Recent Seismicity in the Kiskatinaw Area, British Columbia: What can we learn about the dynamics of fault activation?

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Summary

Recent seismicity in the Kiskatinaw area of British Columbia has been attributed to ongoing resource development activity in the area. Here, we take a number of distinct sequences of seismicity and investigate the temporal and spatial evolution of such seismicity, including understanding event source characteristics. Events associated with nearby hydraulic fracture stimulation activities in February/March 2021 appear to have swarm-like characteristics rather than follow a typical mainshock-aftershock sequence but are temporally and spatially correlated to activity at a nearby injection well. We also investigate the largest detected seismic event in the area in 2020 (~M_L 3.2). This event was preceded by a short precursory sequence of seismicity (~4 hours) but occurred following a general period of quiescence in the Kiskatinaw area (~4 months). Understanding why and how such an event occurred, and comparing with other seismic sequences occurring in this area of British Columbia thought to be related to ongoing hydraulic fracturing operations, may allow us to better understand how faults and fractures initiate at depth, and the processes associated with this activation.

Introduction

Hydraulic fracturing and wastewater disposal operations have significantly increased in the Western Canada Sedimentary Basin (WCSB) over the past 20 years in the resource plays of the Montney and Duvernay. A temporal and spatial correlation between increased seismicity and increased operations in this area has raised awareness of such developments with the public and government, although actually very few hydraulic fracturing operations (0.8%) are actually linked to seismic activity with felt seismicity (Ghofrani and Atkinson, 2020). With growing concerns from regulators and the public, the BC Oil and Gas Commission (BC OGC) implemented a special order in 2018 (BC Oil and Gas Commission, 2018) within the area now known as the Kiskatinaw Seismic Monitoring and Mitigation Area (KSMMA), which requires operators to undertake a pre-assessment of the seismic hazard, fully inform residents in the area of upcoming operations and to monitor seismic activity in real-time before, during and after completions. Of particular importance was the introduction within the KSMMA of the suspension of operations following an event with a local magnitude (M_L) of ≥ 3.0 (BC Oil and Gas Commission, 2018), which is lower than the M_L 4.0 threshold that is standard elsewhere in BC (e.g., Babaie-Mahani and Kao, 2020).

In early 2020, 13 additional broadband seismometers and 2 accelerometers were installed within the KSMMA to enhance the monitoring capabilities of ongoing operations, improve risk assessments and inform mitigation strategies. Prior to the installation of this new dense array, nine public sensors maintained by Natural Resources Canada (NRCan; Geological Survey of Canada) existed within the KSMMA, along with six co-located accelerometers poised to better capture higher levels of ground motion from larger seismic events. The installation of this new array of seismometers aimed to complement the existing stations in the area but extend the monitoring capabilities by providing better azimuthal coverage (in particular in the central areas of KSMMA and the south-west), as well as increasing the density of stations. Accelerometers were placed close to areas where felt events had recently been recorded (Salvage et al., 2021).

Recent Seismicity in the KSMMA

From 22 January 2020 to 31 March 2021, 9740 events were detected within the KSMMA using the newly installed EO network, in addition to public stations in the area. Events cluster spatially within a corridor in the KSMMA orientated NW-SE, which is similar to the locations of events in previous years. Magnitudes ranged from -0.7 to 3.2 (Babaie-Mahani and Kao, 2020), with an estimated magnitude of completeness (Mc) of 0.17 and an estimated *b*-value of 1.74 (Gutenberg and Richter, 1944). Distinct heightened periods of seismicity were observed in February, March, August and September 2020, as well as in February and March 2021. This reflects ongoing operations in the area during these times. A clear period of quiescence was observed from April until August 2020, representing the unprecedented situation that occurred in 2020 with the lockdown of people, businesses and cities due to the COVID-19 pandemic and the subsequent downturn in the energy industry (and major fall in stock prices) that led to the suspension of almost all operations within KSMMA for ~4 months (Salvage and Eaton, 2021).

The largest magnitude event of 2020 in the KSMMA occurred on 11 September at 22:37 UTC (M_L 3.41 using the formula of Hutton and Boore (1987)). In line with the BC OGC Special Order of 2018, operations in the immediate area were suspended following this. A short precursory sequence of activity was identified in hindsight, consisting of 73 events in the previous ~4 hours, with events locating within a small spatial extent (~300 by 150 m). These events are probably directly related to ongoing operations in the area based on the correlation in space and time of events and injection. It is interesting that the largest recorded event in 2020 occurred following a period of quiescence in the KSMMA (~4 months) when almost all operations were suspended. Re-evaluation of the magnitude of this event using the specifically calibrated formula of Babaie-Mahani and Kao (2020) for the KSMMA estimates M_L to be ~3.2. This re-calibrated magnitude agrees better with a Bayesian centroid moment tensor (CMT) inversion analysis for this event, which estimates that the focal mechanism is dominated by strike-slip, at a depth of 2.6 km (Salvage et al., 2021). The results are consistent with other studies of source mechanisms within the KSMMA, which suggest mechanisms are dominated by strike-slip faulting, with some evidence of thrust faulting (Wang et al., 2018; Babaie-Mahani et al., 2020).

Detected seismicity at the beginning of 2021 was low, with an average of 5 – 10 events being detected in the KSMMA per day in January. However, at the end of February 2021, a short sequency of seismicity began south of Farmington, where almost 650 events were detected between 23rd February and 5 March (Figure 1a). Events were temporally clustered, with the majority of the events occurring from 24th February 12:00 UTC to 26th February 00:00 UTC. Hourly event rates peaked on 25th February from 00:00 to 12:00 UTC, where over 35 events were recorded in one hour. Two shorter swarms with far less events occurred from 28th February to 1st March, and on 4th March 2021. The first of these swarms included the largest magnitude event in the sequence: a M_L 2.03 (28th February, 23:50 UTC at a depth of 1.72 km). Recorded magnitudes throughout this sequence have ranged from M_L -0.32 to M_L 2.03 (Babaie-Mahani and Kao, 2020 M_L calculation), in a typical swarm-like sequence with limited evidence of a mainshock-aftershock type decay. Detected seismicity also appears clustered spatially (Figure 1b), close to a known active hydraulic fracturing well in the area. Events depict linear features in map view and are highly clustered at depth, above the target formations for hydraulic fracturing (Montney).

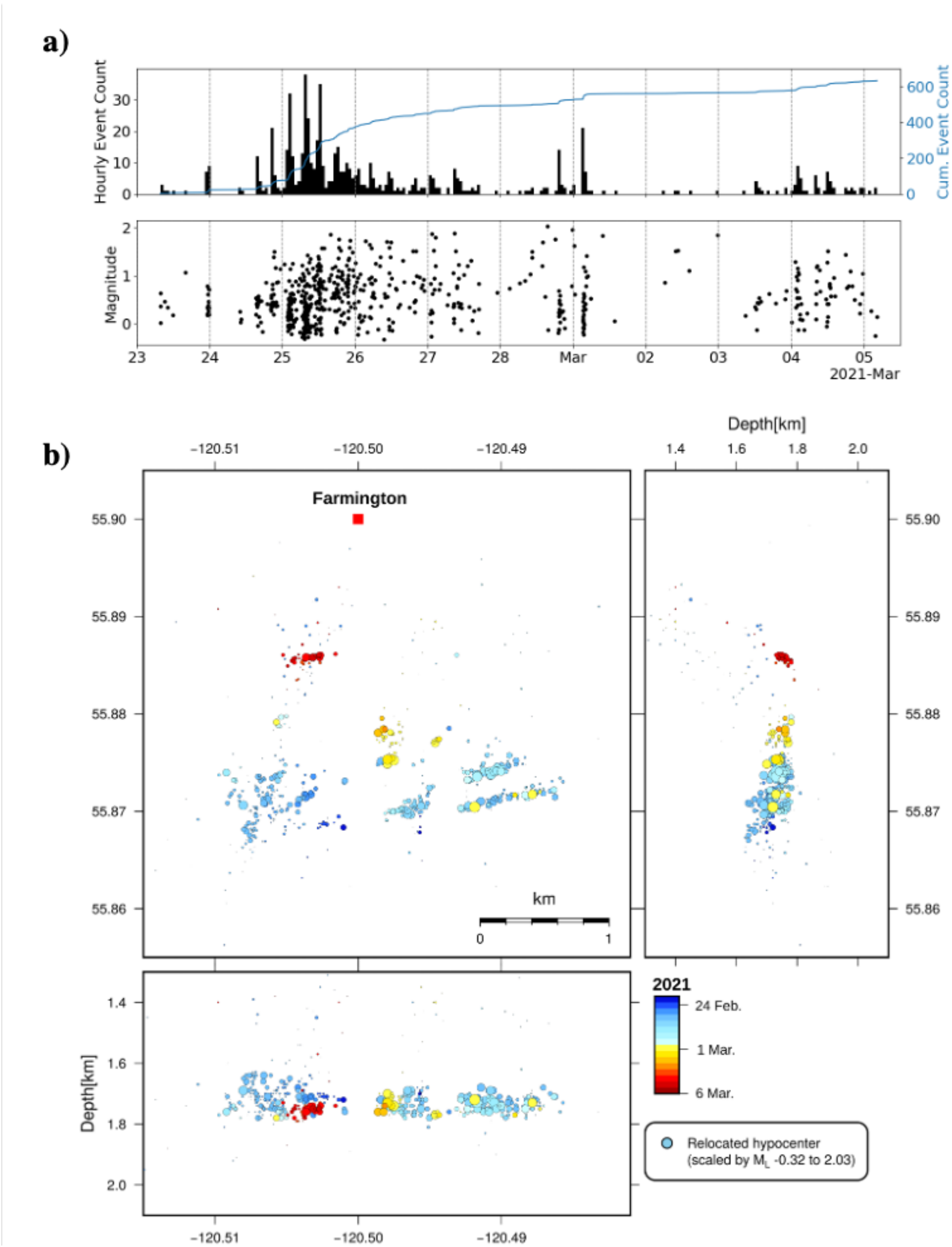

Figure 1: Temporal (a) and spatial (b) evolution of seismicity from 23rd February to 5 March 2021 close to Farmington, British Columbia.

The magnitude of completeness for this sequence of events, calculated using the maximum-curvature method of Wiemer and Wyss (2000), was estimated to be 0.38, which is higher than the estimated Mc for all the detected seismicity in 2020 (Mc ~ 0.074, Salvage et al., 2021). This is part reflects the number of events within each distribution (over 7000 events were used for calculating the Mc for 2020). The estimated *b*-value for the detected sequence near Farmington is ~1.42, which is higher than that estimated for 2020 (*b*-value ~1.13, Salvage et al., 2021). This likely reflects that the sequence detected near Farmington is a direct response of ongoing hydraulic fracturing at a nearby well. Such stimulation typically produces higher *b*-values (e.g., Maxwell et al., 2009), compared to natural seismicity (e.g., El-Isa and Eaton, 2014). The *b*-value estimated for the entirety of 2020 includes events that are likely related to salt-water disposal, as well as natural seismicity, potentially lowering the estimation.

Discussion and Conclusions

The installation of a dense seismic network in 2020 in the KSMMA is enabling us to better capture ongoing seismicity in this area. Much of the seismicity in the KSMMA has been previously attributed to ongoing hydraulic fracturing and salt-water disposal activities. However, our understanding of actually how faults and fractures at depth initiate (and therefore generate seismicity) in response to this is still not well understood. A number of theories exist, including that an optimally orientated fault structure responds directly to increased pore fluid pressures, or a response due to poro-elastic stress transfer or aseismic deformation (Bao and Eaton, 2016; Eyre et al., 2019; Salvage and Eaton, 2021).

We plan to use the recent seismicity in the KSMMA to investigate how and why faults and fractures may initiate at depth in response to fluid injection. A detailed understanding of the source characteristics of detected events within the seismic sequences of September 2020 and February 2021 may allow us to better understand why heightened seismicity was detected in response to this fluid injection, and is not detected in other instances. The KSMMA is tectonically complex, however Babaie-Mahani et al. (2020) recently suggested that the majority of seismicity from hydraulic fracturing experiments exhibit strike-slip characteristics with maximum horizontal stress orientated between N22°E and N33°E. We will investigate our seismic sequences to determine whether they agree with this finding. The largest detected event in the KSMMA since the installation of our array in early 2020 occurred following a very short precursory sequence. Investigating this precursory sequence may allow us to better understand why an event of this magnitude occurred.

Understanding fault architecture within the KSMMA is an ongoing research topic. The installation of 15 additional sensors in early 2020 has increased the density of sampling in the area and given better azimuthal coverage to better detect low magnitude events. This allows us to investigate specific earthquake sequences (e.g., the February/March 2021 sequence near Farmington) in great temporal and spatial detail, to better understand how and why such sequences initiate. Understanding the source characteristics of events within such sequences may allow us to determine local fault architecture, and consequently better understand the risk associated with ongoing unconventional resource development in this area.

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