PaperID AU449

Author Arvind Kumar , Schlumberger , India

Co-Authors Chandreyi Chatterjee, Arvind Kumar, Siddhartha Nahar

An integrated approach for Far-field Stress characterization using Caliper, Image and advanced Acoustics measurements

Abstract

Recent advancement in drilling practices allows the drilling of complex trajectories like horizontals, snake profiles etc. With this came the concept of having a more robust pre-drill mud window planning. The concept of Mechanical Earth Modeling (MEM) is a leap change in resolving the mud window uncertainty by running a wellbore stability model (WBS) taking into account all the three stresses and rock mechanical properties. Correct estimation of horizontal stress magnitudes, regime and direction play a critical role in such models. However, correlations established in the past had a lot of uncertainty associated with estimating these stress magnitudes. This paper showcases the use of Integrated Stress Analysis (ISA) which uniquely uses the best of industry standard processes, collaborates with the all available logs like caliper, image and acoustic logs to estimate the magnitude as well as direction of the horizontal stresses, which would be helpful in building 1D- MEM more accurately, and eventually will help in mitigating well-bore stability issues, cap-rock integrity study, completion and sand production prediction etc.

Introduction

All rocks in the sub-surface are defined by its intrinsic rock mechanical properties. Young's Modulus and Poisson's Ratio define the rock's elastic properties, whereas unconfined compressive strength, tensile strength and internal friction angle define the rock's strength properties. These five elastic and strength properties, that can be measured in the laboratory is used in building a Geomechanical model.

Rocks are affected by three in-situ stresses; overburden stress (Sv), minimum horizontal stress (Shmin) and maximum horizontal stress (SHmax). Since rocks have pores and fluids in it, pore pressure in the rocks also play a critical role in Geomechanical model.

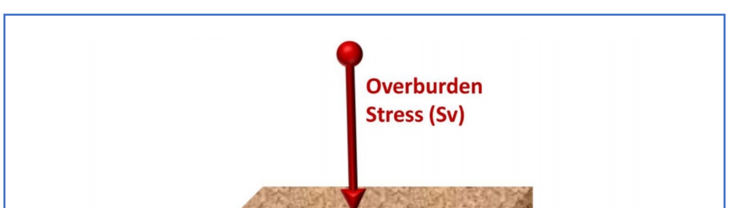
Quantification of stresses is very critical for geomechanical modeling and operational decision. Generally, the overburden stress can be computed easily by integrating the bulk density of rocks from the surface to the depth of interest. However, estimating both the principal horizontal stresses is relatively complicated.

Micro-Frac testing is the most reliable and direct technique available to measure the minimum horizontal stress magnitudes, which involves creating a hydraulic fracture, the pressure at which the created fracture closes is commonly associated with the minimum in-situ stress.

Mohr's Coulomb, Uniaxial Strain, Poro-elastic stress and effective stress ratio method are some of the industry-wise established methods for estimating the horizontal stress magnitude. Nevertheless, estimating the maximum horizontal stress magnitude has been a challenge in the industry.

Methodology

Figure 1: Diagram of stresses and pore pressure acting on a rock mass



A novel approach was used for estimating the maximum and minimum horizontal stress magnitudes and direction, while limiting its associated uncertainty.

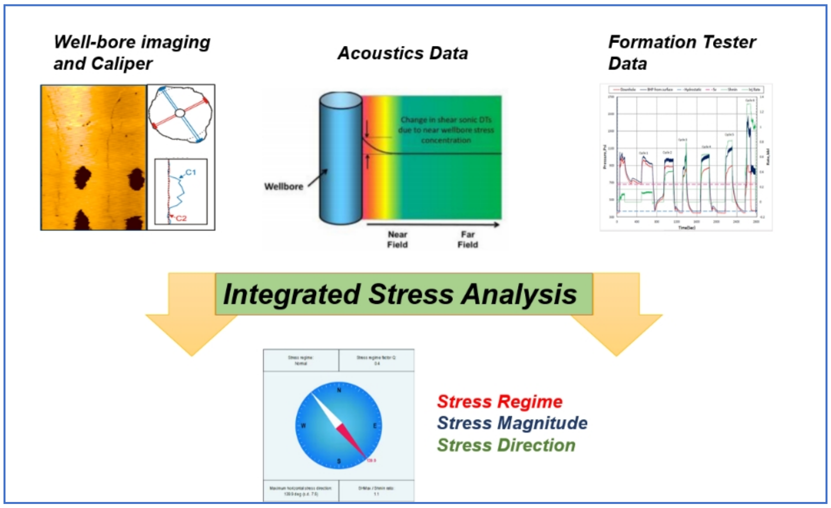
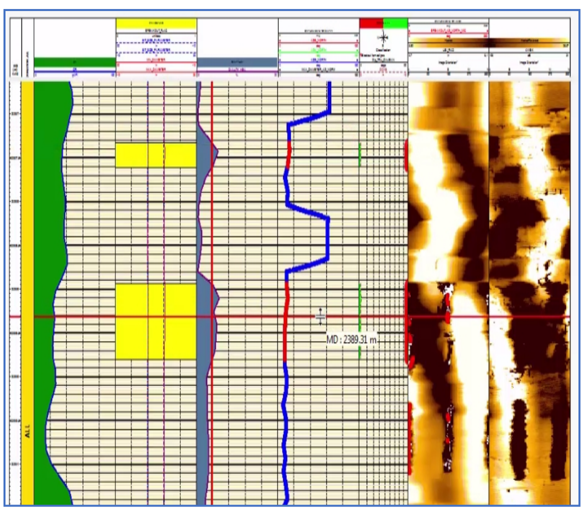


Figure 2: Sketch of the input data and output of Integrated Stress Analysis

Borehole images and multi-arm caliper data are very useful for identifying the borehole stress indicators such as breakouts, keyseats and fault-slips. Breakouts indicate the direction of minimum horizontal stress and drilling induced fractures occurs in the direction of maximum horizontal stress.



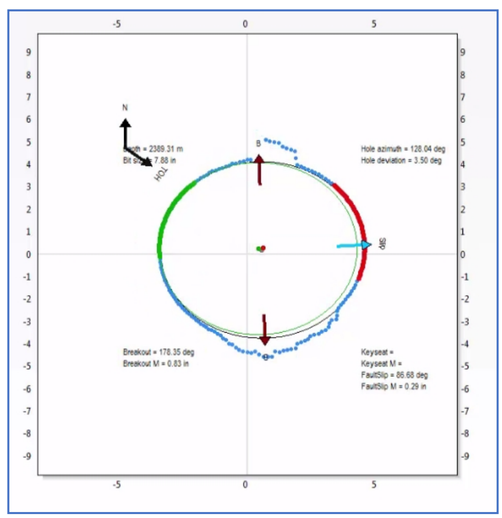
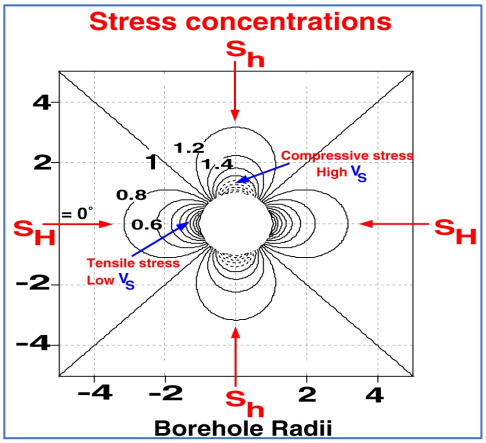


Figure 3a: Borehole Image showing Breakout; Figure 3b: Hole Shape Analysis

Modern day borehole sonic measurements are capable of recording axial, radial and azimuthal waveforms, thereby characterizing near well bore as well as the far field. Estimations of horizontal stresses can be made by using the near field and far-field sonic measurements, since shear slowness changes can be caused by stress concentration around the borehole. Near-wellbore stresses cause varying radial stress distributions in the near well bore due to the presence of the borehole itself. In the low stress direction (Sh), there will be a region of compressive stress near the borehole wall. Shear waves in this near region will propagate faster than in the far field. In the high stress direction (Sh), there will be a region of tensile stress near the borehole wall. Shear waves in this near region will propagate slower than in the far field. Low frequency acoustic measurements read far from the well-bore, whereas high frequency measurements read near the well-bore.



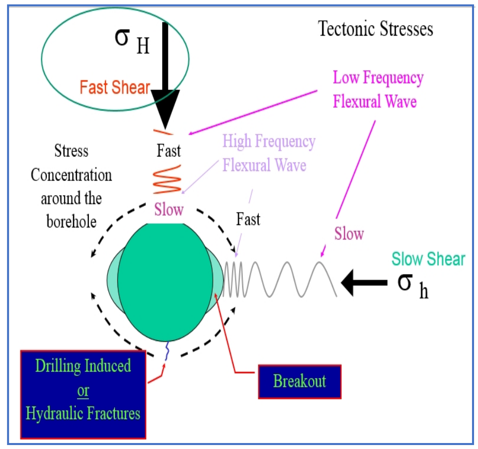
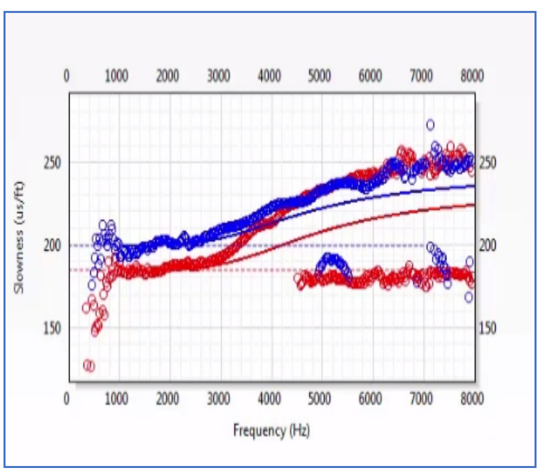


Figure 4a, 4b: Stress distribution for a vertical well and its concentration around the well bore

This workflow begins with acquiring monopole and dipole acoustic data subsequently processing it to extract a reliable compressional and shear slowness of the formation. Post this, a 2-D anisotropy processing using Alfred rotation helps in determination of the 2 orthogonally distributed components of Fast Shear and Slow Shear; along with quantification of energy, time and slowness anisotropy.

Slowness-dispersion analysis plots are created by transforming fast and slow flexural data in the frequency slowness domain. Model flexural curves are generated by using the shear slowness, bulk density, caliper and mud parameters. In case of anisotropy, deviation of the measured data is seen from modeled data.



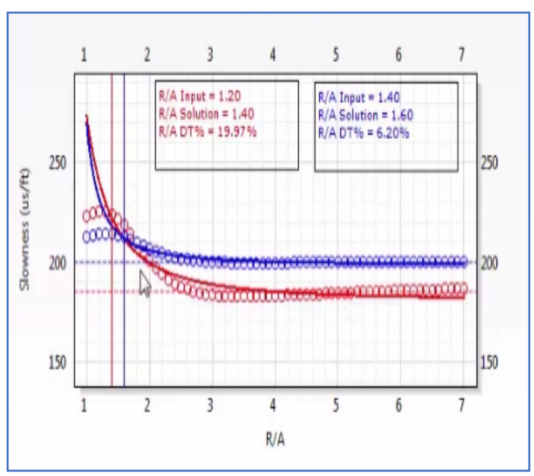


Figure 5a: Dispersion Plot- Slowness vs Frequency; Figure 5b: Variation of shear slowness as a function of distance from borehole wall

This deviation of the modeled data from measured data allows inversion from frequency slowness to distance- slowness. Execution of radial profiling of the dipole data helps in understanding the shear slowness variations laterally around the borehole, and Stoneley radial profiling provides shear in the third dimension. Utilizing all these results, 3-D anisotropy is performed to quantify the three shear moduliepsilon, gamma and delta for the TIV (Transverse isotropic vertical anisotropic) formations. Overburden stress, pore-pressue, friction angle are also computed, which goes as input in this workflow.

All these inputs are coupled to determine the horizontal stress magnitudes using ISA. Homogeneous zones with minimum thickness of 6 ft, negligible ovality and exhibiting stress induced anisotropy are selected for the analysis.

The derived anisotropic horizontal stress magnitudes are validated with radial profiling vs slowness and further calibrated with the direct measurements like formation tester induced micro-fractures. Micro-fracturing or 'micro-frac' is a technique used to generate near well-bore fractures by pumping fluid into an isolated interval and pressurizing the formation to failure. This enables us to identify the *insitu* minimum formation stress direction and magnitude, which is a critical parameter in building a robust geo-mechanical model. A typical micro-frac operation (see Figure 6 below) will have a primary pressure injection cycle (via pumping fluid) to initiate rock failure, which provides the *fracture initiation pressure or breakdown pressure*. As the pumping continues, the fractures in the failed formation will continue to grow; this is called the *fracture propagation pressure*. The pumping is then stopped and the pressure is allowed to bleed off into the formation. As the pressure falls below a minimum threshold, the fracture at the rock face closes shut; this is the *instantaneous shut-in pressure (ISIP)* which defines the minimum pressure required to hold the fracture at the rock face open. As the pressure imparted to the formation continues to bleed off deeper into the formation (as a function of permeability), it approaches the *fracture closure pressure (FCP)*, where all the propagated fractures close. Multiple cycles of pressuring and leak-offs can be conducted to get an accurate understanding of the above parameters, except for ISIP as this can occur only once at the time of fracture initiation. Post-closure, all effects become reservoir dominated rather than fracture dominated.

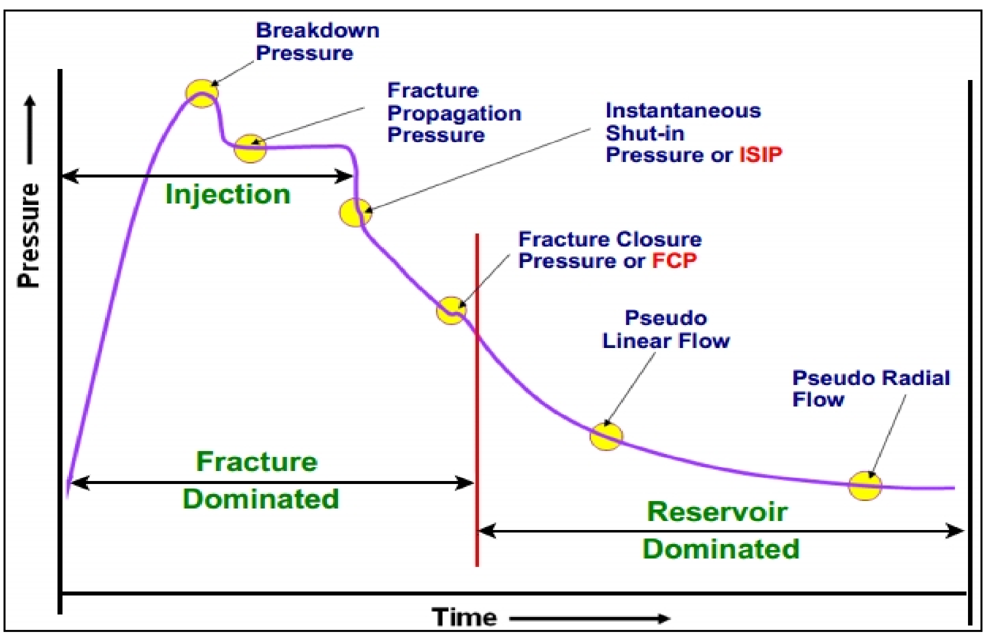
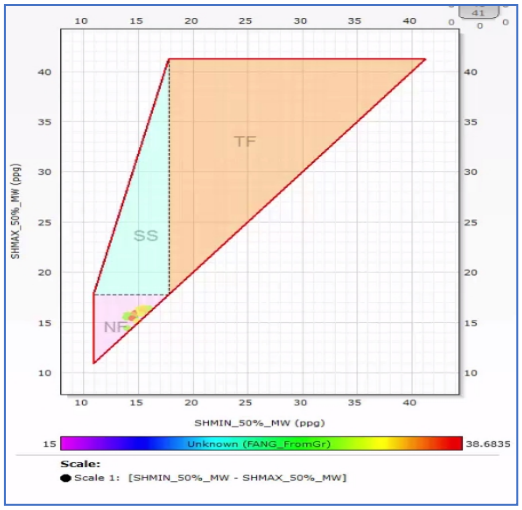


Figure 6a: Example of a typical micro-frac cycle as a function of time

Analytical techniques using G-function, SQRT function and log-log diagnostic plots can be applied to determine and reconcile the fracture closure pressure (FCP) and also to determine the type of leak-off (normal, pressure dependent, tip extension, etc.).

Results

The final results of the Integrated Stress Analysis are stress direction, magnitude and regime from all data sources are presented in various ways; Stress magnitudes can be shown in stress polygon plot as well as log plot vs depth.



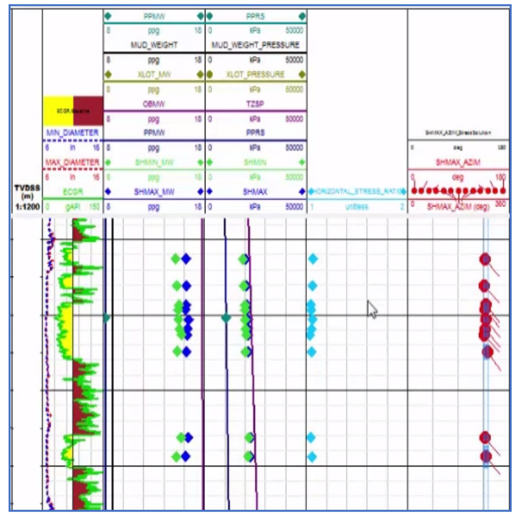


Figure 7a: Stress Polygon Plot; Figure 6b: Computed Stress magnitudes presented in log plot

Final results can be shown in compass plot, illustrating the direction, regime, stress ratio and stress- Q factor. The relationship among Sv, Shmin and SHmax determines the stress regime. Where 0>Q>1 is normal fault regime,1>Q>2 is strike slip regime and 2>Q>3 is thrust fault regime.

The stress magnitudes, direction and regime are helpful in building 1D- MEM accurately, which eventually will help in mitigating well-bore stability issues, cap-rock integrity study, completion and sand production prediction etc.

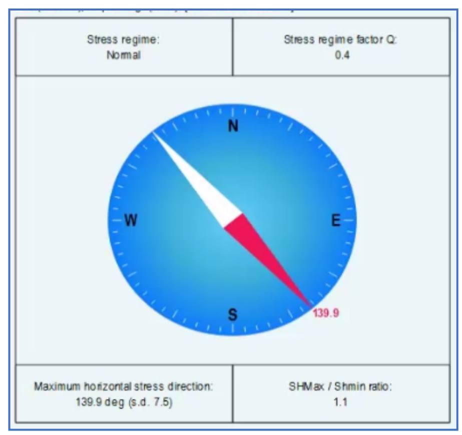


Figure 8: Compass Plot

Conclusion

This study has showcased the successful characterization of stress regime, magnitudes and direction, using an innovative approach, hereby described as Integrated Stress Analysis, utilizing the Acoustics, Image and Caliper data and validated using the Micro-frac/DFIT results. A unique amalgamation of several domain specific workflows has been demonstrated, opening new ways of collaboration between several forms of formation logs and data for accurate and detailed stress characterization.

References

1. Lei, T., Sinha, B.K. & Sanders, M. 2012, Estimation of horizontal stress magnitudes and stress coefficients of velocities using borehole sonic data: *Geophysics* 77(3): WA181- WA196
2. Thiercelin, M.J., Plumb, R.A., Desroches, J., Bixenman, P.W., Jonas, J.K., and Davie, W.R., 1996, A New Wireline Tool for In-Situ Stress Measurements: SPE Formation Evaluation, March 1996, pp 19-25