Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 1 – December 31, 2019

NWMO-TR-2021-10

November 2021

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ABSTRACT

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Report No.: **NWMO-TR-2021-10**
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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 a number of 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 and compile a catalogue of seismic activity in northern Ontario.

This report summarizes operational statistics and additions to the earthquake catalogue for the year 2019.

During 2019, 35 earthquakes were located in the northern Ontario study area, ranging in magnitude from 1.2 to 3.3 m_N. The pattern of seismicity generally conformed to that of previous years. The largest earthquake was an event at 15 km depth, north of Kapuskasing. There were no felt earthquakes in the study area in 2019.

The network detection threshold was reduced during the FedNor deployment, resulting in a greater number of earthquakes detected per year, during the years 2004–2010 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.

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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 a number of organizations, including the NWMO. This report summarizes earthquake activity for the year 2019.

To record seismic activity, CHIS operates fifteen 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 are located at Chalk River (CRLO/CHRO), Eldee (EEO/KIPQ), Kapuskasing (KAPO) and Thunder Bay (TBO). The digital data from a temporary station at Victor Mine (VIMO), supported by the diamond mining industry, and a station at Pinawa (ULM), which has funding from the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO: http://www.ctbto.org) are 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 (GTO/GTOO), Pickle Lake (PKLO), Pukaskwa National Park (PNPO) and Sioux Lookout (SOLO). The partially funded stations are Kirkland Lake (KILO) and Sudbury (SUNO). This network is augmented by a temporary CHIS station at McAlpine Lake (MALO). 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). These stations are currently 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 other former POLARIS stations and the rest of the Canadian National Seismograph Network (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: 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.

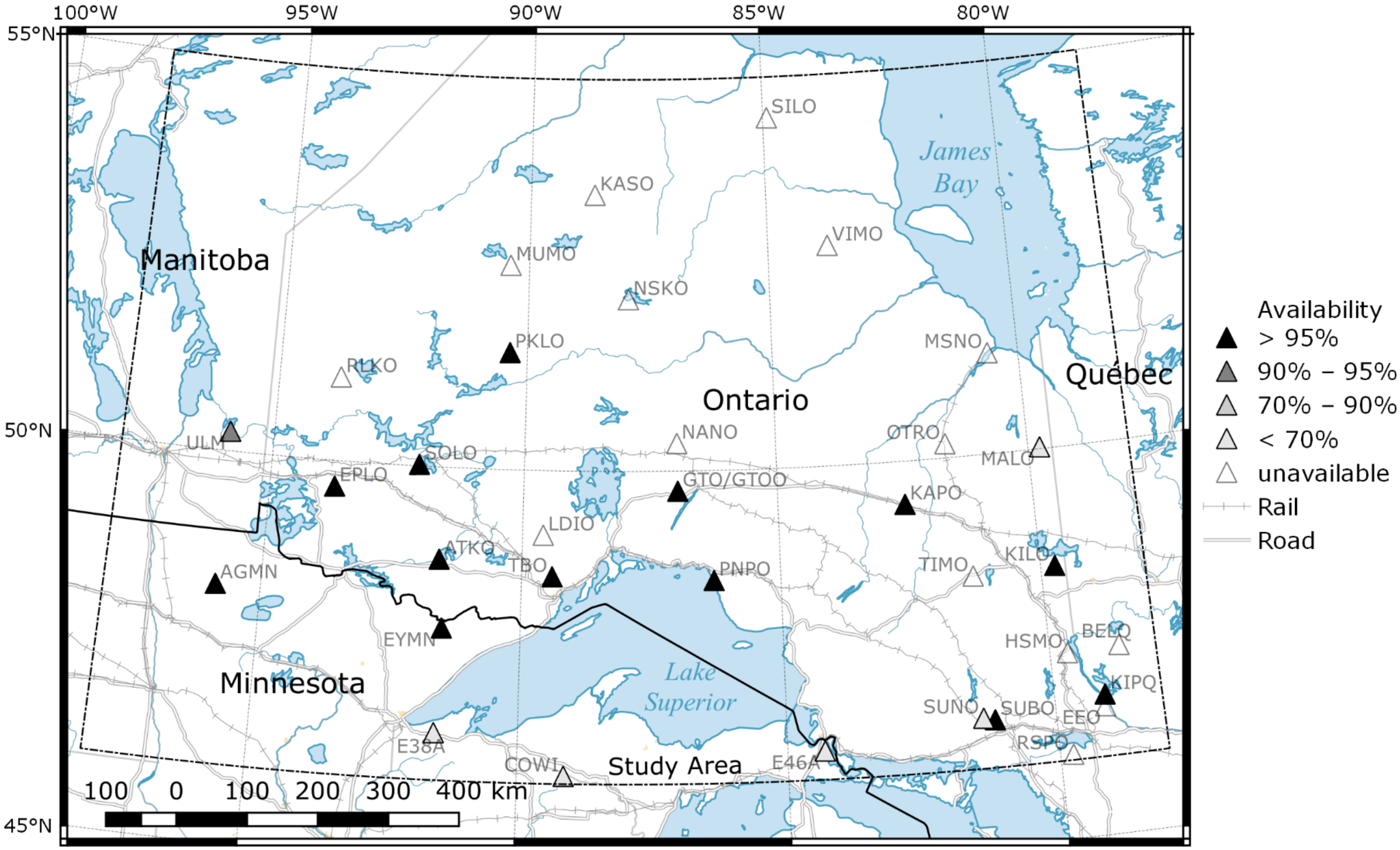

Figure 1: Seismograph Stations in northern Ontario, 2019. The study area is outlined with a dash-dotted line. Historical and currently active stations are shown as triangles, with the triangle filled according to data availability for 2019 (see also Table 1). Most of the stations shown as “unavailable” are former FedNor stations which were mainly active 2006–2009; an exception is EEO, which was replaced by KIPQ 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 m_{bLg} (Bormann and Dewey 2012). In eastern Canada, m_N is the magnitude used by CHIS for moderate-sized earthquakes[2]. Note that in some figures, a more generic "M" is used to indicate magnitude.

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 twelve months of 2019, 35 earthquakes were located in the study area. The magnitudes of the earthquakes located in 2019 ranged from 1.2 m_N to 3.3 m_N. The largest earthquake occurred north of Kapuskasing. There were 27 other events between magnitude 3.0 and 3.6 m_N, but all were mining-related events. The second largest earthquake, with a magnitude of 2.9 m_N, had an epicentre at the mouth of James Bay.

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, et al. 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.

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[2] The Richter or local magnitude m_L is used for small events when amplitudes are not available from at least one station that is farther than 50 km from the epicentre.

2. STATION OPERATIONS

2.1 CANADIAN NATIONAL SEISMOGRAPH NETWORK

More than 4500 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, 1632 earthquakes over magnitude 2.0 had been located in Canada during the year 2019. Of these, 35 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 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).

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 2019, the first full year of operation post-refurbishment.

Table 1 summarizes operational statistics for stations in northern Ontario for the past two years (2018–2019), to highlight year-over-year differences. Yearly data availability was 99% or greater for all but one of the thirteen stations with long-term funding (ATKO, CRLO, EEO/KIPQ, EPLO, GTO/GTOO, KAPO, KILO, PKLO, PNPO, SOLO, SUNO, TBO, ULM). The slightly lower data availability at ULM is due to data flow interruptions during refurbishment. Two temporary stations (MALO, VIMO) were closed in 2018-2019.

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. 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.

Table 1: Operation statistics for stations in northern Ontario, 2018–2019

station	net.	lat. [°N] [g]	lon. [°W] [h]	elev. [m] [b]	on date [c]	off date [i]	type [e]	availability [f]		num. gaps [g]	
							2019	2018	2019	2018	2019
ATKO	CN	48.8231	-91.6004	383	2004-06-09		H	100%	100%	450	44
CRLO→CHRO [a,c,d]	CN	46.0375	-77.3800	169	1994-11-17	2018-10-16	H	74%	99%	186	70
EEO [c]	CN	46.6410	-79.0735	121	1993-10-05	2018-08-09		58%		1243	
EPLO	CN	49.6737	-93.7258	437	2004-06-11		H	92%	99%	27	1382
GTO→GTOO [c]	CN	49.7454	-86.9611	351	2001-01-04	2019-01-31	H	100%	100%	702	90
KAPO [d]	CN	49.4510	-82.5077	221	1998-01-14		H	100%	100%	2	66
KILO	CN	48.4972	-79.7232	314	2003-06-22		H	98%	100%	1083	62
KIPQ	CN	46.7919	-79.0567	274	2017-06-04		H	100%	100%	8	4
MALO	CN	50.0244	-79.7635	271	2003-06-20	2019-05-02	H	90%	31%	198k	66215
PKLO	CN	51.4987	-90.3522	376	2004-06-15		H	100%	100%	3	0
PNPO	CN	48.5957	-86.2846	219	2004-06-18		H	96%	100%	3	1
SOLO [c]	CN	50.0215	-92.0808	370	1998-11-04		H	68%	100%	30	83
SUBO	CN	46.6115	-81.1321	281	2017-06-06		H	100%	100%	2	4
SUNO	CN	46.6438	-81.3442	343	2003-06-23	2019-01-31	H	85%	2%	43k	3138
TBO [c]	CN	48.6472	-89.4085	475	1993-10-05		H	100%	99%	22	71
ULM [c]	CN	50.2503	-95.8750	251	1994-12-07		B→H	95%	97%	90	60
VIMO	CN	52.8173	-83.7449	78	2003-06-11	2018-12-07		35%		7102	
E38A	N4	46.6058	-91.5540	341	2013-11-26		B→H	100%	20%	22	4
E46A	N4	46.3665	-84.3062	269	2013-11-26		B→H	100%	27%	21	16
AGMN	US	48.2977	-95.8619	351	2006-08-12		B	96%	100%	32	7
COWI	US	46.1003	-89.1369	523	2006-09-25	2019-09-14	B	85%	60%	47	42
EYMN	US	47.9462	-91.4953	475	1994-09-26		B	100%	100%	12	10

Note:

[a] CHRO (formerly CRLO) 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: GTO 1982, EEO 1984, ULM 1984, TBO 1987, SOLO 1988.

[d] Some stations effectively replaced nearby stations: CHRO/CRLO near CKO (1981–1994), KAPO near KAO (1982–).

[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.

[h] Some stations that were refurbished replaced stations that were very close by, but were not close enough to the original station to have the same station code. In these instances, the coordinates listed are that of the new station.

[i] Some stations closed in 2018 or 2019: CRLO, replaced by CHRO; EEO, replaced by KIPQ; GTO, replaced by GTOO, MALO, not replaced; SUNO, replaced by SUBO; VIMO, not replaced, COWI, not replaced.

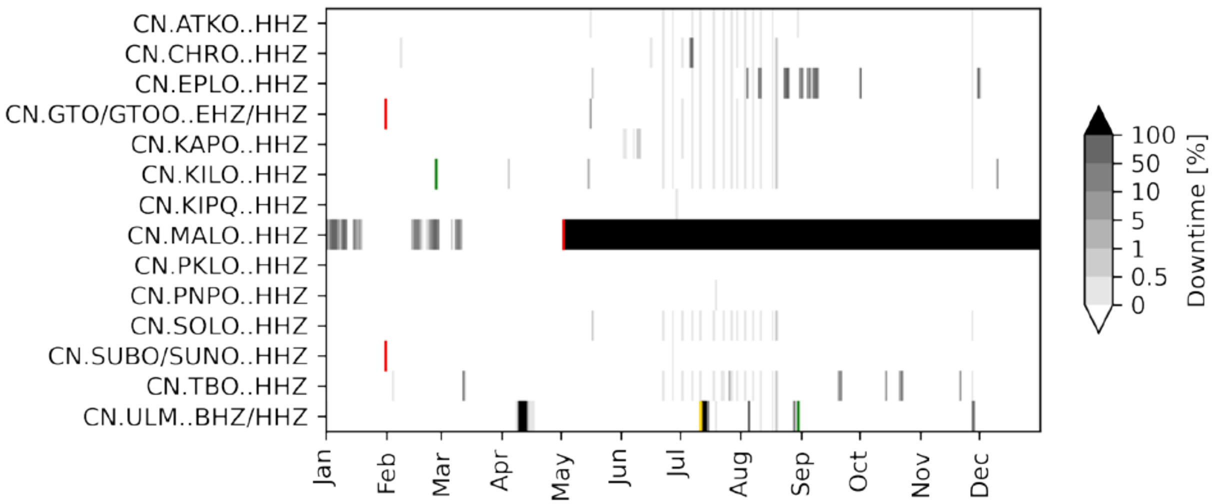


Figure 2: Daily downtime for CN network in northern Ontario, 2019. Downtime is the complement of availability as defined in Table 1. Refurbishment dates (see Appendix A) are marked in yellow; validation dates are marked in green; closure dates are marked in red. Note that for rows listing a station and its replacement, the combined availability is the higher of the two.

In April of 2019, seismographs worldwide that use Navsync GPS engines were affected by a GPS week rollover bug, which caused them to stop producing waveform data. Of the stations important to monitoring seismicity in northern Ontario, only ULM was affected.

Figure 2 is a representation of daily data availability in northern Ontario for 2019. The post-refurbishment data availability is close to 100% at all stations with long-term funding.

The major outages affecting data availability in 2019 were as follows:

- SILO has been down since 2015. There were no plans to refurbish this station so it was closed with an “off date” of 2015-03-15.
- VIMO was a solar powered site that struggled through winter months, one that has been down since 2018. There are no plans to refurbish this station so it was closed with an “off date” of 2018-12-07.
- MALO had a failure of a satellite communications device on 2019-05-02. There were no plans to refurbish this station, so it was marked closed as of that date.
- GTO is closed as of 2019-01-30; GTOO is its replacement.
- ULM had a minor (2.4 minute) outage on 2019-01-21.
- CHRO had a minor (2.4 minute) outage on 2019-02-08 due to a firmware update.
- TBO had a minor (2.4 minute) outage on 2019-02-04.
- TBO had a 5-hour outage on 2019-03-12 due to a lengthy mains power cut.
- Channel names for station in the CEUSN (network code N4) changed in March of 2019, without prior notification to CHIS, resulting in an interruption of real-time data acquisition. Of the stations important to monitoring seismicity in northern Ontario, N4.E38A and N4.E46A were lost on 2019-03-13. Real-time data acquisition of N4.E46A and N4.E38A as restored on 2019-09-23 and 2019-10-22, respectively.

- ULM was affected by a GPS week rollover bug starting 2019-04-06. This bug affected seismographs worldwide that use Navsync GPS engines. Data flow resumed on 2019-04-13 when the problem partially self-corrected. Correct timing was re-established on 2019-04-16.
- EPLO had additional solar panels added on 2019-05-07 without interruption of data flow.
- KILO had a replacement sensor installed on 2019-05-15, resulting in the loss of 32 minutes of data.
- GTOO had its telemetry upgraded from cellular to satellite modem on 2019-05-16, resulting in the loss of 1.3 hours of data.
- ATKO had a firmware upgrade on 2019-05-16, which resulted in the loss of 2.4 minutes of data.
- SOLO had its telemetry upgraded from cellular to satellite modem on 2019-05-17, resulting in a 3.2-hour communications outage and the loss of 10 minutes of data.
- EPLO had a replacement sensor installed on 2019-05-17, resulting in the loss of 8.5 minutes of data.
- ULM had a 22-hour communications outage from 2019-05-27 to 2019-05-28 that was caused by a temporary error in the configuration of the primary data acquisition system at CHIS. A secondary system acquired all the data successfully, so no data was lost.
- Multiple short outages were observed simultaneously across stations of the CNSN that employ different types of satellite telemetry, between 2019-06-22 and 2019-08-19. The outages were typically 10 minutes long. In northern Ontario, the stations affected were ATKO, CHRO, EPLO, GTOO, KILO, KAPO, SOLO, TBO and ULM. This problem was noted and corrected in August of 2019 by upgrading the data acquisition software at the data centre.
- CHRO had a significant power outage on 2019-07-04. The station's battery maintained power for 44 hours until its charge was exhausted, but 28 hours of data were lost before power was restored.
- ULM was upgraded between 2019-07-11 and 2019-07-15 resulting an outage while work was under way. The sample rate was increased from 40 to 100 sps, resulting in the band code being changed from “B” to “H”.
- EPLO experienced recurring outages between 2019-08-03 and 2019-09-09, due to issues with the satellite link to the station, resulting in a cumulative loss of data of 7.6% in August and 6.2% in September. Adjustments were made to the EPLO satellite link in mid-September, which increased the available bandwidth and should reduce the likelihood of further outages.
- ULM was serviced between 2019-08-27 and 2019-08-30 to replace a malfunctioning seismometer and to install a new strong motion sensor. This resulted in the loss of 6 hours of data.
- TBO experienced intermittent outages of unknown origin on 2019-09-20, 2019-09-21, 2019-10-14, 2019-10-21, and 2019-10-22.
- USNSN (network code US) station COWI closed on 2019-09-14.
- EPLO experienced an issue on 2019-10-01 with the satellite hub through which traffic from that station is routed, resulting in the loss of 13 hours of data. Power to the hub was increased to resolve the issue.
- EPLO experienced a problem with a satellite hub on 2019-11-30, resulting in the loss of 14 hours of data.
- TBO experienced an outage on 2019-11-21 that is suspected to be due to a loss of mains power, and which resulted in the loss of 1.3 hours of data.

- ULM had an issue from 2019-11-27 to 2019-11-28 with the voltage supplied to the station's digitizers, which resulted in the loss of 16.4 hours of data. To rectify this issue, the low voltage tolerance range on the digitizers was adjusted.

3. EARTHQUAKES

This section focuses on the natural tectonic seismicity of northern Ontario, placing the earthquakes detected in 2019 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 2019 are discussed individually. Then regional patterns of seismicity for the year 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 35 earthquakes catalogued in 2019, of all magnitudes, are compared to previous years in Table 2. The other yearly statistics shown in Table 2 are explained below.

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

Table 2: Earthquake and station counts in northern Ontario, 2000–2019

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

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.

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 and Knopoff 1974) using magnitude-dependant time-space windows (van Stiphout, Zhuang and 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, Lamontagne, 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.

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

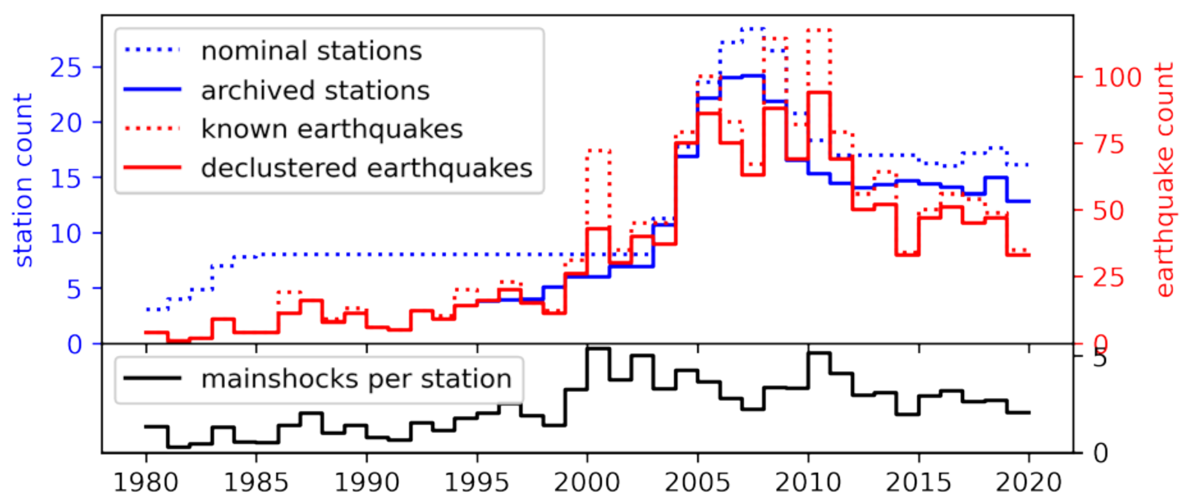
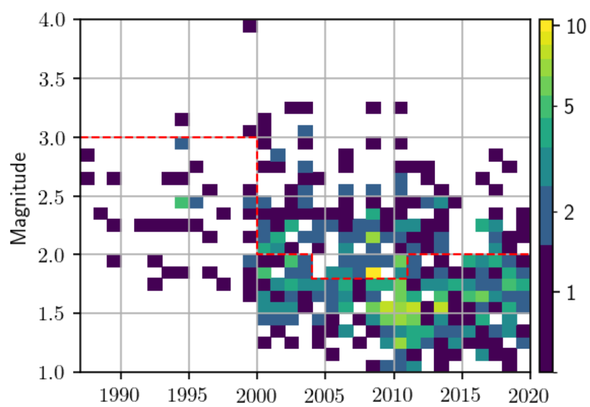


Figure 3: Earthquake and station counts in northern Ontario, 1980–2019. See Table 2 for explanation of terms. Note the national waveform archive only contains continuous data starting in 1995. The number of earthquakes per station is the number of declustered earthquakes per nominal station.

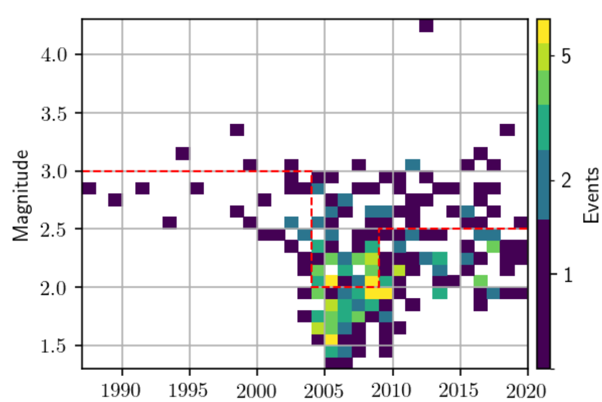
shows that the earthquakes detected per year decreased after 2010. The six-year rolling average rate of declustered seismicity (all magnitudes) dropped from a high of 79.2/year 2005–2010 to 42.7/year 2014–2019. This is still significantly greater than the 27.5/year observed prior to the FedNor deployment (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, et al. 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.

The degradation and finally the closure of SILO, VIMO and MALO, 2015–2019 means that network detection capability has been decreasing in the northeastern corner of the study area. Figure 4 shows earthquake counts, binned by year and magnitude, for two sub-regions of northern Ontario. In the Severn Highlands, yearly earthquake counts were similar just before and after the FedNor deployment 2004–2010 and only slightly higher during it. In contrast, today far fewer earthquakes are presently being catalogued per year in James Bay than during FedNor, although still more than prior to it. Dashed red lines in Figure 4 are provisional estimates of the time-history of the magnitude of completeness, the magnitude above which all earthquakes are believed to have been located. The magnitude of completeness has not



a) Severn Highlands seismic zone



b) James Bay seismic zone

Figure 4: Earthquake magnitude-time densities for selected sub-regions, 1987–2019. Earthquakes have not been declustered. Dashed red lines are crude estimates of the magnitude of completeness with time, and are only intended to guide the eye.

increased much in the Severn Highlands since the FedNor closures, but in James Bay, it has increased by approximately 0.5 units, indicating poorer monitoring, though it is still better than prior to FedNor.

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 2019 followed that of previous years, with earthquakes being detected mainly in the Severn Highlands, James Bay and Kipawa-Cochrane regions. See Figure 5 for a map and Table 3 for a detailed listing of all earthquakes in the study area in 2019. In all, 35 known earthquakes were documented, the smallest of which had its magnitude estimated at 1.2 $m_{N.}$

Figure 5 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 includes the best estimate of depth for each event in the study area in 2019. 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 2019, two events had depths estimated by Regional Depth Phase Modelling (RDPM) and 17 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 5 shows the earthquakes located in the study area in 2019 together with all known earthquakes since 1982. The representation, using red-filled circles for the 2019 earthquakes and partially transparent circles for the prior activity, makes it easy to judge which 2019 earthquakes happened in regions of prior seismicity as well as which areas of past activity did not have an earthquake in 2019.

The largest earthquake in the study area was a 3.3 m_N event on 2019-09-24, the only earthquake over 3.0 m_N, north of Kapuskasing (see Figure 5). The earthquake depth was estimated via RDPM to be 15 km.

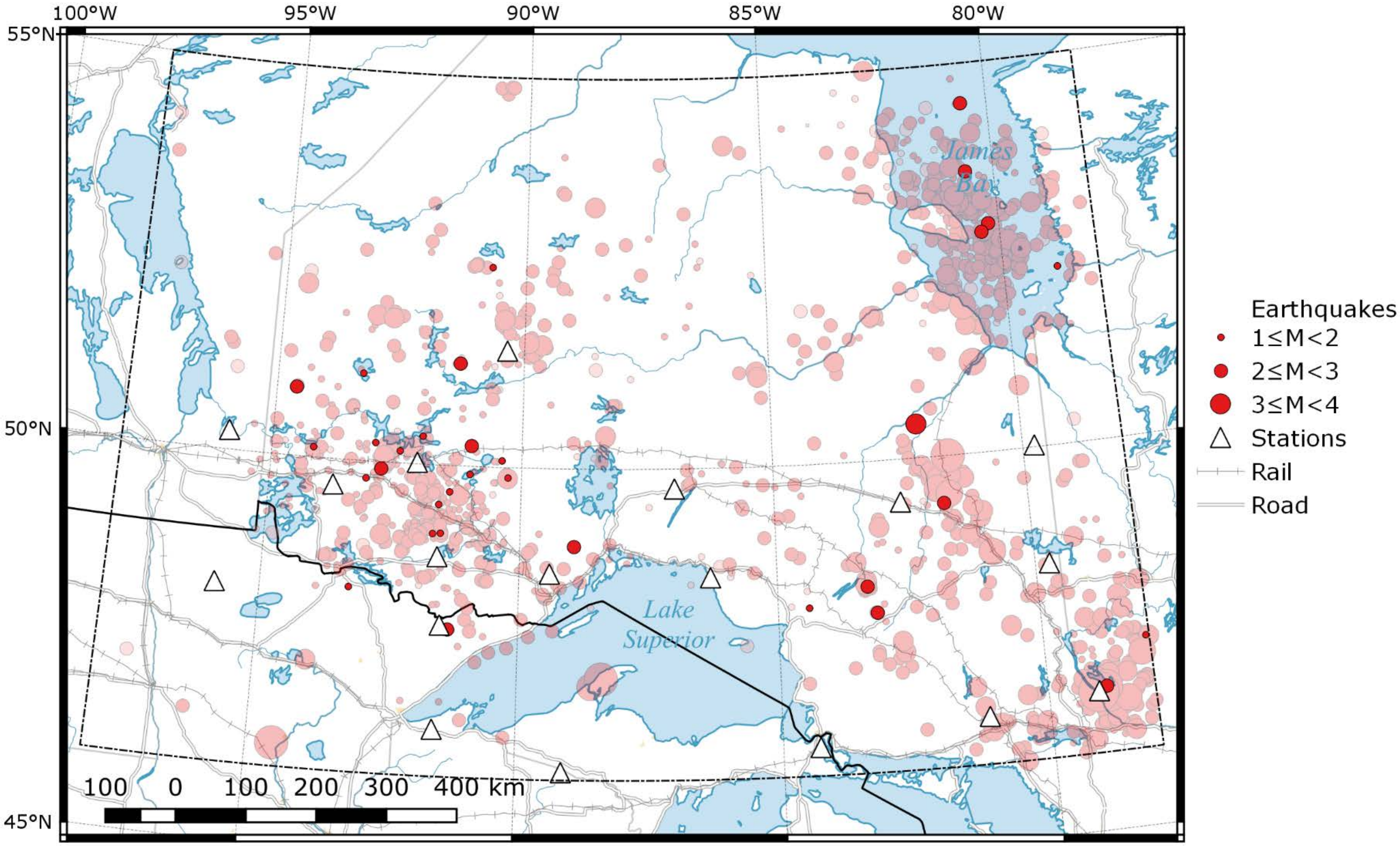


Figure 5: Earthquakes in northern Ontario, 2019. Events in 2019 have black outlines, while events from 1900–2018 are plotted semi-transparently and have grey outlines. Events and stations are plotted in the study area only. The study area is outlined with a dash-dotted line. Only stations with data available in 2019 are shown.

Table 3: Earthquakes in northern Ontario, 2019

time[a] [UTC]	mag.		lat. [°N]	lon. [°W]	dep. [km]	F[b]	S[b]	P[b]	D[c]	zone[d]	comment
2019-01-01 13:02	1.7	m_N	49.1172	91.7101	2		4	8	R	SVH	41 km N of Atikokan, ON
2019-01-09 05:21	1.6	m_N	48.3726	93.2799	5		5	10	F	SVH	27 km S of Fort Frances, ON
2019-01-13 07:27	1.8	m_N	51.1218	93.2702	5		5	10	F	SVH	33 km E of Red Lake, ON
2019-02-01 02:18	1.7	m_N	49.6628	91.4116	2		6	11	R	SVH	61 km SE of Sioux Lookout, ON
2019-02-07 07:23	1.9	m_N	52.2740	78.8706	18		3	5	F	JMS	25 km W of Eastmain, QC
2019-02-09 08:56	1.3	m_N	49.1267	91.5569	5		5	10	F	SVH	42 km N of Atikokan, ON
2019-02-12 00:12	1.9	m_N	50.8726	94.6100	18		5	8	F	SCC	65 km W of Red Lake, ON
2019-02-12 00:12	2.6	m_N	50.8825	94.6045	18		9	16	F	SCC	65 km W of Red Lake, ON
2019-02-14 00:53	2.2	m_N	52.9189	80.2199	18		5	8	F	JMS	94 km W of Wemindji, QC
2019-02-17 03:05	2.2	m_N	49.9153	92.7921	2		9	17	R	SVH	16 km N of Dryden, ON
2019-02-27 12:28	2.1	m_N	51.3156	91.3036	2		9	15	R	SVH	79 km W of Pickle Lake, ON
2019-03-09 08:07	1.9	m_N	47.4286	78.0607	18		9	17	F	GATW	78 km S of Val-d'Or, QC
2019-03-10 09:05	1.9	m_N	48.1600	84.3961	18		4	7	F	SCC	35 km NE of Wawa, ON
2019-03-11 01:18	1.9	m_N	50.3610	91.9938	2		8	13	R	SVH	33 km N of Sioux Lookout, ON
2019-03-13 08:48	2.4	m_N	48.9993	88.9367	2		12	22	R	SCC	50 km N of Mackenzie, ON
2019-03-13 08:56	1.6	m_N	48.9917	88.9350	2		6	11	R	SCC	49 km N of Mackenzie, ON
2019-03-27 23:23	2.5	m_N	52.8179	80.3792	18		8	13	F	JMS	107 km W of Wemindji, QC
2019-05-20 04:16	2.3	m_N	48.3947	83.2603	2		7	13	R	SCC	63 km N of Chapleau, ON
2019-07-03 03:11	1.2	m_N	49.7813	93.0816	2		3	6	R	SVH	18 km W of Dryden, ON
2019-07-10 15:47	2.7	m_N	46.8432	78.9050	14.5		13	24	V	KIP	20 km NE of Témiscaming, QC
2019-07-18 00:42	2.3	m_N	48.0523	83.0972	2		8	15	R	SCC	33 km NE of Chapleau, ON
2019-07-18 06:35	1.9	m_N	52.5637	90.7104	2		5	9	R	SCC	127 km N of Pickle Lake, ON
2019-07-24 00:29	2.3	m_N	53.6100	80.5975	18		4	8	F	JMS	113 km W of Chisasibi, QC
2019-07-24 19:02	1.5	m_N	49.8682	90.2648	2		2	4	R	SVH	42 km S of Allanwater Bridge, ON
2019-09-03 22:15	1.8	m_N	50.0856	90.3922	5		6	11	F	SVH	24 km SW of Allanwater Bridge, ON
2019-09-13 06:11	1.5	m_N	49.4937	91.6156	2		5	10	R	SVH	69 km SE of Sioux Lookout, ON
2019-09-24 13:41	3.3	m_N	50.4360	82.0838	15		15	25	V	SCC	116 km NNE of Kapuskasing, ON
2019-10-02 20:52	2.3	m_N	49.3948	81.6522	18		7	11	F	COCN	57 km E of Kapuskasing, ON
2019-10-04 07:45	2.3	m_N	50.2633	91.0101	2		8	16	R	SVH	60 km W of Allanwater Bridge, ON
2019-10-23 02:10	1.7	m_N	50.1312	94.1665	2		5	10	R	SVH	40 km NE of Kenora, ON
2019-11-04 00:37	1.2	m_N	50.1555	92.4349	2		5	9	R	SVH	34 km W of Sioux Lookout, ON
2019-12-01 13:07	2.0	m_N	47.8940	91.3398	18		7	11	F	SCC	97 km S of Atikokan, ON
2019-12-06 08:19	1.7	m_N	50.2429	92.9342	2		5	10	R	SVH	53 km N of Dryden, ON
2019-12-26 19:36	2.9	m_N	54.4846	80.5608	18		6	9	F	SCC	133 km NW of Chisasibi, QC
2019-12-26 23:22	1.6	m_N	49.8967	91.0203	5		5	9	F	SVH	72 km E of Sioux Lookout, ON

Notes:

[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.

[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.

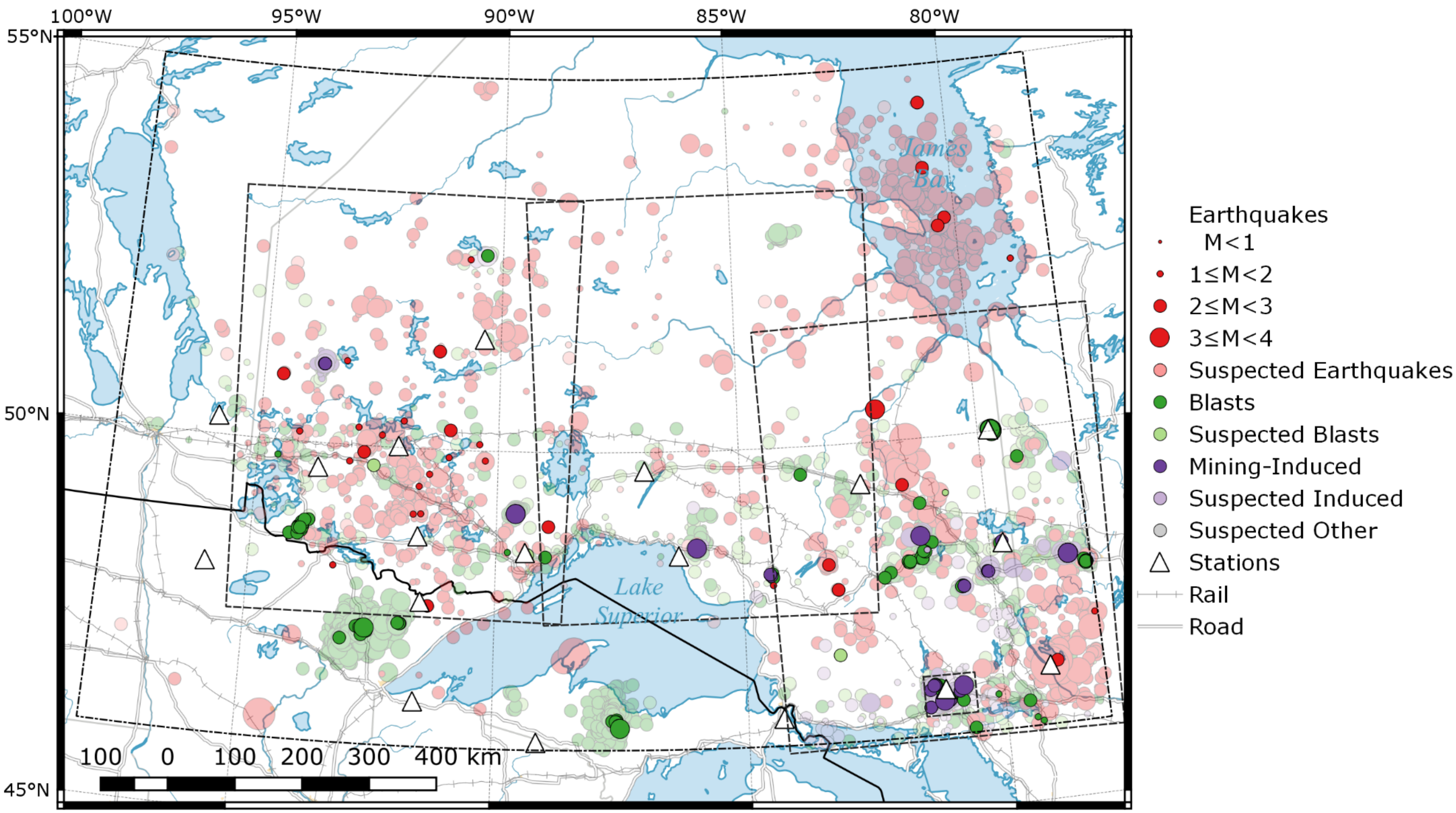


Figure 6: Seismic events in northern Ontario, 2019. Events in 2019 have black outlines, while events from 1900–2018 are plotted semi-transparently and have grey outlines. Events and stations are plotted in the study area only. The study area is outlined with a dash-dotted line. Areas mapped in more detail in Figures 7–10 are outlined with a dashed line. Only stations with data available in 2019 are shown.

A significant part of the effort of cataloguing earthquakes is distinguishing them from anthropogenic seismic sources. Figure 6 shows the earthquakes, mining explosions and mining-induced events catalogued in northern Ontario in 2019 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 7 shows this region in detail, along with the locations of active mines.

No events near Sudbury in 2019 were categorized as natural earthquakes. However, Figure 7 shows a cluster of seismicity which occurred 2015–2017 and for which blasting and rock bursts within the mines have 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. This cluster was apparently dormant in 2019.

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

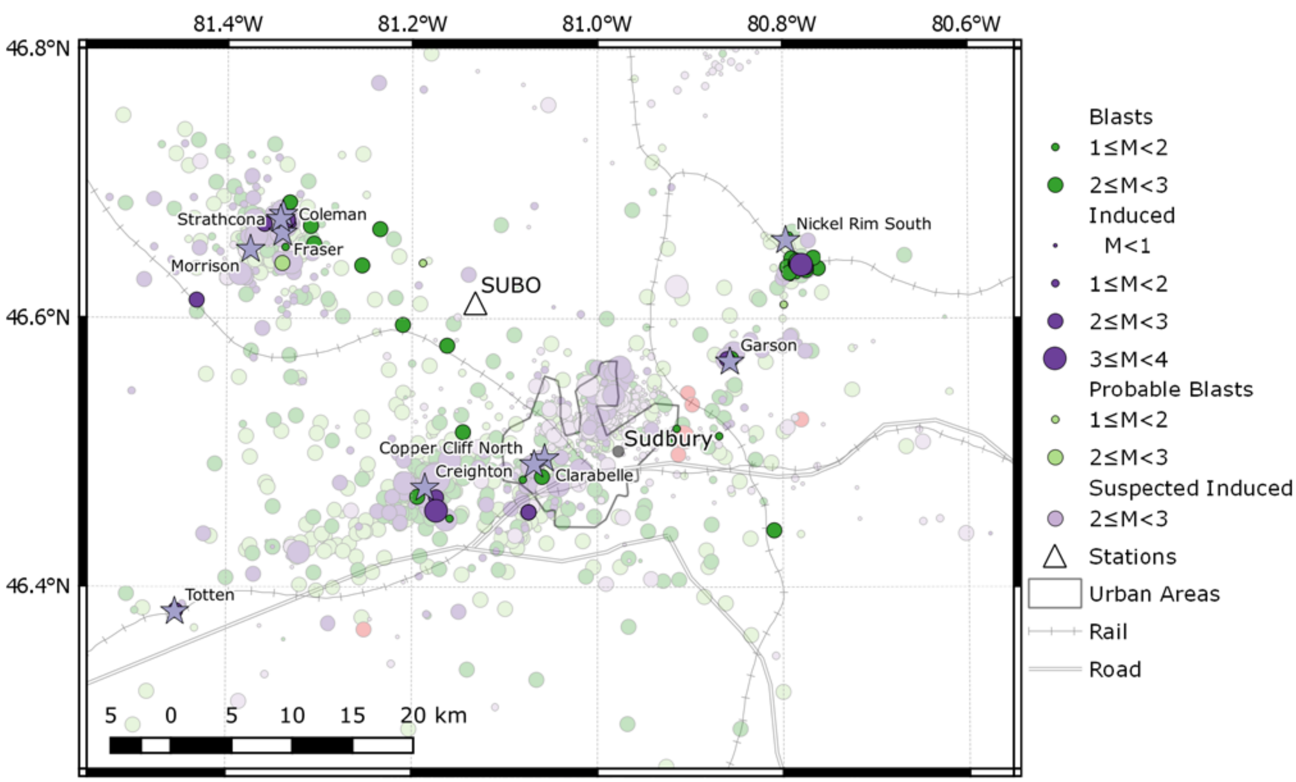


Figure 7: Seismic events near Sudbury, 1982–2019. Events prior to 2019 are partially transparent and thus have grey outlines. Suspected anthropogenic events in 2019 have pale bodies and black outlines. Producing mines from the Atlas of Canada (Lands and Minerals Sector; National Energy Board 2020) are shown as purple stars. Urban areas, major roads and railways are from Natural Earth (Schneider, Friedl and McIver, et al. 2003, Natural Earth 2009).

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 6–7, any proximity of blast and earthquake symbols leads to checking as to whether a blast might have been misidentified as an earthquake.

Figures 8–10 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 8 shows the Severn Highlands northwest of Lake Superior, Figure 9 shows Sault Ste. Marie and the area northeast of Lake Superior and Figure 10 shows Sudbury and the area north of Lake Huron.

The Severn Highlands seismic zone of the 2015 National Seismic Hazard Model (NSHM) (Halchuk, et al. 2014) continued to produce small earthquakes (see Figure 8). In all, there were 17 events in this zone in 2019, ranging from 1.2 to 2.3 m_N. The largest was 67 km ENE of Sioux Lookout on 2019-10-04. The second largest was 16 km N of Dryden, at the southern tip of the “Dryden swarm” of 2002–2003 (Ma, Eaton and Adams 2008). Of these events, 12 were assigned a depth of 2±3 km based on the observation of crustal Rayleigh waves and the rest were assigned a representative shallow depth for the region, 5 km.

The two largest events in the western end of the study area shown in Figure 8 actually occurred just outside the Severn Highlands seismic zone. The largest was a 2.3 m_N earthquake 65 km west of Red Lake, ON, on 2019-02-12, and was assigned a mid-crustal depth of 18 km. The second largest was a 2.3 m_N earthquake 71 km NNE of Thunder Bay, ON, on 2019-03-13, assigned a 2±3 km depth based on the observation of crustal Rayleigh waves.

The largest event located in Minnesota in 2019 was a 2.0 m_N 36 km E of Ely, MN, on 2019-12-02. Since there is no systematic effort to locate earthquakes south of the border, the actual level of activity in Minnesota is likely similar to that in adjacent Ontario, rather than lower, as shown in these maps.

The cluster of seismicity north of Chapleau, ON, that was active 2012–2013 and 2015 produced a 2.3 m_N earthquake (see Figure 9) on 2019-05-20. A second 2.3 m_N earthquake, just outside this cluster, occurred on 2019-07-18 just 33 km NE of Chapleau. Both were assigned a 2±3 km depth based on the observation of crustal Rayleigh waves.

The largest earthquake in the study area, a 3.3 m_N event on 2019-09-24, occurred 116 km NNE of Kapuskasing, just outside the Cochrane north seismic zone (see Figure 10). The 15 km depth of this event, estimated via RDPM, is typical for the region. Within the Cochrane north seismic zone, the only earthquake catalogued in 2019 was a 2.3 m_N earthquake 57 km E of Kapuskasing Figure 10 on 2019-10-02. It was assigned the default depth for the region, 18 km.

The third largest earthquake in the study area had a magnitude estimated at 2.7 m_N and occurred on 2019-07-10, 20 km NE of Témiscaming, QC, in the Kipawa seismic zone (Figure 10). This was the only other earthquake with a depth estimated by RDPM in 2019; it was found to be relatively deep, at 14.5 km. This is close to the depth of the 5.2 m_N “Millennium” earthquake of 2000-01-01, which was estimated to be between 12 and 17 km, by a variety of methods (Bent, Lamontagne, et al. 2002).

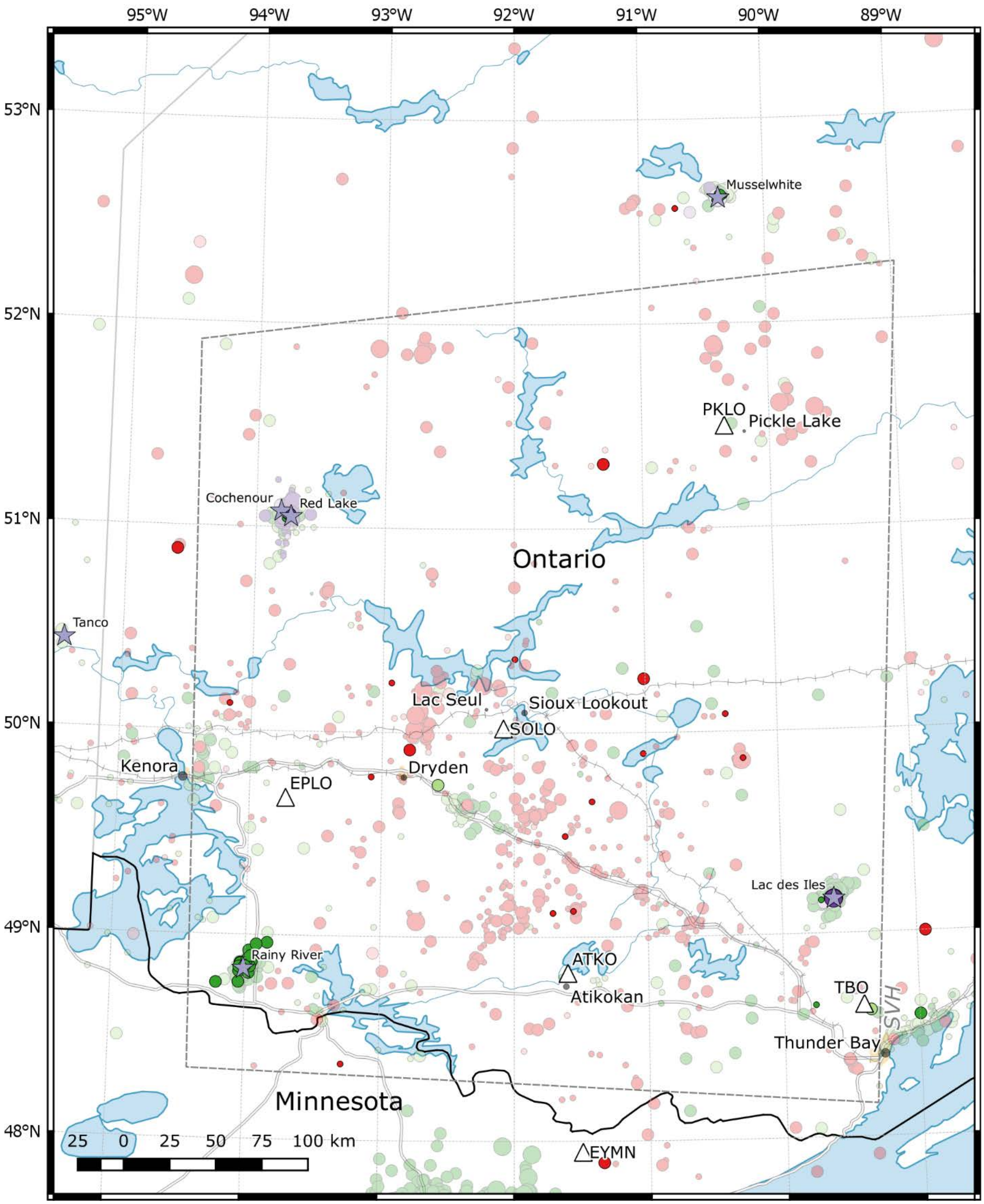


Figure 8: Seismic events in the Severn Highlands, 2019. Legend and notes as for Figure 6. In addition, producing mines from the Atlas of Canada (Lands and Minerals Sector; National Energy Board 2020) are shown as purple stars and seismic zones of the 2015 national seismic hazard model (Halchuk, et al. 2014) are outlined with dashed lines. Seismic zone abbreviations: SVH – Severn Highlands.

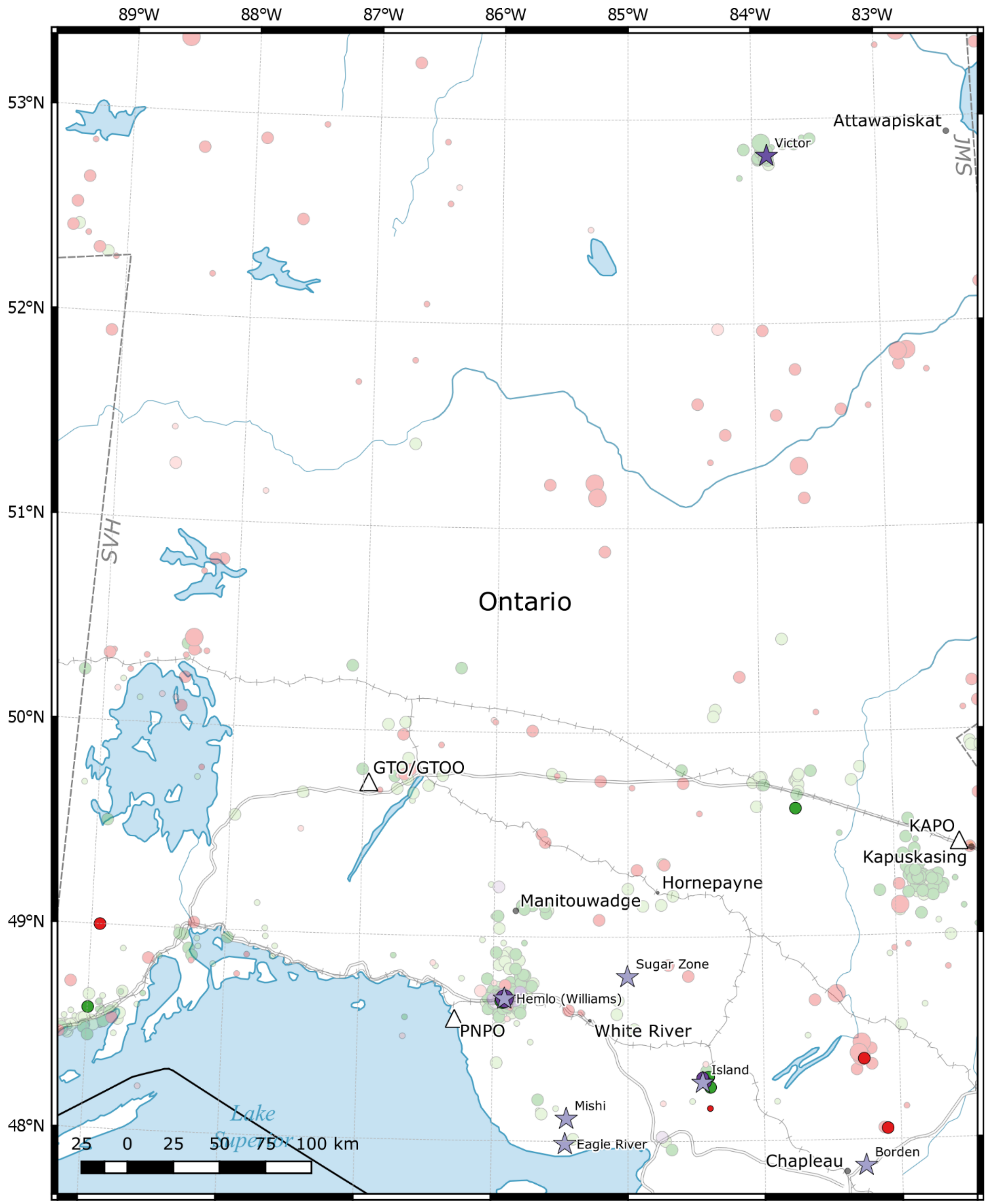


Figure 9: Seismic events northeast of Lake Superior, 2019. Legend and notes as for Figure 8.

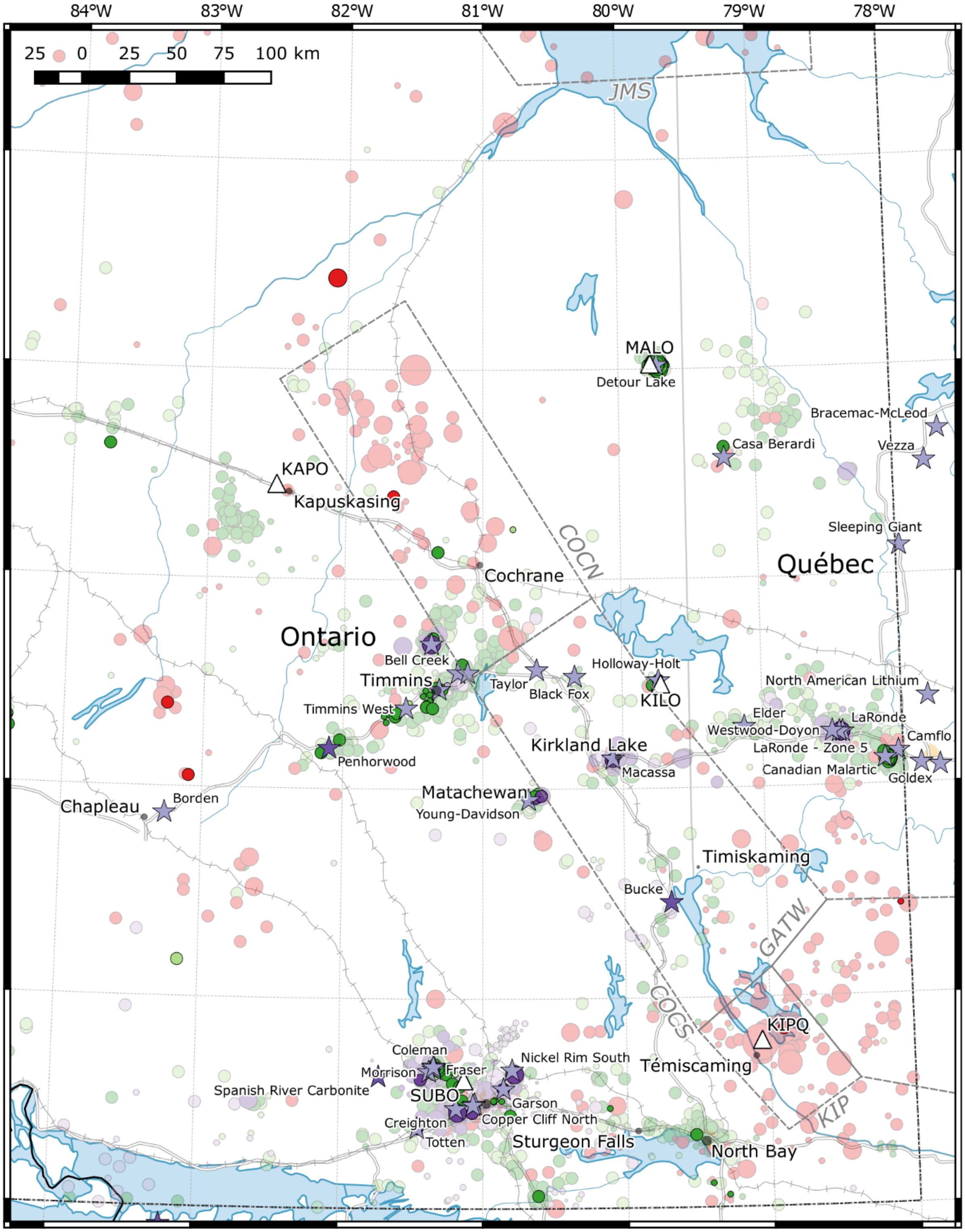


Figure 10: Seismic events north of Lake Huron, 2019. Legend and notes as for Figure 8. Seismic zone abbreviations: JMS – James Bay, COCN – Cochrane North, COCN – Cochrane South, KIP – Kipawa, GATW – Gatineau West.

Figure 11 is effectively a summary of the northern Ontario seismic monitoring project thus far, showing earthquakes in the period 1982–2019.

Figure 12 shows earthquakes of magnitude 3 or greater recorded in the study area during the period 1982–2019 (78 events in 38 years). The pattern of all seismicity echoes the pattern of the larger events, though the Thunder Bay – Atikokan area is active with many small earthquakes and has not yet had an event above magnitude 3.

Figure 13 shows earthquakes of magnitude 2 or greater across eastern Canada in 2019. 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, and less populated areas like northern Quebec being complete to only about 3.0 m_N.

Figure 14 shows earthquakes of magnitude 2 or greater across eastern Canada for the entire monitoring period of 1982–2019. 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.ca/stndon/NWFA-ANFO/index-en.php
The data can be extracted from the archive using an automated data retrieval system (AutoDRM) in SEED, GSE, CA and INT format. SEED and GSE are the standard formats in seismology, as is the AutoDRM protocol. CA is a format developed and used at CHIS and INT is an integer format.
Station metadata is available from the CNSN Station Book:
http://earthquakescanada.ca/stndon/CNSN-RNSC/stnbook-cahierstn/index-en.php
Station response files are available in dataless SEED, RESP and SAC pole-zero format.
Catalog entries for 2019 and previous years are archived in the National Earthquake Database:
http://earthquakescanada.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 2019 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.

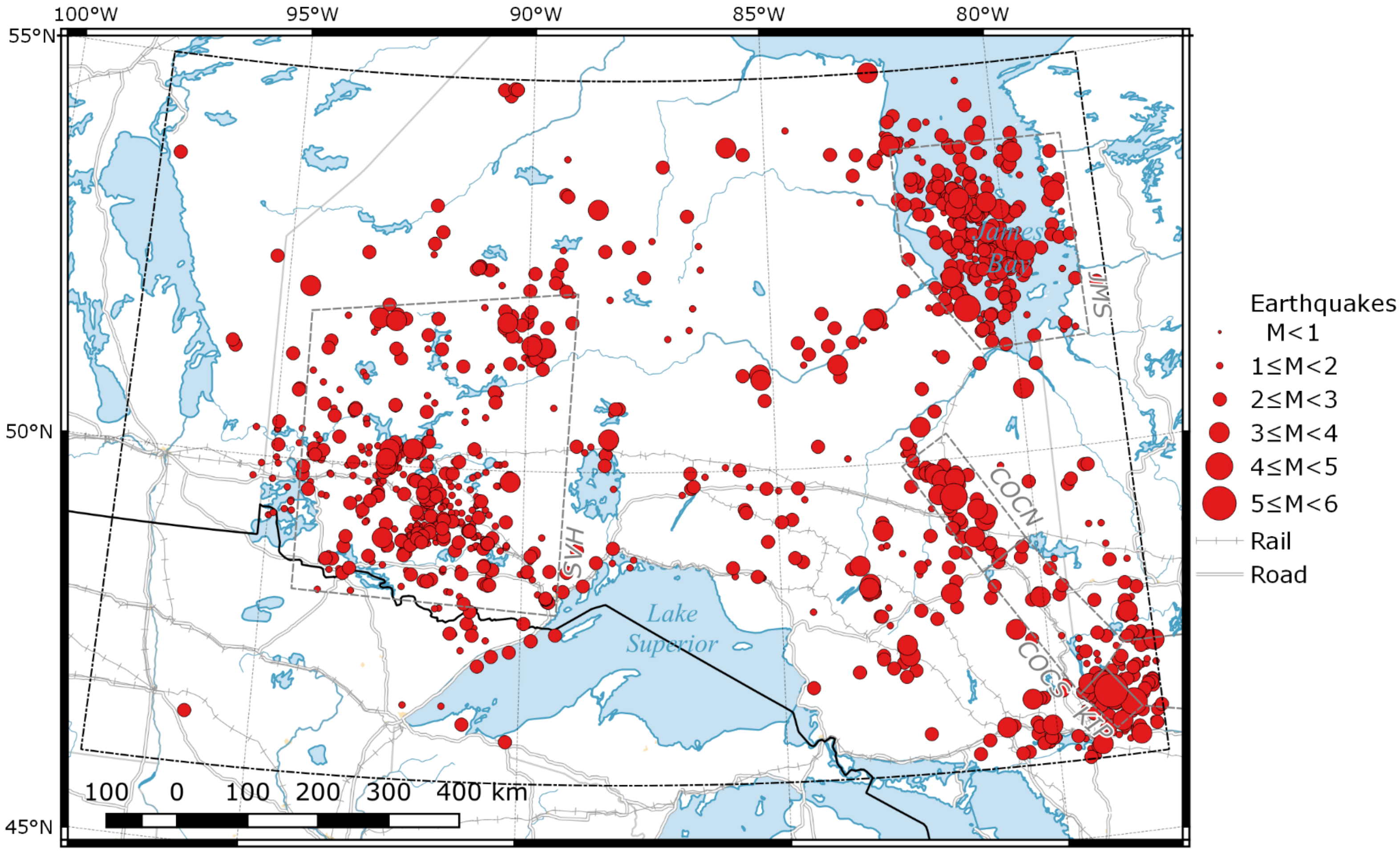


Figure 11: Earthquakes in northern Ontario, 1982–2019. Events and stations are plotted for the region within dashed lines only.

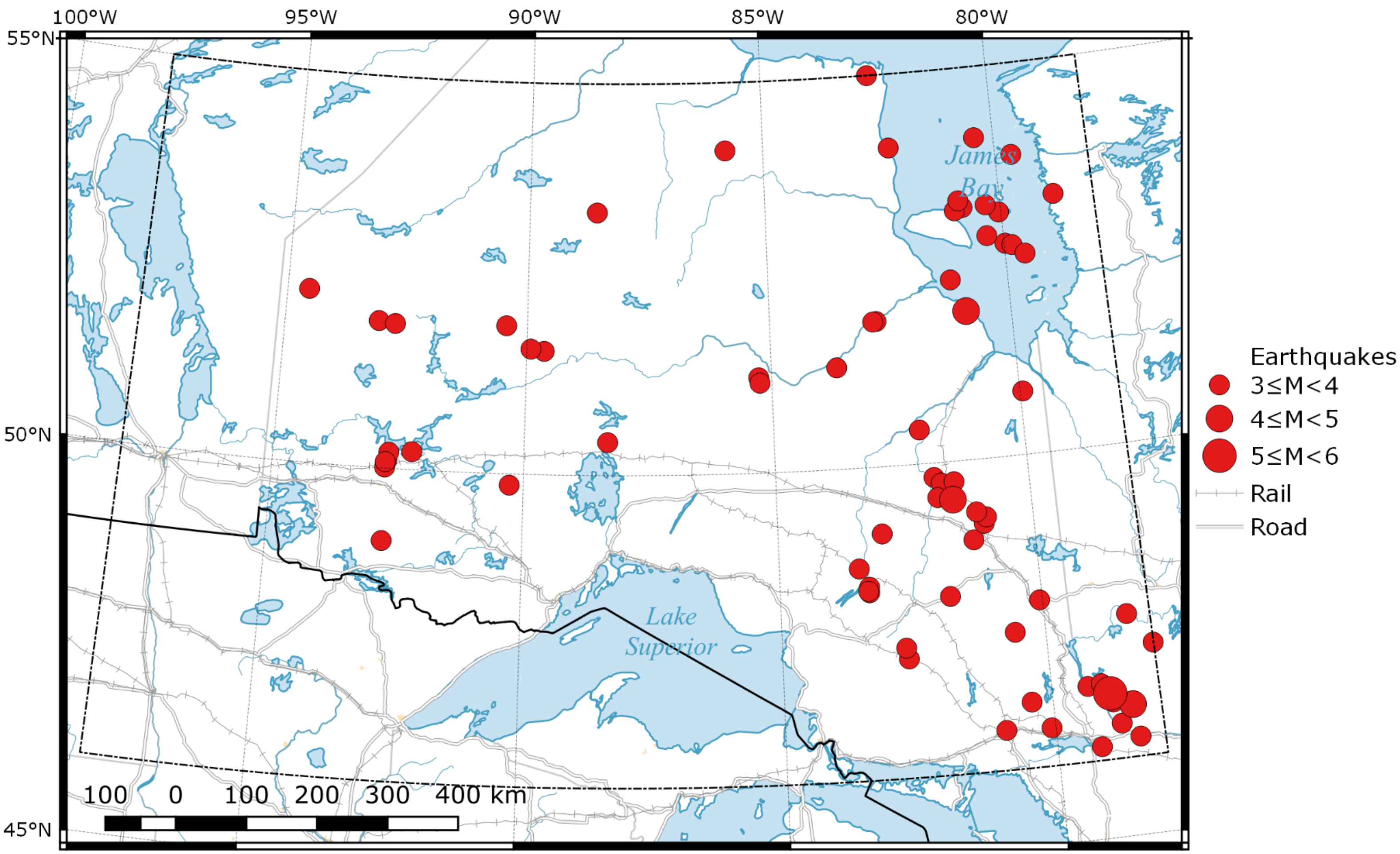


Figure 12: Earthquakes $m_N \geq 3$ in northern Ontario, 1982–2019. Events and stations are plotted for the region within dashed lines only.

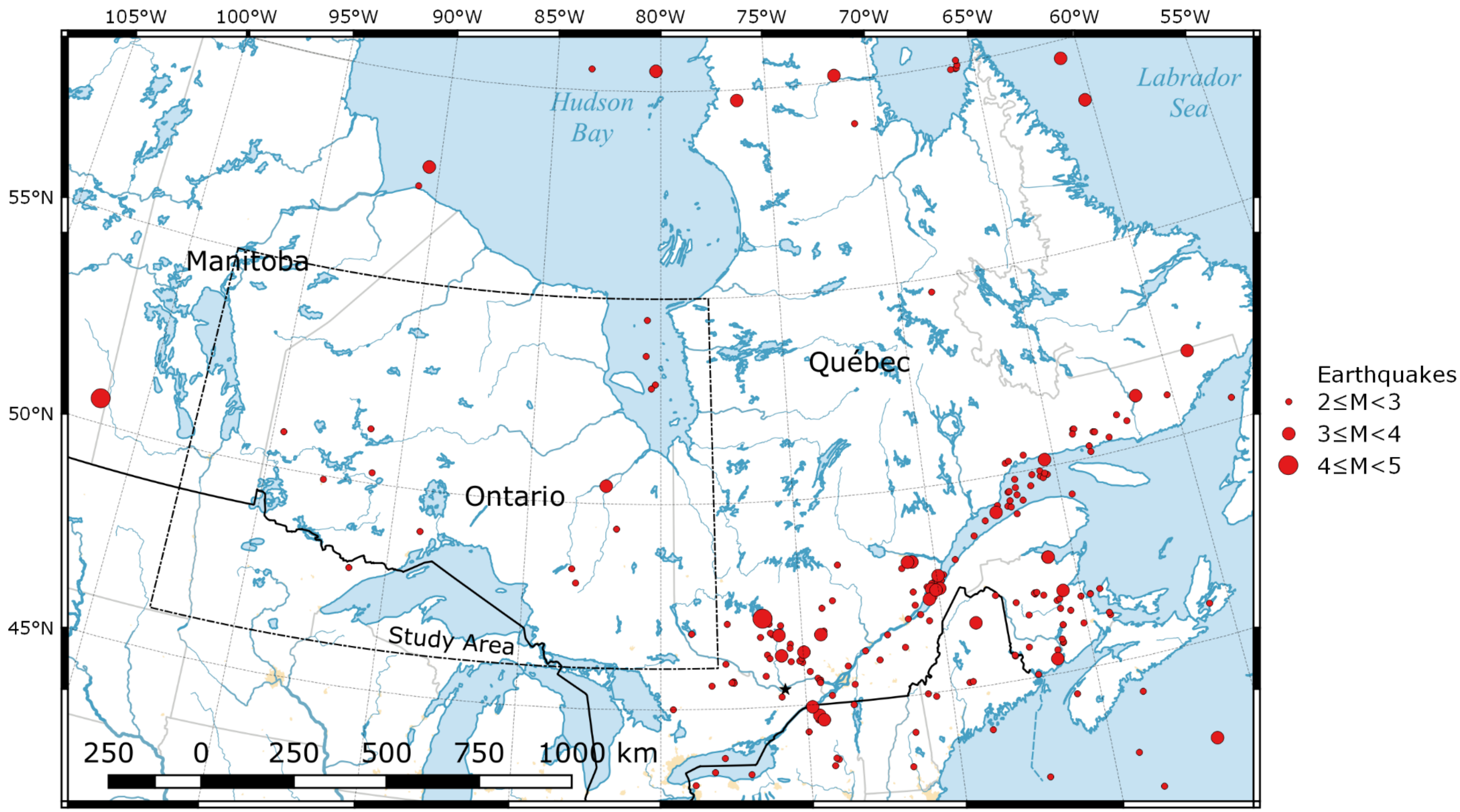


Figure 13: Earthquakes in eastern Canada, 2019

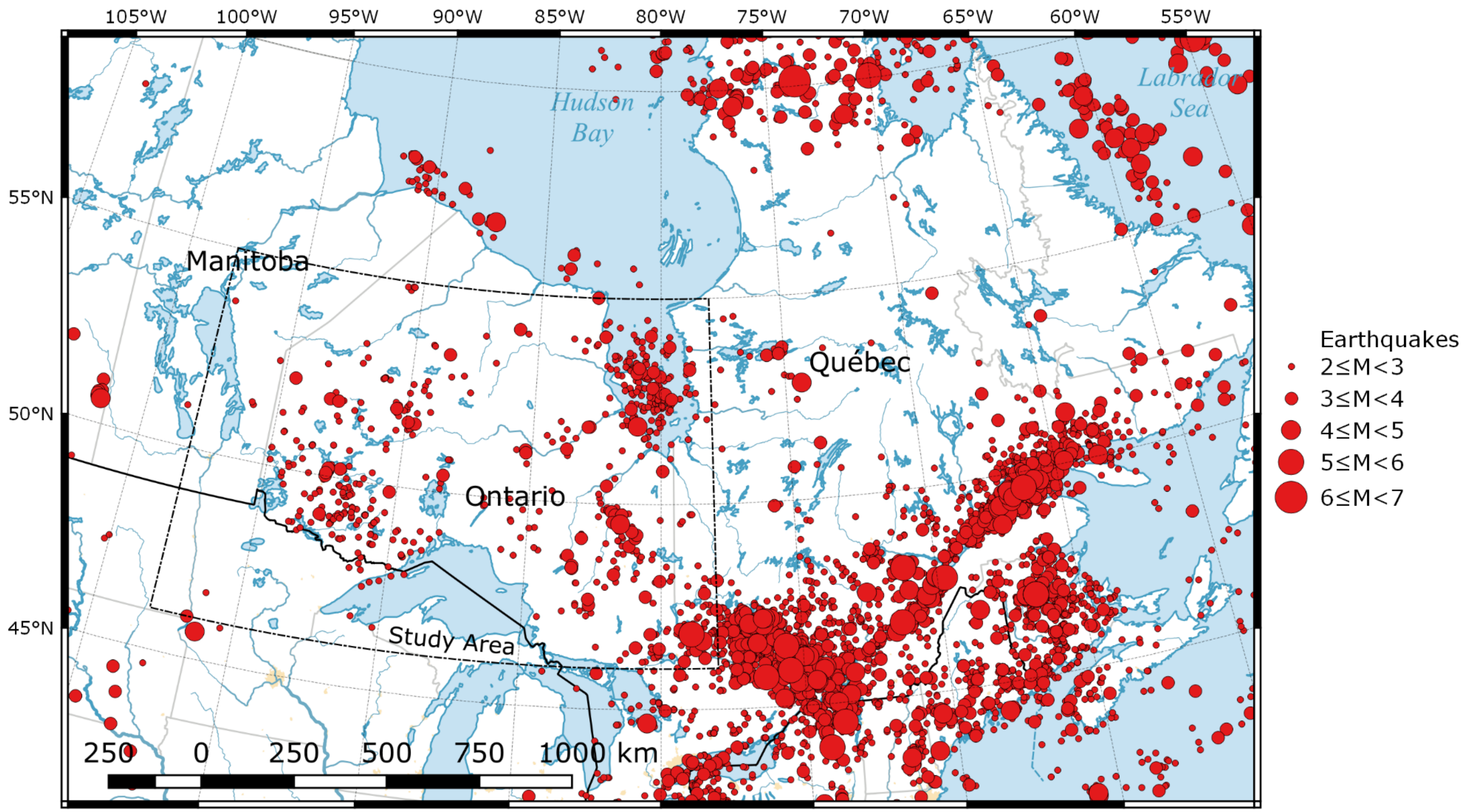


Figure 14: Earthquakes in eastern Canada, 1982–2019

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 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.

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 inaccuracy in the velocity model will not be corrected by recordings from the opposite site. This location inaccuracy will get bigger as the epicentre is located further 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 the 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 2019 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.

Table 4: 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

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 for smaller magnitudes. Different regional depth phases are useful in different distance ranges, as summarized in Table 4 (Ma 2004).

Extensive work using RDPM modelling was done for earthquakes in neighbouring regions, the West Quebec seismic zone and southern Ontario (Ma and Atkinson 2006). A further paper based on Ma (2004) focused on the Severn Highlands of northern Ontario (Ma, Eaton and 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 5 lists the events in northern Ontario in 2019 which had depths estimated by RDPM. In 2019, two earthquakes and six mining-induced events had depths estimated using RDPM. Of the earthquakes, both were close to mid-crust.

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 the depth via RDPM. In 2019, six events had both a depth estimated using RDPM and an accurate depth provided by mine operators (see Table 5). 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 21 events thus far (2016–2019). 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 5: Depths estimated using RDPM, 2019

time [UTC]	mag.	lat. [°N]	lon. [°W]	depth [km] est. [a]	depth [km] act. [a,b]	F [c]	# [d]	T [e]	Comment
2019-01-14 22:22	3.2 m_N	48.2510	78.4420	3.5	3.2	✓	1	R	Laronde Mine, QC
2019-01-14 22:27	3.4 m_N	48.2510	78.4420	3	3.08	✓	2	R	Laronde Mine, QC
2019-01-31 10:00	3.3 m_N	48.2510	78.4420	3	2.66		1	R	Laronde Mine, QC
2019-02-08 07:23	3.6 m_N	46.4570	81.1740	3	2.39	✓	2	R	Creighton Mine, ON
2019-07-10 15:47	2.7 m_N	46.8432	78.9050	14.5			0	L	20 km NE of Témiscaming, QC
2019-09-02 05:46	3.2 m_N	48.6900	81.3700	3	2.4		2	R	Kidd Mine, ON
2019-09-24 13:41	3.3 m_N	50.4360	82.0838	15			0	L	116 km NNE of Kapuskasing, ON
2019-12-14 10:18	3.3 m_N	48.2510	78.4420	3	2.75	✓	1	R	Laronde Mine, QC

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

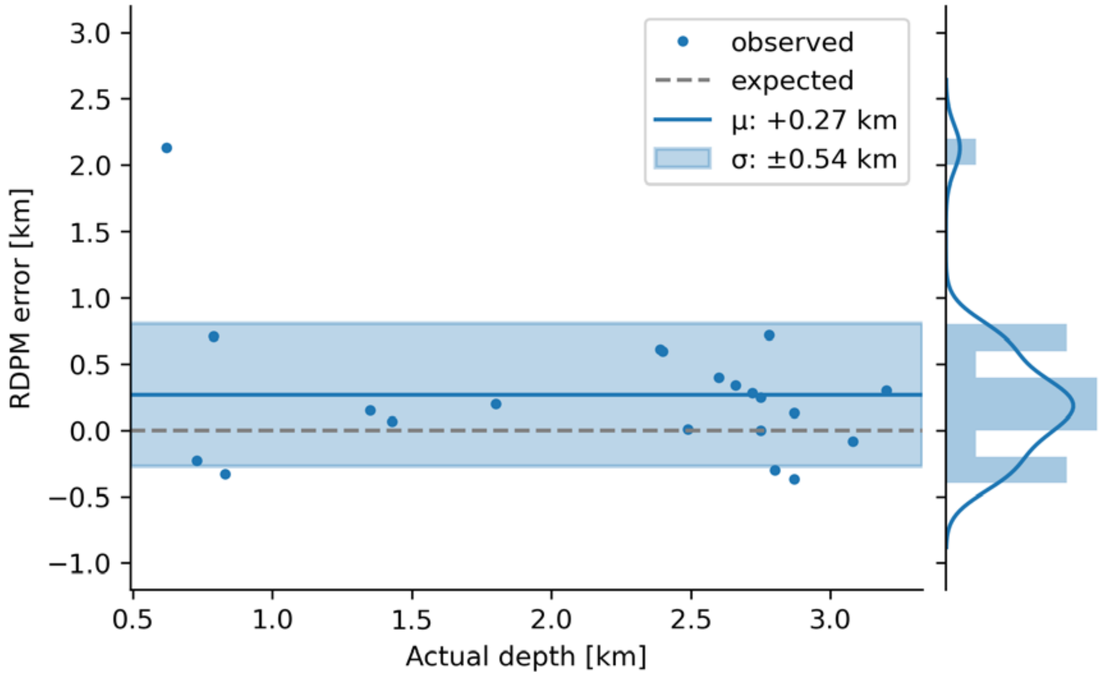


Figure 15: Accuracy of RDPM depth estimates for shallow mining events, 2016–2019. RDPM error is the estimated depth minus the actual depth reported by the mine operator. The mean μ and standard deviation σ of the distribution are indicated.

The difference between the RDPM estimate and the actual depths in the ground truth dataset is plotted against depth in Figure 15. There does not appear to be any trend with depth. The RDPM depth estimates are on average 0.24 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 0.62 km and have an approximately Gaussian distribution. We normally assign a nominal uncertainty of ±1 km to RDPM estimates, independent of depth. This is approximately two times the standard deviation, thus approximately a 95% confidence interval.

The outlier on Figure 15 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, this outlier underscores a need for improvement.

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

The present velocity model for determining earthquake epicentres in northern Ontario is the CN01 velocity model described in Table 6.

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 different models proposed would need to be assessed to determine which one (or combination thereof) would be most appropriate for the region under consideration for this study, as would 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

Table 6: 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) 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 (M_L). 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 (M_w). Bent (2011) suggests that for Nuttli magnitudes above approximately 3.0, the post-1997 relationship is $M_w = m_N - 0.53$, 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 30 years of data for the less-common larger earthquakes. Figure 16 shows the magnitude-recurrence plot for 2019 and 1987–2019. Note that while some of the data points from 2019 may be hidden beneath those for 1987–2019, 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 2019 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 16.

The occurrence rates for 2019 and for 1987–2019 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 2019, the best-fit slope was found to be 0.91 ± 0.24, versus 1.11 ± 0.04 for 1987–2019 (33 years). The difference in slope may seem small – it results in a less than two-fold difference in the rate for M≥5.0 earthquakes (the ones important for seismic hazard) – but when uncertainties are taken into account this becomes an almost ten-fold difference. This example underlines the value 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.

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).

The earthquake occurrence rates estimated from the single year 2019 are lower than those estimated over three decades by a factor of up to one-half, over a range of magnitudes, from 2.0 to 2.6. The “kink” at magnitude 2.3 in the cumulative rate for the year is due to there being five events in that magnitude bin, versus at most two in the other bins. These sorts of discrepancies are typical of the random fluctuations observed from one year to the next.

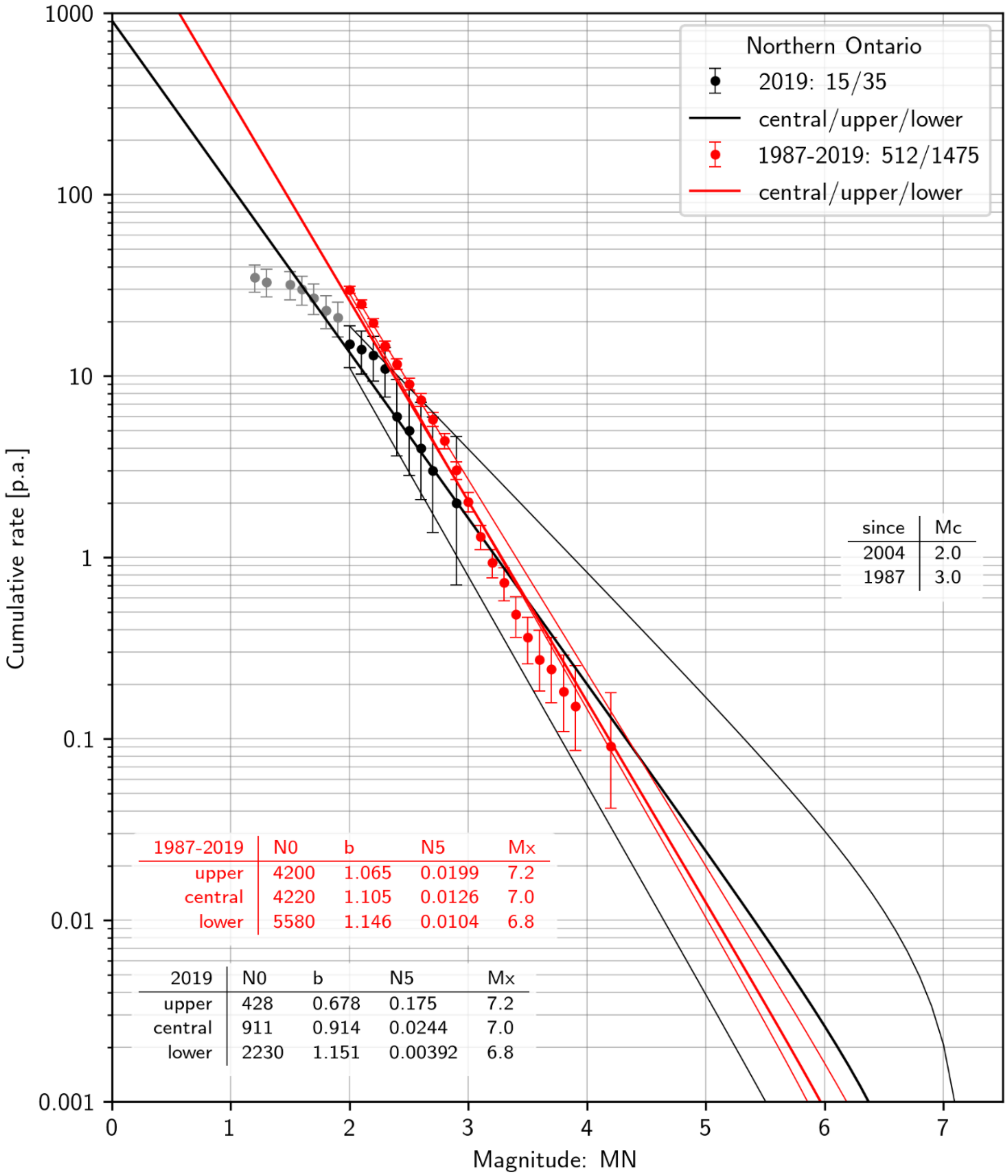


Figure 16: Recurrence curves for Northern Ontario, 2019 and 1987–2019. Yearly earthquake occurrence rates in 0.1 magnitude unit wide bins are shown as points with error bars, while fitted curves are shown as lines. The incomplete part of the catalogue for 2019 is shown in grey. Standard fit statistics 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 300 non-earthquakes per year have been catalogued since the inception of the northern Ontario monitoring project.

Of 29 events with magnitude greater than or equal to 3.0 m_N in the study area in 2019, just one was a natural tectonic earthquake, 14 were blasts, and the remainder were mining-related events, including the three largest. Similarly, of eight felt events, ranging in magnitude from 1.8 to 3.6 $m_{N,}$ the smallest was a blast, and the remainder were mining-related events.
In all, 208 known and 9 suspected mining induced events were located in the study area in 2019. These events ranged in magnitude from of magnitude 1.3 to 3.6 m_N. Thirty-nine of these mining-induced events recorded in the study area in 2019 had magnitude 2.5 or larger; these are listed in Table 7.

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 7: Mining-induced events m_N ≥ 2.5, 2019

time [UTC]	mag.		lat. [°N]	lon. [°W]	depth[a] [km]	felt	D[b]	mine	notes
2019-01-09 06:44	2.6	m_N	48.6940	81.3720	2.95		H	Kidd	Event followed blast
2019-01-14 22:22	3.2	m_N	48.2510	78.4420	3.2	✓	H	Laronde	
2019-01-14 22:27	3.4	m_N	48.2510	78.4420	3.08	✓	H	Laronde	
2019-01-14 22:27	3.2	m_N	48.2510	78.4420	2.96	✓	H	Laronde	
2019-01-18 01:24	3.1	m_N	49.1700	89.6100	0.75		H	Lac-des-Iles	
2019-01-18 10:21	2.9	m_N	48.2510	78.4420	2.87		H	Laronde	
2019-01-24 23:21	2.7	m_N	46.6380	80.7750	1.45		H	Nickel Rim South	
2019-01-24 23:32	2.5	m_N	46.6380	80.7752	1.45		H	Nickel Rim South	
2019-01-26 20:47	2.9	m_N	48.2510	78.4420	2.99		H	Laronde	
2019-01-31 04:39	3.2	m_N	48.6960	85.9150	1		H	Williams	
2019-01-31 10:00	3.3	m_N	48.2510	78.4420	2.66		H	Laronde	
2019-02-06 22:08	2.9	m_N	46.5700	80.8600	1.6	✓	H	Garson	Event followed blast
2019-02-08 07:23	3.6	m_N	46.4570	81.1740	2.39	✓	H	Creighton	Event followed blast
2019-05-20 16:21	2.8	m_N	46.4570	81.1740	2.46		H	Creighton	
2019-06-11 05:58	2.8	m_N	48.6940	81.3720	2.96		H	Kidd	
2019-06-12 07:09	2.6	m_N	48.2510	78.4420	2.9		H	Laronde	
2019-06-15 06:09	2.6	m_N	48.6940	81.3720	2.37		H	Kidd	
2019-07-08 21:26	3.2	m_N	48.2510	78.4420	2.96		H	Laronde	
2019-07-15 09:24	2.9	m_N	48.2510	78.4420	2.84		H	Laronde	
2019-07-28 21:23	3.1	m_N	48.2510	78.4420	2.84		H	Laronde	Event followed suspected blast
2019-08-09 05:59	3.1	m_N	46.6400	80.7800	0.41		H	Nickel Rim South	
2019-08-17 06:11	2.6	m_N	48.2510	78.4420	2.84		H	Laronde	
2019-08-20 12:44	2.5	m_N	46.6400	80.7800	1.56		H	Nickel Rim South	
2019-08-30 10:32	3.1	m_N	49.1670	89.6130	0.73		H	Lac-des-Iles	
2019-09-02 05:46	3.2	m_N	48.6900	81.3700	2.4		H	Kidd	
2019-09-06 09:17	2.9	m_N	48.2510	78.4420	3.05		H	Laronde	
2019-09-19 09:53	2.6	m_N	47.9670	80.5830	0.7		H	Young-Davidson	
2019-10-11 22:44	2.5	m_N	46.3820	81.4540	1.3		H	Totten	
2019-10-14 06:13	2.5	m_N	46.4570	81.1740	2.44		H	Creighton	
2019-10-20 09:35	2.6	m_N	48.2510	78.4410	2.93		H	Laronde	
2019-10-21 01:23	2.5	m_N	48.2885	84.4308	0.66		H	Island Gold	
2019-10-28 06:35	2.6	m_N	48.5140	79.7390	1		H	Holt	
2019-11-02 21:58	2.6	m_N	46.4560	81.0740	1.1		H	Copper Cliff	
2019-11-16 22:23	2.5	m_N	48.2510	78.4420	2.93		H	Laronde	
2019-12-01 05:59	2.6	m_N	48.2510	78.4420	2.84		H	Laronde	
2019-12-05 14:28	2.7	m_N	48.2510	78.4420	2.87		H	Laronde	
2019-12-09 06:16	2.5	m_N	48.2510	78.4420	2.87		H	Laronde	
2019-12-10 23:32	2.9	m_N	48.2510	78.4420	2.9	✓	H	Laronde	
2019-12-14 10:18	3.3	m_N	48.2510	78.4420	2.75	✓	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

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 the twelve months of 2019, 35 earthquakes were located, 33 after declustering, somewhat lower than the average of 42.7/year over the previous 6 years. The magnitudes of the earthquakes located in 2019 ranged from 1.2 to 3.3 m_N. The largest earthquake occurred at 15 km depth, north of Kapuskasing. There were 28 other events between magnitude 3.0 and 3.6 m_N, but they were all confirmed to be blasts or mining-induced events. The second-largest earthquake, with a magnitude of 2.9 m_N, was at the mouth of James Bay. No earthquakes were reported as felt in 2019.

Based on the logarithmic frequency-magnitude relationship discussed in Section 6, the distribution of magnitudes indicates the catalogue for 2019 is complete down to approximately magnitude 2.0 m_N.

The distribution of the majority of the detected earthquakes in this region for 2019 conformed to the pattern of previous seismicity.

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Appendix A: 2019 Field Season

This is a progress report on refurbishment of the Canadian National Seismograph Network in northern Ontario, focusing on the 2019 field season.

Status

Refurbishment of stations in northern Ontario was completed in 2019 with the upgrade of Lac Du Bonnet (ULM), the addition of solar panels at Experimental Lakes (EPLO) and the validation of Kirkland Lake (KILO).

The status of refurbishment at that time is summarized in Table 8, including dates of installation, first data flow, and validation of waveform data and station metadata quality. At the time of writing of this report, there are no outstanding issues with stations in northern Ontario.

At ULM, the sensor installed upon initial refurbishment developed issues and was replaced, starting 2019-08-27. At EPLO, solar panels were added to increase uptime in winter. At KILO, replacement sensors were installed on 2018-08-08 and again, along with a solar charger, on 2019-02-26, in order to address excess ambient noise at long periods. The long period noise did not improve and was ultimately determined to be actual ground motion of anthropogenic origin, so KILO was finally validated, and entered into routine use on 2019-02-26.

Table 8: Upgrade status of stations in northern Ontario, 2019

Station	Location	Tasks [a]				Dist. [km] [d]	Installation	Data Flow	Validation
ATKO [b]	Atikokan, ON	B	V	S	D		2017-07-11	2017-07-15	2017-12-06
CRLO→CHRO [e]	Chalk River, ON	SB	N	X	A	0.057	2018-10-17	2018-11-20	2018-11-30
EEO→KIPQ	Eldee/Kipawa, ON	SB	N	SC	A	16.8	2017-06-04	2017-06-07	2017-12-06
EPLO [b]	Experimental Lakes, ON	B	V	S	D		2017-07-14	2017-08-01	2017-10-04
GTO/GTOO [b,e]	Geraldton, ON	SB	N	S	A	0.058	2017-06-11	2017-06-27	2017-07-12
KAPO	Kapuskasing, ON	B	V	X	A		2017-06-09	2017-06-19	2017-07-27
KILO [c]	Kirkland Lake, ON	B	V	S	D		2017-06-14	2017-06-14	2019-02-26
PKLO [b]	Pickle Lake, ON	B	V	SC	D		2017-07-17	2017-07-20	2017-08-10
PNPO [b]	Pukaskwa, ON	B	V	SC	D		2017-07-09	2017-07-14	2017-09-10
SOLO [b]	Sioux Lookout, ON	SB	V	S	A	0.035	2017-07-06	2017-07-20	2017-09-23
SUNO→SUBO [c]	Sudbury, ON	B	N	SC	D	16.6	2017-06-06	2017-06-07	2017-06-21
TBO	Thunder Bay, ON	SB	V	X	A		2017-07-19	2017-08-01	2017-12-06
ULM	Lac Du Bonnet, MB	B	O	X	A		2019-07-11	2019-07-15	2019-08-30

Note:

[a] Tasks and work planned are coded as follows

- SB – upgrade from short period vertical to broadband three-channel sensor
- B – upgrade broadband three-channel sensor
- V – upgrade vault in same location
- N – new vault in new location
- O – old vault unchanged
- C – upgrade cellular telemetry
- S – upgrade satellite telemetry
- SC – convert from satellite to cellular telemetry
- X – no change to telemetry
- D – upgrade DC power (solar)
- A – upgrade AC power

[b] Station fully supported by NWMO

[c] Station partially supported by NWMO

[d] Distance from old vault to new vault, if greater than 0.01 km.

[e] New station code required because new vault is more than 50 m from old vault.

In an effort to increase the diversity of the modes of telemetry in the region, to protect against outages that affect all stations with a given type, cellular telemetry was reverted to satellite telemetry at Geraldton (GTOO) on 2019-05-16 and Sioux Lookout (SOLO) on 2019-05-17.

An essential feature of refurbishment was the construction of a new broadband vault. 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 Table 1, these stations have been grouped together when evaluating the data availability for the year.

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). The old stations will eventually be decommissioned. In Figure 2 of this report, these stations have been grouped together.