NEW INSIGHTS INTO WELLBORE STABILITY ANALYSIS WITH INTEGRATION OF PETROPHYSICS, ROCK PHYSICS, GEOLOGY, GEOMECHANICS AND DRILLING

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Summary

CCED is the operator of onshore blocks in the Sultanate of Oman. The blocks are located on the eastern flank of the Oman Salt Basin. Within the area of interest, the Barik, Al Bashair, Buah and Khufai Formations form the main oil and gas reservoirs. While trying to reach these targets, CCED faced significant issues while drilling wells through the sandstone-rich claystones of the Barakat and Mabrouk Formations. 1D pore pressure and geomechanical models were built for ten wells chosen based on their representability of the field, data availability, spatial coverage and issues faced during drilling. The main goal of the study was to understand the geomechanical behavior of the different formations and identify measures to optimize future drilling decisions especially when drilling deviated wells through the Mabrouk Formation to land horizontal laterals in the Barik Formation. The study concluded that most of the held up and stuck pipe issues were due to WBOs caused by stress and strength anisotropy (caused by weak bedding planes). Heavier muds were recommended for subsequent drilling operations during which no major borehole issues were detected. Strength anisotropy (caused by WBP) was detrimental only when well deviation exceeded 30 deg.

New insights into Wellbore Stability Analysis with integration of Petrophysics, Rock Physics, Geology, Geomechanics and Drilling

Introduction

CC Energy Development S.A.L. (Oman Branch), henceforth CCED is the operator of onshore blocks in the Sultanate of Oman. The blocks are located on the eastern flank of the Oman Salt Basin (Figure 1). Precambrian, Cambrian and Ordovician carbonates and clastics form the principal reservoir horizons in the blocks, these formations dip NW into the basin.

Within the area of interest, the Barik, Al Bashair, Buah and Khufai Formations form the main oil and gas reservoirs. While trying to reach these targets, CCED faced significant issues while drilling wells through the sandstone-rich claystones of the Barakat and Mabrouk Formations. A lot of tight spots, held ups and wellbore stability/caving issues were observed during drilling. In some of the wells, the drilling string/casing got stuck which resulted in occasions in sidetracking the well. These issues were further exacerbated when a build up section from vertical to horizontal required to be drilled through these unstable formations.

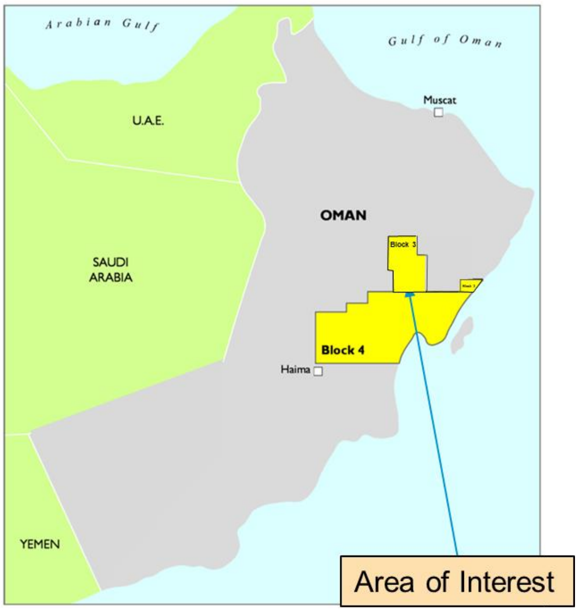

Figure 1: Field location (source: KeyFacts Energy)

A detailed geomechanical study was performed to investigate the causes of the drilling problems. 1D pore pressure and geomechanical models were built for ten wells chosen based on their representability of the field, data availability, spatial coverage and issues faced during drilling. The main goal of the study was to understand the geomechanical behavior of the different formations and identify measures to optimize future drilling decisions especially when drilling deviated wells through the Mabrouk Formation to land horizontal laterals in the Barik Formation. An integrated approach including automated mineralogy, petrophysics and rock physics, image log interpretation and geomechanical modelling was adopted to identify problem zones, assess reasons for well failure and propose new drilling strategies in these problem zones. The study was complemented by a detailed drilling fluids review.

Petrophysics, Drill Cutting Analysis and Rock Physics

The study started with a comprehensive petrophysical evaluation including rigorous data quality control, wireline log conditioning and correction in washout zones. Two simultaneous analyses were implemented to reduce the uncertainty associated with the petrophysical properties. The estimated mineral volumes were first calibrated against drill cuttings data. Rock physics modelling was then performed to ensure consistency between rock properties and elastic

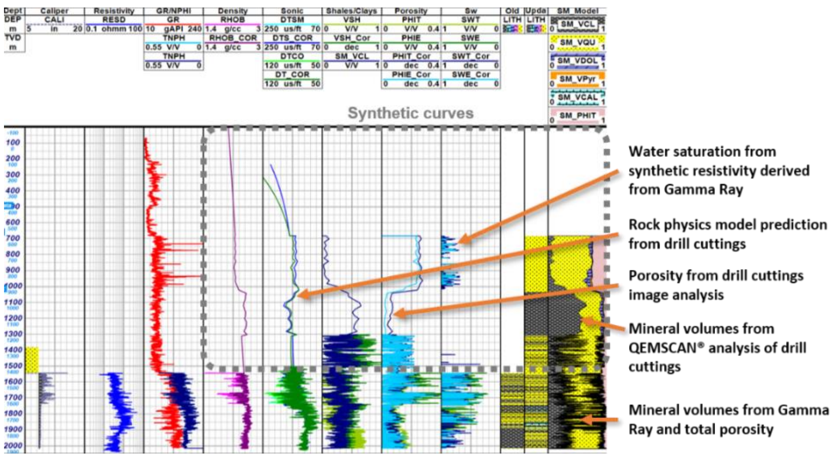

Figure 2: Robust and consistent log suite obtained by integrating input data from petrophysics, rock physics and geology

attributes. The resulting robust petrophysical models provided the input well log suite (illustrated in Figure 2) needed for the geomechanical evaluation.

Drill cuttings were analysed at eight wells from the Ghudun, Barakat and Mabrouk Formations. In addition to calibrating the mineral volumes estimated during the petrophysical analysis, they were also used to predict elastic pseudo-logs in intervals where wireline logs were not available. The cuttings samples, prepared as polished epoxy-resin blocks coated with carbon, were analysed using a Quanta 650F scanning electron microscope fitted with two energy dispersive spectrometers and a back-scattered electron detector. The automated mineralogical analysis using the QEMSCAN® revealed that Ghudun Formation is mainly composed of quartz and potassic feldspars whereas Mabrouk Formation is dominated by clays such as illite as illustrated by Figure 3. These contrasting mineralogies partly explain why the two formations have different geomechanical behaviours.

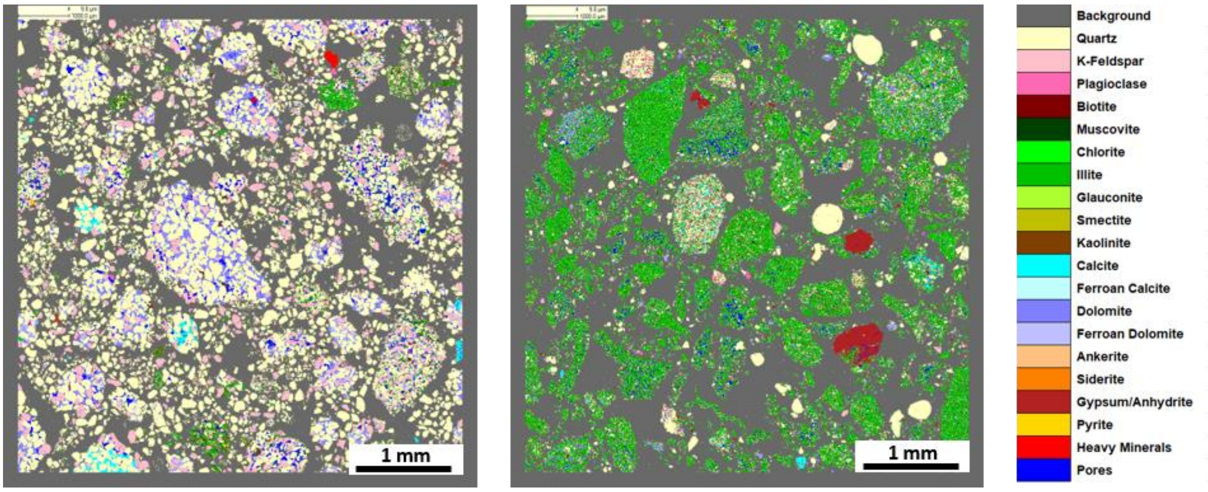

Figure 3: QEMSCAN® mineral map images of drill cuttings from Ghudun (left) and Mabrouk (right) Formations.

A rock physics analysis was performed to calibrate models able to predict elastic logs (density, Vp, Vs, Young's modulus and Poisson's ratio) in the shallow formations of the studied field (Ghudun, Barakat, Mabrouk) where logging is either missing or of insufficient quality. Granular effective medium models from Allo (2019) were applied to the petrophysical logs and the cuttings data. In this novel process, the consistency between log data and cuttings data is checked which helps reduce the uncertainty associated with the correction of the petrophysical logs.

Image Log Analysis

Image log analysis was undertaken to determine wellbore breakout (WBO) location, orientation, length, and width aperture to calibrate the 1D mechanical earth model (MEM) and to provide geological context to changes in the present-day stress regime that may influence drilling operations. WBO orientations demonstrate reasonable consistency across Blocks 3 & 4 and are consistent with the overall tectonic setting of compression from the Oman Mountains Fold Belt and a regional NNE-SSW to NE-SW SH_{max} orientation. Variations in stress with depth and between wells are observed throughout the study area and have been related to remanent stresses in the sedimentary pile. The spatial (lateral) trends of WBO and washouts and regional fault orientations are related to but not directly responsible for the drilling problems encountered in the studied field.

Mechanical Earth Modelling (MEM) and Wellbore Stability Analysis (WBS)

1D-MEMs were constructed along ten well trajectories based on the results from integrated analysis and interpretation of petrophysical, elastic and image logs. Although log interpretation forms the backbone of the process, other information such as mud logs, drilling reports, stress measurements (minifrac/DFIT, LOT, XLOT) and core tests are critical to obtaining fully calibrated stress and failure profiles along the wellbores. More details on the workflow are given in Swami *et al.* (2019).

Removing rock mass during drilling causes stress concentration around the wellbore. This stress concentration depends on in-situ stresses, pore pressure, mud weight, rock strength and well trajectory. Furthermore, this stress concentration can cause failure at the wellbore wall. In a vertical well, maximum stress concentration is at an azimuth of Sh_{min} hence WBOs occur here. Minimum stress concentration is at an azimuth of SH_{max}; hence DITF/HF occur here.

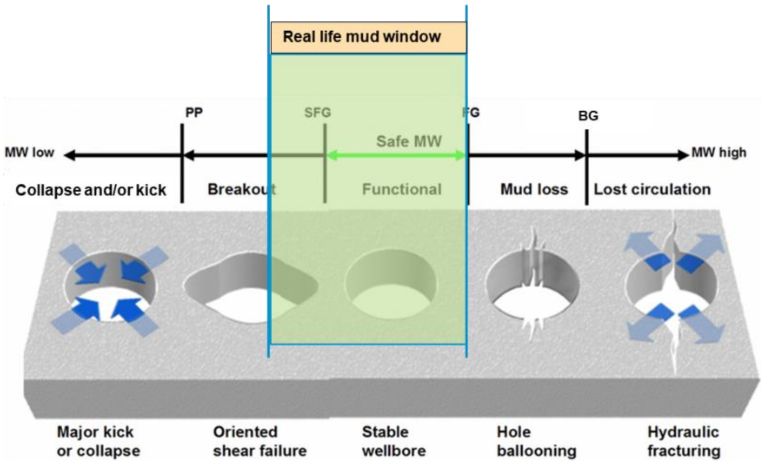

Figure 4: Mud window for safe drilling (Zhang, 2020)

WBOs may cause tight spots, held ups and heavy drags resulting in a stuck pipe during drilling. They are often characterized by cavings at the shakers. A wellbore experiencing a large number of breakouts can be stabilized by increasing the mud weight. *Figure 4* shows the concept of mud window used in drilling.

Figure 5 shows the MEM and WBS models for a well that faced significant washouts in the Mabrouk Formation when drilled in 2010. Calculated WBOs in track 17 tie well with observed ones from caliper (tracks 5 and 6) and FMI (tracks 7 and 8). These WBOs were caused primarily by low mud weights.

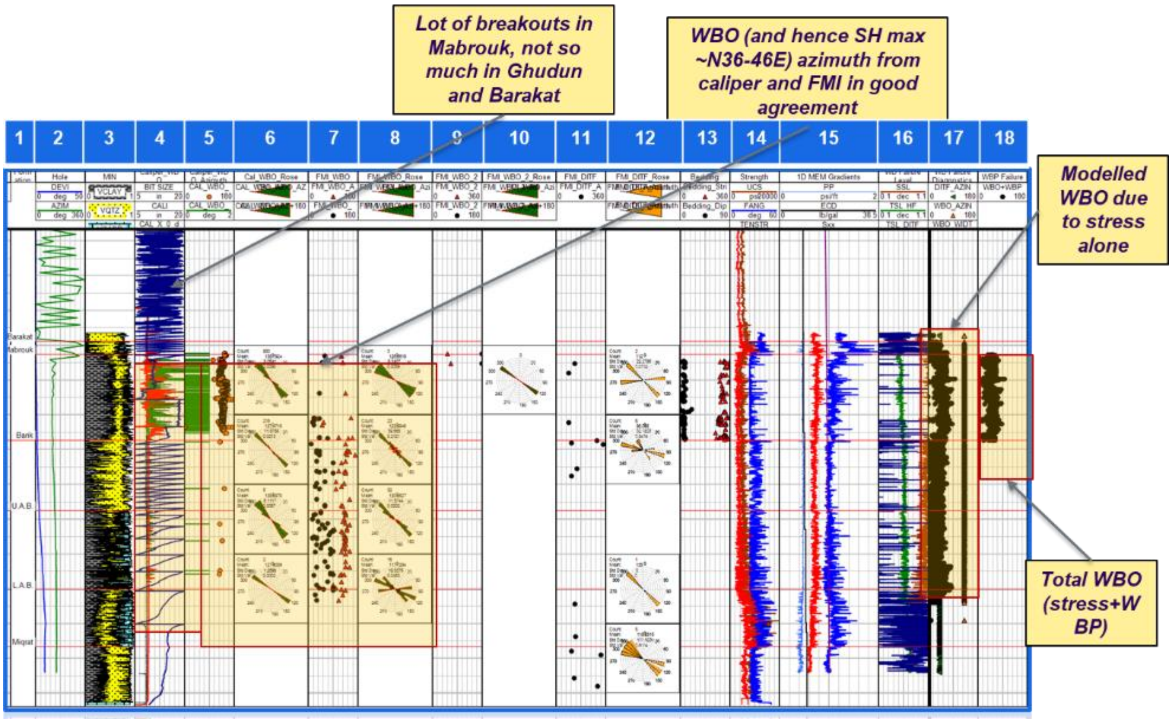

Figure 5: MEM and WBS for one of the problematic wells

Figure 6 shows the mud window to minimize the WBS issues. A MW (mud weight) lower than a computed lower bound may cause WBOs (shown in orange). On the other hand, an ECD (Equivalent Circulating Density) higher than a computed upper bound could result in drilling fluid losses. Driller's objective is to stay within the corridor defined by these two bounds shown in light blue. MW stereonets are shown on the right-hand side. The concentric circles show well deviation and the angular position shows well azimuth from the north. The nearly vertical well is represented by a black circle close to the centre of the stereonet. The normal to the bedding planes is represented by a white circle with a red outline. In this specific case, the formation is made of sub-horizontal layers. The upper stereonet plot shows recommended MW without accounting for weak bedding planes (WBP) whereas the lower plot shows with effect of WBP. Accounting for WBP significantly increases the recommended MW for highly deviated wells but there is virtually no effect for a vertical well.

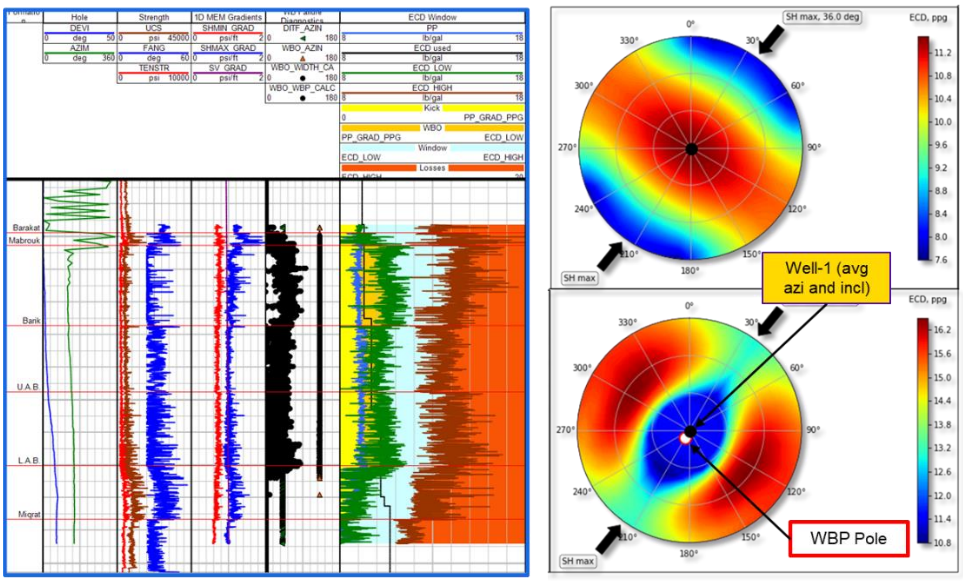

Figure 6: Mud window and stereonet plots to optimize drilling

Conclusions

An integrated study bringing together experts from various fields (petrophysics, rock physics, geology, geomechanics and drilling) was carried out to understand the cause of drilling issues in the studied field.

- For most part, the stress regime was found to be normal (Sv > SHmax > Shmin) or strike-slip (SHmax > Sv > Shmin). While there is some regional variability, SHmax orientation is N36E +/- 10° for most formations/wells
- The laminated and clay dominated Mabrouk Formation was identified as the principal problematic zone, a small number of breakouts were observed in the Barakat Formation but these were not very significant and did not impact drilling performance, Ghudun Formation sandstones did not cause issues in any well.
- The geomechanical evaluation concluded that most of the held up and stuck pipe issues were due to WBOs caused by low mud weights. Heavier muds were recommended for subsequent drilling operations during which no major borehole issues were detected.
- Strength anisotropy (caused by WBP) was detrimental only when well deviation exceeded 30 deg.

Acknowledgements

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