Optimizing Drilling Performance by Wellbore Stability and Pore-Pressure Evaluation in Deepwater Exploration

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Abstract
This paper discusses the most important drilling hazards related to borehole instability and pore pressure in deep water wells. A case study from a deep water well, which has experienced wellbore stability and loss of circulation problems, especially over intervals with higher angles of hole deviation, is presented. The answers provided by the study included properties, such as, recommended mud-weights (minimum & maximum) as a function of angle of deviation, rock strength and computed pore pressure. The determination of rock strength along with the optimum mud-weight windows improved overall the drilling performance in the next deep water well by minimizing washouts, loss of circulation and optimizing casing design by elimination of unnecessary casing strings. Moreover, improvement of bit performance was achieved by using the predicted rock-strength values. As a result, drilling time and well construction costs were significantly reduced.

Introduction
Wellbore stability and pore pressure related issues, especially in deep water blocks, cause frequently serious problems during drilling, logging and production operations. The narrow pore pressure and fracture gradient (PPFG) windows necessitate multiple casing strings to reach the target reservoir formations. Errors in predicting PPFG windows could result in significant loss of rig time and even failure of wells. The removal of rock during the drilling operation disturbs the natural rock formation that is being subjected to a state of compressive in-situ stresses at depth. The redistribution of the stresses around the hole thus produces stress concentrations at or near the borehole wall. Such a high stress buildup around the wellbore may lead to a number of hole problems that include stuck pipe, borehole collapse, sloughing shale and excessive fill. Several billions of dollars are lost each year worldwide directly or indirectly caused by wellbore stability and pore pressure related problems. Therefore, in order to fully obtain the benefits of the directional drilling technology, wellbore stability analysis and pore pressure prediction has been of increasing demand in the planning stage of the wells, especially in deep water where exploration and field development costs are very high.

Wellbore stability can be managed by determining the critical mud weights that provide sufficient wellbore wall support to counteract the redistribution of stresses resulting from the creation of the wellbore. The critical mud weights are mainly dependent on the in-situ stress regime, pore pressures, wellbore direction and inclination, and formation properties and drainage conditions.

In this study, a geomechanical model was developed using all the available data from a deep water well, which experienced significant drilling and wellbore stability problems, especially over shaly intervals. The geomechanical model was then used to provide wellbore stability planning, pore pressure and drilling parameter optimization for a proposed deep water well. The study evaluated the rock-mechanical properties and in-situ stress state of all the prognosed formations. It then interpreted the conditions required for wellbore stability during drilling. The optimum drilling parameters provided by this study included properties such as, recommended mud-weight, rock strength, pore pressure and earth stresses. These parameters can be very useful for a stable, safe and cost-effective drilling.

Drilling performance and wellbore conditions in the new deep water well were improved significantly, which led to lower drilling costs and better quality of logs.

The following sections describe the theoretical background, the methodology and results, followed by the summary, conclusions and recommendations for deep water drilling optimization.

Theoretical Background
The two main-types of mechanical instability that can occur in a wellbore for a given combination of stresses and rock strength are: tensile fracturing-due to excessive pressure exerted by the wellbore fluid, and compressive shear failure (known as breakout, sloughing, spalling or cave-ins) due to insufficient wellbore fluid pressure, as shown in Figure 1. Nearly all wellbore instability problems occur in the weaker rock formations, predominantly shales. The awareness of high-risk shale formations has led to substantial research on shale properties, which comprises either mechanical or chemical investigation or a combination of both. Although
many instances of instability result from a combination of both mechanical and chemical instability, mechanical factors play a dominant role in wellbore instability during the drilling phase of operations. For example, borehole instability is observed even with the most inhibitive drilling fluids, e.g. oil-based mud. Also, mechanically induced instability caused by high in-situ stresses in vertical wells can create a more or less severe environment for inclined wells, depending on the direction and inclination of the wells with respect to the stress field. Significant effort, therefore, has been put into mechanically-induced instability studies. Wellbore stability is closely related to parameters such as, rock strength and deformation, in-situ stress regime, pore-pressure, porosity, lithological composition, clay content, water saturation, type of pore-fluids, temperature, etc. Development of a MEM (Mechanical Earth Model) is essential in incorporating all the above parameters in one consistent model. The mechanical earth model is a computer-based description of the state of stress and rock mechanical properties for a specific stratigraphic section in a field or basin. The model is linked to geologic structure through the local stratigraphy and a 3D seismic cube. In its most complete form, the MEM consists of a full 3D description of pore pressure, stress and mechanical properties. In practice, the complexity of the model evolves in step with the acquisition of new information. From exploration to development, the model evolves from of a sparse set of 1D profiles to a full 3D description of rock properties and earth stresses (Figure 2). Once an MEM is constructed, it can be used to estimate and predict the best possible methods for safely drilling and completing in both a single borehole and for the entire field development.

**Methodology and Results**
The detailed workflow for this study was as follows:

- Initially, all the input data (logs, drilling information, mud-log, etc.) were carefully studied and assessed, so that they could be used with maximum benefit. All available data were correlated with the geological model for the intersected formations to ensure correct depths and structural geometry.

- All the available well logs were depth matched and properly corrected, where needed, for environmental, borehole, and invasion effects. Then, a volumetric lithological property evaluation was performed for accurate determination of porosity and lithology. This part was extremely important for all the rock-mechanical predicted properties are strongly related to petrophysical properties. Thus, all the available geological and log data were utilized for the determination of the most representative petrophysical model.

- Then, the Mechanical Earth Model (Figure 2) and wellbore stability evaluation were obtained in the control well (well1). The concentration of stress around a wellbore will vary according to the magnitude of the in-situ principal stresses and orientation of the wellbore to these stresses. This description of the in-situ state of stress is therefore important to be able to predict failure in any planned well trajectory. The in-situ state of stress is defined in terms of the order and magnitudes of the three principal stresses: one of which is generally vertical, the other two horizontal, and the direction of the horizontal principal stresses. Thus, the study of the in-situ state of stress considers the magnitude of the overburden and the pore pressure, which provides internal support to the rock, and the magnitude and orientation of the horizontal principal stresses. The overburden stress was estimated using a combination of two techniques. The first technique used was by integration of the formation density from the vertical well log model with respect to depth. The second technique, which was applied over the interval where no density data is available, used an exponential extrapolation model. The parameters controlling the computation were optimized by using the deviation azimuth and TVD of the well in conjunction with the best match to the density log values at the top and bottom of the available log density data. Moreover, identifying stress direction and magnitudes allows improved drilling methods and can impact production planning. Several methods for identifying stress direction are available including borehole breakout orientation, natural and induced fracture orientation, shear sonic anisotropy and three component VSP. Available data in this study allowed us to look at the first two methods, i.e., borehole breakout orientation and shear-wave anisotropy. The minimum and maximum horizontal stress magnitudes were computed using a poroelastic model. The in-situ stresses were then calibrated by evaluating wellbore stability (Figures 3, 4, 6 and 7) and comparing the predicted borehole failure with caliper data available.

- Pore pressure, which is a key parameter within the MEM, was determined in shaly intervals using several log-based methods, each typically relating velocity to the pressure signal in the formation due to under-compaction. Normal pressure/sonic trends show DT shale values decreasing with depth due to compaction. In areas of overpressure due to under-compaction, DT values in shale will increase or remain constant as depth increases. Predicted pore pressure, required for the calculation of effective stresses, was calibrated to the available MDT data (Figure 5).

- Following, an evaluation of wellbore stability versus deviation and azimuth was performed, as shown in Figures 3, 4 and 6.

- The determined MEM and wellbore stability evaluation results were then extrapolated to the planned deep water well using the proposed trajectory.

The determination of the MEM along with the optimum mud-weight windows improved overall the drilling performance of the new deep water well by minimizing washouts (Figure 8), loss of circulation and optimizing casing design by elimination of unnecessary casing strings. Moreover, improvement of bit performance was achieved by using the predicted rock-strength values. As a result, drilling time and well construction costs were significantly reduced (15 days drilling time reduction).
Summary and Conclusions
In this study, a Mechanical Earth Model (MEM) was developed using all the available data from a deep water well, which experienced significant drilling and wellbore stability problems. MEM is a description of rock-mechanical properties, rock strengths, in-situ earth stresses and pore pressures as a function of depth, referenced to a stratigraphic column. The MEM model was then used to provide wellbore stability planning, pore pressure and drilling parameter optimization in a new proposed deep water well. The new well was drilled successfully, as per the recommendations of this study. Drilling performance and wellbore conditions in the new deep water well were improved, which led to lower drilling costs and better quality of logs. Post drilling cost evaluations revealed that the total drilling cost savings exceeded $4 million.

The main conclusions drawn from this study are the following:

- Integration between petrophysics, geomechanics and drilling engineering is very beneficial to the design and drilling performance optimization of deep water wells.
- Application of the Mechanical Earth Model (MEM) proved successful in achieving significant drilling cost reductions.
- The return on investment from this study was about 80:1 for the drilling phase alone.

Recommendations for deep water drilling

- In deep water wells, due to the narrow pore pressure and fracture gradient (PPFG) window, it is recommended that pore pressure and fracture gradient evaluation should be conducted in the pre-drilling phase using the MEM model integrated with seismic data. Ideally, a pore pressure cube should be established using seismic tomography or basin modeling approach. A pore pressure profile can then be extracted for any new wells to be drilled in the area. The predicted pore pressure and fracture gradient need to be updated while drilling using LWD data, look ahead VSP data and drilling observations, so that, real-time decisions can be made based on the updated prediction. It needs to be noted that the newly developed formation pressure while drilling (FPWD) technology allows us to calibrate the pore pressure prediction with real-time pore pressure measurement and the annular pressure while drilling (APWD) measurement tells what is the ECD in the annular; therefore, it enables the adjustment of proper mud weight and drilling practices.
- It is also highly recommended to conduct extended leak-off test if possible, which tells the fracture closure pressure more accurately, and provides good quality calibration data for minimum in-situ stress calculation.
- A feasibility and risk analysis should be performed to assess the wellbore stability of deviated wells.
- Drilling optimization through risk management and real-time decision-making: The drilling process is a series of decisions and associated actions made during the planning and execution of the well, that result in the delivery of a completed well. The degree of success or failure and efficiency of the well is determined by the quality of those decisions as a whole. Making good effective decisions depends on having an accurate view of the current conditions, understanding the consequences of the decision and being prepared for the future. Thus, to deliver a successful deep water well, it is critically important to have a very effective well planning, including pore pressure and wellbore stability prediction. It is equally important to have a mechanism to update the prediction while drilling, using real-time data interpretation and observation, and also forecast using the updated model. A risk management process links well planning, executing and contingency planning and ensures the best real-time decision-making.

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References
Fig. 1 Wellbore instability in a Jurassic Shale caused by low mud-weight.

Fig. 2 Schematic drawing of Mechanical Earth Model (MEM), showing a framework model (left), mechanical stratigraphy (center) and rock mechanical and earth stress and Pore Pressure profiles (right) – (after Plumb et al., 2000).

Fig. 3a and 3b Evaluation of wellbore stability versus hole azimuth and deviation. Blue is more stable and red is less stable.
Fig. 4 Evaluation of wellbore stability versus deviation. Green: safe mudweight, blue: shear failure, yellow: tensile failure, red: Tensile and shear failure.

Fig. 5 Pore pressure evaluation calibrated to MDT pore pressure measurements.
Wellbore Stability-5 angles of deviation

Fig. 6 Evaluation of wellbore stability versus hole deviation for five angles of deviation (0, 15, 30, 45, 60°).
Fig. 7 Evaluation of wellbore stability versus deviation for control well (well 1). Note that the hole exhibits a lot of washouts, especially over the shaly sections, as shown by the calipers logs.

Fig. 8 Borehole condition for planned well (well 2) over a thick shale section. Note that despite the shaliness of the formation and the high hole deviation, the borehole is fairly gauged, as shown by the caliper logs.