in pays where there is low contrast between sands and shales,[8] decisions to produce/abandon could be swung by a more accurate assessment.[11] In fact, the example sand in Fig. 1 tends to show EWR value at ~ 1.6, while the ILD values are in the neighborhood of 0.8[5]. Using the arguments as above,

$$S_{hc}^{EWR} = 1 - \frac{S_w^{ILD}}{1.4}$$

Assuming F = 10, $R_w = 0.03$, we calculate $S_w^{ILD} = 0.61$. The corresponding S_w^{EWR} ~ 0.43, with $S_{hc}^{EWR} = 0.57$.

MWD Neutron Porosity

Even with a quantitative resistivity tool, wireline replacement in reservoir sections is limited to situations where the porosity can confidently be inferred from offset wells. Operational considerations such as sticky sands and highly angled holes, which make wireline logging difficult, can force wireline replacement on a limited basis. The recent introduction of a neutron porosity service (CNØ)[12] increases the situations where wireline logs can be replaced. A detailed description of the tool is found elsewhere[13]. If the tool is placed reasonably close to the bit, it is likely to see a borehole in-gauge. The wireline equivalent can require substantial corrections for washout, with attendant interpretational problems. Similarly, because the formation is evaluated before substantial invasion has occurred, the "gas effect" (see Ref. 14 for explanation) is more prominent, leading to a clearer gas/oil demarcation. The ability to "see" the gas before much invasion can be used to advantage. A subsequent pass made hours later can yield an indication of movability of the gas. This technique, known as Time Lapse Logging, has already been used extensively with the EWR[5,12] for differentiating impermeable rock from rock containing movable fluids.

The MWD neutron porosity is a major step forward in formation evaluation. The real breakthrough, however, would be a capability to measure formation density as well, while drilling. At least one company is working on such a capability.

OPERATIONAL CONSIDERATIONS

Use of MWD involves a certain degree of adjustment in operator practices. While this subject does not fit well with the title of this paper, it is being addressed briefly to present information and express viewpoints that the author has not observed in print before.

Hydraulics

Most MWD systems that send data in real time do so with a coded sequence of pressure pulses travelling up the bore of the pipe (one system uses a continuous wave rather than pulses). These pulses are momentary decreases or increases in the drill pipe pressure, and are named negative and positive pulses, respectively. The valves that generate these have the following general characteristics.

TABLE 1

GENERAL CHARACTERISTICS OF PULSER VALVES

	NEGATIVE	POSITIVE
Pressure Drop Across Valve	High	Low
Flow Through Valve	Low	High
Energy to Move Valve	Low	High
Worst Upset Condition	"Open". Short circuit to annulus.	"Shut". Blockage to pipe flow.
Hydraulic Limitation	Minimum valve ΔP to operate.	Minimum flow to operate.

These differences dictate the adjustments required by operators. Because of the high valve operation energy, most positive pulse systems are powered by generators. These have varying limitations on items such as allowable lost circulation materials. Most negative pulse systems are battery operated and can be limited by the available power. Also, most systems require that surface hydraulics be substantially free of acoustic noise through proper operation of pulsation dampeners. The important point of note is that negative and positive pulse systems have very different characteristics. In general though, proper dialogue at pre-job meetings will ensure no surprises on the rig.

Mechanics

The primary consideration is that of ensuring that use of MWD does not adversely affect the control of trajectory. Stiffness is a parameter with strong impact and is commonly defined as

$$\text{Stiffness} = E \times I$$

where E is the Young's Modulus and I is the moment of inertia.

This is a good definition for normal drill collars, with uniform cross-sectional area. However, MWD tools generally have differing areas of cross-section along the length and so the industry has accepted the concept of equivalent diameter(15). For any inside diameter (I.D.) taken as a reference, the equivalent outside diameter (O.D.) is the O.D. of a hypothetical collar of uniform O.D. of the same length and stiffness as the MWD collar with varying sections. For BHA design, therefore, this figure can be used, provided, of course, the material is steel. When considering other materials, differences in the value of E can be a factor. This is especially the case for the relatively new oil field material, beryllium-copper, which has $E \sim 18.5 \times 10^6$ psi, compared to steel with $E \sim 30 \times 10^6$ psi.

Use of static 3-D drill string models[16] has demonstrated that the improper placing of a limber element in a BHA can have a substantial effect. Case: 50,000 lbs. WOB, 40° inclination, 7-3/4 in. collars, pendulum assembly. When a 7 in. MWD tool is placed right on top of the bit, a significant reduction in dropping force is predicted. This, in fact, was observed in the field. The model predicts, however, that if the tool is moved up to just below the first stabilizer, there is virtually no effect relative to the MWD-free assembly. In general, packed assemblies are more forgiving, and the first 150 ft. or so of the assembly is determining. The observation in the case mentioned above can be qualitatively deduced using simple 2-D beam column theory as well. In fact, Millheim's excellent series on BHA design[17] can be used to even intuitively predict the build tendency induced in a dropping assembly of the type exemplified in the case above. The key to the example is not an MWD tool in the assembly, but rather the stiffness mismatch with the rest of the column. For instance, if an 8 in. MWD tool had been used in the example, there would have been virtually no effect. The introduction of a substantially stiffer section will also have an undesired effect. If the effect is understood, however, a desired trajectory can be obtained by BHA redesign. The industry has, after all, learned to live with mud motors, which are significantly more limber than collars.

CONCLUSIONS

MWD sensors have developed to the point where their features, combined with the ability to "see" freshly cut rock, permit formation evaluation in a way not possible with wireline tools. Wireline replacement by MWD in reservoir sections is, therefore, not only possible, but can be the preferred option in development wells. While use of MWD places some restrictions on drilling operations, these are minor if the operator is made aware early in the planning process.

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18. MEL^{SM} and SFL^{SM} are service marks of Schlumberger. EWR^{SM}, CNØ^{SM}, and RLL^{R} are marks of NL Industries, Inc.

ACKNOWLEDGEMENTS

I thank Craig Barnett and Paul Rodney for reviewing the manuscript and NL Baroid for giving permission to publish the paper.

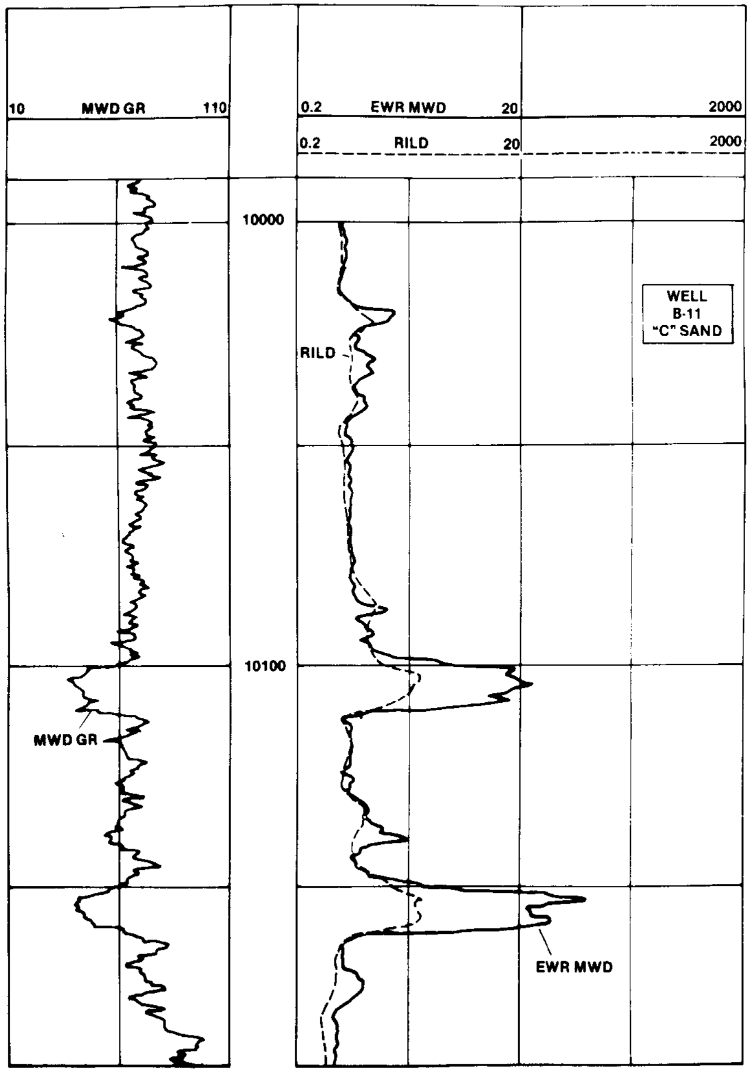

Figure 1—Low contrast pay and wet sand identification with early-time EWR measurements (from Reference 5)

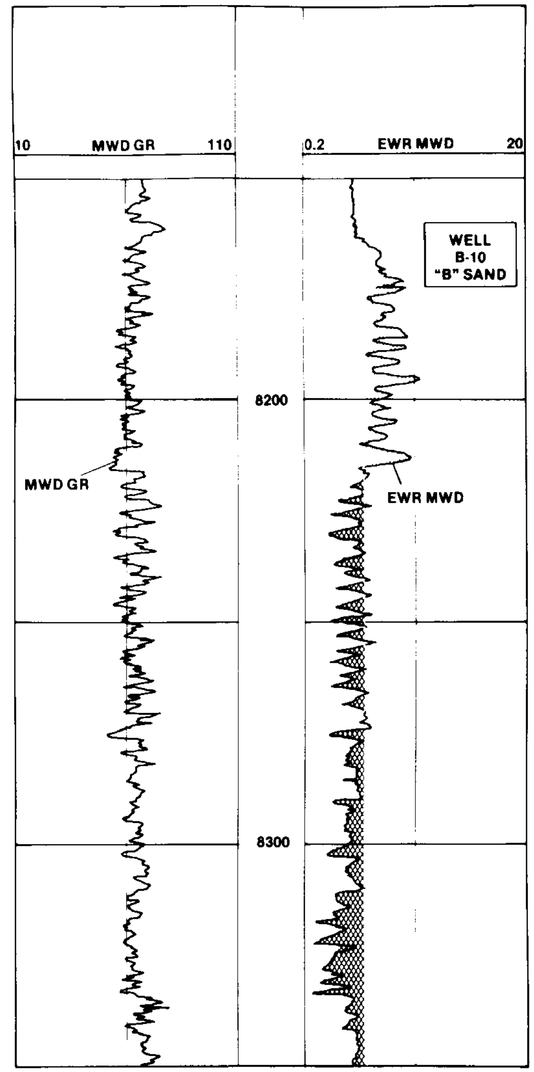

Figure 2—Comparison of EWR with RILD illustrating differences in resistivity responses (from Reference 5)