

# ***Interactive comment on “Unprecedented quiescence in resource development area allows detection of long-lived latent seismicity” by Rebecca O. Salvage and David W. Eaton***

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Received and published: 12 February 2021

[id=ROS]All line numbers refer to line numbers in the updated “clean” manuscript i.e. that without the track changes.

## **1 General Comments**

**This nicely written and well-structured article examines how seismicity rates during quiescent periods can be used to examine driving factors behind “latent”**

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**induced seismicity after direct injection is stopped. The authors study seismicity in the Kiskatinaw area of British Columbia before, during, and after the 2020 COVID-19 government-imposed shutdown to investigate how the seismicity behaves when fluid injection operations in the region temporarily stop. They find evidence for “latent” seismicity during the quiescent period, of which 70% cannot be explained by direct injection, natural seismicity, or triggered earthquakes. After comparing the seismicity trends to those expected from fluid migration models, pore pressure diffusion, poroelastic effects, and aseismic slip, the authors eliminate all but aseismic slip as the most likely driving factor to the latent seismicity. Throughout this process, the authors provide clear analysis and evidence to their arguments.**

**This paper is a unique and timely article with respect to the current pandemic and global lockdowns. The authors apply common and suitable seismological techniques to investigate earthquakes that would otherwise be hidden by direct injection seismicity. I think this article will be of interest to the audience of Solid Earth. Please find the specific and technical comments below.**

*Thank you for these comments - we are glad the reviewer found our article of interest.*

## **2 Specific Comments**

- 1. Line 28: This number (~0.3%) has been updated in a later publication: “Ghofrani & Atkinson (2020), Activation Rate of Seismicity for Hydraulic Fracture Wells in the Western Canada Sedimentary Basin, BSSA”. Regionally, they now estimate ~0.8%.**

*Thank you for bringing this updated rate and reference to our attention. We have updated the reference and value in the text (L 33).*

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2. **Line 64: Could the authors also include why only the Z-component was used in the study, and not any horizontals.**

*We have included a comment here indicating that since a number of the public stations, including R25AM which is used in Fig. 1, are single component sensors, we used the Z-component only in order to be able to compare the noise reduction in a number of different locations (L 72-74).*

3. **Line 80 - Section 3: Please explain why you chose to compare to 2018 and not 2019 in this section. You compared the seismic noise levels to 2019 (lines 77-78), why not also the seismicity?**

*We have included a statement to clarify this (L 132-133). We are unable to compare seismicity within the KSMMA between 2019 and 2020 as the seismicity from 2019 is not yet published. We are able to analyse the seismic noise since this is only computed at a single station (from which data is available on IRIS), whereas a large number of stations are needed to compute accurate hypocenter locations.*

4. **Line 80 - Section 3: Also, please include somewhere how you processed the time series, any band-pass filter applied? SNR?**

*We have included this information within Section 3, as requested (L 115-117).*

5. **Line 82-88: More details on the instruments would be good, e.g., sample rates? Are the newly installed stations specifically chosen in some way for certain magnitudes? Site conditions (same for all stations, or different)?**

*We have extended this paragraph to include more of this information, in particular why the sensors were placed in this array, and the depth of burial of the array (L 96-105). We have also made it more obvious that further information about this array and its installation can be found in Salvage et al., 2021 <http://www.geosciencebc.com/summary-of-activities-2020-energy-water/>.*

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6. **Line 110 - Figure 2: Is the absolute seismicity density the same for the two subplots? I.e. is high density for (a) = high density for (b)? To compare the two periods, it would be good if the colours refer to similar seismicity densities. If not, please make this clear in the caption. Also, is the seismicity used the same as in Figure 3?**

*We have updated Figure 2 to ensure that the absolute seismicity in both a and b are now equal meaning that the high and low density colours can be directly compared between the figures. We have included a comment about this in the figure caption so that the reader is also aware of this. We have updated the caption of Figure 3 to mirror the caption of Figure 2, to make it clearer that this is the same seismicity being plotted. Furthermore, we have updated Figures 2b and 3b to include data to the end of 2020 (which was not available when this paper first went to review).*

7. **Line 113 - Figure 3: Could the authors include the magnitude of completeness for the two different datasets in the figure (to make it easier to compare).**

*We have added this to Figure 3. We have also changed the axes on the plots so that they are the same, allowing a direct comparison of the event counts and magnitudes with time.*

8. **Line 149-150: Could the authors include more details on where the KSM08 station is located? Is it far away from cities/towns? Near any wells?**

*We have included the distance that this station is from the nearest settlement (Rolla), and indicated that the recent seismicity in the vicinity of KSM08 would suggest active wells in the area prior to the lockdown scenario experienced in 2020 (L 174-178).*

9. **Line 153-155 - Figure 4: Any ideas as to why the seismic noise level is low**

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**in July at KSM08? Looks to be down at the same levels as during April. Is this a trend seen at more stations than just KSM08?**

*This is seen at a number of stations (to varying degrees). I have confirmed with the regulator that this is a downturn in the market leading to less operations in the area due to company decisions, rather than a government enforced lockdown. We have added a comment about this to the text (L 182-185).*

10. **Line 165: For the FI value, do you compensate for high-frequency attenuation in some way? You mention that you use one station for all events, won't the low-to-high ratio be different depending on how much high-frequency energy has been attenuated? I.e., events from larger distances have less high-frequency content due to more attenuation than the closer events.**

*We do not compensate for high-frequency attenuation. You are correct in saying that the ratio will be dependent upon attenuation factors, including the distance the event occurs away from the recording station. We stated within the text (L 196-198) that we use station KSM06, which is centrally located in the main clusters of seismic activity. However, we have tested the analysis at all KSM stations and see no temporal patterns within the FI. We have updated the text to make this evident.*

11. **Line 188-189: Visually, Figure 3b appears to have a slightly decreasing magnitude trend with time. The cloud is around ML 0.0 to 1.0 in June, and ML -0.5 to 0.5 in August. Have you looked into this? Any tests done to find trends?**

*We have carefully looked at the magnitudes with time, in both Figures 3 and 5(a). The potential lowering of the lowest magnitudes from April to August may be an artefact since the last 2 stations in the KSM array were installed in May 2020, thus allowing better azimuthal coverage for event detection and location, as well as lowering the magnitude of completeness. As the magnitudes presented are*

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*the average of the magnitude of the event calculated at each station, there is also a degree of error in the estimation.*

12. **Line 191-204: It would be interesting to see a second plot from before lockdown and a third after seismicity picked back up again. How does the b-value change between the three periods?**

*We actually would like to submit this analysis as another paper, showing the effect of the lockdown and the change in b-values with time in this area, hence we are not including it here.*

13. **Line 356: Would it be possible for the authors to instead plot each event as a circle (e.g., based on magnitude as in previous plots) so that they can highlight the events they identified as triggered by a remote event?**

*The way in which we have determined whether any events have the possibility to be triggered by remote earthquakes (following the methodology of Wang et al., 2015), does not allow us to spatially determine which of our detected earthquakes may have been affected. Instead, it is a statistical measure of the temporal evolution of seismicity before and after the teleseism. For this reason, Fig. 7 is the best way to present the potential increase in seismic activity within the KSMMA following a teleseismic event.*

### 3 Technical Comments

- **General technical: figure font size was quite small and needs to be increased.**

*Fonts have been increased on all figures.*

- **Line 7-11: Regarding the three sentences: the authors write that "general characteristics" are similar between active and shutdown periods, but then**

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go on to state two reasons they are different (magnitude and temporal clusters) and only one reason they are similar (spatially). This makes it seem like they are more different than similar. Perhaps rephrase first sentence.

*We have re-written this part of the abstract to try and make our meaning more clear and to avoid confusion.*

- **Line 45: Sentence structure is off.** “We call this latent seismicity i.e. seismicity...”

*We have re-written this sentence for clarity.*

- **Line 62: Comma missing:** “Following the methodology of Lecocq et al. (2020) we compute the...”

*This has been added.*

- **Line 72 - Figure 1: Please also explain what the vertical highlighted (yellowish) periods are in the figure caption (occurring before vertical dashed red line). Also, text is very small.**

*The text in all figures has been updated. We have added a comment in the caption about the highlighted periods before the vertical dashed red line, which indicates weekdays.*

- **Line 75-77: Sentence is confusing, consider rearranging:** “Following the reopening of some businesses in May and June 2020, the increase in noise is interpreted as the increased movement of people, although it remains lower than pre-pandemic levels.” Or something similar.

*Thank you for this suggestion. We have rephrased this sentence to allow clarity.*

- **Line 87: Why not reference Figure 2 here for the station configuration?**

*We have added a reference to Fig. 2 at this point in the text.*

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- **Line 99-101: Sentence doesn't make sense.**

*We have clarified this sentence.*

- **Line 104-107: In Figure 3 caption, you reference Hutton and Boore (1987) as the origin of your ML calculations. This is not who you reference in the text.**

*We have changed the structure of the figure caption to reflect that the Hutton and Boore calculation for magnitude was only used for the 2018 catalogue, in work previously carried out by Visser et al. (2020). Our work (seismicity in 2020) uses the magnitude calculation of Babaie-Mahani and Kao (2020), as referenced in the text.*

- **Line 112: “ML 3-4+” doesn't really make sense, either it's ML 3-4, or ML 3+.**

*We have changed this.*

- **Line 113 - Figure 3: Please use the same y-axis limits on the a) and b) plots since we're supposed to compare them.**

*The axes of Figure 3 have been updated and now includes all data from 2018 and 2020, which was previously unavailable at the point of submission of this manuscript for review.*

- **Line 114-115: You only state in the Figure 3 caption that the seismicity increase in 2020 March, August, and September are due to hydraulic fracturing operations. Please include this in the text instead of in the figure caption.**

*This information was already included in the text on lines 113-118, under Section 3 (now L 136-138).*

- **Line 149-150: Comma placement in this sentence is a bit off.**

*We have re-written this sentence.*

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- **Line 156: “a pre-lockdown levels” is grammatically incorrect.**  
*This was supposed to read “as pre-lockdown levels”. This has been changed.*
- **Line 161 - Figure 5: Here it says you use the Babaie-Mahani & Kao (2020) formula to compute ML. Same or different to the one in Figure 3?**  
*We have updated the caption for Figure 3 to indicate that it was indeed the same formula as used in Figure 5 (Babaie-Mahani and Kao (2020)).*
- **Line 177-178: “2000 m and 2500 m” please switch to km to stay consistent with previous sentence.”**  
*This has been changed.*
- **Figure 6: is not referenced in the text.**  
*This was an oversight on our part. We have added reference to Fig. 6 in the discussion of the  $M_c$  and  $b$ -value section.*
- **Line 247-249: Strange sentence structure with the commas and parentheses.**  
*This sentence has been re-written.*
- **Line 299: “it” is missing: “in areas affected by hydraulic fracturing it is thought to...”**  
*This has been added.*

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Interactive comment on Solid Earth Discuss., <https://doi.org/10.5194/se-2020-203>, 2020.