Microseismic Source Mechanisms and Source Parameters

Pinnacle

GET RESULTS

- Natural Fracture Orientation
- Fault Slip Mode
- Slip Dimension
- Stress Drop

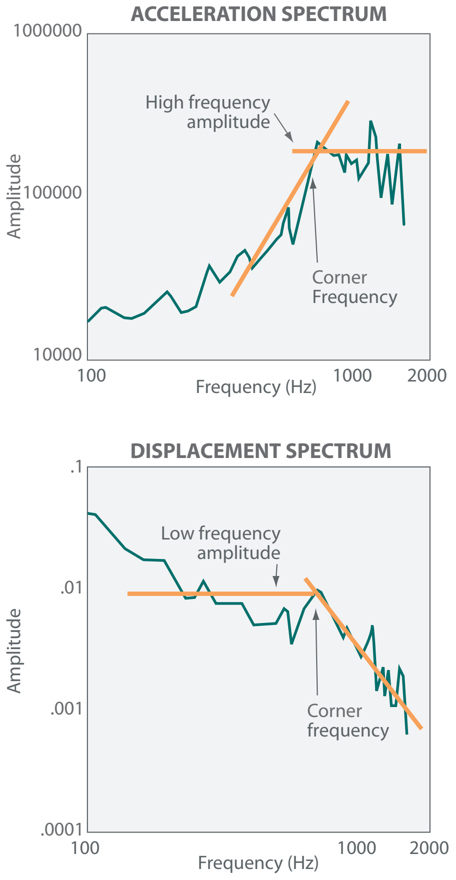

Figure 1. Spectral analysis

Microseismic mapping has proven to be a valuable technology for monitoring hydraulic fractures and other reservoir processes, but it also has the potential to provide estimates of important reservoir features: natural fracture orientations, the stress field, and other information about the hydraulic fracturing process. This additional evaluation is possible because the characteristics of the seismic energy provide significant information on the process that created the microseism. This technical release describes how such data are analyzed, the pitfalls that need to be avoided, and the importance of understanding the structural framework under which the microseism was created.

Since microseisms are simply microearthquakes, the analysis of this seismic energy is rooted firmly in earthquake seismology. If we know the source mechanism, that is the orientation of the fault plane and the direction in which the slippage occurs, then it is possible to extract source parameters from the seismic characteristics and provide information on the fault dimension, stress drop and seismic moment (although only two of these parameters are independent). The classic paper of Brune describes how the shape of the acceleration source spectrum has a simple frequency-squared behavior, with a corner frequency that is dependent on the source dimension and a high frequency level that scales with seismic moment and source dimension. From the seismic moment and the fault dimension, a "stress drop" can be calculated. There are numerous methods from which to calculate these parameters. Some examples include Brune's initial use of the displacement spectrum to determine the corner frequency and the low-frequency amplitude and Hanks and McGuire's use of the acceleration corner frequency and the r.m.s. acceleration amplitude over an appropriate shear-wave window. With excellent quality data, it is almost always possible to extract this type of information from the recorded waveforms. Figure 1 at left shows example shear-wave spectra from an observed microseism. While corner frequencies are usually clear, the value of the high-frequency acceleration or low-amplitude displacement has considerable uncertainty in many cases. In addition, even if the "stress drop" can be calculated, it is not totally clear what this property is. A recent article by Atkinson and Beresnev, titled "Don't Call It Stress Drop" has clearly detailed the problems with the ambiguous nature of this parameter.

This approach may at first appear straightforward, but the data need to be corrected for attenuation (which is generally unknown) and then need to be analyzed with respect to the position of the monitor well relative to the fault plane. Knowledge of the fault plane orientation is critical because the radiation pattern from an earthquake is highly asymmetric and different results will be obtained depending upon where the observation point is located relative to the slippage. As shown in Figure 2 on the next page, the plan-view radiation pattern around a strike-slip double-couple source (best representation of a microearthquake) has alternating P-wave (gold) and S-wave (green) lobes. In other planes, the radiation pattern may be even more complicated. The importance of accounting for the radiation pattern can be seen by considering a simple case. For an observer directly north microseism (up) of the microseism would detect only P waves, so the event appears to be entirely tensile. However, an observer located 45° east of north would detect only S waves, so the event appears to be entirely shear. Thus, for each event, it is first necessary to determine the fault plane and slip direction

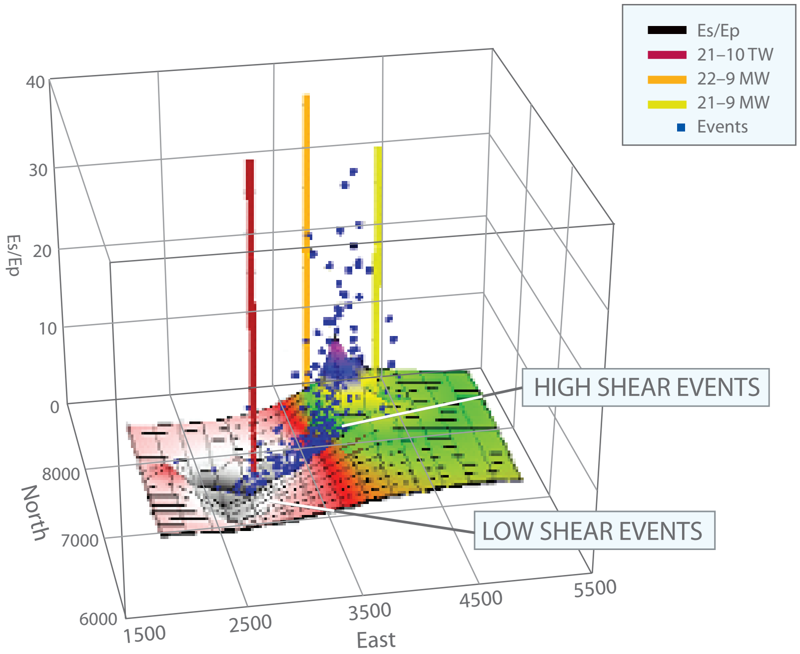

Figure 4. Source parameters can lead to misinterpretation

(source mechanism) before analyzing the waveform data. Yet this analysis is difficult and non-unique (without other data) when only a single observation well is available. Rutledge and Phillips at Los Alamos showed in a recent paper that a previously published interpretation of source parameters from a Cotton Valley experiment was erroneous because the radiation-pattern effects were neglected. Pinnacle's philosophy is that we must be able to adequately identify the source mechanism *before* we perform source-parameteranalyses in order to insure that our customers receive correct information. By analyzing the source mechanism, however, we also obtain valuable information about natural fracture orientations that is very useful for reservoir characterization.

Given a correct analysis of source parameters, there is still an interpretation issue that is generally ignored. For a small earthquake in the absence of the hydraulic fracture, calculated values such as stress drop and S/P ratios might be relatively simple to understand and interpret. However, the hydraulic fracture induces a large stress perturbation due to the opening of the fracture and a large pore-pressure perturbation due to the leakoff of high pressure fracturing fluid. For example, Figure 3 at right shows that there is a large compressive region around the hydraulic fracture, but there is also a tensile zone at the tip and shear lobes to accommodate the change from tension to compression. In addition leakoff alters the compressive region, particularly near the center of the fracture. Any attempt to interpret source parameters (e.g, fault dimension, stress drop, seismic moment) must be performed with a clear understanding of these hydraulic fracture mechanisms as well as the other parameters. Pinnacle has developed a model of the stress and pressure perturbations around hydraulic fractures (Warpinski et al.) for just this purpose. We have found that many previous interpretations of source results without a complete understanding of hydraulic fracturing mechanics leads to erroneous conclusions about the fracturing process and the adequacy of fracture width (e.g., ability to place proppant).

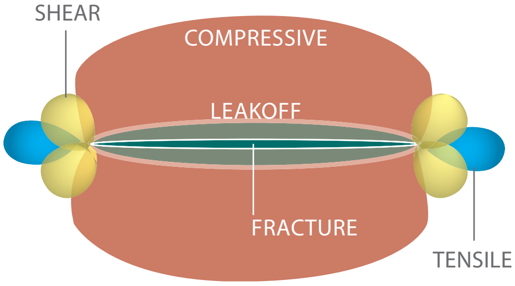

Figure 3. Stress regions around fracture

An example of how a poor understanding of this process can lead to erroneous results is shown in Figure 4 above. This Figure shows a three-dimensional plot of the S/P ratios for a stimulation performed at the Cotton Valley Hydraulic Fracture Imaging site. This example shows the treatment well in reddish brown and the two monitor wells in yellow and orange. The S/P ratios of microseisms are plotted as a function of location and the contour plot at the bottom shows high S/P ratios in green, yellow, blue and violet and low S/P ratios in red. One interpretation that was originally presented for this data was that low shear events (dilational compression) occurred near the treatment well, but mostly high shear events occurred at the eastern extremity. This was further interpreted as implying that there was little opening of the fracture on the eastern half of the fracture, resulting in minimal proppant placement on that side and poor overall stimulation results there.

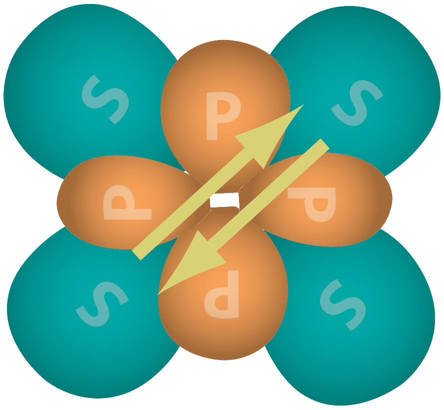

Figure 2. Example microseismic radiation pattern

A Los Alamos geophysicist, Jim Rutledge, re-analyzed those results and found that the S/P ratios had nothing to do with a high or low shear region or other fracture process, but rather were due entirely to the position of the monitor wells relative to the location of the event. Figure 5 on the next page shows S/P ratios versus azimuthal position and is superimposed on a theoretical solution for the radiation pattern expected from an earthquake. In this case, the measured

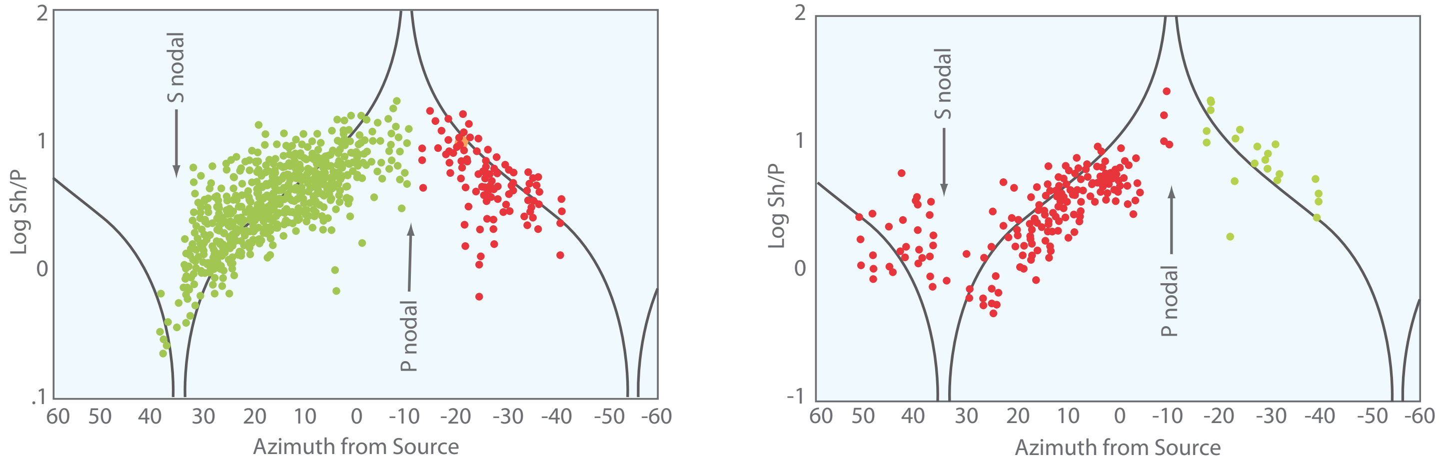

Figure 5. SP ratios vs. azimuth position

results closely match the expected radiation pattern for slippage along natural fractures that are parallel to the hydraulic fracture. In such a case, one encounters nulls in both the S and P amplitudes that create this variable S/P ratio plot. These data provided absolutely no information about the fracture process. However, they do provide useful information on the fault plane that can be useful in characterizing the reservoir. In addition, once the fault plane is known, then one can see if there are variations in the S/P ratios, stress drops, or other parameters that may be important. The important element here is: ***we must understand the source mechanism before interpreting the results.***

When good quality microseisms are available on most levels (at least 6 or 8) of a large array and the data are sampled at a fast enough rate to appropriately analyze the frequency content (at least ¼ millisecond sampling), then accurate source information can be obtained. Figure 6 shows the results of an analysis using the approach developed for Pinnacle by Sorrells. It depicts the locations of all microseisms in plan view, but also shows the fault plane orientations (red lines) for the best quality data. The observed mechanism is strike-slip movement along planes oriented sub-parallel to the hydraulic fracture. This information is very useful, as it suggests that there is a significant natural fracture set that is oriented parallel to the stress field (as would often be expected). More important, the orientations of the slippage planes now correctly orient the radiation pattern of the seismic energy emitted by the microseism. Only with this clear understanding of the radiation pattern can other facets of the fracturing process be understood.

Unfortunately, determining the fault plane orientations is not simple. For standard earthquake analyses, there are stations all over the surface of the earth that provide detailed coverage of the sphere. For microseismic monitoring, there is normally only a single linear array from which to deduce the results. Sorrells has developed a methodology to invert the distribution of amplitude ratios ($S_{v,h}/P$ and S_v/S_h), along with polarity information, in order to calculate the fault plane orientation. Figure 7 on the next page shows typical data at each of 10 stations that were used to determine one of the solution points shown on the previous map. Given the location of the microseism, the ratios of the horizontal S wave and vertical S wave to the P wave should have a unique signature that can be fit to a double-couple source model (most appropriate model for microseisms) and provide both fault plane orientation and slip direction. Because of some symmetry considerations, other information is necessary and is provided by relative polarity data, as indicated by the S_v/S_h sign on the plot. Although this analysis is more complicated, performing this type procedure is the only way to assure that the data are interpreted correctly.

Once the relationships between the microseism and the monitoring position are

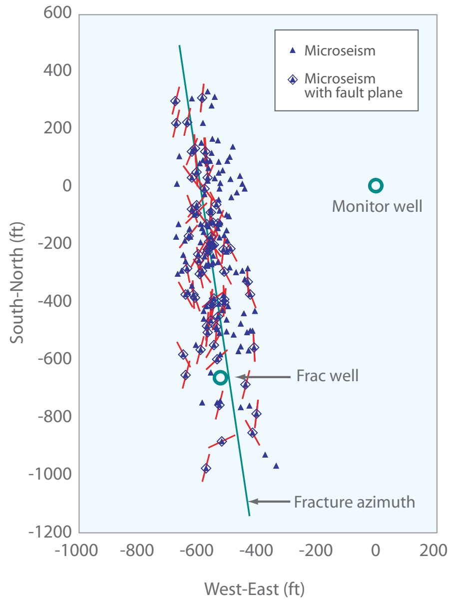

Figure 6. Fault plane map

understood, then other source parameter information can also be gleaned from the data, as in the stress drop data to the left. This plot shows calculated stress drops for each event relative to the largest event. Essentially, there are some large and some small events throughout the field. For this fracture, at least, the results appear normal.

In summary, the Pinnacle approach is to first assure that we can correctly interpret the spectral data and the structural setting *before* providing source data. Only with Pinnacle's high fidelity data can one even attempt to extract estimates of source parameters. To do so, we are using and refining a source-mechanism analysis by Sorrells that has been patented and proven in well-constrained test cases such as M-Site. This analysis allows us to take single-well, multi-level receiver data and extract the fault plane and the slip direction. Next, with the radiation pattern known, the spectral analysis can provide reasonably accurate source-parameter estimates (assuming normal attenuation characteristics). These parameters are then evaluated within the context of the overall structural framework induced by the fracture as well as the far field stresses. Only at this point do we have a result that can be meaningfully interpreted with respect to its application to the hydraulic fracturing process.

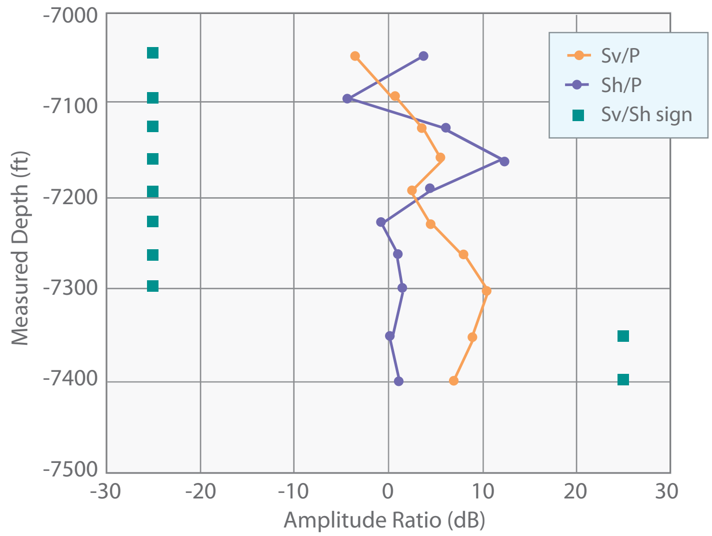

Figure 7. Fault plane orientation

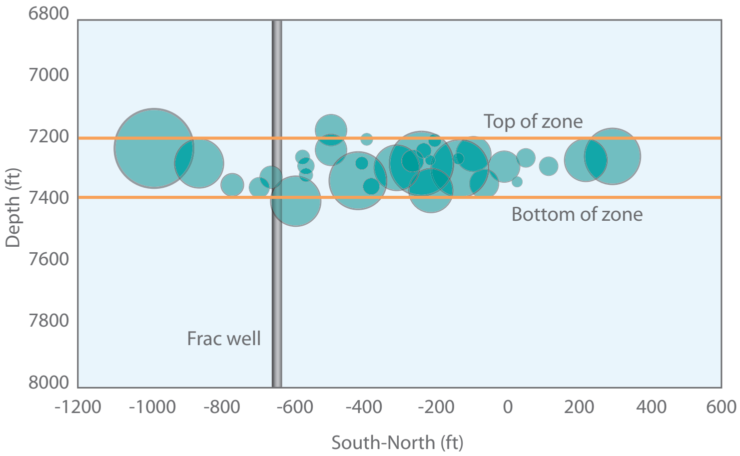

Figure 8. Stress drop

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