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Pore pressure prediction module and poroelastic horizontal strain model

Predikcija pornog tlaka i primjena poroelastičnog modela

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Abstract

Pore pressure prediction methodology relies on a predictable relationship between porosity and effective stress and is therefore essential for executing a safe and cost-effective drilling program. Using this prediction method and it's results, a 1D geomechanical model can be created. Correct pore pressure prediction and wellbore integrity plays an important role in petroleum operations. The various phases of the life cycle of a well such as drilling, completion and production, hydraulic fracture failure, borehole instability, lost circulation, sand production, casing collapse, compaction, subsidence and permeability reduction, cost the oil and gas industry both time and money. Prediction and prevention of these issues requires understanding of the interaction between formation, in-situ stress and drilling parameters.

Mechanical modeling in general, and more specifically pore pressure prediction and poroelastic modeling, provide the methods to help understand the mechanical properties of the subsurface and are regularly used in various subsurface-related industries such as oil and gas, geothermal, and CO_2 storage (CCUS). The principal stress distribution influences the stress regime and dictates the creation of different types of faults and fractures. In cases where gravity is the only source of stress in the model, a normal stress regime is observed across the entire depth. However, in cases where tectonic stress is also involved, the stress regime can change over the depth from reverse, strike-slip to a normal stress regime. Lateral variation of the fault in the 3D model (several 1D mechanical earth models) does not have a large contributing factor, to influence the magnitude is indeed can affect the principal, effective stress, and the stress regime throughout the 1D mechanical earth modeling (1D MEM) – elastic properties calculation as well as a first estimation for the vertical and horizontal stresses at well locations by using log data. This information is then used to populate a 3D finite element model (3D MEM) which is built from seismic data and comprises not only the reservoir but the entire overburden up to the earth's surface. The purpose of this article is to present results obtained through the testing of Emerson's Geolog™ geomechanics functionality and pore pressure prediction module, using all available data. Calculate and present the physical (pore pressure), mechanical properties (elastic: Young's modulus, Poisson's ratio, Bulk modulus and inelastic: rock strength, UCS, friction angle) of the rock, and post-drill mud weight window of the well XX. The properties are derived from various logs e.g. sonic log (compressional and shear), density log, petrophysical analysis (porosity and shale volume) and

image analysis, using various methods and empirical relationships. Magnitudes and orientation of principal stresses in this case, are calibrated using minifrac results to provide a post-drill geomechanical model.

Sažetak

Metoda predikcije pornog tlaka formacije temelji se na povezanosti poroziteta formacije i efektivnog stresa. Koristeći ovu metodu i njezine rezultate, može se pretpostaviti 1D geomehanički model. Ispravna predikcija pornog tlaka i ostalih parametara koji utječu na integritet bušotine igraju važnu ulogu u operacijama bušenja, karotažnih mjerenja i opremanja. Životni ciklus jedne bušotine obuhvaća različite faze i izazove koje one nose prilikom izvedbe bušenja (npr. gubitak cirkulacije, nestabilnost bušotine), opremanja, hidrauličko frakturiranja, proizvodnje (dotok pijeska u kanal bušotina, slijeganje formacije, smanjenje propusnosti). Predikcija i prevencija prethodno spomenutih izazovnih zadataka prilikom izvedbe zahtijevaju dobro razumijevanje i povezivanje svojstava formacije i postojećeg stresa te značajan ulog vremena i novca kako bi se sigurno i uspješno izvele.

Geomehaničko modeliranje, osobito predikcija pornog tlaka i poroelastično modeliranje (kao jedan od načina geomehaničkog modeliranja) služe za računanje mehaničkih svojstava formacije i razumijevanje podzemlja. U svijetu se ova metoda aktivno koristi u radovima u naftnoj i geotermalnoj industriji te također u radovima skladištenja CO_2. Distribucija glavnog stresa utječe na stvaranje stres režima i raznih tipova pukotinskih sustava kao što su rasjedanje i frakture. Kada se smatra da je gravitacija jedini izvor stresa kao vertikalni stres, kroz profil bušotine definira se normalni stres režim. Dok u slučaju prisustva ostalih tektonskih poremećaja (što je uglavnom slučaj) nužno je definirati režim stresa kao reverzni, posmični ili normalni u profilu bušotine. Horizontalno širenje i prikaz rasjeda kao generalni stres režim na širem području se može prikazati u 3D modelu (nekoliko 1D geomehaničkih modela), no na veličinu glavnog stresa te raspodjelu mehaničkih svojstava formacije kroz profil bušotine najviše utječu izračunata mehanička svojstva. 3D model koji sadrži nekoliko 1D modela i seizmičke podatke daje bolju sliku i razumijevanje svojstava stijena ne samo u intervalu ležišta već u cijelom podzemlju.

Svrha ovog članka je prezentirati rezultate koji su se dobili testiranjem softvera Emerson Geolog™, modula za predikciju pornog tlaka i izračun geomehaničkih svojstava (*Pore pressure prediction* i *Geomechanics*) koristeći dostupne podatke. Izračunati i prezentirati rezultate izračuna pornog tlaka, mehaničkih svojstava (elastičnih: Youngov modul, Poissonov koeficijent, Modul gustoće i neelastičnih svojstva: čvrstoća stijene, UCS, kut trenja) stijene te analiza stabilnosti bušotine. Rezultati su dobiveni koristeći razna karotažna mjerenja: zvučno (kompresijsko i posmično), karotaža gustoće te rezultate petrofizikalne analize (krivulja poroziteta i volumena gline) i analize izgleda stijenke bušotine (distribucija pukotina i orijentacija stresa) uz primjenu empirijskih formula. Veličina i orijentacija stresa je u ovom slučaju kalibrirana na podatke minifraka, a prikazani rezultati predstavljaju geomehanički model u fazi nakon bušenja.

1. Introduction

When a porous rock is subjected by a stress, there is a counter pressure from fluid inside the pore space of the rock itself. This fluid pressure is called pore pressure (formation pressure). The concept of effective stress was introduced by Karl Terzaghi. It is said that in the poroelastic material behavior, the difference between the total stress and pore pressure, is effective stress. The stress felt by the grains, is not only the external stress but also the effective stress, which in here includes the pore pressure (Formula 1).

$$\sigma = S - Pp \qquad \text{Formula 1}$$

Where σ is effective stress (can be horizontal or vertical), S is total stress, and Pp is pore pressure.

One of the ways to obtain the magnitude of pore pressure is to use the relation between the porosity and the effective vertical stress (Formula 2).

$$\varphi = \varphi 0 e - \beta \sigma v \qquad \text{Formula 2}$$

Where φ is porosity, β is empirical constant, σv is effective vertical stress.

The porosity can be derived from well logs such as sonic or density as a result of petrophysical analysis and vertical stress (Sv) is calculated using Formula 1. Thus, the pore pressure magnitude can be calculated since it is the only unknown variable here. The ratio between the effective horizontal and vertical stresses is called effective stress ratio. Based on the geological stress convention, positive stress would imply compression and negative stress implies tension. Meanwhile, the engineering stress convention represents positive stress as tension, and the negative as compression.

The area of interest where the wellbore XX is drilled, represents an elongated anticline with two maxima closed by a normal fault on the north wing, which is presumed to be a barrier to another field. On the south side, the structure is separated from another field by a right strike-slip fault. The field is composed of tectonic blocks, limited by reverse, strike-slip and normal faults.

Based on the above theory, the tectonic area and the available log data, it was decided to apply the Eaton Horizontal Ratio method for pore pressure prediction, and the poroelastic horizontal strain method for the geomechanical model and wellbore stability analysis. Stress profile and elastic properties were calibrated to minifrac results.

2. Pore pressure prediction

Pore pressure prediction workflow and modelled pore pressure (formation pressure) represents one of the most important inputs for a geomechanical analysis. The pore pressure is necessary to calculate the effective, principal stress acting on each grain of a rock. The pore pressure defines also the lower limit of the mud weight to drill safely a well without formation fluids entering the borehole during the drilling phase. The quantification of pore pressure requires knowledge of the normal pore pressure trend for the area, the establishment of a normal shale compaction trend line (Figure 1) and the quantification of the deviation of the observed pressure trend from the normal pressure trend. Shale points are usually selected to establish a normal compaction trend line (solid orange line), because normal compaction due to overlying sediments will reduce porosity in shales. Therefore, as burial depth increases shale properties will either increase (density, resistivity, and velocity) or decrease (sonic) in an exponential fashion. A best fine line, drawn through normal compacted clean shale layers, will generally be a straight line plotted on a semi-log plot (depth linear, shale property logarithmic).

Deviation from this normal trend may indicate either under-pressure or over-pressure formations. The pore pressure can be estimated either by using empirical methods, in this case Eaton with parameters (0.225 and 0.248) with the Geolog^{TM} Pore Pressure Prediction module or can be directly measured with wireline formation testers. Prognosed pore pressure was calibrated to the minifrac pressure points (Figure 2).

For the next step of the workflow, it was necessary to calculate overburden and fracture pressures (Figure 3). Overburden pressure is exerted by the weight of the overlying sediments. As an input for this module it is used the mud weight equivalent from mud

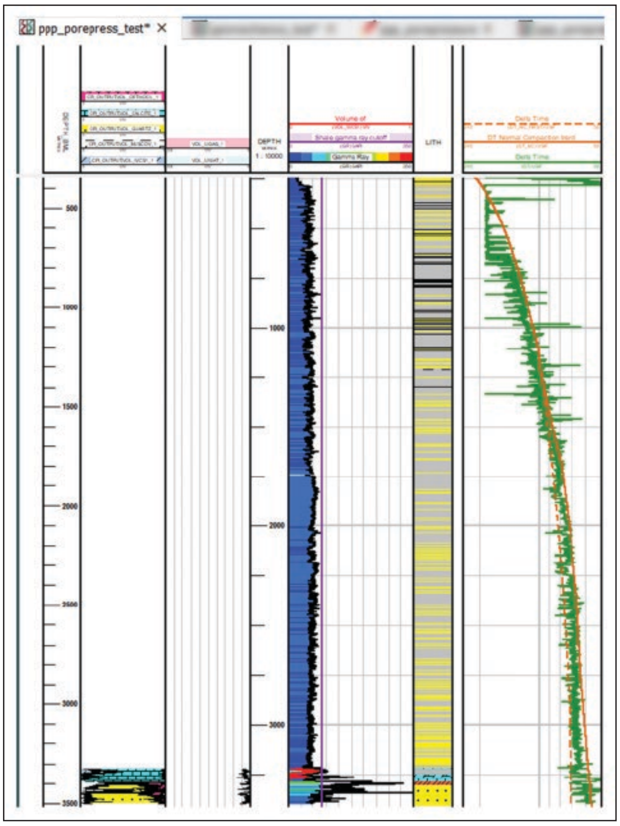

Figure 1. Compaction Trend

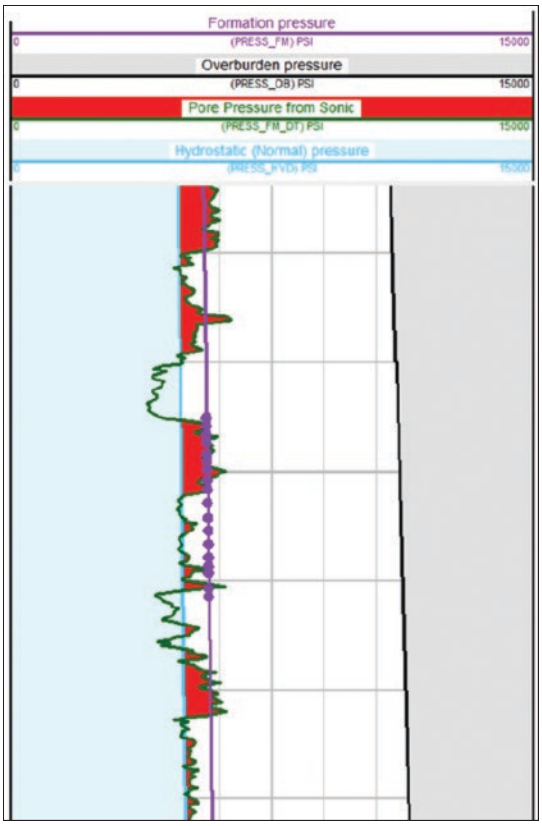

Figure 2. Pore pressure

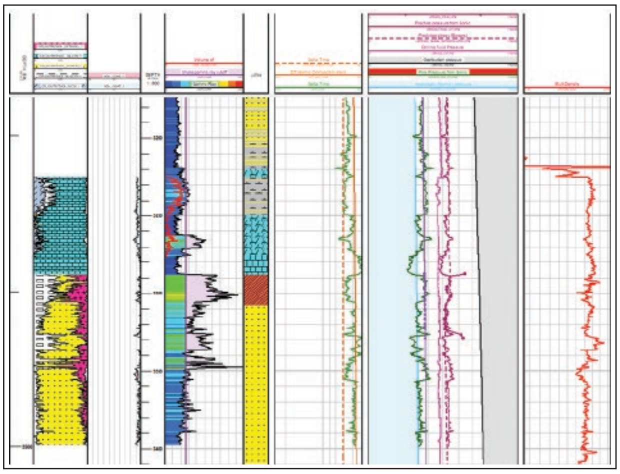

Figure 3. Pore pressure prediction results

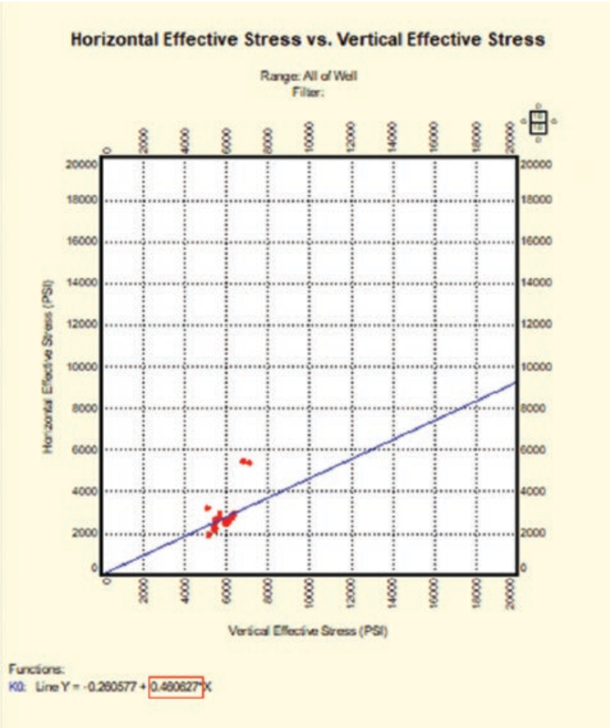

Figure 4. Matrix stress ratio

logging. Fracture pressure is the pressure that is required to initiate fracturing or circulation loss. Since this is a post-drill analysis and the minifrac results were available, it was possible to calculate fracture pressure using FIT *(eng. Fracture Injectivity Test)* (Figure 3) calibration method, where K_0 (Matrix stress ratio) is equal to 0.467 (Figure 4). Matrix stress ratio was delivered using formula 3:

$$K_0 = \frac{HES}{VES} \qquad \text{Formula 3}$$

where HES presents calculated horizontal stress and VES vertical, overburden stress. Calibration plot was built using Vertical and Horizontal effective stresses to obtain K0_grad constant.

3. Poroelastic horizontal strain model

Poroelastic model assumes that the subsurface is a series of sub-horizontal layers and that horizontal stresses, minimal (SHmin) and maximal (SHmax) of isotropic elastic rocks are calculated using Formula 4 and Formula 5 as:

$$SHmax = \frac{POIS * (PRESS_{OB} - BIOT * PRESS_{OB})}{1 - POIS} + BIOT * PRESS_{FM} + \frac{YMOD * STRAIN_{MAX}}{1 - POIS^2} + \frac{POIS * YMOD * STRAIN_{MAX}}{1 - POIS^2}$$

Formula 4

$$SHmin = \frac{POIS * (PRESS_{OB} - BIOT * PRESS_{OB})}{1 - POIS} + BIOT * PRESS_{FM} + \frac{YMOD * STRAIN_{MIN}}{1 - POIS^2} + \frac{POIS * YMOD * STRAIN_{MIN}}{1 - POIS^2}$$

Formula 5

Where inputs for this model are elastic properties; YMOD is Youngs Modulus, KMOD is Bulk Modulus, UMOD is Shear Modulus, MMOD is P-wave Modulus, POIS is Poisson's ratio, BIOT is Biot coefficient, $PRESS_{OB}$ is overburden formation pressure, $PRESS_{FM}$ is Formation pressure, $STRAIN_{MAX}$ is maximal strain and $STRAIN_{MIN}$ is minimal strain. Rock strength properties (UCS, internal friction and tensile strength) and other inputs data are derived from various logs and analysis: image analysis (orientation, azimuth of borehole breakouts) and drilling-induced fractures (DIFs).

3.1. Elastic and rock strength properties

The dynamic elastic rock properties are calculated from bulk density, together with compressional and shear slowness. As the model uses only static properties, the conversion has been done using empirical relations as core-derived static rock properties were unavailable (Figure 5). Mixed Lacy equation was selected, and results were calibrated using data from minifrac results. The results are compared using a linear regression method with the regression coefficient of 0.8 and 0.9 (Figure 6). Rock strength properties, USC, are in this case calculated using Sedimentary_Kazi_1983 equation. Coefficient of internal friction and tensile strength were also calculated (Figure 7).

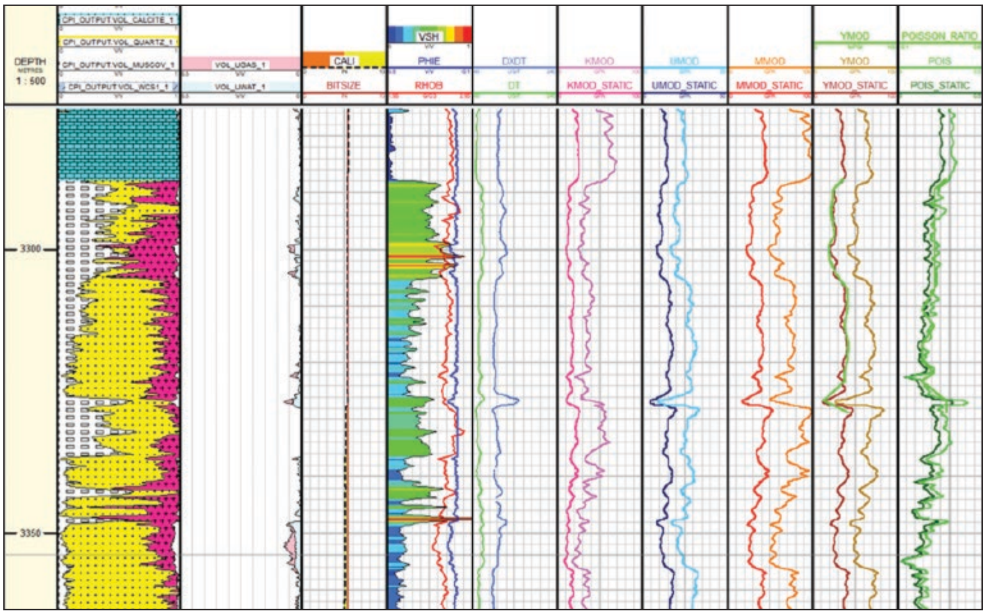

Figure 5. Elastic properties

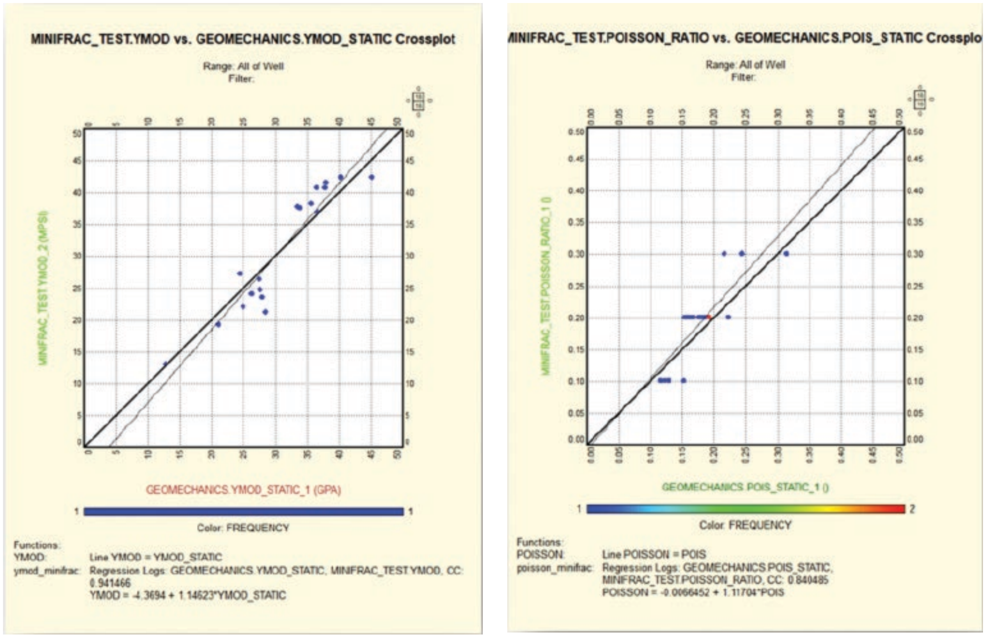

Figure 6. Linear regression YMOD static and POISSON vs MINIFRAC results

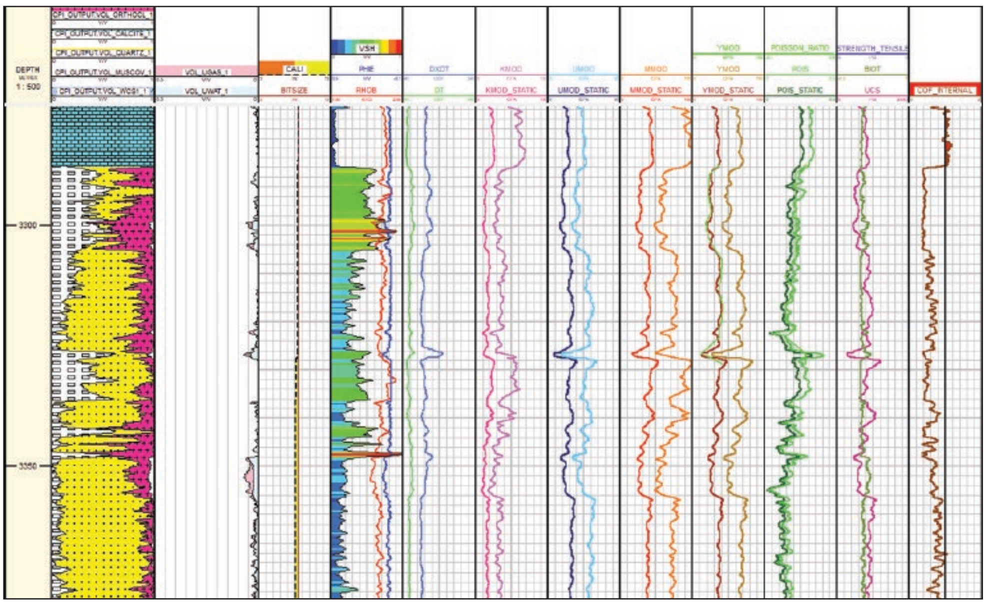

Figure 7. Rock strength properties

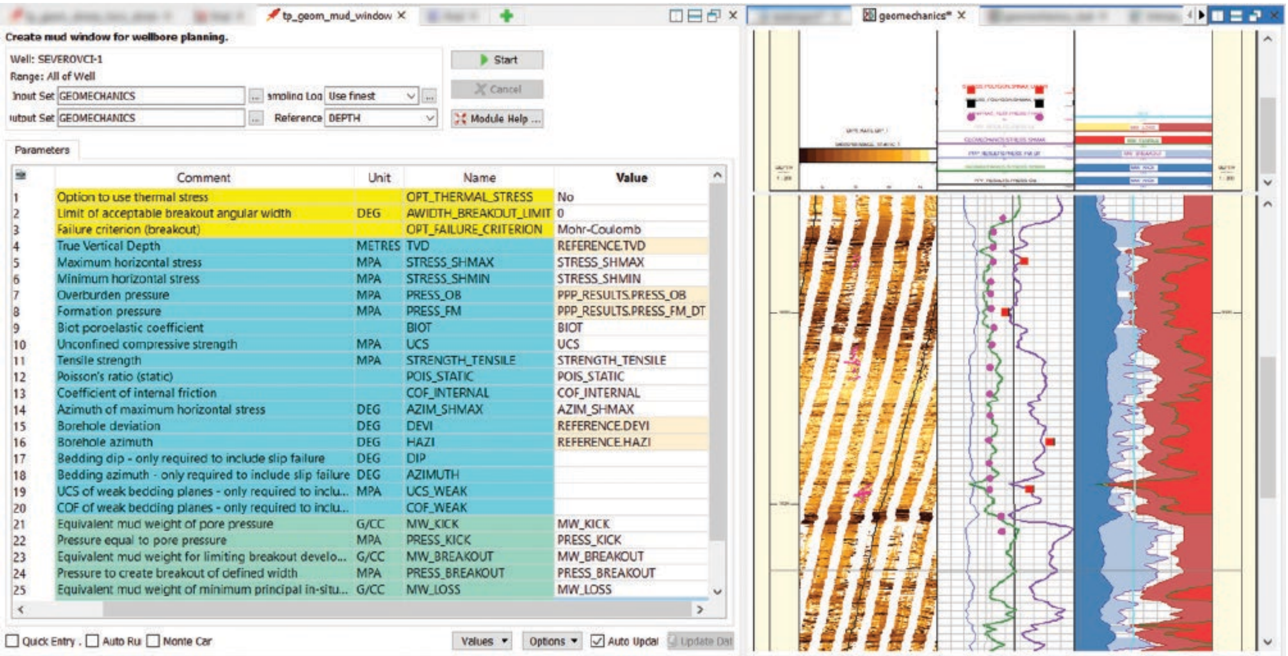

Figure 8. Estimated minimal and maximal horizontal stress and mud weight window

4. Estimation of minimum and maximum horizontal stress magnitudes

Borehole breakouts and drilling-induced fractures (DIFs) from image analysis are important indicators of horizontal stress orientation. In this case, in this zone of interest, breakouts are not present, but tensile fractures do occur. Tensile mean azimuth is 187 deg which corresponds to maximum horizontal stress orientation. Magnitude of SHmax was not calculated from breakouts but is based on failure observations from image logs and the magnitude is calculated using the Stress Polygon Method as a failure criteria. Results calculated using this method are calibrated to minifrac results (pink dots) (Figure 8).

5. Conclusion

This well was drilled in a strike-slip regime area and the available log and well data were of good quality and used in Geolog™ scope of modules. Using the available data, the whole pore pressure prediction and geomechanics workflows for this well are based on many assumptions and estimated parameters, so that the uncertainty of the results is very high. Static elastic properties, UCS, coefficient of internal friction are calculated using existing empirical algorithms – which might not provide the 'real' results for the rocks in this well. But due to available minifrac data, calibration was successfully done.

Without having breakouts developed in the zone of interest, the uncertainty for estimating the horizontal stress magnitudes is relatively high. Minimum and maximum magnitude of stress were calculated using a stress polygon method as a failure criteria. Those results were recalibrated to minimal stress from minifrac results. Drilling fluid pressure varies during drilling and can be higher and/or lower than indicated by the constant mud weight.

This wellbore stability analysis is considered as a post drilling analysis. Due to limited data and knowledge about the rock strength properties, it is hard to come up with a satisfying geomechanical model. Only additional data (drilled wells, rock strength data from cores) will allow us to improve the model and give increased confidence in the results.

It is recommended to perform geomechanical core testing on the target formation for the benefit of improving the geomechanical understanding of the area and to benefit future hydraulic fracturing design and execution.

Modules and workflows were successfully tested and results can be used for assumption and prediction of mechanical properties for further offset wells in this field area.

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