Surface microseismic in an extreme environment

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Abstract

A surface microseismic survey was conducted in a noisy suburban active oilfield environment. Unconventional patch acquisition survey design and careful processing allowed the extraction of over 8,000 events from the noisy data. Patch acquisition and multi-channel noise attenuation were critical components of the success of the project.

Introduction

Surface microseismic recording has been used to define hydraulic fractures in oil and gas fields for several years now. Most of these surveys have been conducted in relatively quiet areas, which has been good for the development of the technology. It is difficult enough to find microseismic events with magnitudes as low as -2 without additional complications. As unconventional reservoir development has progressed, however, these quiet areas are now often becoming very noisy with pump jacks as well as active drilling and hydraulic fracturing (“fracking”) operations on other wells. Add to these noise sources a suburban community and the challenge of recording a survey over an active treatment well where microseismic events can be identified has been made much more difficult.

Dawson Geophysical and NanoSeis planned and recorded a survey in just such an environment in the DJ Basin, Colorado in July-August, 2014. A patch acquisition geometry was used in order to take advantage of the spotty access around other oilfield installations, flooded areas, a gravel quarry, crops, shopping centers and housing developments. A patch acquisition geometry was used to optimize the placement of the surface receivers in order to avoid placing receivers in areas which could not be permitted, as well as to avoid the greatest sources of cultural noise in the area. In fact, one of the patches had to be relocated as the survey began, in order to avoid an active drilling rig that set up right across the road. The dense patches of geophone groups also allowed for advanced noise attenuation techniques in data processing.

Attention to noise attenuation, receiver statics and velocity refinement resulted in a high quality dataset which includes source mechanisms for all events. Careful pre-processing is required in order to determine source mechanisms on such a dataset.

Data Acquisition

During the acquisition, the noise sources included two other active drill rigs, another active well treatment job, several producing wells within the survey area, in addition to all the attendant traffic on the roadways servicing these sites. Most of these noise sources were anticipated prior to the start of the survey, but the two active drill rigs were a surprise.

The patch locations were carefully selected after scouting the area. Traffic patterns were observed and those areas with more traffic than others were avoided when placing the geophone
patches. There were several areas that had to be completely excluded due to dense housing developments, ponds, active gravel pits and crop fields that could not be permitted. The use of geophone patches made it much easier to work around these excluded zones and still obtain a good distribution of receivers to sample the source radiation patterns. In this case, it would have been very difficult to deploy a standard grid- or star-style array.

The survey design used 18 patches of 121 geophone groups each for a total of 2,178 recording channels. These patches were deployed over an area of approximately 16 square miles. Each 121 geophone group patch consisted of 11 lines by 11 rows of geophone groups, separated by 100 feet in the north-south and the east-west directions. The full extent of each patch was a square 1000 feet on each side. A satellite photo map of the area with the patch locations is shown in Figure 1 for reference.

Figure 1: Aerial photo of the survey area. The red rectangle indicates the treatment well coverage. The red squares cover the positions of the geophone patches.
Two strings of 6 10Hz geophones were used for each group, for a total of 26,136 total geophones in the entire spread. The strings were laid out with a rectangular pattern of 3 by 4 geophones, separated by 10 feet in the north-south and east-west directions. The GSR recording system was used with a sample interval of 2 milliseconds and a pre-amp gain of 36 dB. Although this survey was conducted in a “noisy area” by microseismic standards, the geophone output levels are much lower than with a conventional active source seismic survey and a large pre-amp gain is important to ensure there is sufficient dynamic range recorded in order to recover small events.

After the geophone arrays had been deployed in the field, but before the well frac treatment had begun, data were acquired from the geophone patches in order to sample the noise characteristics in the field. A map of the average geophone response is shown in Figure 2. The amplitudes are plotted on a logarithmic scale. It can be seen that the noise amplitudes varied by more than a factor of 10 across the survey area.
The noise source to the southeast is one active drilling rig that was contracted to a different operator. The very strong noise source on the west side is another drilling site that was being prepared while this noise survey was being conducted. The recognition of this western noise source prompted one patch of geophones to be moved to the quieter region to the northeast. The other areas showing higher than average noise are likely due to increased traffic in those areas, particularly in the center of the survey area near a shopping center.

Acquisition was conducted continuously over 4 weeks, recording over 10 terabytes of contiguous 30 second records of 2 millisecond data during the stimulation of approximately 400 stages over 8 wells. A monitor well was used to record the microseismic events simultaneously from a downhole geophone array for part of the survey. The maximum listening distance for this array
did not allow the entire well frac treatment to be monitored using the downhole array. The maximum listening distance was about 4500 feet to identify that an event occurred, but the distance to allow an event to be located with an accurate P-wave and S-wave arrival time was significantly less than this.

**Data Processing**

Surface microseismic data processing requires a very different approach from processing downhole microseismic data. It is much more like surface reflection seismic processing, since the data volumes are more similar and the geometry from the zone of interest to the receiver array is almost the same. The data are still very different from surface reflection data in that most of the data are dominated by noise with only sporadic microseismic events. A typical well may take several days to record and produce several hundred events that are detectable at the surface. In this survey, data were acquired over 28 days of recording and over 8,000 events were detected. This means that only about 0.1 percent of the recorded data contains identifiable microseismic events. Almost all of these events are undetectable in the raw data. Therefore, most of the coherent energy we see on passive recordings is noise energy and a visual scan of the data will not allow the events to be identified. We use a batch computer scan, following pre-processing to improve the signal-to-noise ratio of the data, in order to identify “candidate” events for review.

A typical surface microseismic processing sequence is shown in Table 1. Some of the processes look very similar to a conventional land reflection seismic processing sequence, such as velocity inversion, statics computation and noise attenuation. The primary objective of the processing is to produce a list of events with the magnitudes and source mechanisms of those events, rather than an image of the reflectivity of the subsurface.

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Table 1: Surface microseismic processing sequence.
Noise Attenuation

Noise attenuation was a critical part of the processing sequence for this project. Linear noise trends of variable velocity and direction are found on all records. The noise level is generally lower during the night time, due to lower wind and cultural noise. On this survey, however, the largest noise sources resulted from the active oilfield operations that continued 24 hours per day.

Early surface microseismic surveys used a geometry that assumed that the dominant noise source was the frac well treatment operation on the pad for the well being monitored (Stanek and Eisner, 2012). As such, geophone arrays were laid out to attenuate noise emanating from the well pad. Surface microseismic surveys conducted in an active oilfield, or other very noisy environment, must contend with many other noise sources. Laying out the geophone arrays in discrete patches with sufficient sampling in all directions to sample the noise wavefield allows noise energy to be attenuated no matter the direction of the noise propagation (Crews, et. al. 1989).

Multi-channel filters were designed to attack the noise from several directions. The apparent propagation velocity of the noise trains varied from 6,000 to 9,000 feet/second. Attenuation filters were designed for this range of propagation velocities and several different multi-channel noise attenuation algorithms were used to enhance the signal-to-noise ratio of the data. These included F-K filtering, tau-P beam-steering, F-X deconvolution, median filtering and trimmed mean filtering. All of these methods were helpful and the specific improvements varied with the type of noise encountered.

The methods that allow for a broader range of the velocities attenuated, such as F-K and tau-P filtering, gave better attenuation of dispersive noise trains, but also suffered from smearing of isolated noise bursts due to the size of the aperture of the effective filters in these methods (Claerbout and Muir, 1973). The other, more targeted, approaches did not allow as much latitude in the noises that they would attack, but were not as affected by strong, discrete noise bursts.

The challenge with applying noise attenuation to surface microseismic data is to attenuate the noise without harming the signal. The microseismic event signals are much weaker than the noise and sparsely distributed in time, so that it can be difficult to assess the effect that any filter is having in improving the signal-to-noise ratio of the data. It is tempting to apply processing that will remove all coherent energy, but that may also remove or distort the events that we are trying to extract from the data. Filters may be designed to either attenuate the noise by estimating the noise and removing it, or to enhance the signal of the microseismic events by applying time shifts to flatten the event and then enhance its coherency. Although the second approach can make the events appear cleaner, it may also produce many false positive events by enhancing noise that may be aliased into the signal space. We have found the best success at locating verifiable microseismic events by targeting specific noise velocities for attenuation and not applying multichannel filters to the aligned event data in order to further enhance those events.
Although events may not appear to be substantially cleaner with the noise attenuation applied, the real test of the efficacy of this processing is in the batch triggering search for candidate events. The ideal noise attenuation method would remove all the false positives, which result from noise coincidentally aligning at a similar time and arrival pattern as the expected signal, while not attenuating the microseismic signal events. In reality, there is always a balance between these two goals. We have found that the processing sequence used to obtain the best batch event triggering identification is often quite different from the processing sequence used to analyze and refine the events once they are identified. The use of more aggressive noise attenuation parameters prior to the batch triggering will usually result in a better ratio of true events to false events found by the batch triggering. The strongest events may have some amplitude loss, but they are still detected, and that is what matters early in the processing workflow. The pre-processing, along with different noise attenuation, will be re-done before refining the events.

Examples of raw event locations without and with aggressive noise attenuation are shown in Figures 4 and 6. These figures may be compared with the subset of final refined events from each of these sets of raw events in Figures 4 and 6. Although there are false positives in both of the raw event location maps, the map with the aggressive noise attenuation shows more than twice as many valid events compared to the events without multi-channel noise attenuation. It is important to note that the false positives are removed from the set of candidate events for final reporting during the event refinement stage of processing. The noise attenuation produces fewer false positive events which must be evaluated and discarded before proceeding. It also produces more of the valid events, which are the basis for event refinement to produce the final image shown in Figure 7. The noise attenuation allows us to detect more of these valid events and to discriminate better between what is a valid event and a false positive.

Figure 3: Map of top 1000 raw batch trigger events for Well 2B without multi-channel noise attenuation.
Figure 4: Map of 277 real events for Well 2B without multi-channel noise attenuation. The difference between this and figure 4 is that the false events, which were identified during event refinement, have been removed from the image.

Figure 5: Map of top 1000 raw batch trigger events for Well 2B with multi-channel noise attenuation.
Figure 6: Map of 684 real events for Well 2B with multi-channel noise attenuation. The difference between this and figure 5 is that the false events, which were identified during event refinement, have been removed from the image.

Statics and Velocities

The computation of receiver statics and velocity refinement for surface microseismic are similar to the computation with reflection seismic data. The perforation shots give us a source at a known position in the treatment borehole and the source mechanism of the perforation shot is known. However, since we do not have a highly accurate time of the shot, we cannot directly compute the travel time from the source to the receivers. We must rely on the relative travel time from the source to the array of receivers, similar to velocity analysis from surface seismic data which uses the shape of the moveout curve to determine the velocity function at a given time. Since we do have the actual location of the event, we can solve for the velocity and VTI anisotropy parameters that will focus the perf shot energy at the correct depth. A Monte Carlo inversion method was used to test thousands of different velocity and anisotropy perturbations before converging to an optimal solution. This solution is not unique, but as long as the computed parameters match the shape of the moveout curve and give the correct position of the perf shot sources in depth, it is sufficient.

Receiver statics are first solved on an intra-patch basis. This means that the statics within each patch are computed to align the perf shot energy between the traces recorded only for that patch. The inter-patch statics, the static variations between the patches, are solved separately. This separation of the statics computation into two steps gives an advantage over solving for a global statics solution because the trace-to-trace static shifts within each patch should be relatively small. After optimal alignment of the traces within each patch, we solve for inter-patch statics. Since we have improved the coherency of the traces within each patch with the intra-patch statics, the job of computing the inter-patch statics is easier than to directly compute a global solution in the presence of noise. The computation of the inter-patch and intra-patch statics was iterated until an optimal solution was reached. Please refer to Figure 6 for an example of the improvement in signal-to-noise and event alignment after residual statics computation.
It is more difficult to solve for optimal statics and velocities that will properly align the events with noisy data than with data which has a very high signal-to-noise ratio. It is, however, more important to properly align weak events which have a poor signal-to-noise ratio than it is with large events. The frequencies of small events are higher and, without optimal alignment of energy, many of these small events could not be identified.

![Sub-stack gathers showing a perf shot with successive iterations of statics and velocities. On the left is the gather with the initial pass of statics and velocities. In the middle is the gather after the first iteration of refinement and on the right is the gather after the final iteration of statics and velocity refinement.](image)

**Figure 7: Sub-stack gathers showing a perf shot with successive iterations of statics and velocities. On the left is the gather with the initial pass of statics and velocities. In the middle is the gather after the first iteration of refinement and on the right is the gather after the final iteration of statics and velocity refinement.**

**Source Mechanisms**

One aspect of surface microseismic data processing and analysis which is very different from reflection seismic processing is the necessity to account for the source mechanisms of the microseismic events. Most reflection seismic sources have a source mechanism which may be approximated by an isotropic source. That is, there is not a great deal of directional dependence in the radiation pattern from that source. Most microseismic sources, in contrast, are caused by a shear dislocation of the rock which results in a source mechanism and a resulting radiation pattern which has a strong directional dependence. This directional dependence is evidenced by polarity reversals in an event which has been time aligned (Stanek and Eisner, 2012). The fact that the event amplitudes are variable introduces another source of uncertainty into the processing. If the source mechanism has not been determined correctly, the position of the source cannot be imaged accurately. Also, if the event has not been positioned correctly, the source mechanism cannot be determined due to the residual time errors along the event. The
source energy must be aligned properly in order to estimate the source mechanism. Therefore, if the statics and velocity corrections have not been computed accurately, the source mechanism cannot be determined correctly.

So, while inaccurate statics and velocities with surface reflection data may result in a degraded stack response and misaligned reflections, in surface microseismic data the primary objectives of the exercise, microseismic source locations and source mechanisms, will have serious errors. Using a patch acquisition geometry allows for better noise attenuation and computation of statics, resulting in better source mechanisms.

Figure 8 shows a perf shot which has optimal statics applied. The image representation of this perf shot is a single high-amplitude spot in map view and sub-stacks of the gather traces appear well aligned in time, despite the lack of clear signal at some patches. Inversion for the source mechanism shows an isotropic signature as the highest confidence mechanism. Other mechanisms which were evaluated by the inversion, but which have lower confidence, also show a similar source mechanism. All of these features give us confidence in the location of the source and the source mechanism estimated for it.

Figure 9 shows this same perf shot with imperfect statics applied. The traces are no longer as well aligned and the stack response of the sub-stack traces has been degraded in the time view. The imperfect statics have caused a misalignment of the event amplitudes across the surface recording array. The image representation of this perf shot now shows two closely spaced high-amplitude spots, the signature expected for a dip-slip type of source mechanism (Fish, et al., this issue). However, the other source mechanisms with highly variable radiation patterns have nearly the confidence of the most likely dip-slip mechanism.
Figure 9: Perf shot with degraded statics. On the left is the image map display, trace data in time on the right, and estimated source mechanisms at the top right. Note the double high-amplitude spots near the correct image location for the perf shot, the perf event less well aligned in time and the inconsistent source mechanism estimates for this perf shot.

One way to ensure that a good solution has been computed for statics and velocities is to solve for source mechanisms for the events, even weak events with magnitudes on the order of -2. As shown above, source mechanism inversion will typically not converge consistently if an event is either a noise false positive or a real event which is distorted from poor statics or velocities. Even in the absence of noise, poor velocities and statics will not allow the convergence of the source mechanism inversions to a geologically plausible set of events. The source mechanisms in this project show expected variations, but the variations are typical of the fracture sets expected in this area. The map in Figure 10 shows the overall consistency of the source mechanisms and their correspondence to the regional stress. Please refer to Diller, et al. (this issue), for details about the source mechanism inversion used here.

Imaging

The events are imaged using a derivation of the Source Scanning Algorithm first described by Kao and Shan (2004). This algorithm is the basis for batch event triggering and for final event location. When refining the final event locations, the source mechanism must be known in order to correct for polarity changes in the source radiation pattern. However, in order to determine the source mechanism the source position must be known. This dilemma is solved with an iterating algorithm that solves for both the source mechanism and the event location.

Results

The results of careful data acquisition and processing appear to be very good for this survey. Figure 10 shows a map of the results for all 8 wells. The vector summed amplitude display shows the variable fracture azimuths over the survey area, which were derived from source mechanisms, and the color indicates the intensity of the recorded events. The strong red blobs at
the toe of each well and to the south of the southern-most well appear to be fluid effects associated with the hydraulic stimulation.

Figure 10: Summed amplitude map of the final event locations and source mechanisms. The red blob at the toe of each well indicates a fluid-related event at that location. The three distinct blobs at the bottom of the map indicate fluid-related events associated with a neighboring well. Most other events are double-couple events, indicating a complex fracture network.

Conclusions

We have shown that it is possible to obtain good results from passive microseismic monitoring of a hydraulic fracture operation in a noisy area, so long as careful procedures are followed in the field and in processing to allow for attenuation of the noise that will inevitably be recorded on such a survey. The use of a patch acquisition geometry and the noise attenuation processing that takes advantage of that geometry have allowed microseismic events to be identified, source mechanisms to be extracted and accurate event locations to be determined in a challenging survey area.

References

