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Unprecedented quiescence in resource development area allows detection of long-lived latent seismicity

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Abstract. Recent seismicity in Alberta and British Columbia has been attributed to ongoing oil and gas development in the area, due to its temporal and spatial correlation. Prior to such development, the area was seismically quiescent. Here, we show evidence that latent seismicity may occur in areas where previous operations may have occurred, even during a shutdown in operations. The global pandemic of COVID-19 furnished the unique opportunity to study seismicity during a period of

5   anthropogenic quiescence. A total of 389 events were detected within the Kiskatinaw area of British Columbia from April to August 2020, which encompasses a period with no hydraulic fracturing operations during a government imposed lockdown. Apart from a reduction in seismicity rate, the general characteristics of the observed seismicity were similar to the preceding time period of active operations. During the shutdown, observed event magnitudes fell between M_L -1 and M_L 1.2, but lacked temporal clustering that is often characteristic of hydraulic-fracturing induced sequences. Hypocenters occurred in a corridor

10   orientated NW-SE, just as seismicity had done in previous years in the area, and locate at depths associated with the target Montney formation or shallower (<2.5 km). A maximum of 21% of the detected events during lockdown may be attributable to natural seismicity, with a further 8% being attributed to dynamic triggering of seismicity from teleseismic events. However this leaves over 70% of the seismicity detected during lockdown being unattributable to primary activation mechanisms. Since we know this seismicity cannot be the result of direct pore-pressure increases (as no direct injection was occurring at the time) and

15   we see no patterns of temporal or spatial migration in the seismicity, we suggest that this latent seismicity may be generated by aseismic slip as fluids (resulting from previous hydraulic fracturing experiments) become trapped within permeable formations at depth, keeping pore pressures in the area elevated, and consequently allowing the generation of seismicity. This is the first time that this latent seismicity has been observed in this area of British Columbia.

1   Introduction

20   The number of recorded instances of injection-induced seismicity has risen dramatically over the past decade, in part due to increased operations in hydraulic fracturing, waste-water disposal and enhanced geothermal systems around the globe, as well as enhanced monitoring meaning we are better able to detect smaller events (e.g. Atkinson et al., 2016; Ellsworth, 2013). In western Canada, the Western Canadian Sedimentary Basin (WCSB) is the focus on such activity, where a number of distinct resource plays are located including the Montney and the Duvernay. Despite an apparent flurry of larger magnitude seismic

25   events associated with these operations (e.g. M_L 4.5 near Fort St John, British Columbia in November 2018, Babaie-Mahani

et al. (2019); Peña Castro et al. (2020); M_W 4.1 near Fox Creek, Alberta in January 2016, Eyre et al. (2019b)) very few hydraulic fracturing operations (∼0.3%) are actually linked to seismic activity with $M_W > 3$ (Atkinson et al., 2016).

30 The Montney Play which is Lower-Middle Triassic in age, is formed of extensive fine-grained siliclastic units (inter-bedded sand, silt and mudstones), and stretches from west-central Alberta to north-east British Columbia (Eaton and Schultz, 2018; Dixon, 2000; Armitage, 1962). Over 5,600 multistage horizontal hydraulically fractured wells had been completed within the Montney by December 2018 (Nieto et al., 2018). In recent years, north-east British Columbia has experienced an increasing number of felt seismic events during active development within the Montney play. This led the BC Oil and Gas Commission to implement a special order in 2018, within the area now known as the Kiskatinaw Seismic Monitoring and Mitigation Area

35 (KSMMA), which required operators to undertake a pre-assessment of the seismic hazard, fully inform residents in the area of upcoming operations and real-time seismic monitoring before, during and after completions (BC Oil and Gas Commission, 2018). Of particular importance was the introduction of the threshold for the cessation of operations following a M_L 3.0 or above within the KSMMA, which is lower than the M_L 4.0 threshold that is standard elsewhere in British Columbia (e.g. Babaie-Mahani and Kao, 2020).

40 Prior to the introduction of oil and gas extraction, western Canada was generally seismically quiet, except for the Mackenzie Mountains and the North American plate boundary off the west coast of British Columbia (Lamontagne et al., 2008). Consequently seismicity detected within the KSMMA has been assumed to be directly related to ongoing operations due to its temporal and spatial correlation with active wells. However, there are a number of examples of seismicity thought to be related to hydraulic

45 fracturing that generate events months after operations have ceased (e.g. Eyre et al., 2020). We call this latent seismicity i.e. seismicity that appears after an unusally long delay following primary activation processes with no obvious "trigger" (e.g. enhanced pressurization at the onset of seismicity), and which cannot be explained by other sources (e.g. natural or dynamic triggering processes).

50 Here, we investigate seismicity generated within the KSMMA during the unprecedented period of quiescence that resulted due to the global COVID-19 pandemic. The cessation of operations in the area and the reduction in seismic noise as businesses shut down and people stayed indoors gave us the unique opportunity to study latent seismicity in an area where it would usually go undetected. Given that prior to the development of the Montney play this area was characteristically quiet in terms of natural seismicity (Lamontagne et al., 2008), the detection of latent seismicity over ∼4 months suggests lingering changes in the stress

55 field to allow for its generation.

2 COVID-19 and the reduction of noise globally

The year 2020 was unusual due to the global pandemic that caused the shutdown of many businesses and severely restricted the movement of people worldwide. This reduction in ground motion has been accurately measured by a drop in seismic ambient

noise in many places, and correlated with a decrease in population mobility (e.g. Lecocq et al., 2020; Dias et al., 2020).

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The noise level at a seismic station can be estimated using the probabilistic power spectral density (PPSD) of its records (McNamara and Buland, 2004). Following the methodology of Lecocq et al. (2020) we compute the PPSD from 30-minute windows with 50 percent overlap so that a single value is gained for each window, calculated using Welch's method (Welch, 1967) for the Z-component of different seismic stations. This method reduces numerical noise in the power spectra at the

65 expense of reducing the frequency resolution because of frequency binning, but this effect is minimized with a robust smoothing parametrization. The 30-minute time series are then converted to an average daily PSD, and the RMS of the time-domain displacement is extracted. Anthropogenic cultural noise typically concentrates at high frequencies (> 1-10 Hz, McNamara and Buland (2004)), but is strongly diurnal (e.g. stronger during the day than at night, and stronger during the weekdays compared to the weekends (Lecocq et al., 2020)). To avoid meteorological signals, and in particular oceanic microseisms (which typically

70 manifest below 1 Hz), we use the frequency band of 4-14 Hz to investigate seismic noise during the pandemic.

Figure 1 shows the reduction of seismic noise in the frequency band 4-14 Hz in Gastown, Vancouver, BC during the global pandemic. A clear reduction in noise is observed following the closure of schools (black line) and businesses (red line). During Phase I of the pandemic (i.e. between the closure of businesses and the partial reopening of the city on 5 May 2020 (green

75 line)), noise levels remain lower than previously recorded. Following the reopening of some businesses in May and June 2020, an increase in the noise is seen, although it remains lower than pre-pandemic levels, interpreted as the increased movement of people. To verify that these variations do not occur on an annual basis, we undertook the same noise analysis for the year 2019, and found no such fluctuations during the corresponding months. In fact, ground displacement remained between 20 and 30 nm at station R25AC for the entirety of 2019.

80 **3   Seismicity in the KSMMA**

With increasing oil and gas operations within the KSMMA over the past decade, the number of public monitoring stations has also increased. Prior to 2020, 9 public sensors maintained by Natural Resources Canada and the Geological Survey of Canada existed within the KSMMA boundary, along with 6 co-located accelerometers poised to better capture higher levels of ground motion from larger seismic events. In early 2020, 13 additional broadband seismic stations (Trillium T120 seismometers with

85 Taurus digitizers) and two Titan accelerometers were installed within the KSMMA (expanding the EON-ROSE (EO) network) as part of a joint project between the University of Calgary, Nanometrics, Geoscience BC and a number of universities in South Korea to monitor ongoing seismicity associated with hydraulic fracturing operations (Salvage et al., 2021).

The catalogue of seismic events detected in the KSMMA is based on the newly installed array and available public stations in

90 the area. Events were detected from the incoming continuous seismic data using an STA/LTA triggering algorithm, followed by a separate template-matching algorithm utilising continuously re-trained modules that classify noise from events and remove

unwanted signals. Then, a support vector machine (SVM) machine learning technique was used to identify phase arrivals in continuous real-time waveform streams. These phase arrivals are identified by training an SVM model on historical data. By converting the waveforms into over 250 features using quantities such as time and band-normalized spectrograms, a model is generated which can associate the features with P and S phases (or conversely, with noise).

We take the catalogue of event times and P and S phases, and determine hypocentre locations using NonLinLoc (Lomax et al., 2009, 2000), a probabilistic, global-search non-linear algorithm that generates the maximum likelihood hypocenter location based on the estimated posterior probability density function for each event. A 1D velocity model, specifically calibrated for the KSMMA from compressional and shear sonic logs, formation tops and ground truth locations of previous seismicity (available directly from BCOGC). Events were then re-located using HypoDD, a double difference algorithm, whereby the residual between the observed and calculated travel-time difference (or double-difference) between two earthquakes observed on a single station are related to differences in their relative hypocenter locations and origin times (Waldhauser and Ellsworth, 2000). To calculate magnitudes we use a form of the Richter (1935) magnitude formula that has been modified to better reflect local attenuation characteristics within the KSMMA (Babaie-Mahani and Kao, 2020). In line with calculations conducted by Natural Resources Canada (NRCan), we calculated M_L using the maximum amplitude from the vertical component simulated on a Wood-Anderson (WA) seismometer, rather than the horizontal component, which has been used elsewhere.

Historically, seismicity within the KSMMA appears to occur within spatially distinct regions that fall within a corridor orientated NW-SE (Fig. 2). In both years, the largest magnitude event occurred in an area away from the densest occurrence of seismicity. Since the largest event in 2020 did not occur in the same cluster as the largest event of 2018, it appears that the occurrence of M_L 3-4+ events is not necessarily confined to a single region. Temporally, seismicity within the KSMMA occurs in distinct clusters, attributed to ongoing development activity in the area (Fig. 3). In 2018, heightened periods of seismicity were observed in April, May, July and August (Fig. 3(a)). Similar periods of heightened seismicity were observed in 2020 in March, August and September (Fig. 3(b)). The majority of seismicity detected within the KSMMA is $M_L \leq 2$, and consequently goes unfelt.

3.1 Prior and Post Lockdown: 2020

In March 2020, the Province of British Columbia introduced measures aimed at slowing the spread of COVID-19, including the closure of schools and childcare facilities on 17 March, and the closure of many businesses (in particular those that included daily human interaction) on 21 March. Up until this point in 2020, similar patterns of seismicity to other years were observed in the KSMMA (Fig. 3). A total of 4,268 events were detected from the onset of data collection (22 January 2020) from the updated EO array (yellow triangles, Fig. 2) to 1 April. Following the initial closure of businesses on 21 March, there is evidence of ongoing hydraulic fracture operations for ∼10 days, with associated heightened seismicity (Fig. 3(b)). It is possible this reflects operators in the area undertaking additional hydraulic fracturing jobs during this time, as government restrictions became increasingly tight, and no "end-date" to the restrictions being suggested, or it may be that these 10 days of seismicity

represent the continuation of planned operations with no initiation of new jobs. Magnitudes of recorded seismicity prior to lockdown at the end of March range from M_L-0.73 to M_L2.93.

At the beginning of April, a period of relative seismic quiescence began in the KSMMA (Fig. 3(b)). Operations were once
130 again restarted in British Columbia in the later summer months, after ∼4 months. Seismicity since the resumption of activities is once again temporally clustered, with a total of 2,617 events being recorded since 6 August to present. The largest magnitude event of 2020 at the time of writing occurred on 11 September at 22:37 UTC with an estimated M_L of 3.1, after which proximal operations were shut down in line with the traffic light protocol introduced for the KSMMA (BC Oil and Gas Commission, 2018). A total of 73 precursory events occurred over approximately 4 hours, with events locating within a small spatial extent
135 (∼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 0.2 and M_L 2.6, and were all located at depths of approximately 2.05 km. Moment tensor results for this event suggest a focal mechanism dominated by strike-slip (Salvage et al., 2021).

3.2 Evidence of reduction in seismic noise

140 A clear reduction in the number of seismic events was observed during the lockdown period from April to August 2020 in the KSMMA (Fig. 3(b)). Over the ∼ 4 months of relative quiescence only 389 events were detected using the EO network and available public stations in the area. For comparison, 344 events were detected on our network over a single week from 8 to 15 February when operations were fully underway. On average during this period, the magnitude of events were smaller than during time periods when activity was driven by ongoing operations.

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A reduction in seismic noise and therefore ground motion is also evident in the KSMMA following the introduction of government restrictions in March 2020 (Fig. 4). Unfortunately, the most central seismic stations in the EO array were not installed until immediately before (March) or post lockdown (May) and therefore could not be used to analyze the long term changes in seismic noise. We chose station KSM08, located in the east of KSMMA due to the long, uninterrupted seismic data
150 recorded at this station, as well as its proximity to recent dense clusters of ongoing seismicity (Fig. 2). Heightened seismic ground motion is evident at KSM08 through January to March, as operations are ongoing (Fig. 4). A significant decrease in seismic ground motion is observed following the government restriction in late March 2020, with the average displacement sitting well below the weekday and weekend daytime mean calculated prior to lockdown. As restrictions ease, we see a large increase in ground motion following the reopening of businesses in May 2020, although this once again tails off through June
155 and July. The re-introduction of operations in August is clear from an increase in ground displacement and seismic noise, which has remained elevated (although not as high a pre-lockdown levels) since.

3.3 Latent Seismicity during relative quiescence: 2020

Seismicity occurring during the period of quiescence from April to August 2020 within the KSMMA exhibit a number of characteristics indicative that it is a (latent) consequence of previous operations in the area. Figure 5 shows the temporal
160 and spatial evolution of seismicity during this period. Firstly, perhaps unsurprisingly, seismicity does not occur in a distinct temporal pattern that exhibits clustering (Fig. 5(a)). A small number of events (∼5) occur each day throughout the 4 months. Event magnitudes also reveal no discerning patterns with time, with all events registering M_L-0.66 to ∼M_L1.2. Furthermore, the frequency index (FI) suggests no temporal patterns during the period of relative quiescence. The FI is a proxy for the spectral content of each waveform based upon the ratio of energy in low and high frequency windows (Buurman and West,
165 2010), calculated at a single station. We use station KSM06 (Fig. 2) due to its proximity to the majority of the ongoing seismicity during this period of relative quiescence. A negative FI means the waveform is dominated by low frequency energy (in this case 1 - 40 Hz); a positive FI demonstrates a majority of energy in the high frequency band (40.1 - 80 Hz). In many environments (e.g. volcanic) a lower frequency content of the waveform is proposed as evidence for the direct role of fluids in the generation of the seismicity (e.g. Lahr et al., 1994; Chouet, 1996). The seismicity detected during the period of relative
170 quiescence within the KSMMA shows no discerning temporal characteristics.

Spatially, seismicity detected during the COVID lockdown period exhibits characteristics that are similar to the previously detected seismicity in the KSMMA (Fig. 5(b)). Most events occur in a corridor orientated NW-SE, similar to the spatial distribution of seismicity prior to lockdown. Some spatial clustering is evident (e.g. in May in the south (yellow)), but given
175 the limited number of events this is difficult to determine with certainty. Most events during the quiescence period occur at a focal depths of ∼0-4 km, which is similar for events prior to lockdown within the KSMMA, if potentially slightly shallower. Target formations for hydraulic fracturing within the KSMMA (Upper and Lower Montney) typically sit between 2000 m and 2500 m (total vertical depth), with salt water disposal (SWD) injecting at shallower depths (M. Gaucher, Pers. Comm, 2020). This suggests that events detected during the quiescence were generated in formations similar to those that occur when active
180 hydraulic fracturing and SWD is ongoing.

4 Discussion

4.1 Characteristics of Observed Seismicity

Seismicity generated during this period of quiescence appears to share many characteristics with seismicity generated during
185 hydraulic fracturing operations within the KSMMA. Although low in number, the event rate per day remains fairly constant throughout the ∼4 month period of no hydraulic fracturing operations, with no apparent temporal decay (Fig. 5(a)). This contrasts the "usual" pattern of seismicity during active hydraulic fracturing operations, which is highly temporally (and spatially) clustered around the wells operating (Fig. 3) (e.g. Skoumal et al., 2015). Figure 3(b) also suggests no change in

the recorded magnitudes of events pre- and during lockdown.

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The magnitude of completeness (Mc) during the lockdown period is ∼0.4. The Mc for the entire catalogue to from 22 January to 1 October 2020 (n=7216) is estimated to be 0.074, suggesting that even though relatively few events were detected during this quiescence, the detection of small magnitude events is good. Given the reduction in noise during the period of quiescence (Fig. 4), this is perhaps no surprise. The estimated b-value (Gutenberg and Richter, 1944) of 1.96 is similar to b-values estimated from

195 seismicity associated with hydraulic fracturing experiments in Western Canada, suggesting an abundance of lower magnitude events (Igonin et al., 2018; Eaton et al., 2014). The fact that no large magnitude events were detected during the period of quiescence (no M_L>1.5) is directly influencing the estimated b-value in this case. Interestingly, higher b-values have typically been attributed to seismicity generated in normal faulting regimes (Schorlemmer et al., 2005; Amini and Eberhardt, 2019). The KSMMA is strongly influenced by the Fort St. John Graben complex, an asymmetrical half graben that has also undergone

200 significant strike-slip and rotational movement upon reactivation of the basement faults in the area (Barclay et al., 1990), which may also be directly influencing the estimated b-value. Furthermore, in hydraulic fracturing environments, b-values of >2 have been associated with the stimulation of natural fractures at depth, with smaller b-values associating with large-scale tectonic faults (Wessels et al., 2011; Eaton and Maghsoudi, 2015). In our case, this would suggest that the seismicity being generated is directly related to the complex natural fracture system, rather than any large scale faults in the area.

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Seismicity during the quiescence appears to be spatially concurrent with previous seismicity in the area (Figs. 5(b) and 2). However, there appears to be very little correlation between the spatial extent of seismicity and the most recent hydraulic fracturing activity in the area (active in March 2020 prior to lockdown). Seismicity appears in two planar elongated features, extending in a NW-SE direction, with lengths of up to 30 km (eastern segment), if assumed to be one feature. These features

210 are not coincident with any known faults in the area (Furlong et al., 2020). Seismicity recorded during this period of quiescence is generally located at a similar depth to the target formations of the Montney (∼2 km), as well as in the formations above. This suggests hydraulically connected pathways above the injection zone, perhaps within mechanically stronger lithologies, as has been previously suggested by Eyre et al. (2019b) in the Fox Creek region of Alberta (another area undergoing intensive hydraulic fracturing operations).

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The generation of induced seismicity has often been successfully correlated to a number of injection parameters, including the injected volume of fluid (e.g. Yu et al., 2019; Ellsworth, 2013) and/or the pumping rate (e.g. Goebel et al., 2017). Temporally data is too sparse to draw conclusions as to whether any of these parameters directly influence the generation of induced seismicity within the KSMMA, although given that hydraulic fracturing operations during our period of interest were ceased,

220 we know that this seismicity cannot be a direct response of this type of fluid injection. However, there is evidence that a small number of seismic events identified from April to August 2020 may be associated with salt-water disposal (SWD). Within the KSMMA, only 8 SWD wells were active in 2020, compared to hundreds of hydraulic fracturing wells. Of these, only one well was active during our period of investigation (Fig 5b). We believe the seismicity occurring on 13 April 2020 (Fig. 5a, upper

panel), where over 20 events were registered on the same day (significantly above the background rate of seismicity during
225 this quiescence), may be due to SWD. In this case, ongoing sustained SWD occurred ∼2 km away from the events occurring
on this day. This offset is not unusual for SWD and associated seismicity; Schultz et al. (2014) found an offset of ∼3.5 km
between SWD and associated seismicity in Alberta.

4.2 Estimation of Noise

PPSD is one of the most common methods used to characterize ambient seismic noise. However, the level of smoothing, the
230 size of the data window used in analysis and the methodology itself may all influence the PPSD calculation and distort features
of interest (Anthony et al., 2020). Smoothing is primarily undertaken in order to reduce the uncertainty associated with the
PPSD estimates, and means that short spikes in noise (e.g. due to wind gusts or seismic activity) do not dominate the spectrum.
In our case, the reduction in ground motion is much easier to determine from the average of the PPSD rather than individual
estimates (Figs. 1 and 4, green vs. grey lines). Although we use a period smoothing of 0.025 octaves, this is likely to provide
235 adequate spectral resolution of spectral peaks, as shown by Anthony et al. (2020) and therefore impacts our results minimally.
We also use a window of 30 minutes (overlapping by 50%) to try to reduce spectral leakage and variance when calculating the
PPSD.

Earthquakes, and other transient signals, are likely to impact the estimation of ambient noise by generating large spikes in
240 the data. However, the removal of seismicity from datasets is generally accepted as not necessary since they are low-probability
occurrences within generally high-probability ambient seismic noise (McNamara and Buland, 2004). Only teleseismic earthquakes
appear to have any real affect upon PPSD calculations (Anthony et al., 2020). A number of teleseismic events have been
detected in the KSMMA during the period of quiescence analysis (e.g. $M_w 7.8$ event on 20 July 2020, 99 km off the coast of
Alaska), that may influence our calculation of PPSD. However, since we see no peak in the average ground motion at these
245 times (e.g. no substantial peak in July 2020, Fig. 4), we suggest that teleseismic events are not majorly influencing our results.

One signal that does clearly influence our PPSD results in Fig. 4 is wind. Poor weather reported in the KSMMA, with wind
gusts exceeding 80 km/hour at times were observed at the beginning of May, during an otherwise quiet period (i.e. no hydraulic
fracturing operations in KSMMA, limited movement of people due to lockdown measures). Since the noise generated from
250 wind gusts penetrates a wide frequency band, we are unable to filter it out. Using a filter between 4 and 14 Hz tries to eliminate
some of these transient signals mostly associated with meteorological and oceanic conditions.

4.3 Generation of Latent Seismicity

The cessation of operations within the KSMMA in the summer of 2020 allows us a unique insight into seismicity that cannot
be directly correlated with injection, which is the inferred triggering mechanism for most (if not all) of the seismicity within
255 the KSMMA. The characteristics of the seismicity generated during this period suggest no fundamental differences in terms
of temporal or spatial patterns or magnitudes to previous seismicity within the KSMMA that can be correlated with injection.

In fact, many of the characteristics appear to be equivalent to events detected prior to lockdown. Prior to the development of the Montney play, natural seismicity within the KSMMA was almost non-existent. The Canadian National Seismic Network (CNSN) recorded 20 earthquakes (M_L2.5 - M_L4.3) from 1984 to 2008, which are assumed to be mostly natural events

260   (Halchuk, 2009). The closest event to have occurred with a significantly larger magnitude than this occured in March 1986 (M_w5.4) NE of Prince George, British Columbia (Lamontagne et al., 2008). In order to investigate the likelihood that our detected seismicity is natural seismicity, we calculate the expected recurrence rates of seismicity within the KSMMA greater than M_L2.5 from historical data, which is the magnitude of completeness used for the determination of seismic hazard maps in Canada due to detection thresholds from the Canadian public seismic network. The total number of earthquakes detected

265   by the national network from 1984 to 2008 was 20 (Halchuk, 2009), suggesting a recurrence interval of 0.83 events per year. It is therefore unsurprising that during the period of quiescence, no events greater than M_L2.5 were detected. Following the Gutenberg-Richter formula (Gutenberg and Richter, 1944), it stands that there should be a 100-fold increase in the event rate to estimate the number of events >M_L0.5, suggesting an event count of 83. Therefore, a maximum of 21% of events detected during relative quiescence can be attributed to natural seismicity. Therefore, over 70% of seismicity generated during

270   this period of relative quiescence cannot be explained by this mechanism, and we suggest is likely produced as a remnant to previous operations, and therefore directly related to previous states of stress. With events being generated over 4 months since the cessation of operations, the state of stress at depth must be near-critical for an extended period of time in order to generate this "latent" seismicity.

275   The generation of seismicity in response to hydraulic fracturing is typically attributed to either fluid migration models, poroelastic phenomenon, or potentially aseismic slip (e.g. Bao and Eaton, 2016; Langenbruch and Zoback, 2016; Shapiro and Dinske, 2009; Segall and Lu, 2015; Eaton, 2018; Goebel and Brodsky, 2018; Eyre et al., 2019a). In the fluid migration model, pore fluid pressures are significantly increased upon fluid injection reducing the effective normal stress within a fault zone, which is sufficient to trigger seismicity (e.g. Peña Castro et al., 2020; Bao and Eaton, 2016). Given the temporal and spatial

280   correlation between seismicity and hydraulic fracturing operations within the KSMMA, this appears to be a likely cause of seismicity. Under this model, the seismicity rate is usually observed to be proportional to the pore pressure, and is assumed to track the injection rate (Langenbruch and Zoback, 2016). Consequently, a slow and steady decrease in the rate of seismicity over time would be expected to occur, as fluid pressure leaks into the surrounding formations (Eyre et al., 2020), before seismicity returns to the background (i.e. natural) rate. Since seismicity during the period of quiescence is long-lived, shows no decay and

285   cannot be attributed to increased fluid injection, another process must be involved in its generation. Furthermore, if pore fluid pressure and relaxation as a direct consequence of immediate injected fluid was the trigger of the seismicity during this period of quiescence, we would expect the seismicity to spatially migrate directly outwards from the most recently injected wells. We see no evidence of this (Fig. 5(b)), suggesting direct pore fluid migration cannot be held responsible for the triggering of this sequence.

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Seismicity triggered by pore pressure diffusion can also be estimated by determining the propagating pore pressure fluid front (r_t) related to the hydraulic diffusivity in a homogeneous isotropic saturated poroelastic medium (Shapiro and Dinske, 2009; Parotidis et al., 2003) by:

$$r_t = 4 * \pi * D * t, \tag{1}$$

295

where D is the hydraulic diffusivity and t is time since injection. If the triggering front (r_t) closely follows the maximum distance of seismicity through time, then pore pressure diffusion is thought to play a central role in the triggering of this seismicity (e.g. Shapiro and Dinske, 2009; Parotidis et al., 2003). Diffusivity (D) is generally assumed to range in the Earth's crust between 0.1 m^2/s and 10 m^2/s (Scholz, 2019), although in areas affected by hydraulic fracturing is thought to generally

300 be in the range of 0.1 m^2/s to 2 m^2/s (e.g. Goebel et al., 2017; Shapiro and Dinske, 2009; Parotidis et al., 2003). Yu et al. (2019) suggested similar diffusivity values determined from seismicity related to hydraulic fracturing in the Montney formation to the NW of KSMMA, although others have speculated that much smaller diffusion values would be expected in shale formations (Eyre et al., 2020; Guglielmi et al., 2015). Higher values of diffusivity in hydraulic fracturing scenarios are anticipated due to faults and fractures at depth acting as fluid corridors (Caine et al., 1996), compared to in-tact shales. However, the seismicity

305 generated in the KSMMA during the period of quiescence shows no coherence with a triggering front from the most recently active injection wells (Fig. 7), suggesting that pore pressure diffusion is not the dominant mechanism responsible for triggering these earthquakes.

Other models proposed for the generation of seismicity in response to hydraulic fracturing suggest that both pore pressure

310 and poroelastic effects are feasible mechanisms (e.g. Segall and Lu, 2015; Goebel and Brodsky, 2018). In these instances, the increased pore pressure due to injection is thought to load the surrounding rock matrix, altering the stress field, often at great distances from the original injection site, if the region is well hydraulically connected. Again, however, this model suggests that seismicity is generated as a response to injecting fluid into the Earth, which was not occurring at the time of our latent seismicity. Given that the stress field would likely diminish following the cessation of fluid injection, we would also expect a

315 decay in seismicity with time. We do not observe this. Alternatively, the trapping of fluids within a fault zone with only minor fluid migration along the fault, could result in slow changes to the effective stress due to changes in pore pressure (Sibson, 1992). In this method, seismicity should migrate spatially outwards from this fault zone as the effective stress migrates. We also see no evidence of this spatial migration (Fig. 5(b)).

320 Recently, Eyre et al. (2019a) have suggested that aseismic slip may play an important role in the generation of seismicity, whereby distal unstable regions of a fault are loaded by aseismic slip that initiated due to an increase in pore pressure within a stable zone, leading to the generation of seismicity. Once slip is initiated, far-field intraplate stresses may repeatedly reload unstable regions of the fault, leading to relatively steady seismicity rates. They suggest the driving stresses of such behaviour

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325   are most likely to be elevated pore pressures (as a result of ongoing hydraulic fracturing in the area) becoming trapped within
       fault zones due to low permeabilities within many formations. Given that in the absence of the cessation of operations the
       detection of latent seismicity is extremely difficult, there are few examples of long-lived seismicity associated with hydraulic
       fracturing operations. One recent example comes from a long-lived seismic swarm in Alberta, where seismicity was observed
       over 10 months after injection ceased, and was interpreted as being driven primarily by aseismic slip (Eyre et al., 2020). We
       favour this interpretation of aseismic slip playing an important role in the initiation of seismicity since ongoing hydraulic
330   fracturing operations are not required to generate ongoing seismicity; instead, the previous trapping of fluids within fault zones
       may be enough to sustain the generation of seismicity.

       It is widely reported that earthquakes can be generated by transient stress changes related to the passage of seismic waves
       (i.e. "dynamic triggering", (e.g. Wang et al., 2015; Van der Elst et al., 2013; Hill and Prejean, 2007)). In some cases, this
335   dynamic triggering can also be delayed by days or weeks following a teleseism, potentially related to the re-distribution of
       pore fluid from the passing seismic waves (Brodsky and Prejean, 2005) or through initial aseismic slip on faults triggering
       seismicity (Shelly et al., 2011). During the period of quiescence (28 March to 6 August 2020), 43 earthquakes of >M6 were
       reported by the United States Geological Survey (2020), that may have the potential to cause dynamic triggering. We follow the
       methodology set out by Wang et al. (2015), whereby we first select only the teleseismic events that generated an estimated peak
340   ground velocity of greater than 0.2 cm/s at any station within the KSMMA, as defined by Lay and Wallace (1995), whereby:

$$logA_{20} = M - 1.66log_{10}\delta - 2,$$ (2)

and:

$$PGV \approx \frac{2\pi A_{20}}{T}$$ (3)

       where A_{20} is the peak waveform amplitude when filtered at 20s; M is the magnitude; δ is the epicenter-station distance (in
345   degrees); and T is the surface wave period (assumed to be 20 s). This method identified 40 events from the original list of
       teleseismic events. We then calculated the β statistic (Matthews and Reasenberg, 1988) by:

$$\beta(N_1, N_2, t_1, t_2) = \frac{N_2 - E(N_2)}{\sqrt{var(N_2)}},$$ (4)

       which is a quantitative measure of the level of dynamic triggering, representing the standard deviation in the background
       seismicity rate after a remote event. N_1 and N_2 are the number of earthquakes detected before (t_1) and after (t_2) the remote
350   event, respectively. Here, we take t_1 and t_2 to be 12 hours. $E(N_2) = N_1 x t_2/t_1$ is the expected number of earthquakes after
       the main shock based on the background seismicity rate. If no earthquakes occur in t_1 (i.e. before the main shock), N_1 is set
       to 0.25 based on the equivalent range of the probability density function (Matthews and Reasenberg, 1988; Hill and Prejean,

2007). When $\beta \geq 2$, there is sufficient statistical evidence (at a 95% confidence level) that there is a significant increase in the seismic event rate following the remote event (Hill and Prejean, 2007).

355

We identify 7 remote earthquakes that generate a β value ≥ 2 (Fig. 8), including the largest magnitude event to have occurred to date in 2020 that occurred 99 km SSE of Perryville, Alaska on 22 July at 06:12 UTC, with $M_w 7.8$ (United States Geological Survey, 2020), although the increase in event count in the KSMMA following this remote event is difficult to determine without statistical analysis. In some cases however, such as following the $M_w 6.1$ event on 31 May 2020, 43 km W of Lampa, Peru, a

360 significant increase in the number of events detected in KSMMA is clear. Our analysis therefore suggests that a maximum of 8% of the seismicity detected during this period of relative quiescence may be attributed to dynamic triggering, in particular the events on 31 May 2020, however <70% of the detected seismicity cannot be attributed to primary activation mechanisms such as this, and therefore in our opinion are the result of "latent" ongoing processes.

5   Conclusions

365 Seismicity generated in the KSMMA has always been attributed to oil and gas recovery in the area, primarily due to its temporal and spatial correlation to operations. However, during the COVID-19 pandemic in the summer of 2020, operations in the KSMMA were halted. Despite this, 389 seismic events were recorded by our seismic network. These events occurred within the spatial extent of previous events in the area (a corridor orientated NW-SE), and had similar magnitudes to previously recorded seismicity ($\sim M_L$-1 to $M_L 1.2$). The low magnitude of completeness (Mc = 0.4) is indicative of the general quietening

370 of the area, as operations and the movement of people were restricted with government regulations. The b-value of generated seismicity (~ 1.96) is similar to previous estimates within areas dominated by hydraulic fracturing. Unlike during active hydraulic fracturing operations, events showed no temporal clustering, but instead were generated in a fairly constant manner over the ~ 4 months of quiescence. No spatial correlation between the most recently active wells in the area and seismicity could be determined, however the fact that seismicity occurs at the depths of previous injection (i.e. the target formations)

375 suggests that the area must be hydraulically linked.

Since there is no temporal or spatial evidence that these events are a direct consequence of the most recent hydraulic fracturing in the area (i.e. an aftershock sequence driven by pore pressure diffusion or poroelastic relaxation), and since the area is typically naturally quiet seismically (a maximum of 21% of the detected events), we conclude that most of these events are

380 an indirect response of the increased pore pressures at depth which is causing aseismic slip on already pressurized fault zones, as a result of previous fluid injection in the area. A number of events may be the result of dynamic triggering, from remote events with $M_w > 6$ (up to $\sim 8\%$), however this process cannot account for the majority of the seismicity observed (>70%). We suggest that the prior fluid injection in the area has altered the state of stress, and caused fluids to become trapped in fault and fracture zones at depth. This allows seismicity to be primarily generated by aseismic slip loading unstable regions of these

385 pressurized zones at depth. Once slip has initiated, far-field stresses may repeatedly reload these unstable zones, leading to the relatively stable seismicity rate that is observed.

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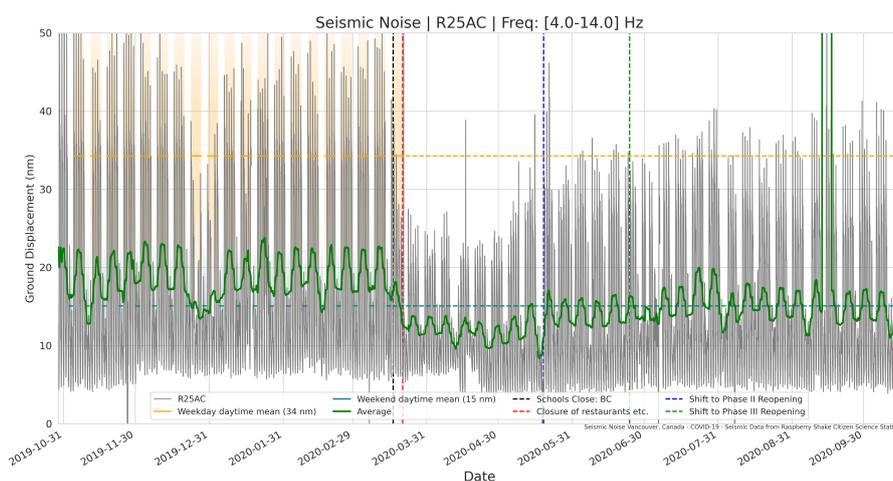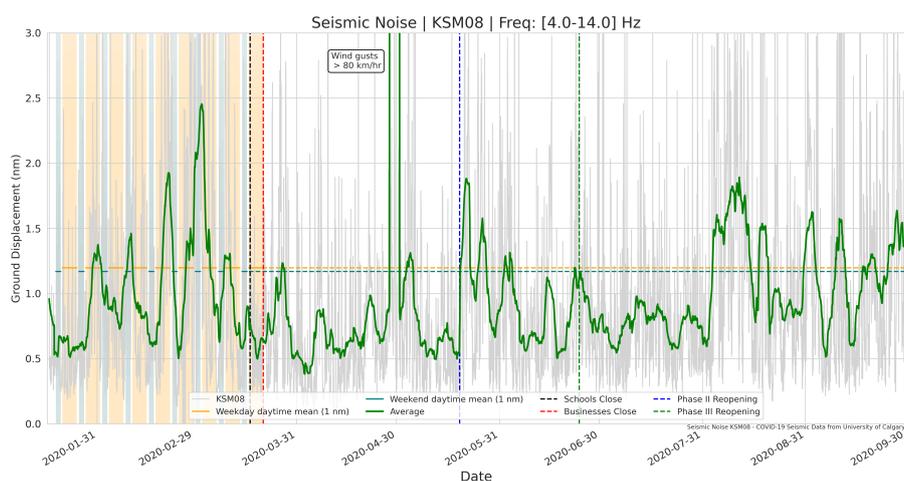
Figure 1. Filtered (4-14Hz) ambient seismic noise displayed as displacement from station R25AC (Z component) located in Vancouver, British Columbia. 30-minute average PPSD (dark grey), with rolling mean (window size = 92 hours) shown in green. The timing of different lockdown scenarios for British Columbia are shown as vertical dashed lines. A clear reduction in the ground motion is observed following initial lockdown conditions in March 2020. The large peak in noise in September is thought to be meteorological, rather than a sudden increase in anthropogenic activity. Figure courtsey of codes developed by Thomas Lecocq and Fred Massin.
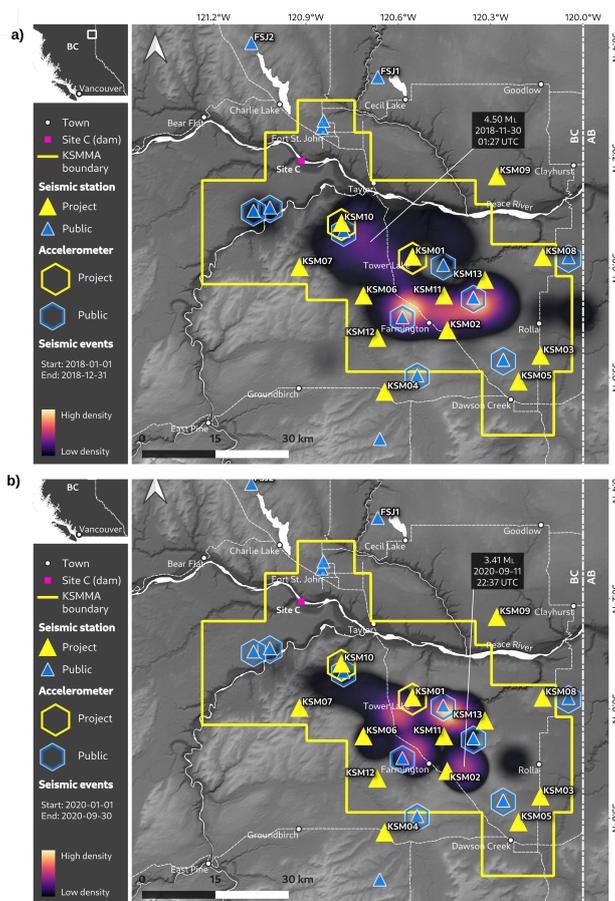
Figure 2. Spatial locations of seismicity concentrations within the KSMMA. Higher density of seismic events is indicated by brighter colours; lower density by darker colours; and no seismicity by grey. The outline of the KSMMA boundary is shown in yellow; public seismic monitoring stations as blue triangles; the newly installed EO network as yellow triangles; and co-located accelerometers as hexagons. FSJ1 and FSJ2 are also part of the EO network but were installed in 2018. FSJ1 was decommissioned on 26 August 2020 but is shown for completeness as it was used in seismic analysis prior to this. The largest measured magnitude event within the KSMMA boundary is marked. (a) Seismic events reported by NRCan between 1 January 2018 and 31 December 2018 (Visser et al., 2020). Note: although the new dense array was not installed at this time, it is shown on the map for reference. The largest event in 2018, occurring on 30 November, north of Tower Lake is shown (M_L 4.5). (b) Seismic events recorded on the newly installed EO network (and incorporating data from public stations) from 22 January 2020 to 30 September 2020. The largest magnitude event, occurring on 11 September 2020 is indicated (M_L 3.4). Figure courtsey of Thomas H. A. Swincoe, using QGIS (https://qgis.org/en/site/about/index.html).
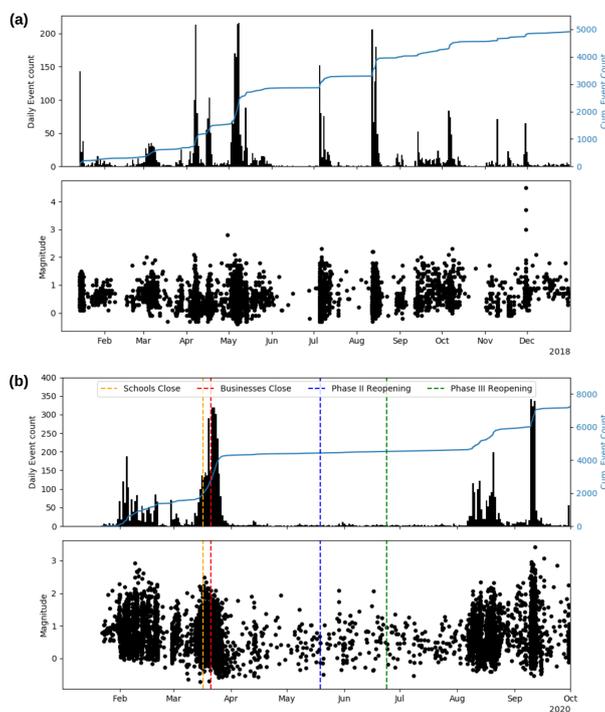
Figure 3. Temporal evolution of seismicity within the KSMMA (daily counts in black, cumulative counts in blue). Magnitudes calculated using the M_L formula of Hutton and Boore (1987). Distinct temporal patterns can be observed in both years, associated with ongoing hydraulic fracturing operations in the area. *Note: the different time (x-axis) scales.* (a) Seismicity within the KSMMA in 2018 from catalogue of Visser et al. (2020). (b) Seismicity within the KSMMA in 2020 from catalogue derived by the newly installed network (yellow triangles, Fig. 2). The timing of different lockdown scenarios affecting the KSMMA are shown as vertical dashed lines. The time period from April to August 2020 represents the period of relative quiescence due to the COVID-19 lockdown. The time lag for seismicity build up after the Phase III reopening reflects the time required for operations in the area to be restarted.

Figure 4. Filtered (4-14Hz) ambient seismic noise displayed as displacement from station KSM08 (Z component) located within the KSMMA. 30-minute average PPSD (dark grey), with rolling mean (window size = 92 hours) shown in green. The timing of different lockdown scenarios for British Columbia are shown as vertical dashed lines. A clear reduction in the ground motion is observed following initial lockdown conditions in March 2020, and significant increases in ground motion as lockdown measures are rescinded. Figure courtsey of codes developed by Thomas Lecocq and Fred Massin.
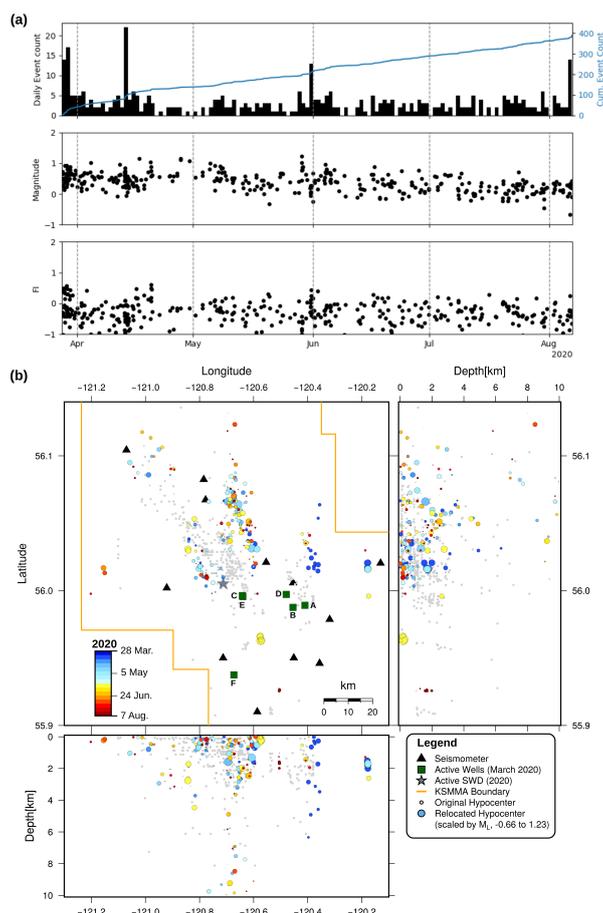
Figure 5. Temporal and spatial evolution of 389 events detected in the KSMMA during the cessation of operations from April to August 2020. (a) *Upper:* Daily event count and cumulative event counts. *Middle:* M_L determined using the formula of Babaie-Mahani and Kao (2020). *Lower:* Frequency Index (FI) detailing the ratio of high frequency energy to low frequency energy within each detected waveform at KSM06. (b) Spatial evolution of events coloured by time and scaled by magnitude. Active wells that initiated seismicity in the month prior to quiescence (March 2020) are shown as green squares labelled A (most recently active prior to lockdown i.e. late March 2020) to E (active in early March); one active SWD well is shown as the grey star. Figure generated using GMT v.6 (Wessel et al., 2019).
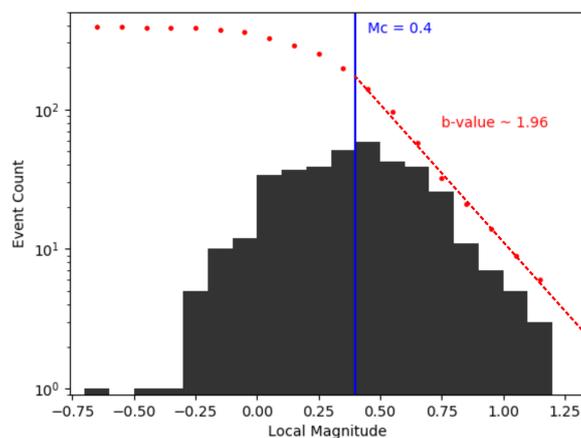
Figure 6. Frequency-Magnitude distribution of events (n=389) detected in the KSMMA during quiescence from 28 March to 6 August 2020. Event counts in magnitude bins of 0.1 are shown as black columns; the cumulative event value per bin is shown as a red dot. The magnitude of completeness (Mc) is 0.4, and the estimated b-value is 1.96 (Gutenberg and Richter, 1944).
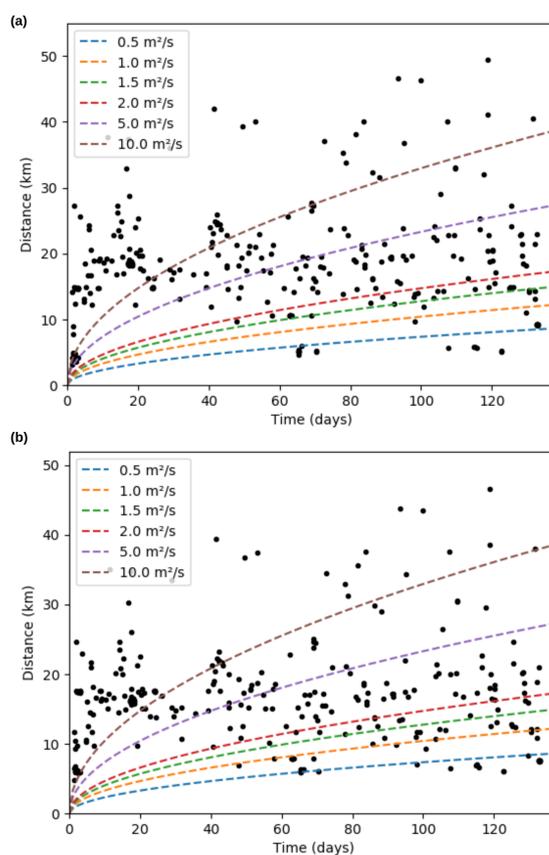
Figure 7. Time-distance plots of latent seismicity from 28 March to 6 August 2020. (a) Distance of events measured away from Well A (Fig. 5) and time zero taken as the last day of injection at this well prior to lockdown (27 March 2020). (b) Distance of events measured away from Well B (Fig. 5) and time zero taken as the last day of injection at this well prior to lockdown (27 March 2020). Representative diffusion curves associated with hydraulic fracturing and waste-water injection (Goebel et al., 2017; Shapiro and Dinske, 2009) are shown. The events during quiescence in the KSMMA cannot be successfully modelled using pore pressure diffusion suggesting it cannot be a primary mechanism for generating this seismicity.
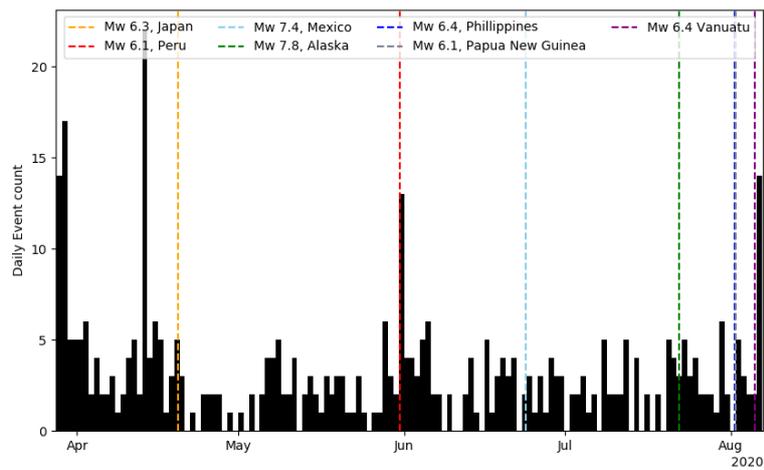
Figure 8. Teleseismic events (dotted vertical lines) that statistically (95% confidence level) generated dynamic triggering of seismicity within the KSMMA.