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# Integrated interpretation of conductive fractures using borehole wall imaging, Stoneley wave derived aperture estimation and reflection shear sonic imaging in a FORGE Geothermal well

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## Summary

The FORGE well 21-31 in Fallon, Nevada, has abundant natural fractures throughout the pre-Miocene section (Perdana et al. 2020). Ground truth for these fractures and other features is achieved by interpretation of borehole wall imaging surveys using SLB's Formation Micro-scanner Image tool (FMI). A limitation of borehole wall imaging is that analysis cannot differentiate between fractures connected beyond the borehole and fractures terminating near the borehole. Next borehole sonic data were acquired using SLB's Sonic Scanner. With the FMI imaging results as a starting point, low frequency Stoneley wave data was used for deeper investigation of conductive fractures using secondary arrivals caused by pressure release into the fractures (Hornby et al., 1989; Hornby 2022). Here the Stoneley wave is used to "pressure test" the fractures as identified by the FMI analysis and processing also provides an estimate of hydraulic fracture width, which has been shown to compare well with electrical borehole imaging inversion at the borehole wall when the fractures extend some distance away from the borehole (Hornby 2022). Next dipole induced body wave shear arrivals are used to directly image the fractures as a function of distant away from the well. It was found that the fractures indicated as most conductive from the Stoneley wave analysis were the most prominent fractures seen by the reflection shear imaging result.

## Borehole wall imaging

Figure 1 shows an example of electrical borehole wall image for 2384 to 2388 m depth (Perdana et al. 2020). Clearly seen are interpreted continuous and non- continuous conductive fractures, drilling induced fractures and possible faults. Figure 2 shows a plot of interpreted conductive fractures through the well. Note the sheer magnitude of the fractures and range of fracture angles between 40 and 80+ degrees.

## Stoneley wave inversion

Figure 3 shows Stoneley wave inversion results. Reflectivity for 3 different frequencies is shown in column 3, estimated fracture width in mm is shown in column 4, and an iso-offset variable density display of recorded Stoneley wave data in column 5.

To probe fractures with Stoneley wave signals imperative is to generate the waves at low frequencies, ideally 500 Hz or below. With low frequencies the Stoneley reflectivity response the signal will mostly respond to conductive fractures and essentially will ignore fracture opening enhancements or small borehole enlargements (Kostek et al., 1998a; Kostek et al., 1998b). Here 500 Hz frequency results are used directly to compute the estimated fracture aperture. The higher

frequencies, 2000 Hz and 3000 Hz are used as quality control - sudden large increases in the high frequency reflectivity with hole size changes gives a clear indication results are suspect for that interval. Results show little activity of the high frequencies and so estimated fracture widths can be considered high quality - sudden large increases in the high frequency reflectivity with hole size changes gives a clear indication results are suspect for that interval. Results show little activity of the high frequencies and so estimated fracture widths can be considered high

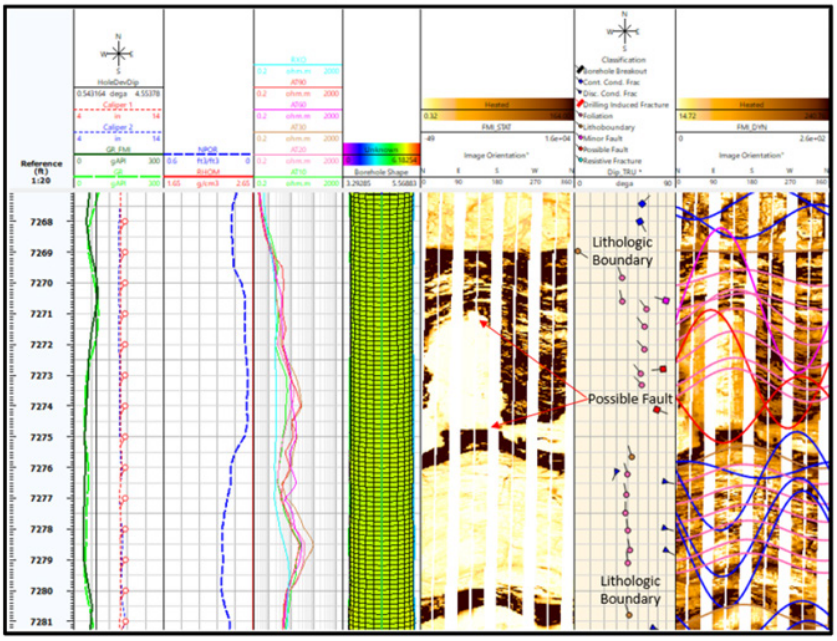



Figure 1. Electrical borehole wall scan for 2384 to 2388 m depth.

confidence. Fracture widths are seen up to 2 mm along several sections. Iso-offset display of raw data shows oblique arrivals (Chevron events) with amplitudes consistent with the magnitude of the interpreted fracture width.

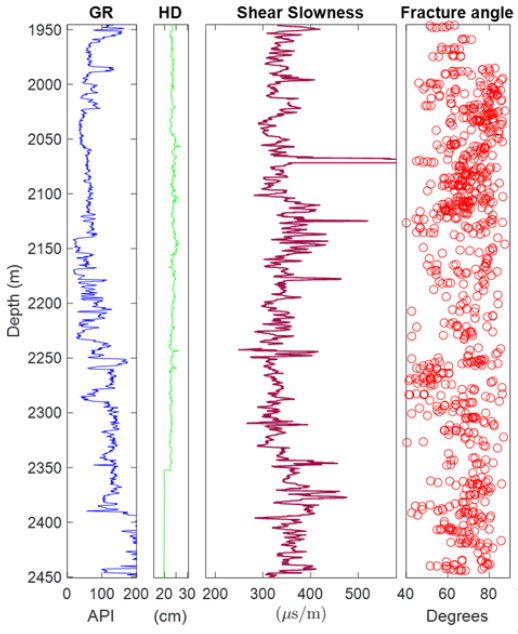



Figure 2. Interpreted conductive fractures from analysis of electrical borehole wall imaging survey.

## Reflection shear sonic imaging

Figure 4 shows sonic imaging results across the entire borehole section. Shown are columns with Gamma ray, hole diameter, fracture angle from borehole wall imaging analysis, fracture width estimated from Stoneley wave analysis and reflection shear imaging. For the shear wave imaging dipole induced body wave shear arrivals were used to directly image the fractures as a function of distance away from the well. Data were processed using pre-stack imaging as detailed in Hornby (2024) and Hornby (2025). Note the many fractures crisscrossing at different angles and directions. In addition, note the higher intensity of the fracture images from 2200 m to 2350 m. This section is where the largest Stoneley wave interpreted fracture widths are located. Now for shear wave reflection imaging, the larger the fluid filled fracture is the larger the reflection shear wave response will be and hence the larger reflection image intensity is expected. And so, the large reflection shear response seen in this section is consistent with the larger Stoneley wave interpreted fracture widths.

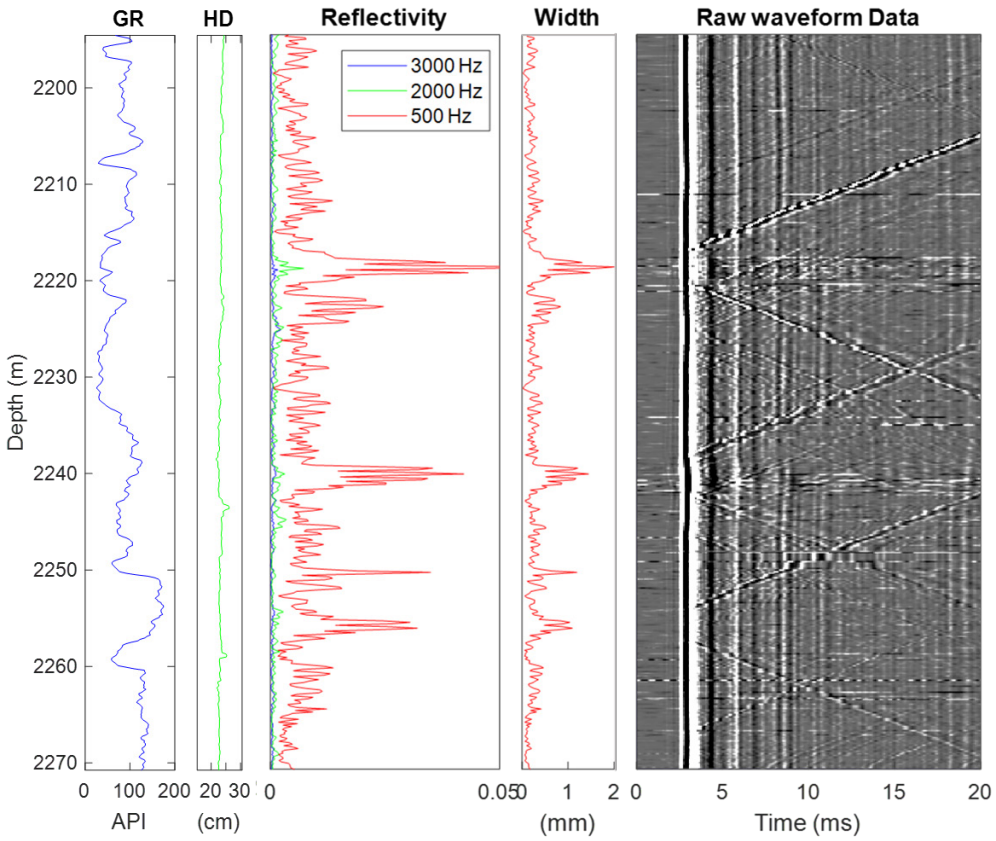



Figure 3. Stoneley wave inversion results for a section of the borehole. Reflectivity for 3 different frequencies, estimated fracture width in mm, and an iso-offset variable density display of recorded Stoneley wave data.

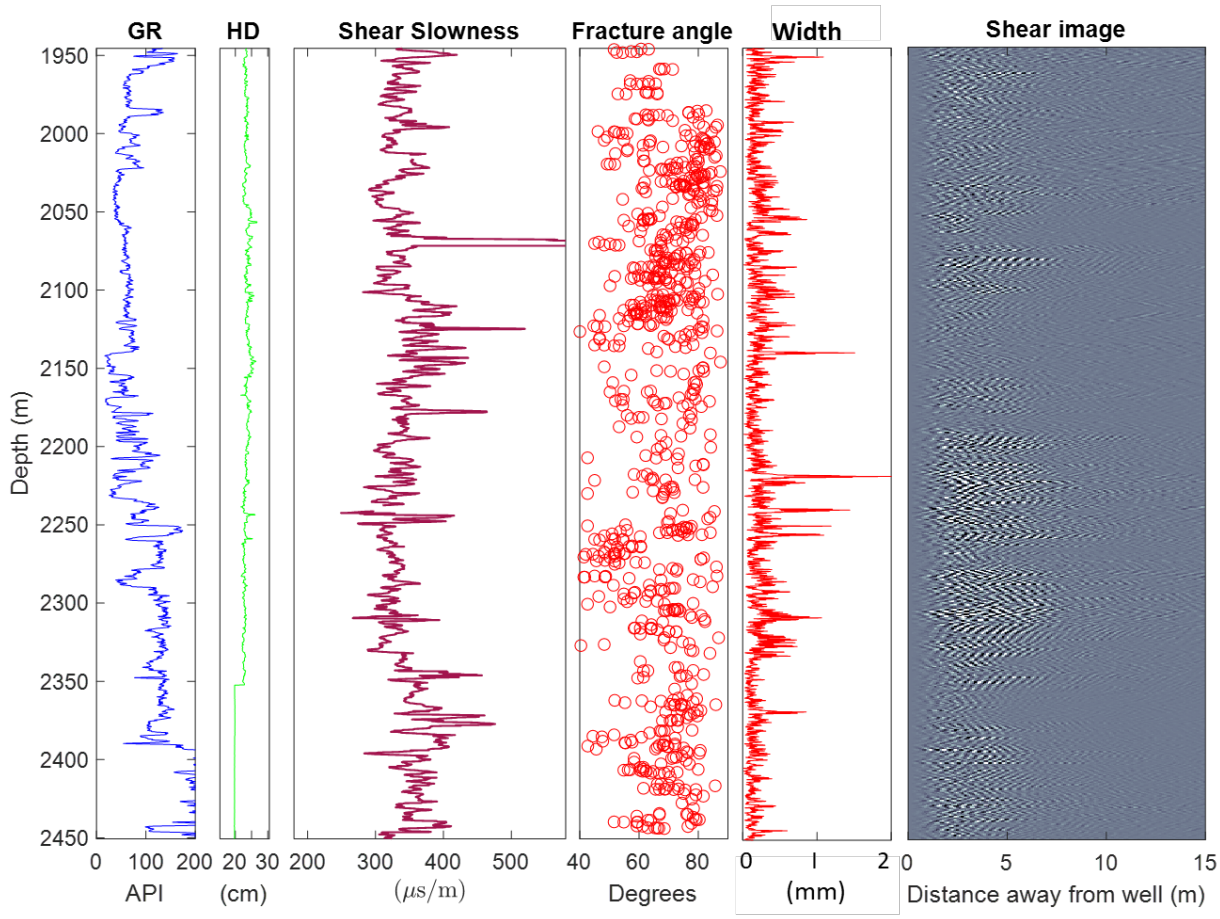



Figure 4. Entire borehole section. Reference GR, hole diameter, shear slowness, fracture location and angle from borehole wall imaging analysis, Stoneley wave estimated fracture width, and reflection shear image.

Figure 5 shows an expanded view of a section. Strong responses are seen up to 10 meters from the borehole with some lower level responses seen up to 15 m from the borehole. Duplicate panel shows an attempt to highlight some of the different fracture images going in different angles and directions.

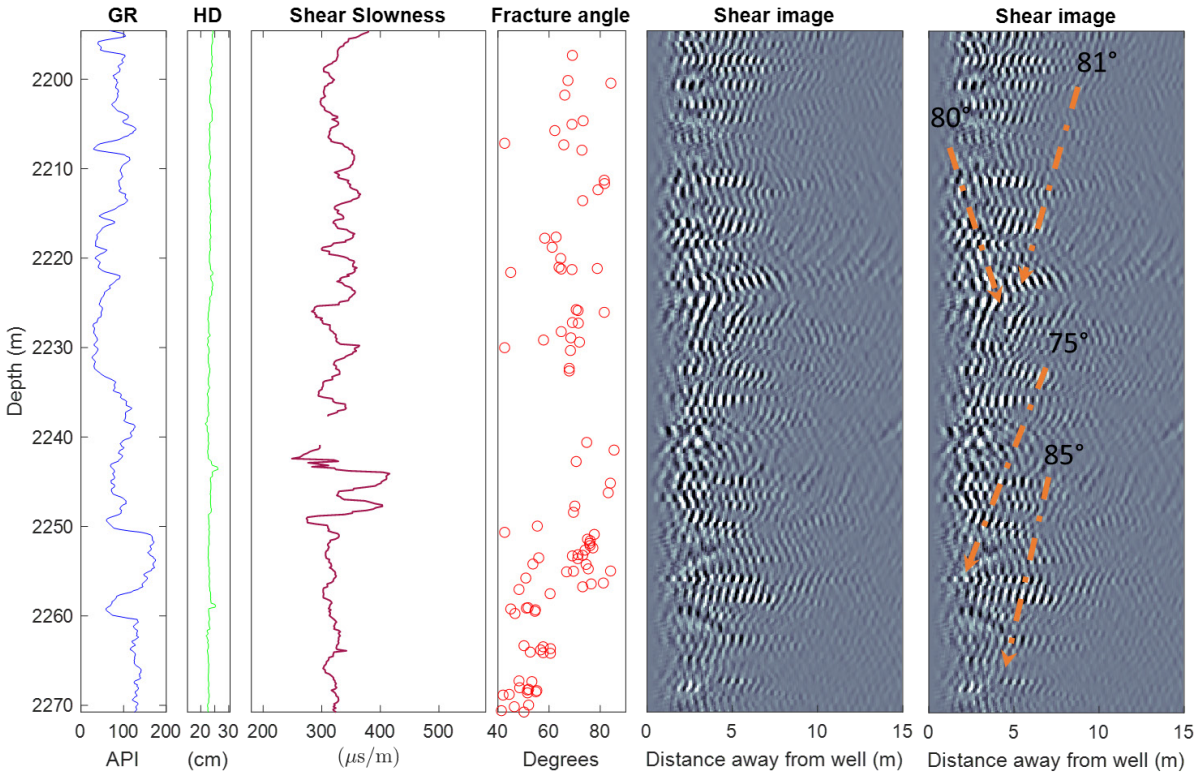



Figure 5: Reflection sonic imaging. Duplicate panel shows an attempt to highlight some of the different fracture images going in different angles and directions.

## Conclusions

The FORGE well 21-31 in Fallon, Nevada, has abundant natural fractures throughout the pre-Miocene section. Interpretation of borehole wall imaging surveys indicates a wide range of fractures crossing the borehole with relative angles between 40 and 85 degrees. Borehole sonic data were acquired and used to estimate fracture width of these fractures using low-frequency Stoneley wave data and dipole induced body wave shear arrivals were used to directly image the fractures as a function of distant away from the well. These different products were complimentary; the Stoneley wave analysis indicated a range of fracture widths up to 2 mm and the reflection imaging showed a large number of fractures at different directions and relative angles, as predicted by the borehole wall imaging analysis. The Stoneley wave results indicated that the conductive fractures extended some distance from the borehole, and this was confirmed by the reflection imaging results with fractures imaged up to more than 10 meters from the borehole. It was found that the fractures indicated as most conductive from the Stoneley wave analysis were the most prominent fractures seen by the reflection shear imaging result.

## Acknowledgements

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**References**

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