Implications of long-lived post-injection induced seismicity near Fox Creek, Alberta

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Summary

Seismicity with moment magnitudes (M_w) of up to 4.1 has been observed since late 2013 close to the town of Fox Creek, Alberta (Canada). This induced seismicity has been correlated with hydraulic-fracturing (HF) operations in the area. This study analyses regional seismic data recorded from November 2015 to March 2016. During this period, seismic activity occurred within five main clusters located near distinct HF operations. Three of these clusters were short-lived, diminishing in intensity quickly after the end of HF operations; however, the remaining two exhibited unusual long-lived seismicity that continued beyond the treatment period and persisted for at least several months. Cluster 1 contained a M_w 4.1 induced event along a north-south fault that is well oriented with respect to the regional stress field. The persistence of this cluster can be explained as a long-lived aftershock sequence. However, cluster 2 was more swarm-like in character, lacking any mainshock event and containing no events with $M_w \geq 2.0$. The swarm-like behavior of cluster 2 resumed and intensified after the M_w 4.1 event in cluster 1, suggesting delayed dynamic triggering. Downhole microseismic data at cluster 2 reveal a series of lineaments with a NW-SE strike direction that is mis-oriented for dynamic rupture in the regional stress field. Moreover, prior to swarm intensification, microseismicity started to penetrate into the formation below the reservoir along inferred, pre-existing faults and/or fractures in the underlying formation. Two possible hypotheses for the generation of this swarm are elevated pore pressure trapped within a fault(s), or slow aseismic slip within adjacent stable strata, both of which can also explain the potential delayed dynamic triggering. Differences in the responses of clusters 1 and 2 (i.e. mainshock-aftershock versus swarm-like) may also be linked to whether the activated fault is optimally oriented for slip in the present stress field. This study illustrates the usefulness of using both microseismic monitoring and regional networks to help interpret the processes involved in induced seismicity.

Method

The aim of this study is to investigate contrasting observed behaviors of induced seismic swarms caused by HF targeting the Duvernay formation in the Fox Creek region, central Alberta. It focuses on the time-period between November 2015 to March 2016. During this time, a large number of seismic events were observed on regional networks, including a M_w 4.1 event, the largest induced event to be recorded in Alberta to date (Schultz et al., 2016; Wang et al., 2017). The regional data are analysed to investigate spatial and temporal patterns. Then, microseismic data from the treatments associated with long-lived seismicity are studied to determine possible reasons for their unusual behavior.

Induced seismicity monitoring was performed using 11 broadband stations in the region. Events recorded by this regional network are shown in Figure 1. The locations of wells targeting the Duvernay formation are also plotted. It is evident that the seismicity in the region during this time-period clustered around individual horizontal HF treatment wells. Five individual clusters of events have been highlighted and numbered. They mostly appear to form a band from west to south of the town of Fox Creek. Cluster 1 included the M_w 4.1 event, the timing of which (on 12 January) has been highlighted in red in the colored time scale. Event magnitudes versus time are plotted in Figure 2. Clusters 3-5 were short-lived, and their timing is correlate with adjacent treatments, as would be expected for HF induced seismicity. However, clusters 1 and 2 showed much longer-lived seismicity, with ongoing activity for periods of months and continuing beyond the end of the monitoring period. Cluster 1 showed a dense cloud of seismicity before and shortly after the M_w 4.1 event; this intense activity is correlated to the injection time of the associated treatment, which was active from 4 January to 12 January 2016. Cluster 2 exhibited a short-lived cluster of events at the end of 2015, which correlated in time with the treatments of two horizontal wells at the east of the cluster. The second (long-lived) cluster began on 12 January 2016. Resumed activity for this cluster coincided with the occurrence of the M_w 4.1 event in cluster 1, despite the associated treatments beginning at an earlier time on 3 January 2016. This timing suggests that there may be some causal relationship between the M_w 4.1 event and the resumption of seismicity in cluster 2. Estimated Gutenberg-Richter *b*-values for the clusters are very different: ~ 1.5 for cluster 1 and ~ 3.3 for cluster 2 (Figure 2).

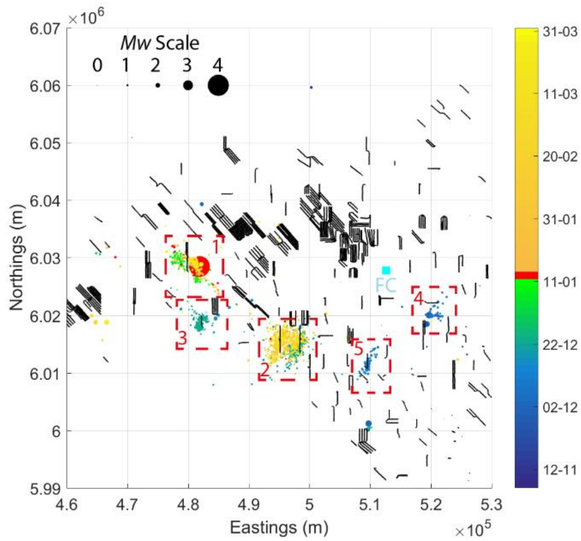

Figure 1: Source locations for induced seismic events from regional monitoring, colored by date (dd-mm) and scaled by magnitude. Numbered boxes around individual clusters of seismicity are referred to in the text. Box 1 shows seismicity for treatment associated with the Mw 4.1 event, and time of the Mw 4.1 event is highlighted in red. Black lines show locations of wells targeting the Duvernay formation, and the town of Fox Creek (FC) is indicated (cyan).

The unusual long-lived seismicity at clusters 1 and 2 warrants further investigation. Although the monitoring periods are much shorter than that of the regional network, microseismic monitoring datasets for the treatments associated with each cluster provide further insights into details of the seismicity. The microseismic monitoring dataset associated with the events in cluster 1 is discussed in Eyre et al. (2018a). The treatment activated a nearby set of N-S to NNE-SSW striking strike-slip faults. After the M_w 4.1 event occurred, abundant seismicity was recorded, located in two vertical planar clusters which appear to be part of the fault system on which the M_w 4.1 event nucleated and is therefore interpreted as aftershocks of the main event. The events after the M_w 4.1 event can be fit with an Omori (1894) decay curve, which describes how typically the frequency of aftershocks decreases roughly with the reciprocal of time after the main shock. This suggests that the long-lived seismicity is indeed caused by the mainshock.

A microseismic dataset was also collected during the HF treatment of two N-S horizontal wells associated with the cluster 2 seismicity. A second pair of horizontal wells was located ~ 3km to the east but were treated at the end of 2015. Microseismic events generally followed the typical patterns expected for microseismic monitoring of a HF treatment, with event clusters for each stage aligning approximately in the direction of maximum horizontal stress (NE-SW). The exceptions were small clusters to the NE of the monitoring well, events located beneath the treatment well, and a cluster west of the heel of the northern well. The events were ongoing when the M_w 4.1 event occurred to the NW and dramatically increased in time (Figure 3), as observed in the regional data. The major increase took place approximately 12 hours after the M_w 4.1 event. Figure 3a shows the evolution of the event depths over time, giving a clearer picture of the progression of events and the relationship to the injection stages and M_w 4.1 event. It is apparent that increases in seismicity especially appeared to coincide with increases in the number of events > 2500 m depth, the approximate depth of the top of the Swan Hills formation.

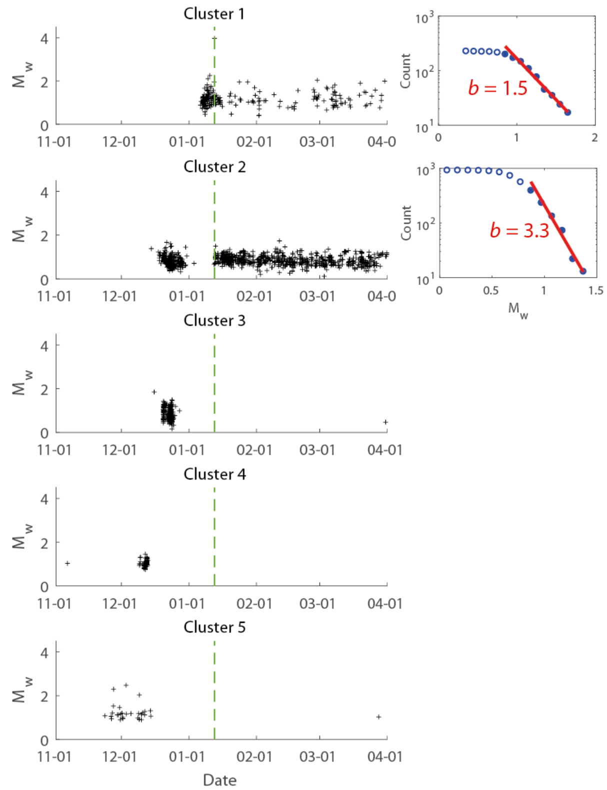

Figure 2: Event magnitudes versus time for the five clusters highlighted in Figure 1. Timing of the Mw 4.1 event is shown by the dashed green line and appears to coincide with the beginning of long-lived swarm-like seismicity in cluster 2. The magnitude-frequency distributions for clusters 1 and 2 are also shown, with estimated *b*-values of 1.5 and 3.3.

Discussion and Conclusion

Seismicity associated with different HF treatments in the Fox Creek region appears to show different characteristics. Some clusters exhibit long-lived seismicity while others are much shorter, spanning times when injections are active. One theory for this behaviour was posed by Bao & Eaton (2016), who suggested that long-lived seismicity is caused by sustained pore pressure changes due to fluid diffusion, whereas short-lived seismicity is caused by stress changes due to the elastic response of the rockmass to HF. However, the short-lived clusters also located very close to the associated treatment wells, suggesting pore pressure communication is likely, and there were also some distinct differences between the two clusters of long-lived seismicity which also need to be explained.

After analysing the data, it is apparent that cluster 1 can be readily explained as a mainshock-aftershock sequence. For cluster 2, the cause of the long-lived seismicity is much less apparent. In this case there is no main shock, and the *b*-value is very high as there are a large number of events within a small magnitude range (limited at the low end by the detection threshold). It is difficult to reconcile what could cause these observations; however, there are two main ideas that we have so far postulated. Firstly, swarms have been convincingly linked to a rise in fluid pressure at seismogenic depths (Raleigh et al., 1976; Daniel et al., 2011; Ake, 2005; Vidale & Shearer, 2006). In the first model, injection causes elevated pore pressure in a fault (or series of faults). However, fluid perturbations might be expected to result in a swarm of seismicity which diminishes rapidly over time (Vidale & Shearer, 2006) especially after injection ceases, due to pore pressure diffusion and fluid leakoff. Therefore to satisfy this model for cluster 2, the fluid must become trapped, resulting in sustained elevated pore pressure, and resulting in a much-accelerated seismic cycle.

A model for trapping fluids in an impermeable fault between earthquakes has been posed by Sibson (1992), who suggests that during dynamic rupture, fault permeability increases, allowing fluids to travel along the fault. Once rupture ceases, these fluids become trapped between impermeable barriers along the faults and between the impermeable fault surfaces. The second model is based on the new model proposed by Eyre et al. (2018b), which suggests that hydraulic-fracturing induced seismicity can be a result of aseismic slip along a pre-existing fault accelerated by the fluid injection. In this case, the swarm-like nature and high *b*-value would be caused by slow aseismic deformation (slow slip). This has been observed at many natural strike-slip fault systems such as the San Andreas fault, California (Roeloffs, 2006; Vidale & Shearer, 2006), where interconnected, vertically stacked creep and dynamic rupture processes occur at separate depths (Roeloffs, 2006). The aseismic creep is hypothesized as the driving process of the observed earthquake swarms (Roland & McGuire, 2009) which have high *b*-values (Vidale & Shearer, 2006).

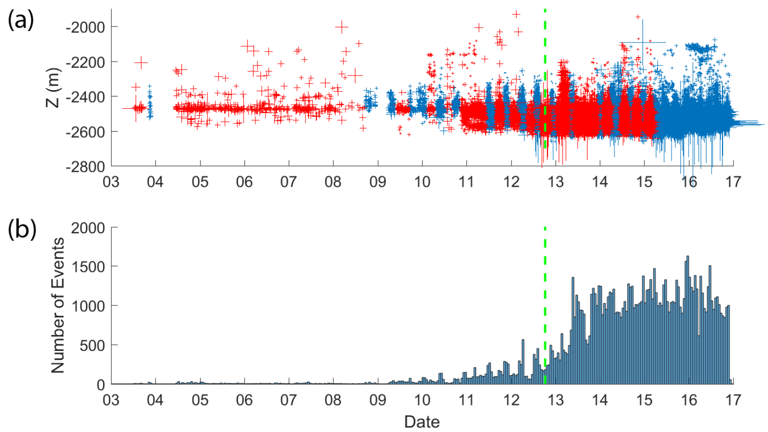

Figure 3: (a) Time versus depth of the microseismic events. Red events occur during treatment of well 4 and blue events occur during treatment of well 3, and events are scaled by magnitude. (b) Number events versus time for the downhole microseismic monitoring. Green dashed line shows the time of the Mw 4.1 event.

The timing of the beginning of the long-lived cluster observed in cluster 2 from the regional data suggests that there may be some causality of the Mw 4.1 event ~ 17 km distant. Two possible mechanisms for this are dynamic triggering or pore-pressure communication. In dynamic triggering, the stress changes caused by the passage of seismic waves can elevate a critically stressed fault to the point of slip initiation (e.g. Hough et al., 2003). However, from the microseismic data it is apparent that there is a delay of approximately 12 hours between the event and the increase in seismicity (Figure 3), which is difficult to explain by dynamic triggering. However, delayed dynamic triggering has been observed in natural environments, and has been explained due to pore pressure diffusion (Wang et al., 2018), triggered creep (Shelly et al., 2011) or a change in fault properties (Parsons, 2005): the first two fit nicely with our two hypotheses for the cause of the long-lived swarm. Pore-pressure communication ("pressure hit") (e.g. Yadav & Motealleh, 2017) between the two regions would require a permeable pathway of regional extent; however, it is unclear whether this mechanism could operate on the time and distance scales that are evident here. It may also be that the timing of resumed seismicity at cluster 2 is coincidental. The increases in seismicity correlate in space and time with active injection stages in the associated treatment wells. Increases in both number and magnitude of events are observed when the seismicity begins to migrate into the Swan Hills formation below the reservoir. This is predominantly carbonate, and therefore more brittle than the shales of the target Duvernay formation.

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