Formation Pressure Testing while Drilling in Horizontal Wells – A Critical Link to Full Data Evaluation and Cost-Efficient Wellbore Construction

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ABSTRACT

Providing formation pressure data while-drilling allows a continuous approach to data evaluation and decision-making. The ability to measure accurate LWD formation pressure data in hole sizes from 5¾" to 17½" represents a significant opportunity for safe and cost-efficient wellbore construction.

Real-time formation pressure measurements enable geosteering decisions based on the pressure regimes encountered. Pressure and mobility data help target the most productive zones and determine the optimal drain length for horizontal wells. In faulted formations, rapid pressure analysis aids effective geosteering between compartments.

Traditionally formation pressure data are acquired with wireline formation testers upon reaching section or well TD. The given challenges often faced in horizontal or highly deviated wells--depleted reservoirs, high overbalance, increased risk of getting stuck, to name a few--significantly reduce the success rate of acquiring representative pressure data or prevent measuring these critical data at all.

Formation testing is a difficult operation which requires pre-planning, good operator communication, incorporation of local best practice, and careful post-well analysis. Even allowing for the above, the success rate of acquiring representative pressure tests is limited, as formation features such as soft or tight formations and sanding can lead to seal quality issues or misinterpretation.

An innovative new technology incorporates an intelligent closed-loop system to control the formation testing process, assuring optimum sealing efficiency and avoiding formation damage while saving significant time for "lost seal" retesting. A smart test function reduces shock effects while drawing down on tight formations, but also avoids sanding in highly unconsolidated formations. Performing self-learning, optimized test sequences improves accuracy of the pressure and mobility data and produces significant cost savings.

Case histories from different applications in horizontal wells from the North Sea, Norway, Asia Pacific and the Middle East demonstrate the value of the above technology and the applicability to conventional formation pressure testing.

INTRODUCTION

When LWD formation pressure testing technology was introduced to the market, it was quickly adopted by many operators. Over the past two years the technology evolved further; today efficiency levels beyond traditional wireline services are common since experience gained in the past and the desire to implement this knowledge resulted in state-of-the-art downhole technology as discussed below.

1) Self-learning, optimized test sequence (SmarTest™) improves accuracy of pressure and mobility data. In addition to mobility-dependent test times, this smart test function incorporates a reduction of shock effects while drawing down on tight formations and also avoids sanding in highly unconsolidated formations.

2) Intelligent pad control (SmartPad™) allows individual and continuous control of the test cycle and the drawdown pump. An intelligent closed-loop control of the pad pressure enables optimum sealing efficiency.

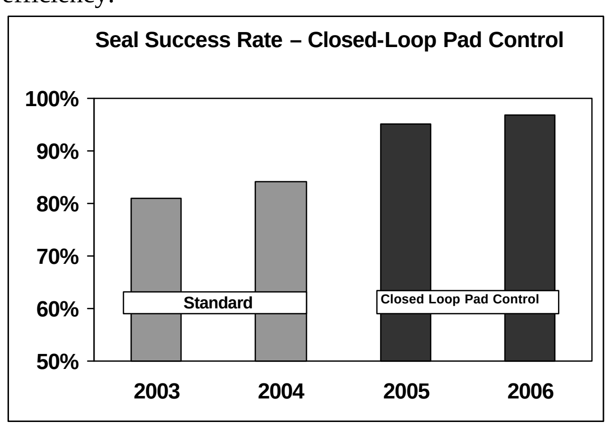

Fig. 1. The introduction of closed-loop pad pressure control increased the seal success rate from 83% to 95%.

A closed-loop control of the pad contact force enables optimum sealing efficiency, saving significant time for "lost seal" retesting and avoids formation damage. Initial LWD formation pressure test results have been good. However, the drive has been to decrease test times and improve seal success and accuracy. **Fig. 1** shows the improvement (on a global basis) in seal success since the introduction of the discussed smart technologies[1].

Description of the LWD Formation Pressure Tester. The tool (**Fig. 2**) utilizes a pad-sealing element, similar to the current generation of wireline tools, to seal off a portion of the borehole wall and establish pressure communication with the reservoir.[1,2,3]

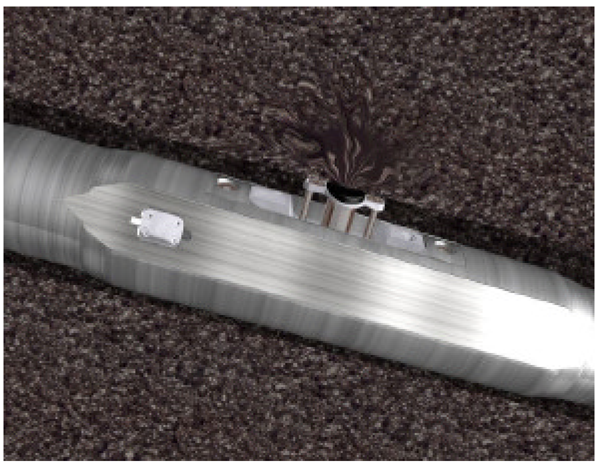

Fig. 2. LWD formation pressure tester (TesTrak).

An intelligent pump control system operates the tool downhole in a closed-loop control with integrated Formation Rate Analysis (FRA)[4,5] and allows different tests to be performed. The tool carries out optimized tests with multiple drawdowns, optimized downhole control in real-time utilizing the FRA algorithms inside the tool. Circulation of drilling fluid is maintained throughout the pressure measurement operation to ensure well safety and provide power to the tool.

Optimized Test. Beside the simple basic test with a single drawdown, this tool has the unique capability of providing optimized tests with repeated drawdown and buildup tests without re-seating the pad. This feature allows in-situ verification of formation pressure measurements. The formation pressure test consists of multiple drawdowns in a sequence (**Fig. 3**). If the three measured buildup pressures do not agree to within the gauge repeatability, the last buildup pressure can normally be used to derive formation pressure, provided the pad seal was maintained and the final buildup pressure was stable. During the repeat tests, different drawdown rates can be used based on the downhole analysis. The downhole intelligent control system analyzes each pressure test data set with an FRA algorithm and adjusts the drawdown rate, volume, and buildup duration based on the FRA quality indicator and formation mobility. Repeat tests provide result confirmation. If the pre-selected buildup criteria are met, the test terminates early, thus reducing test times to a minimum.

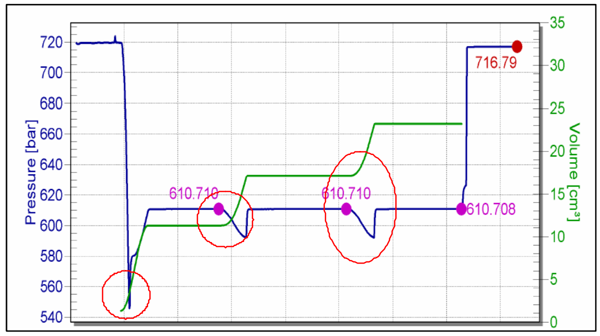

Fig 3. Optimized test sequence with repeat drawdowns.

Conventional Applications

The following examples show Formation Pressure While Drilling (FTWD) data being used in what are considered "conventional" applications, i.e., applications that could also have been performed with wireline tools.

Reservoir Connectivity – North Sea

As part of a North Sea application, FTWD measurements were performed in a horizontal 8½" hole section. The formations encountered are high mobility sands ("clean" or "C" sands), and low mobility mica sands ("M" sands), which are folded and separated by a steep fault zone (**Fig. 4**). One of the objectives was to prove connectivity of the two apparent C-sand compartments to either side of the fault.

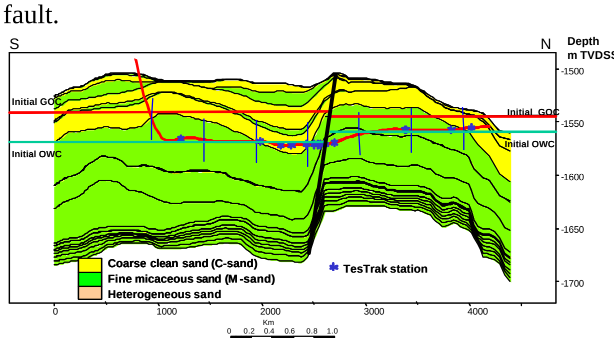

Fig. 4. Wellpath of 31/2-D-4 Y2H (red) and FTWD test-stations (blue) on either side of the fault in "M" and "C" sands.[4]

Eighty-eight pressure and mobility measurements at 34 test-stations showed expected formation parameters in the C-sands. The M-sands were partly supercharged and partly affected by the pad not sealing properly.

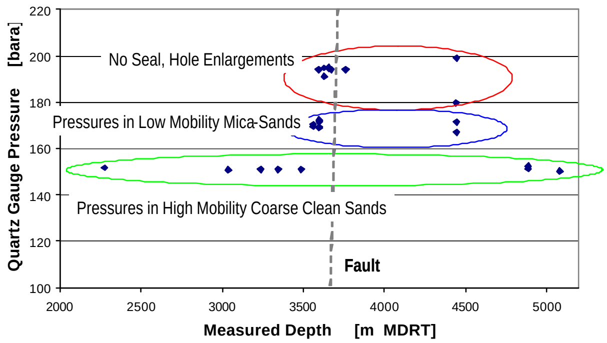

Fig. 5. Three groups of final buildup pressures can be seen, consisting of the no-seal pressures (annular pressures), high and variable supercharged pressures in micaceous M-sands, and the true formation pressures in clean C-sands.[4]

Hydraulic connectivity of the C-sands across the fault could be proven. Re-logging of the low mobility M-sands showed pressure dissipation over time, as to be expected of supercharged formations.

Thin Bed Gas Sands – Asia Pacific

FTWD measurements have been recently performed in thin bed sand/shale sequences. One of these applications dealt with pressure measurements in the vertical producer section of an S-shaped well drilled with a 9-7/8" bit. The objective was to test high mobility gas-bearing sands with minimum thicknesses of only 0.9 m. In such an environment, accurate depth control is crucial to efficient operations.

In total, 26 test-stations with a sealing efficiency of 100% were achieved. The measurements covered a hole section of 673 m MD. Within these 26 test-stations, 51 individual pressure-mobility tests were performed, showing a pressure range from 1,843 to 4,490 psi. The associated mobility values vary from 2 to 230 mD/cP, indicating high mobility sand formations, with intercalations of tight formations. The higher mobility sands are characterized by mobility ranging from 60 to 230 mD/cP. The measured formation pressure values in these zones increase from 1,800 to 4,100 psi with increasing depth.

LWD density-neutron crossover with 6 p.u. difference in the porous interval together with low gamma ray readings indicates light hydrocarbons, which also correlates to the high resistivity values (**Fig. 6**).

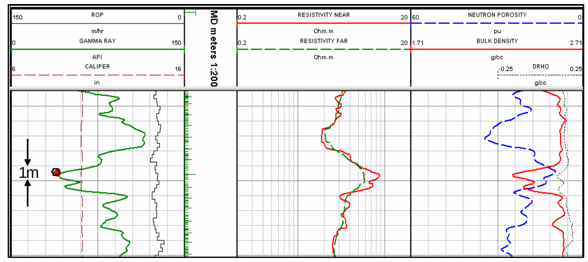

Fig. 6. LWD composite plot, showing density-neutron crossover and high resistivity readings in clean zone at center of the plot. The red dot on the gamma ray track (left) represents the successful pressure test taken in this thin sand layer.

Using a special thin bed operating procedure, which requires data from an LWD gamma ray (GR) tool, the desired sand bodies were identified and characterized in a short time frame. Thus, it was possible to even detect sand bodies of less than 1 m thickness.

The procedure is based on experiences from comparable environments, e.g., turbidite sequences in the Mediterranean Sea, such as found in the Adriatic. It combines off-bottom relog data with short drilling pauses after one pipe stand has been drilled down. The desired test-stations are "marked" during drilling process and relocated after a new connection has been made.

Fluid Contacts from Gradients – North Sea

Formation pressure measurements in a 8½" pilot hole section of a slanted well resulted in several formation gradients. The measurements were performed in horizontally layered sand formations (**Fig. 7**).

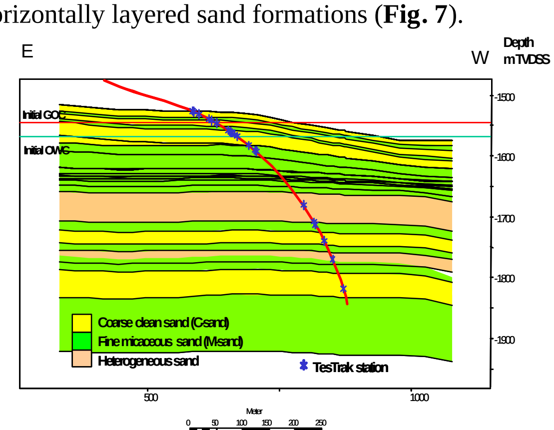

Fig. 7. Wellpath of 31/2-F-5 AH (red) and FTWD test-stations (blue) in different locations of horizontally layered sands.[4]

One gas gradient and two water gradients could be determined in a TVD range of about 300 m (**Fig. 8**).

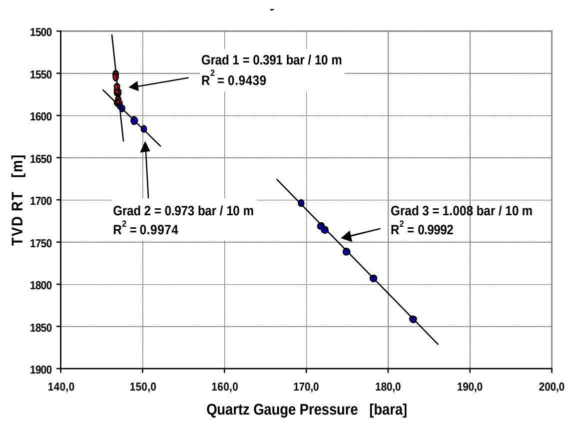

Fig. 8. Pressure gradient plot; based on FRA quality evaluation, 17 individual measurements from 12 test-stations were considered "good", indicating several gradients in different sand compartments.[4]

As the related fields have been subject to oil and gas production for several years, the virgin gradients have been replaced by depleted gradients. The precision of the pressure gauge in the FTWD tool gave a high level of confidence in the accuracy and repeatability of the measurements. Two test-stations, performed at the same depth showed a variation of 0.036 bar between highest and lowest individual value.

Fluid Identification – Gulf of Mexico
Pressure and mobility measurements can be combined with other LWD data, such as gamma ray, resistivity, and density-neutron to enhance the reservoir description process. In a recent application, 7 tests were performed in the upper lobe of a sand interval with a true vertical thickness (TVT) of 20 ft. The density-neutron as well as the resistivity data are indicative of oil. The pressure measurements in this interval provided an oil gradient of 0.362 psi/ft (**Fig. 9**).

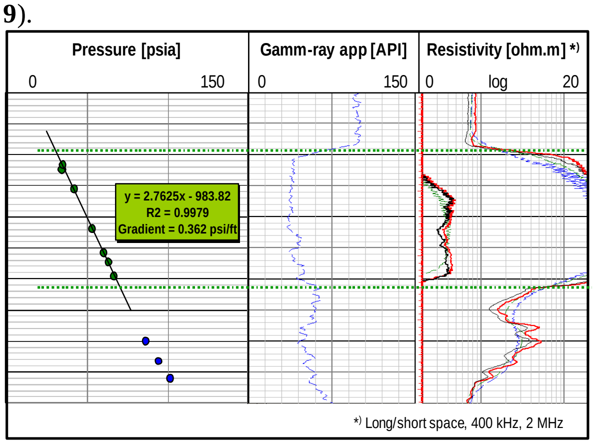

Fig. 9. Pressure gradient vs. LWD log data; the gradient indicating oil, correlates with the others.

LWD Measurements
The LWD data show the lower zone, where three pressure points were taken, to be shalier and less resistive than the upper oil zone. In addition, the two intervals appear to be separated by shale of approximately 5 m thickness, as indicated by gamma ray and resistivity readings. The three pressure measurements performed in the lower zone were not deemed sufficient data to derive a fluid density from the pressure gradient.

However, the pressure gradient in the upper zone and the well location were used with the predictive *PVT^MOD^* software to estimate PVT properties of the oil identified. *PVT^MOD^* uses a vast database of sample-derived PVT information to predict PVT properties based on pressure gradient and well location. In this case, the predicted oil gravity of 24.4°API compared well to the value of 27.4°API of oil produced in this field. In this application, the FTWD tool quantified the reservoir pressure in the target zone without additional wireline evaluation runs. The upper sand was completed as an excellent oil producer.

Formation Testing While Drilling Applications.
As LWD technology continues to evolve, the true value of real-time data is becoming more evident in terms of risk reduction, improvements in wellbore positioning, earlier and higher production, and improved safety. This is especially true for formation pressure data, which is crucial for optimized wellbore pressure control. The examples below highlight some of these novel applications.

Decision-making While Drilling - Casing Point Selection
Usually, casing points are selected based on pre-drill pressure and overburden models, which are derived from field data in offset wells. With the discussed FTWD tool it is possible to verify these models and adjust casing points safely, in some cases allowing the reservoir section to be completed with a larger production casing, which ultimately benefits well productivity and project economics.

In an application offshore West Africa a major blowout disaster was prevented by using TesTrak. The pressure readings from the tool proved to be consistently higher than the upper limit model predicted by exploration (**Fig. 10**). This informed the customer to stop drilling and confirm the data by wireline logs to double-check the reliability of the LWD formation pressure tester since it was the customer's first usage in this area. The wireline values were in perfect agreement with the LWD reading, thus the operator decided to prematurely set a 7-in. liner before penetrating the highly pressured zone just below the present TD.

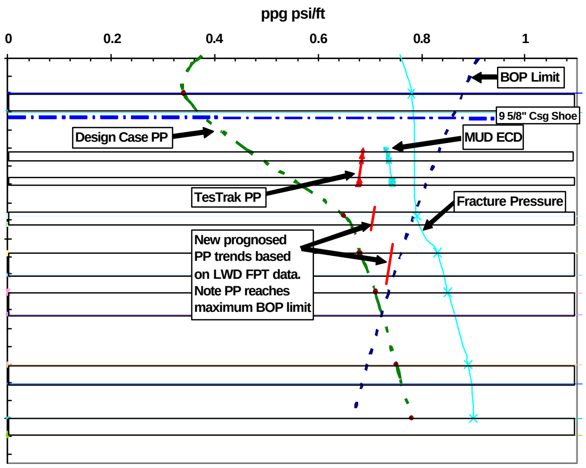

Fig. 10. Pressure gradient vs. depth. The modeled design case pore pressure (PP) was too low. The FPT Tool showed a 0.3 psi/ft higher pressure gradient, bringing PP close to the blowout preventer (BOP) limit. Accordingly, a liner was set early (lower red line), and the BOP uprated early.

Decision-Making While Drilling - Mud Weight Management

If mud weight adjustment is critical, because the well is close to fracture and/or collapse gradient, pore pressure and dynamic annulus or wellbore pressure are key parameters to be determined. Usually, pore pressure is predicted by calculation from gamma ray, resistivity, and acoustic data, with calibration data used from offset wells. With LWD formation testers, pore pressure can directly be measured in real time, with high accuracy, and used for calibrating prediction models. Additionally to a dynamic wellbore pressure, the equivalent circulation density (ECD) is measured and permanently recorded. All values together enable an operator to maintain mud weight, lower overbalance to an optimum, and stay within an ECD window, which is the narrow frame between kick pressure (usually pore pressure) and fracture pressure.

In common applications overbalance is quite often high, sometimes several thousand psi when drilling through depleted zones. In some applications, one of the objectives is to drill with a low overbalance and to keep mud weight close to pore pressure. This lowers drilling risks like stuck pipe.

In deepwater applications the challenge lies in the ability to stay within a very narrow window for the wellbore pressure to avoid kicks on the low end and prevent lost circulation on the high end. An exact knowledge of the formation pressure allows tight control over the well and keeps the drilling operation in the safety window. Preventing kicks or lost circulation is a significant economical aspect as it significantly reduces non-productive time (NPT).

In the challenging application discussed below; high temperature (> 120°C), variable mobility (0.04 to 252 mD/cP), and a high mud weight (2.05 SG), 16 test-stations were performed. The results of these test-stations were confirmed by previous wireline runs and LWD measurements. With an overbalance as low as 7.4 psi (**Fig. 11**), it was possible to adequately maintain a very narrow ECD window. Some of the test-stations were affected by super-charging and were excluded from further evaluation on the basis of the Formation Rate Analysis.

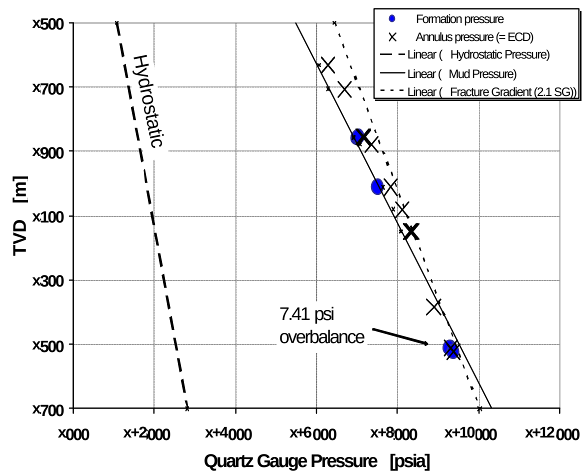

Fig. 11. Pressure vs TVD. Displayed values are measured formation pressure (blue points), measured annulus pressure (black crosses), both with FTWD tool: calculated hydrostatic pressure (1 SG, fresh water, dashed line); calculated mud weight pressure (1.95 to 2.05 SG, straight line); and calculated fracture gradient (2.1 SG, dotted line).

The application was performed in a thick shale sequence with interbedded sand channels over a drilling distance of more than 1,000 m in a vertical 8½" hole section. The average thickness of the sand bodies was 0.75 m, with a maximum of 1.2 m.

Due to the higher drilling risk presented by the narrow pressure window in this well and the potential for overpressured zones being encountered, pore pressure in the shale was predicted in real time based on LWD resistivity data. To further refine the prediction, the FTWD data from the sand intervals were used as a calibration reference, which allowed drilling the well closer to balance at reduced risk.[9]

Deepwater Testing in the Gulf of Mexico

TesTrak's high-precision quartz gauge allows pressure measurements to be performed in a high-temperature / high-pressure environment. In a recent application in the Gulf of Mexico, a tool was equipped with a 30,000 psi gauge since the operating environment was potentially exceeding 25,000 psi annular pressure.

This capability was required to evaluate pore pressure in real time to ensure wellbore stability and integrity. The 30,000 psi pressure rating requirement was critical to success if the predicted pore pressure was encountered.

Novel FTWD Applications

As LWD technology continues to evolve, the true value of real-time data is becoming more evident in terms of risk reduction, improvements in wellbore positioning, earlier and higher production, and improved safety. This is especially true for formation pressure data, which is crucial for optimized wellbore pressure control. The examples below highlight some of these novel applications.

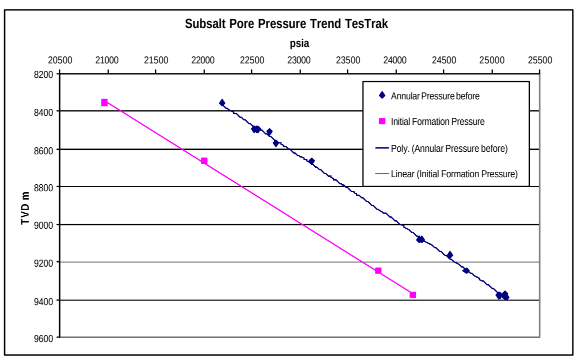

Fig. 12. Comparison between actual and proposed wellplan (based on financial planning).

Based on the original pore pressure and mud weight estimates, 6¾” tools capable of 30,000 psi annulus pressure were requested for the final 8½” hole section of the well. While drilling the upper hole section, pressure estimates were confirmed by the formation pressure tester (8¼” tool) and provided confidence in the actual data. Evaluation of these data derived the decision to extend the 10? ” x 12¼” section and eliminating the need for a planned casing string. To ensure wellbore stability, the application was performed while maintaining circulation.

Formation Pressure Measurement - Distance Pad to Bit

FTWD tools are usually assembled at the top end of a bottomhole assembly (BHA) since directional drilling and LWD measurements such as gamma, resistivity, density and porosity are required first to evaluate the reservoir and to determine the zone of interest **(Fig. 13).** A common operating procedure is to drill a stand down, perform a connection, and then approach the test-station. This approach does not require positioning the formation pressure tester as close as possible at the bit.

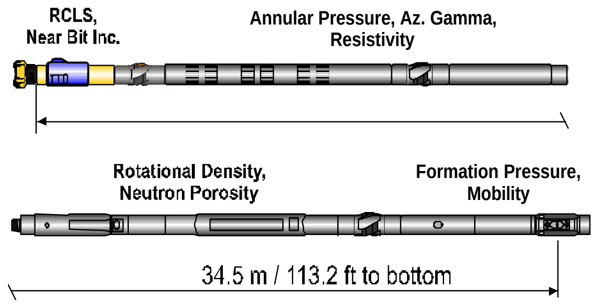

Fig. 13.

With an increasing number of applications focusing on safety aspects, where the FTWD technology is used for ECD management or safer casing point selection, more requests have been made for FTWD assembly further down in the BHA.

Fig. 14 shows such an assembly with the formation pressure measurement only 8.8 m (29 ft) from the bit.

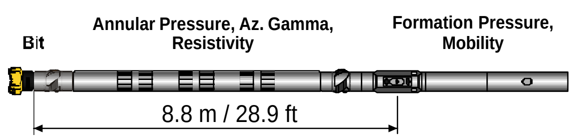

Fig. 14.

This rotary BHA still allows gamma, resistivity measurement and directional measurements prior to the formation pressure measurements.

Fig. 15 shows a rotary BHA, which focuses mainly on well safety; the pad is only 2.8 m from the bit. Such an approach compromises LWD measurements, but could help in challenging drilling conditions (e.g., in a short run to enter a particular zone).

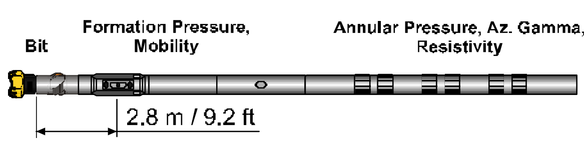

Fig. 15.

Pressure Steering – TVD Control

In a recent deployment, formation pressure measurements were used for pressure navigation. This concept uses common depth survey methods supported by formation pressure tests of high accuracy and good real-time resolution. Common depth survey methods usually include a standard inclination uncertainty of +/- 0.1° degree, excluding BHA SAG effects **(Fig. 16).** This amounts to a TVD uncertainty of max 3.25 m over a horizontal section of 2,000 m, for instance. In comparison, pressure uncertainty of a quartz gauge is 0.015 bar in practice; with the gauge being mounted centrally in the tool, tool orientation effects can be neglected. This amounts to a TVD uncertainty of 0.2 m, whatever the length of the horizontal section (at 0.8 g/cc fluid gradient).

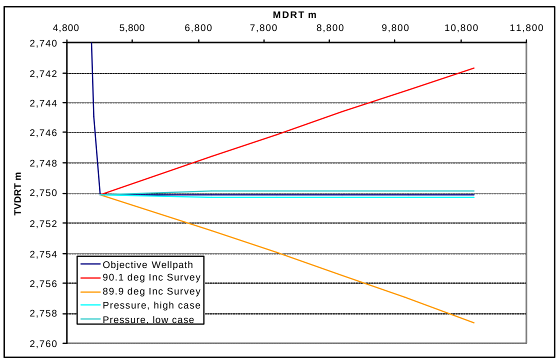

Fig. 16. Depth uncertainty from common depth survey compared to depth survey from LWD pressure measurements.

In the pressure navigation concept, several effects must be considered:

- No reservoir depletion.
- No pressure compartmentalization between considered test-stations.
- A benchmarked, initial pressure test, which has to be repeated if pressure compartmentalization occurs.
- A good pressure gradient (gas, oil, water).
- A real-time differentiation between "good" and "bad" tests, using the optimization process inside the tool (optimized test, quality bit, formation mobility).

A case study of conventional vs. pressure navigated survey in a 900 m horizontal well section showed that the pressure navigation method indicates a 2 m TVD offset compared to the conventional depth survey **(Fig. 17).** This apparent TVD drop at around 9,650 m MD might have been caused by either pressure compartmentalization or by a true TVD drop, which could not be resolved using common depth survey only.

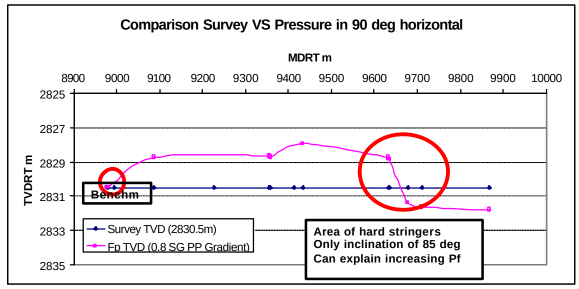

Fig. 17. Comparison between common depth survey and pressure navigation concept; the apparent TVD difference of about 2 m indicates either pressure compartmentalization or a true TVD offset.

Summary, Conclusion, and Outlook

Because of the nature of acquiring formation pressure and mobility while drilling, real-time decisions result in benefits such as increasing wellbore safety with the knowledge of the formation pressure at the time of drilling or active ECD management for advanced drilling such as deepwater or other drilling operations with tight ECD windows.

In terms of reservoir characterization, additional benefits can be derived from integrating the FTWD data with data from other LWD tools. For example, formation mobility derived from the FTWD measurements can be used to calibrate the permeability profile generated by a nuclear magnetic resonance LWD tool to deliver a valid formation producibility profile. Comparison with well test or spinner flow meter data can help ascertain the applicability of this approach.

In difficult environments, it has been observed that when properly prepared and equipped, self-optimizing LWD formation pressure tools can be used to:

- Measure formation pressure in highly unconsolidated soft and friable formations, even in a while-drilling environment.
- Increase wellbore safety with the knowledge of the formation pressure at the time of drilling.
- Provide active ECD management for advanced drilling such as deepwater or other drilling operations with tight ECD windows.
- Calibrate pore pressure prediction modeling during drilling.

- Extend the range of performing formation pressure measurements into extended reach wells.
- Optimize the casing program by selecting a different casing setting point.
- Enhance the safety and efficiency of a wireline sampling program by determining formation overbalance (reducing the risk of "differential sticking") and formation fluid bubble point (reducing the risk of "flashing" the sample, ensuring high-quality monophasic pressure/volume/temperature samples).

Early knowledge of formation pressure and mobility helps to define reservoir parameters earlier in the drilling program to:

- Refine the reservoir pressure model.
- Improve planning for the production phase.
- Reduce NPT while simultaneously improving rig safety.

Additional applications are being investigated to further improve both wellbore placement and reservoir characterization.

NOMENCLATURE

UCS = Unconfined Compressive Strength
FRA= Formation Rate Analysis

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Ashok Thorat completed his Bachelor of Science degree in Electronics Engineering in 1993. During his tenure of 13 years, he has worked in different organizations in various capacities, predominantly in MWD/LWD services. For the last five he has served as an INTEQ Formation Evaluation Manager for India & Bangladesh.

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