Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 1, 2020 – December 31, 2021

NWMO-TR-2022-23
December 2022

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ABSTRACT

The Canadian Hazards Information Service (CHIS) continues to conduct a seismic monitoring program in the northern Ontario and eastern Manitoba portions of the Canadian Shield. This program has been ongoing since 1982 and is currently supported by several organizations, including the NWMO.

CHIS maintains and operates a network of seismograph stations to monitor seismicity in the northern Ontario and eastern Manitoba portions of the Canadian Shield. Data are transmitted in real-time to a central office for analysis. CHIS staff integrate the data with those of the Canadian National Seismograph Network (CNSN) and compile a catalogue of seismic activity in northern Ontario.

This report summarizes operational statistics and additions to the earthquake catalogue for the years 2020 and 2021.

During 2020–2021, 108 earthquakes were located in the northern Ontario study area, ranging in magnitude from 0.7 to 3.6 m_N. The pattern of seismicity generally conformed to that of previous years. The largest earthquake was an event at 3.5 km depth, 22 km north of Kapuskasing. 12 earthquakes in the study area were felt, ranging in magnitude from 1.4 to 3.6 m_N. 11 of these earthquakes were shallow and fixed to a depth of 2 km, and one was fixed to a depth of 18 km.

The network detection threshold was reduced during the 2004–2010 FedNor deployment, resulting in a greater number of earthquakes detected per year, during those years than the years prior or since. The selective decommissioning of FedNor stations preserved the most useful stations for monitoring in northern Ontario. However, three difficult-to-maintain stations in the northeast corner of the study area were ultimately closed between 2015 and 2019. The loss of these stations has resulted in a decreased capability to monitor seismicity in the James Bay region.

In 2016, mine operators began to provide confirmed depths for selected mining-induced events. This is becoming the basis of an important "ground truth" dataset for the assessment of existing methods and development of new methods for estimating the depth of natural tectonic earthquakes. During 2020–2021, 472 known mining events with confirmed depths, ranging between 0.32 to 3.17 km, were entered into the database.

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1. INTRODUCTION

The Canadian Hazards Information Service (CHIS), a division of Natural Resources Canada (NRCan), continues to conduct a seismic monitoring program in the northern Ontario and eastern Manitoba portions of the Canadian Shield. This program has been ongoing since 1982 and is currently supported by several organizations, including the NWMO. This report summarizes earthquake activity for the years 2020–2021.

To record seismic activity, CHIS operates twelve seismograph stations in northern Ontario and southeast Manitoba. The activity in southeast Manitoba is of interest because the crust is geologically similar to the Ontario part of the Canadian Shield. Figure 1 includes an outline of the study area.

Backbone stations of the Canadian National Seismograph Network (CNSN) are located at Chalk River (CRLO), Kipawa (KIPQ), Kapuskasing (KAPO) and Thunder Bay (TBO). A station at Pinawa (ULM), which has funding from the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO: http://www.ctbto.org) is also used in this study.

Eight more stations are funded fully or partially by the NWMO. The fully funded stations are Atikokan (ATKO), Experimental Lake (EPLO), Geraldton (GTOO), Pickle Lake (PKLO), Pukaskwa National Park (PNPO) and Sioux Lookout (SOLO). The partially funded stations are Kirkland Lake (KILO) and Sudbury (SUBO). Temporary CHIS stations at Victor mine (VIMO) and McAlpine Lake (MALO) were decommissioned in December 2018 and May 2019 respectively. A temporary CHIS station at Sutton Inlier (SILO) has ceased to operate and there are no plans to repair it. Most of these stations were established between 2003 and 2005 with the support of Industry Canada's FedNor program and the Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity consortium (POLARIS: http://earthsci.carleton.ca/polaris). The remaining operational stations are operated by CHIS.

All stations record real-time, continuous, digital data, which are transmitted by satellite to the data laboratory in Ottawa. The data are made freely available (see Section 3.3) along with former POLARIS stations and the rest of the CNSN.

Relevant data from stations in the U.S. are routinely used in monitoring northern Ontario, particularly the station at Ely, Minnesota (US.EYMN[1], see Figure 1). Since 2013, selected former stations of the USArray transportable array (see http://www.usarray.org/) have been operating as the Central and Eastern U.S. Network (CEUSN, network code N4: http://ceusn.ucsd.edu/). In 2016, a few of these entered routine use in monitoring seismicity in northern Ontario: Brule, Wisconsin (N4.E38A), Sault Ste. Marie, Michigan (N4.E46A), Eben Junction, Michigan (N4.E43A) and Chassel, Michigan (N4.D41A). The data is received through CHIS's Antelope data exchange system. Although these stations are routinely used when events have already been identified on a CNSN station, they are not scanned by CHIS for new events. The addition of the U.S. data has mainly helped locate events in the Atikokan region. Similarly, CNSN stations in Québec are particularly helpful in James Bay.

[1] In this report, for stations not part of the CNSN (network code CN) the station code is sometimes prefixed by the network code and a period.

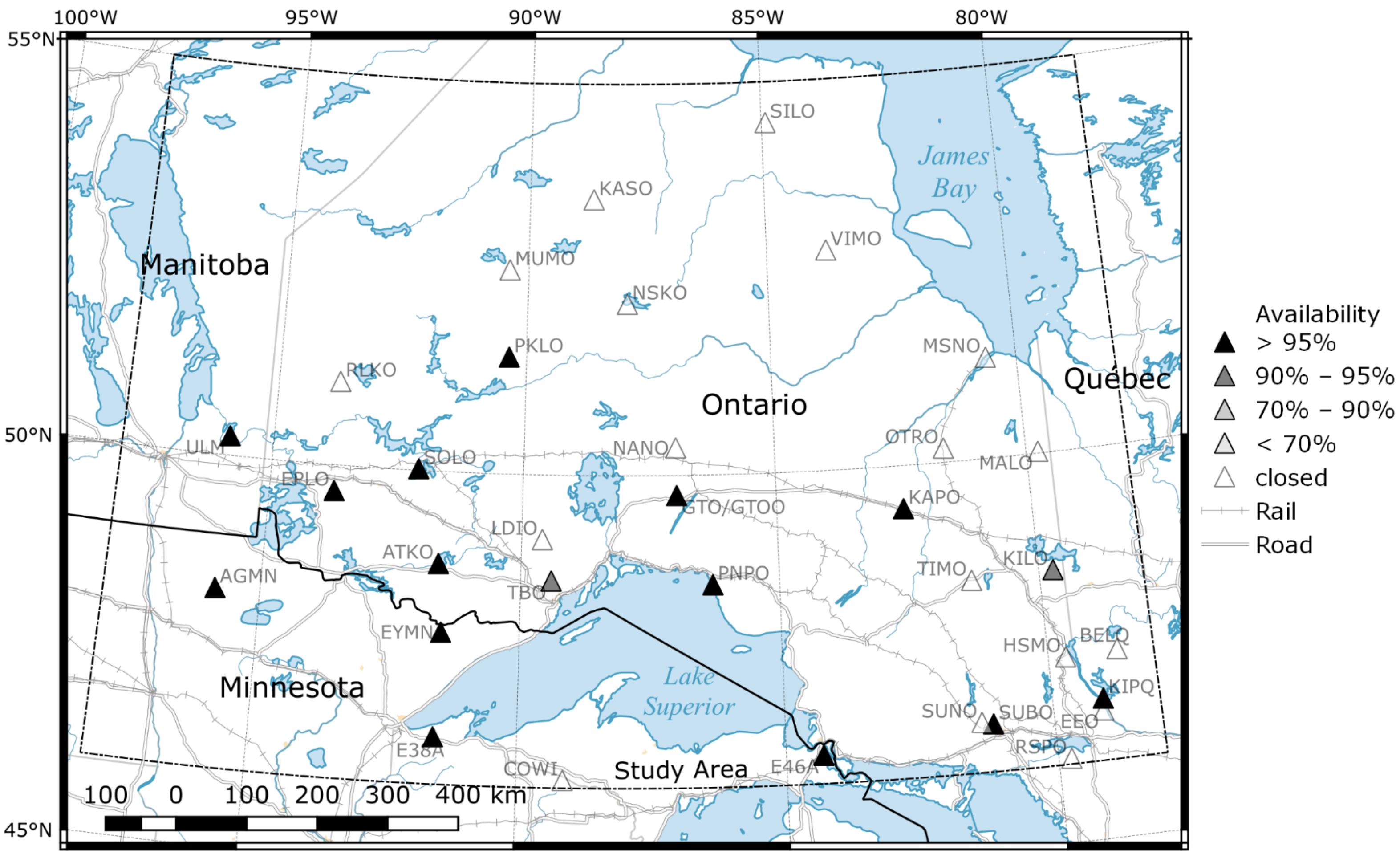

Figure 1: Seismograph Stations in northern Ontario, 2020–2021. The study area is outlined with a dash-dotted line. Historical and currently active stations are shown as triangles, with the triangle filled according to data availability for 2020–2021 (see also Table 1). Most of the stations shown as “unavailable” are former FedNor stations which were mainly active 2006–2009; exceptions are EEO and SUNO, which were replaced by KIPQ and SUBO, respectively, in 2018. Historical analog stations are not shown.

Earthquake magnitude scales attempt to estimate energy release. All magnitude scales are logarithmic. Almost all earthquakes in this series of annual reports will have magnitudes calculated using the Nuttli scale (see Section 5). Magnitudes calculated on the Nuttli scale are formally written m_N in this report. This is a regional magnitude based on Lg amplitudes, similar to mbLg (Bormann & Dewey, 2012). In eastern Canada, m_N is the magnitude used by CHIS for moderate-sized earthquakes. Note that in some figures, a more generic "M" is used to indicate magnitude, even when more than one magnitude type is represented.

The frequency of earthquakes of a given magnitude is a logarithmic function of magnitude: for each magnitude 4.0 earthquake in a region, one can expect approximately 10 magnitude 3.0 earthquakes, 100 magnitude 2.0 earthquakes, 1000 magnitude 1.0 earthquakes, etc. The benefit of detecting the many smaller earthquakes happening in northern Ontario is that it teaches us something about the spatial distribution and rate of the less-common larger earthquakes that could happen in the future and are of engineering design interest.

During the two-year period 2020–2021, 108 earthquakes were located in the study area. The magnitudes of the earthquakes ranged from 0.7 m_N to 3.6 m_N. The largest earthquake occurred 23 km north of Kapuskasing. There were 39 other events above magnitude 3.0 m_N, 6 of which were earthquakes, 6 were blasts, and 27 of which were mining-related events, including a m_N 4.1 mining-related event associated with the Laronde mine. The second largest earthquake, with a magnitude of 3.5 m_N, had an epicentre 13 km south-west of Sturgeon Falls, Ontario.

The CNSN is able to locate all earthquakes of magnitude 3.5 and above anywhere within Canada, except in some parts of the high Arctic. Across northern Ontario, this was lowered to approximately magnitude 3 with the installation of the core stations (CRLO, EEO, GTO, KAPO, SOLO, TBO and ULM) in the early 1980s. This detection threshold was reduced even further, particularly in the northeastern portion of the region, with the installation of temporary stations starting in 2003 (including ATKO, EPLO, KILO, MALO, PKLO, SILO, SUNO and VIMO, but also many stations that have since closed). A program to upgrade the seismograph stations of the CNSN began in 2014 (Bent, Côté, Seywerd, McCormack, & Coyle, 2020). The aims of the program are to improve overall station reliability and data quality. Station upgrades in northern Ontario started in the summer of 2017. With the exception of MALO, SILO and VIMO, all stations mentioned above were refurbished. Active and closed stations in the study area are mapped in Figure 1.

Section 2 is an overview of station operations, including key operational statistics such as data availability.

Section 3 documents earthquakes detected in the area of study. Section 3.1 looks for long-term trends in location thresholds since the inception of the program. Section 3.2 focuses on individual earthquakes, discussing macroseismic data and depth estimates when available as well as their conformity with pre-existing patterns of seismicity.

Sections 4 and 5 discuss the accuracy of estimates of epicentral location, depth and magnitude. Earthquakes for which depths have been estimated (rather than assigned regional defaults) are tabulated. Examples of depth estimation by regional depth phase modeling are given.

Section 6 discusses earthquake occurrence rates.

Section 7 discusses mining-induced activity and an initiative to collect confirmed event depths from mine operators.

2. STATION OPERATIONS

2.1 CANADIAN NATIONAL SEISMOGRAPH NETWORK

More than 4000 earthquakes are located in Canada every year. CHIS operates approximately 150 instruments, called seismographs, across the country to detect and locate these events. Together, these instruments make up the CNSN. Each seismograph site, or "station", consists of a small computer and a very sensitive seismograph that can record ground movement on the order of one nanometre per second. The location of these stations is particularly important. They need to be located where bedrock is exposed at the surface and as far as possible from noise such as traffic, heavy industry and trains. Natural background noises, such as waves on nearby oceans or lakes, are also avoided and heavily wooded areas are unsuitable, because the ground vibrates when the wind shakes the trees. All these factors can hide, or "mask" the very small signals produced by earthquakes. The goal of national seismograph network operations is to support the detection and location of all earthquakes above magnitude 3.5 in Canada and its offshore areas, and above magnitude 2.5 in regions of enhanced socio-economic importance, such as urban areas, hydrocarbon development zones, nuclear power plant sites, and short-term aftershock survey areas.

CHIS also receives and archives the data from the US National Seismic Network (USNSN), former POLARIS stations and other networks operating in the region. Together, approximately seven gigabytes per day of waveform data are acquired, quality controlled, processed and archived by the national seismology data centre. At the time of writing this report, 3879 earthquakes over magnitude 2.0 had been located in Canada during 2020 and 2021. Of these, 55 occurred in the study area.

Equipment at stations across northern Ontario were upgraded 2017–2019. With the upgrade of station ULM in 2019, refurbishment in northern Ontario is complete. See Appendix A of (Ackerley, et al. (2021) for an overview of the work done, with details of the 2019 field season.

An essential feature of each refurbishment was the construction of a new broadband vault to replace existing vaults that were designed for short-period sensors. If the new vault was more than 50 m from the old one, a new station code was assigned. On this basis, Geraldton (GTO) was given a new station code (GTOO) but Sioux Lookout (SOLO) was not.

In some cases, the old site was deemed unsuitable and a completely different site was sought. Fieldwork done in the summer of 2016 included evaluation of site noise and logistics. A site at Kipawa (KIPQ) was chosen to replace Eldee (EEO) and another in the Blezard Valley, Sudbury (SUBO) was chosen to replace Onaping, Sudbury (SUNO), both operational since June 2017.

2.2 OPERATIONAL STATISTICS

Station operation statistics for key stations in northern Ontario are presented in this section. In summary, data availability was excellent in 2020–2021, the second and third years of operation post-refurbishment.

Table 1 summarizes operational statistics for stations in northern Ontario for the past two years (2020–2021), to highlight year-over-year differences. Yearly data availability was 98% or greater for all but two of the thirteen stations with long-term funding (ATKO, CRLO, EEO/KIPQ, EPLO, GTO/GTOO, KAPO, KILO, PKLO, PNPO, SOLO, SUNO, TBO, ULM). Lower data availability at TBO is due to issues with the batter backup power supply, while at KILO the issue has to do with degrading performance of solar charging system. Both of these issues were addressed during the 2022 field season. A temporary station (MALO) was closed in 2019.

Table 1: Operation statistics for stations in northern Ontario, 2019–2021

station	net.	lat. [°N]	lon. [°W]	elev. [m] [b]	on date [c]	off date	availability [f]			num. gaps [g]		
							2019	2020	2021	2019	2020	2021
ATKO	CN	48.8231	-91.6004	383	2004-06-09		100%	100%	100%	44	25	8
CHRO [a,d]	CN	46.0375	-77.38	169	2018-10-16		99%	100%	99%	70	45	21
EPLO	CN	49.6737	-93.7258	437	2004-06-11		99%	100%	98%	1382	21	17648
GTOO [d]	CN	49.7454	-86.9611	351	2019-01-31		100%	100%	100%	90	30	9
KAPO [d]	CN	49.451	-82.5077	221	1998-01-14		100%	100%	99%	66	50	4399
KILO	CN	48.4972	-79.7232	314	2003-06-22		100%	100%	94%	62	51	78
KIPQ [d]	CN	46.7919	-79.0567	274	2017-06-04		100%	100%	100%	4	4	5
MALO	CN	50.0244	-79.7635	271	2003-06-20	2019-05-02	31%	-	-	66215	NA	NA
PKLO	CN	51.4987	-90.3522	376	2004-06-15		100%	100%	100%	0	3	3
PNPO	CN	48.5957	-86.2846	219	2004-06-18		100%	100%	100%	1	3	5
SOLO [c]	CN	50.0215	-92.0808	370	1998-11-04		100%	99%	100%	83	3231	14
SUBO [d]	CN	46.6115	-81.1321	281	2017-06-06		100%	100%	100%	4	2	3
TBO [c]	CN	48.6472	-89.4085	475	1993-10-05		99%	100%	92%	71	44	44
ULM [c]	CN	50.2503	-95.875	251	1994-12-07		97%	100%	99%	60	46	19
E38A	N4	46.6058	-91.554	341	2013-11-26		20%	100%	98%	4	56	363
E46A	N4	46.3665	-84.3062	269	2013-11-26		27%	100%	98%	16	53	368
AGMN	US	48.2977	-95.8619	351	2006-08-12		100%	99%	100%	7	84	9
EYMN	US	47.9462	-91.4953	475	1994-09-26		100%	100%	100%	10	20	11

Note:
[a] CHRO is included because of its historical importance even though it is not strictly within the study area.
[b] Elevations are with respect to sea level.
[c] On date given for core stations is, for some stations, that of conversion to digital recording. Initial site commissioning dates were earlier: ULM 1984, TBO 1987, SOLO 1988.
[d] Some stations effectively replaced nearby stations: CHRO near CKO (1981–1994) and then CRLO (1994–2018), GTOO near GTO (1982–2019) KAPO near KAO (1982–), KIPQ near EEO (1984–2018), SUBO near SUNO (2003–2019).
[e] Station type is “E” for short period vertical, or “B” (40 sps) or “H” (100 sps) for broadband 3-channel.
[f] Availability is the fraction of total possible samples that are actually in the waveform archive, for vertical channels of the type indicated. This is considered representative of all channels available to analysts during routine processing.
[g] “Num. gaps” is the number of gaps in the archived waveforms for a year.

Operation of the CEUSN started transitioning from Incorporated Research Institutions for Seismology (IRIS) to the United States Geological Survey (USGS) in September 2018. Channel names changed in March 2019, without prior notice to CHIS, resulting in an interruption of real-time data acquisition. The CEUSN stations important to monitoring of seismicity in northern Ontario are N4.E38A and N4.E46A. Real-time acquisition was re-established in September-October of 2019 under new location and channel codes, and since then data availability has been 98% or greater. The location codes changed from “” to “00” and the band codes changed from “B”, meaning 40 samples per second (sps), to “H”, meaning 100 sps.

Figure 2 is a representation of daily data availability in northern Ontario for 2020–2021. The post-refurbishment data availability is close to 100% at all stations with long-term funding.

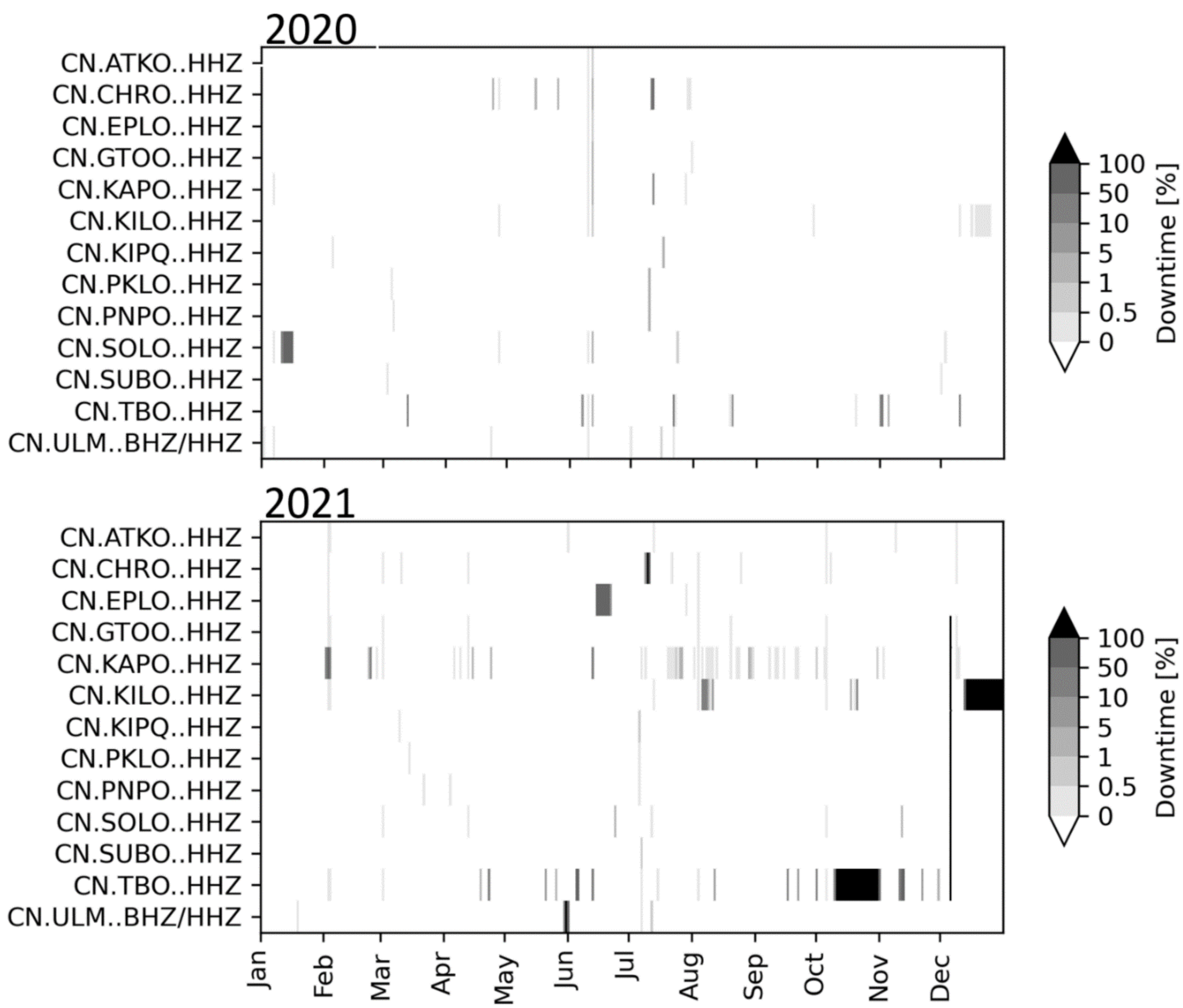

Figure 2: Daily downtime for CN network in northern Ontario, 2020–2021. Downtime is the complement of availability as defined in Table 1. Note that for rows listing a station and its replacement, the combined availability is the higher of the two. Stations MALO, SUNO, and COWI are not included as they were closed in 2019.

The major outages affecting data availability in 2020–2021 were as follows:

- KAPO had a firmware update on 2020-01-07, which resulted in a brief data gap.
- SOLO experienced a failure of a satellite transceiver on 2020-01-10 resulting in some data loss until the device was replaced on 2020-01-19.
- TBO experienced a mains power outages on 2020-03-13,2020-06-07, 2020-08-20, 2020-11-01, 2020-11-02 and 2020-12-10 which lasted longer than the site's battery could sustain backup power. TBO continued recording for most of the outage, but in each case between 2 and 5 hours data was lost before power was restored.
- CHRO experienced a mains power outage on 2020-07-09, which lasted until 2020-07-12. The battery was able to sustain power until 2020-07-11, but just over one day of data was lost before mains power was restored on 2020-07-12.
- KAPO experienced a mains power outage on 2020-07-12. The battery was able to sustain power for most of the outage, but 6.5 hours of data was lost before mains power was restored.
- TBO had maintenance performed resulting in 3h35m of data loss on 2020-07-22 and 2020-07-23.
- TBO experienced unexpected power resets on 2020-08-20, and again on 2020-11-01 and 2020-11-02, resulting in 2h10m and 5h20m of data loss respectively.
- ATKO had a firmware upgrade on 2021-11-09, which resulted in the loss of 2.5 minutes of data.
- ATKO, CHRO, EPLO, GTOO, KAPO, KILO, TBO, and SOLO experienced a problem with data acquisition software for stations using satellite communications between 2021-02-02 and 2021-02-05. For the affected period, recoverable data ranged between >99% at stations ATKO, EPLO, KILO, SOLO to between 20% and 40% at CHRO, GTOO, KAPO, TBO (~35 hours). The issue was resolved after updating data acquisition software.
- TBO experienced mains power outages on 2021-04-19, 2021-04-23, 2021-05-21, 2021-05-26, 2021-06-05, 2021-06-13, 2021-09-17, 2021-09-22, 2021-11-11, 2021-11-22 and 2021-11-30 which resulted in a total of approximately 6 days of data loss.
- ULM experienced a mains power outage between 2021-05-30 and 2021-06-01, resulting in 1d17h data loss. A tree fell on Manitoba Hydro's nearby overhead distribution line, taking out power and damaging the station's backup power supply.
- EPLO experienced outages between 2021-06-14 and 2021-06-22 totalling just over 5 days of data loss. The problem was determined to be signal interference at the CHIS satellite data acquisition facility in Ottawa and was resolved by reconfiguring time-division multiple access (TDMA) time slots.
- CHRO experienced a mains power outage starting on 2021-07-08 and lasting almost 4 days. Battery backup power kept the station online for a day and a half, but just under two days of data was lost, between 2021-07-09 and 2021-07-11.
- KILO experienced several outages between 2021-08-06 and 2021-08-11 which appear to have been caused by a software problem on the digitizer, resulting in 17h of lost data.
- TBO had a vault power circuit breaker trip on 2021-10-10, cutting power to the sensor and digitizer. Intervention by the CHIS local contact was required, who restored power on 2021-11-01. No data was recorded for the entire duration of the outage until power was restored.
- KILO experienced an outage on 2021-10-21, which appears to have been caused by a software problem on the digitizer, and which resulted in approximately 9h of lost data.
- KAPO experienced interruptions to its satellite network communications due to bad weather in 2021-11, but a software problem prevented it from re-sending the data it

missed. Approximately 3h of data was lost. The software problem at KAPO has since been fixed.

- KILO is generating insufficient power from its solar charging system to keep the station online, resulting in an ongoing outage, which began on 2021-12-13.

3. EARTHQUAKES

This section focuses on the natural tectonic seismicity of northern Ontario, placing the earthquakes detected in 2020–2021 in the context of historical seismicity. Changes in the seismograph network configuration are discussed first, in order to help understand apparent changes in yearly occurrence rates. Next, selected earthquakes of interest from 2020–2021 are discussed individually. Then regional patterns of seismicity for the reporting period are compared to the catalogue generated thus far. Finally, the means of dissemination of waveforms and catalogue data are documented.

3.1 NETWORK PERFORMANCE

Due to increased station density in the northern part of the province beginning in 2003, the magnitude location threshold decreased, from approximately 3.0 m_N down to approximately 2.0 m_N, for about six years. Although earthquakes smaller than 2.0 m_N can be located with the current network, locations will tend to be less accurate and the catalogue of events will not be complete. In regions of poorer coverage, it must be assumed that events smaller than 2.0 m_N have been missed.

The earthquakes catalogued in 2020–2021, of all magnitudes, are compared to previous years in Table 2. The other yearly statistics shown in Table 2 are explained below.

Table 2: Earthquake and station counts in northern Ontario, 2000–2021

year	known earthquakes	declustered [a,e] (mainshocks)	suspected [b,e] earthquakes	nominal [c] stations	available [d,e] stations
2000	72	43	5	8.0	6.0
2001	35	30	6	8.0	6.9
2002	45	40	5	8.0	6.9
2003	45	37	7	11.3	10.7
2004	79	75	9	17.7	16.9
2005	100	86	4	23.6	22.2
2006	83	75	1	27.1	24.0
2007	67	63	5	28.4	24.2
2008	114	88	8	26.4	21.8
2009	82	69	10	20.8	16.5
2010	117	94	11	18.3	15.3
2011	79	69	3	17.0	14.4
2012	56	50	11	17.0	14.0
2013	64	52	13	17.0	14.3
2014	34	33	4	17.0	14.6
2015	50	47	9	16.2	14.3
2016	56	51	9	16.0	14.0
2017	54	45	1	17.2	13.5
2018	49	47	3	17.6	14.9
2019	35	33	0	16.1	12.8
2020	54	48	0	16.0	13.0
2021	54	46	0	16.0	12.8

Note:
[a] Declustering is a procedure for attempting to identify and remove aftershocks from catalogue (see text for detail).
[b] Suspected earthquakes are events, typically of small magnitude, which are unlikely to be anthropogenic, but which were detected at too few stations for the location to be accurate enough to be certain.
[c] Nominal station count only includes stations in Canada, and includes CRLO, just outside the study area.
[d] Available station count is the number of stations in the study area weighted by the data availability of that data in the digital waveform archive.
[e] Numbers of suspected and declustered earthquakes and available stations have not been tabulated in previous reports.

In 2008, the POLARIS-FedNor project ended, and stations had to be closed. Eight stations were closed initially, with the poorest stations (based on uptime statistics, and/or background noise levels) chosen in order to minimize the impact on the location threshold. Two additional sites were closed in 2010. Therefore, we investigate whether the network detection threshold increased starting in 2011, relative to 2004–2009.

The rate of earthquakes above a given magnitude in a given region is assumed time-independent in a classical probabilistic seismic hazard assessment. The apparent rate of occurrence of smaller earthquakes will vary, however, as the magnitude of the smallest locatable event (magnitude of completeness) of the seismograph network changes. The magnitude of completeness depends on the network configuration and station ambient noise levels, but most crucially on the total number of stations. Consequently, the number of earthquakes of all sizes detected is a measure of the performance of the network. The number of stations and the number of earthquakes detected are tabulated in Table 2 since 2000 and plotted in Figure 3 since 1980, just before the inception of the northern Ontario seismic program in 1982.

While mainshocks are assumed time-independent, foreshocks and aftershocks are causally related to mainshocks and interfere with attempts to estimate the time-independent part of an occurrence rate. A simple declustering algorithm (Gardner & Knopoff, 1974) using magnitude-dependant time-space windows (van Stiphout, Zhuang, & Marsan, 2012) was applied to the catalogue to identify and remove foreshocks and aftershocks. Some of the “spikes” in seismicity disappear after declustering, a dramatic example being the year 2000, which was dominated by the aftershocks of the Kipawa “Millennium” Earthquake (Bent, et al., 2002). After declustering, some of the variability of yearly occurrence rates of earthquakes of all magnitudes will be due to the intrinsic randomness of the underlying process, but some of it will be due to changes in the magnitude of completeness of the network.

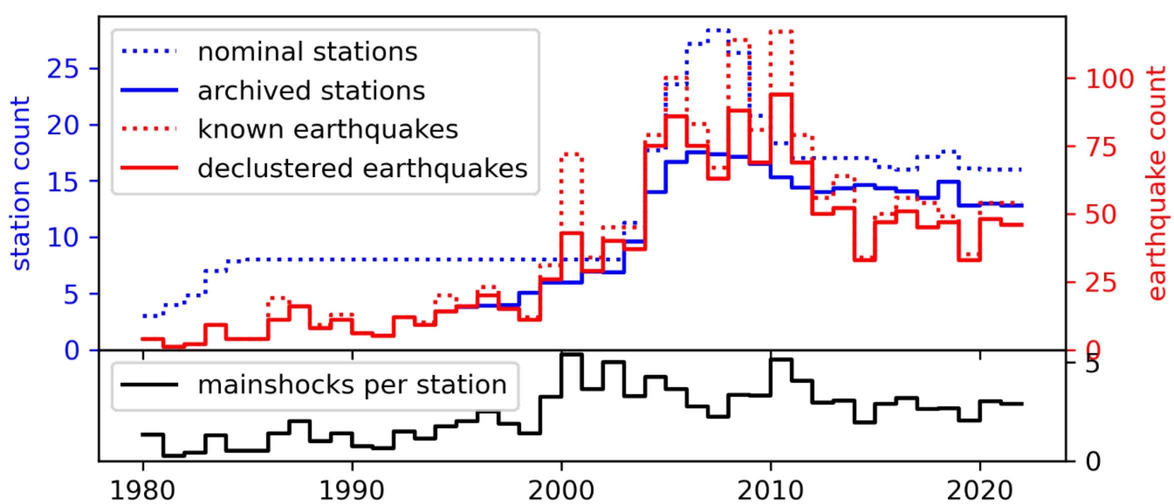

Figure 3: Earthquake and station counts in northern Ontario, 1980–2021. See Table 2 for explanation of terms. Note the national waveform archive only contains continuous data starting in 1995. The number of earthquakes per station is the number of declustered earthquakes per nominal station.

As explained above, the selective decommissioning of FedNor stations in 2008–2010 was intended to have as little impact as possible on network magnitude of completeness. This was accomplished by removing the stations with the lowest data availability and highest station noise, while ensuring that the remaining stations provided good coverage of the region. Figure 3 shows that the earthquakes detected per year decreased after 2010. The six-year rolling average rate of declustered seismicity (all magnitudes) dropped from a high of 79.2/year 2005–2010 to 45.0/year 2016–2021. This is still significantly greater than the 27.5/year observed prior to the FedNor deployment (1997–2002), not to mention the 8.7/year of 1983–1988. However, the yearly rate of mainshocks detected per station has been relatively constant since 1999, so changes in the yearly rate imply changes in the network magnitude of completeness. The yearly rate of mainshocks per station is still higher than before the FedNor deployment, suggesting that selective decommissioning succeeded in retaining the stations most useful to monitoring in northern Ontario. Figure 1 shows that in the northern half of the study area the station density is lower, so it is likely here that the magnitude of completeness has seen the greatest increase. The yearly rate of mainshocks per station increased through the 1990s. This may reflect an improved ability of analysts to find and catalogue events with the CNSN becoming fully digital, beginning in 1991 (Bent, Côté, Seywerd, McCormack, & Coyle, 2020).

In section 2.2, it was observed that data flow from the CEUSN (network code N4) to CHIS was interrupted from March to October 2019. During this outage, there may have been some slight degradation of monitoring capabilities at the southern edge of northern Ontario, due to the loss of N4.E38A and N4.E46A. The effect of losing N4.E38A is expected to have been negligible, as US.AGMN, US.EYMN and US.COWI were operating normally. The effect of losing N4.E46A near Sault-Ste-Marie may have been more significant, as the nearest stations in Ontario, TOBO, SUBO and PNPO, are quite far away. However, the lower number of catalogued earthquakes in 2019 relative to 2015–2018 is mainly attributed to the random nature of seismicity and not the temporary loss of data from the CEUSN.

As noted in Ackerley, et al. (2021), the degradation and finally closure SILO, VIMO and MALO, 2015–2019 means that network detection capability in the northeastern corner of the study area, in particular near James Bay, is significantly less than it was during the FedNor deployment 2004–2010.

The station distribution means that the portions of the study area that are in Manitoba, Minnesota, James Bay and extreme northwestern Ontario are less well monitored than the rest of northern Ontario. Hence, the lack of earthquakes located there need not represent a lack of natural seismicity.

3.2 EVENTS OF INTEREST

The geographic distribution of seismic activity for 2020–2021 followed that of previous years, with earthquakes being detected mainly in the Severn Highlands, James Bay and Kipawa-Cochrane regions. Slightly unusual, perhaps, was that four of the five largest events were located in what would be considered background seismic zones, and that none of the largest events occurred in James Bay. See Figure 4 for a map and Table 3 and Table 4 for a detailed listing of all earthquakes in the study area in 2020–2021. In all, 108 known earthquakes were documented, the smallest of which had its magnitude estimated at 0.7 m_N.

Figure 4 also shows earthquakes that have been located in the study area since 1900. Since the inception of the northern Ontario seismic program in 1982, 1542 earthquakes have been documented.

Table 3 and Table 4 include the best estimate of depth for each earthquake in the study area in 2021. Depths of moderate-sized events in eastern Canada cannot be calculated from direct arrivals unless there are at least three stations within approximately 3 times the depth. In northern Ontario, the station spacing is typically 200–300 km so depths are not normally estimated in this way. In 2020–2021, 7 events had depths estimated by Regional Depth Phase Modelling (RDPM) and 55 more were assigned 2±3 km depths based on the observation of crustal Rayleigh phases. With a few exceptions, the remaining events were assigned default depth values based on nearby historical seismicity. The difficulty of estimating earthquake depths is discussed in detail in Section 4.2.1, including an assessment of the accuracy of RDPM for shallow events.

Figure 4 shows the earthquakes located in the study area in 2020–2021 together with all known earthquakes since 1982. The representation, using red-filled circles for the 2020–2021 earthquakes and partially transparent circles for the prior activity, makes it easy to judge which 2020–2021 earthquakes happened in regions of prior seismicity as well as which areas of past activity did not have an earthquake in 2020–2021.

The largest earthquake in the study area was a 3.6 m_N event on 2020-10-14, north of Kapuskasing (see Figure 4), one of 7 earthquakes over 3.0 m_N. The earthquake depth was estimated as 3.5km, based on RDPM.

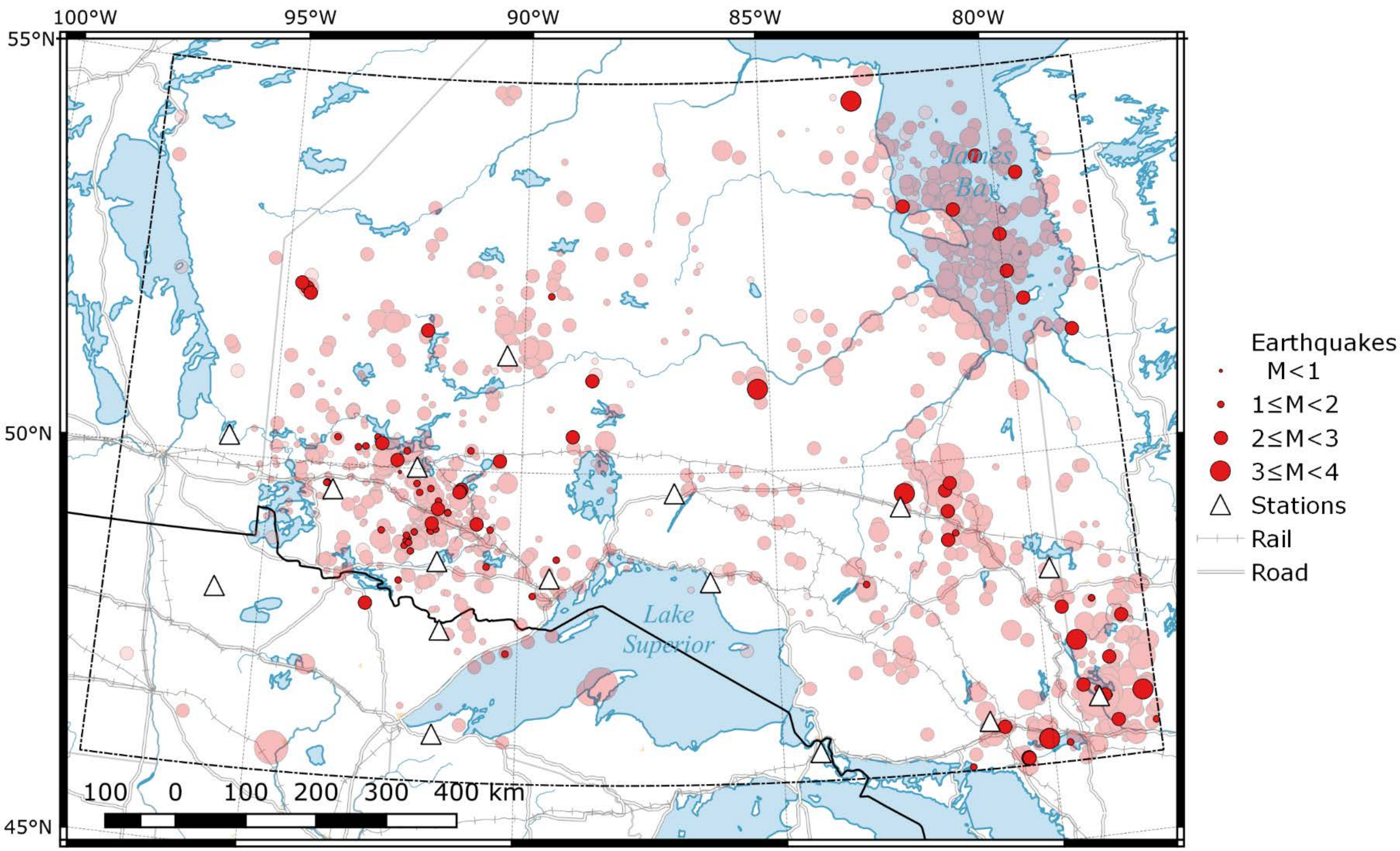

Figure 4: Earthquakes in northern Ontario, 2020–2021. Events in 2020–2021 have black outlines, while events from 1900–2020 are plotted semi-transparently and have grey outlines. Events and stations are plotted in the study area only. The study area is outlined with a dash-dotted line. Only stations with data available in 2020–2021 are shown.

Table 3: Earthquakes in northern Ontario, 2020

time[a] [UTC]	mag.		lat. [°N]	lon. [°W]	dep. [km]	F[b]	S[b]	P[b]	D[c]	zone[d]	comment
2020-01-01 14:00	1.9	m_N	52.2695	89.4655	5		4	6	F	SCC	103 km NE of Pickle Lake, ON
2020-02-08 21:51	2.3	m_N	50.0972	92.4833	2		8	15	R	SVH	36 km W of Sioux Lookout, ON
2020-02-18 09:20	1.5	m_N	49.0987	92.1862	5		5	9	F	SVH	57 km NW of Atikokan, ON
2020-02-28 02:15	2.9	m_N	53.8565	80.3346	18		8	14	F	JMS	95 km W of Chisasibi, QC
2020-03-11 13:47	1.4	m_N	50.2210	92.2972	2		3	6	R	SVH	28 km NW of Sioux Lookout, ON
2020-03-12 02:18	1.6	m_N	50.3449	93.7033	5		4	7	F	SVH	79 km NE of Kenora, ON
2020-03-27 07:25	1.9	m_N	49.4855	91.6316	2		7	13	R	SVH	69 km S of Sioux Lookout, ON
2020-03-30 10:05	3.0	m_N	54.6855	82.9391	18		14	24	F	SCC	157 km NE of Attawapiskat, ON
2020-04-01 16:47	3.0	m_N	47.5429	79.3605	13	✓	16	31	V	COCS	23 km NE of Haileybury, ON
2020-04-05 12:53	1.5	m_N	50.3774	92.8995	2		5	10	R	SVH	67 km N of Dryden, ON
2020-04-06 10:12	1.5	m_N	49.1875	92.0703	2		4	8	R	SVH	59 km NW of Atikokan, ON
2020-04-24 18:36	1.8	m_N	49.1890	92.7198	2		6	12	R	SVH	66 km S of Dryden, ON
2020-04-25 21:07	2.0	m_N	50.3018	92.8085	2		7	13	R	SVH	59 km N of Dryden, ON
2020-05-01 06:55	2.4	m_N	49.6152	81.6003	18		7	13	F	COCN	64 km E of Kapuskasing, ON
2020-05-02 14:56	1.9	m_N	48.0497	78.9819	18		5	9	F	SEBN	21 km S of Rouyn-Noranda, QC
2020-05-08 03:39	2.7	m_N	53.2908	81.9857	18		8	15	F	JMS	50 km NE of Attawapiskat, ON
2020-06-28 11:23	1.8	m_N	46.8827	79.0689	18		11	20	F	KIP	19 km N of Témiscaming, QC
2020-07-01 09:08	1.5	m_N	46.1000	80.4800	2		7	13	R	OBGH	53 km SW of Sturgeon Falls, ON
2020-07-08 14:19	2.1	m_N	49.3471	81.5833	18		5	10	F	COCN	52 km NW of Cochrane, ON
2020-07-10 02:44	1.6	m_N	48.4849	83.2690	2		3	6	R	SCC	73 km N of Chapleau, ON
2020-07-15 00:11	1.9	m_N	48.4177	89.7305	2		7	11	R	SVH	31 km W of Thunder Bay, ON
2020-08-07 18:13	3.5	m_N	46.3188	80.0662	2	✓	18	34	V	OBGH	13 km SW of Sturgeon Falls, ON
2020-08-18 17:48	1.8	m_N	49.2220	91.7670	2		6	11	R	SVH	54 km N of Atikokan, ON
2020-08-22 07:49	1.4	m_N	49.6987	92.0064	2		4	7	R	SVH	41 km S of Sioux Lookout, ON
2020-08-26 07:22	1.6	m_N	50.2517	93.1321	2		6	11	R	SVH	57 km N of Dryden, ON
2020-08-26 21:55	2.0	m_N	51.1935	88.6028	5		4	7	F	SCC	116 km E of Pickle Lake, ON
2020-09-02 10:35	2.4	m_N	49.7039	81.4974	18		8	14	F	COCN	75 km NE of Kapuskasing, ON
2020-09-05 01:17	1.1	m_N	49.7536	93.8508	2		3	5	R	SVH	43 km E of Kenora, ON
2020-09-05 01:18	0.7	m_N	49.7500	93.8500	2		2	3	R	SVH	43 km E of Kenora, ON
2020-09-08 04:46	1.8	m_N	50.2343	93.2807	2		7	13	R	SVH	60 km NW of Dryden, ON
2020-09-10 02:55	2.4	m_N	46.0849	80.4877	2		11	21	R	OBGH	54 km SW of Sturgeon Falls, ON
2020-09-10 05:03	2.3	m_N	52.8262	79.9887	18		5	8	F	JMS	81 km WSW of Wemindji, QC
2020-09-21 13:02	1.6	m_N	49.2538	90.5882	5		5	10	F	SVH	94 km NE of Atikokan, ON
2020-09-27 08:22	2.4	m_N	53.1974	80.9245	18		7	11	F	JMS	105 km ENE of Attawapiskat, ON
2020-10-01 22:52	2.1	m_N	46.5240	80.8645	2	✓	10	20	R	IRME	11 km E of Sudbury, ON
2020-10-04 12:04	2.0	m_N	49.4980	91.6292	2		8	15	R	SVH	68 km S of Sioux Lookout, ON
2020-10-06 00:57	1.3	m_N	49.7542	93.8371	2		4	7	R	SVH	44 km E of Kenora, ON
2020-10-06 04:30	2.2	m_N	46.0973	80.4854	2		9	18	R	OBGH	53 km SW of Sturgeon Falls, ON
2020-10-07 00:46	1.8	m_N	46.0981	80.4864	2		7	13	R	OBGH	53 km SW of Sturgeon Falls, ON
2020-10-07 02:11	2.1	m_N	46.1053	80.4784	2	✓	13	26	R	OBGH	52 km SW of Sturgeon Falls, ON
2020-10-07 02:15	2.0	m_N	46.0979	80.4856	2		12	21	R	OBGH	53 km SW of Sturgeon Falls, ON
2020-10-08 07:53	1.9	m_N	46.1003	80.4849	2		12	22	R	OBGH	53 km SW of Sturgeon Falls, ON
2020-10-14 00:19	1.9	m_N	46.0939	80.4767	2		10	19	R	OBGH	53 km SW of Sturgeon Falls, ON
2020-10-14 13:48	3.6	m_N	49.6179	82.4097	3.5	✓	11	21	V	IRB	22 km N of Kapuskasing, ON
2020-10-24 18:55	1.8	m_N	46.7873	78.8751	18		5	9	F	KIP	19 km NE of Témiscaming, QC
2020-10-27 09:59	2.6	m_N	46.0918	80.4832	2	✓	9	18	R	OBGH	53 km SW of Sturgeon Falls, ON
2020-11-10 10:04	2.7	m_N	49.7585	91.1810	2		8	16	R	SVH	67 km SE of Sioux Lookout, ON
2020-11-21 19:53	2.6	m_N	46.0978	80.4740	2	✓	11	22	R	OBGH	52 km SW of Sturgeon Falls, ON
2020-11-27 11:27	1.9	m_N	49.7548	91.7890	2		7	13	R	SVH	37 km S of Sioux Lookout, ON
2020-12-15 02:40	1.4	m_N	46.1075	80.4804	2	✓	5	10	R	OBGH	52 km SW of Sturgeon Falls, ON
2020-12-15 14:11	2.1	m_N	46.0938	80.4823	2		8	16	R	OBGH	53 km SW of Sturgeon Falls, ON
2020-12-18 00:15	2.2	m_N	46.4636	78.7515	18		9	17	F	KIP	17 km N of Mattawa, ON
2020-12-25 14:56	2.6	m_N	47.9824	79.5704	18		11	19	V	COCS	29 km NE of Englehart, ON
2020-12-30 14:38	2.2	m_N	46.0988	80.4843	2	✓	6	12	R	OBGH	53 km SW of Sturgeon Falls, ON

[a] Times given are Coordinated Universal Time (UTC), not local times.
[b] "F" indicates whether an event was felt. "S" and "P" are the number of stations and phases used in the solution, respectively.
[c] Depth type coding ("D") is as follows (see Section 4.2.1 for detail): F – operator assigned, V – RDPM, R – Rg observed; assigned shallow depth, M – fixed depth based on waveform similarity.

Table 4: Earthquakes in northern Ontario, 2021. Footnotes to Table 3 apply.

time[a] [UTC]	mag.		lat. [°N]	lon. [°W]	dep. [km]	F[b]	S[b]	P[b]	D[c]	zone[d]	comment
2021-01-10 00:29	1.6	m_N	46.0465	81.5101	5		9	17	F	OBGH	31 km SE of Espanola, ON
2021-01-11 22:12	2.3	m_N	46.1011	80.4911	2	✓	10	19	R	OBGH	53 km SW of Sturgeon Falls, ON
2021-01-17 08:53	3.1	m_N	46.3158	80.0652	3		10	20	V	OBGH	13 km SW of Sturgeon Falls, ON
2021-01-26 10:57	2.9	m_N	51.5170	78.7161	18		5	9	F	JMS	4 km NE of Waskaganish, QC
2021-02-01 23:01	2.0	m_N	46.7963	78.9475	18		6	12	F	KIP	15 km NE of Témiscaming, QC
2021-02-16 00:19	1.9	m_N	48.8905	89.2780	2		7	12	R	SVH	44 km NW of Mackenzie, ON
2021-02-23 03:41	1.7	m_N	49.8117	92.0685	2		5	9	R	SVH	29 km S of Sioux Lookout, ON
2021-02-28 21:24	1.7	m_N	48.5589	92.3324	2		5	10	R	SVH	57 km W of Atikokan, ON
2021-03-03 03:45	2.3	m_N	48.9786	81.6250	18		8	13	F	IRB	46 km W of Cochrane, ON
2021-03-16 23:40	2.1	m_N	49.3096	91.7372	2		9	19	R	SVH	13 km SSW of Ignace, ON
2021-03-26 07:49	2.0	m_N	49.7289	91.2105	5		8	15	F	SVH	67 km SE of Sioux Lookout, ON
2021-03-26 08:10	1.5	m_N	49.7291	91.2428	5		6	10	F	SVH	65 km SE of Sioux Lookout, ON
2021-03-26 08:38	2.1	m_N	49.7237	91.2214	5		8	16	F	SVH	67 km SE of Sioux Lookout, ON
2021-04-01 01:48	1.3	m_N	49.0092	92.2535	5		4	7	F	SVH	55 km NW of Atikokan, ON
2021-04-01 03:46	1.5	m_N	49.0746	92.2196	5		5	8	F	SVH	57 km NW of Atikokan, ON
2021-04-01 03:48	1.0	m_N	49.0474	92.1720	5		2	4	F	SVH	52 km NW of Atikokan, ON
2021-04-08 00:11	2.2	m_N	49.3206	90.8551	2		8	16	R	SVH	84 km NE of Atikokan, ON
2021-04-13 16:09	2.0	m_N	46.0986	80.4740	2	✓	7	14	R	OBGH	52 km SW of Sturgeon Falls, ON
2021-04-13 19:08	3.4	m_N	46.8062	78.2341	1		11	22	V	GATW	65 km NE of Mattawa, ON
2021-04-16 05:18	2.6	m_N	53.5947	79.5122	18		6	9	F	JMS	45 km WSW of Chisasibi, QC
2021-04-22 06:21	1.4	m_N	49.4558	91.4308	2		5	10	R	SVH	79 km SE of Sioux Lookout, ON
2021-04-22 09:09	1.4	m_N	49.4530	91.4326	2		5	10	R	SVH	79 km SE of Sioux Lookout, ON
2021-05-04 10:06	2.6	m_N	46.8083	78.2289	2		12	24	R	GATW	66 km NE of Mattawa, ON
2021-05-06 04:19	1.8	m_N	46.8065	78.2312	2		10	19	R	GATW	65 km NE of Mattawa, ON
2021-05-27 19:17	2.2	m_N	46.9563	79.3285	18		8	16	F	COCS	32 km NW of Témiscaming, QC
2021-06-12 22:58	1.4	m_N	49.5990	91.6277	5		5	9	F	SVH	58 km SE of Sioux Lookout, ON
2021-06-13 01:28	1.7	m_N	47.6690	90.2245	18		5	8	F	SCC	106 km SW of Thunder Bay, ON
2021-06-17 03:08	2.7	m_N	50.1421	90.4365	5		7	15	F	SVH	22 km SW of Allanwater Bridge, ON
2021-06-29 02:14	1.7	m_N	48.7776	90.6398	2		6	10	R	SVH	72 km E of Atikokan, ON
2021-07-03 07:31	1.4	m_N	49.0593	81.4660	18		3	5	F	COCN	33 km W of Cochrane, ON
2021-07-11 12:21	2.1	m_N	51.7802	92.0101	18		6	12	F	SVH	130 km W of Pickle Lake, ON
2021-07-16 15:34	2.3	m_N	46.0939	80.4717	2	✓	10	20	R	OBGH	52 km SW of Sturgeon Falls, ON
2021-07-24 07:24	1.8	m_N	50.2617	91.0267	2		7	13	R	SVH	61 km W of Allanwater Bridge, ON
2021-08-10 18:40	2.5	m_N	46.8148	78.2232	2		8	16	R	GATW	66 km NE of Mattawa, ON
2021-08-13 14:52	2.4	m_N	47.2750	78.7841	18		7	12	F	GATW	67 km N of Témiscaming, QC
2021-08-29 06:52	0.9	m_N	49.9466	92.4198	2		4	6	R	SVH	34 km SW of Sioux Lookout, ON
2021-09-08 06:26	1.6	m_N	48.9416	92.1273	5		5	9	F	SVH	43 km NW of Atikokan, ON
2021-09-16 04:04	1.5	m_N	46.3167	80.0721	2		10	18	R	OBGH	9 km SW of Cache Bay, ON
2021-09-18 02:12	1.5	m_N	49.2084	91.7476	5		7	13	F	SVH	24 km SSW of Ignace, ON
2021-09-21 08:51	1.9	m_N	49.3167	90.8618	5		9	15	F	SVH	58 km E of Ignace, ON
2021-10-12 08:53	2.2	m_N	47.7949	78.4602	18		18	39	F	SEBN	25 km NNE of Winneway, QC
2021-10-21 06:59	1.9	m_N	49.7471	93.8554	2		4	6	R	SVH	39 km N of Whitefish Bay 32A, ON
2021-10-31 03:56	2.7	m_N	51.9808	79.6413	18		22	49	F	JMS	83 km NW of Waskaganish, QC
2021-11-02 11:24	1.4	m_N	49.2352	91.6531	5		7	14	F	SVH	20 km S of Ignace, ON
2021-11-04 04:35	2.0	m_N	48.2431	92.9443	2		8	15	R	SCC	53 km SE of International Falls, MN
2021-11-10 02:37	1.7	m_N	49.1383	92.2203	2		7	13	R	SVH	51 km SW of Ignace, ON
2021-11-16 10:52	2.7	m_N	52.3470	79.9204	18		21	35	F	JMS	104 km SW of Wemindji, QC
2021-11-24 05:08	2.0	m_N	46.2425	79.6887	2		15	26	R	OBGH	17 km ESE of Nipissing, ON
2021-11-28 04:17	3.4	m_N	51.0592	85.2364	18		20	41	F	SCC	82 km SE of Marten Falls, ON
2021-11-30 08:24	2.3	m_N	50.4716	88.9876	5		10	18	F	SCC	18 km NNE of Whitesand, ON
2021-12-21 05:17	1.6	m_N	46.4027	78.0570	18		11	19	F	PEM	25 km NE of Head, Clara and Maria, ON
2021-12-31 13:02	2.7	m_N	52.2231	94.5784	12		9	15	V	SCC	23 km NW of Poplar Hill, ON
2021-12-31 17:31	2.0	m_N	52.1587	94.4979	18		4	5	F	SCC	15 km WNW of Poplar Hill, ON
2021-12-31 19:31	2.3	m_N	52.2802	94.6929	18		6	10	F	SCC	33 km NW of Poplar Hill, ON

[d] Seismic zones from the 2015 NSHM (Halchuk, et al. 2014): SVH – Severn Highlands Seismic Zone, IRME – Iapetan Rift Margin Extended Seismic Zone, JMS – James Bay Seismic Zone, SCC – Stable Cratonic Core, SEBN – Southeast Canada Background Northern Portion Seismic Zone, GATW – Gatineau West Seismic Zone, KIP – Kipawa Seismic Zone, COCN – Cochrane North Seismic Zone, COCS – Cochrane South Seismic Zone. The most active zones are shown on Figures 7–9.

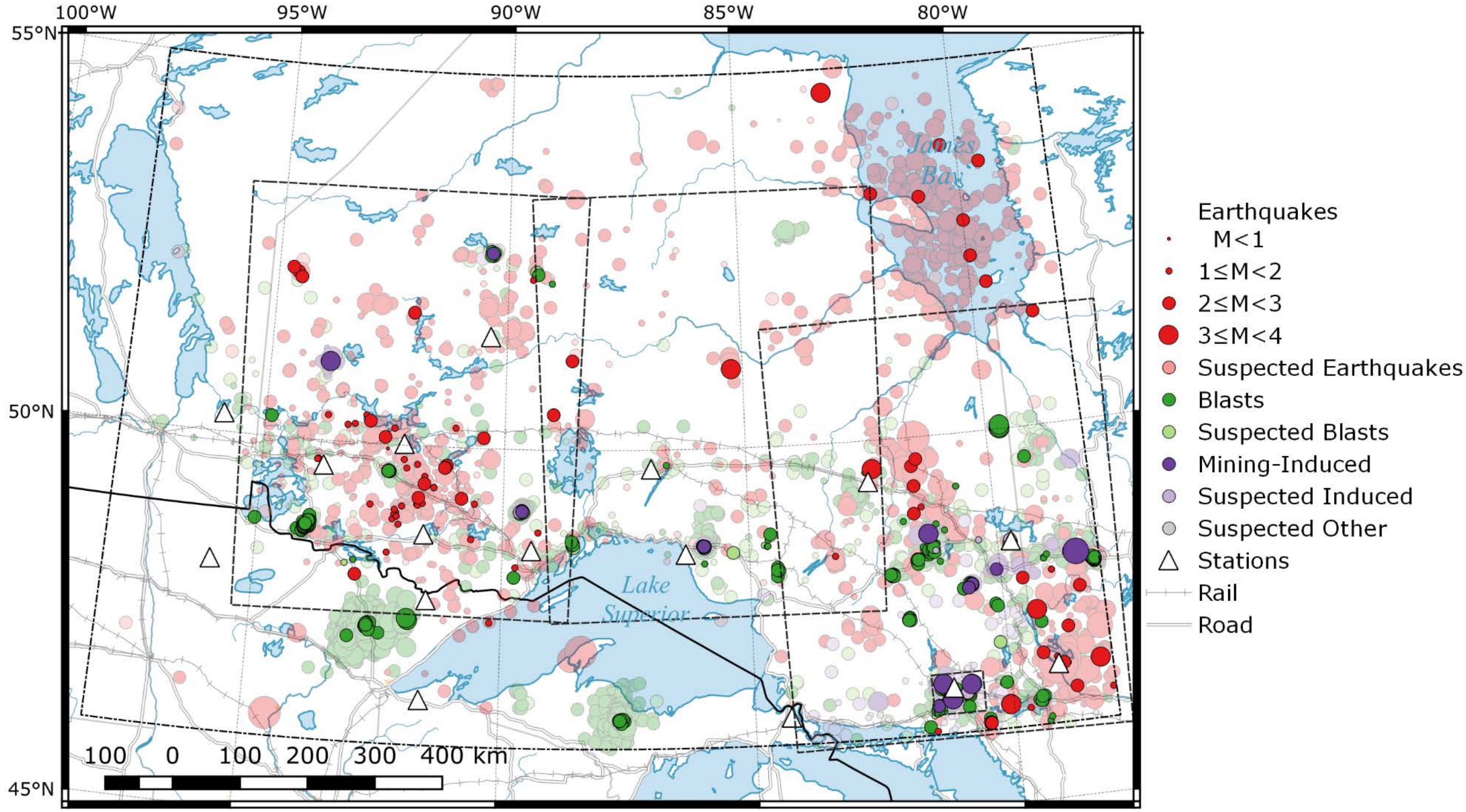

Figure 5: Seismic events in northern Ontario, 2020–2021. Events in 2020–2021 have black outlines, while events from 1900–2020 are plotted semi-transparently and have grey outlines. Events and stations are plotted in the study area only. The study area is outlined with a dash-dotted line. Areas mapped in more detail in Figures 6–9 are outlined with a dashed line. Only stations with data available in 2020–2021 are shown.

A significant part of the effort of cataloguing earthquakes is distinguishing them from anthropogenic seismic sources. The procedure for event type discrimination is described in GSC Open File 8253 (Ackerley, Bird, Kolaj, Kao, & Lamontagne, 2022). Figure 5 shows the earthquakes, mining explosions and mining-induced events catalogued in northern Ontario in 2020–2021 along with the seismicity of previous years, back to 1982. The mining district of Sudbury illustrates the effort required to distinguish different types of events correctly in many parts of northern Ontario. Figure 6 shows this region in detail, along with the locations of active mines.

Among the many seismic events near Sudbury in 2020–2021, just one, on 2020-10-01, was categorized as a natural earthquake. This 2.1 m_N event was shallow (Rg was observed) and felt by many in in Sudbury and Garson but could not be associated with any of the mines. Figure 6 shows that the epicentre was approximately 3 km east of a cluster of seismicity primarily active in 2015–2017 and for which blasting and rock bursts within the mines have also been ruled out. These events occurred within a mining district, so it is possible that they were triggered by unloading due to regional mining activity, but they are currently categorized as natural tectonic earthquakes.

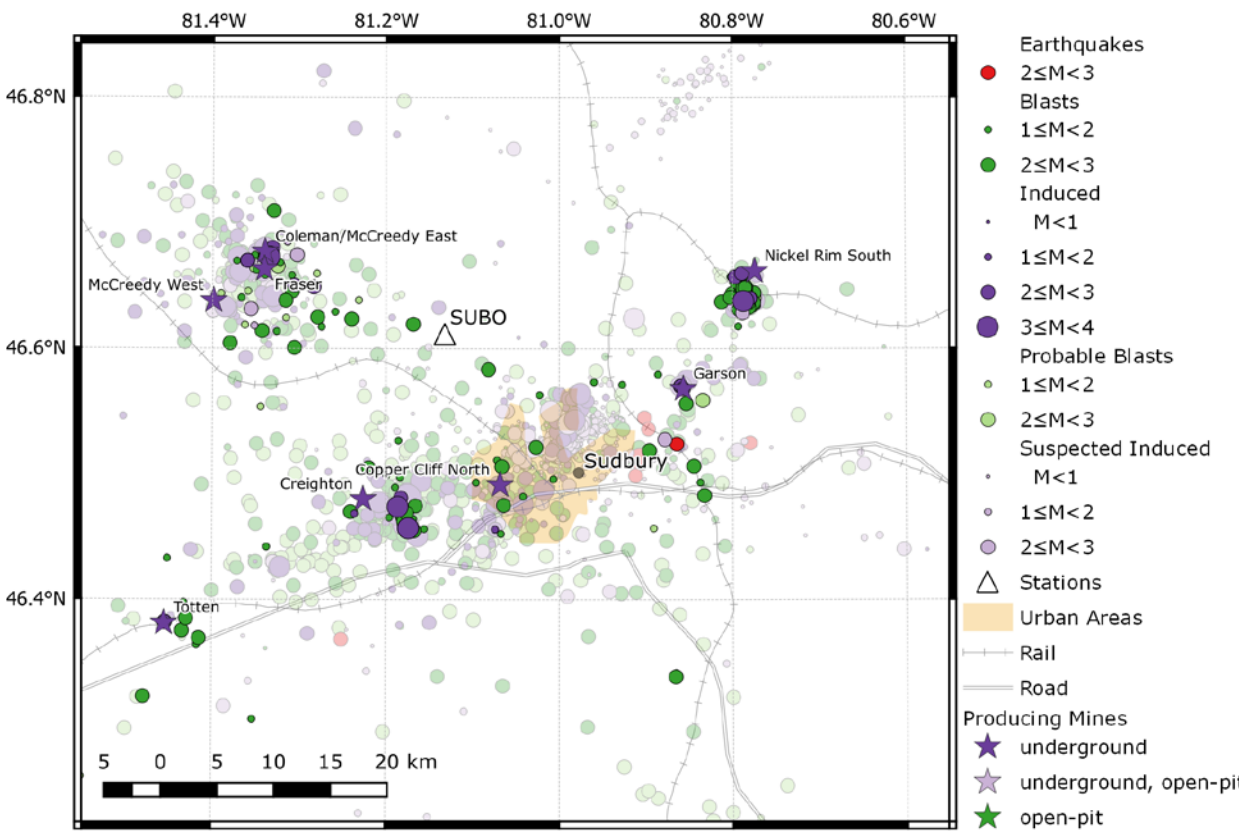

Figure 6: Seismic events near Sudbury, 1982–2021. Events prior to 2020–2021 are partially transparent and thus have grey outlines. Suspected anthropogenic events in 2021 have pale bodies and black outlines. Producing mines from the Atlas of Canada (Lands and Minerals Sector; National Energy Board, 2020) are shown as purple and green stars. Urban areas, major roads and railways are from Natural Earth (Schneider, Friedl, McIver, & Woodcock, 2003; Natural Earth, 2009).

Many mining explosions are repetitive (same location at similar times each day) and perhaps ten thousand in eastern Canada are dismissed each year without being located by the analyst, based on their experience. Events that occur at unusual times or in unusual places are investigated as potential mining-induced events or earthquakes.

It can be difficult or even impossible to distinguish between blasts, earthquakes and mining-induced events solely based on the recorded waveforms. Hence, for unusual events confirmation is sought from any nearby quarry or mine. This is a time-consuming process, further complicated by possible non-repetitive construction blasts such as those due to road construction. With plots like Figures 5–6, any proximity of blast and earthquake symbols leads to checking as to whether a blast might have been misidentified as an earthquake.

Figures 7–9 show seismic events of all types in three sub-regions of northern Ontario, as well as indicating the locations of active mines and other places of interest. Figure 7 shows the Severn Highlands northwest of Lake Superior, Figure 8 shows Sault Ste. Marie and the area northeast of Lake Superior and Figure 9 shows Sudbury and the area north of Lake Huron.

Northwest of Lake Superior (Figure 7), the Severn Highlands seismic zone of the 2015 National Seismic Hazard Model (NSHM) (Halchuk, Allen, Adams, & Rogers, 2014) continued to produce small earthquakes. In all, there were 46 events in this zone in 2020–2021, ranging from 0.7 to 2.7 m_N. Of these events, 30 were assigned a depth of 2±3 km based on the observation of crustal Rayleigh waves, while the remainder were assigned the representative shallow depth for the region. The two largest events were located 51 km northeast of Ignace on 2020-11-10, and 106 km east of Sioux Lookout on 2021-06-17.

An intriguing triplet of earthquakes was catalogued just north-east of the Severn Highlands seismic zone on 2021-12-31, ranging from 2.0 to 2.7 m_N. Only one event, a 3.2 m_N earthquake in 1986, had previously been located in the vicinity. The events were designated as earthquakes based on the time of day (the first occurred at 7 am local time, before sunrise), the size of the largest, and similarities between the waveforms of all three events. The similarity of the waveforms also suggests that they occurred close together; the spatial distribution of the estimated epicentres (see Figure 7) may be an indication of the epicentral uncertainty in the area. Attempts to verify potential blasting activity by contacting the municipality of Poplar Hill 15-30 km away were unsuccessful, but the municipal gravel pit was ultimately deemed too small to have produced such large seismic signatures anyway.

Northeast of Lake Superior (Figure 8), the largest event was a 3.4 m_N earthquake on 2021-11-28, 82 km southeast of Marten Falls. This occurred outside of any recognized seismic zone, but close to a pair of $m_N > 3$ earthquakes on 1987-10-17 and 1987-10-27. The cluster of seismicity north of Chapleau, that was active 2012–2013, 2015, and 2019 produced a single very small 1.6 m_N earthquake on 2020-07-10, located 72 km north of Chapleau.

North of Lake Huron (Figure 9), four earthquakes were located within the Cochrane north seismic zone – three in 2020, and one in 2021, ranging between 1.4 and 2.4 m_N. All four were assigned the default depth for the region, 18 km. An additional 2.3 m_N event on 2021-03-03 was located just outside the Cochrane north seismic zone, 45 km west of Cochrane, and was assigned the default depth of 18 km. The largest earthquake in the study area, a 3.6 m_N event on 2020-10-14, occurred 23 km north of Kapuskasing, just outside the western boundary of the Cochrane north seismic zone (see Figure 9) as defined in the NSHM. A depth of 2±3 km was assigned based on the observation of crustal Rayleigh waves.

The second and fifth largest earthquakes in the study area in 2020–2021, at 3.5 and 3.1 m_N, were located in the northwest section of Lake Nipissing, 12 km west of Sturgeon Falls. The earthquakes were remarkable in that they occurred 5 months apart, with less than a kilometer between epicenters. The events occurred in what would be considered a “background” zone of the NSHM. Both were assigned depths of 2±3 km based on the observation of crustal Rayleigh waves.

Three earthquakes were located in the Cochrane South seismic zone (also Figure 9), ranging between 2.2 and 3.0 m_N. The largest occurred on 2020-04-01 23 km NE of Haileybury. All three were assigned the default depth for the region, 18 km.

The Kipawa seismic zone produced only small earthquakes in 2020–2021, between 1.8 and 2.0 m_N. All were assigned the default depth for the region, 18 km.

The largest event near James Bay in 2020–2021 was just east of it (Figure 5) and outside the James Bay seismic zone, at least as it is defined in NSHM. This was a 3.0 m_N on 2020-03-30, 157 km northeast of Attiwapiskat.

Four of the five largest events in northern Ontario in 2020–2021 occurred in what would be considered background seismicity zones of the national seismic hazard models. Two of these events occurred near more active zones, and could plausibly be associated with them, but this sort of diffuse seismicity is exactly why no part of Canada can be considered completely aseismic.

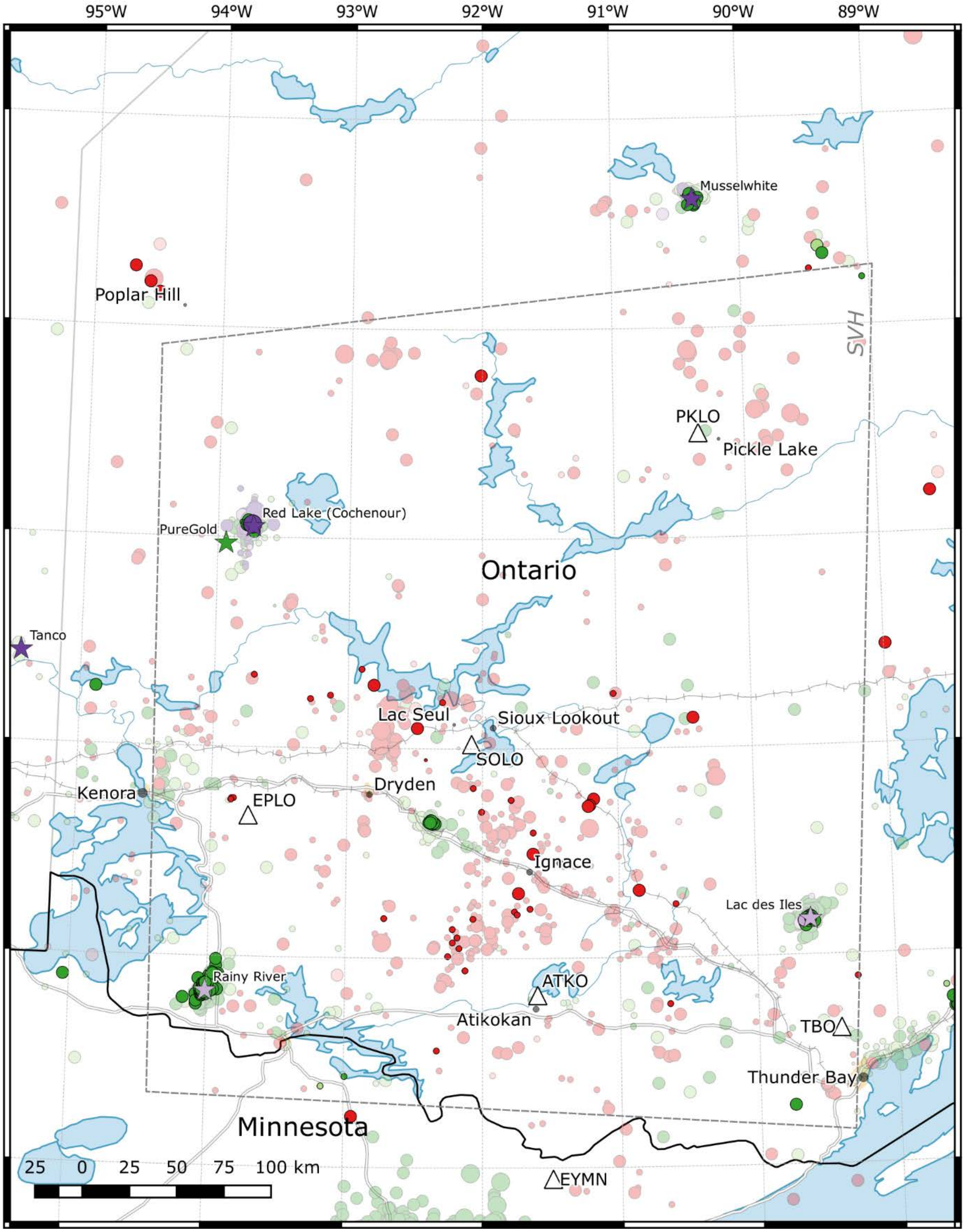

Figure 7: Seismic events in the Severn Highlands, 2020–2021. Legend and notes as for Figure 5. In addition, producing mines from the Atlas of Canada (Lands and Minerals Sector; National Energy Board, 2020) are shown as purple stars and seismic zones of the 2015 national seismic hazard model (Halchuk, Allen, Adams, & Rogers, 2014) are outlined with dashed lines. Seismic zone abbreviations: SVH – Severn Highlands.

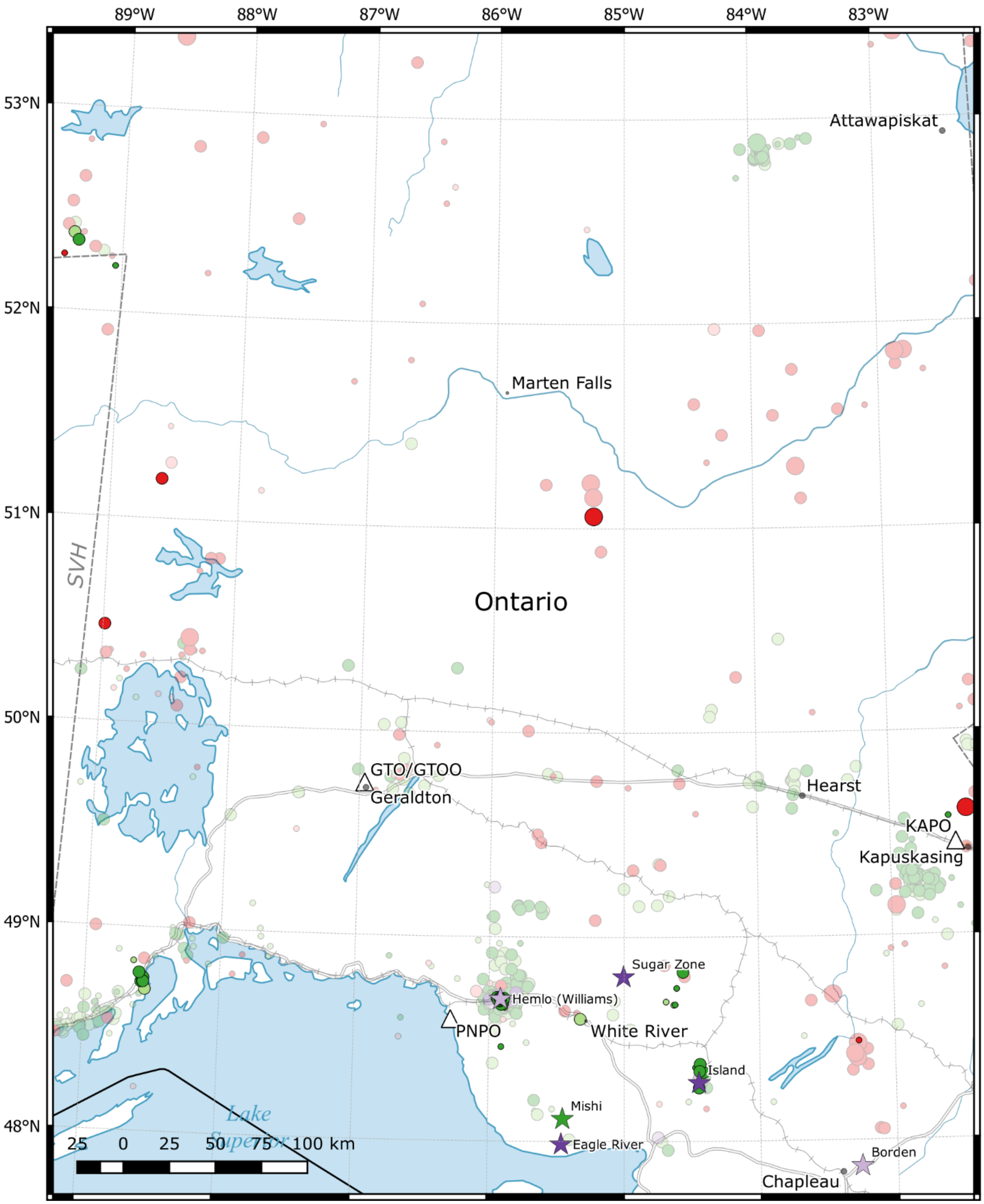

Figure 8: Seismic events northeast of Lake Superior, 2020–2021. Legend and notes as for Figure 7.

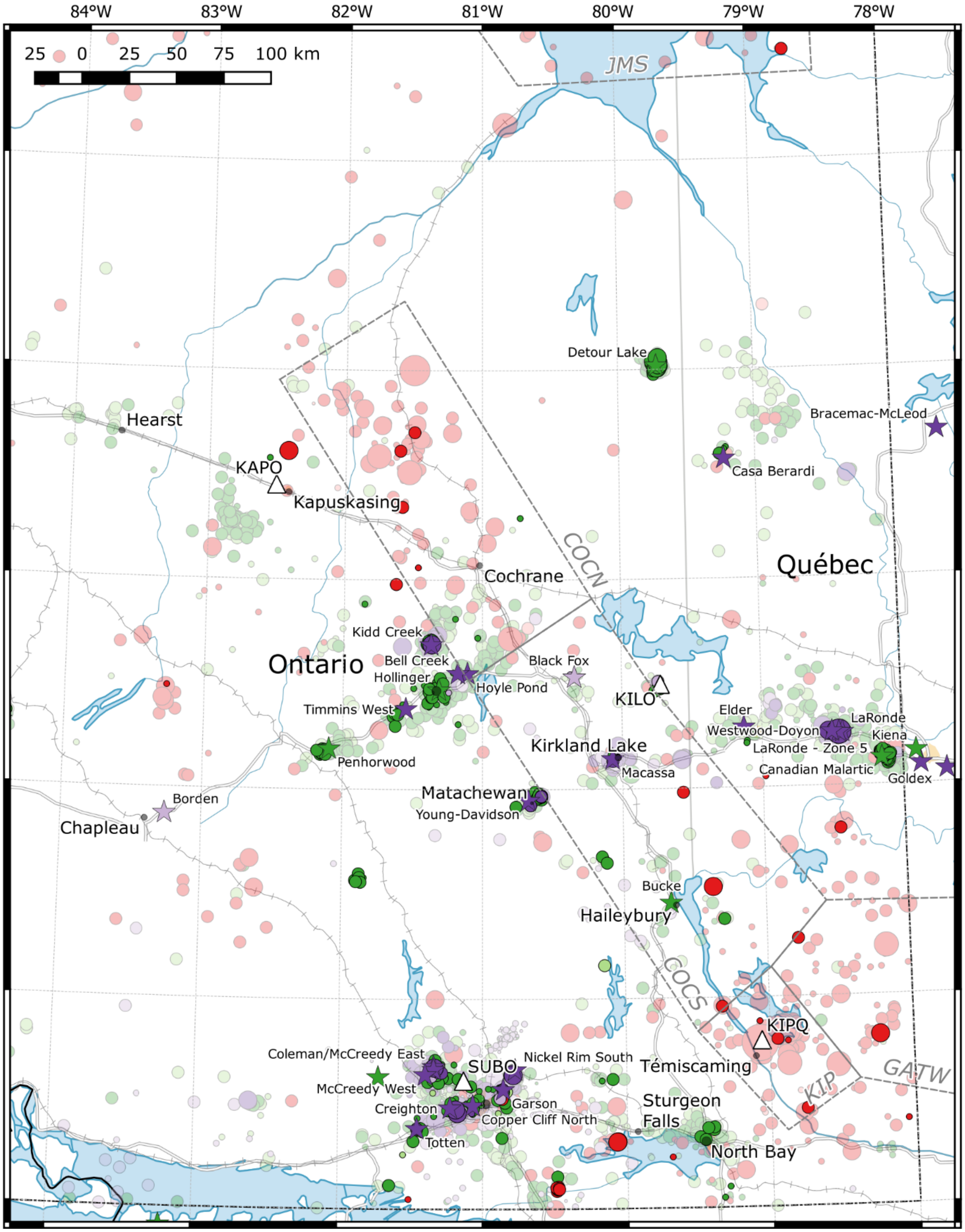

Figure 9: Seismic events north of Lake Huron, 2020–2021. Legend and notes as for Figure 7. Seismic zone abbreviations: JMS – James Bay, COCN – Cochrane North, COCN – Cochrane South, KIP – Kipawa, GATW – Gatineau West.

Figure 10 summarizes the northern Ontario seismic monitoring project thus far, showing earthquakes in the period 1982–2021.

Figure 11 shows earthquakes of magnitude 3 or greater recorded in the study area during the period 1982–2021 (84 events in 40 years). The pattern of all seismicity echoes the pattern of the larger events, though the Thunder Bay – Atikokan area, while active with many small earthquakes, has not yet had an event above magnitude 3.

Figure 12 shows earthquakes of magnitude 2 or greater across eastern Canada in 2020–2021. The rate of seismicity in northern Ontario was among the lowest rates of regions in eastern Canada. Note that the threshold of completeness varies across eastern Canada, with the southern more populated areas having completeness thresholds down to 2.5 m_N or even lower in some areas such as the Charlevoix seismic zone, and less populated areas like northern Quebec being complete to only about 3.0 m_N.

Figure 13 shows earthquakes of magnitude 2 or greater across eastern Canada for the entire monitoring period of 1982–2021. There have been relatively few earthquakes in northern Ontario as compared to the Ottawa and St. Lawrence valleys and the Appalachians of eastern Canada. Within the southern half of northern Ontario, the central part (Hearst-Nipigon) has fewer earthquakes than the eastern or western parts. In the northern half of northern Ontario, James Bay (and southernmost Hudson Bay) appears to be more active than the onshore region. Ma, Eaton and Adams (2008) suggest that earthquake activity in the James Bay region is linked to deep structures reactivated by a hot spot.

Recurrence curves for the study area for the year and since 1987 are discussed in detail in Section 6.

3.3 DATA RESOURCES

Waveform data, station metadata and earthquake data are archived by CHIS.

Waveform data is archived in the National Waveform Archive:

> http://earthquakescanada.nrcan.gc.ca/stndon/NWFA-ANFO/index-en.php

Station metadata is available from the CNSN Station Book:

> http://earthquakescanada.nrcan.gc.ca/stndon/CNSN-RNSC/stnbook-cahierstn/index-en.php

Waveform data in miniSEED format and station metadata including instrument response in StationXML format can be downloaded from the FDSN web service at:

> https://earthquakescanada.nrcan.gc.ca/fdsnws/.

Catalog entries for 2021 and previous years are archived in the National Earthquake Database:

> http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/index-en.php

The same search tool can access preliminary solutions for earthquakes more recent than the ones documented in the 2021 report, however that list may not be complete, and solutions may still be revised.

The catalogue of known earthquakes in northern Ontario catalogue since 1982 is included as an electronic supplement to this publication, in a pipe-delimited text format.

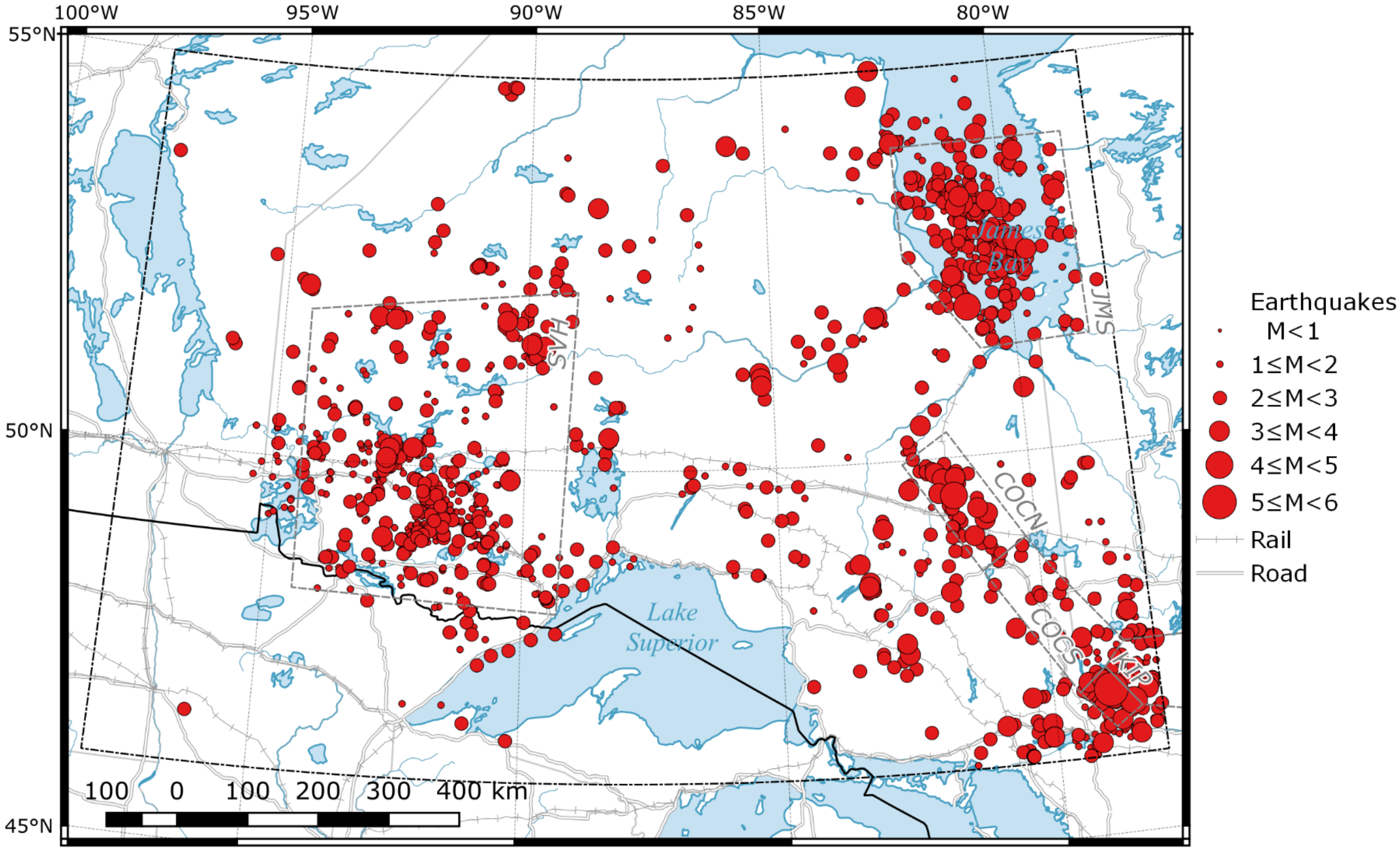

Figure 10: Earthquakes in northern Ontario, 1982–2021. Events and stations are plotted for the region within dashed lines only.

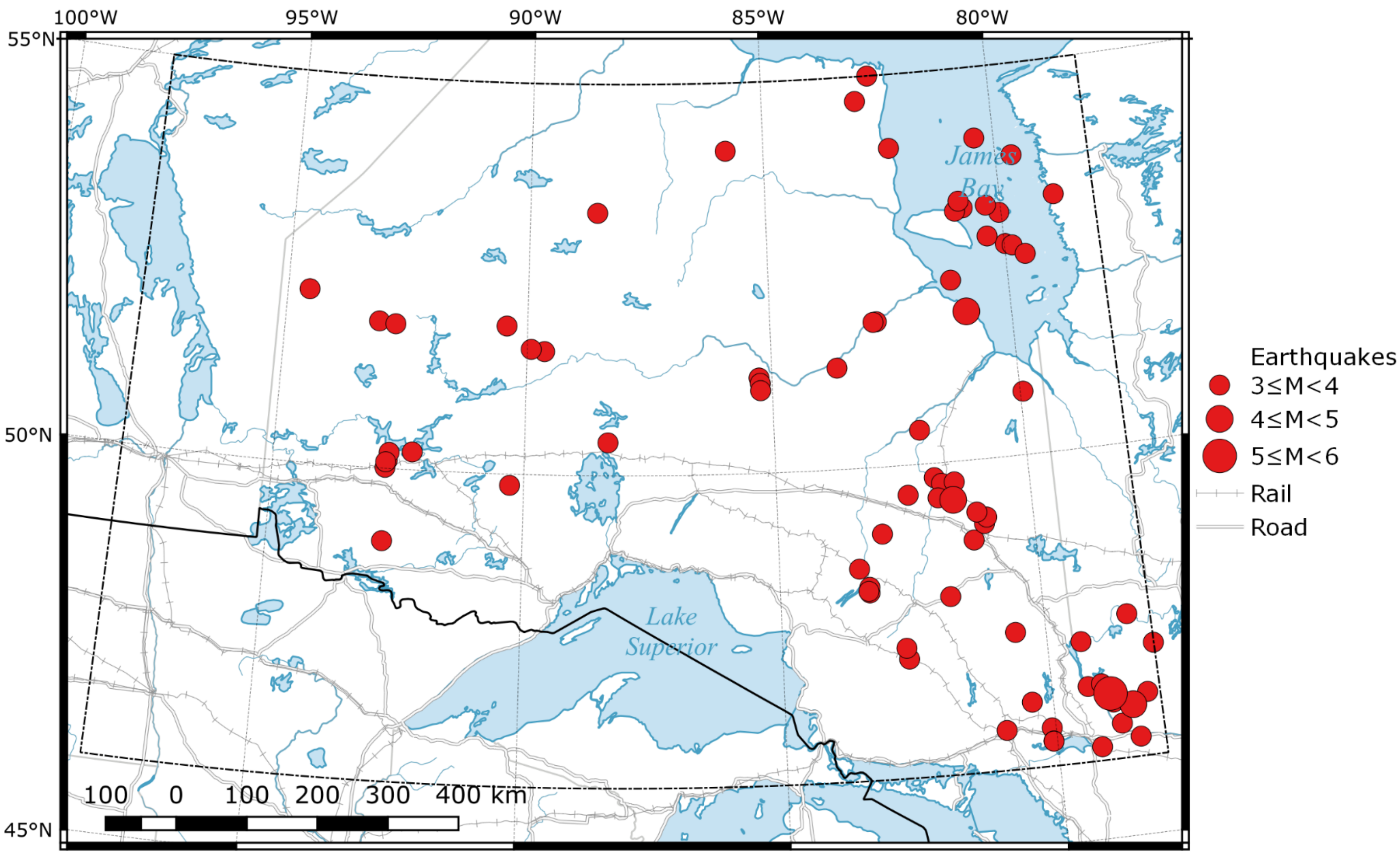

Figure 11: Earthquakes $m_N \geq 3$ in northern Ontario, 1982–2021. Events and stations are plotted for the region within dashed lines only.

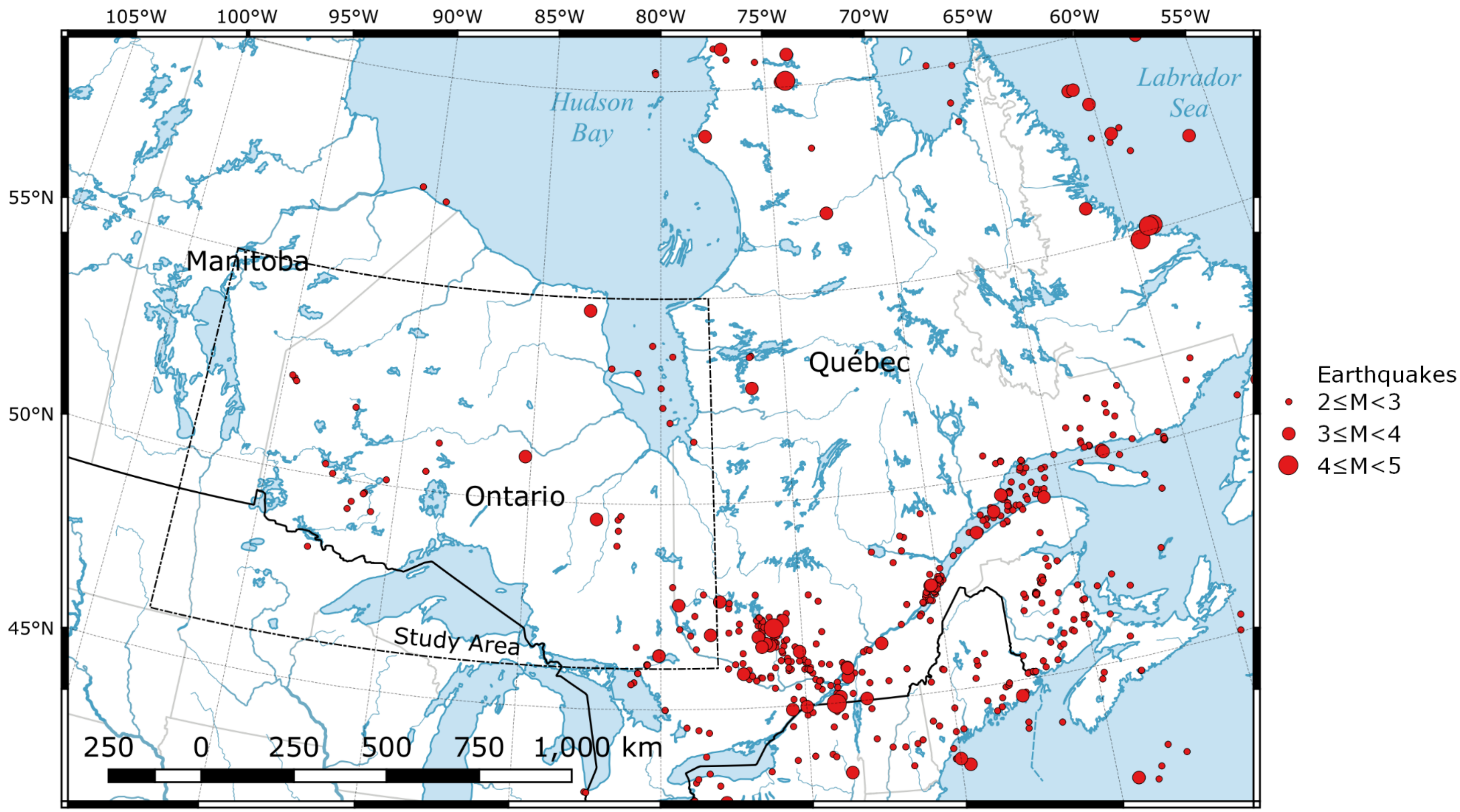

Figure 12: Earthquakes in eastern Canada, 2020–2021. Record is likely incomplete for M<3, north of 47°N.

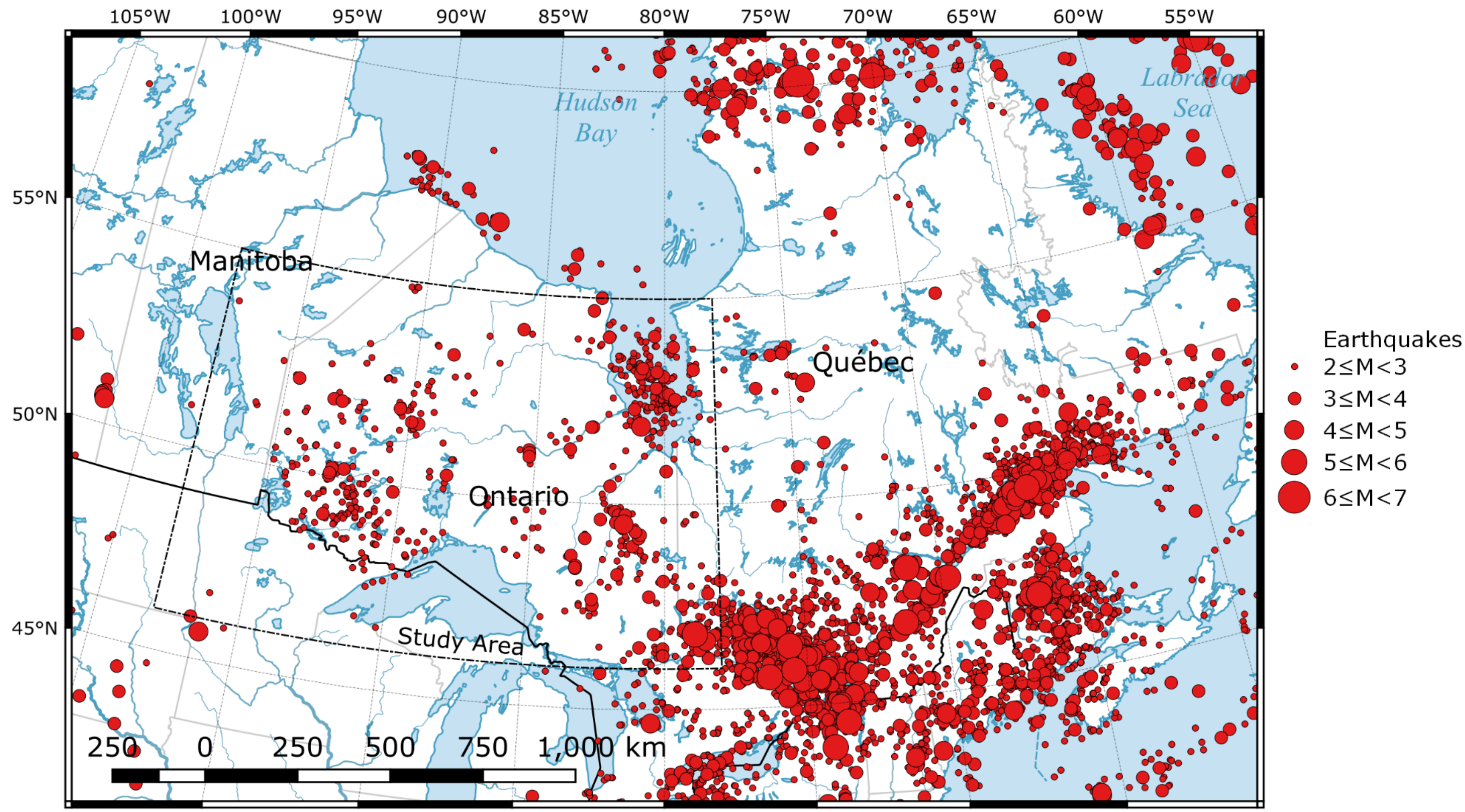

Figure 13: Earthquakes in eastern Canada, 1982–2021. Record is likely incomplete for M<3, north of 47°N.

4. LOCATION ACCURACY IN NORTHERN ONTARIO

4.1 PARAMETERS

The minimum requirements to estimate the epicentre of an earthquake given an assumed depth are three stations and five phases (P-wave, S-wave). The basic parameters calculated for any earthquake location are latitude, longitude, and origin time. Additional phases can improve accuracy, and permit estimation of epicentral uncertainty and/or depth.

Some events may have aftershocks that are visible on less than three stations, sometimes only on the single closest station. In these cases, judgement is used to label the event an aftershock (often based on the short interval after a larger event and similar waveforms on the closest station). The event is assigned to the location of the larger, well-located event, and then the available seismograph readings are used to determine the origin time and magnitude of the aftershock. All earthquakes in Table 3 and Table 4 were located using three or more stations or by pegging to that of an event with strong waveform similarity (e.g. a mainshock).

The three crucial variables associated with the calculations of earthquake parameters are clarity of phase arrival (particularly important when working with minimal data), azimuthal coverage, and the accuracy of the crustal models used (e.g., seismic velocity models and composition of the earth's layers). It is assumed that station timing is precise. The numbers of stations and phases used in determining the location of each earthquake are indicated in Table 3 and Table 4.

4.2 LIMITATIONS

Location accuracy in northern Ontario is hampered by the following factors:

i. Socio-geographical constraints meant that the core stations installed in the 1980s were more or less in a straight line, so that azimuthal coverage was not ideal. The situation improved with the addition of temporary stations in the early 2000s, but station density is still quite low in many places.
ii. Low station density means that that phase arrivals may be ambiguous (as a rule the closer the station the sharper the arrival) or completely hidden by station noise.
iii. Some stations have high background noise, which masks phase arrivals for small events.
iv. Depths are difficult to estimate, as discussed in Section 4.2.1.
v. Models of velocity structure are imperfect, as discussed in Section 4.2.2.

An incorrect depth or velocity model will introduce an error into a computed epicentre, particularly for events recorded on only a few stations or with poor azimuthal coverage.

The uncertainties associated with earthquake locations (and in particular, for events of magnitude 2.0 or less) must be taken into consideration when attempting to relate these events to specific geological features or trends. Furthermore, accurate locations are an important and necessary component of any probabilistic model using geological structures to assess seismic hazard, even though the probability of a future earthquake is not simply a function of previous seismic activity at a particular place.

For the current network, assuming all stations are recording optimally, a magnitude 2.0 event located within the network (that is to say, the epicentre was surrounded by stations on all sides), will have an approximate location accuracy of ±10 km. As the event gets larger, and the recordings on the stations get clearer, the associated error decreases. Being able to determine the depth of an earthquake will further decrease this error. In the Atikokan region, where there is currently a slightly higher density of stations, this error is likely closer to ±5 km, and even less, if the approximate depth is known.

On the other hand, for events located to one side of the network (in particular to the west and north), the location accuracy will decrease as the epicentre will not be well surrounded. This means that any bias arising from inaccuracy in the velocity model will not be offset by recordings from the opposite site. This location inaccuracy will increase the further the epicentre is located from the network.

In addition, as the size of the event decreases, the number of stations that clearly record that event will decrease, and the onset of the phases will become less clear. This will increase the amount of error associated with an epicentre. Moreover, a station which stops recording or which is noisy will have the same effect on the location uncertainty as a decrease in magnitude.

4.2.1 Focal Depth

Stevens (1994) in her paper dealing with earthquakes located in the Lake Ontario region warns of taking into account the reliability of earthquake parameters before proposing a seismotectonic model. She noted that determining an accurate epicentre using direct calculation for a particular event requires that the recording stations be fairly evenly distributed in azimuth about the epicentre (to allow triangulation). In addition, an accurate estimate of depth within the crust requires that several of these stations be located close to the epicentre, at distances smaller than the local crustal thickness (approximately 30–50 km). In general, unless a special network of closely spaced stations has been installed to study a small area, station spacing is seldom less than 50 km (the Charlevoix, Quebec network is an example). Thus, few earthquakes will be recorded within 50 km of more than one station, and depth cannot be calculated from direct phases, but is instead assumed, as is the case in the study area. Where depth of earthquake activity in continental terranes is well known (for example the Charlevoix seismic zone), earthquake depths seldom exceed 30 km and mostly fall between 10 and 20 km. In most of eastern Canada, the default depth is generally assumed mid-crust, i.e., 18 km, unless other information is available. An exception is a region including the Appalachians, southern Ontario and the southern part of northern Ontario, where the default is assumed to be shallower, at 5 km, to reflect the shallower seismicity observed in these regions.

There are ways of determining earthquake depth other than from direct phases. The classical "depth phase" method relies on phases recorded on the far side of the earth that have been reflected off the earth's surface; the difference in travel time between the direct, downward arrival and the surface reflection establishes the earthquake's depth. However, none of the earthquakes in northern Ontario, in 2021 or in any previous year since the study began in 1982, has been large enough to be recorded clearly at such great distances.

A modification of the classical depth phase method is the regional depth phase modelling (RDPM) method developed by Ma (2004) in conjunction with CHIS seismologists. RDPM requires neither a dense network near the epicentre, nor clear arrivals at teleseismic distances. Ma found that, "we can reliably estimate focal depth with regional depth phase modelling method for moderate and small earthquakes without records from nearby stations in northern Ontario." (Ma, 2004) RDPM is being applied to the larger eastern Canadian earthquakes. It is generally useful down to at least $m_N > 3$, although depending on station quality and azimuthal distribution, it can work well

Table 5: Regional depth phases and their ranges of utility

reference phase	depth phase	range well-developed [km]	Notes
Pg	sPg	60–120	
PmP	sPmP	130–300	
Pn	sPn	> 300	weak; rarely useful for smaller earthquakes

for smaller magnitudes. Different regional depth phases are useful in different distance ranges, as summarized in Table 5 (Ma, 2004).

Extensive work using RDPM modelling was done for earthquakes in neighbouring regions, the West Quebec seismic zone and southern Ontario (Ma & Atkinson, 2006). A further paper based on Ma (2004) focused on the Severn Highlands of northern Ontario (Ma, Eaton, & Adams, 2008). In both cases, it was noted that while deeper events were limited to specific sub-regions, shallower events were found over the entire region.

Table 6 lists the events in northern Ontario in 2020–2021 that had depths estimated by RDPM. In 2020–2021, seven earthquakes and six mining-induced events had depths estimated using RDPM. Of the earthquakes, three were close to mid-crust, and four were shallow crustal earthquakes.

Starting in the summer of 2016, mine operators began to provide a confirmed depth for some events in their mines when it was requested by CHIS. For some of the larger events, it is possible to estimate their depth via RDPM. In 2020–2021, six events had both a depth estimated using RDPM and an accurate depth provided by mine operators (see Table 6). We call these “depth-constrained ground truth” events. Note that in the Canadian National Earthquake Database (NEDB) the depths of events estimated using depth phases or fixed to a depth obtained from a mine operator are given with respect to surface, whereas depths estimated from direct phases are with respect to sea level.

The depth-constrained ground truth dataset consists of 27 events thus far (2016–2021). As this dataset expands, it becomes possible to assess the accuracy of existing depth estimation techniques. It is expected that the dataset should eventually enable the improvement of existing techniques and/or the development of novel techniques.

Table 6: Depths estimated using RDPM, 2020-2021

time [UTC]	mag.		lat. [°N]	lon. [°W]	depth [km] est. [a]	depth [km] act. [a,b]	F [c]	# [d]	T [e]	Comment
2020-01-03 06:49	3.2	m_N	48.692	81.367	2.2	2.3		4	R	Timmins, ON
2020-04-01 16:47	3	m_N	47.528	79.373	13		✓	3	L	21 km NE of Haileybury, ON
2020-08-07 18:13	3.5	m_N	46.3188	80.0662	2		✓	1	L	13 km SW of Sturgeon Falls, ON
2020-10-14 13:48	3.6	m_N	49.6114	82.423	3.5		✓	2	L	22 km N of Kapuskasing, ON
2020-10-30 18:28	3.6	m_N	48.258	78.525	1	1.32	✓	2	R	Westwood Mine, QC
2020-12-25 14:56	2.6	m_N	47.9803	79.5709	17.5			1	L	29 km NE of Englehart, ON
2021-01-16 03:19	3.7	m_N	46.474	81.1861	2.6	2.36	✓	5	R	Creighton Mine, ON
2021-01-17 08:53	3.09	m_N	46.3171	80.069	3			2	L	9 km SW of Cache Bay, ON
2021-03-03 22:22	3.2	m_N	46.673	81.335	2	1.21		3	R	Coleman/McCreedy East Mine, ON
2021-04-13 19:08	3.52	m_N	46.8072	78.2331	1			3	L	48 km ESE of Hunter's Point, QC
2021-07-08 06:36	2.9	m_N	46.657	80.797	1.3	1.4		3	R	Nickel Rim South Mine, ON
2021-12-28 23:22	4.07	m_N	48.2517	78.4518	2.8	2.93	✓	3	R	LaRonde Mine, QC.
2021-12-31 13:02	2.73	m_N	52.2069	94.5747	12			1	L	22 km WNW of Poplar Hill, ON.

In addition to the notes to Table 3, the following notes apply:

[a] Estimated and actual depths are given with respect to the surface.

[b] Actual depths for mining-induced events are given when confirmed by mine operator.

[c] “F” indicates whether an event was felt.

[d] “#” indicates the number of RDPM depth phases used, when applicable.

[e] Event type coding (“T”) is as follows (see Section 4.2.1 for details): L – earthquake, R – confirmed mining event, U – unconfirmed mining event

The difference between the RDPM estimate and the actual depths in the ground truth dataset is plotted against depth in Figure 14. There does not appear to be any trend with depth. The RDPM depth estimates are on average 0.23 km too deep. Some bias towards larger depths should be expected for the shallowest events because the method can never give an estimate less than zero, therefore this bias may be associated exclusively with shallow events. The estimates have a standard deviation of 0.52 km, but the distribution is closer to uniform than to normal (Gaussian). We normally assign a nominal uncertainty of ±1 km to RDPM estimates, independent of depth. This is approximately two times the standard deviation, and would approximately represent a 95% confidence interval, were the distribution Gaussian. More data is needed to determine whether the results are normally distributed.

The outlier on Figure 14 is an important cautionary example. A mine operator reported an event on 2018-09-12 to have occurred at a depth of 0.62 km, 2.13 km shallower than the RDPM estimate of 2.75 km, based on estimates from three stations between 2.5 and 3.0 km. The error is 3.4 times the standard deviation, an occurrence that should happen at a rate of less than one in a thousand, for a truly Gaussian process, and yet here it has occurred among the first fifteen.

The RDPM method has known shortcomings. The synthetic waveforms used make significant assumptions about source duration and focal mechanism, and a subjective judgment is made when matching observed to synthetic waveforms. In many cases, including the above example, the signals showed more high-frequency content than the synthetics, suggesting a shorter source duration and making the matching of waveforms more difficult. While the accuracy of RDPM depth estimates for shallow mining events is generally quite good, the outlier in Figure 14 underscores a need for improvement.

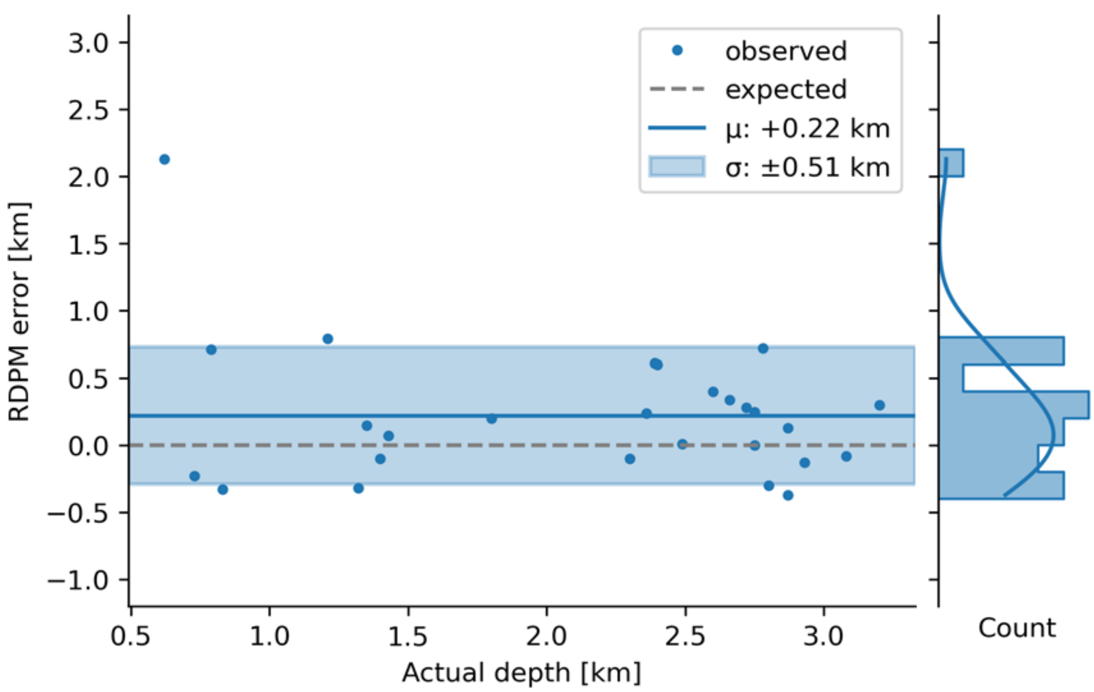

Figure 14: Accuracy of RDPM depth estimates for shallow mining events, 2016–2021. RDPM error is the estimated depth minus the actual depth reported by the mine operator. The mean μ and standard deviation σ of the distribution are indicated.

An alternative method of depth determination involves the observation and modeling of the relatively long-period crustal Rayleigh wave (Rg). These Rg waves are strongly excited by shallow (<5 km depth) events and are nearly always present in surface explosions. The presence of a strong Rg-phase indicates that the depth of an event is likely shallower than 5 km. Ma and Motazedian (2012) used the maximum power Rg/Sg spectral ratio to estimate depths of small shallow events in eastern Canada. They concluded that lack of knowledge of the focal mechanism would contribute no more than ±0.5 km uncertainty when comparing to modeled spectral ratios. This method has not entered routine practice.

Prior to 2016, the practice at CHIS was to assign a 5 km depth when Rg is observed (or 1 km when Rg is particularly pronounced) for these events. This practice is problematic because these depths are also assigned when no other depth estimate is available, in some cases (5 km is the default for earthquakes in some regions, while 1 km is the default for underground mining events). Furthermore, it is misleading to peg the depth at the maximum likely depth, rather than somewhere in the middle of the range. For these reasons, starting in 2016, the practice is to assign a 2 km depth when Rg is observed, with an implicit ±3 km uncertainty. This is to be understood as a depth below sea level, to allow for underground events that are nonetheless above sea level.

4.2.2 Velocity Models

At present, the velocity model for determining earthquake epicentres in northern Ontario is the CN01 velocity model described in Table 7.

A Lithoprobe seismic experiment carried out throughout northern Ontario in the summer of 1996 yielded a suite of small magnitude explosions whose epicentres, depths and origin time were precisely known. Using results from this experiment, Musacchio et al. (2004) found:

- Large variations in lower crustal velocities (6.7–7.5 km/s)
- Higher upper mantle velocities (8.0–8.8 km/s);
- Crustal thickness variations (31–45 km); and
- An 8% azimuthal crustal velocity anisotropy.

Work by Bent and Kao (2015) using teleseismic receiver functions have also found that the crustal thickness varied from 35–45 km under many of the stations in eastern and central Canada, with the majority being in the thicker range, from 40–42 km. A strong anisotropy is also noted by Darbyshire and Lebedev (2006) in their work using surface wave analysis. Motazedian et al. (2013) used Rayleigh wave dispersion to calculate shear wave velocities for the eastern North America region. The Regional Seismic Travel Time (RSTT) methodology (Myers, et al., 2010) shows promise as a way of incorporating regional variations like these into a pseudo-3D velocity model. The RSTT model currently in use at the International Data Centre of the CTBTO (Begnaud, et al., 2020) is not suitable for use in the study area, however, because the ground truth dataset it is based on lacks raypaths (particularly Pg) through northern Ontario. Efforts are currently underway to develop a RSTT model suitable for locating earthquakes across Canada. In the end, any model proposed for adoption would need to be assessed to determine whether it is

Table 7: Parameters of velocity model CN01

Parameter	Layer	Value	Note
P-wave velocities	crust	6.2 km/s	Pg travels at this velocity
	upper mantle	8.2 km/s	Pn travels mainly at this velocity
S-wave velocities	crust	3.57 km/s	Sg travels at this velocity
	upper mantle	4.7 km/s	Sn travels mainly at this velocity
thickness	crust	36 km	

Note: This model was first described in Stevens, Milne, Wetmiller, & Horner (1972) appropriate for the region under consideration for this study, and the consequences of applying such a model for the earthquake locations in this report.

If the velocities in the lower crust and upper mantle are higher than the current model, this might mean that the earthquakes are farther away from the recording stations than currently computed. However, the effects of using a poor velocity model are greatest when the station azimuthal coverage is poor, and currently the station distribution is good enough that for events detected at many stations the effects of velocity model errors are mitigated. That was not the case for the 1982–2003 epicentres, recorded by few stations mainly on an east-west line. Therefore, some of those epicentres may be biased (probably towards being too close to the line of stations) relative to the current ones.

5. MAGNITUDE ESTIMATION

Earthquake size is expressed by magnitude, a mathematical quantity derived from the amplitude of seismic signals recorded at a given distance. For regional-scale monitoring of eastern Canada and for this report, most magnitudes are based on the Nuttli magnitude scale (m_N), a variation on the Richter scale (ML). The magnitude scale is a logarithmic scale, so that a 10-fold decrease of earthquake size decreases the magnitude by one unit. For example, the amplitude read off a seismograph record for a magnitude 1 earthquake is ten times bigger than the amplitude for a magnitude 0 earthquake and 100 times bigger than the amplitude for a magnitude -1 earthquake. Negative magnitudes are found for very weak events not felt by humans but recorded by extremely sensitive seismograph networks. Magnitude 3 earthquakes are generally big enough to be felt (if they occur close to populated areas) and magnitude 5 events are generally large enough to cause minor property damage.

The magnitude of an earthquake is determined by averaging the estimates made at each recording station, and so the precision of the final magnitude can be computed. As typical precisions are about 0.1 magnitude units (for the standard error of the mean), the errors in the magnitude are not considered further in the discussion.

For purposes of international comparison, it is useful to express earthquake magnitude in terms of moment magnitude (Mw). Bent (2011) suggests that for Nuttli magnitudes above approximately 3.0, the post-1997 relationship is $Mw = m_N - 0.53$, so as an approximation this relation could be applied to the smaller m_N magnitudes in this report.

6. EARTHQUAKE OCCURRENCE RATES

As stated in the Introduction, the annual frequency of earthquakes of a given magnitude is a logarithmic function of magnitude. The function, termed a magnitude-recurrence curve, can be established by fitting the northern Ontario earthquakes on a plot of logarithmic cumulative frequency versus magnitude. To establish the most reliable recurrence curve it is necessary to include earthquakes over the longest possible duration. The dataset for $m_N > 2.0$ is considered complete since 1987, providing 34 years of data for the less-common larger earthquakes.

Figure 15 shows the magnitude-recurrence plot for 2020–2021 and 1987–2021. Note that while some of the data points from 2020–2021 may be hidden beneath those for 1987–2021, their error bars are always larger.

Below magnitude 2.0 and down to the minimum magnitude observed of 1.0, the occurrence rates deviate significantly from the long-term straight-line fit. This suggests that the northern Ontario catalogue for 2020–2021 is complete down to approximately magnitude 2.0. The magnitudes of completeness (Mc) used when fitting the slopes of the occurrence rates are indicated on Figure 15.

The occurrence rates for 2020–2021 and for 1987–2021 were fit using the maximum likelihood estimation procedure of Weichert (1980). As expected, the fit for a single year has much greater uncertainty than the long-term fit. For 2020–2021, the best-fit slope was found to be 0.89 ± 0.12, versus 1.09 ± 0.04 for 1987–2019 (35 years). The difference in slope may seem small but it results in a four-fold difference in the rate for M≥5.0 earthquakes (the ones important for seismic hazard), and when uncertainties are taken into account this becomes an almost ten-fold difference. This example underlines the importance of long-term seismic monitoring. Ackerley, Kolaj, Peci, & Adams (2019) furthermore argue that when estimating the rates of the largest earthquakes in stable continental regions, data from analogous regions globally should be incorporated, which we are not doing here.

A more detailed discussion of magnitude-recurrence curves and comparisons amongst different years and for different time periods for the northern Ontario region was given in Section 6 and Appendix A of report NWMO TR-2007-02 (Hayek, et al., 2007).

While the cumulative rate for 2020–2021 near M2.3 is the same as the 30-year rate, the rate for M>3.3 is two to three times higher than the 30-year rate. These sorts of discrepancies (four M>3.3 vs less than 1 expected) are typical of the random fluctuations observed in a short catalogue.

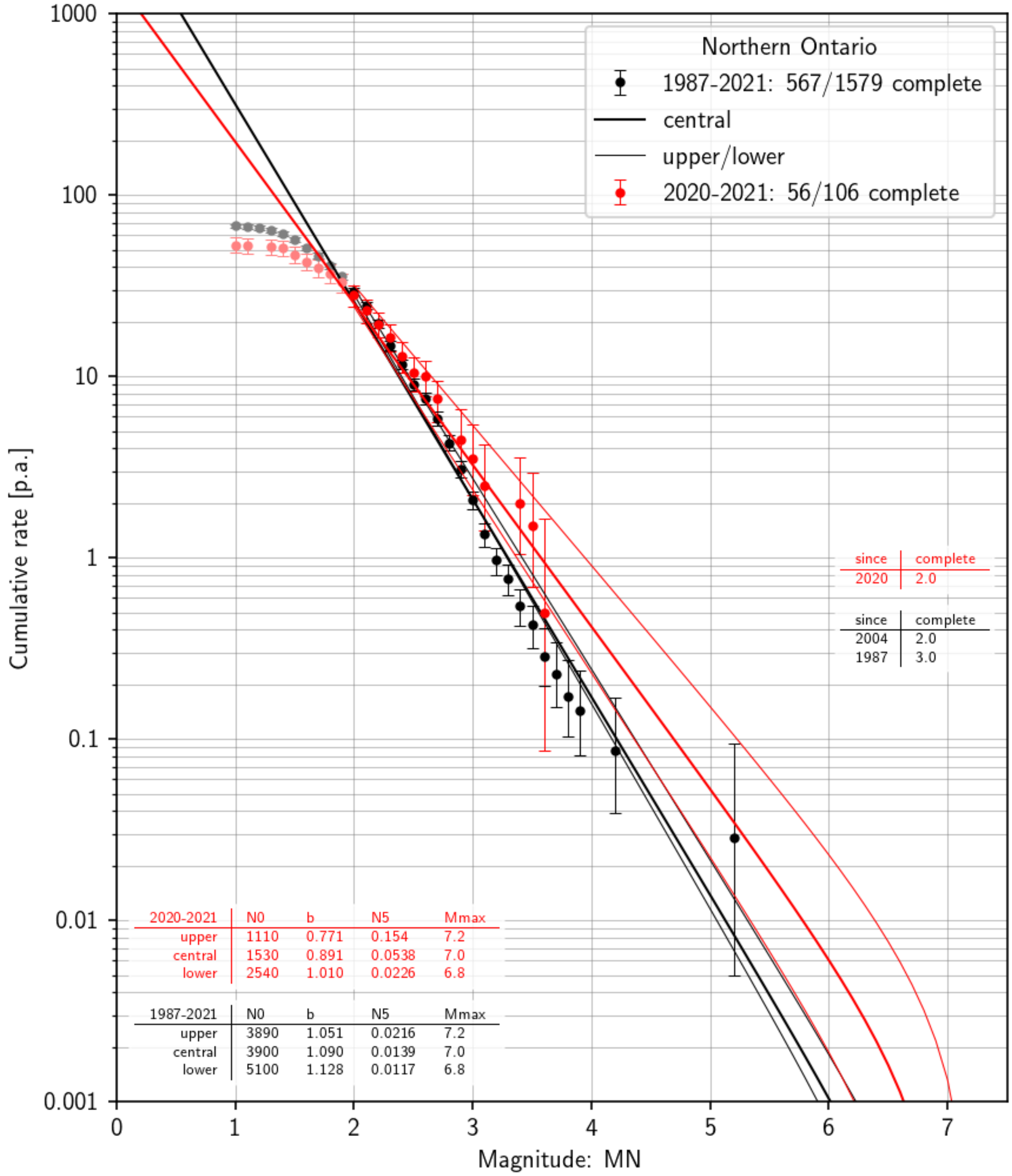

Figure 15: Recurrence curves for Northern Ontario, 2021 and 1987–2021. Yearly earthquake occurrence rates in 0.1 magnitude unit wide bins are shown as points with error bars, while fitted curves are shown as lines. The incomplete part of the catalogue for 2021 is shown in grey. Standard fit statistics are given in boxes, including the fitted slope b-value and the assumed maximum magnitude Mx. For each dataset, the middle line is the maximum likelihood estimate, while the outer lines are upper and lower bounds on this estimate.

7. MINING-RELATED ACTIVITY

CHIS does not document mining-induced events or mining explosions in a comprehensive manner, as this does not fall within our mandate. Suspected mining-induced events and mining explosions are typically only located if the event is larger than 2.5 m_N, felt, unusual in some way, or the subject of an information request from a mine operator. On this basis, an average of approximately 350 non-earthquakes per year have been catalogued since the inception of the northern Ontario monitoring project.

Of 41 events with magnitude greater than or equal to 3.0 m_N in the study area in 2020–2021, 7 were natural tectonic earthquakes, 6 were blasts, and the remaining 28 were mining-related events, including the three largest. Similarly, of 21 felt events, ranging in magnitude from 1.4 to 4.1 m_N, 12 including the smallest were earthquakes, and the remainder were mining-related events.

A 4.1 m_N mining-induced event on 2021-12-28 was the largest event in the study area in 2020–2021. This event had the same magnitude as a 2006 Sudbury event, which was previously considered the largest anthropogenic seismic event in eastern Canada. The event occurred at the Laronde mine. The mine operator provided a depth of 2.93 km; our estimate, based on RDPM, was 2.8 km. This event is potentially a very important ground-truth event for seismic characterisation in eastern Canada.

In all, 472 known and 43 suspected mining-induced events were located in the study area in 2020–2021. Ninety of these mining-induced events recorded in the study area in 2020–2021 had magnitude 2.5 or larger; these are listed in Tables 9 and 10.

Although the monitoring of mining-related activity does not fall within the core mandate of CHIS, the accumulated data can serve several important purposes. First, the development of new methods for event type discrimination depends on the existence of a reliable “training” dataset consisting of events of known types, including both earthquakes and non-earthquakes. Second, confirmed locations at mines can help serve to evaluate location accuracy in a given region, incorporating errors due to network geometry, arrival picking accuracy and velocity models. Third, events with depths confirmed by mine operators can serve as a “ground-truth” dataset for developing new methods or evaluating the accuracy of existing methods of depth estimation (see Section 4.2.1).

Table 8: Mining-induced events $m_N \geq 2.5$, 2020

time[a] [UTC]	mag.		lat. [°N]	lon. [°W]	dep. [km]	felt	D[b]	mine	notes
2020-01-03 06:49	3.2	m_N	48.692	81.367	2.3		H	Timmins	
2020-01-11 22:50	3.2	m_N	51.062	93.742	1.0		H	Red Lake	
2020-01-14 10:19	3.2	m_N	48.251	78.442	2.93		H	Laronde	
2020-01-22 22:23	2.5	m_N	48.251	78.442	2.9		H	LaRonde	
2020-01-27 22:27	2.5	m_N	48.251	78.442	1.0		H	Laronde	
2020-02-11 11:03	3.0	m_N	48.251	78.442	2.69		H	Laronde	
2020-02-12 04:32	2.8	m_N	48.251	78.442	2.93		H	Laronde	
2020-02-26 13:22	2.8	m_N	48.251	78.442	2.81		H	Laronde	
2020-03-03 05:49	2.5	m_N	51.062	93.742	0.47		H	Red Lake	
2020-03-05 13:41	2.6	m_N	51.062	93.742	0.45		H	Red Lake	
2020-03-06 01:16	2.5	m_N	48.251	78.442	2.99		H	Laronde	
2020-03-13 19:35	3.5	m_N	46.673	81.335	1.28		H	Sudbury	
2020-03-13 21:35	2.7	m_N	48.251	78.442	2.99		H	Laronde	
2020-03-26 03:18	2.5	m_N	48.696	85.915	1.15		H	Williams	
2020-03-29 05:59	2.7	m_N	48.692	81.367	2.9		H	Timmins	
2020-04-23 07:10	3.6	m_N	46.457	81.174	2.44	F	H	Sudbury	
2020-04-25 01:44	2.9	m_N	46.570	80.860	1.58	F	H	Sudbury	
2020-05-30 10:16	2.6	m_N	46.640	80.780	1.56		H	Sudbury	
2020-06-03 09:14	2.8	m_N	48.251	78.442	2.93		H	Laronde	
2020-06-04 09:58	2.8	m_N	46.640	80.780	1.6		H	Sudbury	
2020-06-28 05:13	2.8	m_N	48.251	78.442	3.05		H	Laronde	
2020-07-25 12:12	3.3	m_N	48.251	78.442	2.75		H	Laronde	
2020-08-01 21:29	2.5	m_N	48.251	78.442	3.11		H	Laronde	
2020-08-16 07:16	2.5	m_N	46.457	81.174	2.47		H	Sudbury	
2020-08-18 06:10	2.5	m_N	48.251	78.442	2.75		H	Laronde	
2020-09-05 09:27	2.8	m_N	48.251	78.442	2.75		H	Laronde	
2020-09-07 21:36	3.2	m_N	48.251	78.442	3.08		H	Laronde	
2020-09-08 13:26	2.8	m_N	48.251	78.442	2.96		H	Laronde	
2020-09-18 09:53	2.6	m_N	46.457	81.174	2.4		H	Sudbury	
2020-10-22 00:09	3.0	m_N	48.251	78.442	2.75		H	Laronde	
2020-10-30 14:21	2.7	m_N	48.251	78.442	2.81		H	Laronde	
2020-10-30 18:28	3.6	m_N	48.258	78.525	1.32	F	H	Westwood	
2020-11-01 01:56	2.7	m_N	48.251	78.442	2.93		H	Laronde	
2020-11-13 00:34	2.6	m_N	46.570	80.860	1.3		H	Sudbury	
2020-11-21 10:31	2.8	m_N	48.251	78.442	2.84		H	Laronde	
2020-11-22 06:41	3.1	m_N	48.692	81.365	2.96		H	Timmins	Double event
2020-12-06 01:53	2.7	m_N	48.251	78.442	2.93		H	Laronde	
2020-12-06 01:53	2.6	m_N	48.251	78.442	2.93		H	Laronde	
2020-12-20 10:29	2.9	m_N	48.251	78.442	2.9		H	Laronde	
2020-12-20 22:28	2.8	m_N	48.251	78.442	3.08		H	Laronde	
2020-12-29 23:03	2.9	m_N	46.640	80.780	1.43		H	Sudbury	
2020-12-30 14:41	2.5	m_N	48.251	78.442	3.11		H	Laronde	
2020-01-03 06:49	3.2	m_N	48.692	81.367	2.3		H	Timmins	
2020-01-11 22:50	3.2	m_N	51.062	93.742	1		H	Red Lake	
2020-01-14 10:19	3.2	m_N	48.251	78.442	2.93		H	Laronde	
2020-01-22 22:23	2.5	m_N	48.251	78.442	2.9		H	LaRonde	
2020-01-27 22:27	2.5	m_N	48.251	78.442	1		H	Laronde	
2020-02-11 11:03	3.0	m_N	48.251	78.442	2.69		H	Laronde	

In addition to the notes to Table 3 the following notes apply:

[a] A default depth of 1 km is assigned for underground mining events when no better depth estimate is available.

[b] Depth type coding ("D") is as follows (see Section 4.2.1 for detail): F – operator assigned, V – RDPM, R – Rg observed; assigned shallow depth, M – fixed depth based on waveform similarity, H – assigned hypocenter, but calculated origin time.

Table 9: Mining-induced events m_N ≥ 2.5, 2021

time[a] [UTC]	mag.		lat. [°N]	lon. [°W]	dep. [km]	felt	D[b]	mine	notes
2021-01-06 16:12	2.5	m_N	48.251	78.442	2.84		H	Laronde	
2021-01-06 17:39	2.6	m_N	48.251	78.442	2.84		H	Laronde	
2021-01-09 10:36	2.7	m_N	47.967	80.583	0.75		H	Young-Davidson	
2021-01-14 16:40	2.8	m_N	48.251	78.442	3.08		H	Laronde	
2021-01-16 02:09	3.2	m_N	46.457	81.174	2.47	F	H	Creighton	
2021-01-16 02:10	2.6	m_N	46.457	81.174	2.38	F	H	Creighton	
2021-01-16 03:19	3.7	m_N	46.457	81.174	2.36	F	H	Creighton	
2021-01-17 04:08	2.5	m_N	48.251	78.442	2.84		H	Laronde	
2021-01-19 11:03	2.5	m_N	47.967	80.583	0.80		H	Young-Davidson	
2021-01-25 22:29	3.2	m_N	48.251	78.442	3.02	F	H	Laronde	
2021-01-31 04:28	2.7	m_N	48.251	78.442	2.69		H	Laronde	
2021-02-02 19:08	2.7	m_N	48.251	78.442	1.97		H	Laronde	
2021-02-10 22:15	2.5	m_N	46.570	80.860	1.42	F	H	Garson	
2021-02-25 22:41	2.9	m_N	47.967	80.583	0.70		H	Young-Davidson	
2021-03-03 22:22	3.1	m_N	46.673	81.335	1.21		H	Coleman	
2021-03-17 07:16	3.1	m_N	48.251	78.442	2.87		H	Laronde	
2021-03-17 07:33	2.7	m_N	48.251	78.442	2.93		H	Laronde	
2021-03-26 21:18	2.6	m_N	46.640	80.780	1.00		H	Nickel Rim South	Event followed blast
2021-04-17 05:49	2.7	m_N	48.690	81.370	1.11		H	Kidd Creek	
2021-04-20 07:54	2.9	m_N	46.673	81.335	1.43		H	Coleman	
2021-04-25 17:12	2.8	m_N	48.251	78.442	2.87		H	Laronde	
2021-04-29 21:51	2.9	m_N	48.700	85.920	1.30		H	Hemlo (Williams)	
2021-05-03 18:22	3.1	m_N	48.251	78.442	2.96		H	Laronde	
2021-06-08 09:54	3.5	m_N	48.251	78.442	2.87		H	Laronde	
2021-06-09 10:30	2.5	m_N	48.251	78.442	2.90		H	Laronde	
2021-06-18 21:22	3.2	m_N	48.251	78.442	2.90		H	Laronde	
2021-06-18 21:35	2.7	m_N	48.251	78.442	2.90		H	Laronde	
2021-06-20 21:22	2.6	m_N	48.251	78.442	3.02		H	Laronde	Double event
2021-06-20 23:13	2.5	m_N	48.251	78.442	2.87		H	Laronde	
2021-06-24 22:12	2.9	m_N	47.970	80.580	0.80		H	Young-Davidson	
2021-06-30 21:31	2.5	m_N	47.970	80.580	0.90		H	Young-Davidson	
2021-07-08 06:36	3.0	m_N	46.640	80.780	1.40		H	Nickel Rim South	
2021-07-21 09:50	2.6	m_N	52.614	90.362	1.27		H	Musselwhite	Blast + double event
2021-08-10 21:21	2.7	m_N	48.251	78.442	3.02		H	Laronde	
2021-08-10 22:46	3.3	m_N	48.251	78.442	2.99		H	Laronde	
2021-08-16 03:57	3.5	m_N	48.251	78.442	2.87		H	Laronde	
2021-08-23 02:53	3.0	m_N	48.251	78.442	2.84		H	Laronde	
2021-09-03 21:51	2.7	m_N	48.251	78.442	2.90		H	Laronde	
2021-09-18 09:05	2.7	m_N	46.680	81.331	1.28		F	Coleman	
2021-09-29 22:01	3.4	m_N	46.638	80.788	1.00		F	Nickel Rim South	
2021-11-21 05:13	2.5	m_N	47.924	80.658	0.70		H	Young-Davidson	
2021-11-29 22:41	2.7	m_N	48.252	78.452	2.99		H	Laronde	
2021-11-29 22:45	3.2	m_N	48.252	78.452	2.99		H	Laronde	
2021-12-13 22:36	3.2	m_N	48.251	78.442	2.93		H	Laronde	
2021-12-14 00:43	2.9	m_N	48.254	78.447	2.93		F	Laronde	
2021-12-18 22:30	3.0	m_N	48.251	78.442	3.02		H	Laronde	
2021-12-19 16:23	2.5	m_N	48.252	78.448	2.93		H	Laronde	
2021-12-28 23:22	4.1	m_N	48.252	78.452	2.93	F	H	Laronde	Largest ever observed In eastern Canada

In addition to the notes to Table 3 the following notes apply:

[c] A default depth of 1 km is assigned for underground mining events when no better depth estimate is available.

[d] Depth type coding ("D") is as follows (see Section 4.2.1 for detail): F – operator assigned, V – RDPM, R – Rg observed; assigned shallow depth, M – fixed depth based on waveform similarity, H – assigned hypocenter, but calculated origin time.

8. SUMMARY

With the upgrade of ULM in 2019, refurbishment of the stations in the CNSN relevant to seismic monitoring in northern Ontario is complete, and post-refurbishment data availability is close to 100%. Since 2015, three temporary stations, SILO, VIMO and MALO have stopped operating and been closed. This leaves monitoring of the northeastern-most portion of the study area in a reduced state, with significantly fewer earthquakes being catalogued per year than during the FedNor deployment 2004–2010.

During 2020–2021, 108 earthquakes were located, slightly higher than the six-year rolling average rate of 45/year over the previous 7 years. The magnitudes ranged from 0.7 to 3.6 m_N. The largest earthquake occurred north of Kapuskasing, at less than 5 km depth. There were 40 other events between magnitude 3.0 and 4.1 m_N, just 6 of which were earthquakes, with the remainder confirmed as blasts or mining-induced events. The second-largest earthquake, with a magnitude of 2.9 m_N, was just east of James Bay. Twelve earthquakes were reported as felt in 2020–2021, ranging in magnitude from 1.4 to 3.6.

Judging from the logarithmic frequency-magnitude relationship discussed in Section 6, the distribution of magnitudes indicates the catalogue for 2020–2021 is complete down to approximately magnitude 2.0 m_N.

The distribution of the majority of the detected earthquakes in this region for 2020–2021 conformed to the pattern of previous seismicity.

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