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Subsurface geomechanical analysis, comparison with prestack azimuthal AVO analysis, and implication for predicting subsurface geomechanical properties from 3-D seismic data

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Summary

Preliminary geomechanical analysis of image log data from the RSU #1 well in southwestern Wyoming, USA, shows a maximum horizontal stress (SHmax) orientation of N85°E with a standard deviation of 18°. Fractures identified from the image log show a range of orientations, with predominant directions between N65°E and S20°E. Fractures parallel to the orientation of SHmax and perpendicular to minimum horizontal stress (Shmin) are open, and therefore affect the velocity of P- and S-waves. Prestack azimuthal amplitude-variation-with-offset (AVO) analysis of P-wave seismic data from this location show a fracture orientation of N80°E-N90°E, which corresponds directly with the orientation of open fractures documented through geomechanical analysis. Our results suggest that relating seismic data to geomechanics at the well location can potentially lead to prediction of geomechanical conditions away from the well using seismic data over 3-D seismic data volumes.

Keywords: *Geomechanics, fracture, breakout, stress orientation*

Introduction

Fluid flow in the subsurface can be greatly affected by the orientation of open fractures, and consequently determining their direction is of great practical importance in the exploration of fractured reservoirs. As the oil and gas industry shifts its focus towards exploration of unconventional reservoirs, such as shale gas/oil and tight gas sands where reservoirs are hydraulically fractured to optimize production, a prior knowledge of the direction of open fractures is critical (Starr, 2011). In order to predict the orientation of open fractures, it is necessary to understand the mechanical stratigraphy, fracture system and in situ stress field. Lithology can be interpreted from outcrop, core, and well logs, and can be converted to mechanical stratigraphy based on rock properties and fracture patterns. Fractures are documented from core and image logs, in terms of density, distance to nearest neighbor, length, orientation, aperture and fill. Geomechanical models require detailed understanding of in situ stress orientations, in situ stress magnitudes, pore pressure, unconfined compressive strength, and rock properties such as cohesion, friction and elastic moduli (Zoback, 2010).Vertical stress can be determined from integrated bulk density, or a pseudo density log can be created from a sonic log. The orientation of maximum horizontal stress (S_{Hmax}) and minimum horizontal stress (S_{hmin}) can be identified from oriented fractured core or from wellbore breakouts recorded on the image log. S_{hmin} magnitude is measured by extended leak-off tests, leak off tests, and minifrac tests. Pore pressure can be directly measured from drill stem tests or pressure-while-drilling measurements; it can also be calculated from sonic and resistivity logs. The unconfined compressive strength can be measured directly from core tests or calculated from sonic, density, and resistivity logs. These data are then used to determine the orientation of hydraulically conductive fractures, i.e. those fractures oriented to the in situ stress field in such a way that they are open and allow fluid flow (Zoback, 2010).

Although the procedures outlined above can predict geomechanical properties and the orientation of open fractures at the well location, it is necessary to use seismic data to predict conditions away from the well. Using new techniques in prestack azimuthal AVO analysis of P-wave seismic data, it is possible to identify the orientation of open fractures, as well as make a qualitative measure of open

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fracture density. This technique is presented in Mallick et al, “Characterization of the unconventional and carbon sequestrated reservoirs-the new challenges to the prestack waveform inversion” (this volume). However, it is necessary to calibrate seismic data to well data in order to use seismic data to accurately predict stress and fracture conditions away from the well.

Newly acquired well log and image log data are available from the RSU #1 well in southwestern Wyoming, USA, as well as 3D/3C seismic data. Using these new data we have conducted a preliminary geomechanical analysis of image logs to determine the orientation of fractures and in situ horizontal stress, which we compare to the orientation of fractures identified from seismic data. Our comparison suggests that the seismic data can be effectively calibrated at the well location, and this technique shows promise for predicting geomechanical conditions throughout the seismic data volume.

Method for geomechanical analysis

Image logs from the RSU #1 well were analyzed for fractures and well bore breakouts using the GMI Imager software donated by Geomechanics International, a division of Baker Hughes Inc. Sonic and resistivity image logs were imported to GMI Imager, and fractures were picked from a measured depth of 9736 to 12810 ft (2968 to3904 m) by fitting sinusoids to fractures shown on the images (Figure 1). Borehole breakouts were also identified on the image logs and interpreted to determine the orientation of S_{Hmax} and S_{hmin} using GMI Imager (Figure 2). The breakout occurs in the direction of S_{hmin}, perpendicular to maximum compression.

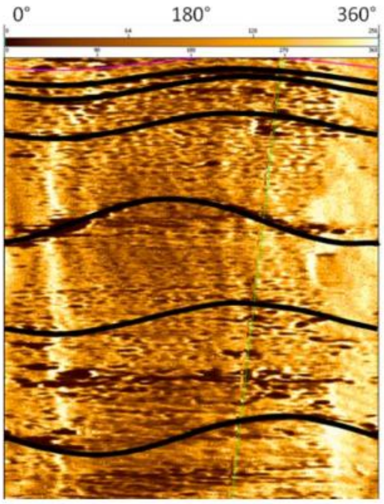

Figure 1: Example of fractures seen on the acoustic image log. Each fracture is fit to the unwrapped image of the well bore with a sinusoid (black line) to determine strike and dip. The color in the image represents the amplitude of the reflected pulse.

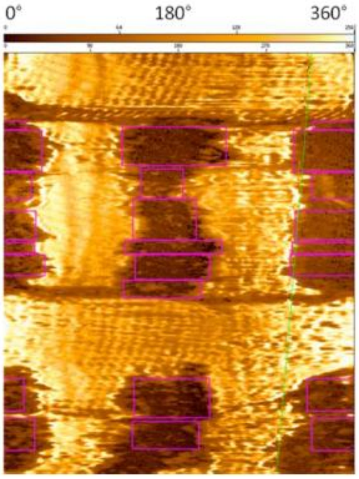

Figure 2: Example of wellbore breakouts seen in the acoustic image log. Each breakout pick is marked in a pink box. The color in the image represents the amplitude of the reflected pulse.

Analysis from the RSU #1 Well

Interpretation of sonic and resistivity image logs from the RSU #1 well show a mean orientation of wellbore breakouts at S05°E (175°), with a standard deviation of 18° (Figure 3). Breakouts occur in the direction of S_{hmin}, and perpendicular to S_{Hmax}. In light of these subsurface in situ stress orientations, we would expect open fractures to occur in the orientation N85°E ±18°.

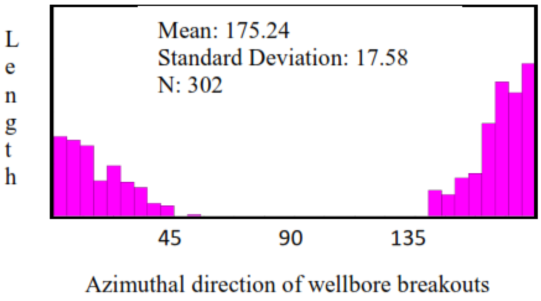

Figure 3: Histogram showing the orientation of wellbore breakouts over the length of the image log (9736-12,810 ft, 2968-3904 m, measured depth). The y-axis shows the relative length of the breakouts.

Ninety-nine fractures were observed throughout the length of the image log. These fractures show a variety of orientations, with no clear dominant fracture set due to the prolonged and complex tectonic history of this area (Figure 4).

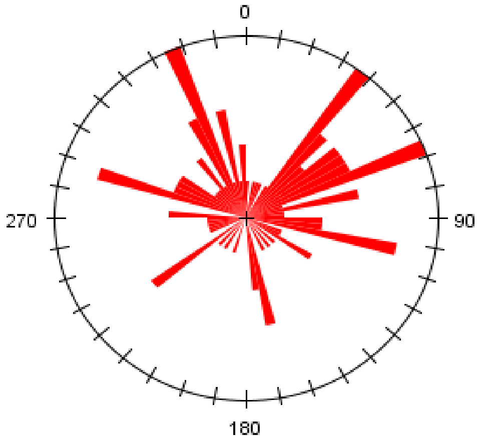

Figure 4: Rose diagram showing the dip direction of fractures documented over image log (9736-12,810 ft, 2968-3904 m, measured depth). Note that fracture strike is perpendicular to dip direction (shown).

Results from the prestack azimuthal AVO analysis of P-wave seismic data from this location (Mallick et al., this volume) predict open fractures in an orientation of N80°-90°E (Figure 5); this orientation coincides perfectly with the orientation determined by the geomechanical analysis of the image logs at the RSU #1 well location.

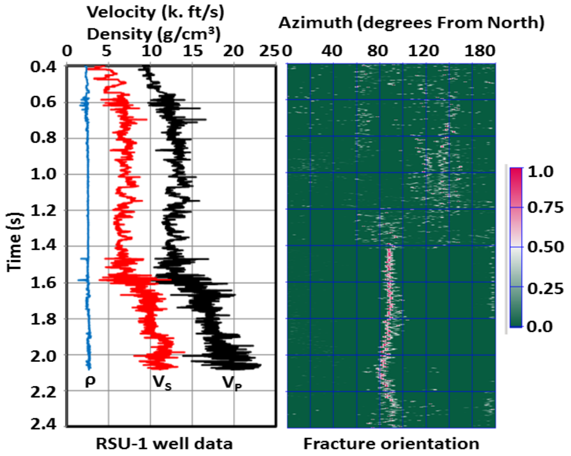

Figure 5: Fracture analysis of seismic data at the RSU #1 well location. The RSU #1 sonic data with the P-wave velocity (V_P), S-wave velocity (V_S) and density (ρ) are displayed (left) along with the computed fracture orientations N80°-90°E (right).

Conclusions

Comparison of the preliminary geomechanical analysis of image log data from the RSU #1 well in southwestern Wyoming, USA, to results from azimuthal AVO analysis of P-wave seismic data show close correlation between the orientation of fractures identified from the seismic data and open fractures determined from image logs. The geomechanical analysis indicates that, although fractures exist in a variety of orientations due to a complex tectonic history, fractures will be open in the direction of N85°E±18° due to the orientation of the in situ stress field. Fracture orientations computed from seismic data at this location lie within the range N80°-90°E. This correlation suggests that the seismic data, calibrated with geomechanical analyses at the well location, can potentially be used to predict subsurface geomechanical properties over 3-D seismic data volumes.

References

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