The rise, peak and decline of the induced seismicity related to hydraulic fracturing activities in the Duvernay play, Fox Creek area, Alberta.

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Summary

We analyze the temporal evolution of the induced seismicity related to hydraulic fracturing activities in the Duvernay Fm., near Fox Creek, Alberta. For this analysis, we calculate time-dependent earthquake recurrence parameters, $a(t)$- and $b(t)$- values, which are the base for the probabilistic seismic hazard analysis. From these earthquake recurrence parameters, we calculated the annual likelihood of earthquakes larger than magnitude M>4 from 2014 until 2019. We found that the seismic hazard in Fox Creek has consistently decreased since 2015, from a 95% probability to have an earthquake M>4 in 2015 to a 4% probability in 2019. This contrasts with the peak in the overall number of earthquakes larger than M>2, which occurred in 2017, and the peak in the total volumes and the number of hydraulic fracturing wells per year in the Duvernay Fm., both occurring in 2019. On the other hand, the b-values rapidly increased after 2016, leading to a steady decrease in the likelihood of moderate events. We think that this trend in decreasing seismic hazard, which contrasts with increasing human activity, could be associated with implementation of regulatory instruments (Alberta Energy Regulator, Subsurface Order No. 2), active mitigation strategies implemented by the operators, and avoidance of areas identified to be susceptible to induced seismicity.

1. Introduction: induced seismicity in the Fox Creek area

Induced seismicity related to hydraulic fracturing activity in the Duvernay Fm., near Fox Creek, started in December 2013. Since then, this area has become one of the most seismic active regions of the province, with over 220 events larger than magnitude $M_L > 2.5$ (Schultz et al., 2017). However, most of these events are of minor magnitude, and only four earthquakes correspond to events with a magnitude larger than M > 4.0 (Alberta Geological Survey, 2021), with the largest event occurring in January 2016 ($M_L = 4.8$). The seismic hazard caused by induced seismicity could be higher than the natural seismic hazard, especially in areas with small-to-moderate natural background seismicity, like Fox Creek. To address these concerns, since February 2015, operators performing hydraulic fracturing in the Duvernay Fm. are mandated to monitor adjacent seismicity activities during the operations and follow the traffic light protocol (Subsurface Order No. 2, SSO2). Under the traffic light protocol, operators performing hydraulic fracturing activities in the Duvernay Fm. must inform the regulator of any event larger than M>2 (yellow-light event threshold), as well as actively implement mitigation strategies. If a red-light event occurs (M>4), the operator must cease operations immediately (Alberta Energy Regulator, 2015).

In this study, we analyze the temporal evolution of the seismic hazard in Fox Creek, expressed in the annual likelihood of moderate events with a magnitude larger than M>4 (red-light earthquakes). To do this, we define time-dependent Gutenberg-Righter parameters, $a(t)$- and $b(t)$- values and calculate the annual likelihood of events M>4 assuming a Poisson distribution.

We found that the seismic hazard in Fox Creek has consistently declined since 2015, from a 95% probability to have an earthquake M>4 in 2015 to a 4% probability in 2019. In contrast, the peak in the number of hydraulic fracturing wells and the total volumes injected into the Duvernay Fm., SSO2 area, occurred in 2019. We think that the consistent decrease in the likelihood of red-light events could be associated with implementation of regulatory instruments (SSO2), and active mitigation strategies applied by the operators.

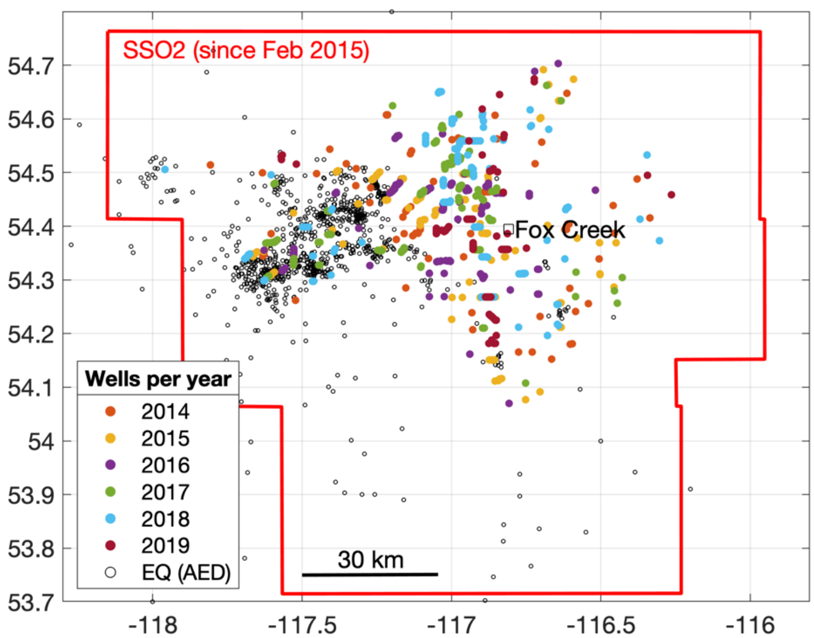

Figure 1. Location map of the wells hydraulic fractured inside the Duvernay Zone designated in the AER's Subsurface Order No. 2 (SSO2, Alberta Energy Regulator, 2015) between 2014 and 2019, and the earthquakes (EQ) reported in the same period in the Alberta Earthquake Dashboard (AED, Alberta Geological Survey, 2021). The Total injected volume of fluid in the same wells is shown in Figure 2.

2. Theory and methods

2.1 Time-dependent Gutenberg-Richter Parameters

To account for non-stationarity seismic sources like induced seismicity, we define time-dependent Gutenberg Richter (GR, Gutenberg and Richter, 1944) parameters, $a(t)$-and $b(t)$-values. To study the temporal evolution of the GR parameters during the period of induced seismicity, we define a moving time window of 1-year duration to screen the catalog. Then, the GR values are assigned to the last month of the time window. This process is repeated by moving the entire time window one month ahead every time until the last month of the catalog has been reached. For the calculation of the GR parameters, we use maximum likelihood methods (MLM, Aki 1965), considering only the earthquakes with magnitude equal to or larger than the magnitude of completeness (Mc). For the estimations of the b-value error, we use the method described by Shi and Bolt (1982). For the estimation of the Mc per year, we perform Maximum curvature methods (MCM, Wiemer and Wyss, 1997).

Reyes Canales and van der Baan (2019) derived analytical expressions required in Probabilistic Seismic Hazard Analysis for non-stationary seismic sources, as well as modifications in the Monte Carlo simulation method to generate non-stationary synthetic earthquake catalogs. Some of the derived non-stationary expressions include the total expected number of earthquakes $N(M_{min} \leq m \leq M_{max}; \mathrm{t})$ per time unit in the range $\mathrm{M} = [M_{min}, M_{max}]$, which is given by:

$$N(M_{min} \leq m \leq M_{max}; \mathrm{t}) = 10^{a(\mathrm{t})-b(\mathrm{t})M_{min}} - 10^{a(\mathrm{t})-b(\mathrm{t})M_{max}}, \text{ (1)},$$

where the $b(t)$-value indicates the ratio of small and large magnitude events, the $a(t)$-*value* is related to the cumulative number $N_0(t)$ of earthquakes with a non-negative magnitude up to time t, $N_0(t) = 10^{a(t)}$. M_{min} and M_{max} are the minimum and maximum magnitude, respectively.

2.2 Non-stationary Poisson distribution

The Poisson distribution has been traditionally used to describe the number of events within a certain time interval for stationary earthquake rates (Baker 2008). It is easily modified to represent non-stationary rates. The non-stationary Poisson model has a rate of occurrence that varies with time. Assuming a non-stationary Poisson distribution, the probability $P[N = n; t_a, t_b]$ to have n events in a time interval $t = [t_a, t_b]$ is given by (Sigman, 2013):

$$P[N = n; t_a, t_b] = \frac{{m_\lambda}^n(t_a,t_b)(t_b - t_a)^n e^{-m_\lambda(t_a,t_b)(t_b - t_a)}}{n!}, \text{ (2)}$$

where $m_\lambda(t_a; t_b)$ is the mean of the time-varying rate of occurrence $\lambda\,(t)$. In this analysis, the rate of occurrence $\lambda\,(t)$ is a function of the GR parameters. For more details, the reader is referred to Reyes Canales and van der Baan (2019).

3. Evolution of the induced seismicity and hydraulic fracturing activities in the Fox Creek area (2014-2019)

For this study, we analyze the Alberta Geological Survey Catalog from 2013 to 2019. The number of earthquakes in the Fox Creek area increased dramatically after December 2013, in line with the emergence of seismogenic wells related to hydraulic fracturing activities in the Duvernay Fm. The peak in the overall number of earthquakes larger than M>2 was reached in 2017, with more than 150 earthquakes recorded that year (See figure 2 (A)). It should be noted that the Mc in the area drops to values equal to or below Mc=2.0 from 2014 onwards. On the other hand, the number of earthquakes larger than M>3 peaked in 2015, with 12 events, and since then, the number of earthquakes M>3 has declined (See figure 2 (B)). The difference between the peak in the number of earthquakes M>2 (2017) and the peak in the number of earthquakes M>3 (2015) is associated with the rapid increase in the b-values after 2016 (See figure 2 (C)). Increasing b-values are associated to a reduction in the likelihood of large events, therefore, decreasing seismic hazard. Figure 2 (C) shows the evolution of b-values using a time-screen window. This increase in the b-values indicates a reduction in the likelihood of large events. However, this does not necessarily mean a reduction in the overall number of earthquakes. On the other hand, notice that the total volume injected in the Duvernay Fm., SSO2 area, related to hydraulic fracturing activities has steadily increased, except for the year 2016. The same occurs with the total number of hydraulic fracturing wells in the Duvernay Formation, SSO2 area (See figure 2 (D)), which increased steadily until 2019.

Figure 3 (A) shows the evolution of annual b-values in the Fox Creek area. For the estimation of b-values, we relied on annual catalogs and implemented MCM. Notice that 2 phases have been identified: Phase 1 (2013-2015) with b-values below b<1, a transition phase (2016) and Phase 2 (2017-2019) with b-values above b>1. These phases are equivalent to the evolution of the seismic hazard in the Fox Creek area. Figure 3 (B) shows the annual likelihood of events with a magnitude larger than M>4, assuming a Poisson distribution (Eq. 2). The likelihood of events larger than M>4 peaked in 2015, with a 95% probability. However, since then, the likelihood has decreased consistently to 60% in 2016, 18% in 2017, 10% in 2018 and 4% probability in 2019. It is worth mentioning that 3 earthquakes M>4 were recorded in 2015, and 1 earthquake M>4 in 2016. Notice that the peak in the overall seismicity occurred in 2017. However, due to a drastic increase in the b-values, the likelihood of large earthquakes decreased to 18%. Furthermore, no earthquakes with a magnitude M>4 have been recorded since 2016 in the Fox Creek area.

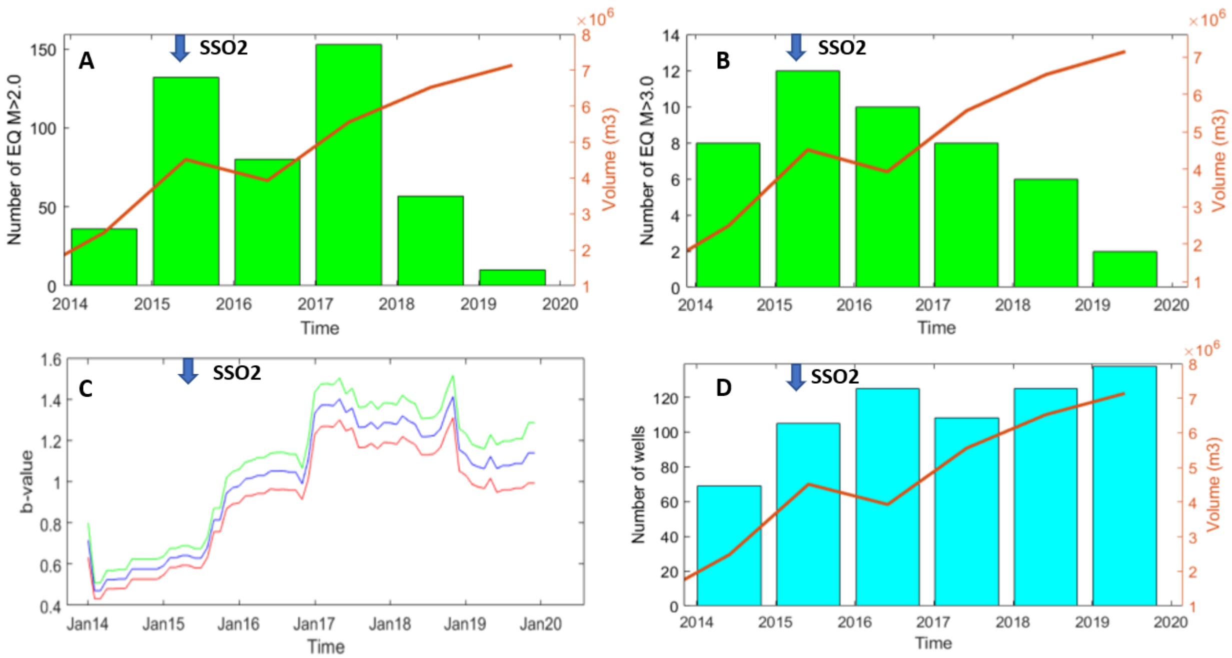

Figure 2. Annual number of earthquakes larger than M>2 (A, green bars) and M>3 (B, green bars) and total volume injected per year in the Duvernay Fm., SSO2 area, related to hydraulic fracturing activities (orange line). (C) shows the evolution of the b-values using a time-screening window. (D) shows the total number of hydraulic fracturing wells in the Duvernay Formation, SSO2 area (blue bars) and the total volume injected per year (orange line). The blue arrow shows the time when SSO2 was implemented.

4. Conclusions

The likelihood of moderate events with magnitudes larger than M>4 in the Fox Creek area has consistently decreased since 2015, from a 95% probability to have an earthquake M>4 to a 4% probability in 2019. This contrasts with the peak in the total volumes and the number of hydraulic fracturing wells per year in the Duvernay Fm., SSO2 area, both occurring in 2019. We believe that this trend in decreasing seismic hazard, which contrasts with increasing human activity, could be associated with the implementation of regulatory instruments like SSO2, active mitigation strategies implemented by the operators, and avoidance of areas identified to be susceptible to induced seismicity. These active mitigation strategies could explain the increase of the b-value in the area. The increase in the b-values, from b=0.92 in 2015 to b=1.48 in 2017, indicates a reduction in the seismic hazard and the likelihood of large earthquakes. The case of Fox Creek is interpreted as an example of how the seismic hazard has been reduced due to regulatory and industry collaboration.

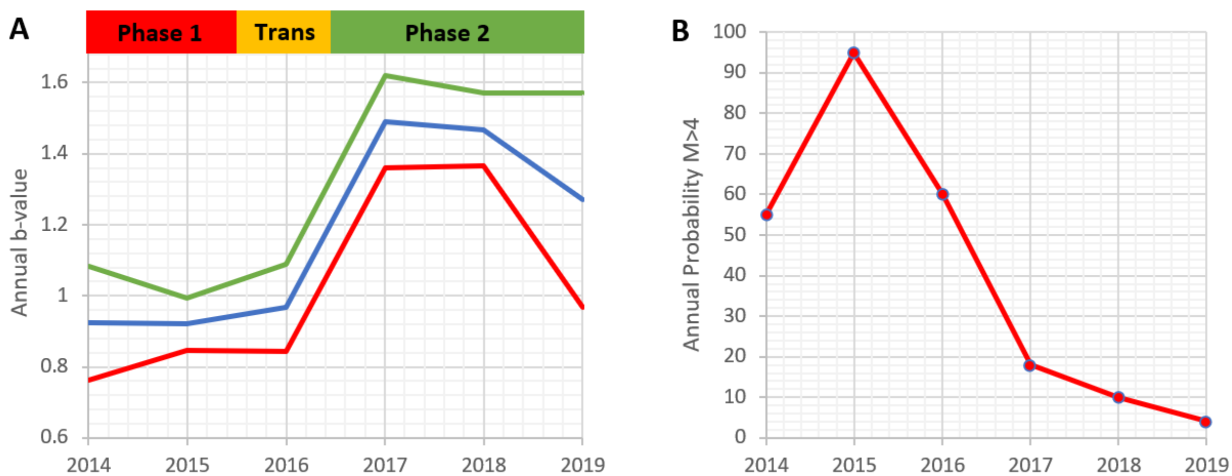

Figure 3. (A) temporal evolution of the annual b-values, showing the identified phases observed in the Fox Creek induced seismicity case. (B) Annual probability of earthquakes larger than M>4 in the Fox Creek area.

Acknowledgments

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