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Rupture Characteristics of Hydraulic Fracture Induced-Triggered Seismicity

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Summary

Through the use of a unique hybrid seismic recording network, we investigate the rupture characteristics of induced-triggered events with M>0 associated with a hydraulic fracture stimulation in an unconventional reservoir. This unique approach incorporates high-frequency recordings utilizing downhole 3C 15 Hz omni-directional geophones situated in close proximity to the reservoir and thereby the point of rupture initiation, intermediate-depth downhole 3C Force Balance Accelerometers (0.1Hz) and geophones (4.5Hz), and near-surface, low-frequency 3C recordings obtained using Force Balance Accelerometers (0.1Hz) and geophones (1 Hz, 2Hz and 4.5Hz) that allowed for the investigation of overall rupture characteristics within the frequency bandwidth of effectively 0.1Hz to over 500Hz. For these larger induced events, the recordings allowed for an in-depth investigation of the dynamics of the sub-fracture failures during the rupture process and growth of the overall fracture from initiation to rupture arrest. More specifically, we were able to examine different aspects of the rupture processes, including the role of asperities, roughness, the role of fluids and the failure mechanisms (shearing versus tensile dominance of behavior) associated with these induced-triggered events and their sub-events. Our initial results suggests that overall shearing is the dominant mode of failure, whereas the rupture characteristics of the sub-fracture failures are more complex than a simple shearing process and include a strong tensile component of failure. Our measurements of rupture complexity, seismic efficiency, rupture velocity and estimates of stress release further support the idea that the sub-fractures are characterized by the failure of multiple asperities that exhibit self-similar behavior within themselves. These observations are part of ongoing investigations that may allow for the assessment of conditions under which induced-triggered failures may occur.

Analysis

In general, most hydraulic fracture stimulations are monitored utilizing only high-frequency sensors situated near reservoir depth. More recently, public concerns have resulted in the deployment of low-frequency sensors close to the surface. Rarely has an integrated approach been taken to record the failure processes by combining these two sensor configurations along. In this study, these data have been combined along with an intermediate depth distribution of sensors thereby providing a signal spectrum that covers not only the overall rupture process associated with recorded induced events but the sub-processes of the rupture associated with the rupture process. As shown in Figure 1, signals recorded on a high-frequency sensor for an event with M>0. As observed, the rupture process consists of three distinct slip phases, each representing the failure of different patches on a larger slip surface. Also shown in Figure 1 are the displacement spectra for the three phases. It is evident that the size distribution varies suggesting variable patch sizes or asperities that fail as part of a larger fault or fracture surface.

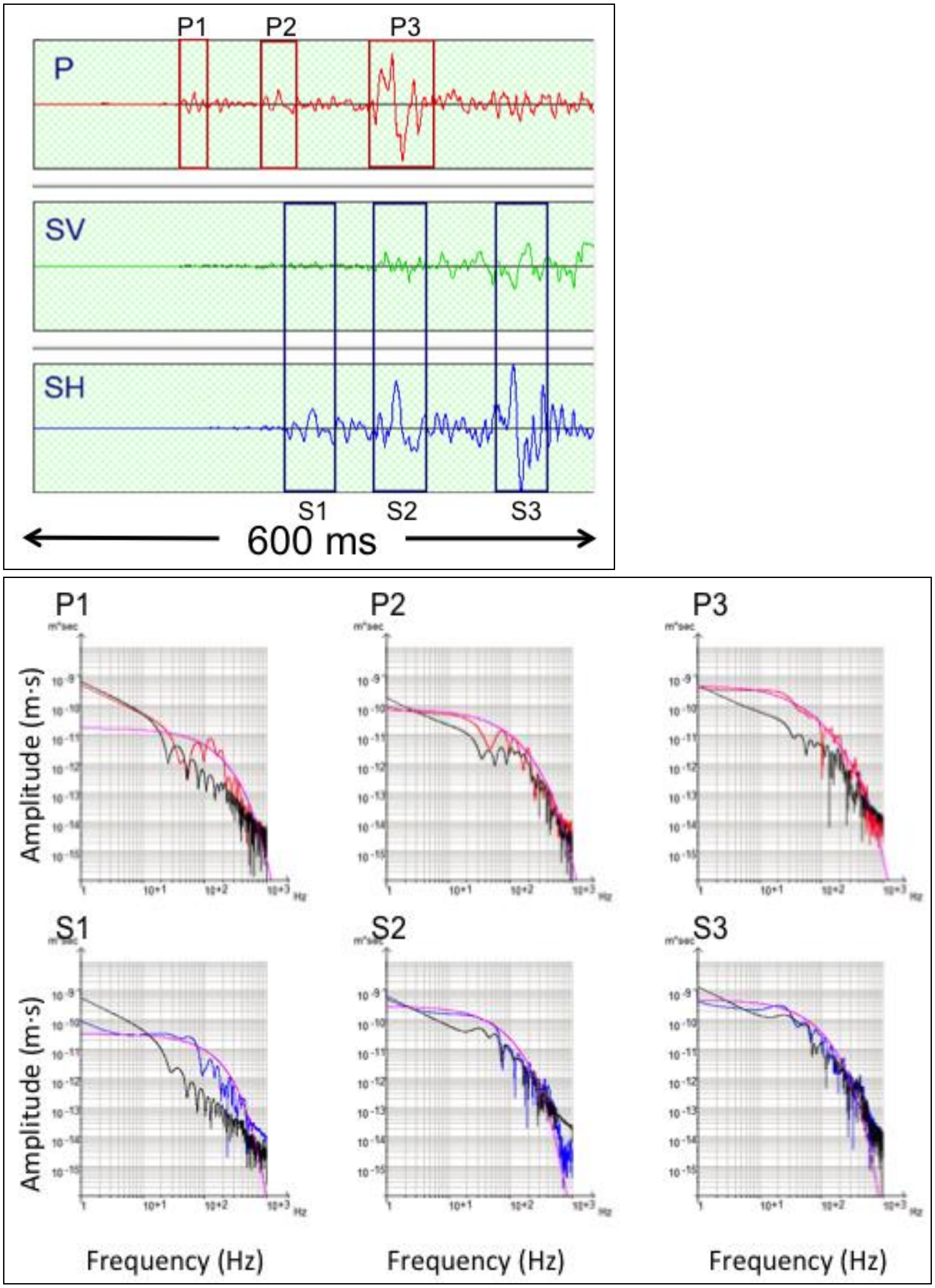

Figure 1. Rotated waveforms as recorded on a high-frequency sensor situated close to the reservoir. The observed event consists of three sub-events with P (1,2,3) and S (1,2,3) wave groups. Also provided are the displacement spectra for the observed wave groups along with the associated event noise spectra. Spectra have been fit utilizing a Brune model where the plateau represents the relative strength of the sub-events and the corner frequency is as determined from the intersection of the asymptote corrected for attenuation (Q=75) and is used to assess the relative dimensions of the sub-rupture surfaces based on a penny-shaped model of crack failure.

Additionally, as shown in Figure 2, the overall rupture process was recorded with the near surface low-frequency sensors. As in Figure 1, both the signals and spectra are shown, in this case for the S-wave. As observed the signals suggest a rather simple rupture process, suggesting a singular rupture with overall dimensions larger than the observed sub-rupture failures associated with the sub-events, The magnitude as observed of the overall rupture is significantly larger than that observed for the sub-events.

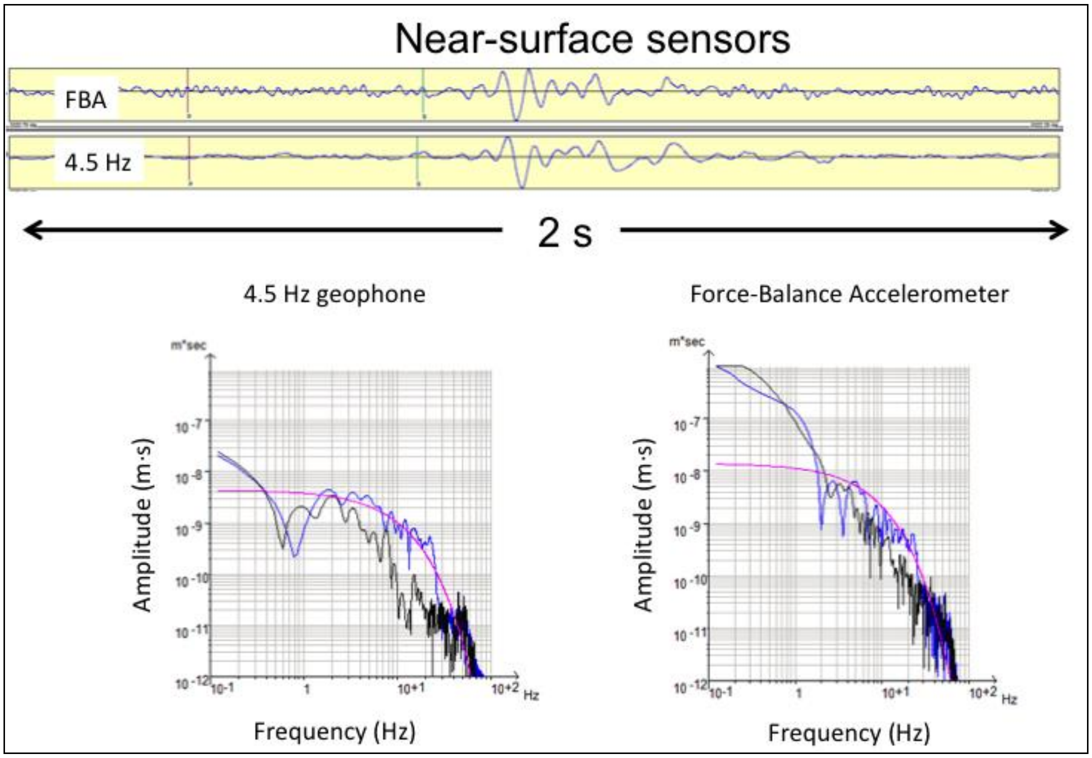

Figure 2. Rotated waveforms as recorded on low-frequency sensors situated close to the surface. The observed event appears as a singular event thereby representing the overall rupture process. Also provided are the displacement spectra for the observed SH wave along with the noise. Spectra have been fit utilizing a Brune model where the plateau represents the relative strength of the sub-events and the corner frequency is as determined from the intersection of the asymptote corrected for attenuation (Q=30) and is used to assess the relative dimensions of the sub-rupture surfaces based on a penny-shaped model of crack failure.

Considering that the surface-deployed geophones are receiving clear signals from reservoir depths of approximately 2.5 km, this apparently discrete event on the surface represents a relatively large magnitude event during the completion, with a (moment) magnitude of 0.7 and a source radius of approximately 20 m based on the corner frequency of the spectrum. The downhole data, observed on 15 Hz geophones, considering the largest sub event nonetheless seem much smaller, with an apparent magnitude of 0. Despite the fact that we correct for the instrument response of these phones, the saturation of these instruments prevents the correct estimation of magnitude.

Summary

This study is part of on-going work looking at the rupture characteristics of hydraulic fracture stimulation induced events with M>0. Additional materials will be presented on our examination of the different aspects of the rupture processes, including the role of asperities, roughness, the role of fluids and the failure mechanisms (shearing versus tensile dominance of behavior) associated with these induced-triggered events and their sub-events. Although preliminary, our initial results suggest that overall shearing is the dominant mode of failure, whereas the rupture characteristics of the sub-fracture failures are more complex than a simple shearing process and include a strong tensile component of failure. Measurements of rupture complexity, seismic efficiency, rupture velocity and estimates of stress release further also support the idea that the sub-fractures are characterized by the failure of multiple asperities that exhibit self-similar behavior within themselves.