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Pre-survey planning assures value from microseismic monitoring

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Each fracture stimulation program has unique aspects that make a one-size-fits-all approach to microseismic monitoring bound to fail. Appropriate design and matching of equipment to the task is essential to delivering high quality information to improve stimulation performance.

Pre-survey modeling is important

As unconventional resource activities boom, the need to understand the effectiveness of drilling and stimulation programs has led to increased use of microseismic data for well completion evaluation and to define the ideal parameters for future completions.

Fracture stimulation monitoring is still a relatively new and immature practice within geophysics, with abundant opportunities for smarter data acquisition, processing, and interpretation. This may seem odd given that the foundations of this emerging field rest on decades-old seismological theory and practice. However, with the exploration and development community focused intensely on reflection seismic data in recent decades, some of these basic principles appear to have been forgotten.

Moreover, as is often the case with new technology applications, the specific questions an operator needs to and can answer through the acquisition and analysis of microseismic data are not often fully considered beforehand. As a result, limitations of the monitoring effort may be revealed only after the fact.

The first step an operator should take in planning a microseismic survey is to pose a series of questions for which they need answers. Questions about well and frac stage spacing will likely come to mind first, as these are two important planning areas which contribute profoundly to the economics of resource plays. But there are other challenges and every well is, to some extent, in a unique geologic setting, and influenced by the dynamics of historic production and the stimulation program as a whole.

For example, in-fill drilling introduces significant uncertainty in the stimulation effort since there are likely depletion pressure cells in the formation that may have substantial impact on the character and direction of the fracture network. Even in unproduced zones, we are finding that symmetric fracture systems centered on the well bore are not nearly as common as initially expected.

> It is critical to define the objectives of a fracture monitoring program carefully, and then design a program that has the best chance of success.

Like any complex measurement, success hinges on appropriate planning and modeling before acquisition to ensure that we actually collect the data we need for analysis. The good news is that this modeling and analysis is one of the strongest disciplines in seismology, with accumulated expertise from a century of earthquake studies. (Like earthquakes, microseisms are most often small double-couple faults and sometimes tensile events). Unfortunately, there are few

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standard tools familiar to oil and gas geophysicists to provide the right answers.

Although the geophysical literature contains many examples of forward modeling initiatives, the published studies are often designed to promote a specific acquisition geometry being marketed by a contractor, or they are simply ignored in practice. In our practical experience, the implications of acquisition geometry are most often not well appreciated until after the survey is completed and the data set is unalterable.

In this article we present intuitive figures created with petrophysical properties and target depths appropriate for the North American resource plays. I will show that the radiation of energy from expected seismic emissions illustrates the importance of planning the acquisition geometry, and that weak seismic emissions can be recorded successfully with a newly-available family of highly sensitive, three-component arrays purpose-built for stimulation monitoring.

Establish clear goals

Microseismic data can provide a suite of information of different types, and each of these products has acquisition requirements and degrees of elegance required in processing.

A catalog of event locations is a standard product that helps illuminate the induced fractures and allows us to interpret these fractures with respect to the reservoir interval and existing faults in the subsurface. General trends or lineaments in the event groups can also indicate the azimuth of the local stress field.

The depth resolution of events can also be a critical product of a survey. Surveys for regulatory compliance and/or proof of containment are growing in importance. Lack of containment within the appropriate depth interval can also waste stimulation energy and fluids and establish connectivity with adjacent water zones that can lead to early abandonment of a well.

As the industry matures, more sophisticated methods for studying the induced fracture system are developing. We can now solve for and even directly image the fracture planes causing the seismicity. Resolving the angles of the fracture planes gives us a direct measure of the local stress field at each event location. Moreover, understanding the relationship between the effective stress changes and the size and distribution of events can add information to the reservoir simulation that has direct impact on flow models used to estimate each well's ultimate productivity.

After establishing the goals of a proposed survey within an integrated asset team, the geophysicist must then plan and execute the survey to extract the necessary information.

Match equipment to the task

Low-noise, high-sensitivity instruments are essential for capturing relatively weak microseismic energy in most settings, even when using a costly fit-for-purpose observation well.

The standard, general expressions for the radiation of seismic energy from a faulting event are well known and given, for example, in Aki and Richards (2002). Because S-wave velocity is usually about half the P-wave velocity, the Sv and Sh mode amplitudes from a faulting event are 2^3 times greater than P events. Therefore, considering both S modes together, a microseismic event generates 16 times more shear than compression energy.

Since most of the energy radiated from the source travels as S waves, our first conclusion is that the survey design and processing scheme must properly handle S waves (see Figure 1). While using 3C geophones is common practice in downhole applications today, it is unfortunately still the norm to find surface deployments, and even permanently installed near-surface arrays, constituted only of vertical phones. Microseismic analysis is fundamentally different from familiar reflection surveys, where P-only, vertical component, acoustic approximations have performed so well historically.

Figure 1 is a real data example showing the dominance of S-wave energy on the horizontal components. Not only does 3C data enable a more complete description of the fractured reservoir, 1C data simply ignores a huge amount of important energy from the fractures.

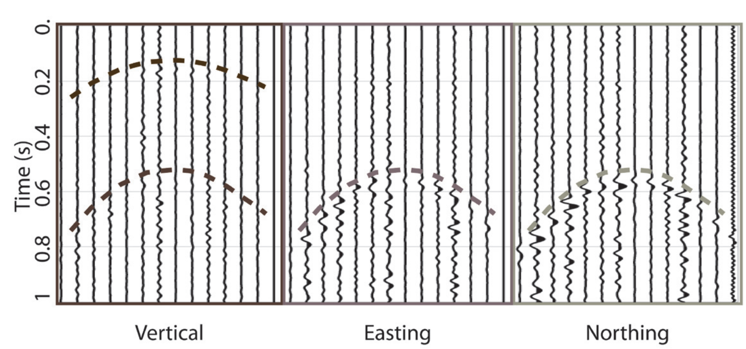

Figure 1: Strong shear wave arrivals recorded by a line in a surface array over a shale gas play in North America. Dashed lines are drawn just above the P and S arrivals.

Finally, the amplitude spectrum of a faulting source has been empirically confirmed to follow a model (Brune, 1970) that is a function of the size of the event. With a local velocity model and an estimate of attenuation, we can quickly generate estimates of event energy at any given distance of an array from the event. In the models that follow I assume the event is 2,000 ft away, a constant Q of 150, and Vp=9,600 ft/s.

Figure 2 shows modeled amplitude spectra of nominal events compared to average background noise levels and two geophone sensitivity curves, plotting seismic energy as a function of frequency. The series of red lines are magnitude -3.5 to -1.0 events in steps of 0.5. The gray lines are the upper and lower bounds of seismic background noise continuously present in the Earth's crust. The blue dashed line is the sensitivity threshold, or noise floor, of a generic 15 Hz geophone often used for surface and downhole microseismic monitoring.

> The survey design and processing scheme must properly handle S waves.

The green dashed line is the same measure for the receiver in the UltraSense™ nodal array system, recently launched by my company, Spectraseis. The receivers achieve a 50x sensitivity increase, enabling the recording of half-magnitude weaker events from the same distance (or the same magnitude from much further away). The sensors record events that are stronger than background noise, rather than being limited by instrument self-noise. These arrays have successfully been deployed in both surface and borehole geometries.

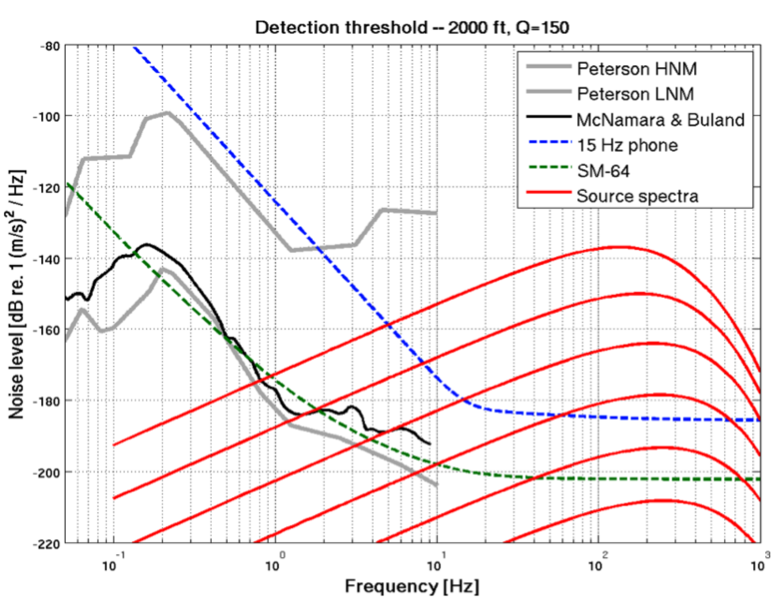

Figure 2: The sensors in Spectraseis' UltraSense™ arrays (green dashed sensitivity curve) have a 4.5 Hz corner frequency, 4800 V/m/s sensitivity, and an excellent broadband frequency response from 0.1-1000hz. Blue sensitivity curve is a conventional geophone, and the red lines are modeled microseisms from magnitude -3.5 to -1.0 (bottom to top).

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Understand the measurement sweet spot

Figure 3 shows the radiation pattern of P-wave energy from a (double-couple) fault. Figure 4 shows the sum of Sv and Sh amplitudes. The horizontal plane shows the distribution of energy incident on the surface, while the sphere below shows the relevant information for planning a borehole deployment. Note that the color bar limits for Figure 3 are +/- 1/8 of the scale on the S-wave energy plot in Figure 4. The vertical fault plane is assumed to strike E-W, indicated by the transparent planes in both. We will assume a horizontal well is drilled perpendicular to the fault plane, through the hypocenter (red dot).

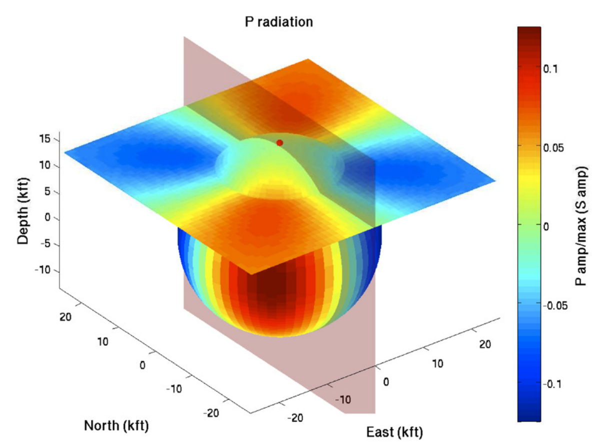

Figure 3: P-wave radiation pattern for a microseismic faulting event. The green colors show two nodal planes where no P energy is recorded. Maximum P energy is 45o from the transparent fault plane. Color scale range is 1/8th of that in Figure 4.

Both figures show that there is no energy, P nor S, radiated directly to the surface above the event. Figure 3 shows that a line of geophones on the surface above the horizontal should also record no P arrival. The maximum P amplitudes are 45o from the well axis, at a surface offset from the source equal to the depth of the source for this constant velocity example. In a medium where velocity increases with depth, the surface maximum will be closer to the hypocenter due to ray bending. Conversely, in Figure 4, we see that the maximum azimuths for S energy are exactly in the orthogonal coordinate system defined by the well and the fault plane, and S energy is zero where the P is a maximum.

With only three parameters (depth=9,600 ft, Vp/Vs = 2, and fault azimuth) such a simple figure shows where we should plan to record the information in a microseismic acquisition. But what information is required is dictated by the questions we need to answer.

The first priority is usually event location. An array's ability to localize a source within the aperture of the array is trivial, while the distance away from the array is difficult. So, as a general statement, we should expect excellent precision for x,y coordinates from a surface array, while a vertical array should excel at depth resolution. If map coordinates are most important, then an areal array is the obvious choice. If depth accuracy is of paramount importance, recording the hyperbola top by deploying as close to across the stimulated interval is the best possible option. However, most borehole arrays have limited aperture, and often don't record the minimum travel path (the top of the hyperbola) when they do not span the reservoir interval.

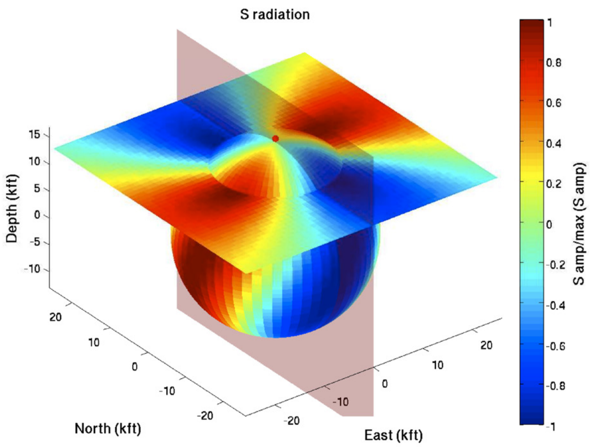

Figure 4: S-wave radiation pattern for a microseismic faulting event. The green colors show two nodal planes where no S energy is recorded. Maximum S energy is within and perpendicular to the transparent fault plane.

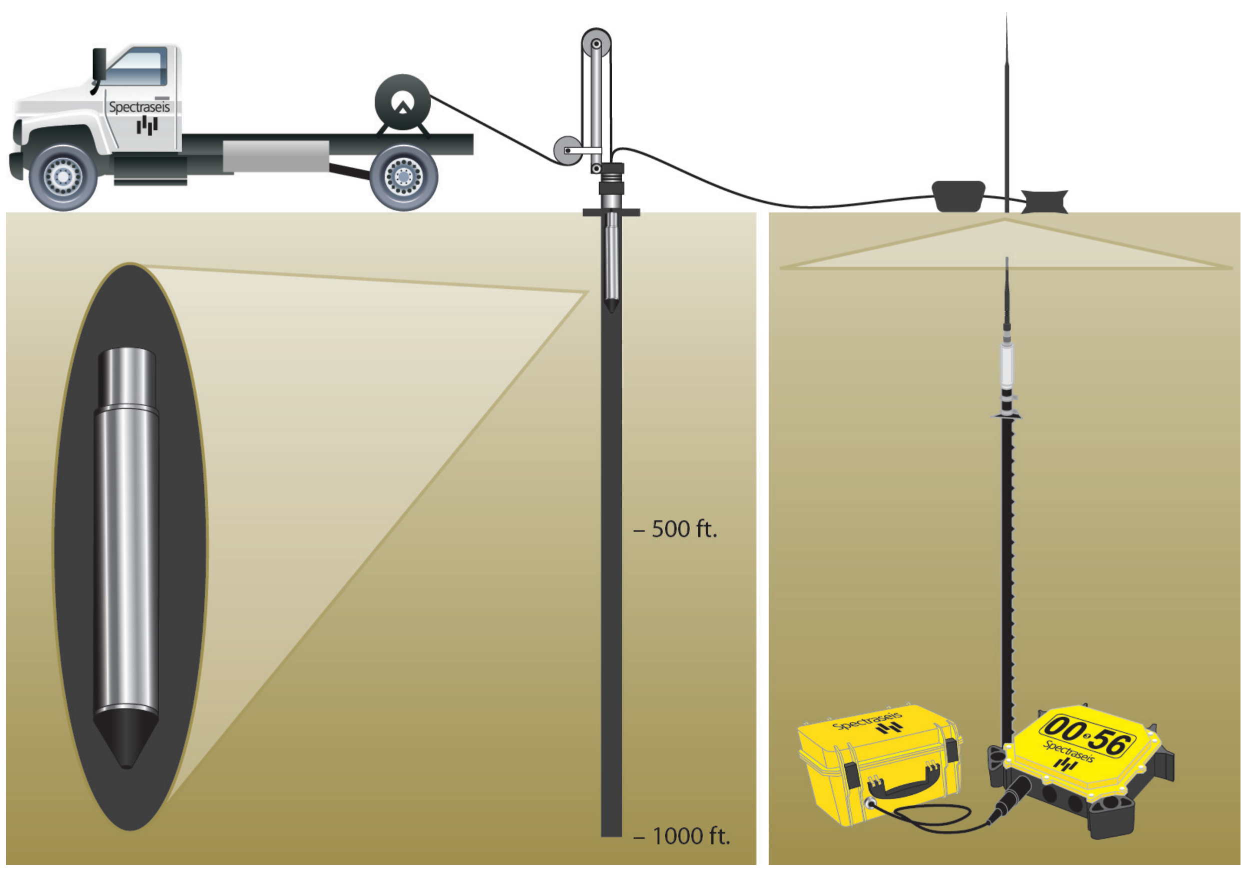

Figure 5: The UltraSense™ shallow borehole system deploys a high-performance broadband tool below the weathered layer at a lower cost than a conventional deep borehole tool, enabling multiple deployments over a lateral well. UltraSense™ arrays have recorded events with strong signal-to-noise at distances greater than 6000'.

Algorithms for both deployments have strengths and weakness that are beyond the scope of this article. However we will note that the errors inherent in areal geometries are roughly static for all events, while for linear arrays they increase substantially with distance.

A curious counterpoint arises when we assume a monitor well offset from, but still within, the length of the producer. The minimum distance to the monitor well from a seismic event will be from the stage

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where the expected fracture planes include the monitor well. Therefore P arrivals are likely to be very weak or not recorded. So even though we know something happened by recording a booming S arrival, calculating locations with only an S event (though theoretically possible) is rarely attempted. Large aperture arrays of surface or borehole sensors do allow location by acoustic approximations using the S arrivals.

To get both P and S arrivals, the sweet spot for a vertical monitor array is therefore halfway between the maximum and minimum of any mode. In this example, the first of 8 best azimuths around the compass is about 25o from North, or when the monitor well is located in the back-azimuth from the perforations: 180o +25o =205o.

No one-size-fits-all

As microseismic service providers gain experience and perfect their craft, more insightful products are being delivered that answer important questions about the effectiveness of the stimulation dollars being spent on North American resource plays. Our experience is built on solid physical foundations, but each program has unique aspects that make a one-size-fits-all approach likely to fail.

It is critical to define the objectives of a fracture monitoring program carefully, and then design a program that has the best chance of success. Selecting the acquisition geometry, equipment and processing methods most appropriate for the stimulation will assure delivery of a valuable product.

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