Geomechanical aided drilling and frac design optimization for Z field

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Abstract

Several development wells have been drilled in Z field, to target the main commercially producible reservoir, K_I pay sand, which belongs to Mid Eocene to Lower Eocene period. This pay zone is overlaid by weaker interbedded shale formation of the same age. The main challenges encountered during drilling the wells in this area include wellbore stability related issues, which is always a major concern for acquiring good quality data for reservoir evaluation, especially where formation pressures and stress directions are not known. All the wells drilled in this area are producing on artificial lift. The crude oil in the area is viscous in nature and has high wax content. Hence, despite having substantial oil-in-place, the wells don't flow on self. Hence, proper hydro fracture design is required to improve the productivity index of the field. To minimize drilling related risks in future vertical/deviated wells of the field and to optimize hydro-fracturing design, a comprehensive Geomechanical study of the field has been conducted by constructing post-drill 1-D mechanical earth model for the selected wells, as per the availability of hi-tech image and acoustic logs. The developed models were further calibrated using the available data (well testing results etc.). Image data was also analyzed to capture the presence of fractures/faults along the borehole, to calibrate the stresses. Based on the analysis results, it was concluded that most of the wellbore instability issues (caving etc.) occurred due to insufficient mud weights used during drilling. The present study will help in better characterization of the formations and will provide useful information for planning future wells and optimize HF design to improve the productivity.

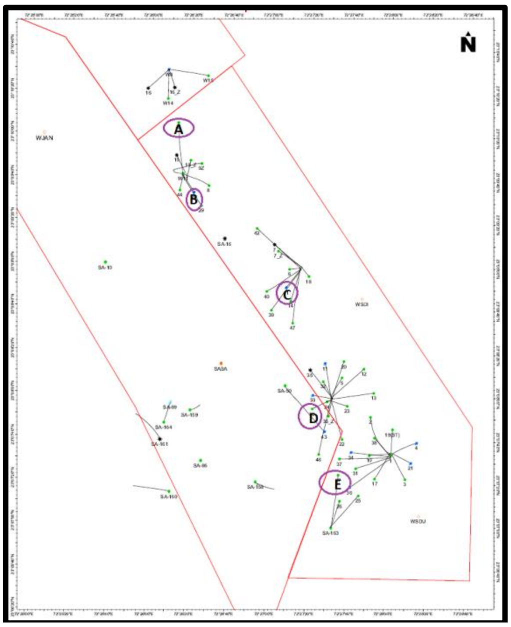


Figure 1: Basemap of the wells under study

Introduction/Scope of work

Z field has been put into production since 2007. K_I pay sand in Z field is extended like a single continuous hydrodynamic channel from North to South. All the wells drilled in this area are producing on artificial lift. Despite having good reservoir characteristics (as seen in the logs displayed in figure 2) and substantial oil-in-place, the wells don't flow on self, due to high viscosity of oil in this area. Hence, proper hydro fracture design is required to improve the productivity index of the field. Some of the challenges encountered during drilling include wellbore instability issues across the weaker formations. As a result, proper Geomechanical understanding is crucial to address the present drilling related and production-related problems and use it for drilling and completion strategies for future wells successfully. The key objective of this study is to provide solution for drilling optimization by maintaining proper mud weight to avoid shear failure in the wells, characterization of pore pressure and fracture gradient for Hydraulic fracturing optimization. Figure 1 shows the prospect map of Z field and marks the locations of the wells under study.

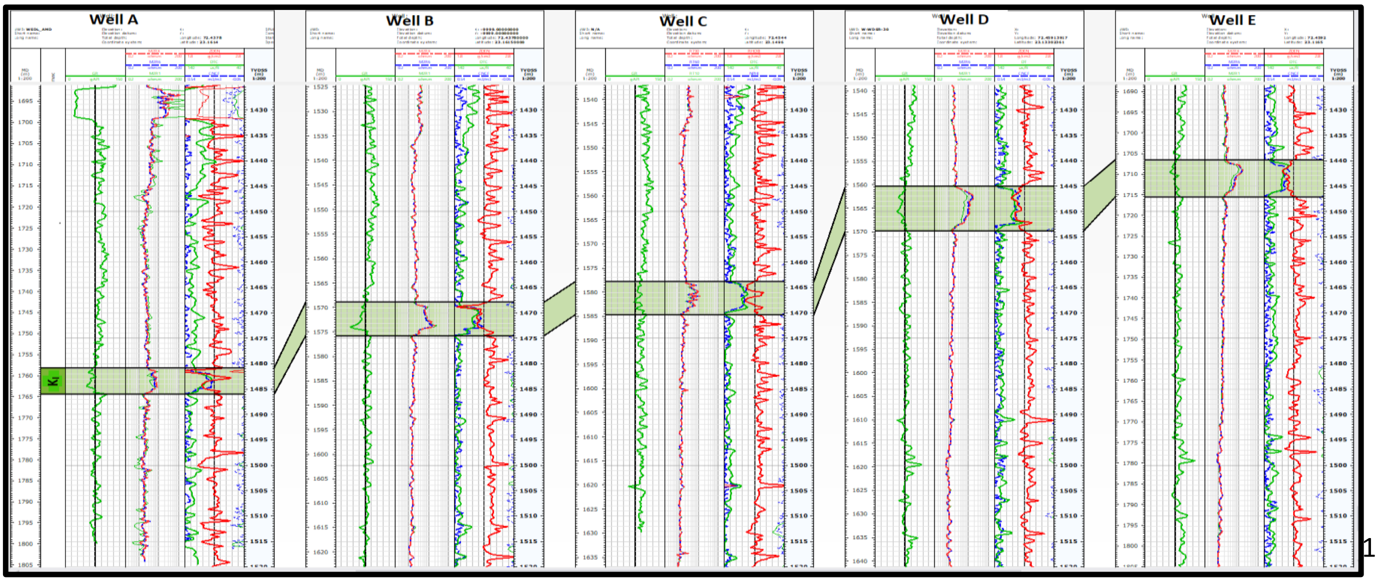


Figure 2: Multiwell correlation of the wells under study. From North to South, K_I pay sand moving up-dip.

General workflow implemented for the current study

Overburden/Vertical stress

For all the wells under study, overburden stress has been computed using density log extrapolation method and the results are shown in figure 3. For all the wells, overburden stress gradient varies in the range of 1.99-2.1g/cc.

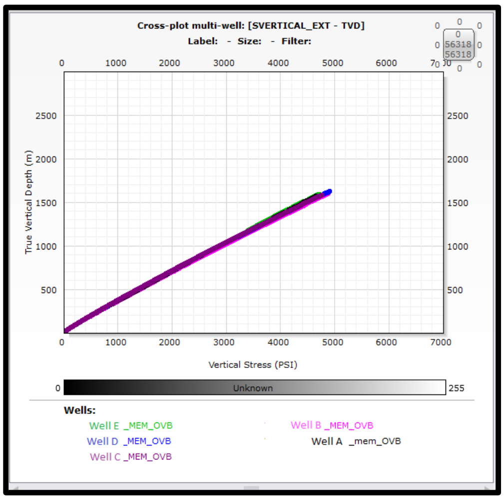


Figure 3: Overburden / Vertical stress

Pore pressure Trend

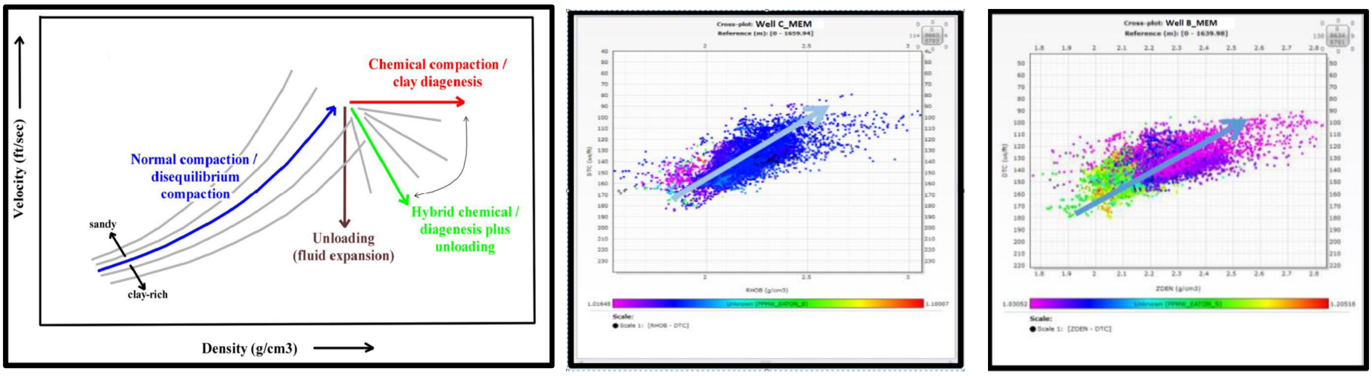


Figure 4: Hoesni's plot: DTC vs. Density, showing pore pressure, as normal compaction

In the current study, pore pressure in the shale has been estimated by Normal Compaction Technique (NCT) using Eaton's method (Figure 5). The resultant profile has been calibrated against SBHP measurement recorded in one of the wells measuring, approx. 166.8kg/cm^2 (2372psi). The estimated pore pressure gradient is just above the hydrostatic, in the range of 0.43-0.49 psi/ft.

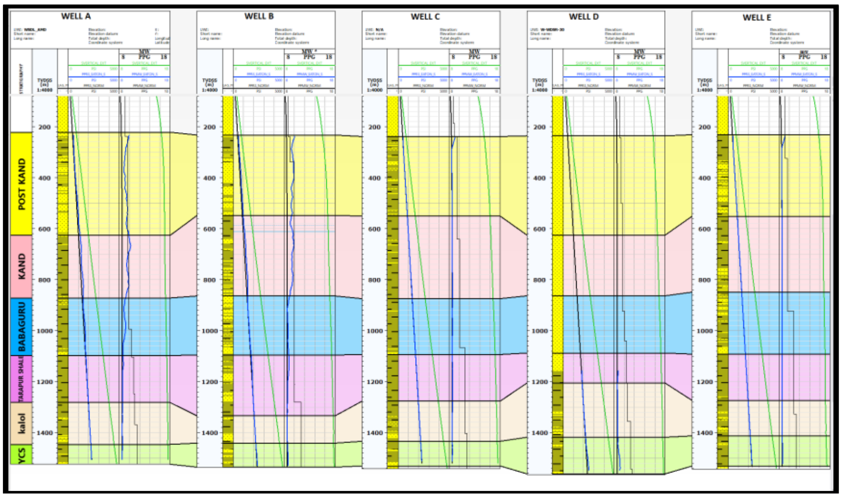


Figure 5: Pore pressure profile for Z field from North (left) to south (right)

Rock Mechanical properties

Rock mechanical properties are essential parameters for any Geomechanical analysis. The basic rock mechanical properties include Young's modulus, Poisson's ratio, unconfined compressive strength (UCS) and angle of internal friction (FANG).

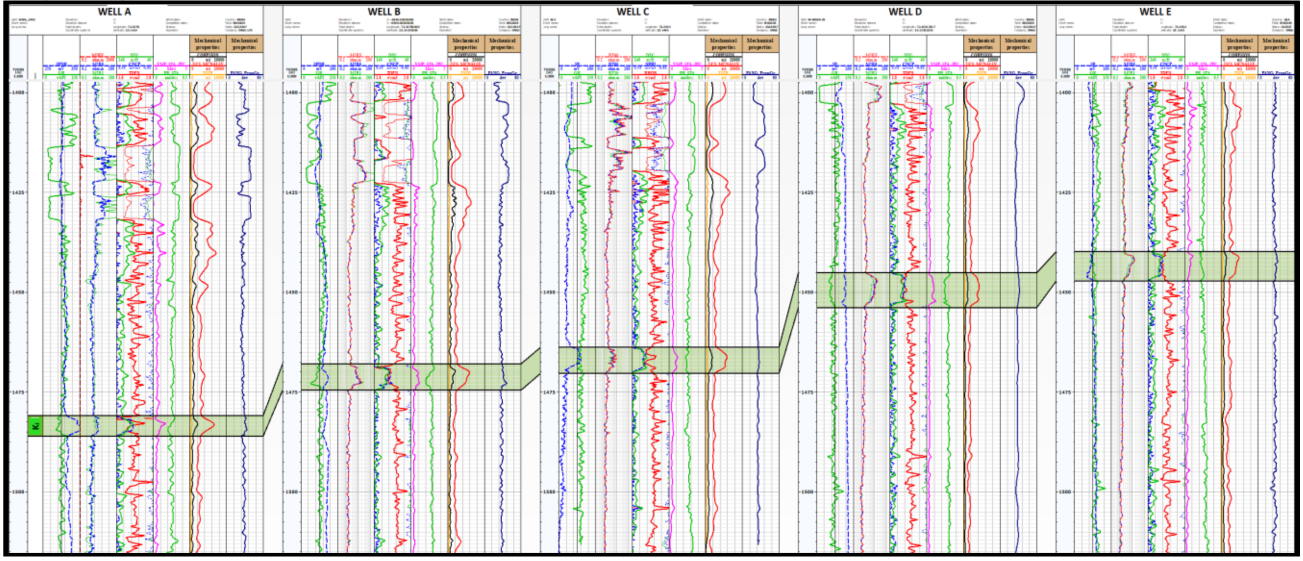


Figure 6: Conventional openhole logs and rock mechanical properties for the well under study; From North (left) to South (right)

Log data, namely compressional and shear slowness and bulk density, have been utilized to compute Young's Modulus, Poisson's ratio and UCS along the depth in a given formation. Dynamic elastic properties (Young's modulus and Poisson's ratio) have been converted into static elastic properties using correlation equations. The continuous profile of this data along the depth of a wellbore gives an important indication of natural variations of the formation's stiffness and strength in different layers. Figure 6 shows the resultant elastic and rock strength properties for all the wells under study. The results have been presented in Table 1.

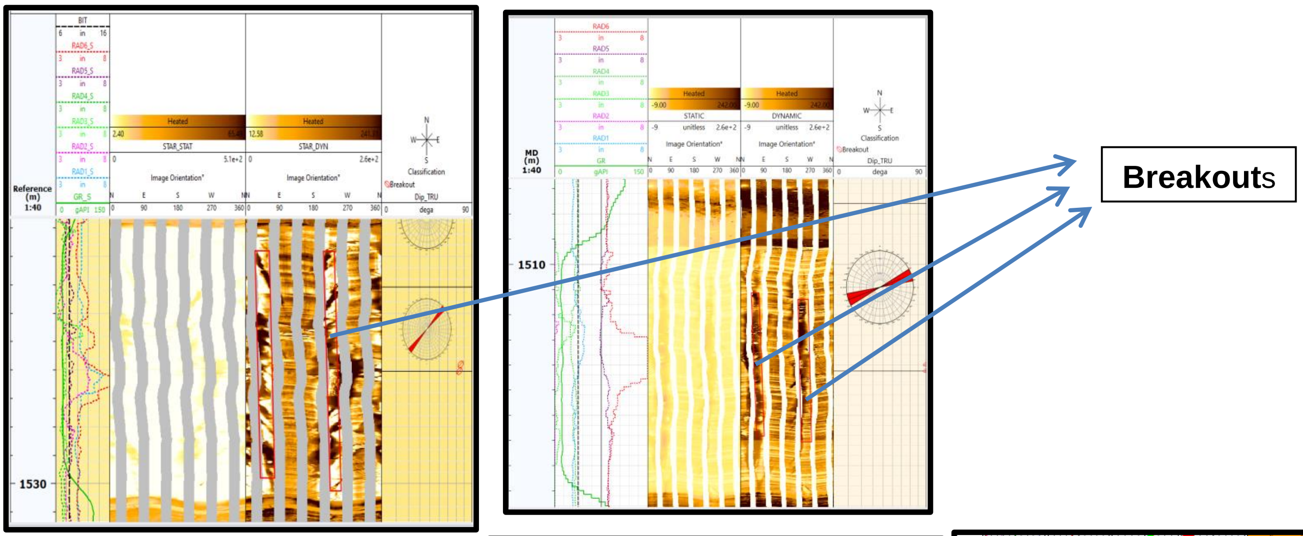
WELL No.	Static Young's Modulus YME_STAT_IFC (Mpsi)	Static Poisson's ratio PR_STA (unitless)	Unconfined compressive strength UCS_MCNALLY (psi)	Tensile strength TSTR (psi)	Friction angle FANG_FromGr (deg)	Log-derived permeability KINT (mD)
A	0.75-1.77	0.2-0.26	4500-6650	300-600	29-33.5	100-400
B	0.8-1.12	0.2-0.3	4000-5920	440-562	29-36	50-150
C	0.7-1.18	0.22-0.27	4500-5840	400-553	26-28	5-8
D	0.7-0.9	0.23-0.27	2700-4300	300-350	29.5-31.5	30-180
E	0.6-1.16	0.21-0.27	3363-4380	300-390	27.5-32	30-400

Table 1: Average elastic properties and rock strength against K_I pay sand, derived using well logs.

On the basis of rock mechanical properties and rock strength profiles for all the wells (as shown in figure 6), good permeability, high Young's modulus, low Poisson's ratio and high UCS is observed against the target K_I pay zone. The pay sand is sandwiched between shale layers having comparatively low Young's modulus, high Poisson's ratio and low UCS. Since oil viscosity is high in this region, hydro fracturing is essential for hydrocarbon extraction. The target reservoir, K_I acts as a perfect candidate for hydro fracturing and the adjacent shale acts as barrier, restricting the fracture propagation within the reservoir. It has also been observed that on moving towards the south direction, there is decrease in Young's modulus and UCS against the target reservoir. This implies that the wells drilled towards the Northern side of the field appears to be better candidates for hydro fracturing as the stress barrier appears to reduce, on moving towards the south direction. However, the additional core and pressure data may be acquired and the elastic properties can be calibrated using laboratory studies for better analysis.

Horizontal stress direction

The image data available in the wells X, Y and D was processed and interpreted. Figure 7 presents the processed static, dynamic image and orientation of the identified breakouts. It is well known that breakouts are developed in the direction of minimum horizontal stress. The identified direction of minimum horizontal stress is 40-50°NE as shown in figure 7. The fast shear azimuth data in anisotropic zones (as shown in figure 8) indicated maximum horizontal stress direction to be around 130-140° SE, which is almost perpendicular to the minimum horizontal stress direction.



(a)

(b)

Figure 7: Image data that shows static & dynamic image logs for a) Well Y and b) Well D and the orientation of identified borehole breakouts i.e. the direction of minimum horizontal stress.

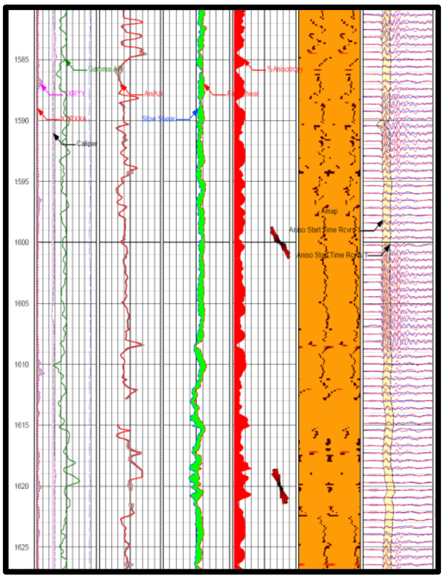


Figure 8: Fast shear azimuth data in Well D, indicating maximum horizontal stress

Horizontal stresses magnitude estimation

To compute the magnitudes of the minimum and maximum horizontal stresses, poro-elastic horizontal strain model was implemented (Fjaer et al., 1992).

$$\sigma_h = \frac{\nu}{1-\nu}\sigma_v + \frac{1-2\nu}{1-\nu}\alpha P_p + \frac{E}{1-\nu^2}\varepsilon_x + \frac{\nu E}{1-\nu^2}\varepsilon_y$$

$$\sigma_H = \frac{\nu}{1-\nu}\sigma_v + \frac{1-2\nu}{1-\nu}\alpha P_p + \frac{E}{1-\nu^2}\varepsilon_y + \frac{\nu E}{1-\nu^2}\varepsilon_x$$

In the above equations, σ_H is the maximum horizontal stress; σ_h is the minimum horizontal stress; σ_v is the vertical stress; v is the static Poisson's ratio; P_P is the pore pressure; α is the Biot's coefficient, which is maintained at unity to account for the brittle failure of rocks (conventionally α =1); E is the static Young's modulus; and ε_y and ε_x are tectonic strains in the maximum and minimum horizontal stress directions, respectively. The two horizontal strains (ε_y and ε_x) have been computed by using the following equations (Kidambi and Kumar, 2016) and used to calculate the horizontal stresses.

$$\varepsilon_y = \frac{\sigma_v \nu}{E}\left(1 - \frac{\nu^2}{1-\nu}\right)$$

$$\varepsilon_x = \frac{\sigma_v \nu}{E}\left(\frac{1}{1-\nu} - 1\right)$$

Calibration of minimum horizontal stress (S_{hmin})

The most reliable measurements of in-situ least principal horizontal stress are those provided by analysis of minifrac and/or extended leak-off test (XLOT). Since leak-off tests were not carried out in any well, results of past HF operations were considered. Step rate test results, consisting of ISIP gradients have been tabulated with respect to the pay sand, as shown in Table-2. These results have been used to indirectly calibrate S_{hmin}.

Well	Depth (m)	BHISIP gradient (psi/ft.)	BHISIP (psi)
A	X762	0.625	3613
C	X579	0.70	3626
B	X572	0.57	2940
D	X562	0.72	3689

Table 2: BHISIP gradients against K_I pay sand, observed in the wells under study

Wellbore stability analysis

The wellbore stability analysis includes modeling of the shear and tensile failures in the wellbore.
For the current study, a Mohr Coulomb failure criterion was used.
The wellbore stability analysis results (as shown in figure 9) suggest the following:

- The predicted rock failure overall agrees well with the caliper log and wellbore instability related drilling events. The breakouts observed in the formations could be explained by inadequate mud weight (being on low side).
- The shale layers present in Post Kand, Kand and Babaguru formations are characterized by relatively lower strength. Breakouts observed in these formations could be due to the presence of low density, swelling clay minerals.

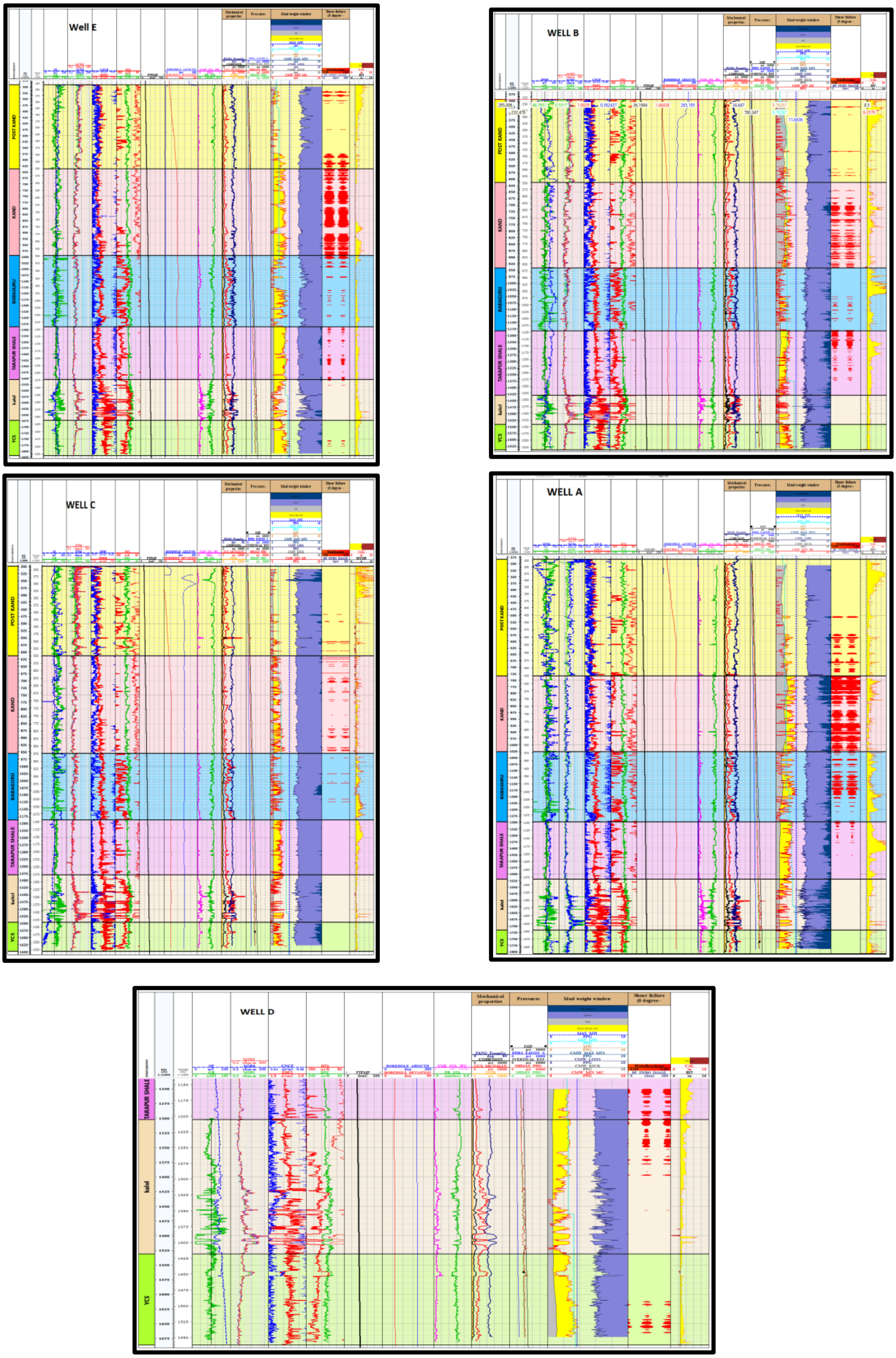


Figure 9: MEM & wellbore stability analysis of the wells in Z field

Trajectory sensitivity analysis

To evaluate the impact of deviation and azimuth on the trajectory-dependent parameters of the mud weight window, sensitivity analysis was conducted on critical depths across the problematic formations (especially shale and weak sandstone). Figure 10 and 11 shows the mud weight window versus well inclination for single depths in Kalol and YCS formations. Figure 12 and 13 present stereo net plots, showing mud weight versus well orientation/azimuth in Kalol and YCS formations.

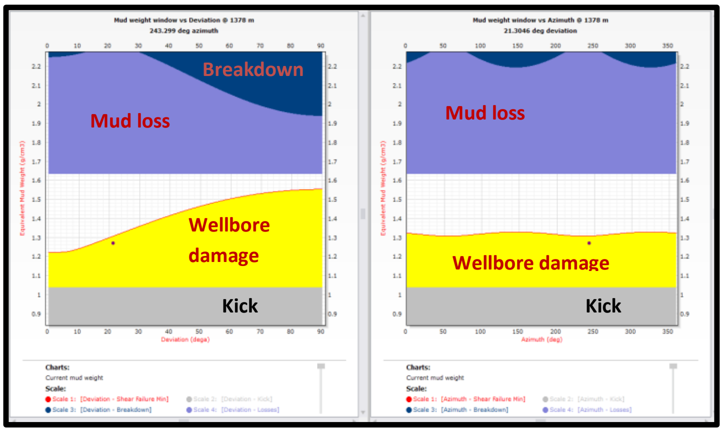


Figure 10: Minimum mud weight plots: (a) breakout mud weight vs. deviation and (b) breakout mud weight vs. azimuth against Kalol formation.

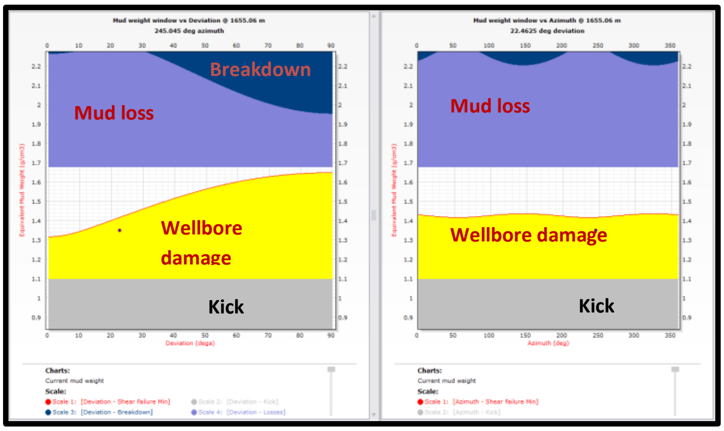


Figure 11: Minimum mud weight plots: (a) breakout mud weight vs. deviation and (b) breakout mud weight vs. azimuth against YCS formation.

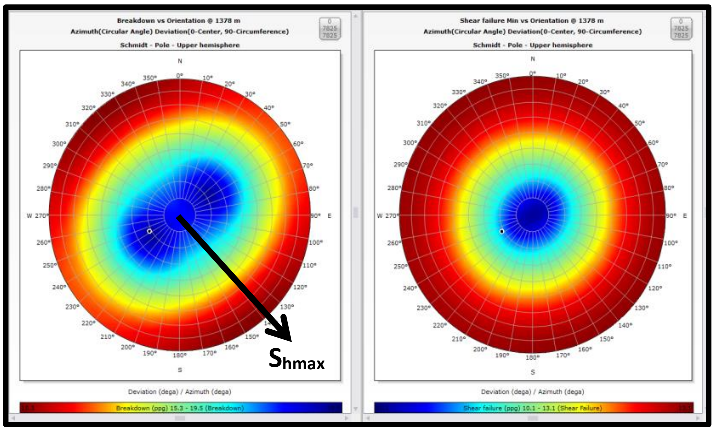


Figure 12: Minimum mud weight plots: (a) breakdown mud weight vs. orientation and (b) breakout mud weight vs. orientation against Kalol formation.

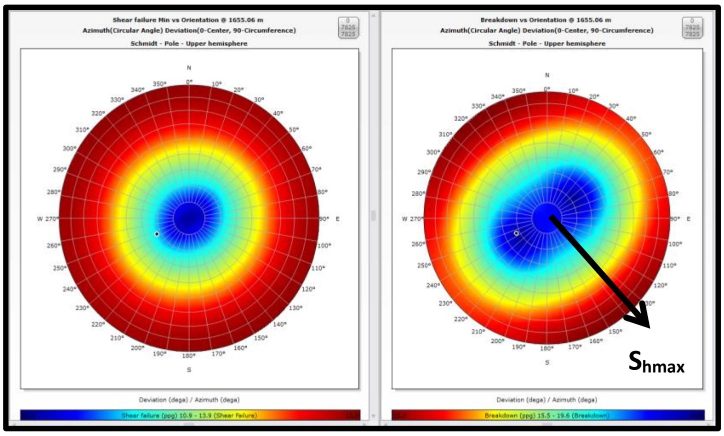


Figure 13: Minimum mud weight plots: (a) breakout mud weight vs. orientation and (b) breakdown mud weight vs. orientation against YCS formation.

The conclusions drawn from the sensitivity analysis are as follows:

- ✓ The safe mud weight window of shear failure (breakouts) becomes narrow in wells with deviation above 30° in Kalol and YCS formations.
- ✓ No significant effect of wellbore azimuth on breakout mud weight was observed due to low stress contrast.
- ✓ The wellbore trajectory should be designed to avoid a high deviation, or the mud weights should be high enough to prevent the collapse failure and to tolerate limited mud loss.
- ✓ Relatively higher breakdown mud weights are anticipated for wells drilled in direction of the minimum horizontal stress with inclinations more than 50° compared to wells drilled towards the maximum horizontal stress direction.
- ✓ It can be concluded that the preferred wellbore orientation to drill deviated wells is along the minimum horizontal stress (40°). This orientation will provide a relatively wider mud weight range for safe and stable drilling.

Results

Wellbore stability analysis was done for five wells of Z field using 1DMEM and drilling mud weight. Mud weight used to drill the wells is 1.05-1.4 g/cc (8.76-11.6ppg). Main conclusions from the Geomechanics modeling are summarized below:

- ✓ Estimated pore pressure gradient shows normal compaction trend. The estimated pore pressure gradient was just above the hydrostatic, in the range of 0.43-0.49 psi/ft. Pore pressure is 2200-2270 psi, against the target pay sand K_I.
- ✓ Estimated stress profile shows normal faulting stress regime ($S_V > S_{hmax} > S_{hmin}$).
- ✓ Ratio of maximum horizontal stress to minimum horizontal stress is 1.04-1.2.
- ✓ Maximum horizontal stress direction is 130-140° SE.
- ✓ On moving towards the south direction, there is decrease in Young's modulus and UCS against the target reservoir. This implies that the wells drilled towards the Northern side of the field appears to be better candidates for hydrofrac as the stress barrier appears to be reducing on moving towards the south direction.
- ✓ The predicted rock failure overall agrees well with the caliper log and wellbore instability related drilling events. The breakouts observed in the formations could be explained by inadequate mud weight (being on low side).
- ✓ The shale layers present in Post Kand, Kand and Babaguru formations are characterized by relatively lower strength. Breakouts observed in these formations could be due to the presence of low density, swelling clay minerals.

The conducted sensitivity analysis gave the following information that could be applied to drilling the future wells successfully:

- ✓ Relatively higher breakdown mud weights are anticipated for wells drilled in direction of the minimum horizontal stress with inclinations more than 50° compared to wells drilled towards the maximum horizontal stress direction.
- ✓ The stable mud weight window becomes narrower with increasing deviation; higher mud weight is required to minimize shear failure with increasing deviation.
- ✓ Lower limit of stable mud weight window is equivalent to breakout mud weight which varies with deviation. To minimize breakouts, the recommended mud weight range for Kalol formation for inclinations upto 30° is 1.2-1.35 g/cc (10-11.2ppg), while hole inclinations higher than 40° will require higher mud weights (1.38-1.5 g/cc).
- ✓ The recommended mud weight is in the range of 1.32-1.44g/cc (11-12ppg) for YCS formation for well inclination upto 30°.
- ✓ Based on the sensitivity analysis of the critical shale sections, preferred orientation to drill highly deviated wells (inclinations higher than 50°) is along the minimum horizontal stress (40-50° NE). This direction will provide relatively wider mud weight range for safe and stable drilling.

Conclusions

This paper introduced an integrated workflow, which will help in better characterization of the formations, to minimize drilling related risks in future vertical/deviated wells of the field Z and to optimize hydro-fracturing design and ultimately enhance the hydrocarbon production from K_I pay sand. The study recommends drilling of wells in the direction of $S_{hmax,}$ to have a wider mud weight window for stable drilling. The wellbore trajectory should be designed to avoid a high deviation, or the mud weights should be high enough to avoid the collapse failure and to tolerate limited mud loss. The variation in the rock mechanical properties as observed across the field will help to optimise the parameters for effective HF design.

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