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Abstract

This open file report presents the outcomes of comprehensive earthquake monitoring conducted in northeastern British Columbia (NE BC) for 2021 and 2022. The monitoring effort encompasses two primary seismic observation areas: the Kiskatinaw Seismic Monitoring and Mitigation Area (KSMMA) and the Ground Motion Monitoring Permit Condition Area (GMMPCA), each characterized by differing oil and gas operations, as well as population densities. A cutting-edge machine-learning based workflow was employed for earthquake detection and phase picking. A manual review step was included to ensure the quality of all earthquake detections and locations. From 1 January 2021 to 31 December 2022, a total of 9655 seismic events were detected, with an average monthly rate of 420 events. The KSMMA recorded 8468 events during this period, characterized by tight clustering, while the GMMPCA registered 899 events. Variations in seismicity rates were observed when compared to previous reports, potentially influenced by changes in industrial activities and seismic monitoring capabilities. The magnitude of completeness for KSMMA increased to 1.01, reflecting changes in the seismic monitoring network, while the GMMPCA exhibited a magnitude of completeness of 1.45, slightly higher than the previous reporting period. This report underscores the dynamic nature of induced seismicity in NE BC, emphasizing the need for continued monitoring, adaptive mitigation measures, and robust seismic data collection to inform decision-making and enhance earthquake preparedness.

1. Introduction

It has been known for several decades that injecting high-pressure fluids into subsurface formations may induce earthquakes (Healy et al., 1968). Thus, the seismic risk associated with injection activities such as hydraulic fracturing (HF) and wastewater disposal (WD) cannot, and should not, be ignored. HF operations in Canada are mostly conducted in the Western Canadian Sedimentary Basin (WCSB), mainly due to the abundant unconventional hydrocarbon resources. Most developments of unconventional hydrocarbons in WCSB focus on two specific formations, known as the Montney and Duvernay Plays.

Over 20,000 seismic events have been detected in NE BC from the year 2000 up until the end of 2020 (Visser et al., 2020). In this time period, there have been several events with magnitude larger than 4.0. While the Canadian Hazard Information Service is responsible for the operation of the Canadian National Seismograph Network (CNSN) and the routine monitoring of significant earthquakes in and around Canada, most of the seismic signals from events induced by injection activities in NE BC are too small to be picked up by CNSN stations. This apparent lack of adequate monitoring capability posed a serious challenge to both the research community and the regulator. To properly deal with this important issue, the BC Seismic Research Consortium (SRC) was established in 2012 with the goal of addressing critical knowledge gaps about injection-induced earthquakes and monitoring seismic events from industry activities in NE BC.

Several organizations are involved in the research effort of the BC SRC, including Geoscience BC, the Canadian Association of Petroleum Producers (CAPP), Natural Resources Canada (NRCan) and the BC Energy Regulator (BCER). The Yukon Government was also involved for a short period. The BC SRC has also partnered with several Canadian universities to improve the seismic monitoring capabilities in NE BC.

There are two enhanced seismic monitoring areas in NE BC. These two areas are known as the Kiskatinaw Seismic Monitoring and Mitigation Area (KSMMA) and the Ground Motion Monitoring Permit Condition Area (GMMPCA) (Figure 1). These two areas are very different in terms of the character of oil and gas operations, as well as differences in population density. Due to differences in seismic station density, the magnitude of completeness and location uncertainty vary between these two seismic monitoring areas. Generally, the KSMMA has a lower magnitude of completeness and location uncertainty than the GMMPCA, mainly due to the higher seismic station density. In this report we will describe the methodology and results of routine earthquake monitoring for 2021 and 2022.

2. Method

The goal of routine earthquake monitoring is to detect and locate earthquakes with efficiency, accuracy, and precision. We accomplish this using a machine-learning workflow, with a review process performed by an earthquake analyst. There are several steps in this workflow. These include acquiring and pre-processing the seismic waveforms, phase picking, phase association, earthquake location, and calculating the earthquake magnitudes. The details of each of these steps are outlined below.

2.1. Phase Picking

In our workflow, the seismic waveforms are downloaded on a daily basis. These waveforms are then subject to the earthquake detection and phase picking steps. Both of these tasks are performed using a machine learning approach. The well established EQTransformer software (Mousavi et al., 2020) is used. Because EQTransformer estimates probabilities of earthquake and phase detection, different probability thresholds can be employed. In our case, earthquake detection probability must exceed the threshold of 0.1 in order for further processing to continue. Once an earthquake has been detected, the probability of either P- or S-wave arrival must exceed the threshold of 0.08 in order for the phase to be accepted. Such low probability thresholds are selected because EQTransformer has a low rate of false detections and to ensure that the catalog has a high level of completeness.

2.2. Phase Association

Phase association is performed using a grid-search method. A coarse grid is defined over the entire study area. Travel times for each combination of grid node and seismic station are calculated. For each phase detected by EQTransformer, all other phases within a specified time window are selected. This time window is calculated as the maximum possible S-wave travel time in the study area, plus twenty seconds. For each grid node in the study area, the arrival times are back-projected using the calculated travel time grid. This yields an estimated origin time for each phase at each grid node. If the back-projected origin time of enough phases falls within a four second time window at any grid node, this grid node will be considered as an initial solution. Seven phases are required for a grid node to pass this step. If several grid nodes have more than the minimum number of accepted phases, then the grid node with the most accepted phases will be accepted as the candidate solution. This phase association technique may remove some real events, although with the thresholds as defined, this is unlikely.

2.3. Earthquake Location

Earthquake location is performed using the NonLinLoc software (Lomax et al., 2000). In order for an event to be considered for location, the event must have at least four associated phases. NonLinLoc offers several different options for sampling the solution space of the earthquake location problem. For our workflow, we use the Oct-Tree algorithm (Lomax and Curtis, 2001) to sample the solution space. If any event falls on the pre-defined boundary of the study space, then this event is removed. Events that fall on the boundaries of the study area are unlikely to be real, and even if they are real, they hold little relevance for seismic monitoring applications.

2.4. Magnitude Calculation

Magnitude calculation is performed using an in-house program, in which amplitudes are measured on the vertical component of the seismograms for all phase picks. The magnitude calculation methodology of Kao and Mahani (2019) is used.

2.5. Quality Control Measures

All earthquake detections and locations are reviewed by an earthquake analyst after the automatic procedure has finished. This is done on a daily basis, and any false events are discarded. Only standard P- and S- phases are used, and any phase picks at an epicentral distance greater than 1.5 degrees are discarded. The earthquake catalog is divided into several segments (e.g., CNSN, KSMMA_working, KSMMA_plus_working, etc.). An earthquake is assigned to a specific segment of the catalog depending on where the earthquake occurs, as well as the monitoring entity that provided the earthquake solution. The quality control measures are different for each segment of the catalog. These quality control measures are outlined in Appendix 1

3. Results

From 1 January 2021 to 31 December 2022, there were 9655 events detected by the routine monitoring program. There were 420 events per month on average, with 6984 events in 2021, and 2671 events in 2022.

3.1 The KSMMA

In this time period, there were 8468 events detected in the KSMMA (Figure 2). Events in the KSMMA are tightly clustered, with a prominent NW to SE lineament. On average, there were 368 events per month during the study period. Visser et al. (2021) reported a seismicity rate of 730 events per month in 2019 and 2020. The rate of seismicity in the current study period is significantly lower than that reported by Visser et al. (2021). Several hypotheses could explain this drop in seismicity rate. One explanation is the possible changes in industrial activities, which can be confirmed by the regulatory agency. Another possible explanation is the increased ability of operators to avoid triggering seismicity. It is also possible that changes in the seismic monitoring network in the KSMMA led to a decrease in observed seismicity. Several stations were decommissioned in the study period, which could lead to fewer events being detected. The maximum number of events per month in the KSMMA was 2488, which occurred in December 2021. The fewest number of events per month was 2, which occurred in October 2022 (Figure 3). The magnitude of completeness in the KSMMA was estimated to be 1.01 (Figure 4), which is significantly higher than the magnitude of the completeness of 0.7 determined in the last reporting period by Visser et al. (2021). This is likely due to changes in the seismic monitoring network during the study period.

3.2 The GMMPCA

During the study period, 899 events were detected in the GMMPCA, at an average rate of 39 events per month (Figure 5). This is a higher rate of seismicity than detected by Visser et al. (2021). The average rate of seismicity is higher than the highest month in the previous reporting period. A maximum of 301 events per month were recorded in November 2022. No event was recorded in September 2021. Surprisingly, the number of events detected in the GMMPCA exceeded the number of events in the KSMMA in the last three months of 2022 (Figure 3). The magnitude of completeness in the GMMPCA was 1.45 (Figure 6), which is also slightly higher than the value of 1.36 determined in the last reporting period by Visser et al. (2021).

4. Conclusion

This open file presents the outcomes of routine monitoring of seismic activities in NE BC from 1 January 2021 to 31 December 2022. A machine-learning workflow is employed to ensure timely and consistent earthquake detections and locations. A manual-review step is included to ensure that all earthquake solutions are of high quality. The workflow has generally stabilized since the publication of the GSC Open File of Visser et al. (2021), leading to consistent routine monitoring operations. The source solutions presented in this open file extend the earthquake catalogue in NE BC by two more years with an addition of 9655 events. The majority of seismic events were recorded in the KSMMA (8468 events), with much fewer being detected in the GMMPCA (899 events). The difference between the two areas is due to differences in monitoring capabilities and the amount of oil and gas operations. The magnitude of completeness in both areas has increased slightly since the last reporting period, likely due to the removal of several seismic monitoring stations.

5. References

Healy, J. H., Rubey, W. W., Griggs, D. T., & Raleigh, C. B. (1968). The Denver earthquakes. *Science*, *161*(3848), 1301-1310.

Lomax, A., & Curtis, A. (2001). Fast, probabilistic earthquake location in 3D models using oct-tree importance sampling. In *Geophys. Res. Abstr* (Vol. 3, p. 955).

Lomax, A., Virieux, J., Volant, P., & Berge-Thierry, C. (2000). Probabilistic earthquake location in 3D and layered models. In *Advances in seismic event location* (pp. 101-134). Springer, Dordrecht.

Mahani, A. B., & Kao, H. (2019). Accurate determination of local magnitude for earthquakes in the Western Canada Sedimentary basin. *Seismological Research Letters*, *90*(1), 203–211. https://doi.org/10.1785/0220180264

Mousavi, S. M., Ellsworth, W. L., Zhu, W., Chuang, L. Y., & Beroza, G. C. (2020). Earthquake transformer—an attentive deep-learning model for simultaneous earthquake detection and phase picking. *Nature Communications*, *11*(1), 1–12. https://doi.org/10.1038/s41467-020-17591-w

Visser, R., Kao, H., Dokht, R.M.H., Mahani, A.B., and Venables, S. (2021). A comprehensive earthquake catalogue for northeastern British Columbia: the northern Montney trend from 2017 to 2020 and the Kiskatinaw seismic monitoring and mitigation area from 2019 to 2020; Geological Survey of Canada, Open File 8831, 1 .zip file. doi:10.4095/329078.

Appendix 1: Quality Control Measures

- CNSN
    - The latitude must be >= 55.5° N and < 60° N
    - The longitude must be >= -123.5° E and < -119.8° E
- DAWSON_antelope
    - The depth must be less than 15 kilometres deep
    - At least 4 phases must be used to determine the earthquake hypocentre
    - The latitude must be >= 55.6° N and < 56.5° N
    - The longitude must >= -122.0° E and < -119.8° E
- WORKING_cat
    - There are three different sets of criteria for this segment

    1.
        a. The latitude must be >= 54.0° N and < 56.5° N
        b. The longitude must be >= -121.5° E and < -119.8° E
    2.
        a. The latitude must be >= 56.0° N and < 60.0° N
        b. The longitude must be >= -123.0° E and < -120.5° E
    3.
        a. The latitude must be >= 51.0° N and < 57.0° N
        b. The longitude must be >= -120.0° E and < -113.5° E

Appendix 2: Earthquake origins

Column	Type	Description
id	int	Unique id given to each origin. Used to join arrivals and station magnitudes.
Latitude	float(4)	Latitude in degrees North.
Longitude	float(4)	Longitude in degrees East.
Depth	float(1)	Depth of event in km.
Mag	float(1)	Median of station magnitudes.
MagType	string	All rows are Mlv - local magnitude determined on the vertical waveform component.
Datetime	datetime	The date and time of the event origin.
LocationError	float(2)	Standard Error - RMS of the travel time residuals of the arrivals used for location.
MajaxError	float(2)	Maximum horizontal uncertainty of 68% confidence ellipse in km
MinaxError	float(2)	Minimum horizontal uncertainty of 68% confidence ellipse in km.
Azimuth	float(1)	Azimuth of major axis of 68% confidence ellipse in degrees.
VelocityModel	string	Local velocity model used to locate event. Either NMT or KSMMA.
Ndef	int	Number of phases used to locate event.
Nmag	int	Number of station magnitudes used to determine event magnitude.

Appendix 3: Earthquake arrivals

Column	Type	Description
id	int	Unique id given to each origin. Used to join origins, arrivals, and magnitudes.
Datetime	datetime	The date and time of the phase arrival.
Sta	string	The station code used to identify the station.
Chan	string	The channel code used to identify on which channel the arrival was picked.
Phase	string	The phase code used to identify the phase – either *P* or *S*.

Appendix 4: Earthquake magnitudes

Column	Type	Description
id	int	Unique id given to each origin. Used to join origins, arrivals, and magnitudes.
Datetime	datetime	The date and time that the station amplitude value was taken.
Net	string	The network code to identify the network.
Sta	string	The station code used to identify the station.
Chan	string	The channel code used to identify on which channel the arrival was picked.
Mag	float(2)	The local station magnitude value calculated on the vertical component.

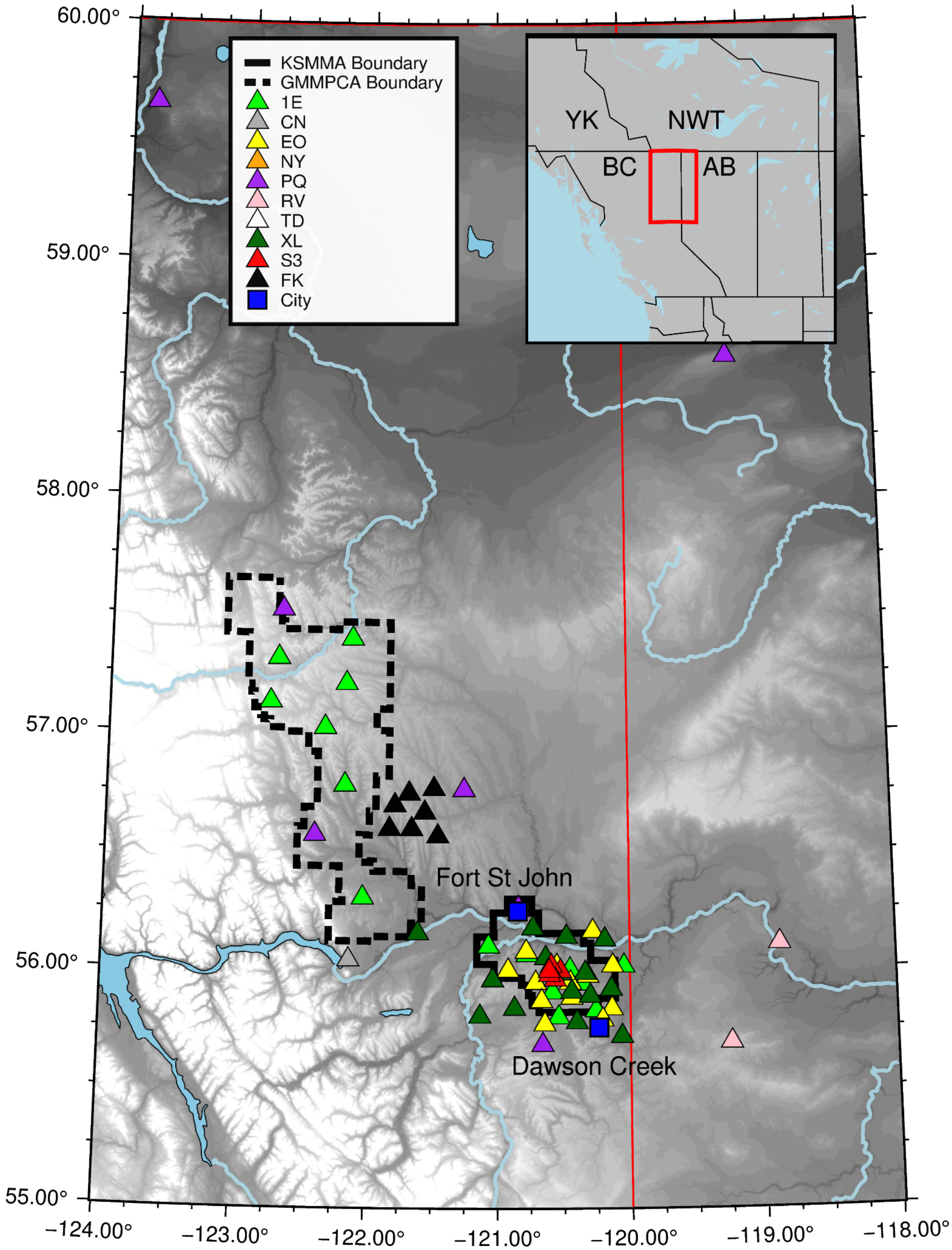

Figure 1: A map of seismic stations used for routine monitoring from 2021-2023, as well as the KSMMA and GMMPCA boundaries.

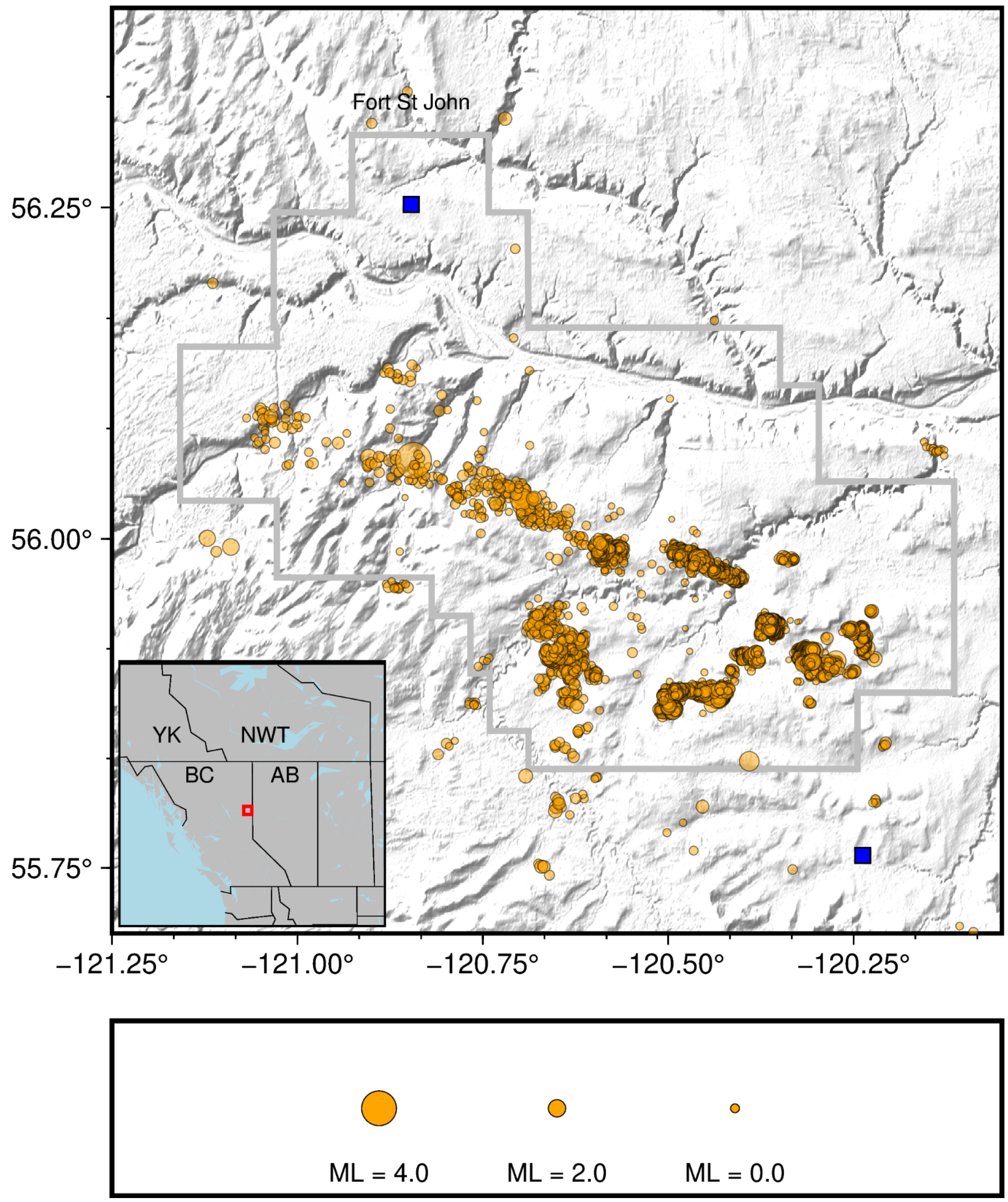

Figure 2: Map view of earthquakes in the KSMMA for this study period.

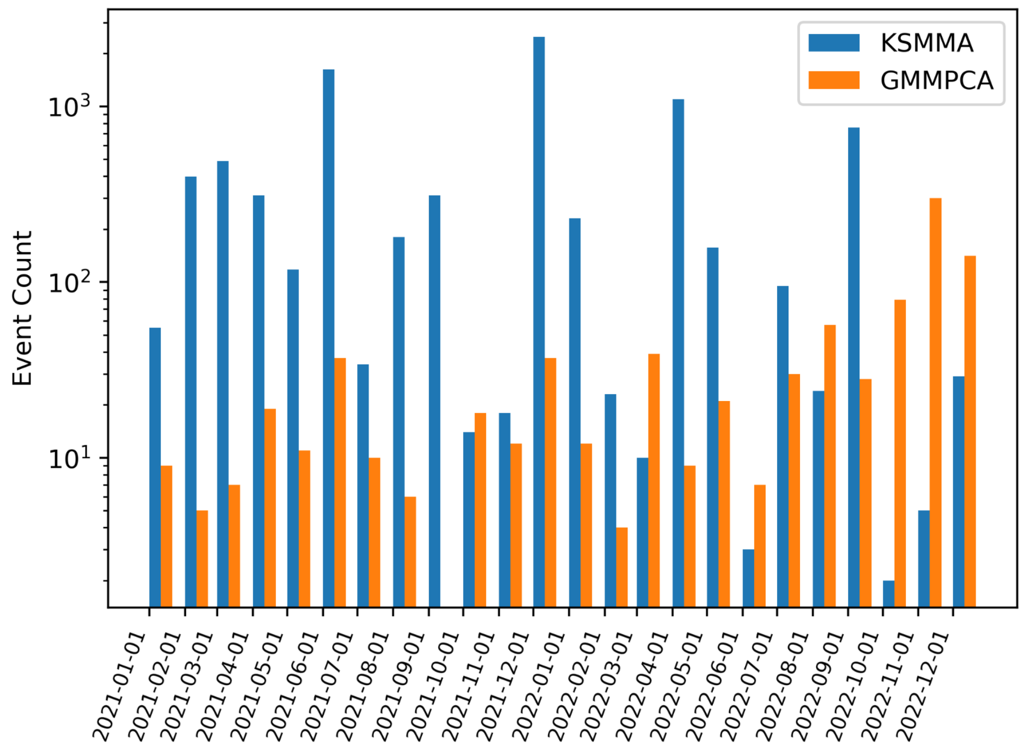

Figure 3: The number of earthquakes per month in the KSMMA (blue) and GMMPCA (orange) from 2021-2023

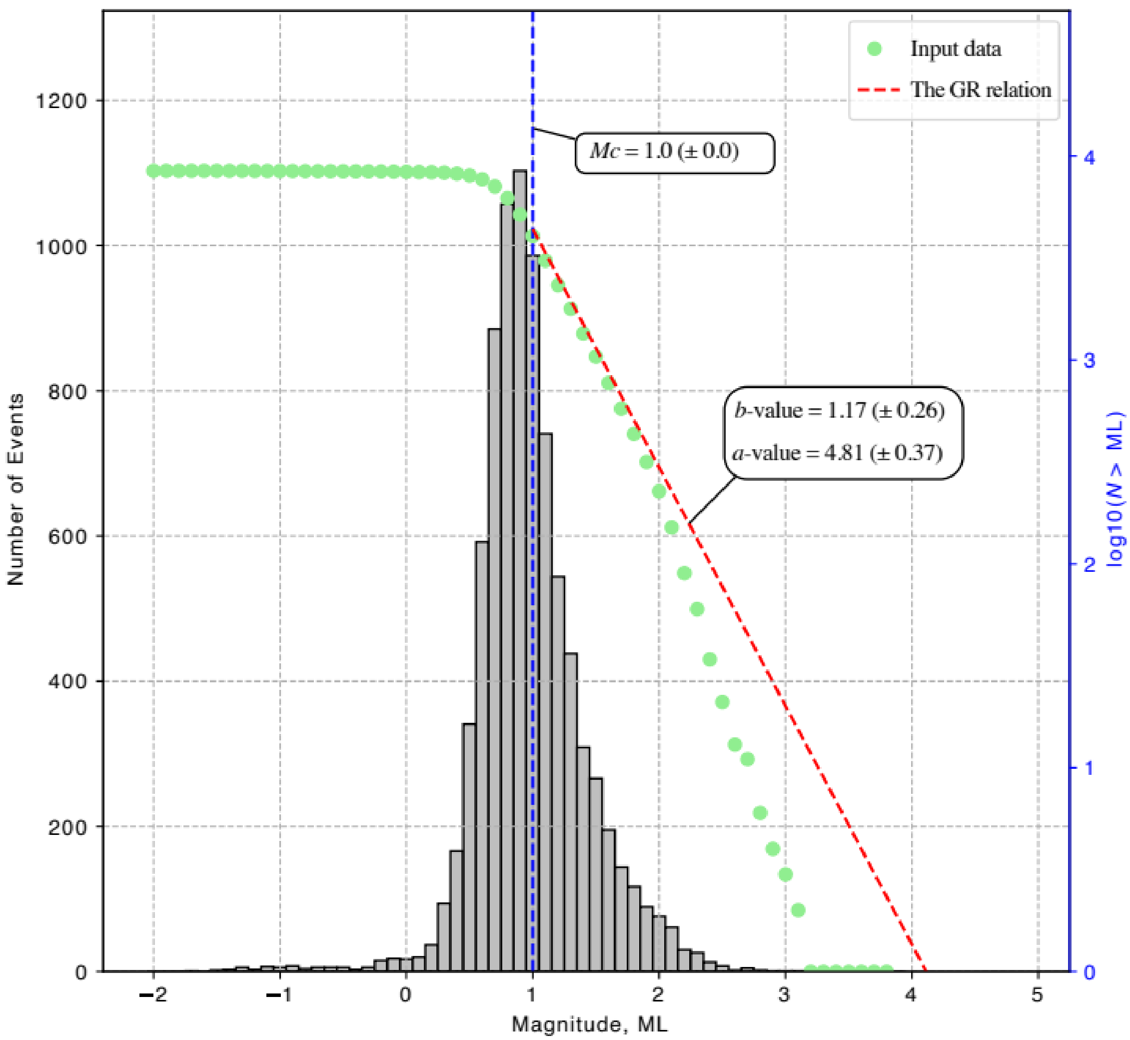

Figure 4: Frequency-magnitude distribution for the seismicity within the KSMMA. The Gutenberg-Richter (GR) relation parameters and their corresponding uncertainties are reported.

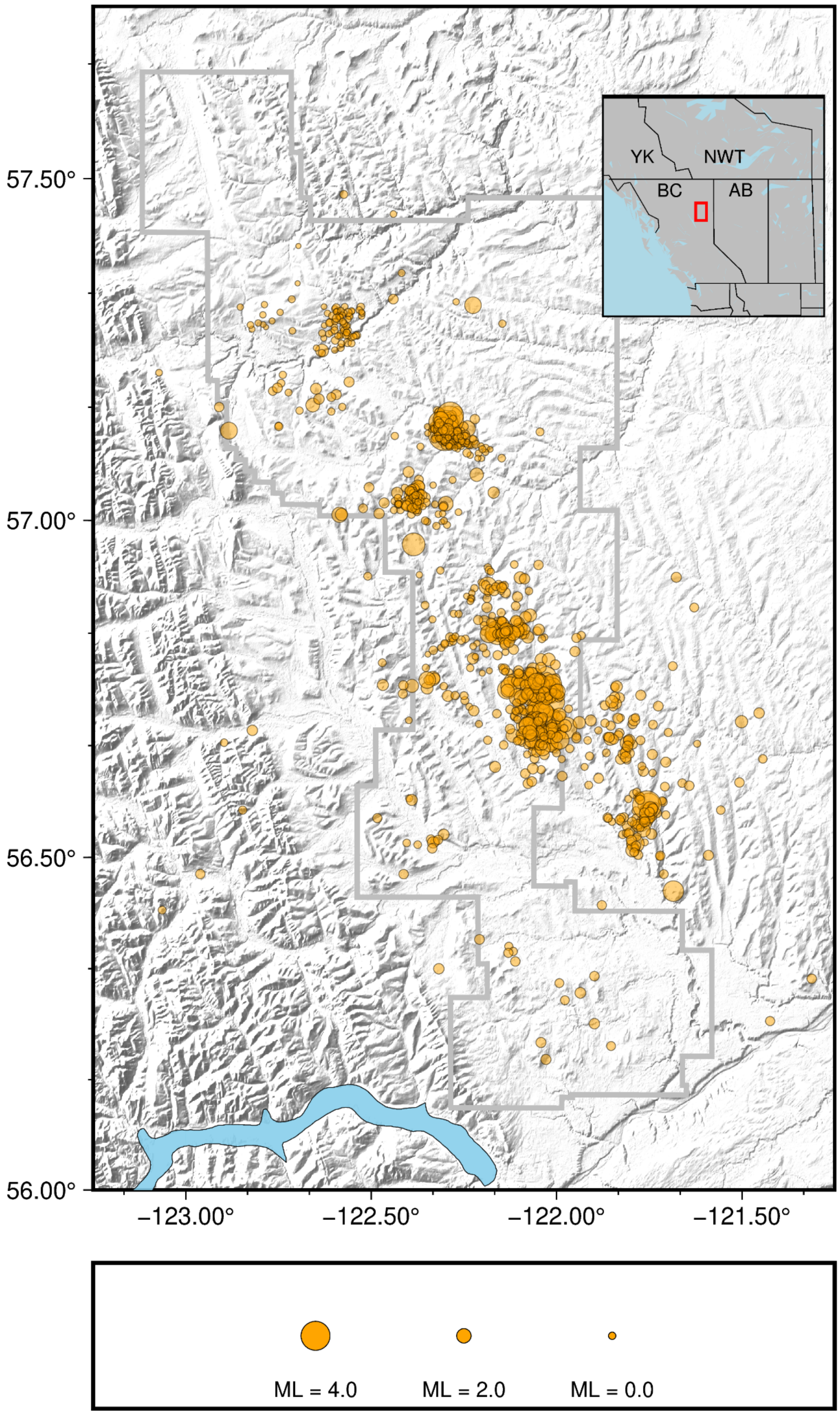

Figure 5: Map view of earthquakes in the GMMPCA for this study period.

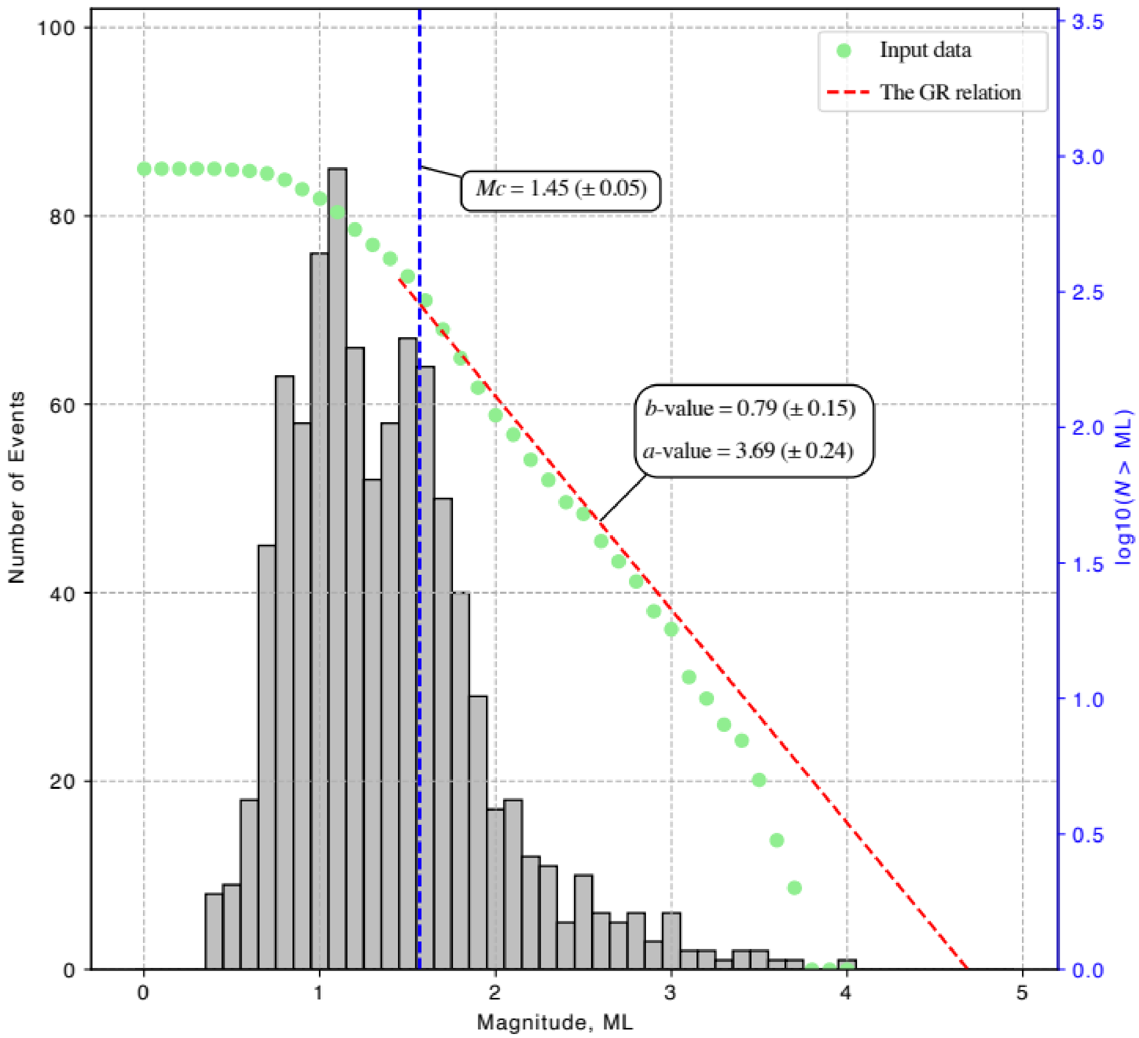

Figure 6: Frequency-magnitude distribution for the seismicity within the GMMPCA. The GR relation parameters and their corresponding uncertainties are reported.