Anisotropic Aided Drilling & Completion Optimization for the Structurally Complex Bengal Onland Basin, India

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Abstract

After the successful discovery in the Ashoknagar well of Onland Bengal Basin, exploration into deeper Miocene intervals was planned by ONGC. The deeper wells were planned to be drilled to examine the hydrocarbon potential of Pandua Formation. The key challenges in this area include very high overpressures, loss-gain scenarios, wellbore instability issues and presence of TIV (Transverse Isotropic Vertical) anisotropy and associated anisotropic stresses etc. Absence of analogous nearby offset wells led to huge uncertainty in prediction of overpressures to drill the well safely. To investigate the root causes for issues faced in time of drilling and to provide robust inputs to optimize the perforation design, an advanced geomechanical analysis, incorporating the effect of intrinsic anisotropy mechanisms, was performed. A TI stress profile was built from advance acoustic data to capture hi-resolution variation in expected closure and breakdown pressure across target zones in 8.5-inch drilling section.

Integrated results helped to establish the overpressure mechanism and stress profile in the area. An understanding of mechanism and stresses helped to predict the lookahead mud weight window and assist in safer well planning. To further reduce the uncertainty, well was monitored in real-time using mud logging data to correct for uncertainties associated with well behavior. Post completion of the well, wireline logs were recorded to validate the results and incorporate in the upcoming planned wells.

Density velocity crossplot suggest overpressure in the deeper intervals of Pandua Formation could be because of clay dewatering. However, fluid expansion cannot be completely ruled out as observed in offset well. It is found that drop in compressional slowness is observed from 3060m MD onwards resulting in increase in pore pressure estimate from hydrostatic to 1.26gm/cc at 12.25-in Section TD. The maximum pore pressure expected at the well TD ~1.7gm/cc which was further validated by measured formation pressures. The difference between the predicted pore pressure and actual pressure was less than 5%. Wellbore image logs and fast shear azimuth established the maximum horizontal stress direction. It is found to be 30-50deg from North, parallel to regional hinge zone. Anisotropic stress model validated with near wellbore observations and leak-off tests data indicate stress regime to vary between normal ($\sigma_V > \sigma_H > \sigma_h$) to strike slip ($\sigma_H > \sigma_V > \sigma_h$). The transition zone where stress regime changes from normal to strike slip lies close to ~2600m. Robust lookahead model followed by real-time monitoring helped in successful drilling of well.

Introduction

Drilling of wild-cat wells requires robust workflow and data acquisition program followed by real-time monitoring. After successful discovery in the Ashoknagar well of Onland Bengal Basin, exploration into deeper Eocene intervals was planned by ONGC. Presence of very high overpressures, loss-gain scenarios, wellbore instability issues and TIV anisotropy posed a high risk for safe drilling. Absence of analogous nearby offset wells added huge uncertainty in prediction of overpressures and fracture gradient. To ensure risk free drilling and completion of the well, an advanced geomechanical analysis, incorporating overpressure characterization and understanding the effect of intrinsic anisotropy mechanisms using advance acoustic data was planned.

Workflow Adopted in the Bengal Basin

The basic approach to geomechanical analysis is to use the available data for interpretation of rock strength, stress, and pressure to construct a Mechanical Earth Model (MEM). 1-D MEMs were constructed for 12.25” section of the planned well to develop a geomechanical understanding of the reservoir as well as in the overburden and underburden layers. Figure 1 captures the essence of the geomechanical analysis workflow developed for Ashoknagar area planned well.

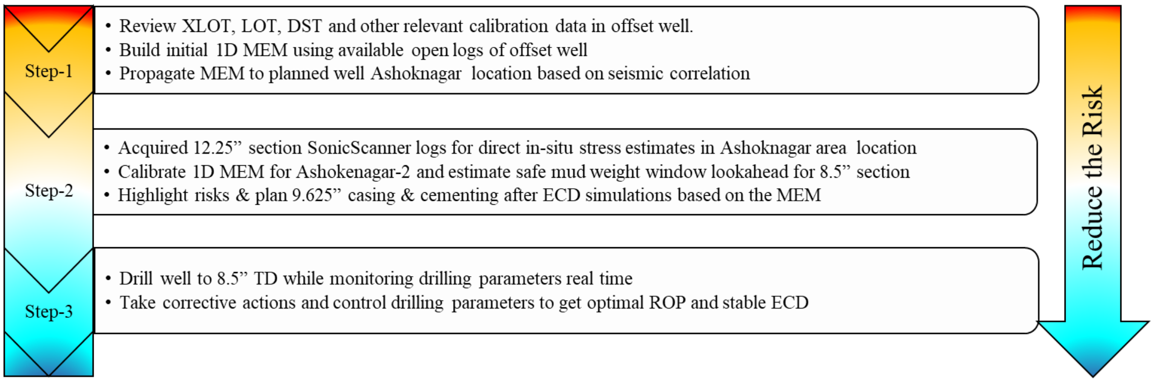

Figure 1. Geomechanical Analysis Workflow Adopted for the planned well in Ashoknagar area

Pore Pressure Characterization:

Pore pressure is a vital component of the MEM, and critical to the calculation of horizontal stresses, wellbore stability analysis and other Geomechanical applications. Apart from direct measurements from well test / MDT tests (no measurement available in 12.25-inch drilling section), pore pressure can be estimated in shaly intervals using several log-based methods (Eaton B.,1975 and Bower G.L.,1995, 2001), each typically relating velocity or/and resistivity to the pressure signal in the formation due to under-compaction. Abnormal pore pressure regimes caused by methods other than under-compaction however need to be investigated in tectonically stressed areas. Figure 2 is a cross plot between velocity and density which is called a Hoesni curve (Hoesni MJ., 2004). It differentiates between different mechanisms of overpressure generation. It is based on the theory that overburden stress related compaction increases the grain-to-grain contact of rock matter leading to progressive increase in the density and velocity in these intervals. In case of abnormal pressure due to under compaction / disequilibrium compaction, the density-velocity relationship follows the normal (virgin) curve while any significant deviation from the normal trend reflects either a change in the shale composition or a different overpressure mechanism such as an episode of unloading / lateral compaction, clay diagenesis or fluid expansion (hydrocarbon maturation, thermal expansion) effects. The idea is to compare Stress vs Porosity. Another way to look at the plot would be to compare Primary vs. Secondary porosity. The compressional velocity is a proxy for the stress tensor and secondary porosity while the Density is a pseudo for total porosity. The analysis usually is done by studying the mud supported rocks. In the absence of thick shales or varying shale composition, and many times in carbonates, a lot of care needs to be taken while doing this analysis. The investigation into overpressure mechanism in area reveal that:

- Most data points lie in the loading compaction trend for Miocene sediments.
- Overpressure in the deeper intervals of Pandua Formation could be because of Clay Dewatering.
- However, Fluid expansion cannot be completely ruled out towards the bottom interval of Pandua Formation

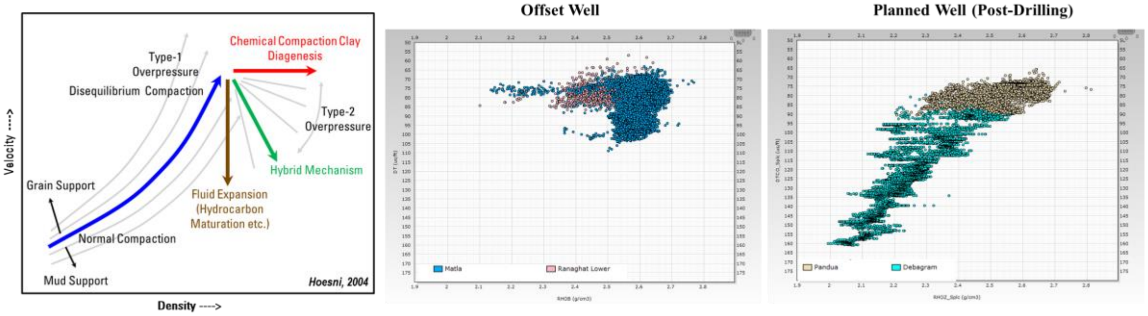

Figure 2:Depth wise Density-Velocity Crossplot to understand the overpressure mechanism in the area

Concept of Wellbore Stability Analysis & Constrained Inversions from Advanced Acoustic 3D Acoustic Shear Velocity Profiling Data.

The initial state of existing compressive stress in the rock formation can be resolved in three components: vertical stress (σ_V), minimum horizontal stress (σ_h), and maximum horizontal stress (σ_H). As the well is drilled, stress redistribution takes place near the wellbore wall with replacement of the initial support of drilled out rock by mud pressure. The redistributed stresses can be resolved in form of hoop stress acting circumferentially along wellbore, the radial stress and the axial stress acting parallel to the wellbore axis. With well deviation, the additional component of shear stress comes into play. If the rock strength is enough to sustain redistributed stresses, in either compression or tension, the wellbore will remain stable with the present mud weight.

Wellbore Stability Analysis (WBS) is a methodology to check the validity of a Mechanical Earth Model (MEM) comprising of rock mechanical properties and stress profile. MEM based predicted borehole failure (losses, breakouts, tensile induced fractures, etc.) is checked against the actual drilling events observations, breakout or tensile induced fractures observed on caliper or image logs. In case of a discrepancy, strain parameters and/or estimated unconfined compressive strength (UCS) parameter (assuming no core data is available) are modified to obtain a better history match. In the absence of borehole images or complex wellbore failures, advance acoustic 3D Shear velocity radial profiling provides valuable insight. The far field shear velocities can be used to interpret anisotropy due to natural features whereas, the near wellbore shear velocities can be used for near wellbore alteration or skin due to hoop stresses.

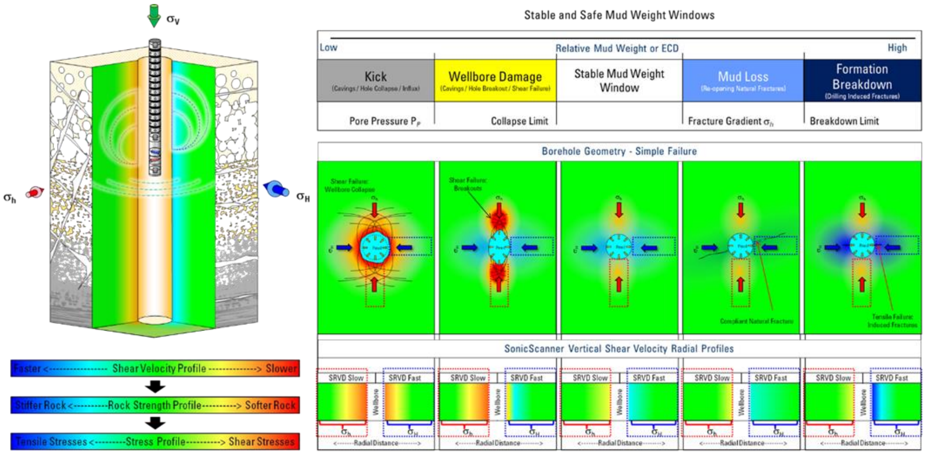

Figure 3. Validation of Mechanical Earth Model Using Wellbore Stability Analysis and advance acoustic Shear Velocity Radial Profiles

Horizontal Stress Magnitude Estimation

In this study, a poro-elastic horizontal strain model (Fjaer et al., 1992) is used to estimate the magnitudes of the minimum and maximum horizontal stresses. This technique does not pre-determine or pre-conceive the order of the in-situ stresses but instead allows the convergence towards estimates of stress magnitudes (and hence stress regimes) that are driven by the available log and well data. The method applies poro-elastic theory to the long-term sedimentation and deposition of formations buried deep below the ground's surface, accounting for lateral spreading and/or horizontal compression via strains that may occur in the horizontal stress directions. Hence, the two strains, ε_h (in the Minimum Horizontal Stress direction) and ε_H (in the Maximum Horizontal Stress direction) can be used as calibration factors to match the above stress model to the current state of stress in the ground. From this approach, we obtain

$$\sigma_h = \frac{\nu}{1-\nu}\sigma_v - \frac{\nu}{1-\nu}\alpha P_p + \alpha P_p + \frac{E}{1-\nu^2}\varepsilon_h + \frac{\upsilon E}{1-\nu^2}\varepsilon_H$$

$$\sigma_H = \frac{\nu}{1-\nu}\sigma_v - \frac{\nu}{1-\nu}\alpha P_p + \alpha P_p + \frac{E}{1-\nu^2}\varepsilon_h + \frac{\upsilon E}{1-\nu^2}\varepsilon_H$$

Contrary to the wide assumption in the industry sedimentary rocks in the subsurface have intrinsic anisotropy associated to the grain and texture. For simplified workflows it is often assumed that the sedimentary rocks are isotropic in nature where sonic velocity parallel and perpendicular to bedding planes are same (Donald et al., 2021). Often shale layers exhibit anisotropy due to their finely layered texture (TIV anisotropy). Similarly, permeable formations such as sandstones or carbonates show stress related anisotropy or anisotropy due to natural fractures (TIH anisotropy). In presence of TI anisotropy, poro-elastic stress model is modified to consider the anisotropy in horizontal and vertical rock elastic properties. The anisotropy effect on Horizontal stresses is captured in the equations below.

$$\sigma_h = \frac{E_h}{E_V} \cdot \frac{v_V}{1-v_h} \cdot \left(\sigma_V - \alpha_V \cdot P_p\right) + \frac{E_h}{1-{v_h}^2} \cdot (\varepsilon_h + v_h \cdot \varepsilon_H) + \alpha_h \cdot P_p$$

$$\sigma_H = \frac{E_h}{E_V} \cdot \frac{v_V}{1-v_h} \cdot \left(\sigma_V - \alpha_V \cdot P_p\right) + \frac{E_h}{1-{v_h}^2} \cdot (\varepsilon_H + v_h \cdot \varepsilon_h) + \alpha_h \cdot P_p$$

σ_h = Minimum Horizontal Stress, σ_H= Maximum Horizontal Stress, σ_V = Overburden Stress
α = Isotropic Biot elastic coefficient, α_V & α_h = Anisotropic Biot's constants
E = Isotropic Young's Modulus, E_V & E_h = Vertical and Horizontal Young's modulus respectively
ν = Isotropic Poisson's Ratio, v_V & v_h = Vertical and Horizontal Poisson's ratio respectively
P_p = pore pressure
ε_h = Strain in Minimum horizontal stress direction
ε_H = strain at Maximum horizontal stress direction

The 3D shear velocity radial profiling data can also be used to invert the Minimum and Maximum Horizontal Stresses (Sinha et. al, 2006 & 2009) and invert TI anisotropic elastic properties and acoustic anisotropy parameters (Donald et. Al. 2018). The TI anisotropy data provides the necessary inputs to get reliable estimates of anisotropic elastic properties. By integrating the identified mineralogy, fluids and rock texture data with the inverted stress regimes, an accurate in-situ mechanical stratigraphy with constrained rock mechanical properties can be obtained via suitably modified rock physics workflows (Xu-Payne et. al, 2009, Shetty et. Al, 2014). The invariable advantage of the above methodology is the minimal dependence on external calibration data in wild-cat exploratory situations and a robust MEM for timely applications. The estimated horizontal stresses were estimated using anisotropic poro-elastic stress model capturing the TIV behavior shales. The Figure 4 below shows the difference between the isotropic and anisotropic stress model for drilled 12.25" section of planned well. There is a clear increase in stresses in the laminated shales whereas a minor drop in sands. Figure 5 shows Anisotropic mechanical properties, stress profile and estimated mud weight window in the drilled 12.25" section of planned well. The failure predicted by the model agrees with actual failure seen on caliper and acoustic shear radial profiles. The shear radial profiles suggest mud weight used in this section is sufficient to prevent any major hole collapse. Cement slurry was designed considered the estimated pore pressure and fracture gradient of the rocks. The cement quality on cement bond logs (CBL) is of good quality.

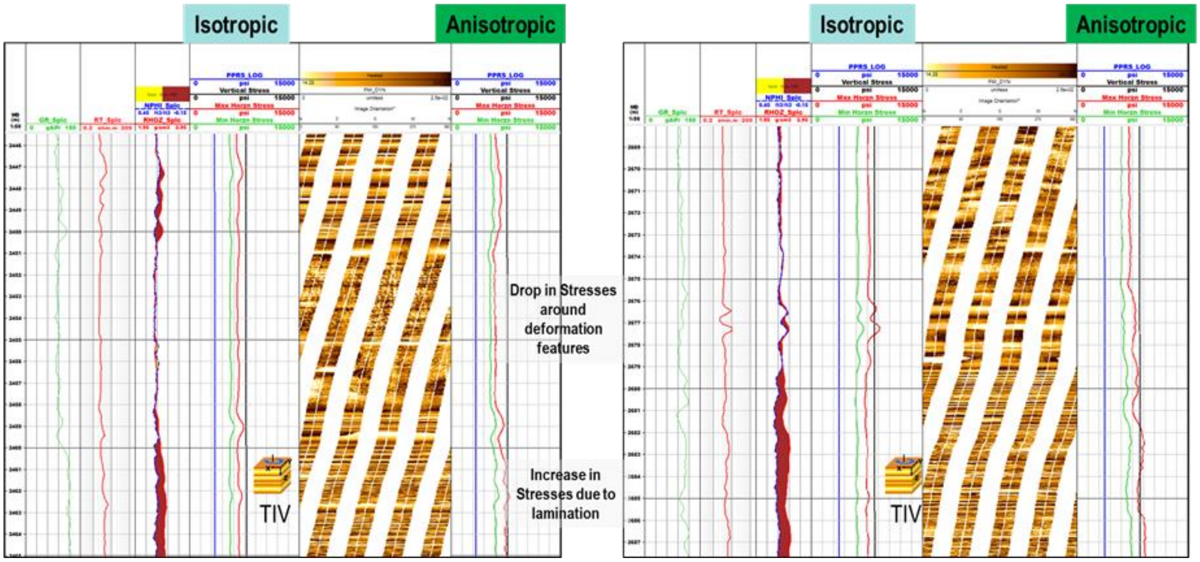

Figure 4. Anisotropic mechanical properties and stress profile of the drilled 12.25” section.

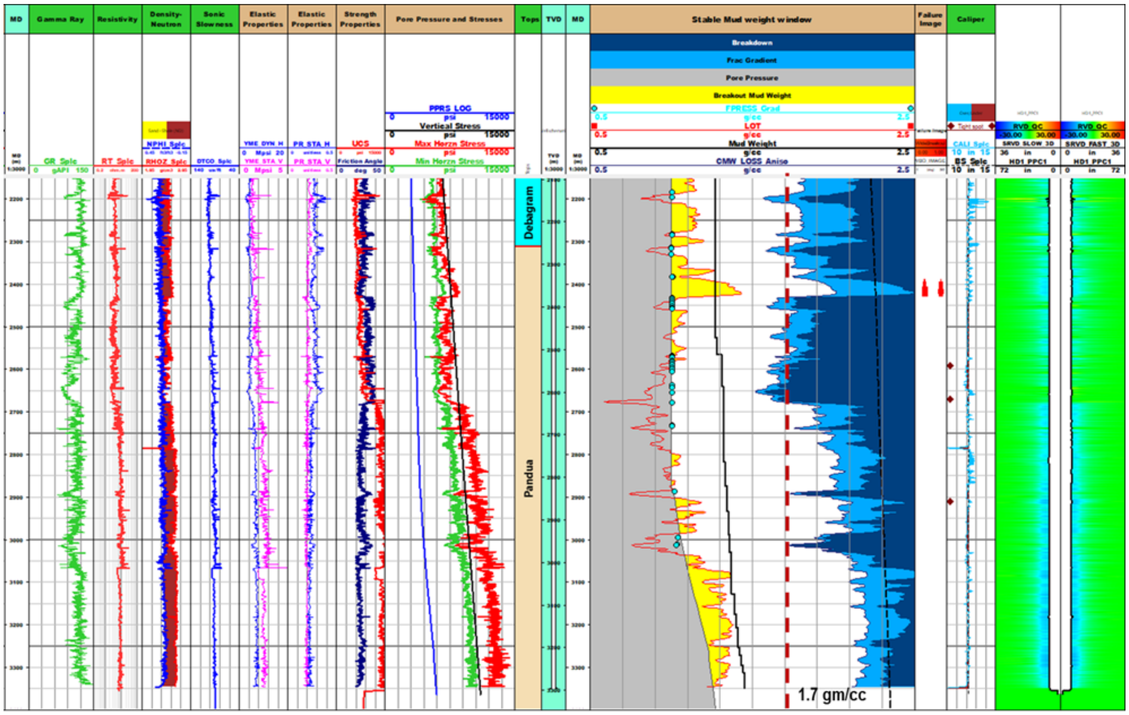

Figure 5. Anisotropic mechanical properties, stress profile and estimated mud weight window of the drilled 12.25” section.

Summary and Conclusion

A robust and integrated data-driven geomechanical workflow was adopted for the challenging Ashoknagar exploratory well of Bengal Onland Basin. Accurate Lookahead model followed by real-time monitoring helped in successful drilling of the planned well with minimal drilling events. A detailed geomechanical understanding of overpressure, stresses and mud weight window will help well planning and completion design of future wells in the area. Figure 6 shows the comparison of predicted and final mud weight window for 8.5" drilling section. Minor variation observed in the pre-drill and post-drill pore pressure model can be attributed to lower resolution of seismic interval velocity. The following key points summarize the analysis performed and results achieved for Ashoknagar area

- Overpressure in the deeper intervals of Eocene interval could be because of clay dewatering. However, fluid expansion cannot be completely ruled out as observed in offset well.
- Maximum pore pressure expected at the well TD ~1.71gm/cc (0.74psi/ft). This was later confirmed by formation pressure measurements in the 8.5" drilling section.
- Maximum Horizontal stress is oriented 30^0-50^0 from North, parallel to the regional hinge zone in Bengal Onland Basin. The stress regime has been validated based on drilling induced fractures observed on borehole image and fast shear azimuth log from advance acoustic processing.
- Stress Regime is seen vary between Normal ($\sigma_V > \sigma_H > \sigma_h$) to Strike Slip ($\sigma_H > \sigma_V > \sigma_h$). Stress regime is normal in the shallow Miocene and Eocene formations. Deeper Eocene rocks show transition towards Strike Slip Stress Regime.

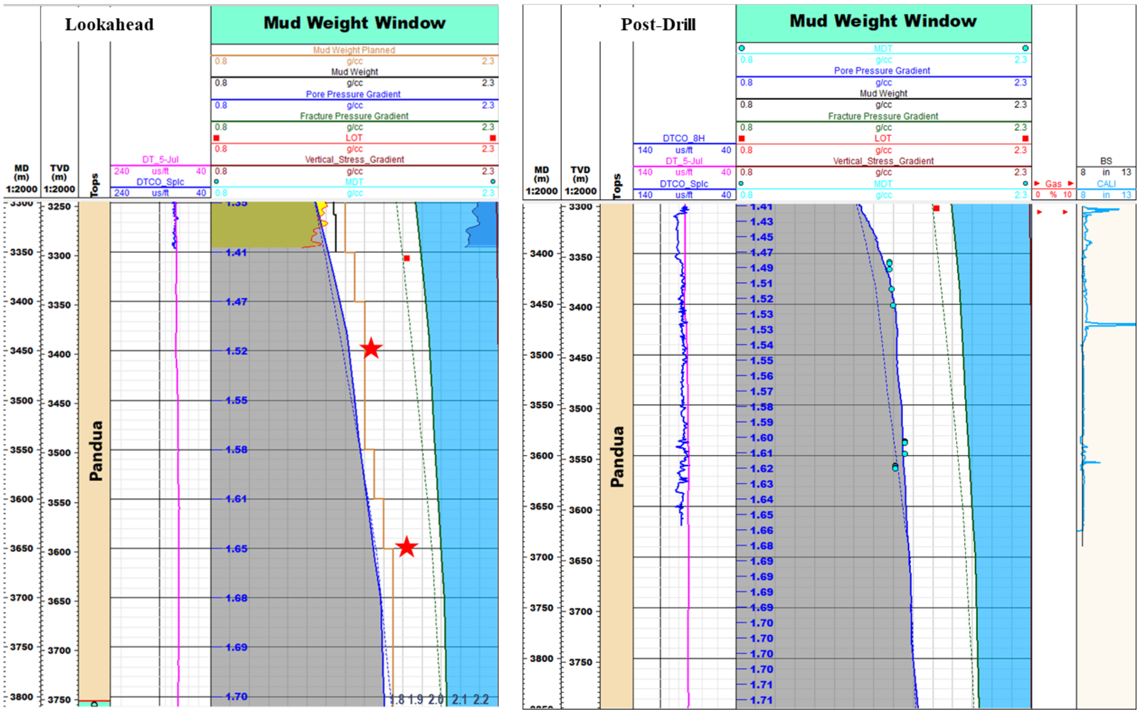

Figure 6. A comparison of predicted and final mud weight window for 8.5" drilling section.

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