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Are Source Characteristics of Fluid Driven Hydraulic Fracture Induced Earthquakes Distinct from Natural Tectonic Earthquakes?

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Summary

We investigate source and failure properties of -M3 to M1 earthquakes recorded during a hydraulic fracturing stimulation of a shale reservoir in NE British Columbia, Canada, looking for signals of characteristic ruptures indicative of fluid flow or stress transfer. In this case study two distinct types of events have been identified: events smaller than M0, which are generally located within the stimulated reservoir; and events larger than M0 which are associated with slip on pre-existing geological features underneath the reservoir. The comparison of a suit of static and dynamic source parameters indicates a distinct signature between the two event types associated to two distinct failure processes. Deeper and positive magnitude earthquakes have slightly higher static and dynamic stress drops and energy than the reservoir earthquakes, reflecting harder rock types and higher confining stresses, but also suggesting the release of stored strain energy within the fault zone. These induced events release in general less stress and energy than natural occurring tectonic earthquakes of comparable size at similar depths. Considering the ample discussion regarding the existence of cause-effect relationship between fluid injection programs and nearby deeper earthquakes this study suggests that source parameters can be used as a discriminant factor between the two types of earthquakes.

Introduction

Rock properties, local stress and pore pressure conditions and external-driving forces dictate the failure response of a rock to an applied stimulus. Once the characteristic response of a rock type to a specific stimulus is understood in terms of earthquake source parameters and failure mechanism, these can be used to distinguish seismic events between different areas of the reservoir. For example, Muskwa shale is more brittle than Keg River limestone, that is, the shale can sustain less forcing stressess before failing, resulting is seismic fractures with low stress drops. Another example, some formations in the reservoir may be over-pressured in their natural state, needing only a small increase in stress to fail. This will result in a larger density of fractures per unit volume in that formation when compared with other formations.

In the rupture process the energy release is partitioned into different physical processes such as fracture energy, frictional energy and radiated energy. The different energies relative ratios are changed by the presence of fluids or rotations in the local stress field with relation to the frictional resistance in the fracture plane. Fractures occurring in the same host rock under the same stress conditions are expected to rupture similarly, independent of their size (self-similarity). Changes in the scaling relationships of fractures are indicative of a change in the failure process, host rock or in-situ stress. Correlation of failure process data with reservoir rock properties and in-situ stress field will help identify regions within the reservoir with characteristic types of failures.

In this case study we are interested in determining the source and failure characteristics between induced reservoir events, induced deep under reservoir events and natural tectonic events. We are also interested in characterizing failure under hydrostatic conditions and higher pore pressure conditions. During hydraulic stimulations pressurized fluids propagate through existing and newly generated fractures changing the local stress field. An effect of stress transfer to nearby regions (loading or un-loading) also occurs, but in this case there will not be a fluid signature in the source/failure process.

Horn River Basin Stimulation Program

More than 30,000 earthquakes with magnitudes ranging from -M3 to M1 were recorded during a hydraulic fracturing stimulation of a shale reservoir at the Horn River Basin in NE British Columbia, Canada. This multi-well zipper-frac completion program was monitored using a hybrid system of (1) multi-arrays of high frequency three component geophones deployed in wells next to the reservoir and of (2) a sparse network of near-surface lower frequency three component sensors. The hybrid system assures the necessary bandwidth is available to accurately estimate source characteristics of the induced earthquakes which span a broad magnitude range. In this dataset events with M < 0 generally locate within the stimulated reservoir whereas events with M > 0 tend to be associated with slip on pre-existing features below the reservoir. Figure 1 illustrates the seismicity depth distribution in a section of the reservoir where larger deeper events were detected.

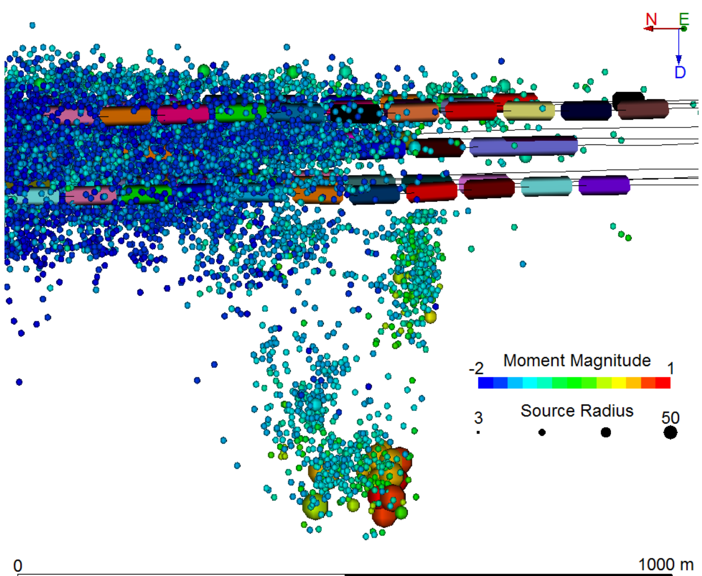

Figure 1. Cross-section of part of of the reservoir showing seismicity recorded during the completion program. The seismic events are colored by Moment Magnitude and scaled by fracture diameter. Besides typical reservoir seismicity it is also observed deeper and larger magnitude seismicity associated with reactivation of larger geological structures below the treatment formations. Horizontal wells (black lines) and perforation stages (colored cilinders) are also shown.

Source Parameters and Energy Budget

We calculate a suite of static and dynamic source parameters such as dynamic and static stress drop, radiated energy, seismic efficiency, moment tensor solutions, fracture plane orientation, slip direction and rupture velocity, and their energy budget looking for similarities and differences between deep and reservoir events. On average, the reservoir induced events had low static and dynamic stress drops, apparent stress, radiated energy and seismic efficiency, and had shear-tensile mechanisms varying between dominant tensile closing and tensile opening, and slip on fault planes with orientations dominated by the rock fabric and not always optimally oriented to the regional stress field. These source characteristics are expected for events driven by increased pore pressure, reduced fault friction due to fluid lubrication and decrease of contact areas, and slow rupture velocities for un-favorably oriented slip-fracture planes. Figure 2 shows the difference in source parameters of deep and reservoir events occurring during the same treatment stage. Deeper and positive magnitude earthquakes have slightly higher static and dynamic stress drops and energy than the reservoir earthquakes, reflecting more competent rock and higher confining stresses at depth, and also suggesting the release of stored strain energy within the fault zone.

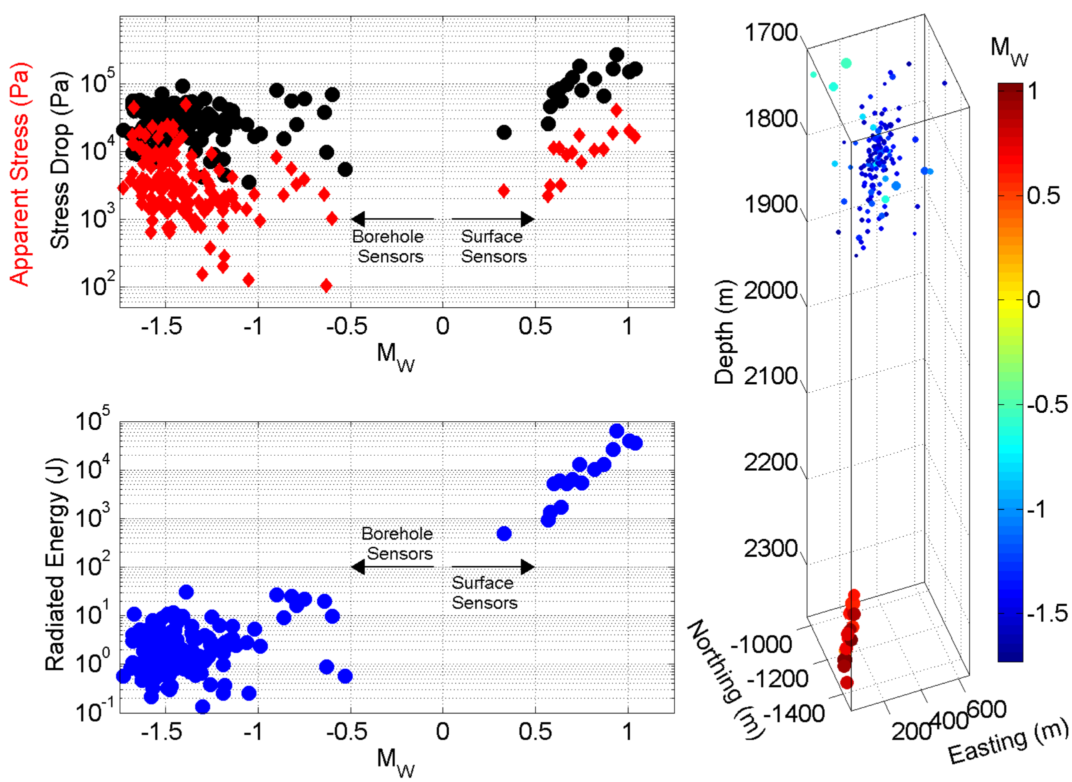

Figure 2. Source parameters of selected seismic events from one stage. The left panel shows the spatial distribution of these events, which are color coded by magnitude and scale by fracture diameter. >M0 events are located deeper and have strong enough signal to be recorded by the near-surface network whereas <M0 events are located in the reservoir and are only recorded by the borehole arrays. Deeper events have on average higher stress drop and apparent stress (top left panel) and radiate more energy (bottom left panel).

These induced events release in general less stress and energy than natural occurring tectonic earthquakes of comparable size at similar depths (Figure 3). Considering the ample discussion regarding the existence of cause-effect relationship between fluid injection programs and nearby deeper earthquakes this study suggests that source parameters can be used as a discriminant factor between the two types of earthquakes.

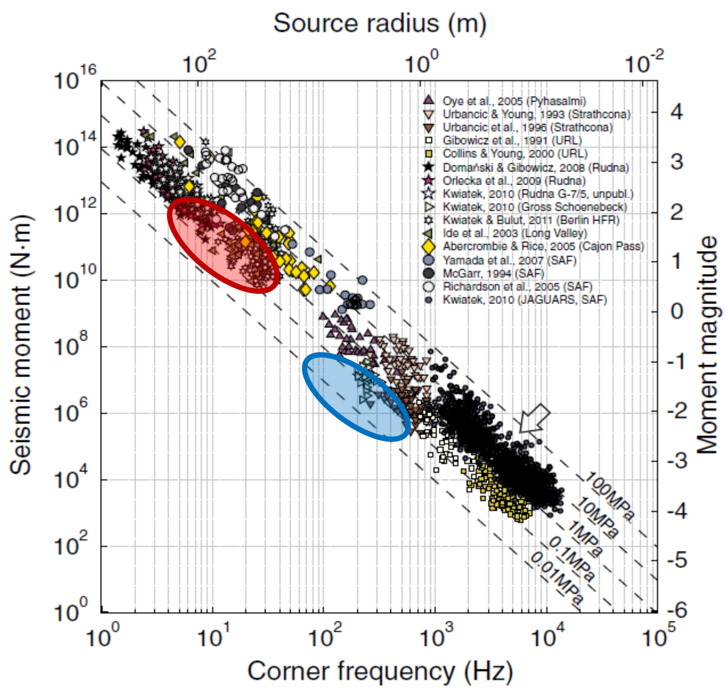

Figure 3. Scaling relations. The two color elipses show the overal average distribution of fracture length versus event strength of the deep (red) and reservoir (blue) induced events by hydraulic fracturing relative to other induced seismicity (for example mining) and natural occuring earthquakes (Kwaitek et al., 2010). The dashed lines indicate constant stress drop trends for which seismic events scale linearly with size. In terms of stress drop trends, hydraulically induced deep events (red) are in the lower end of stress drop (0.1 MPa) relative to other type of events, and reservoir events have much lower stress drops (0.02 MPa).

Conclusions

We investigated the source properties of earthquakes (-M3 < M1) associated with hydraulic fracture stimulations of a shale reservoir in NE British Columbia, Canada. Events with M < 0 generally were located within the stimulated reservoir whereas events with M > 0 were generally associated with slip on pre-existing features below the reservoir. On average, events located below the reservoir were generally larger in magnitude, had higher static and dynamic stress drops, and energy than the reservoir events. This not only reflects the higher confining stresses but also potentially the release of stored strain energy within the fault zone. In general, these deeper events release more stress and energy than the reservoir induced events and are dominated by shear failures, however, the observed source characteristics are smaller than for natural occurring tectonic earthquakes of comparable size. Considering the cause-effect relationship between fluid injection programs and nearby deeper earthquakes our study suggests that source parameters can be used to discriminate between fluid induced and stress induced failures associated with hydraulic fracture stimulations.

References

Kwiatek, G., Plenkers, K., Nakatani, M., Yabe, Y., Dresen, G., and JAGUARS-Group (2010) Frequency-magnitude characteristics down to magnitude -4.4 for induced seismicity recorded at Mponeng gold mine, South Africa, Bull. Seismol. Soc. Am. 100, 1165–1173.