Induced Seismicity Monitoring Project (ISMP): May 2022 - May 2023 Report

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Executive Summary

The BC Seismic Research Consortium (BC SRC) was established by Geoscience BC, the Canadian Association of Petroleum Producers (CAPP), and the BC Energy Regulator (BCER) (formerly the BC Oil and Gas Commission) and works closely with Natural Resources Canada (NRCan) to monitor seismicity in Northeastern British Columbia (NEBC). It followed a recommendation from the BCER in response to concerns regarding induced seismicity associated with hydraulic fracturing in the Horn River Basin. The Yukon Geological Society (YGS) joined the consortium briefly in 2016 to provide an expanded and comprehensive network covering oil and gas activity in NEBC, but due to funding challenges, the YGS left the consortium the following year. The BC SRC is responsible for maintaining the PQ and 1E seismic networks and collaborates with McGill University for station maintenance of the XL network. In addition, the BC SRC has access to additional stations from the CN, EO, and S3 networks operated by NRCan, the University of Calgary (U of C), and Symroc (under a NRCan contract), respectively. See Table 1 for network and station details.

The BC SRC is made up of representatives from each of the consortium partners – Geoscience BC, CAPP, BCER, and the BC Oil and Gas Research and Innovation Society (BC OGRIS). Funding for the BC SRC is shared between Geoscience BC and the BC OGRIS. NRCan provides critical in-kind technical and operational support, based at the Pacific Geoscience Centre in Sidney, B.C.

This report summarises the actions and research taken by the BC SRC for the period May 1, 2022, to May 1, 2023. An update on the seismic monitoring efforts in NEBC is provided, along with an overview and earthquake catalogue of the seismicity detected in the past year. There were 4113 events detected, with 190 of these events having a local magnitude (M_L) greater than 2.0, with the largest M_L being 4.02. No reports of damage were relayed to the BCER.

Update on Seismic Monitoring in NEBC

A map view of seismic stations monitored by the Consortium is shown in Figure 1, and station data availability are shown in Figure 2. Minor changes were made to the seismic monitoring capabilities in NEBC in the past year. Four seismic stations were deployed, as of November 2022 (see Figure 2, stations MONT B, C, D and E). These stations are part of the 1E seismic network and are operated jointly by the Geological Survey of Canada (GSC), and the BCER. The stations deployed by Ruhr University were decommissioned at the beginning of the reporting period, as the 3-year research window for these stations expired at that time (see Figure 2, stations RU01, 02, 04 & 06). No other stations were decommissioned during the reporting period of May 2022 - May 2023. An earthquake catalogue for the reporting period has been developed and included with this report as Appendix A. Seismic event details are also available at https://geoweb-ags.bc-er.ca/portal/apps/webappviewer/index.html?id=a1ecce14d6ae4c92a5295c62a3ee618b, with information such as date, time (UTC), latitude, longitude, depth, and local magnitude. The seismic stations used to locate events in this catalogue are listed in Table 1.

Table 1: Seismic stations used to locate events for the induced seismicity monitoring project.

Array	Network	Station	Latitude ˚N	Longitude ˚E	Elevation (m)
AER	RV	BDMTA	54.8129	-118.9149	935
AER	RV	FAIRA	56.1087	-118.8648	642
AER	RV	WTMTA	55.6942	-119.2398	1030
CNSN	CN	BMTB	56.0451	-122.1332	1099
CNSN	CN	FNSB	58.8061	-122.7328	440
CNSN Plus	1E	BCH1A	55.8324	-120.2590	689
CNSN Plus	1E	BCH2A	55.9461	-120.3561	761
CNSN Plus	1E	MONT1	55.9102	-120.5865	697
CNSN Plus	1E	MONT2	56.0197	-120.0470	642
CNSN Plus	1E	MONT3	56.0058	-120.4539	783
CNSN Plus	1E	MONT4	57.3184	-122.7057	1110
CNSN Plus	1E	MONT5	57.0269	-122.3360	1097
CNSN Plus	1E	MONT7	56.3079	-122.0316	797
CNSN Plus	1E	MONT8	56.0673	-120.7774	695
CNSN Plus	1E	MONT9	55.8039	-120.5388	832
CNSN Plus	1E	MONTA	56.1043	-121.0700	651
CNSN Plus+	1E	MONTB	57.4026	-122.1302	959
CNSN Plus+	1E	MONTC	57.1338	-122.7622	1181
CNSN Plus+	1E	MONTD	56.7848	-122.1778	737
CNSN Plus+	1E	MONTE	57.2138	-122.1745	1024
CNSN Plus	PQ	NAB1	56.7663	-121.2587	754

CNSN Plus	PQ	NBC5	57.5231	-122.6776	1161
CNSN Plus	PQ	NBC7	56.2678	-120.8426	676
CNSN Plus	PQ	NBC8	56.5731	-122.4044	709
McGill	XL	MG01	56.0548	-120.6380	721
McGill	XL	MG03	55.9122	-120.4414	697
McGill	XL	MG04	55.9914	-120.3380	682
McGill	XL	MG05	55.8951	-120.3019	795
McGill	XL	MG07	55.7836	-120.4024	749
McGill	XL	MG08	55.8412	-120.8731	722
McGill	XL	MG09	56.1591	-121.6081	795
McGill	XL	MG10	55.7229	-120.0633	798
McGill	XL	MG11	55.9222	-120.1423	657
Ruhr-	XL	RU01	56.1451	-120.4800	612
Ruhr-	XL	RU02	56.1320	-120.1882	611
Ruhr-	XL	RU04	55.9614	-121.0388	892
Ruhr-	XL	RU06	55.9896	-120.5269	773
Symroc	S3	016	56.0224	-120.5961	802
Symroc	S3	020	55.9635	-120.5647	619
Symroc	S3	029	55.9843	-120.6081	784
Symroc	S3	031	56.0000	-120.6097	762

\+ Denotes stations added during the report period

\- Denotes stations removed during the report period

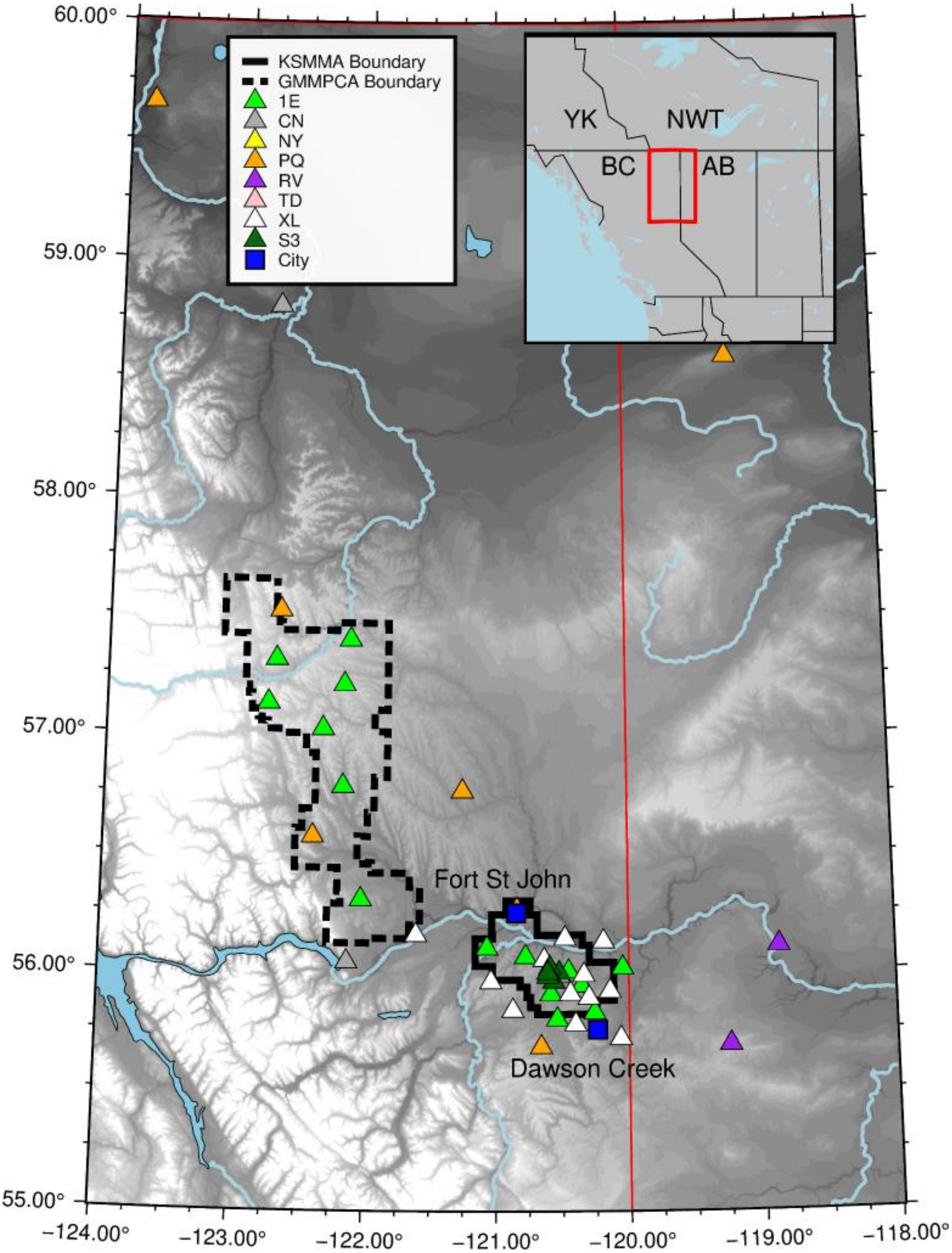

Figure 1: Seismic stations in NE BC and surrounding area coloured by network code.

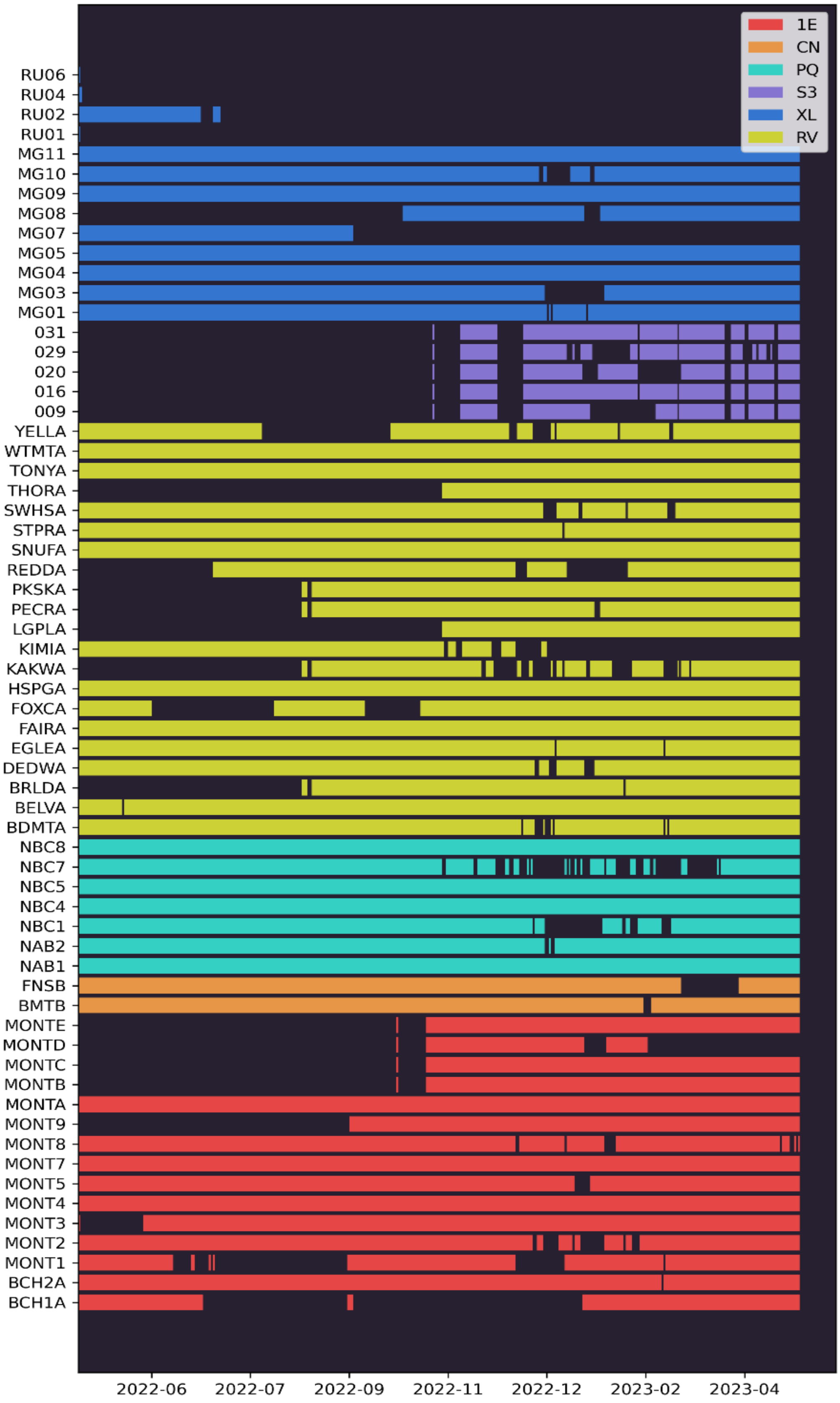

Figure 2: Gantt chart of station availability. Only stations with registered phase arrivals within the last year are shown.

Seismicity from May 1, 2022, to May 1, 2023

In total, there were 4113 events detected for this study period. A map view of the seismicity in the Kiskatinaw Seismic Monitoring and Mitigation Area (KSMMA) is shown in Figure 3 and seismicity for the Ground Motion Monitoring Permit Condition Area (GMMPCA) is shown in Figure 4. In the KSMMA, there were 3074 events, while in the GMMPCA, there were 1032 events. There were 190 events with a M_L greater than 2.0, and only one event with a M_L greater than 4.0 (which was 4.02). Figures 5 and 6 show the magnitude frequency distribution and Gutenberg-Richter relationship of seismicity in the KSMMA and GMMPCA areas, respectively. The magnitude of completeness, above which the catalogue is considered to be complete, was 1.01 for the KSMMA and 1.12 for the GMMPCA.

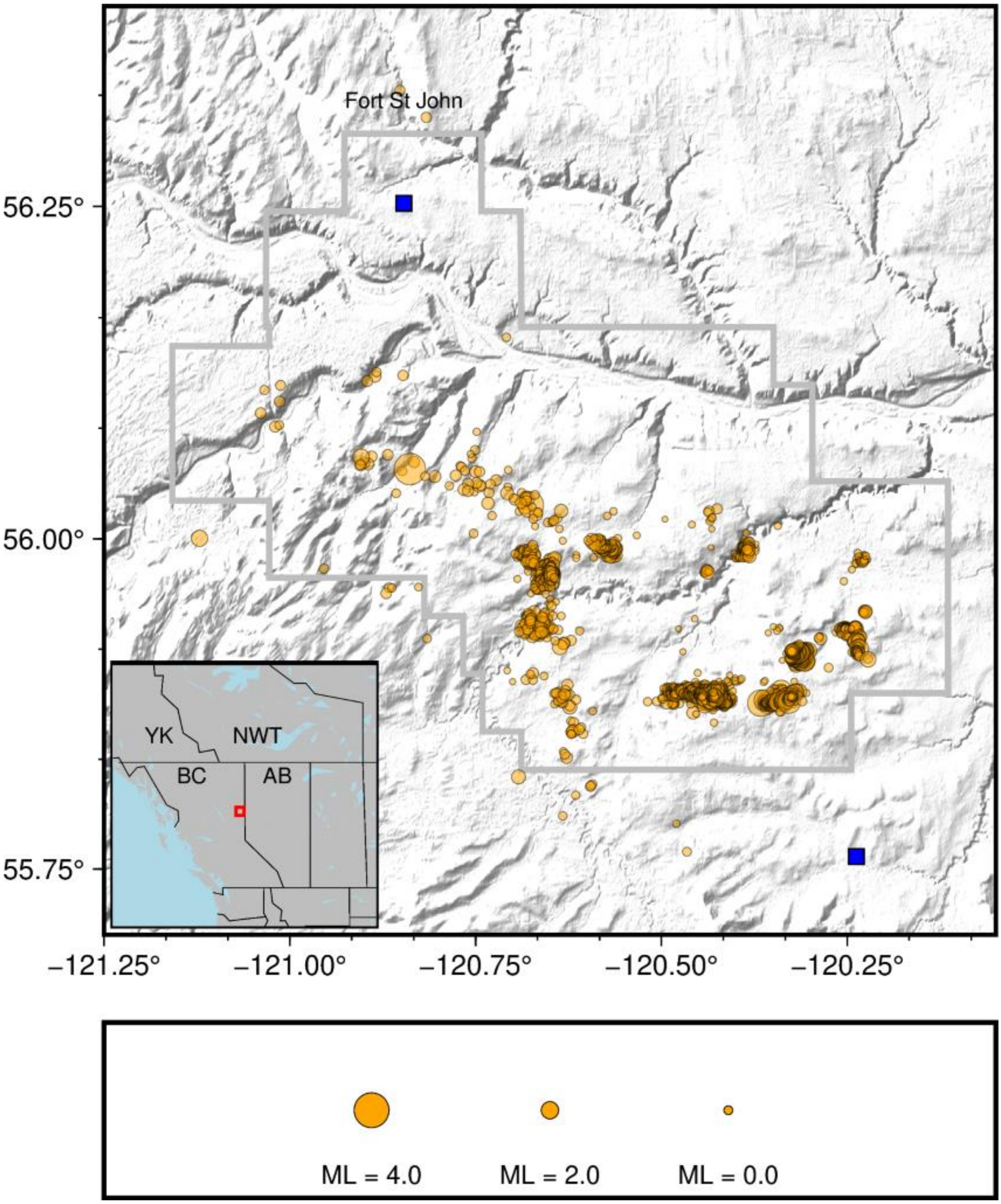

Figure 3: Map view plot of seismicity in the KSMMA.

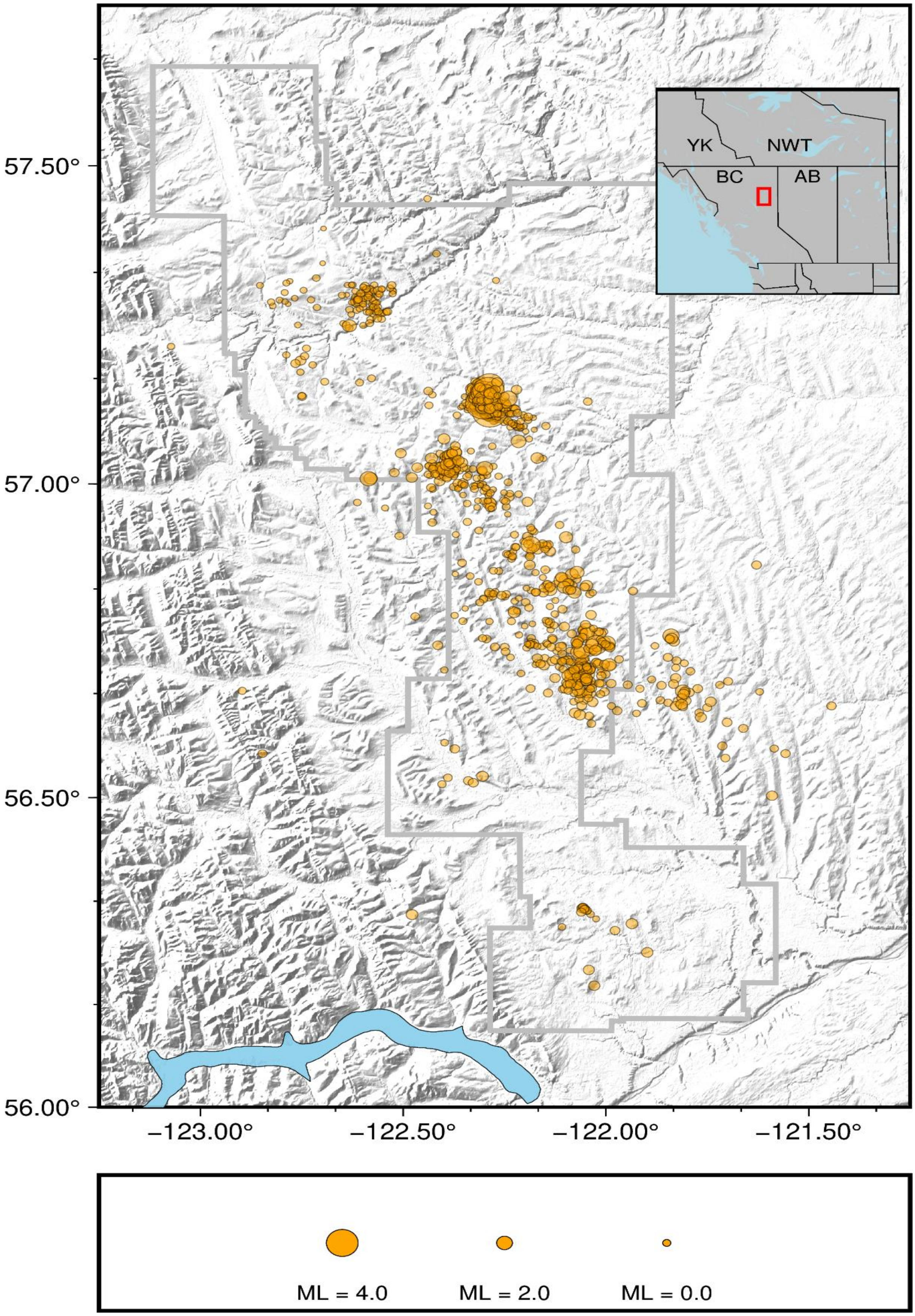

Figure 4: Map view plot of seismicity in the GMMPCA.

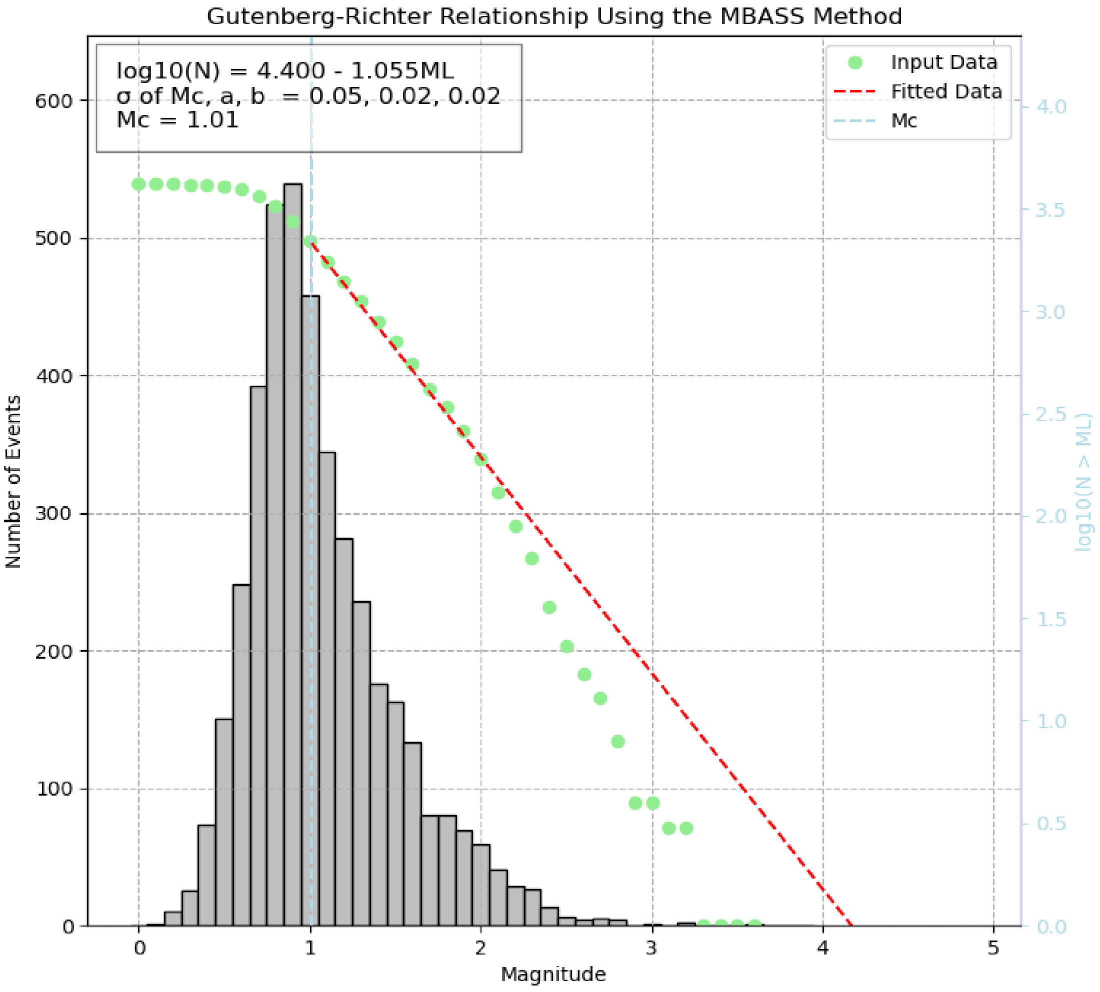

Figure 5: Magnitude frequency distribution for the KSMMA region.

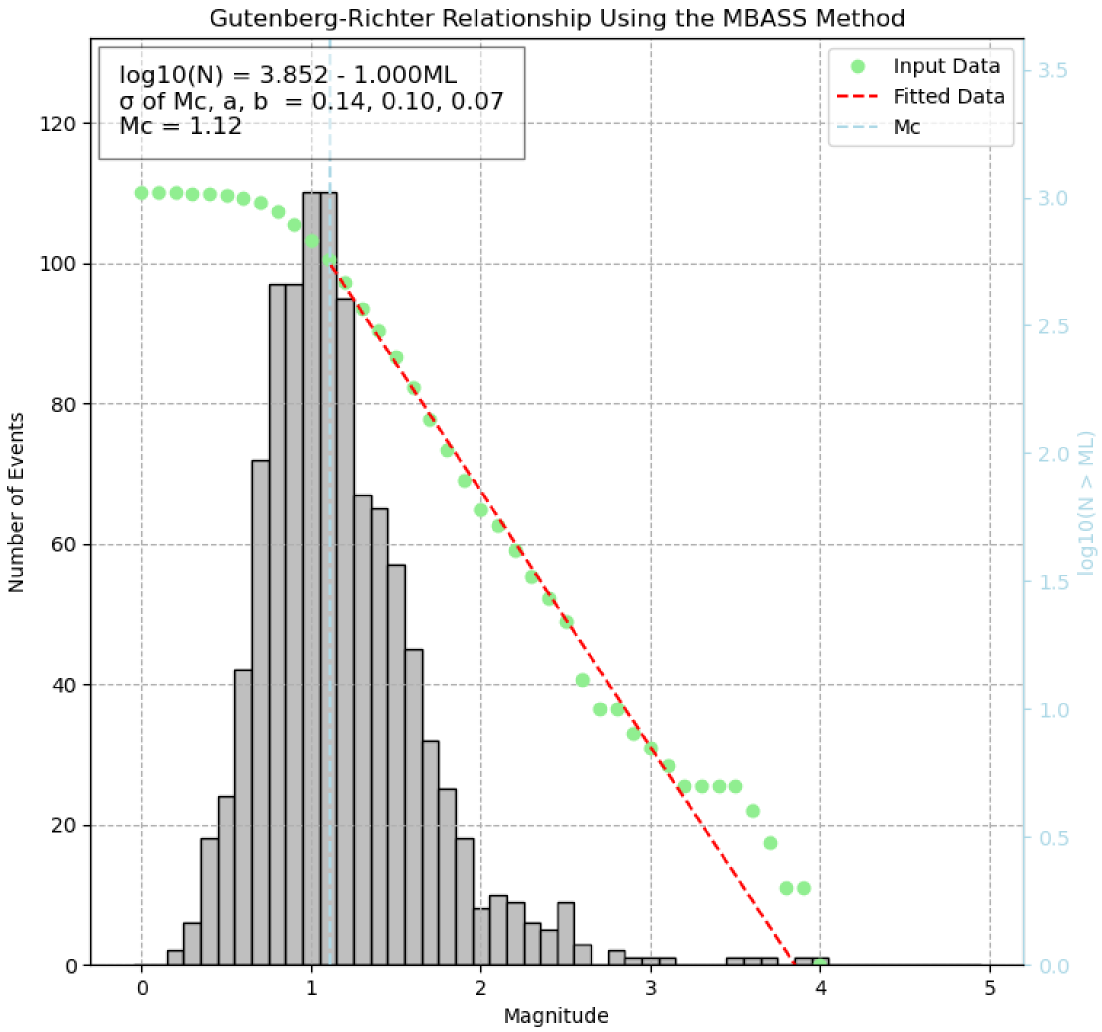

Figure 6: Magnitude frequency distribution for the GMMPCA.

Changes to Routine Seismic Monitoring in NEBC

The routine seismic monitoring for NEBC has had several years to mature and develop and is now reaching a relatively stable state of routine operation. Thus, few changes were made to the routine seismic monitoring in the last year. One notable development is the enhancement of real-time earthquake monitoring. The real-time system does not directly feed into the catalogue developed for routine monitoring, but rather provides notifications to interested parties within minutes of a seismic event occurring. The real-time system uses a similar workflow to the automatic portion of the catalogue development, with EQTransformer (Mousavi et al., 2020) providing the earthquake phase arrival time estimates, and NonLinLoc (Lomax et al., 2000) calculating the earthquake origin parameters. For the real-time system, slightly different parameters are used, such that the events detected by the real-time system are not identical to events detected by the routine monitoring. If any events are detected by the real-time system that are not detected by the routine monitoring, an analyst can manually add these events to the routine catalogue.

The other notable development in the last year is a change in seismic analyst. Chet Goerzen will be acting as seismic analyst until September 30, 2023.

Research Communication

Members of the BC SRC are associated with the following presentations post May 1, 2022.

Kao, H. (2022). Induced Seismicity Research Project: Highlights of Accomplishments in 2021-2022, Environmental Geoscience Program Annual Scientific Presentations. 10 May.

Kao, H. (2022). Discovery of a new type of injection-induced earthquakes and the implications for seismogenesis, invited lecture at the Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, 2 June.

Kao, H. (2022). Resolution limit of seismic waveform similarity, invited lecture at the Central Weather Bureau, Taipei, Taiwan, 8 June.

Kao, H. (2022). An update of induced seismicity research results and their regulatory implications, invited talk at Canadian Association of Petroleum Producers (CAPP) Induced Seismicity Meeting, 20 September.

Kao, H. (2022). A systematic assessment of induced seismic risk in Canada from carbon sequestration, invited talk at GSC CCUS Workshop, 15 Nov.

Tan, F., C. Goerzen, J. Hutchinson, D. Gao, A.M. Farahbod, K.M. Yi, H. Kao, and E. Nissen (2022). Source untangler guided by artificial intelligence image recognition (SUGAR), presented at 2022 Fall Meeting, AGU, Dec.

Wang, B., Kao, H., H. Yu, and R. Visser (2022). Hybrid foreshock patterns of injection-induced earthquakes in western Canada, presented at the GeoConvention conference, 20-22 June.

Technical Reports and Papers

The following reports or papers are associated with BC SRC research post May 1, 2022.

Dokht, R.M.H., H. Kao, H. Ghofrani, and R. Visser (2022). Combining deep learning and the Source-Scanning Algorithm for improved seismic monitoring, Bull. Seismol. Soc. Am., doi:10.1785/0120220007.

Eyre, T.S., S. Samsonov, W. Feng, H. Kao, and D.W. Eaton (2022). InSAR data reveal that the largest hydraulic fracturing-induced earthquake in Canada, to date, is a slow-slip event, Science Reports, 12, 2043, doi:10.1038/s41598-022-06129-3.

Wang B., H. Kao, R.M.H. Dokht, R. Visser, and H. Yu (2022). Delineating the controlling factors of hydraulic fracturing-induced seismicity in the Northern Montney Play, Northeastern British Columbia, Canada, with machine learning, Seismol. Res. Lett., doi:10.1785/0220220075.

Wang, B., H. Kao, H. Yu, R. Visser, and S. Venables (2022). Physical factors controlling the diverse seismogenic behaviour of fluid injections in western Canada, Earth and Planetary Science Letters, 589, 117555, doi:10.1016/j.epsl.2022.117555.

Wang, B., H. Kao, H. Yu, R. Visser, and A. Verdecchia (2023). Quantitative evaluation of the competing effects of wastewater disposal and hydraulic fracturing on causing induced earthquakes: A case study of an M3.1 earthquake sequence in western Canada, Journal of Geophysical Research: Solid Earth, 128, e2022JB025048, doi:10.1029/2022JB025048.

Wang, B., H. Kao, H. Yu, R.M.H. Dokht, R. Visser (2023). Forecasting the activity level of hydraulic fracturing induced earthquakes in western Canada based on machine learning, Earth and Planetary Science Letters, in revision.

Yu, H., H. Kao, B. Wang, and R. Visser (2022). Long-term fluid injection can expedite fault development: Riedel shear structure illuminated by induced earthquakes in Alberta, Canada, Journal of Geophysical Research: Solid Earth, 127, e2022JB025126, doi:1029/e2022JB025126.

Work In Progress

The seismic monitoring process has generally stabilized. However, improvements to the process may still be made. The performance of automatic seismic analysis programs is continuously improving, and further testing and verification must be made as these programs are investigated and adopted. There is potential for other processes such as station health monitoring to be automated as well.

Conclusions

Through the development of the seismic monitoring process, and addition of new seismic stations, the seismic monitoring capabilities for NEBC were improved. The addition of four stations in the 1E seismic network should allow for more events to be detected in the North Montney Trend area, as well as improving the quality of the determined earthquake source parameters. A total of 4113 events were detected for this reporting period, with magnitudes between 4.02 and 0.2.

Several research themes have been investigated by members of the BC SRC over the past year. These themes include advanced earthquake detection methods, earthquake forecasting, and investigating induced earthquake initiation. A list of research products from the last year has been included, along with the routine monitoring catalogue for the past year.

References

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

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.