GeoFit™ GEOMECHANICS

GeofitGeomechanics_WHP_ALL_20181008_REV00

Revision History

Documents are reviewed annually to ensure relevance to the systems and process that they define.

Rev	Date	Originator/Reviser	Dept	Reason for Change
0.0	10 - 2018	Oyedokun, F.		
0.0				

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Geomechanics as a Discipline

Geomechanics is a discipline that applies geology, solid mechanics, fluid mechanics, mathematics, and physics to study how rocks or soils respond to forces due to fluid flow, temperature, in-situ stresses, formation pressure, and excavation. In the Oil and Gas industry, the understanding of the mechanical properties and behaviors of geological formations during exploration, appraisal, development, production, and abandonment of O&G assets is highly essential for safe operations and increased productivity.

Figure 1 provides a summary of typical geomechanics applications in the O&G industry. At the wellbore scale, geomechanics is applied to understand bit-rock interaction, breakout, tensile fracturing, stability of perforation tunnels, and design of hydraulic fracturing stimulation operation. At the reservoir scale, the variation of the reservoir permeability, compaction, and subsidence are typical issues often investigated by engineers.

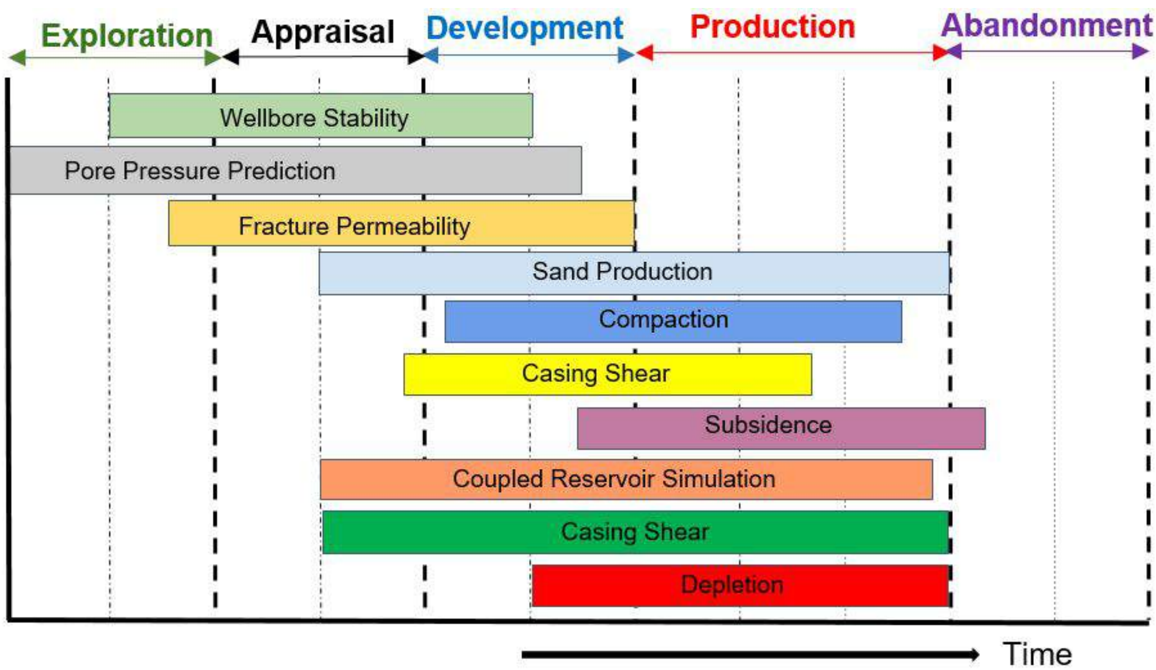

Figure 1. Geomechanical applications at different phases of asset development in the oil and gas industry.

In geologic carbon storage (GCS) operations, geomechanics plays a key role in identifying the potential risks - fault reactivation and CO2 leakage, which can pollute the subsurface water-table (**Figure 2**).[1]

[1] Rutqvist, J., 2012. The geomechanics of CO_2 storage in deep sedimentary formations. *Geotechnical and Geological Engineering*, *30*(3), pp.525-551.

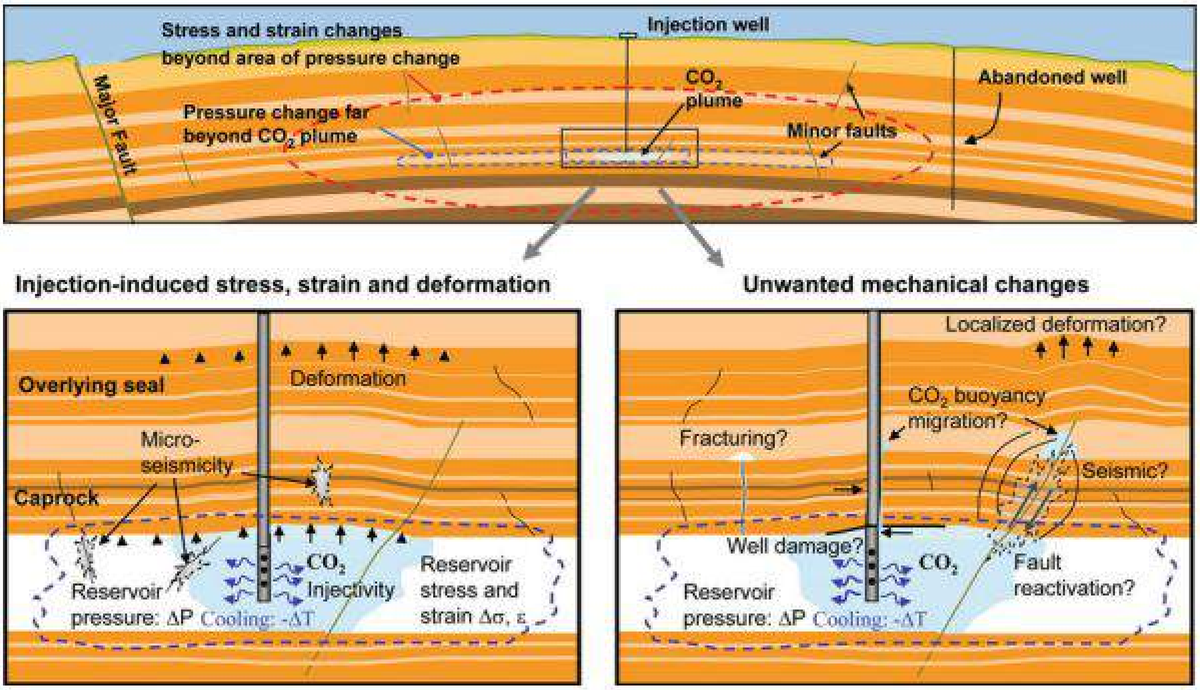

Figure 2. Geomechanical processes associated with GCS in sedimentary formations. Pressure and temperature changes induce stresses and strains in the reservoir and cap rocks, thus increasing the chances for fault activations and reduction in sealing capability. (Rutqvist 2012)

The introduction of Kirsch's equation in the early 1900's, effective stress concept by Terzaghi, and Biot's poroelasticity in the early 1940's provided solid foundation for petroleum geomechanics[2]. Most of the issues identified above have been studied since the early days of oil exploitation (see **Figure 3**). But with advancement in science and computational methods, more improved tools are now being used to solve similar and more complex problems. As conventional resources deplete and global energy demand increases, the exploitation of unconventional resources has since increased. Although, the development of unconventional resources brings with it more challenging problems, including inelastic matrix behavior, rock anisotropy, chemical interactions between wellbore fluid and rock, production from critically stressed natural fractures, failure at weak planes, and low permeability.

The computation of the stresses around a planned wellbore or in a reservoir is essential before any detailed quantitative analysis can be conducted. For instance, to drill through a particular formation, the computed wellbore stresses are compared with the strength of the rock and a mud program is designed for such a well. The resulting program would be such that the mud weight is above the critical collapse mud weight and less than the critical mud weight to cause tensile failure. Lower mud weight results in compressive shear failure of the wellbore, and the borehole enlarges in the direction of maximum compression (see **Figure 4**). On the other hand, high mud weights can cause tensile failure of the wellbore. To compute

[2] Addis, M.A., 2017. The geology of geomechanics: petroleum geomechanical engineering in field development planning. *Geological Society, London, Special Publications*, *458*, pp.SP458-7.

these stresses, a Mechanical Earth Model (MEM) for the field of interest needs to be built. An MEM can be simple or complex, 1D, 2D, 3D, or 4D.

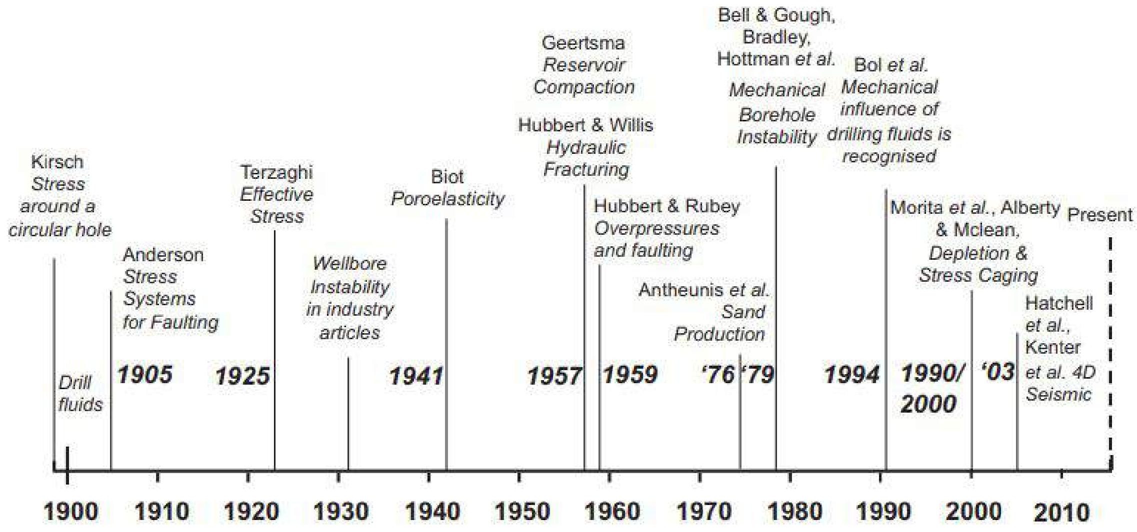

Figure 3. Timeline of notable scientific developments that now constitute the foundation of petroleum geomechanics today. (Addis 2017)

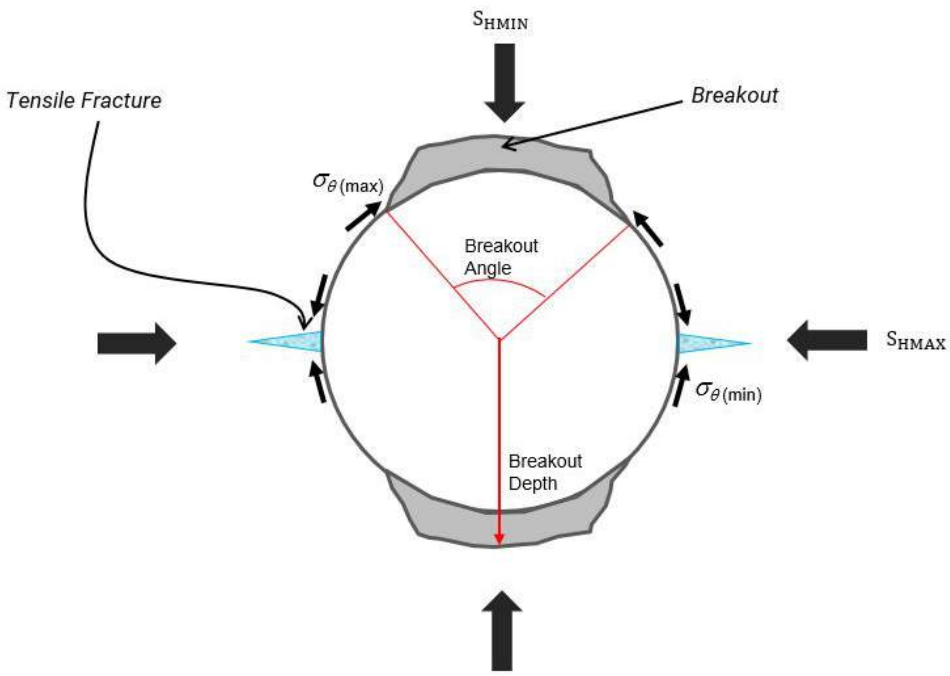

Figure 4. Tensile and compressive shear failure around vertical well.

Mechanical Earth Model: GeoFit™ Approach

An MEM is a collection of measurements and models of rock mechanical properties, in-situ stresses, pressures, and temperatures in a specific field. The model can be constructed for the virgin conditions of the reservoir and further updated as conditions change during exploration and development.

In GeoFit™, the construction of the 1D MEM starts with the building and calibration of the overburden stress models (see **Figure 5**), although it is expected that data cleaning is done prior to the start of building the MEM.

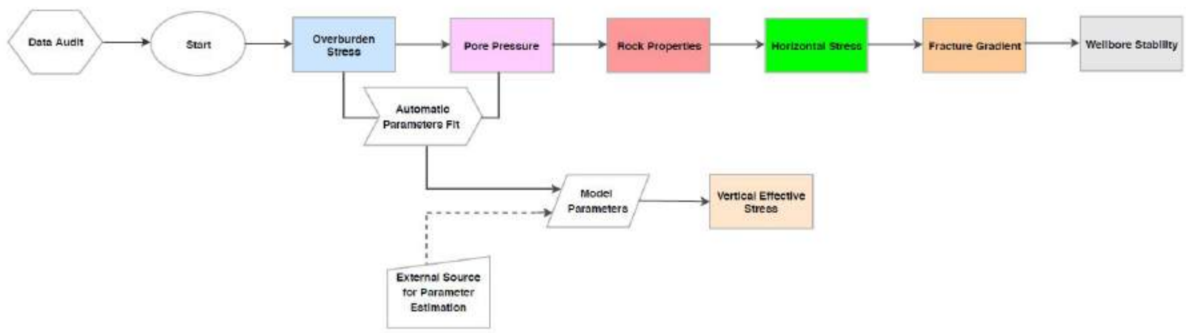

Figure 5. GeoFit geomechanics workflow

Figure 5. GeoFit^{TM} geomechanics workflow..

Overburden Stress

This the stress imposed on a rock layer by the weight of rocks and fluids overlying it. As simple as this particular workflow is, it is very crucial in developing the mud program. Incorrect estimation of the overburden stress will lead to errors in many of the workflows in the MEM (pore pressure, fracture gradient, horizontal stress) and mud program. On GeoFit™ platform, six different methods are available for computing the average bulk density and overburden stress - Amoco, Gardner, Wyllie, Belloti and Giacca, power-law extrapolation, and conventional bulk density equation. The parameters of these model often need to be recalibrated to mimic the measurements in density logs.

Pore Pressure

The pressure of the fluids contained in the pores of rock formation provides information on the available reservoir energy to produce the hydrocarbons and also helps in planning the mud program. In shallow depths the pore pressures are usually hydrostatic while in deep sedimentary formations the pressure often are not hydrostatic; subnormal and abnormal pore pressure are often observed. In subnormal pore pressure conditions, the pore pressure is lower than the normal hydrostatic pressure profile. With an abnormal pore pressure, the formation pressure is higher than the normal hydrostatic profile for that area.

Some of the sources of overpressure include compaction disequilibrium, hydrocarbon generation and gas cracking, aqua-thermal expansion, tectonic compression, mineral transformation, and buoyancy effects[3]. In conventional resources, disequilibrium compaction is the most common and primary source of overpressure; and the porosity of the formation is preserved as the pore fluids bear more overburden weight. The presence of secondary pressure mechanisms in unconventional resources mean that the strong connection between porosity and overpressure cannot be solely used for predicting pore pressure. The relationships existing among key variables (vertical effective stress, density, acoustic velocity, and resistivity) follow the unloading path.

In GeoFit™, three popular pore pressure prediction methods are available, Eaton-Sonic, Eaton-Resistivity, and Bower. Bower's method can be applied to many hydrocarbon basins and it captures unloading effects, but care must be taken when using it to estimate pore pressure for shallow unconsolidated formations.

To calibrate the models, direct formation pressure test data are used in conventional plays, but in unconventional resource plays the formation pressure tests are seldom conducted because of the low permeability of shale. In lieu of this, it is common to drill underbalance in unconventional resource plays so as to use the kicks data to calibrate the model.

Rock Properties

The estimation of rock mechanical properties provides insights into the mechanical constitutive behavior of the rock. The determination of these properties is critical for drilling programs, well placement, well-completion design, reservoir management, and $CO2$ geological sequestration. Through acoustic logging and availability of the density data (from density logs or validated correlations), the dynamic elastic elastic properties of the rock can be estimated. For many geomechanical analysis, the static elastic properties are more relevant because the static measurements represent the in-situ reservoir mechanical properties more accurately.

Elastic moduli of a rock material is its ability to resist deformation from external loads[4]. Static moduli are measured from responses to slowly varying applied stresses while dynamic moduli are measured from responses to low amplitude oscillations (acoustic waves). The difference

[3] Zhang, J., 2011. Pore pressure prediction from well logs: Methods, modifications, and new approaches. *Earth-Science Reviews*, *108*(1-2), pp.50-63.
[4] Fjaer, E., 1999. Static and dynamic moduli of weak sandstones. *Rock mechanics for industry*, pp.675-681.

between the static and dynamic properties have been attributed to presence of cracks[5] and difference in strain amplitude.[6]

Static elastic properties are often derived through correlations with dynamic elastic properties. Some authors have developed empirical correlations for static elastic properties from logs; to name just a few Horsrud[7], Brocher[8], Lal[9], and Chang et al[10].

In GeoFit™, the dynamic and static mechanical properties of both isotropic and anisotropic media can be computed - Young's modulus, shear modulus, Poisson ratio, bulk modulus, Biot's coefficient, cohesion, unconfined compressive strength, confined compressive strength, internal friction angle, shear strength, and tensile strength.

Horizontal Stress

The estimation of the in-situ horizontal stresses is critical for wellbore stability analysis, reservoir geomechanics, well completions, and other geomechanical analysis. Both the minimum and maximum horizontal stresses can be estimated from extended leak off test (XLOT) with fracture reopening test[11]; these values are determined at specific points where the tests were conducted and the average value of the strains can be used for calibrating horizontal stress models.

The geomechanics application in GeoFit™ provides five different methods for estimating in-situ horizontal stresses - Blanton-Olson model, poroelastic isotropic model, poroelastic anisotropic model, Q-factor model, and Mohr-Coulomb. Mohr Coulomb describes the relationship between two principal stresses at the brink of formation failure; the model is based on the assumption that the maximum in-situ shear stress is governed by the shear strength of the formation. Thus, this model can be used for sedimentary basins that are subject to active tectonic compression or extension. Q-factor and poroelastic anisotropic models were developed for anisotropic formations, especially laminated shale formations, while Blanton-Olson and poroelastic isotropic were developed for isotropic formations.

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[5] Tutuncu, A.N., Podio, A.L. and Sharma, M.M., 1994, January. Strain amplitude and stress dependence of static moduli in sandstones and limestones. In *1st North American Rock Mechanics Symposium*. American Rock Mechanics Association.
[6] Walsh, J.B. and Brace, W.F., 1966. Elasticity of rock: A review of some recent theoretical studies. *Rock Mechanics and Engineering Geology*, *4*(4), pp.283-297.

[7] Horsrud, P., 2001. Estimating mechanical properties of shale from empirical correlations. *SPE Drilling & Completion*, *16*(02), pp.68-73.
[8] Brocher, T.M., 2005. Empirical relations between elastic wavespeeds and density in the Earth's crust. *Bulletin of the seismological Society of America*, *95*(6), pp.2081-2092.
[9] Lal, M., 1999, January. Shale stability: drilling fluid interaction and shale strength. In *SPE Asia Pacific Oil and Gas Conference and Exhibition*. Society of Petroleum Engineers.
[10] Chang, C., Zoback, M.D. and Khaksar, A., 2006. Empirical relations between rock strength and physical properties in sedimentary rocks. *Journal of Petroleum Science and Engineering*, *51*(3-4), pp.223-237.
[11] Bredehoeft, J.D., Wolff, R.G., Keys, W.S. and Shuter, E., 1976. Hydraulic fracturing to determine the regional in situ stress field, Piceance Basin, Colorado. *Geological Society of America Bulletin*, *87*(2), pp.250-258.

Fracture Gradient

Fracture pressure is the pressure required to lose mud to the formation due to induced fractures, while fracture gradient is the fracture pressure divided by the true vertical depth. Fracture gradient is always higher than the critical collapse mud weight but less than the breakdown mud weight. The knowledge of the fracture pressure profile of the location is very critical for safe drilling operations.

One of the earliest contributions on fracture gradient prediction is by Hubbert and Willis[12], who assumed elastic behavior of the formation and that the rock is stressed by tectonic action to point of failure by faulting. Many other correlations, based on the concept of matrix-stress ratio, have since been developed. GeoFit™ geomechanics application provides several methods for estimating fracture gradient - Hubbert and Willis, Pilkington, Rocha and Bourgoyne, Aadnoy and Larsen, Eaton, and Holbrook. Aadnoy and Larsen[13] is applicable when the fracture pressure obtained in leak-off tests taking in the vertical section of the well are to be extended to the inclined sections of the well.

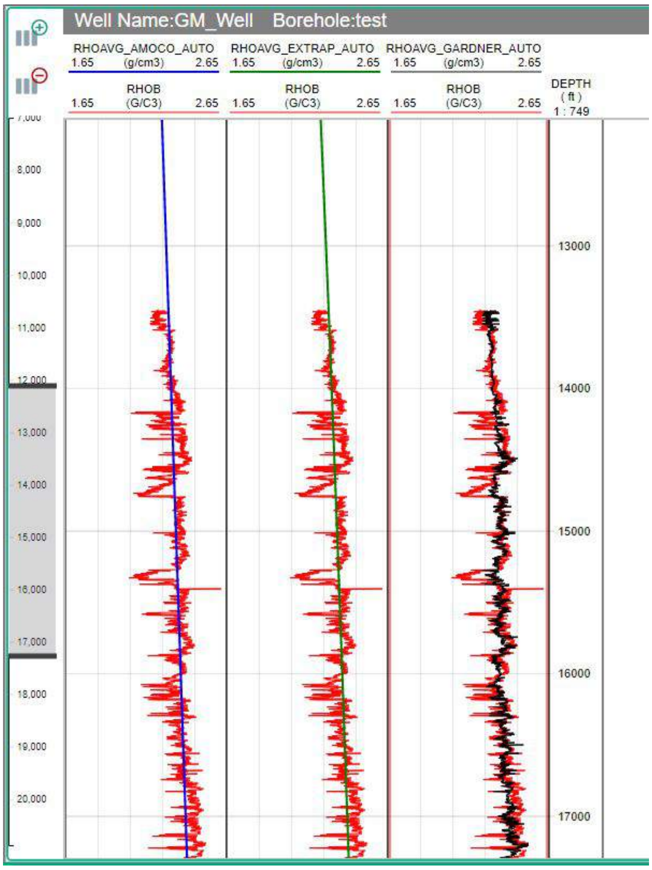

Figure 6a. Overburden stress predictions on GeoFit™ geomechanics module

[12] Hubbert, M.K. and Willis, D.G., 1972. Mechanics of hydraulic fracturing.

[13] Aadnoy, B.S. and Larsen, K., 1987, January. Method for fracture gradient prediction for vertical and inclined boreholes. In *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.

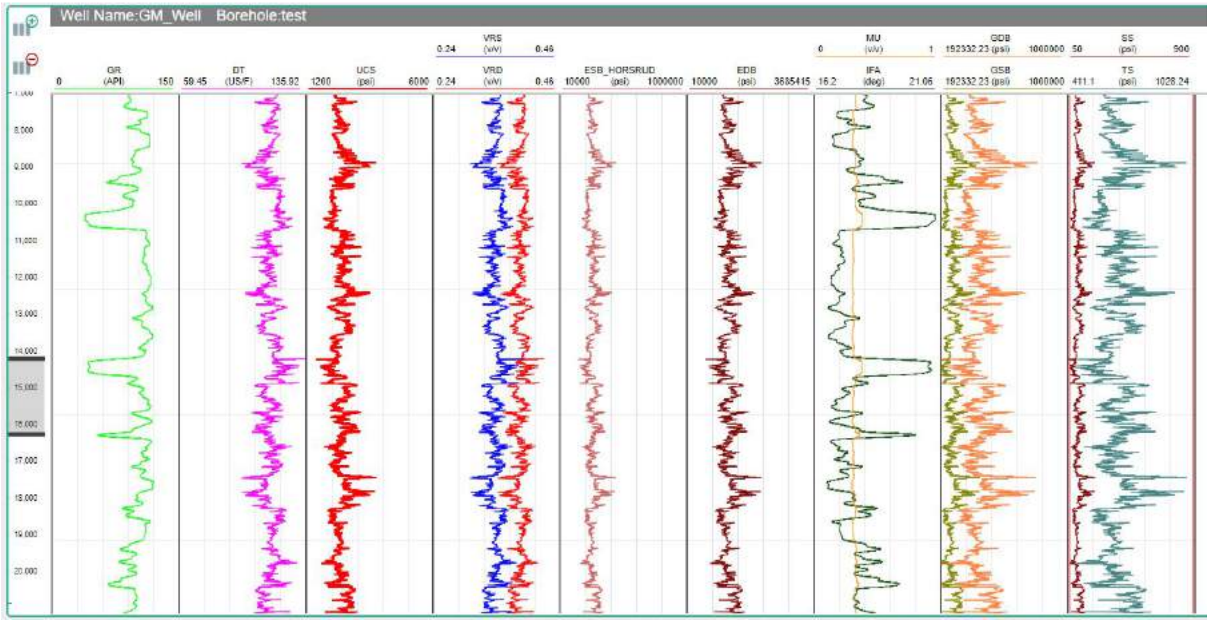

Figure 6b. Elastic properties of an Isotropic Rock on GeoFit^{TM} geomechanics module

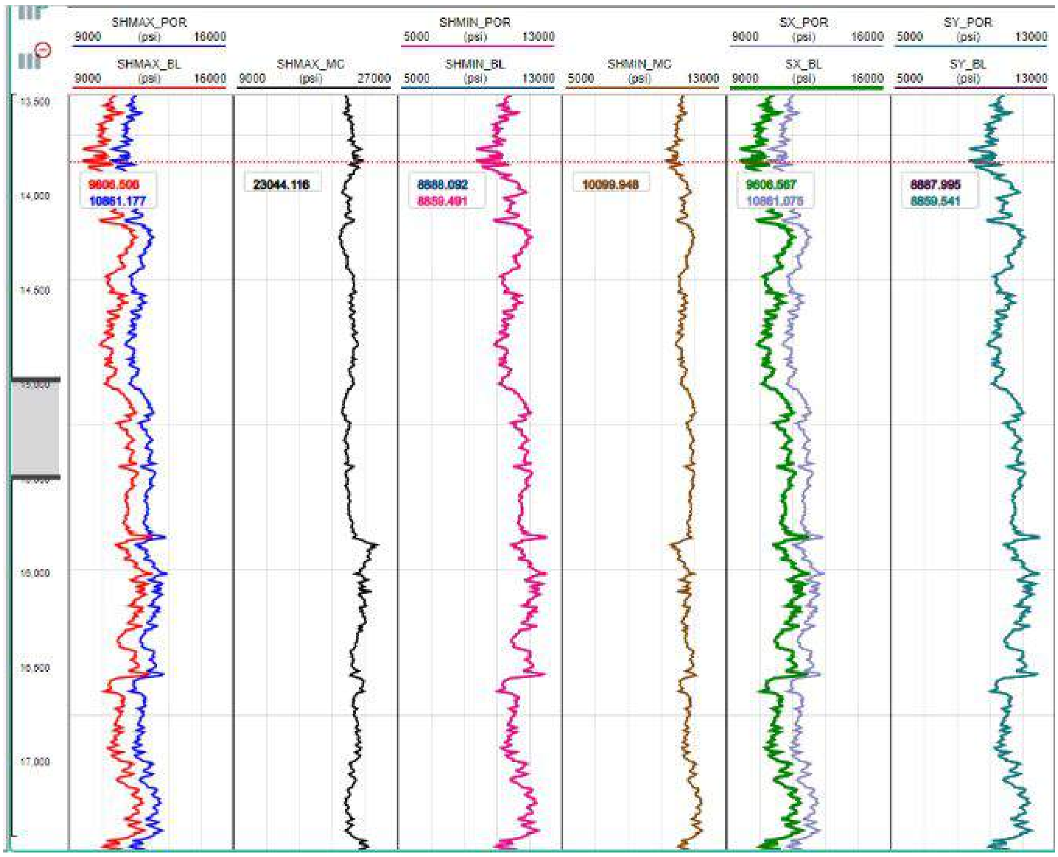

Figure 6c. Comparing the results of few of the methods for estimating horizontal stresses on GeoFitTM geomechanics module

Wellbore Stability Module on GeoFit™

Wellbore instability is a major concern in drilling operations, and it is one of the major causes of non-productive time during drilling. The costs of dealing with wellbore instability issues during drilling is around $6 billion worldwide annually[14]. The combined set of equations of stresses around a circular by Kirsch[15] is a powerful tool for analysing the stability of a wellbore, although most wellbores are not perfectly circular. Most wellbore stability analysis are offshoots of these equations. One of the setbacks of these set of equations developed from Kirsch is that they cannot be applied for more complex cases. The use of advanced numerical methods (like finite element) are often used for more complex wellbore stability analysis.

GeoFit™ Wellbore Stability module performs analysis on the states of stresses and strains around the wellbore. With the Mechanical Earth Model (MEM) and well trajectory information available, the stress concentrations and strains around the wellbore are estimated for both formation with weak bedding planes or without. The impacts of thermal and chemical effects on the stresses around the wellbore are considered, as well as flow-induced stresses.

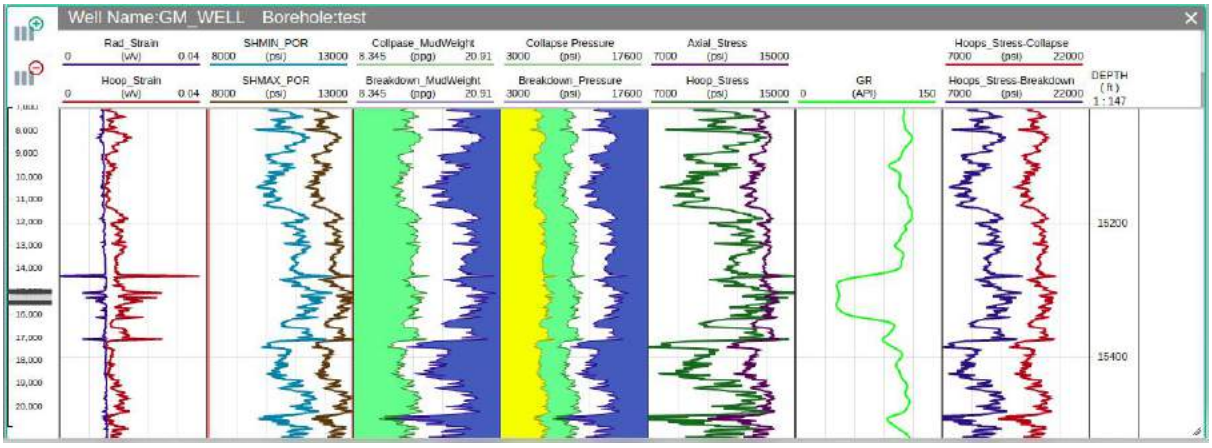

Figure 7. Designing mud weight program in GeoFit™ geomechanics module. The critical mud weights, stresses and strains along the length of the wellbore are some of the outputs of running the wellbore stability module on GeoFit™ platform. Static chemo-thermo-poroelastic equations are used in the module development.

[14] Kang, Y., Yu, M., Miska, S.Z. and Takach, N., 2009, January. Wellbore stability: A critical review and introduction to DEM. In *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.
[15] Kirsch, C., 1898. The theory of elasticity and the requirements of strength theory. *Journal of the Association of German Engineers* , *42* , pp.797-807.

Wellbore failure can be due to shear or tensile failure. Shear failure occurs as a result of low mud weight, while tensile failure occurs as a result of high mud weight. Two failure criterias are used in the compressive shear failure analysis around a wellbore drilled in a formation with no weak bedding plane - Mohr Coulomb and Modified Lade failure criteria.

Whilst only Mohr Coulomb is used for the shear failure analysis around a wellbore in a formation with weak bedding plane. The four critical mud weights for defining mud weight window are available in this plugin - kicks, shear failure, losses, and breakdown. Anisotropic tensile failure criteria are used for estimating the breakdown pressure for formation with weak planes while isotropic tensile failure is used for formation with no weak plane.

In addition, single-depth sensitivity analysis (see sample in **Figure 8**) are provided in the module to analyze the variations of the shear and tensile failures of the formation with varying well deviation, azimuthal, and orientation angles are available for computation.

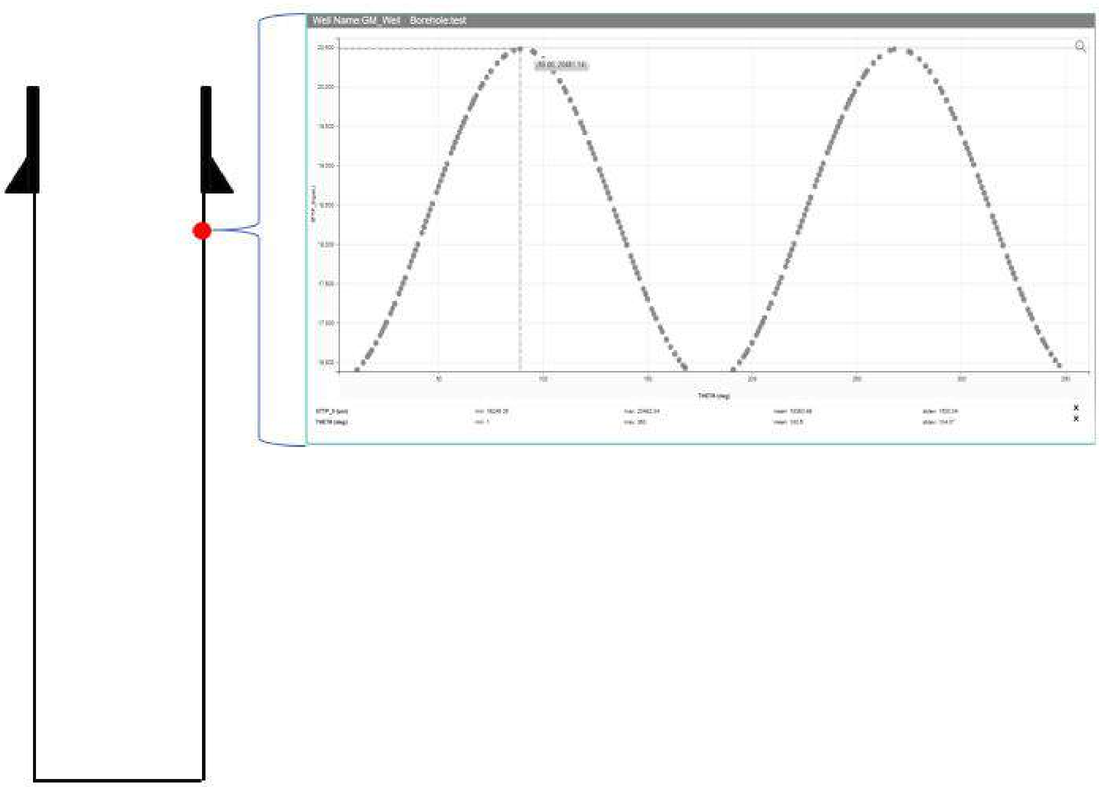

Figure 8. Single-Depth Sensitivity Analysis estimates the variation of variable of interest around the wellbore orientation angle.