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Dense array monitoring in the Kiskatinaw Area of British Columbia reveals both expected, and unexpected, patterns of induced seismicity

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Summary

The installation of a dense seismic network within the Kiskatinaw Seismic Monitoring and Mitigation Area (KSMMA) in NE British Columbia between January 2020 and February 2022 has enabled the detection and analysis of over 19,000 seismic events. Seismicity appears temporally and spatially concurrent with ongoing hydraulic fracturing and waste-water disposal operations within the area. Events recorded local magnitudes between -0.8 and 3.4, with a magnitude of completeness for the current catalog sitting at ~0.4. Typically, seismicity occurs within a well-defined corridor orientated NW-SE, possibly related to the Fort St. John Graben structure. We investigate in detail the largest felt events in the region during the dense array installation: an M_L3.1 on 11 September 2020 and an M_L3.4 on 26 July 2021. The event in 2020 has been associated with ongoing nearby hydraulic fracturing operations, however the July 2021 event appears to be related to a disposal well, with the events appearing offset from the point of injection. In addition to seismicity in this region appearing to be generated via direct pore pressure increases and poroelastic phenomena as a direct result of injecting into the subsurface, there is some evidence that aseismic slip may play an important role in generating seismicity, as shown by repeating seismicity and the generation of latent seismicity during periods of operational quiescence. Furthermore, we investigate changes in the local stress field within KSMMA on a regional scale, using ambient seismic noise.

The Kiskatinaw Seismic Monitoring and Mitigation Area (KSMMA)

In recent years, north-east British Columbia, Canada has experienced an increasing number of felt seismic events during active oil and gas development within the Montney play, because of horizontal drilling and multistage fracturing (e.g., Atkinson et al., 2016; Schultz et al., 2020). This has included several events > Mw 3 (e.g., Babaie Mahani et al, 2017; Amini and Eberhardt, 2019; Babaie Mahani et al., 2020), inferred to be anthropogenically induced since the area is not historically prone to natural seismicity (e.g., Horner et al., 1994; Lamontagne et al., 2008; Stern et al., 2013). In 2018, the British Columbia Oil and Gas Commission (BCOGC) implemented a Special Order within the area known as the Kiskatinaw Seismic Monitoring and Mitigation Area (KSMMA), which requires operators to undertake heightened real-time monitoring and hazard analysis of ongoing operations (BC Oil and Gas Commission, 2018). This special order also resulted in the lowering of the red-light threshold for the suspension of operations in response to felt seismicity (the Traffic Light Protocol): in the KSMMA this threshold is set at M 3, whereas the threshold is set at M 4 elsewhere in British Columbia.

Pre-existing faults are prominent in the KSMMA due to the presence of faults that formed as part of the Late Carboniferous Dawson Creek Graben complex (Evoy, 1997; Eaton et al., 1999;

Wozniakowska et al, 2021), which today manifests as three large scale sub-surface features: the Fort St. John Graben (FSJG, 50 x 220 km); the Monias structure; and several smaller satellite grabens including Hines Creek (Barclay et al., 1990; Furlong et al., 2020). In addition to the extensional regime creating the graben structures, this area has also undergone younger strike-slip and compressional movement coupled with significant rotation resulting in a variety of faulting regimes within this area (Barclay et al., 1990; Babaie Mahani et al., 2020; Wozniakowska et al., 2021; Salvage and Eaton, 2022).

Observations of seismicity recorded between January 2020 and February 2022

In early 2020, 13 additional broadband seismic stations (Trillium T120 seismometers with Taurus digitizers) and two titan accelerometers were installed within the KSMMA as part of a joint project between the University of Calgary, Nanometrics, Geoscience BC and a number of universities in South Korea (Eaton et al., 2021). Between 22 January 2020 and 1 February 2022, 19,044 seismic events were detected in the KSMMA using the EO network (and available public stations) in the area. Events ranged in magnitude from -0.8 to 3.4, with Mc = 0.4. Temporally, seismicity within the KSMMA occurs in distinct clusters, attributed to ongoing development activity in the area. Since 2020, distinct heightened periods of seismicity in the KSMMA have been observed from February to April 2020, August to September 2020, March to April 2021, June 2021, and December 2021. From April to August 2020, almost all operations in the KSMMA were suspended due to the indirect effects of the COVID-19 pandemic, which led to a period of almost complete quiescence for ~4 months (Salvage and Eaton, 2021). The majority of seismicity detected within the KSMMA is $M_L < 2$, and consequently goes unfelt, however a number of larger, felt events have been detected since January 2020, the largest of which occurred on 26 July 2021, with an estimated ML of 3.4. Spatially, seismicity within the KSMMA appears to occur within distinct regions, in a corridor orientated NW-SE. Focal mechanisms appear to show a variety of faulting mechanisms within a small spatial extent, although the area is dominated by reverse- and oblique-type mechanisms (Babaie Mahani et al., 2020; Salvage and Eaton, 2021). \\

The largest magnitude event of 2020 occurred on 11 September at 22:37 UTC with an estimated M_L of 3.1 (Babaie Mahani et al., 2020), following which operations in the area were shut down in line with the traffic light protocol introduced for the area. Due to the global COVID-19 pandemic in 2020, operations only re-started in the KSMMA at the beginning of August, following approximately 4 months of almost total quiescence. The event on 11 September occurred quickly following this resurgence of activity. A total of 73 precursory events occurred over approximately 4 hours, with events locating within a small spatial extent (~300m x 150m), probably directly related to ongoing operations in the area due to the correlation in space and time of events and injection. Events within this precursory sequence had magnitudes between M_L 0.5 and M_L 2.8. The mainshock located at a depth of ~2.75 km (Salvage et al., 2021). The mainshock appears to be an oblique reverse mechanism, with a small amount of strike-slip (determined using a probabilistic Bayesian approach with P-wave polarity and P/S amplitude ratio information; Pugh and White, 2018).

The largest event to occur in 2021 within the KSMMA occurred on 26 July at 09:32 UTC, with an estimated magnitude of M_L 3.4. This event is unusual since it is believed to have been generated in response to water disposal (SWD) into the Cadomin formation, rather than a hydraulic fracturing operation which tend to dominate the KSMMA. Unlike seismicity generated by hydraulic fracturing, which typically correlates well in time and space with ongoing operations, seismicity generated by SWD is often offset from the point of injection, both temporally and spatially (Schultz et al., 2014). Within the KSMMA, seismicity associated with one of the active SWD in April 2020 appears to be offset from the point of injection by ~2 km (Salvage and Eaton, 2021), although distinguishing between seismicity generated from SWD and hydraulic fracturing at the height of operations is an ongoing challenge. In this case, 72 events were detected between 19 July and 2 August 2021, with no precursory sequence prior to the M_L 3.4. Spatially, the majority of events in this sequence appear clustered close to the southern boundary fault of the Fort St. John Graben that may have played an important role in the 30 November 2018 M_L 4.5 event (Salvage and Eaton, 2022), offset from the injection well by over 3 km. The ML 3.4 event occurred ~500 m below the point of injection at ~1.6 km (the target Cadomin Formation lies at ~1 km depth in this location), again suggesting the seismicity is offset from the point of injection.

Many studies have shown that changes in seismic wave properties can be detected using ambient noise, which can be inferred to relate to mechanical changes in the subsurface (e.g., changes to a volcanic edifice, stress changes in fault zones) (Wegler and Sens-Schonfelder, 2007; Brenguier et al., 2008). Temporal analysis of ambient seismic noise at individual stations within the array using the methodology set out by Lecocq et al. (2020) suggests significant spatial variations in ambient noise (likely related to local site conditions), as well as changes in the average seismic velocity over time. We plan to further this analysis using the MSNoise package (Lecocq et al., 2014), which computes seismic velocity changes by first computing cross-correlation functions of ambient seismic noise for different pairs of sensors in the array, then measuring travel time delays of different phase arrivals, and finally averaging these travel time delays generating a relative velocity change with time within a given study area. This will allow us to better understand both spatial and temporal changes in ambient seismic noise, across a regional scale.

Mechanisms for the generation of Seismicity within the KSMMA

Given that most seismicity appears to be temporally and spatially correlated with fluid injection, the most obvious explanation for the generation of these seismic sequences is a pore-pressure migration model, whereby pore fluid pressures are significantly increased upon fluid injection reducing the effective normal stress within a fault zone, which is sufficient to trigger seismicity (Bao and Eaton, 2016; Pena Castro et al., 2020). Under this model, the seismicity rate is usually observed to be proportional to the pore pressure and is assumed to track the injection rate (e.g., Langenbruch and Zoback, 2016), as well as producing a spatial migration of seismicity (e.g., Shapiro and Dinske, 2009). Alternatively, poroelastic models for the generation of seismicity suggest the increased pore pressure due to injection may load the surrounding rock matrix, altering the stress field, often at great distances from the original injection site when the region is well hydraulically connected (Segall and Lu, 2015; Goebel and Brodsky, 2018). This would lead to a spatial migration in seismicity away from the point of injection, as well as a typical Omori-type decay in seismicity with time (Utsu, 1961). Some sequences of seismicity appear to follow these trends (e.g., events in March 2020), suggesting that these mechanisms may account for some of the seismicity generated within the KSMMA.

Recently it has been hypothesized that repeating seismicity can be the result of aseismic creep since repeating events are generated by the repeated rupture on a single fault patch though the reduction of normal stress on a fault due to fluid pressure which leads to slow slip (Uchida and Burgmann, 2019; Hatch et al., 2020). Salvage and Eaton (2022) suggested that the existence of repeating seismicity during a seismic sequence in 2018 in KSMMA may be evidence for ongoing aseismic processes. We are investigating the extent of repeating seismicity during the monitoring period to assess whether this may provide evidence of aseismic processes.

Conclusions

Seismicity in the KSMMA generally appears to follow consistent temporal and spatial patterns related to ongoing hydraulic fracturing and wastewater disposal operations in the area. Typically, events occur at the time of operations and are spatially limited around the point of injection if associated with hydraulic fracturing. On a larger scale, seismicity appears to concentrate in a corridor orientated NW-SE, coincident with the depths of target formations. Seismicity associated with SWD in the KSMMA is more difficult to identify and separate, due to the much larger number of hydraulic fracturing operations. However, evidence from sequences of seismicity induced in April 2020 and July 2021 suggest that there may be some spatial offset between the point of injection and the generation of seismicity (Salvage and Eaton, 2021).

Several felt events have occurred in KSMMA over the past few years, possibly due to the density of ongoing operations within the KSMMA, or perhaps because of the structural complexity of the area. Although the Fort St. John Graben complex was formed during a long period of extension during the Carboniferous to Permian (Barclay et al., 1990), the bounding faults show alternating zones of both compressional and extensional structures, attributed to early strike-slip faulting and re-activation of the fault zones associated with the Late Cretaceous-Paleocene development of the Rocky Mountain fold and thrust belt to the west (Wozniakowska et al., 2021). Focal mechanisms appear to show a variety of faulting mechanisms within a small spatial extent, although dominated by reverse-type mechanisms (Babaie Mahani et al., 2019; Salvage and Eaton, 2022). Recent analysis (Babaie Mahani et al., 2020; Salvage and Eaton, 2022) in the Montney using focal mechanisms suggests that the magnitudes of sigma 2 and sigma 3 are similar, which is consistent with the generation of a mixture of strike-slip and reverse faulting within a small spatial extent. This suggests that small changes in stress (perhaps initiated by increased pressures from injected fluid) can cause different faults (or parts of faults) to be (re)activated.

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