Prudent and Integrated Approach to Understanding Wellbore Stability in Canadian Foothills to Minimize Drilling Challenges and Non-Productive Time

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Summary

A proactive and analytic tasks were undertaken to circumvent anticipated drilling problems in a challenging Canadian Foothills project. The geology and structure were complex with multiple sheets of overthrust fault and highly dipping beds. Some of the faults were associated with coal seams which was one of the major concerns in terms of wellbore stability if the borehole drilled through such zones. Therefore, a comprehensive study was performed using several offset well data to predict instability across three coal zones. Additionally, fault stability analysis was done for all the faults. Based on wellbore and fault stability analysis, and offset wells drilling events' log, a drilling strategy was mapped taking into consideration all the risks, mitigation, and prevention of possible drilling problems with the best mud weight and trajectory design recommendation. The results from this study helped drill the challenging well with no major problems.

Introduction

Reduction of drilling cost and time is one of the main goals of drilling communities, and to achieve those goals, they commonly battle with wellbore instability related drilling problems—often unarmed. Many operators drilling in the Canadian Foothills region, like similar foothill areas around the globe, often face extremely challenging environments to drill due to wellbore instability related to the tectonic stresses and associated faults, fractures, complex structures, and/or anomalous pore pressure. Additional challenges arise due to complicated and highly deviated well designs where planes of weakness in the formation being drilled and their relative angle with respect to the well path become crucial factors in assessing stability of the borehole. Also, highly laminated rock like shale and coal commonly exhibit substantial differences in rock properties and their strengths parallel versus perpendicular to the laminations. Therefore, to successfully achieve the most cost- and time-effective drilling, it is prudent to be armed with proper assessment and understanding of wellbore stability along with optimizing the most appropriate drilling strategy.

Theory and/or Method

The first step in such a study and the central building block involves creation of Mechanical Earth Model (MEM) which is the numerical representation of the geomechanical information consisting of mechanical properties and behavior of the rock that extends from well to field and to basinal scale. Construction of a MEM is a 10 step process (See Figure 1 & 2) which, relies upon the availability and quality of data. The minimum but exhaustive data requirement for a MEM is as follows besides being aware that the amount, quality, and completeness of the data affect the outcome and accuracy of the pore pressure and geomechanical models.

- **Compressional and shear sonic velocities**
- Well locations and deviation surveys

- Open and cased hole well logs of density and porosity
- Well tops or geological horizons
- Daily drilling reports
- Formation pressure and/or closure stress direct measurements (MDT, Mini-frac, LOT, etc)
- Seismic or checkshots data
- Borehole image logs or calliper data; and Mechanical properties measurements on core

The aim of the 10 step process is to achieve following elements that make up the MEM using several proven correlations to determine them from petrophysical and sonic logs:

- Elastic mechanical properties
    - Young’s Modulus
    - Poisson’s Ratio
- Rock strength
    - Unconfined Compressional Strength (UCS)
    - Tensile strength
    - Friction angle
- In situ stress
    - Vertical tress
    - Maximum horizontal stress
    - Minimum horizontal stress
    - Direction of principal stresses
- Pore pressure

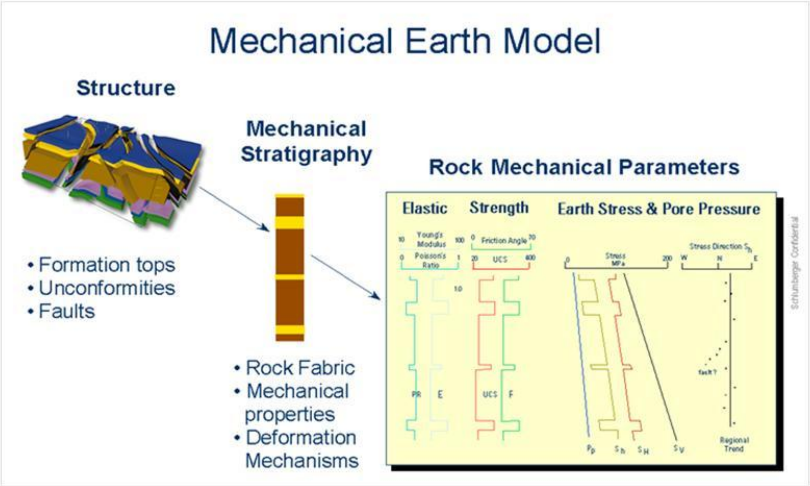


Figure 1: The Mechanical Earth Model concept

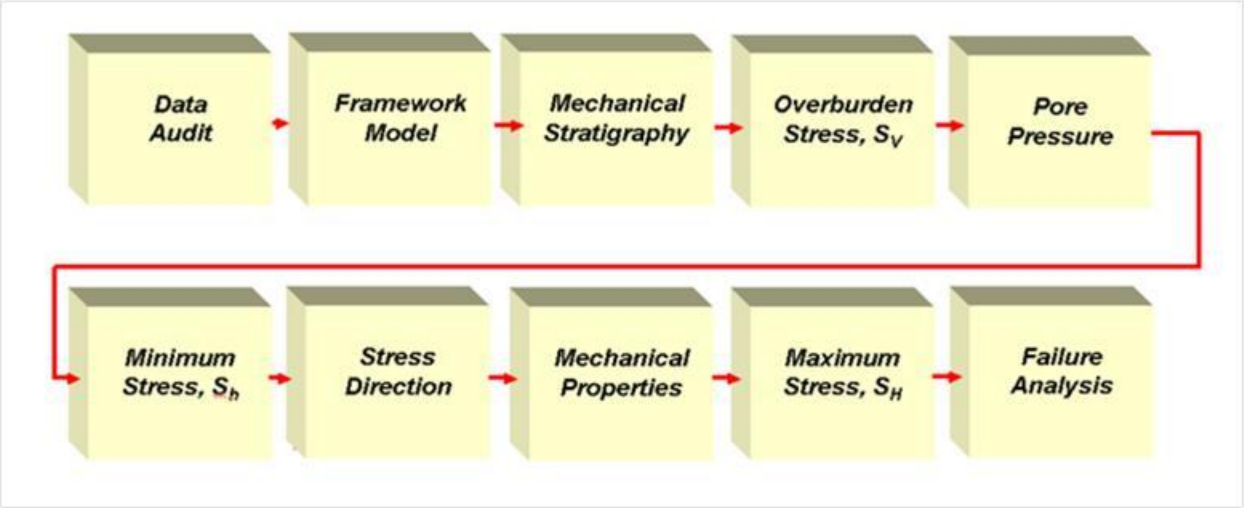


Figure 2: A 10-step workflow for construction of a MEM and Failure Analysis for Wellbore Stability

Theory of Wellbore Stability Analysis

The best way to validate the WBS model is to verify the predictability of the model with field observations. By conducting WBS analysis using the log-based computed rock properties, estimated pore pressure and horizontal stresses, and then comparing the predicted WBS with the drilling events observations in the offset wells, one can see how robust the MEM is.

Accurate estimation of stresses is critical to wellbore stability analysis. Before a well is drilled, compressive stresses exist within the rock formations. With the exception of structurally complex areas (e.g. near salt diapirs), the in-situ stresses can be resolved into a vertical stress, (σ_V), and the horizontal stresses (σ_H and σ_h), which are generally unequal. When the well is drilled, the rock stresses in the vicinity of the wellbore are redistributed as the support originally offered by the drilled out rock is partially replaced by the hydraulic pressure of the mud. The redistributed stresses are normally referred to as the hoop stress, σ_t, which acts circumferentially around the wellbore wall, the radial stress, σ_r, and the axial stress, σ_a, which acts parallel to the wellbore axis as shown in Figure 3.

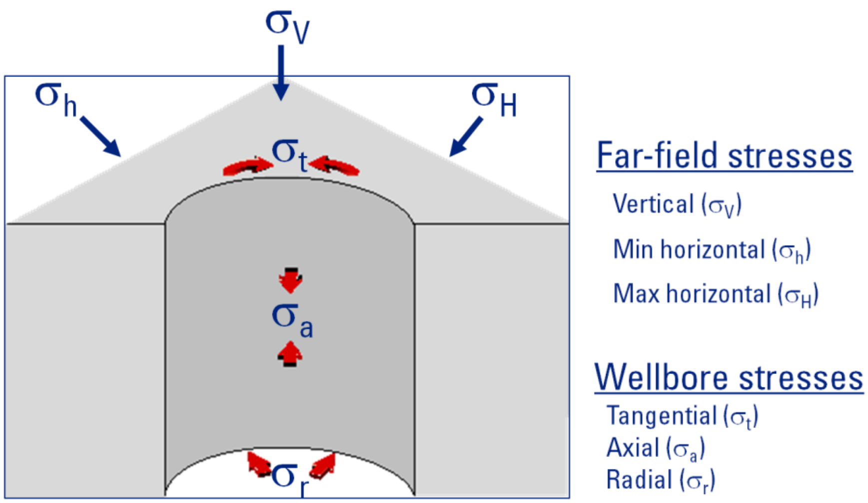


Figure 3: Redistribution of stresses near wellbore wall.

Successful drilling requires that the drilling fluid pressure stay within a safe mud-weight window defined by the pressure limits for wellbore stability. The lower pressure limit is either the pore pressure in the formation or the limit for avoiding wellbore collapse (breakout due to compressive/shear failure). Normal burial compaction trends lead to hydrostatically pressured formations, where the pore pressure is equal to that of a water column of equal depth. If the drilling fluid pressure is less than the pore pressure, then formation fluid or gas could flow into the borehole, with the subsequent risk of a blowout at surface or underground.

Typically, a “safe” mud weight is computed so that

$$P_p < P_w < \sigma_h \qquad (1)$$

Where P_p is the formation pressure, P_w is the drilling fluid pressure, and σ_h is the minimum horizontal stress. A borehole is considered “stable” when the mud weight is such that no shear or tensile failure develops. To compute the stable mud weight window, the stresses around the borehole must be determined first, and then use certain failure criteria to compare the stress state at the borehole wall with the rock strength.

Rock Failure Criteria

There are numerous methods exist for predicting rock failure and wellbore instability. The most commonly used failure criteria include Mohr-Coulomb criteria to determine shear failure, and *Maximum Tensile Stress criteria* to determine tensile failure.

Compressive or Shear Failure Criterion:

Mohr-Coulomb criterion

The Mohr-Coulomb criterion uses unconfined compressive strength (UCS) and angle of internal friction (ϕ) to assess the failure.

Mogi-Coulomb criterion

The Mogi-Coulomb model describes the shear failure mechanism using a linear relationship of shear stress and normal stress, similar to that of Mohr-Coulomb model. It is well known that Mohr-Coulomb model is over conservative (predicts failure at lower stresses) for wellbore condition, as it ignores the effect of intermediate principal stress (σ_2).

Modified Lade criterion

Like Mogi-Coulomb, the Modified Lade model also considers the effect of intermediate principal stress (σ_2)

Tensile Failure Criterion:

The criterion for tensile failure initiation is simply determined by whether the minimum effective stress at the wellbore wall is less than the tensile strength of the formation (assuming compression is positive).

Fault Stability Analysis

Strength of faults in the subsurface varies widely depending on factors such as the faulted material, type of mineralization in fault, and age of faulting. Fault strength is typically determined from frictional sliding and sample loading experiments. The coefficient of friction for cohesionless faults obtained from frictional sliding experiments typically range between 0.55 and 0.80 (i.e. friction angle of 30 deg and 40 deg) [Handin, 1969 and Byerlee, 1978]. Cohesion of fault depends on whether the fault is open or healed, if the fault is a healed one then it depends on type of secondary mineralization occurred in the fault. It is relatively difficult to get this data. For this reason, faults are typically assumed as open faults in fault stability analysis which is a conservative case. Several fault stability studies [e.g. Barton et al., 1995 & 1998; Wiprut and Zoback, 2000] assume faults to be cohesionless and behave according to a Byerlee [1978] type friction law. It should be noted that "healed" faults can have considerable cohesion and, in some cases, can be stronger than the intact rock.

Shear strength of fault, pore pressure and in-situ stresses are the key parameters to assess fault stability. Estimation of critical values of these parameters that may cause fault slippage requires the knowledge of these parameters at current conditions.

Rock strength can be estimated empirically from wireline log data and then can be calibrated against core data, but not fault strength. Since no fault strength data was available in this study, faults are assumed to be open, cohesionless ($C_0 = 0$) and have a coefficient of friction (μ) of 0.4-0.7 (ϕ=20-40 deg). Fault stability against slippage is assessed using Mohr-Coulomb criterion. As was discussed earlier, the MC criterion considers two strength parameters, cohesion (C_0) and frictional angle (ϕ) for fault. Fault stability analysis was conducted for a total of fourteen (14) faults

Fault stability analysis was conducted using **Stability Advisor*** (Schlumberger proprietary software), which determines fault reactivation or fault slippage risk by estimating the increase in pore pressure and decrease in fault strength required to cause reactivation. The risk of fault slippage presented in this study solely reflects the fault strength, orientation and relative dip with respect to well trajectory, and did not consider changes in pore pressure.

Case Study

Based on the integrated methodology described above, wellbore stability analysis (WBS) was conducted for a well in the foothills using three different failure criteria, Mohr-Coulomb (MC), Mogi-Coulomb (MGC) and Modified Lade (ML). All three methods show approximately similar results. Three major wellbore instability sections have been identified, they were all in coal formations: Coal 1: 1627-1634m MD, Coal 2: 1690-1706m MD, and Coal 3: 2642-2648m MD. All three methods predicted similar amount of failure in the top two sections (coal 1 & coal 2), where as ML indicated moderate level of failure in coal 3. Failure predicted in coals was mainly large and deep breakouts that could lead to cavings, hole pack-off, and hole cleaning could be a challenge. The final WBS analysis results from MC method are shown in Figures 4.

Coal is typically fractured and has special fabric a cleat network. It is difficult to form a good quality mud cake in coal, consequently, fractures can reopen, and mud can infiltrate coal cleats causing mud losses. Since no information on fractures and coal cleats was available, this effect was not considered in the analysis.

The brief description of tracks used in Figures 4 is given below:

- **Track 1:** Measured depth (MD)
- **Track 2:** Simplified Mechanical stratigraphy. Bright yellow with dots sections are grain supported (sand), olive with black dashed lines sections are clay supported (shale), cyan sections are carbonates, and black sections are coals.
- **Track 3:** True vertical depth (TVD)
- **Track 4:** Pore pressure and in situ stresses

- **Track 5:** Rock mechanical properties and rock strength, YME: Young's modulus; PR: Poisson's ratio; FANG: Friction angle; UCS: Unconfined compressive strength; and tensile strength
- **Track 6:** Wellbore stability and mud weight window. Red represents breakouts, black represents breakdown, purple represents kick (pore pressure), and blue represents mud loss. The green vertical line is the actual mud weight used, and the blue one is 10% more than the mud weight to represent the equivalent circulation density (ECD). The model predicts breakouts when the mud weight (green line) is smaller than the breakout (red color) profile. The model predicts drilling induced tensile fractures when the tensile breakdown (black area) profile is less than the ECD (blue line). The white area is the safe mud weight window
- **Track 7:** Predicted wellbore rock failure. Black lines/dashes/dots are predicted drilling induced fractures; yellow-red areas are predicted breakouts

Sections where major breakouts can occur are clearly seen in coal section in Figure 4. Dark yellow and slightly red colored area in Track 7 represents major breakouts predicted by the model. Zoomed snapshots of wellbore stability analysis at selected depths where major breakouts were predicted.

A close look at the sections of wide wellbore breakouts indicates that most wide breakouts occur in coal sections, some minor breakouts also occur in sand and shale sections. Coal is soft and highly fractured formation with inherent cleated structure; has significantly lower UCS values, this could be one of the causes for major breakouts in coal sections. Although carbonates have quite high UCS values compared to sand and shale, some of the carbonate sections also show breakouts apparently in the direction of maximum horizontal stress; this is due to the presence of natural fractures in carbonates which can lead to loosen blocks and breakouts in these zones. Since image logs or any other information that can help us ascertain natural fractures in carbonates were not available, it was difficult to quantify effect of natural fractures on wellbore stability.

It is well known that Mohr-Coulomb failure model is a conservative model, meaning it shows worse than it is. Considering the amount of uncertainty in mechanical properties and stresses in this study, it could be safer to consider results from MC model.

In order to understand the range of failure in coal sections, MGC and ML models were also run and the WBS results from these models in coal sections are not shown here. Based on the WBS analysis and information from offset wells, a number of minor and major drilling events are predicted in planned target well as listed in Table 1.

To understand safe mud weight windows in problematic sections, WBS sensitivity analysis was conducted at selected depths and the results are presented in Figures 5 to 8. In these figures, the left part represents mud weight sensitivity with respect to well deviation and the right part represents mud weight sensitivity with respect to well azimuth. Brown, yellow and green colors represent formation fracture, breakouts and safe mud weight respectively.

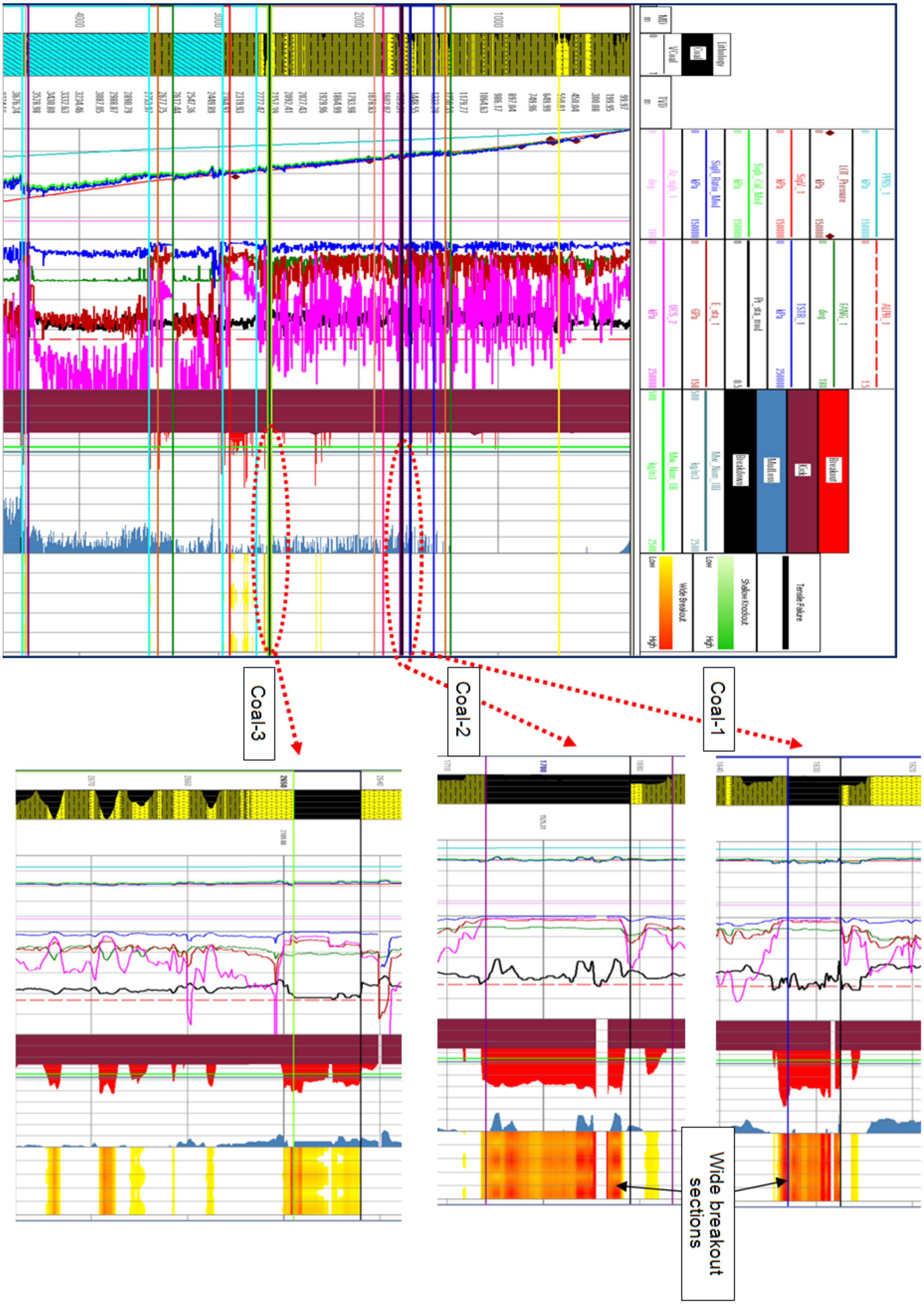
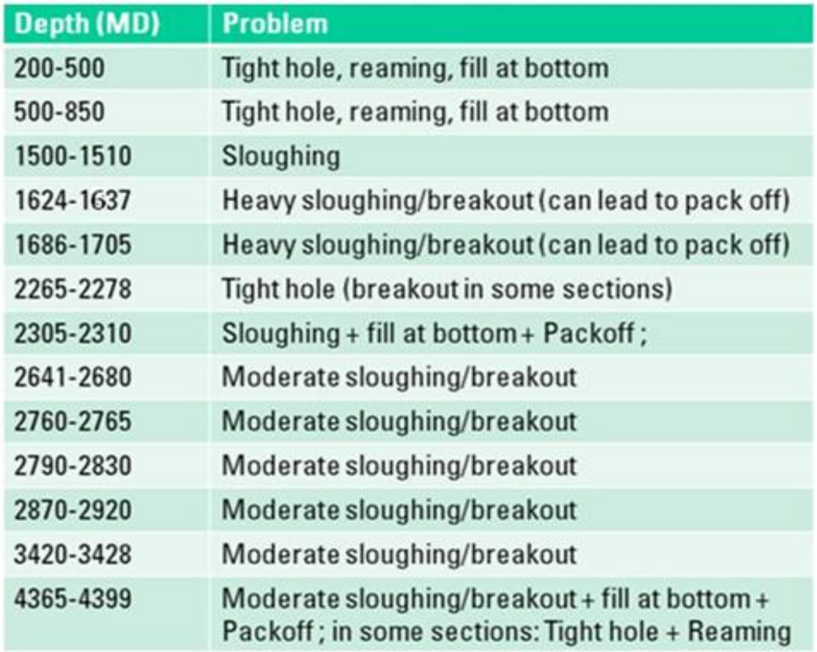


Figure 4: Wellbore stability analysis of planned target well using Mohr-Coulomb criterion.



Depth (MD)	Problem
200-500	Tight hole, reaming, fill at bottom
500-850	Tight hole, reaming, fill at bottom
1500-1510	Sloughing
1624-1637	Heavy sloughing/breakout (can lead to pack off)
1686-1705	Heavy sloughing/breakout (can lead to pack off)
2265-2278	Tight hole (breakout in some sections)
2305-2310	Sloughing + fill at bottom + Packoff ;
2641-2680	Moderate sloughing/breakout
2760-2765	Moderate sloughing/breakout
2790-2830	Moderate sloughing/breakout
2870-2920	Moderate sloughing/breakout
3420-3428	Moderate sloughing/breakout
4365-4399	Moderate sloughing/breakout + fill at bottom + Packoff ; in some sections: Tight hole + Reaming

Table 1: Drilling events predicted in planned target well.

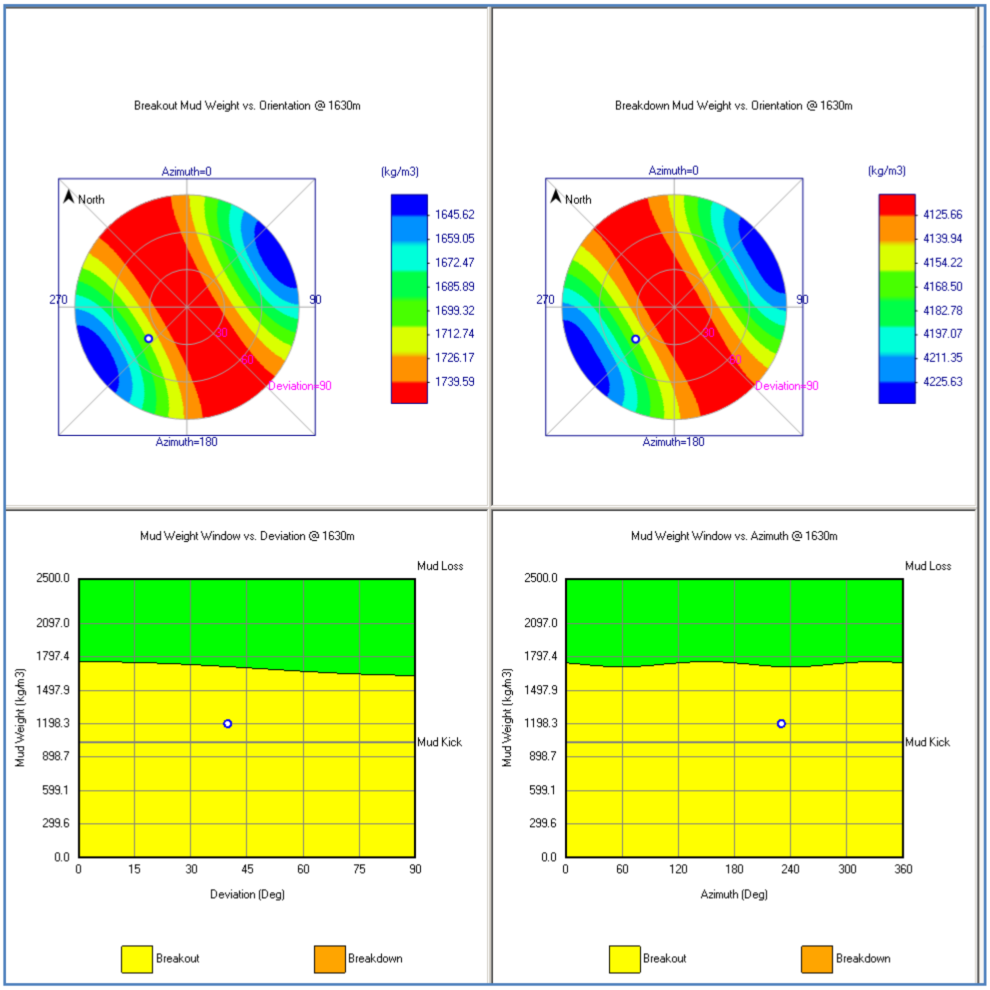


Figure 5 : WBS sensitivity analysis for planned target well at depth 1630m (MD).

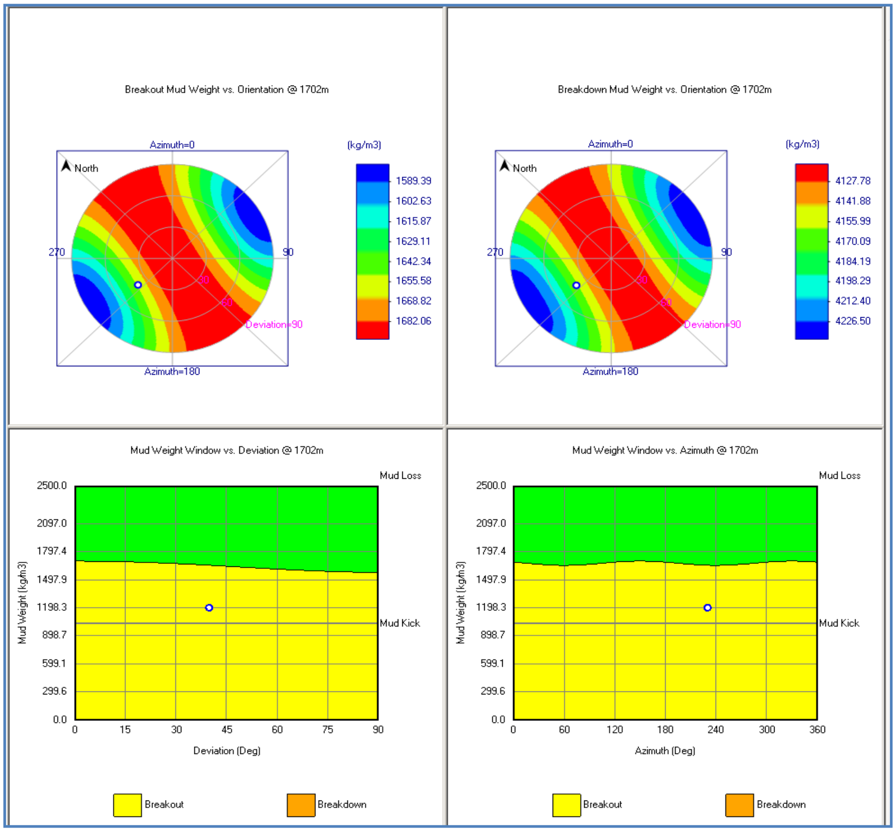


Figure 6 : WBS sensitivity analysis for planned target well at depth 1702m (MD).

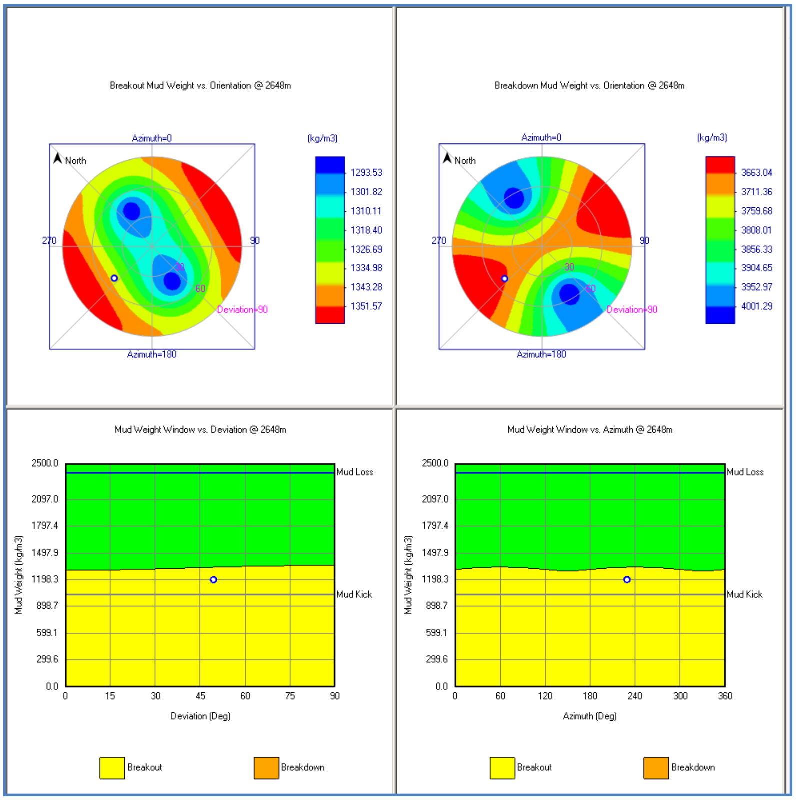


Figure 7: WBS sensitivity analysis for planned target well at depth 2648m (MD).

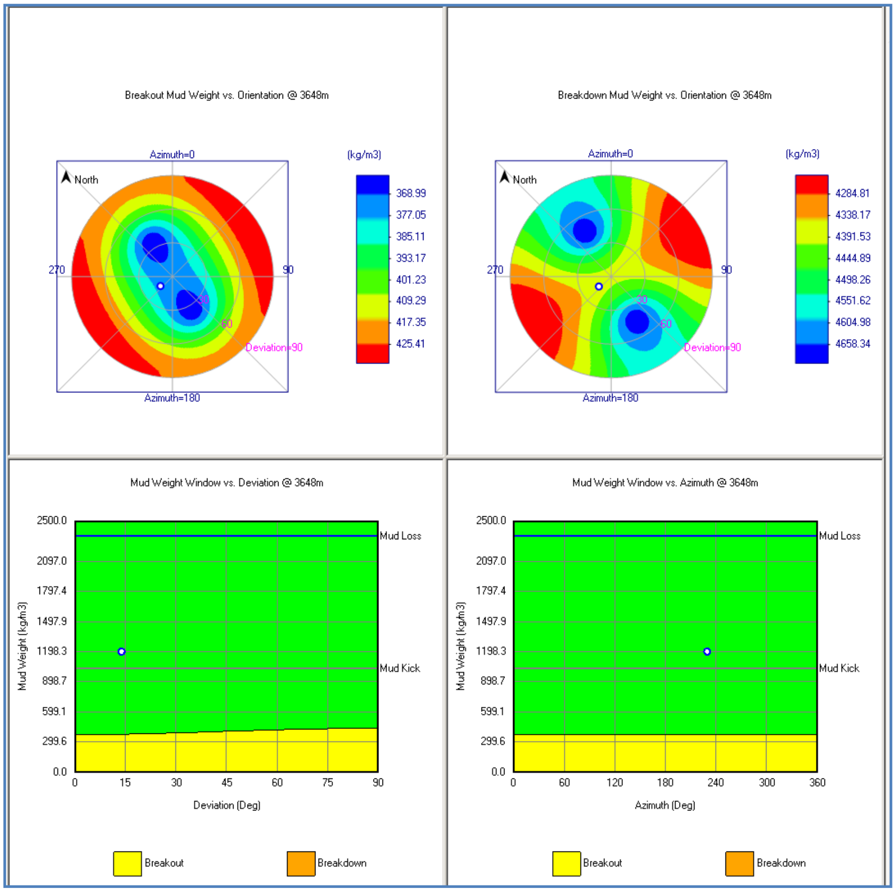
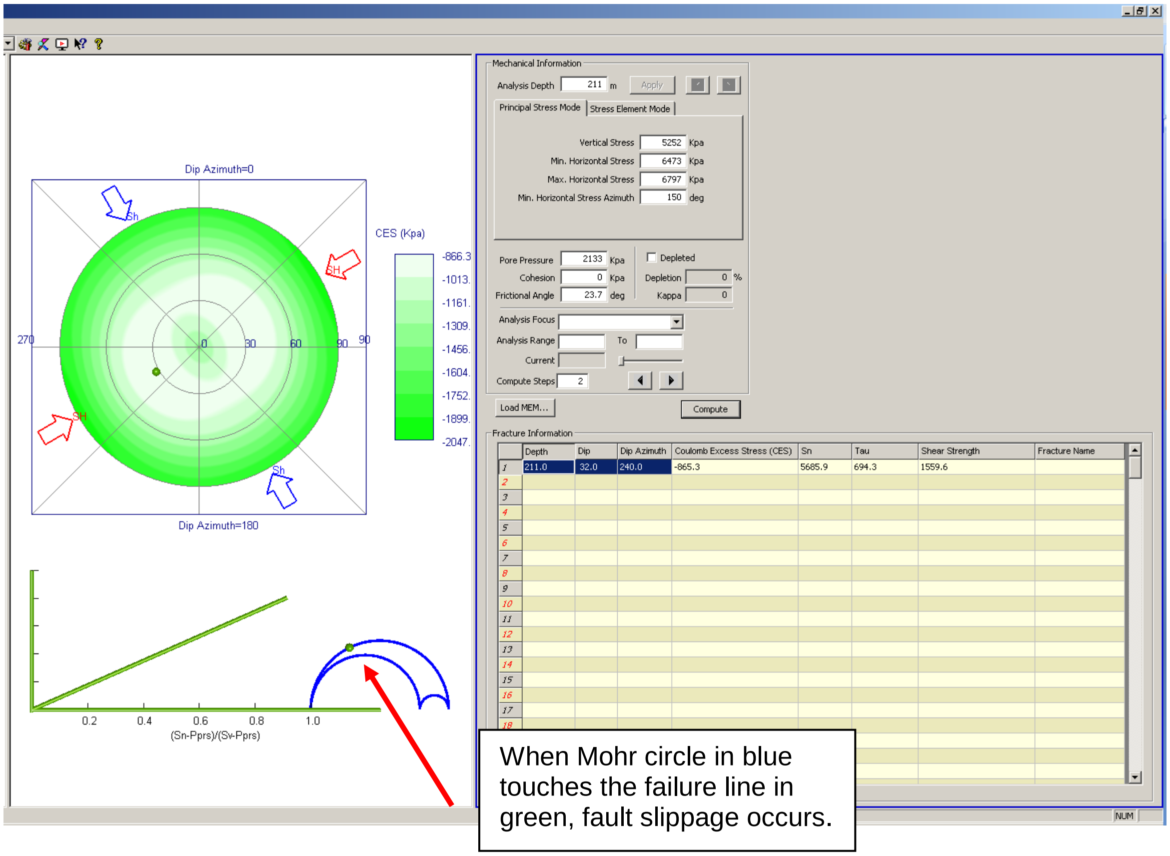


Figure 8: WBS sensitivity analysis for planned target well at depth 3648m (MD)

Fault stability analysis using Mohr-Coulomb failure criterion with cohesion=0, frictional angle as 30°, and the proposed mud weight of 1200 kg/m^3 indicated that all the 15 faults were stable from fault slippage standpoint. If drilling fluid enters the faults, friction angle can be reduced significantly and instantaneous increase in pore pressure can occur in the near wellbore region which can potentially cause fault instability (fault slippage or fault reactivation). Sensitivity analysis on friction angle indicated that faults #1 at 211m MD and #2 at 426m MD could become unstable when fault friction was reduced by 50% (i.e. 10° to 15°). All other faults were found to be stable even at reduced friction angle. Sensitivity analysis with variation in pore pressure was not conducted. As an example the fault stability results for fault#1 at 211m are presented in Figures 9 and 10.

Possible reasons of fault stability in deeper sections are (i) high stresses and low pore pressure (i.e., high effective stress), and (ii) attack angle of well trajectory with respect to fault is generally over 30 degrees.



Mechanical Information

Analysis Depth 211 m

Principal Stress Mode | Stress Element Mode

Vertical Stress 5252 Kpa
Min. Horizontal Stress 6473 Kpa
Max. Horizontal Stress 6797 Kpa
Min. Horizontal Stress Azimuth 150 deg

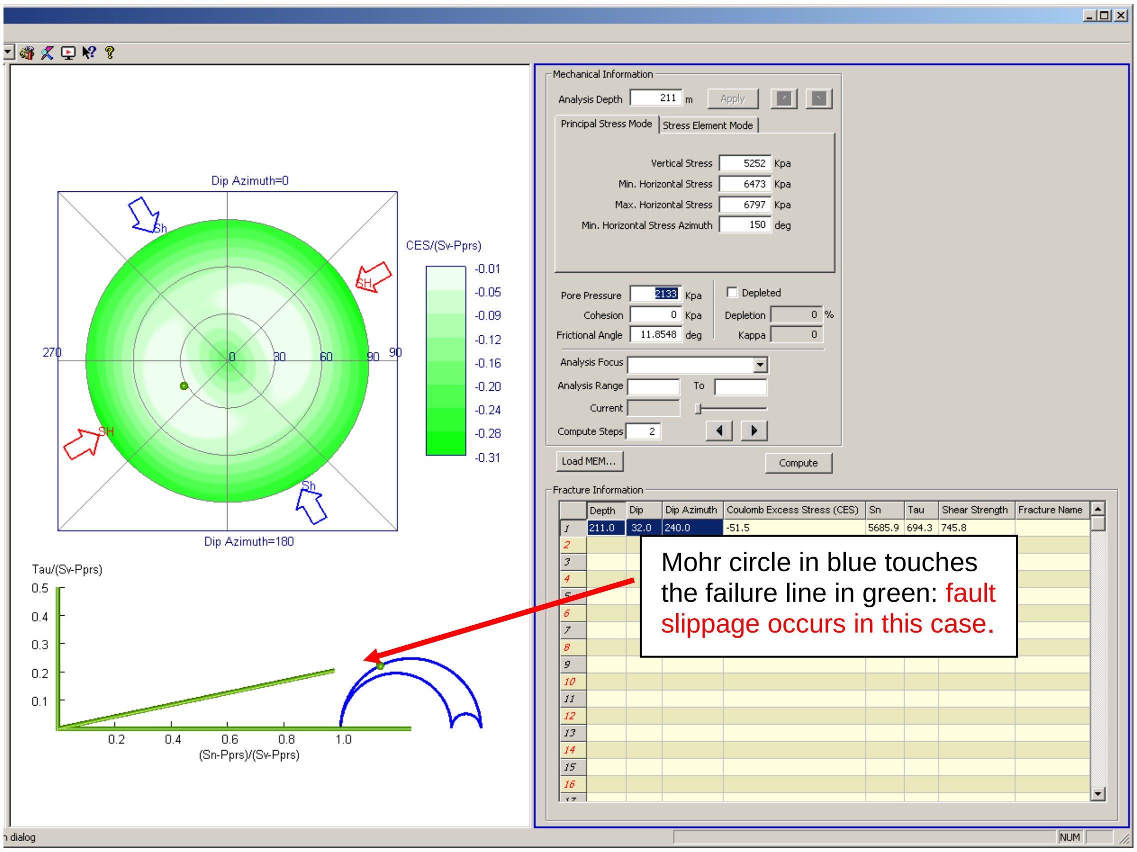
Pore Pressure 2133 Kpa
Cohesion 0 Kpa
Frictional Angle 23.7 deg
☐ Depleted
Depletion 0 %
Kappa 0
Analysis Focus
Analysis Range To
Current
Compute Steps 2

Fracture Information

	Depth	Dip	Dip Azimuth	Coulomb Excess Stress (CES)	Sn	Tau	Shear Strength	Fracture Name
1	211.0	32.0	240.0	-865.3	5685.9	694.3	1559.6	

When Mohr circle in blue touches the failure line in green, fault slippage occurs.

Figure 9: Stability of fault #1 (211m MD) with original frictional angle.



Mechanical Information

Analysis Depth 211 m

Principal Stress Mode | Stress Element Mode

Vertical Stress 5252 Kpa
Min. Horizontal Stress 6473 Kpa
Max. Horizontal Stress 6797 Kpa
Min. Horizontal Stress Azimuth 150 deg

Pore Pressure 2133 Kpa
Cohesion 0 Kpa
Frictional Angle 11.8548 deg
☐ Depleted
Depletion 0 %
Kappa 0
Analysis Focus
Analysis Range To
Current
Compute Steps 2

Fracture Information

	Depth	Dip	Dip Azimuth	Coulomb Excess Stress (CES)	Sn	Tau	Shear Strength	Fracture Name
1	211.0	32.0	240.0	-51.5	5685.9	694.3	745.8	

Mohr circle in blue touches the failure line in green: fault slippage occurs in this case.

Figure 10: Stability of fault #1 (211m MD) with REDUCED frictional angle (50%).

Conclusions

As a result of the study, we recommended a slight but vital modification of trajectory mainly regarding the coal zones and fault, as well as mud weight design, which was rightfully put in practice and resulted in problem-free performance drilling to TD of the well. Additionally, a complete risk management flow chart was constructed integrating the WBS and fault stability results along with analysis drilling problems observed in the four offset wells. It served as road map to manage drilling hazards and risks through recommended prevention and mitigation best practices

Acknowledgements

Shell Canada Energy

References

1. Al-Ajmia, A.M. and Zimmerman, R.W. [2006]. Stability analysis of vertical boreholes using the Mogi–Coulomb failure criterion, ISRM, v.43 pp 1200-1211.
2. Barton, C.A., Zoback, M.D., and D. Moos, Fluid flow along potentially active faults in crystalline rock, Geology, 23, 683-686, 1995.
3. Barton, C., Hickman, S., Morin, R., Zoback, M. and D, Benoit, Reservoir-scale Fracture Permeability in the Dixie Valley, Nevada, Geothermal Field. SPE/ISRM 47371, 1998.
4. Bell, J. S. and Babcock, E. a. [1986]. The stress regime of the Western Canadian basin and implications for hydrocarbon production. Bulletin of Canadian Petroleum Geology, Vol 34, pp. 364-378.
5. Bowers, G., 1995 – Pore Pressure Estimation from Velocity Data: Accounting for Overpressure Mechanisms Besides Undercompaction. SPE 27488.
6. Byerlee, J.D., Friction of Rocks, Pure and Applied Geophysics, 116, 615-626, 1978.
7. Eaton, B., 1975 – The Equation for Geopressure Prediction from Well Logs. SPE 5544.
8. Ewy, Russell T. [1998]. Wellbore Stability Predictions Using a Modified Lade Criterion. SPE 47251.
9. Fjaer E., Holt R.M., Horsrud P., Raaen A.M. and Risnes R., 1992 - Petroleum Related Rock Mechanics. Developments in Petroleum Science, 33; Elsevier; 1992.
10. Foster, J.B. and Whalen, H.E., 1966 - Estimation of Formation Pressures From Electrical Surveys-Offshore Louisiana. SPE 1200.
11. Handin, J., Hager, R.V.Jr., Friedman, M. and J.N. Feather, Experimental deformation of sedimentary rocks under confining pressure: pore pressure tests. AAPG Bulletin, 47, 718-755, 1963.
12. Mclean, M.R. and Addis M.A., 1990: “Wellbore Stability Analysis: A Review Of Current Methods Of Analysis And Their Field Application”, Paper SPE/IADC 19941.
13. Mclean, M.R. and Addis M.A, 1990: “Wellbore Stability: The Effect of Strength Criteria on Mud Weight Recommendations”, Paper SPE 20405.
14. Plumb, R. A., Edwards, S., Pidcock, G. and Lee, D., 2000 - The Mechanical Earth Model Concept and its Application to High-Risk Well Construction Projects. SPE 59128.
15. Plumb, R.A. (1994) “Influence of Composition and Texture on the Failure Properties of Clastic Rocks”. SPE 28022.
16. Wiprut, D., and M.D. Zoback, Fault reactivation and fluid flow along a previously dormant normal fault in the northern North Sea, Geology, 28, 595-598, 2000.
17. Woodland, D. C. Borehole Instability in the Western Canadian Overthrust Belt. SPE Drilling Engineering, Mar. 1990, pp. 27-33.