Accidental Geomechanics in Highly Depleted Reservoir: Reducing Uncertainty in Estimation of In-Situ Stresses

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Keywords

Depleted reservoir, Deep-water, Geomechanics, Stress estimation.

Summary

The use of geomechanical solution is increasing day by day during drilling and completion operations as the trend of drilling challenging wells increases. However the quality and quantity of applicable input data to solve the geomechanical problem is often inadequate and has uncertainty.

The study area is a part of deep water producing field where the reservoir pressure has depleted more than 50% of its original reservoir pressure .This paper highlights how the mud losses and other drilling events were efficiently used to reduce the uncertainty in estimation of horizontal stresses magnitude. Which was further used to optimize the Mud Weigh (MW) for safe and cost-effective drilling in highly depleted reservoir.

The reservoir pressure depletion due to production causes horizontal stress to decease and further reduce the drilling margin in case of deviated wells in deep water setting. In such narrow drilling window (0.5-0.6 ppg), even 5- 10% uncertainty in the horizontal stress magnitude can induce high drilling risks e.g. mud losses and wellbore failure. The magnitude of horizontal stresses in the depleted reservoir zone can be estimated by performing extended leak off test / minifrac test. But in deep water setting, it's highly un-economical and has some inbuilt uncertainty /operation limitations. However sometimes high quality stress measurement can be made accidently while drilling during the well events like mud losses and wellbore failure. These well events can be further integrated with stress polygon to calibrate and constrain the magnitude of horizontal stresses.

The paper illustrate, how accurate estimation of minimum & maximum horizontal stress (estimated from well events & constrained by stress polygon) has reduced the uncertainty in wellbore stability model. The paper also highlights the use of the calibrated wellbore stability model in optimally designing the casing/MW planning, drilling and completion stagey in highly depleted reservoir especially in deep water setting, which proved to be one of key parameters in reducing non-production times.

Introduction

The study area is a depleted oil, condensate & gas field in Krishna –Godavari basin, east coast of India and reservoir sandstone are Mesozoic in age. To achieve incremental gas & condensate production, nearly horizontal wells were planned and drilled through highly depleted sandstone reservoir

The reservoir has depleted more than 50 % of initial reservoir pressure which causes decrease in the horizontal stress of the reservoir rock, however pressure decrease within the intra reservoir shale (more than 8-10m thickness TVD) is expected to have lesser than reservoir sand. This less decrease of pressure within intra-reservoir shale causes relatively small reduction in horizontal stresses as compared to reservoir sand .This causes requirement of higher mud weight for intra reservoir shale stability, which further increases challenges for drilling the reservoir section.

Drilling and completion of high angle deviated extended reach drilling (ERD) wells in highly depleted reservoirs is one of the most challenging job, which can be achieved successfully by optimum casing and mud weight planning through wellbore stability model. The magnitude of horizontal stresses are one the most important parameter in wellbore stability model. The minimum horizontal stress (Shmin) determine the upper limit of mud weight. Stress measurements within hydrocarbon reservoir show that the minimum horizontal stress (fracture gradient) decreases with declining reservoir pressure in depleted reservoirs (Addis, 1997; Segall, Fitzgerald, 1996; Jayanta, Ashutosh, 2015). A mud weight heavier than the reduced fracture gradient could induce hydraulic fracturing and mud losses in depleted reservoir sandstone. Higher uncertainty in minimum horizontal stress (Shmin) can lead to loss of expensive mud fluid and increase in non-productive time. This can lead to loss of million dollars in deep water drilling operations.

Apart from determining upper limit of MW, the horizontal stresses (Shmax & Shmin) are the key input to wellbore stability model for estimating the shear failure gradient (lower limit of mud weight) for deviated wells. The differential stress increases as reservoir pressure decreases and increasing differential stress can account for depletion-induced wellbore collapse, despite increase in effective stress (Hillis, 2000). Therefore, high uncertainty in the horizontal stresses magnitude can lead to risk of wellbore failure which can cause problem during drilling and completion operations within depleted reservoir.

In this study mud loss event was used to estimate and calibrate the minimum horizontal stress magnitude and stress path for the depleted reservoir. The calibrated horizontal stresses (Shmax & Shmin) were taken as input in wellbore stability model to estimate the optimum mud weight (MW) for depleted reservoir drilling. The optimized MW based on input of updated stress magnitude (from well events) was key driver for successful drilling (without loss and wellbore collapse) and completions of wells in this field.

Predrill Wellbore Stability Model & Drilling Plan

Prior to drilling well, the wellbore stability modeling was performed for the planned trajectory to characterize in-situ stresses, pore pressure, mechanical properties of the reservoir & surrounding rocks, and to understand the influence of reservoir pressure changes on stresses. The estimated stresses at points around the wellbore is being compared against the formation strength of the rock, points where the stress state exceed the formation strength (either in compression or tension) failure is considered to have initiated (M.R.Mclean, 1990). A failure criterion determines the optimum mud weight window required to drill a well successfully without wellbore collapse. Modified Lade failure criterion was found to be most applicable (verified by offset wells) in this field to predict the onset of failure and estimation of minimum mud weight without any failure (shear failure gradient or SFG).

The casing design and mud weight planning were based on the predrill wellbore stability model. The presence of thick intra-reservoir shale (thickness more than 8m) caused very narrow drilling margin for the reservoir section. The lower bound (minimum MW requirement to prevent wellbore collapse) of mud weight window was shear failure gradient (9.45ppg) of intra-reservoir shales (Figure 1). Whereas, upper bound of the mud weight window was fracture gradient or Shmin gradient (10ppg). Thus, overall drilling window within reservoir section was very narrow (0.55 ppg). Whereas, a relatively good drilling window (>2 ppg) was available for drilling overburden section. It was planned to set casing at reservoir top (minimal or no exposure of overburden shale) in order to isolate the overburden section first prior to entering into the depleted reservoir. Therefore, planned well was designed to drill with different MW in overburden (11ppg MW) and reservoir section (9.5 ppg MW) (Figure 1).

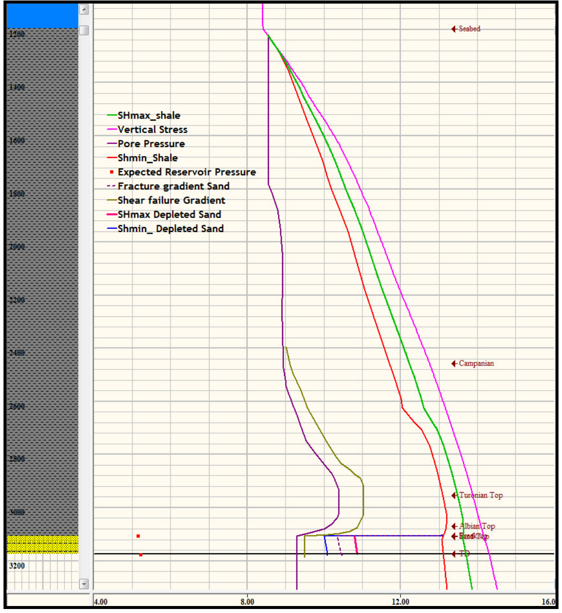

Figure 1. Predrill Wellbore Stability Model.

Well Event Analysis and Interpretation of Horizontal Stresses Magnitudes

The well was drilled without any wellbore stability problem in the overburden section (up to 3104m TVDRT, 5035m MDRT). No torque and drag was observed while drilling as well as reaming the drilled section. Additionally, the size and shape of cuttings were normal indicating the used MW (11ppg) is optimum for drilling the overburden shale section. Catastrophic mud losses were encountered while drilling near the top of reservoir with same mud weight (11ppg) prior to reach section TD (to set casing). The catastrophic mud losses were due to depleted nature of reservoir sand having lower fracture gradient/ Shmin than the used MW. The annular pressure while drilling (APWD) data provide information on borehole annular pressure in the circulating fluid and has the potential for providing information about the magnitude of the least principal stress. This measurement is generally taken 5–10m behind the bit and calculate accurate down hole equivalent mud weight. The down hole wellbore pressure during drilling are measured in terms of equivalent static density (ESD) during pump off time & equivalent circulating density (ECD) during pump on time and is being recorded by pressure-while-drilling tools (PWD). The time dependent PWD data of the mud loss event was integrated (Figure 3) with mud logging and drilling data to estimate the magnitude of minimum horizontal stress in the depleted reservoir section.

Sudden drop in pit level was observed as reservoir sand was penetrated while drilling at 5035m MDRT with ECD of 11.5 ppg (Figure 2A & 2B).As a quick response to total mud losses, the pump was shut down and well was monitored on trip tank. The ECD significantly exceeded the predrill predicted fracture gradient (10.3 ppg) and minimum horizontal stress (10 ppg) of reservoir sand.

Time based recorded mode PWD data was analysed to investigate the mud loss event. Figure 3A shows decease in active while drilling at 5035m MDRT (Figure 2B) and followed by sudden decrease in annular pressure. These events suggest generation and then propagation of new fractures. Subsequently, the pump was shut down to observe the down hole behavior.

Later pump was turned on again with low flow rates. However, active volume was showing continuous decreasing trend (Figure 2A), suggesting continuous fracture propagation away from wellbore. The slow increase in the ECD (Figure 2A) during this propagation period was due to added mud loss preventive additives in the mud.

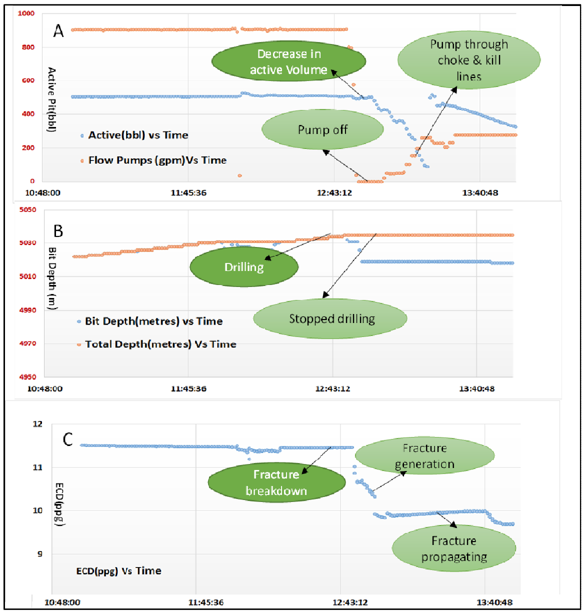

Figure 2. Mud loss Event Analysis. A: Showing active mud pit level & pump flow rate while drilling & during mud loss, B: total drill depth and bit depth in MDRT C: the variation of ECD while drilling, shut in & during circulations.

Minimum Horizontal Stress Estimation:

The best method to estimate the minimum horizontal stress is to determine the closure stress. The plot (Figure 3) of ECD vs the square root of shut-in time (pump-off period just after mud loss event) was used to estimate the closure stress. There are two distinct trend of pressure decline rate and sudden drop of pressure can be seen at around 2.5 minute. Closure stress was interpreted at the intersection point (9.85 ppg) between this sudden drop of pressure line and slope of trend 2.

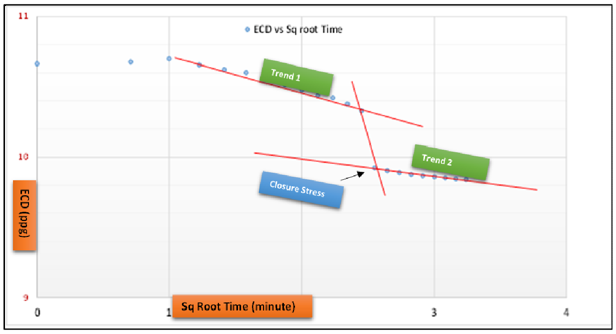

Figure 3. ECD vs square root of Shut in time showing the interpretation closure stress.

Maximum Horizontal Stress Estimation:

The drilling induced fracture and wellbore breakouts are indicative of difference in horizontal stress magnitudes and can be used to calibrate the magnitude of maximum horizontal stress magnitude (Zoback et al., 2003). However the wellbore failure features (breakout and tensile fracture) will occur provided the used mud weight for drilling is not optimum. In such cases where the wellbore failure features are not present, the stress magnitudes can be constrained by the strength of pre-existing faults [Moos et al., 1999; Zoback et al., 2003; Zoback, 2007; Chang et al., 2010]. With the help of stress polygon, it is possible to constrain and reduce the uncertainty in the maximum horizontal stress magnitude. In stress polygon, the µ (coefficient of friction) of the fault planes is likely to be between 0.6 and 1.0 for deep wells and boreholes [Barton et al., 1988; Zoback et al., 2003; Zoback, 2007].

In this study, magnitude of Shmax within the depleted reservoir zone was determined using the stress polygon analysis for a given Sv and Shmin and constrained by the strength of the pre-existing oriented faults (µ of 0.6). The stress polygons (Figure 4) were generated considering different breakout angles and rock strengths. As there was no evidence of wellbore collapse during drilling phase, a maximum breakout angle of 5° was used to constraint Shmax magnitude. Thus, stress polygon will estimate the upper limit of Shmax.

Stress polygon was generated for the depleted reservoir with inputs of vertical stress within reservoir (7518psi), minimum horizontal stress of reservoir (5265psi –interpreted from mud loss event analysis), rock strength of offset well reservoir (2450psi), and maximum breakout angle of 5 degree. The Table 1 given below represents the reservoir stress condition at 50% depletion. The estimated Shmax /Shmin stress ratio for the reservoir sand is 1.03. This is the upper bound limit of stress anisotropy.

Interval	Sv (psi)	Shmin (psi)	Shmax (psi)	UCS (psi)
Reservoir Sand (3110m)	7518	5265	5430	2450

Table 1: Stress State of depleted Reservoir

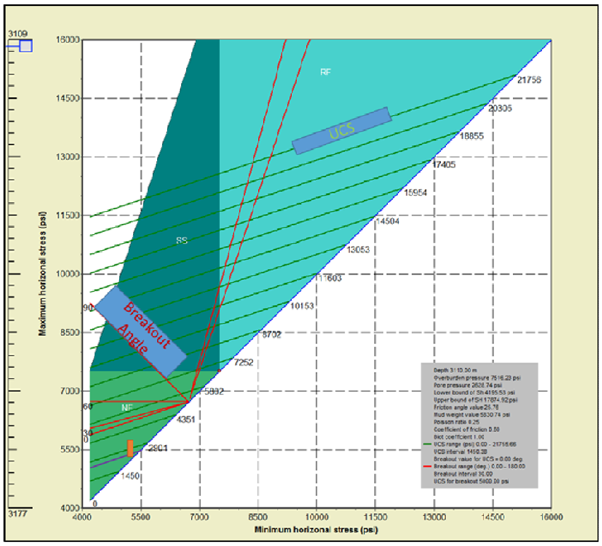

Figure 4. Stress polygons: stress state condition for whole reservoir section. The light purple shaded area indicates the possible Shmax range. For analysis purpose in WBS model, Shmax value of 5430 psi at reservoir top was used in model.

Application of Stress Estimation in Wellbore Stability Model and Reservoir Drilling

Wellbore stability model was updated for drilling the reservoir section of the present well. The estimated magnitude of minimum horizontal stress, maximum horizontal stress and stress anisotropy was taken as input in the wellbore stability model for estimation of shear failure. The wellbore stability model (Figure 5) suggests that optimum required minimum MW (lower bound of MW window) for drilling the reservoir sand as well as intra-reservoir shale without any wellbore collapse is 9.4ppg. Whereas, maximum allowable MW (upper bound of MW window) within reservoir section is 9.85 ppg. Thus, it gives a very narrow challenging MW window (0.45 ppg) having minimum uncertainty than predrill.

Subsequently, the well was drilled and completed successfully with 9.3 ppg MW, keeping the ECD below Shmin (9.85ppg) and ESD above the shear failure gradient (9.4 ppg). No torque/drag and mud losses was observed during drilling the reservoir section. This suggests that the hole was in good condition and the designed MW was optimum for the section. The Azimuthal density image data (Figure 6) were used for wellbore stability analysis and hole condition indication. The image log indicates that the hole is in good condition against the reservoir sand as well as intra-reservoir shale for the drilled section without any wellbore failure (breakout & tensile fracture). The geomechanical model was updated and further used for other sidetrack wells drilling in this field for reducing the NPT and optimize the mud weight. Model was further used in sanding analysis and completion strategy.

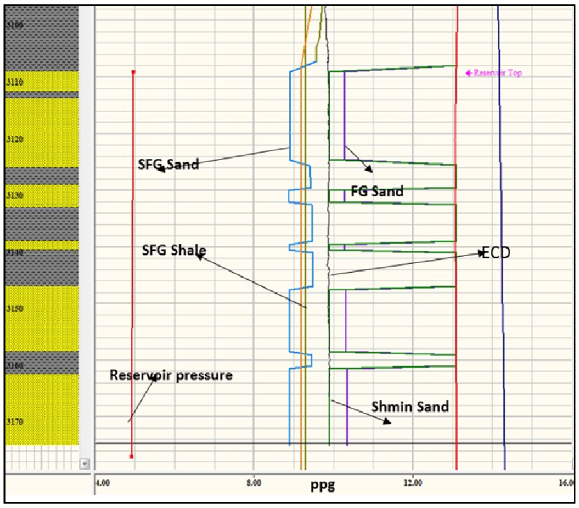

Figure 5. Wellbore stability model after inputs of horizontal stresses estimated from well event and stress polygon. Figure also shows the ECD of well drilled later based on this model.

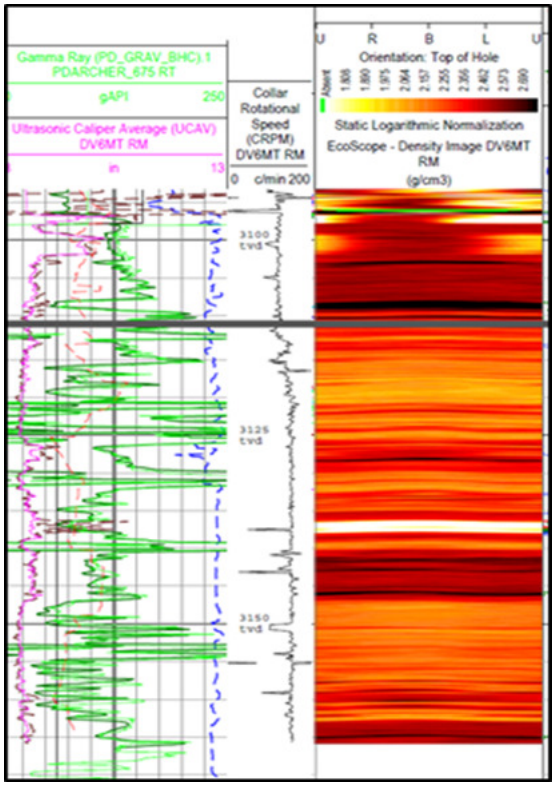

Figure 6. Azimuthal density image log showing hole is in good condition without wellbore failure.

Conclusions

This work highlights how well event in a well was analysed in geomechanics platform to successfully drill & complete wells. The Shmin magnitude can be estimated accurately by analysis of time dependent down hole pressure data of a mud loss event. This data give same high quality Shmin estimation as in mini-frac or extended leak-off test and provide much better quality of minimum horizontal stress measurement than standard LOP data. Such accurate Shmin will allow the Geomechanics engineer to better estimate the maximum horizontal stress (Shmax) using stress polygon. Most importantly, Geomechanics engineer will be able to provide drillers accurate mud weight window. It will be highly beneficial in challenging environments (especially deep water, depleted reservoir) where mud weight window is very narrow. The optimum mud weight would reduce the probability of wellbore failures and would lead to smooth drilling & completion of wells.

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Nomenclature:

APWD = Annular Pressure While Drilling
ECD = Equivalent Circulation Density
ESD = Equivalent Static Density
FG = Fracture Gradient
MW = Mud Weight
Sv = Vertical Stress
Shmax = Maximum Horizontal Stress
Shmin= Minimum Horizontal Stress