Full Wave Imaging of Downhole Microseismic; using all the data

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Microseismic monitoring of hydraulic fracture stimulation in shale oil and gas development is gaining acceptance around the world as an important tool for understanding how the reservoir is responding to the treatment. This data can provide important information in real-time that allow the completion engineer to optimize frac parameters, stage spacing and well spacing. The legacy method of monitoring required the deployment of a string of geophones at close to reservoir depth in a nearby observation well. Over the last decade the industry has developed the ability to use surface arrays for many monitoring applications, eliminating the expense of providing a monitoring wellbore. In order to recover the microseismic signals using surface arrays a combination of high fold stacking and full waveform imaging is required, much as is used in conventional 3-D reflection seismology. The full waveform imaging methodology has recently been extended for use with downhole arrays. The advantages over the more traditional arrival time picking technique of event location include a less labor intensive workflow and a less processor dependent location solution as well as the opportunity to detect and locate smaller magnitude events. This paper will compare and contrast both methods of downhole microseismic processing and highlight results from a downhole imaging data set.

DOWNHOLE PROCESSING TECHNIQUES

Traditional P&S Picking

The traditional method of downhole microseismic processing is referred to as "P&S picking." This processing methodology was borrowed from earthquake seismology and utilizes the arrival times of faster compressional (P-waves) and slower shear (S-waves) waves that are emitted when fractures open in the earth during stimulation. The goal is to determine the event locations (where fractures occurred) and origin times (when fractures occurred) associated with the stimulation.

The geophones in the downhole array typically have one vertical and 2 orthogonal horizontal components (3-C geophone) allowing for a complete characterization of the earth's motion as the waves travel through the array. The array itself will consist of between 6 and as many as 100 of these 3-C geophones, deployed typically at 25 to 50 foot intervals. Since the S-waves travel more slowly than the P-waves, the difference between the arrival times of the 2 phases will increase as the distance between the fracture location and the geophone location increases (see Figure 1). If one knows the difference between the arrival times of each phase at a given geophone and the velocity of the waves in the earth, one can estimate the distance from the geophone to the fracture location, without knowing the actual time that the fracture erupted. The key is to know precisely the time of arrival of each wave type at each geophone location. Since each wave is bandlimited, the arrival is not seen as a spike at a unique time, but rather as a wavelet with finite width. In practice the first excursion or break of the wavelet away from the zero amplitude state is chosen as the arrival time of the wave front. In the absence of noise, and with a sufficient recording resolution (digitization interval) this first break might be selected or "picked" with an accuracy of a few 10ths of a millisecond. Unfortunately there is often a large amount of noise, some random and some coherent, also reaching the geophone such that picking accuracies of closer to +/-1 millisecond are more typical. To overcome the noise, more than one geophone is used. The separate estimates of location are then averaged in some way to get a most likely event location. The variation of the individual locations around this average location is a measure of the internal error of the estimated event position, in other words the precision of the estimate. Systematic errors, for instance an error in the velocity model, are not captured by this variance so it is possible to have a tight cluster of locations, but all in the wrong place. A calibration shot in a known location is the preferred way of correcting for such systematic errors.

A 3-C geophone also allows for a measurement of the direction in which the wave is travelling. This is achieved by making a 2 or 3 dimensional plot of the signed signal value as a function of time with each observed component on its own axis. Such a plot is known as a hodogram. In the absence of noise, this plot is a straight line pointing toward the event location and 180 degrees away from the location. One normally selects the more probable of these two directions given some knowledge of the well and the geophone location. Azimuthal errors of +/- 10 degrees are typical of such hodogram analyses.

If both distance and direction can be estimated, then a single 3-C geophone may be sufficient to make an estimate of the fracture location. Multiple geophones in one string, or even better, in 2 or 3 strings located in different observation wells provide a redundancy that allows for more precise and accurate event locations in the presence of noise.

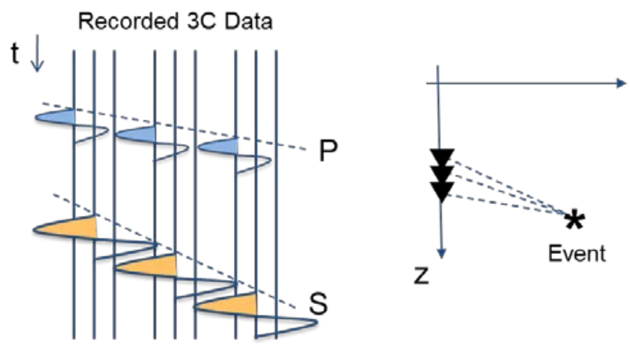

Figure 1: Three component recordings for a microseismic event illustrating the P&S wave arrivals (left), and a representation of an event next to the downhole array with the seismic wave paths (right). The slope of the arrivals across the array is an indication of the wave's velocity. The dashed line represents the pick of the wave arrival time in this noise free case.

Full Waveform Imaging

The PSET® (Passive Seismic Emission Tomography) full waveform imaging technique for determining microseismic event locations using a surface array was introduced in 2003 (Duncan et al., 2008). The development was driven by a desire to monitor fracs without the limitations and expense of deploying phones at depth in a monitor well. However, the bandwidth of the signal received at or near the surface is typically not adequate to pick the P-wave and S-wave arrivals with sufficient accuracy to achieve location estimates that meet our requirements. Furthermore, it should be noted that most of the S-wave field is absorbed before it reaches a surface array. Fortunately, with proper aperture and fold, P-wave data are sufficient alone to locate and characterize the event.

In this methodology the recorded seismic traces from each geophone are time shifted relative to each other in proportion to the travel time differences as a result of the differing distances of the receivers from the hypothetical event location. The travel time calculations require a reasonable knowledge of the seismic velocity in the project area. The time shifted traces are stacked (summed) and the resulting stacked trace is then scanned over its entire time range for the characteristic amplitude signature of a fracture event. This stack and search process is repeated for every possible event location in the subsurface. The successful imaging of frac events from the surface requires a large enough array aperture to provide the spatial resolution required and a sufficient fold to overcome the noise present in the array. By most standards, the aperture must be twice the depth and the fold must be such that the signal-to-noise ratio after stack is 3 or greater.

An added benefit of the large spatial array is that even though only P-waves are recorded, a sufficient sample of the wavefront is obtained to allow for an estimate of the focal mechanism of the seismic event. For example, was the fracture rupture strike-slip or dip-slip in nature? The wavefront sample in most downhole monitoring realizations is insufficient to make an estimate of the full moment tensor that describes the focal mechanism of the event. In fact, with a single vertical downhole array a P-wave only sample does not allow for the determination of mechanism at all. If both P and S are recovered, the shear component of the mechanism may be determined. It requires at least 2 reasonably separated observation wells with good P and S wave resolution to determine the complete mechanism when vertical downhole arrays are employed.

Recently, PSET was adapted for use with downhole arrays. The motivation for developing an imaging solution for downhole arrays was that the arrival time picking process is labor intensive and the results are very "picker dependent." One might assume that robust computer algorithms could be developed to detect an event arrival based on the increased motion of the earth as evidenced by the sudden increase in amplitude of the seismic trace. Given sufficient signal strength over a broad frequency band, this is indeed possible but in real world situations noise of various forms tends to complicate the arrival waveform and automated pickers become unstable. Experienced interpreters are required to pick "through the noise" and estimate the arrival times. When there are thousands of events to pick on tens or hundreds of traces, the picking effort becomes formidable and completely destroys any hope for real-time results. Furthermore, the same dataset will end up with different picks at the hands of different processors often leading to conflicting interpretations and a lack of confidence in the entire process.

A full waveform migration approach which uses the power of the stack to overcome the noise is well posed to stabilize the travel time estimates, particularly when both the P-wave and the S-wave have been recorded. In the case of downhole full wave imaging the location estimate is driven by the independent colocation of both the P and S wavefield (see Figure 2), meaning that PSET locates the event location that produces the biggest P-wave and S-wave stack after each has been moved out with the appropriate velocity.

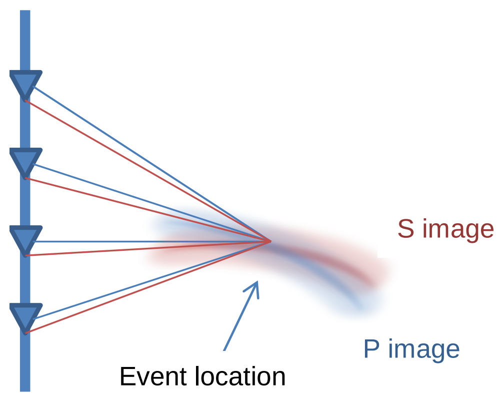

Figure 2: A representation for downhole recording of a PSET migrated P&S imaged event. The event location is where the energy of the migrated images intersect.

Imaging Distance and Downhole Arrays

A large concern when monitoring a frac process with a downhole array is the offset of the monitoring array from the treatment location. Two issues are at play here. One issue is the geometry of the array. As the array gets farther away from the location of the frac events, the uncertainty in image location grows because there is not much travel time difference between when the signals arrive at the various geophones in the array. At extreme distances the array acts as if it were a single phone and the uncertainty in location is large (see Figure 3). A general principle is that events located farther away than 3 times the length of the array are most likely poorly positioned.

The second issue is signal attenuation. The fractured rocks tend to absorb the seismic signals with this absorption being worse for horizontally travelling signals than for vertically travelling signals. In our experience, a practical limit for detecting signals with sufficient confidence is about 3,000 feet.

The distance considerations discussed here are relevant to both P&S picking and full waveform downhole imaging. The latter method, because it uses more of the actual signal may be able to push further down into the noise and slightly further in range. The former method allows the interpreter to "phantom" in picks even when they cannot really see the arrival. This will produce a result that may seem fine, but be very much in error.

Surface Array

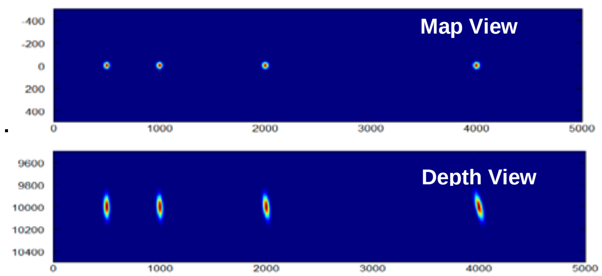

Figure 3a: Map and depth view of growth in uncertainty with distance of event location underneath a surface array. Uncertainty remains relatively constant across the entire array.

Downhole Array

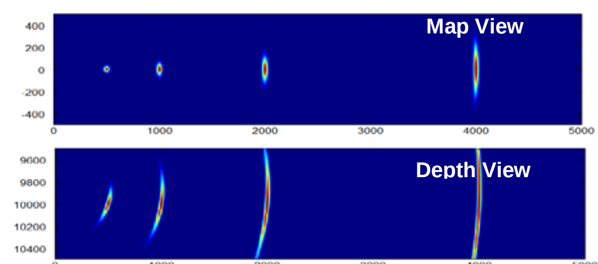

Figure 3b: Map and depth view of uncertainty of event location showing increase in uncertainty as distance from the downhole array increases.

COMPARISON OF PICKING TO IMAGING

Pros/Cons of P&S Picking

P&S picking is a relatively simple, straightforward, computationally cheap, but labor intensive method for processing a downhole microseismic dataset. Since events must be visible on the trace to be picked, there is high confidence that the events are real. At reasonable distances relative to the array length the location accuracy is good and the minimum magnitude of detection is generally better than for surface arrays. However, the final pointset is influenced by the analyst that is picking event arrivals and can be quite subjective. Additional points to consider for P&S picking include the following:

- There is high sensitivity to velocity errors and changes in velocity during stimulation when the wave path between the event and the receiver array includes the reservoir volume undergoing stimulation. This sensitivity extends to the relevant velocity anisotropy parameters needed to accommodate processing challenges due to variations in the direction of wave propagation between individual events and the downhole array. This can cause significant and systematic event location error.
- P&S picking is quite difficult when arrivals are weak, nonexistent, or contaminated by other arrivals such as refracted waves or noise. These difficulties lead to a high number of false positive events in a P&S picking based pointset relative to a full waveform approach. The challenge of weak arrivals increases with event distance from the downhole array.
- For events very close to the array, it is difficult to nearly impossible to properly differentiate P&S arrivals due to significant P vs. S mode wavelet overlap.

- Monitoring with a 1-D array includes an inherent 180 degree uncertainty in determination of event direction due to wavefield sampling limitations.

Pros/Cons of Full Waveform Downhole Imaging

Downhole imaging is more algorithmically complex and computationally intensive than P&S picking. However, downhole imaging is less people intensive and generally locates more real events than P&S picking (increased accuracy) while removing operator/analyst bias. With less reliance on a picker, imaging can offer a more complete and reliable real-time solution. Additional points for consideration include the following:

- Full waveform processing extends the distance and magnitude range of real event detection and location.
- Editing of the raw event pointset to final pointset status is accomplished via sophisticated workflows that use a rich set of migration-based event catalog attributes and multivariate machine learning algorithms rather than subjective experience.
- There is no 180 degree ambiguity in placing event locations from the monitoring array since the radiation pattern of the events is taken into account. The event image search is performed after component rotation to radial and transverse, allowing for separation of P&S energy before stacking.

PERMIAN BASIN CASE STUDY

A downhole imaging case study from the Permian Basin is used to illustrate imaging capability. In Figure 4, the rich downhole imaged pointset surrounding the monitoring borehole is displayed showing good zonal control and excellent event count near the monitoring borehole. Since the imaging utilizes both P-wave and S-wave energy, but does not depend on the separation in time of the P-wave and S-wave arrivals as in P&S picking, the imaging contains valid events close to the wellbore and extends the distance and magnitude range of real event detection away from the monitor well. The pointset extends approximately 3,000 feet from the monitoring borehole. Events from beyond this threshold possess unacceptable uncertainty and are not passed through the imaging and event editing workflow. In Figure 5, the surface acquired imaging pointset is not as rich, however the imaging extends underneath the entire footprint of the surface array with acceptable uncertainty throughout.

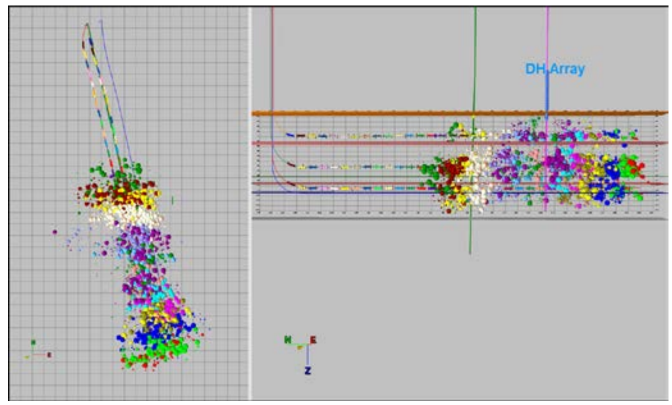

Figure 4: PSET® Downhole imaged pointset for Permian Basin case study. Note excellent event detail from the downhole monitoring borehole. Left: map view Right: depth view looking east

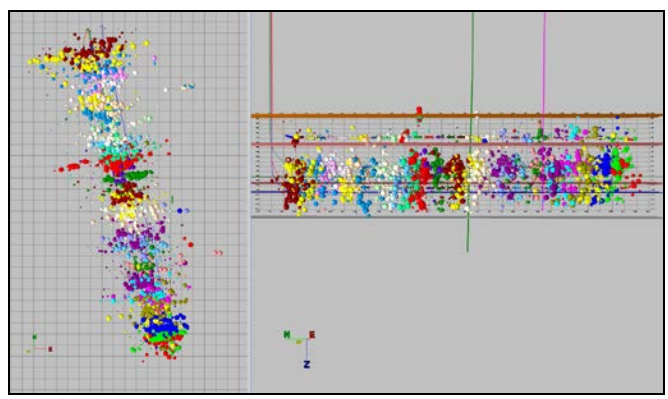

Figure 5: Surface imaged pointset for Permian Basin case study. Note pointset extends across entire well due to larger surface array footprint. Left: map view Right: depth view looking east

In this Permian Basin example, propped fracture half-lengths and heights were determined for three wells completed in the Middle Spraberry, the Lower Spraberry, and the Wolfcamp A. The wells were vertically stacked above each other indicating potential for optimization of the current wellbore spacing, Figure 6. The microseismic data shows a gap in the propped fracture volume between the Middle and the Lower Spraberry indicating that the vertical wellbore spacing between the two is likely excessive. There is potential for adding a wellbore in the Jo Mill formation for ideal exploitation of the reservoir. Additionally, proppant placement analysis indicates the need for two wellbores in both the Middle and the Lower Spraberry laterally offset from each other for optimal reservoir drainage. Current vertical wellbore spacing between the Lower Spraberry and the Wolfcamp A seems to be appropriate with sufficient coverage of the Dean formation. This analysis significantly shortened the appraisal timeline and accelerated the learning process for this asset, while maximizing the net present value by optimizing vertical and lateral wellbore spacing.

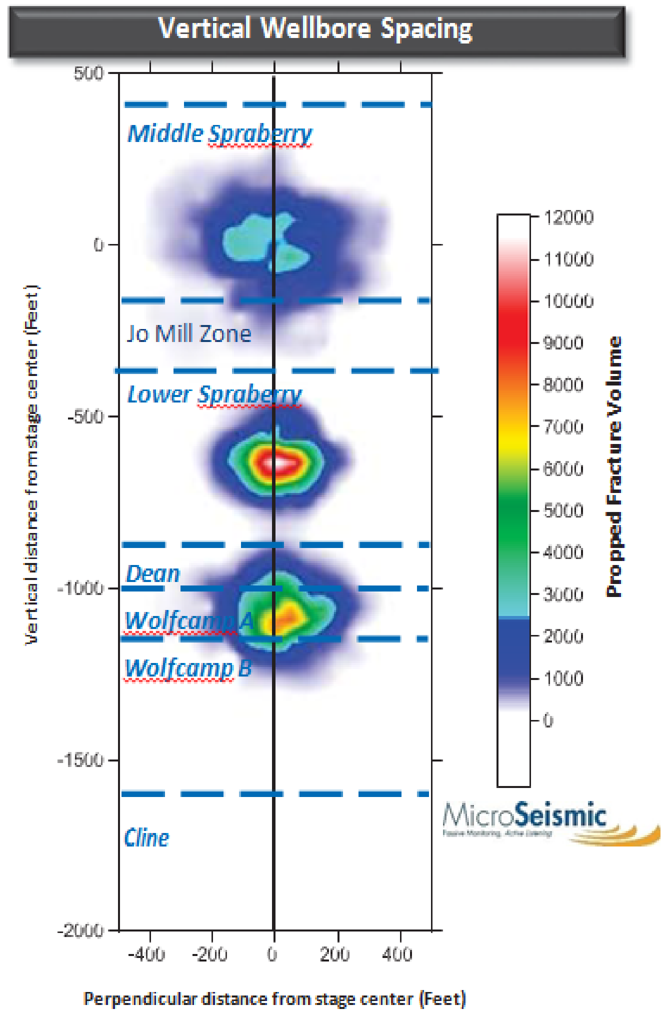

Figure 6: Vertically stacked formations in the Permian illustrating zones of microseismic coverage indicating good reservoir access and gaps where further development is indicated.

References

Duncan, P. M., J. D. Lakings, and R. A. Flores, 2008, Method for passive seismic emission tomography: U. S. Patent Application Publication US 2008/0068928A1.