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Felt Seismicity Related to Hydraulic Fracturing

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Summary

Hydraulic fracturing is well known to generate seismic events, most of these events are very small magnitude and are of great use when recorded by a properly calibrated array of geophones to delineate the geometry or the fractures and in other microseismic monitoring applications. However, there have been increasing numbers of reports of larger magnitude seismicity. In this presentation, we discuss the instrumentation aspects of properly recording and these larger magnitude events. We discuss a case study where seismicity was recorded by a near-surface network of 4.5 Hz geophones and force-balanced accelerometers that corresponded to events up to moment magnitudes of 3, large enough to both be felt on surface and to be recorded by distance regional seismic stations up to 100 km away. These events are also accompanied by hundreds of events seen on the near-surface network with magnitudes between 1 and 3.

The presence of these events has implications for previous microseismic studies where generally high-frequency (15Hz) geophones are employed to derive the locations. In these cases, the magnitudes of large events together with parameters like the radius of the rupture, will be systematically underestimated. Therefore, this saturation effect will cause a general mis-estimation of the discrete fracture network activated during the fracture. Events that may appear isolated below zone, if they are large enough, can have size dimensions in the range of hundreds of meters to kilometers. Features of such scales can have dramatic effects on the observed seismicity and so their accurate identification using instruments in the appropriate bandwidth is critical to obtaining an accurate picture of the DFN and the potential for seismic hazard associated with hydraulic fracturing.

Introduction

Hydraulic fracturing is well-known to induce microseismicity, and a significant amount of effort has been made in recent years to locate these events, typically as strong as -M1, to infer the trend, height growth, and horizontal extent of the fractures. Answering these first-order geometrical questions is of prime importance to understand the effectiveness of the fracture design. Higher-order questions can also be addressed: are fault being activated? what are the sizes and orientations of the fractures being activated? How does the fracture grow in relations to the injection parameters?

Recent reports of relatively large >M1 event during hydraulic fracturing, such as in Lancashire, UK (Green et al., 2012) or in Oklahoma (Holland, 2011) have introduced a need to understand how these events are generated. Unfortunately, in both these cases, the nearest seismic stations were 10s of kilometers away from the injections and the resulting locations from these stations do not have the appropriate resolution to unambiguously associate these events with the injection wells. Complicating this picture is the apparent dearth of large magnitude events as reported by Warpinski et al. (2012), as reported using signals from downhole arrays. Surface arrays methods, however, do frequently observe some signals, even on unstacked data (Duncan et al., 2010) and the moment mangitudes for these events to be generally observed on unstacked data will necessarily need to be relatively large.

These contradiction highlights the need for appropriate monitoring arrays to be employed to capture the large magnitude seismic signals associated with hydraulic fracturing. Most seismic monitoring of hydraulic fractures uses instrumentation tuned to the microseismic events, that is 15 Hz geophones with flat responses in over the expected frequencies for events between –M4 and –M1. However, larger events will have corner frequencies that can be well below 15 Hz resulting in a underestimation of the observed magnitudes (Viegas et al, 2012). Only by deploying sensors more appropriate for larger magnitude events, such as 4.5 Hz geophone (or lower) and force-balanced accelerometers can such events be accurately characterized. However, because of the strength of the events necessary to register such large magnitudes, sensors deployed on the surface over the treatment should be able to observe such events without an additional processing to improve signal quality, such as stacking.

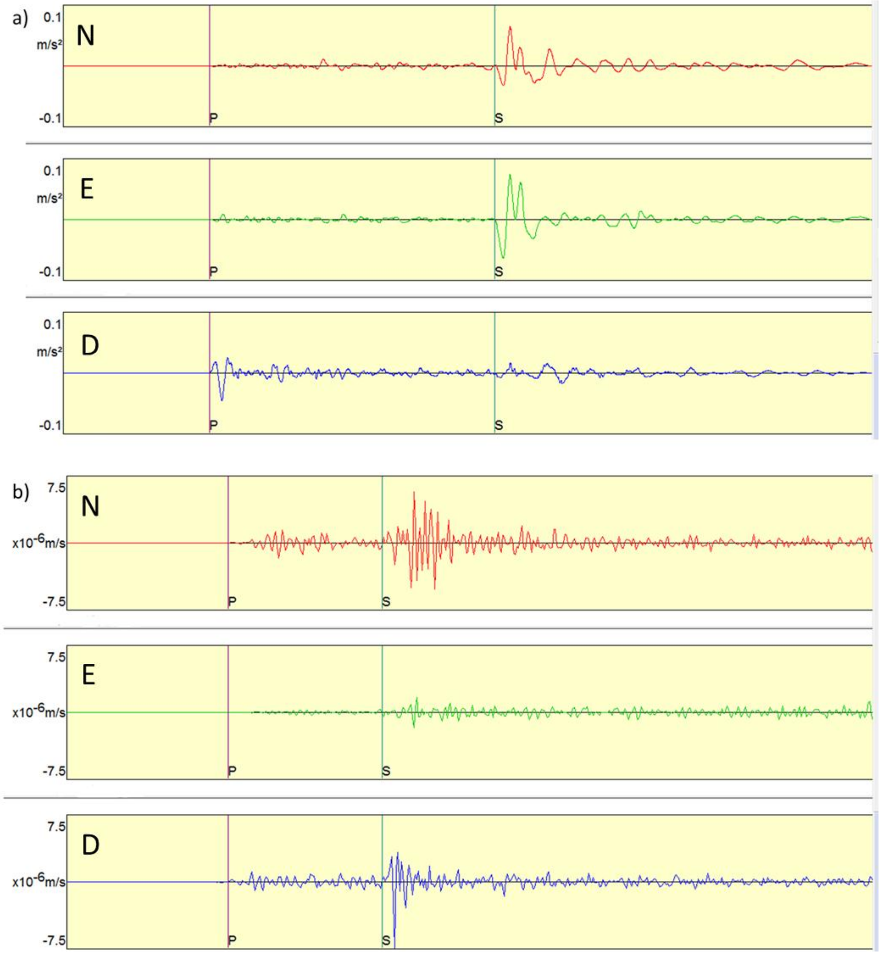

Figure 1. Three component waveforms of the largest magnitude event in the dataset from a) a regional station around 100 km away (15 second long window) and b) an FBA deployed above the treatment zone (4 seconds long window). For both screen captures, the traces are in order of Northing, Easting, Depth. Note that the regional station is measuring velocity while the FBA is recording acceleration.

Case Study: Hydraulic Fracture Related Events Detected Locally and on National Networks

For this example, we document large events detected with a surface network of 4.5 Hz geophones and Force-Balanced Accelerometers. Two of these events reached magnitudes close to M3, and were strong enough to be seen on a regional seismic station around 100 km away from the treatment site. The regional network can only locate such events to accuracies of 10 km or better, which is insufficient to be able to distinguish whether such events are occurring on pad or off pad, let alone answer critical questions on the depth of the events (are they in zone, above zone, or below zone?) and other spatio-temporal relationships to the completion program. A local array of 4.5 Hz geophones and FBAs was in place, however, providing enough resolution to answer these questions. Furthermore, given the anecdotal reports of these events being felt on surface, the surface accelerations could be sufficient to begin to affect equipment on the frac site. In this case, it is necessary to gain a quantification of the peak ground accelerations that can be experienced.

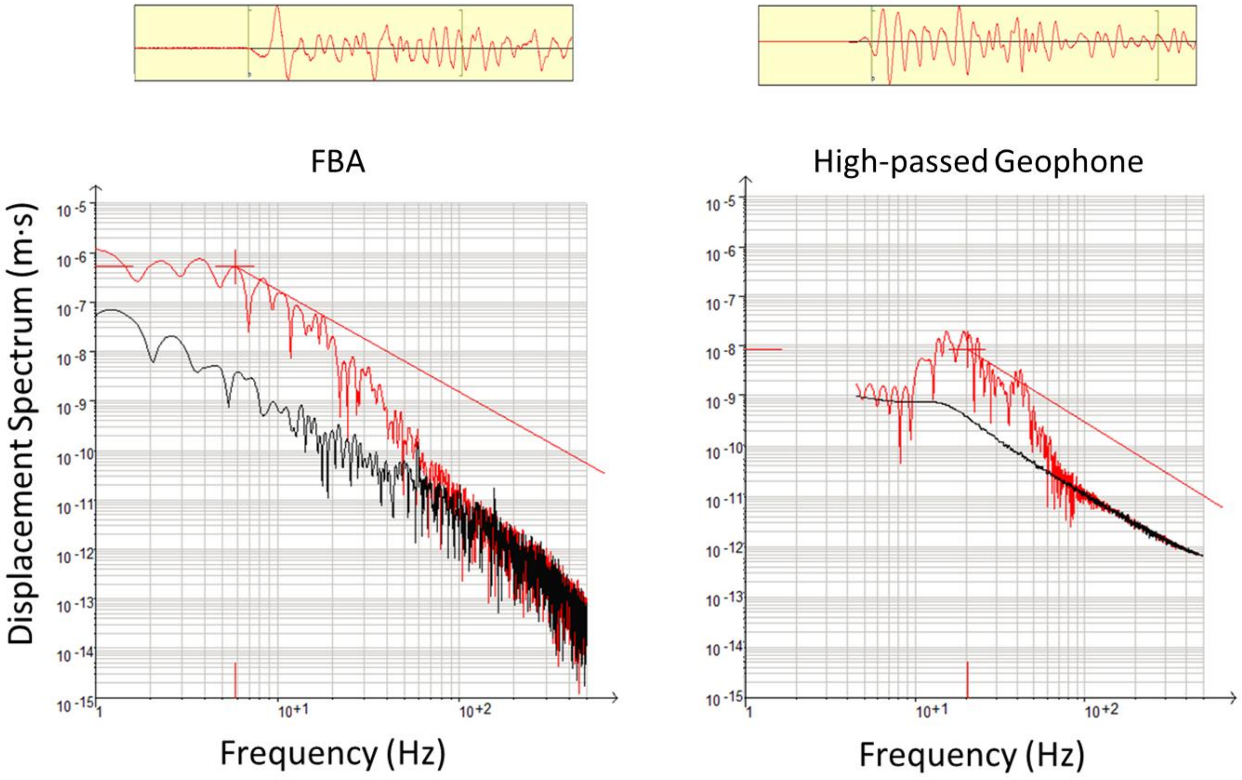

Figure 2. (left) The waveform (above) and displacement spectrum (below) of the Mw2.9 event follows the classical (Brune) profile with a corner frequency around 6 Hz. (right) To simulate the signals seen on the typical 15 Hz geophones usually deployed for microseismic monitoring, the signal from one of the 4.5 Hz geophones is highpass filtered (Butterworth taper) with a 15 Hz corner. The wavefrom and spectrum are displayed above and below respectively. The low frequency plateau estimated from such a saturated signal is well below the actual low-frequency plateau faithfully recorded by the FBA (10^{-8} m·s as compared to 10^{-6} m·s).

Two relatively large magnitude events occurred within close proximity of a hydraulic fracture completion on two consecutive days subsequently followed by hundreds of smaller events with M>0. The signals from these larger events are shown in Figure 1a from a relatively close-by broadband station (around 100 km from site). These signals were simultaneously recorded on a 5-station network of 4.5 Hz geophones and FBAs and the signal from one of these FBAs is shown in Figure 1b. Each station consists of three, three-component sensors deployed in a wellbore. Two 4.5 Hz phones are deployed at

25 m and 30 m depth, while the FBA sits closer to the surface at about 5m depth. The continuous data is sent from these phones to a central computer and are analyzed for potential triggers using an STA/LTA methodology, and then sent to an analyst for further interpretation.

The acceleration signals from the FBA and shown in Figure 1b for the largest events show peak values reaching about 10 cm/s^2. The modified Mercalli scale (see Wald et al., 1999) relates these measures of the acceleration to the perceptions of people on the surface. The fact that this value for peak acceleration is observed lends credence to reports of these largest events being felt on surface, as these values for acceleration fall into the weak range that nevertheless should be felt.

On the left of Figure 2, we show the spectrum of one of the largest magnitude event in the dataset as recorded on one of the FBAs. The corner frequency for this event is around 5 Hz and therefore the spectrum is only reliably recorded on the FBA. This estimate for the event corner frequency indicates that the size of the fault being activated is of a radius of 200m-300m. Although events are locating below the treatment zone would suggest that they are being activated by stress transfer from the treatment, their dimension (up to .4-.6km) suggest there could be fluid pathways between the reservoir and the surrounding formations.

The illustrate the effect of magnitude saturation with a typical downhole geophone, we apply a highpass (15 Hz corner frequency) Butterworth filter to one of the 4.5 Hz geophone signals in the same well as the FBA highlighted on the left of Figure 2. Because the axes in both spectral plots are the same, one can immediately observe how much smaller the spectral plateau is for this signal plotted on the right of Figure 2. Therefore, without the lower-frequency component to the spectra, the magnitudes that are computed from the values of the low-frequency plateau of these signals will be completely underestimated. In this case, there is a full magnitude unit of underestimation observed for this signal. Perhaps more importantly, the signals in the time domain (above) are distorted relative to the clean discrete arrivals observed for the unfiltered low-frequency signals for the FBAs. One can conjecture that were signals observed in the time domain as in such events could be ignored as they would not be recognized as events that could be located.

As mentioned above, during the completion of the pad, not only were the two events at regional distances felt, but numerous other events were picked up by the local array with M>0. These events are depicted in plan view on the left of figure 3 with the well pad and surface stations shown for reference, and they are coloured by elapsed time and their size scale corresponds to their moment magnitudes. In order for a location to be determined, the event needs to be strong enough to be detected across the five stations. The colourscale reveals that these events are following the well pad up the well to the heels over the days taken for the completion to be pumped. A depth view is shown on the right of Figure 3. These large events appear to be located beneath the wells and the target formations, suggesting the locations of the events tend to fall along two main trends, the early events follow a trend roughly 30° from S_{Hmax} and the later events follow a lineation approximately parallel to S_{Hmax}. In addition, there is another cluster of events, spatially located between the two linear distributions. The distribution of the first cluster of events is optimally oriented to slip given the direction of S_{Hmax}. The second linear cluster is in good agreement with the expected event trend, if the regional stress were controlling the overall event distribution. Furthermore, the trend of these locations with time is following the treatment program, earliest events are towards the toes of the wells, and the events drift towards the heels with time, reflecting the completion.

Discussion

We have detailed an example of relatively large magnitude seismicity begin associated with hydraulic fracture operations. For the example discussed, we hypothesize that the large events observed are activating larger, fault-scale features beneath the treatment formation that are optimally oriented to slip in the stress field in which the events are occurring. The recorded waveform peak values are in accord with the reports of these events being felt on surface.

The recognition that events generated during hydraulic fractures can have the potential to be felt on surface is important for a number of reasons. From a perspective of due diligence, such events need to be as accurately characterized in terms of location and source parameters as possible (including magnitudes, but also source radii). The public concern about connections from the treatment zone to groundwater aquifers can be answered with these data. From the perspective of fault activation, often this is an undesirable consequence of hydraulic stimulation if these faults provide pathways for fluid to escape formation. Again, being able to position these faults with respect to the reservoir stimulation is of prime concern. Finally, if these events are generating ground motions large enough to be felt on surface, there needs to be an assessment of seismic hazard on site to answer questions about where shaking may be most intense and to what standards equipment needs to be built to withstand such motion.

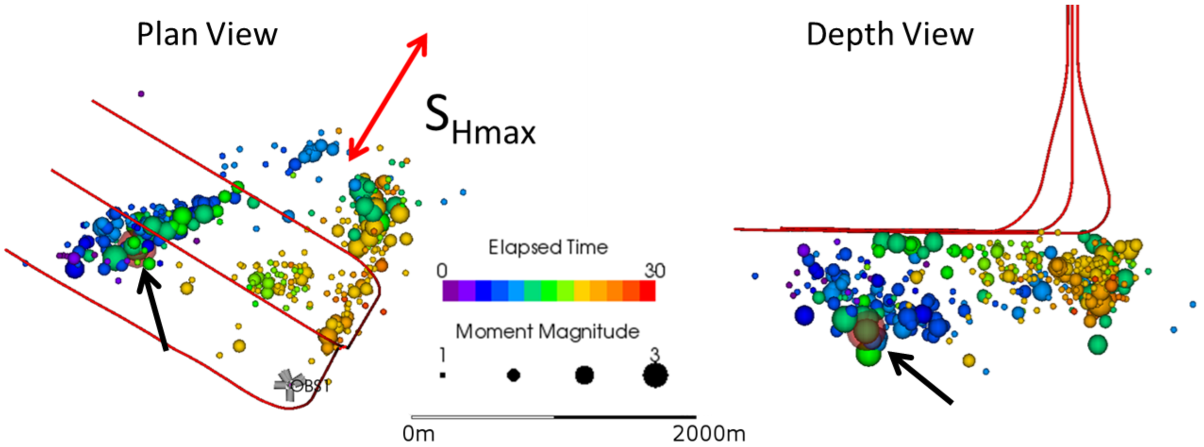

Figure 3 (left) Plan view and (right) depth view of the event distribution over the pad where the events are coloured by elapsed time and the size scale corresponds to moment magnitude. There is a black arrow in both views pointing to the event shown in Figure 1. One of the five observation stations is depicted in the plan view and the direction of S_{Hmax} is also noted.

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