Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 1 – December 31, 2016

NWMO TR-2017-20 **May 2017**

N. Ackerley[1]
V. Peci[2]
J. Adams[1]
S. Halchuk[1]
P. Street[1]

[1] Canadian Hazards Information Service, Natural Resources Canada

[2] V. Peci under contract to the Canadian Hazards Information Service

NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Nuclear Waste Management Organization
22 St. Clair Avenue East, 6th Floor
Toronto, Ontario
M4T 2S3
Canada

Tel: 416-934-9814
Web: www.nwmo.ca

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ABSTRACT

Title: **Seismic Activity in the Northern Ontario Portion of the Canadian Shield - Annual Progress Report for the Period January 01 – December 31, 2016**
Report No.: **NWMO TR-2017-20**
Author(s): N. Ackerley, V. Peci[2], J. Adams[1], S. Halchuk[1], P. Street[1]
Company: [1]Canadian Hazards Information Service, Natural Resources Canada
[2]V. Peci under contract to the Canadian Hazards Information Service

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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 the catalogue for the year 2016.

During 2016, 54 earthquakes were located in northern Ontario, ranging in magnitude from 1.1 to 3.1 m_N. The pattern of seismicity generally conformed to that of previous years. The largest earthquake was in James Bay, while the second largest, with magnitude 3.0 m_N, was widely felt in North Bay.

A slight but definite decrease in the average yearly number of detected earthquakes, from 74.7/year to 49.5/year has been detected over the past six years as compared to six years before that. This is believed to be due to a slight increase in the location threshold of the monitoring network with the decommissioning of some of the FedNor seismograph stations in 2008-2010, and not a decrease in the actual level of seismicity.

In 2016, mine operators began to provide confirmed depths for selected mining-induced events. This may become the basis of an important “ground truth” dataset for the assessment 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 2016.

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), Eldee (EEO), 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), 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.

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

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

formally written m_N in this report. This is a regional magnitude based Lg amplitudes, similar to m_{bLg}. (Bormann & Dewey, 2012). In eastern Canada, m_N is the magnitude used by CHIS for moderate-sized earthquakes[2].

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 2016, 54 earthquakes were located, close to the average of 49.8/year over the previous 5 years. The magnitudes of the earthquakes located in 2016 ranged from 1.1 m_N to 3.1 m_N. The largest earthquake, with a magnitude of 3.1 m_N, occurred under James Bay; the second largest, with a magnitude of 3.0 m_N was felt widely in North Bay. There were 10 other events between magnitude 3.0 and 3.3 m_N, but they were all confirmed to be mining-related events.

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. Since then, the smaller earthquakes in the study area have been located with the aid of additional data provided temporary stations added after 2003 (ATKO, EPLO, KILO, MALO, PKLO, SILO, SUNO and VIMO), resulting in a slightly reduced location threshold for the northeastern portion of the region.

A program to upgrade the seismograph stations of the CNSN began in 2016. 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 are to be 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.

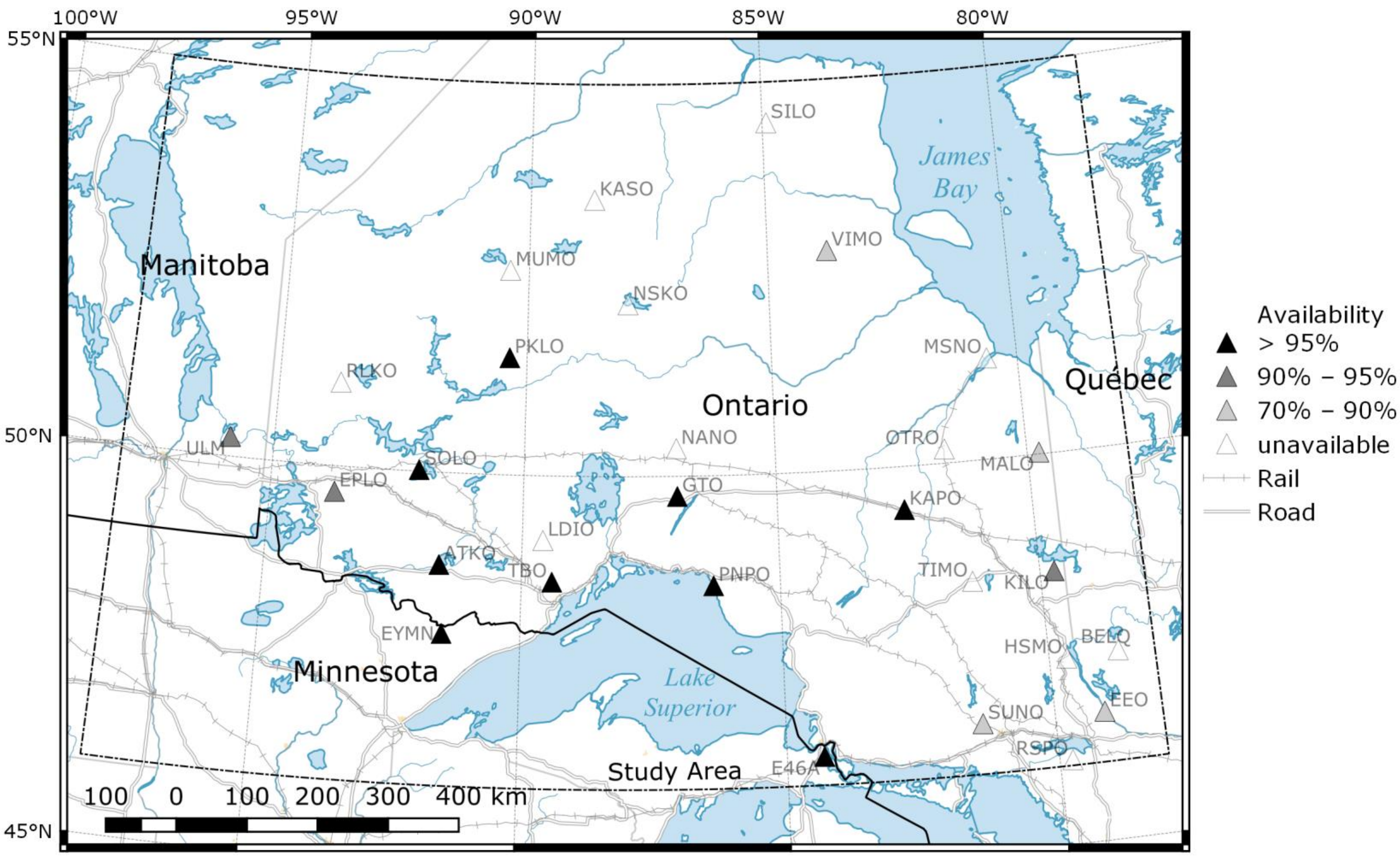


Figure 1: Seismograph Stations in northern Ontario. The study area is outlined with a dash-dotted line. Historical and currently active stations are shown as triangles, with the triangle filled according to data availability. Stations with no availability in northern Ontario are closed, former FedNor stations, mainly active 2006–2009. Historical analog stations are not shown.

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 many of the former POLARIS stations. Together, approximately four gigabytes per day of digital network data are acquired, quality controlled, processed, archived, and disseminated by the national seismology data centre. At the time of writing this report, 2292 earthquakes over magnitude 2.0 had been located in Canada during the year 2016. Only 28 of these occurred in the study region.

2.2 OPERATIONAL STATISTICS

Station operation statistics for key stations in northern Ontario are given in Table 1. Data capture was in excess of 95% for five of the seven core seismograph stations (CRLO, EEO, GTO, KAPO, SOLO, TBO, ULM), but above 95% for just three of the eight temporary stations (ATKO, EPLO, KILO, MALO, PKLO, PNPO, SUNO, VIMO).

Many of the solar powered sites, including VIMO, MALO, SUNO, and EPLO experienced power failure and had poor telecommunications during the winter months, particularly January and December. SILO remains down and there is no plan to repair it. It should be noted that although data from VIMO and MALO continue to be available, there is no plan to repair them should they go down. Data availability at all other stations is expected to improve in 2017, thanks to refurbishment efforts currently underway.

Table 1: Operation statistics for stations in northern Ontario, 2015–2016

station	net.	lat. [°N]	lon. [°W]	elev. [m] [b]	on date	type [e] 2016	availability [f] 2015	availability [f] 2016	number of gaps 2015	number of gaps 2016
ATKO	CN	48.8231	91.6004	383	2004-06-09	BB	74%	97%	137633	29953
CRLO [a]	CN	46.0375	77.3801	168	1994-11-17 [d]	SP	96%	96%	498	331
EEO	CN	46.6410	79.0735	121	1993-10-05 [c]	SP	87%	82%	941	1517
EPLO	CN	49.6737	93.7258	437	2004-06-11	BB	100%	93%	1530	13379
GTO	CN	49.7455	86.9610	350	2001-01-04 [c]	SP	100%	96%	1464	1249
KAPO	CN	49.4504	82.5079	210	1998-01-14 [d]	BB	99%	99%	419	308
KILO	CN	48.4972	79.7232	314	2003-06-22	BB	96%	94%	852	4595
MALO	CN	50.0244	79.7635	271	2003-06-20	BB	98%	89%	1098	289
PKLO	CN	51.4987	90.3522	376	2004-06-15	BB	100%	99%	783	395
PNPO	CN	48.5957	86.2846	219	2004-06-18	BB	99%	99%	1069	338
SILO	CN	54.4792	84.9126	195	2003-06-09	BB	13%		646	
SOLO	CN	50.0213	92.0812	373	1998-11-04 [c]	SP	98%	100%	2389	335
SUNO	CN	46.6438	81.3442	343	2003-06-23	BB	89%	82%	1018	3880
TBO	CN	48.6472	89.4085	475	1993-10-05 [c]	BB	86%	95%	723	552
ULM	CN	50.2503	95.8750	251	1994-12-07 [c]	BB	100%	94%	173	799
VIMO	CN	52.8173	83.7449	78	2003-06-11	BB	99%	88%	2312	9740
D41A	N4	47.0605	88.5657	271	2013-11-26	BB		95%		4
E43A	N4	46.3758	86.9954	303	2013-11-26	BB		95%		490
E46A	N4	46.3665	84.3062	269	2013-11-26	BB		96%		1
EYMN	US	47.9462	91.4953	475	1994-09-26	BB	92%	97%	61	71

Note:

[a] 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 that of upgrade to provide continuous digital data. Installation dates were earlier: EEO 1984, GTO 1982, SOLO 1988, TBO 1987, ULM 1984.

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

[e] Station type is "BB" for broadband 3-channel or "SP" for short period vertical.

[f] Availability statistics are for vertical channels of seismometers, as seen in the waveform archive. This is considered representative of all channels available to analysts during routine processing.

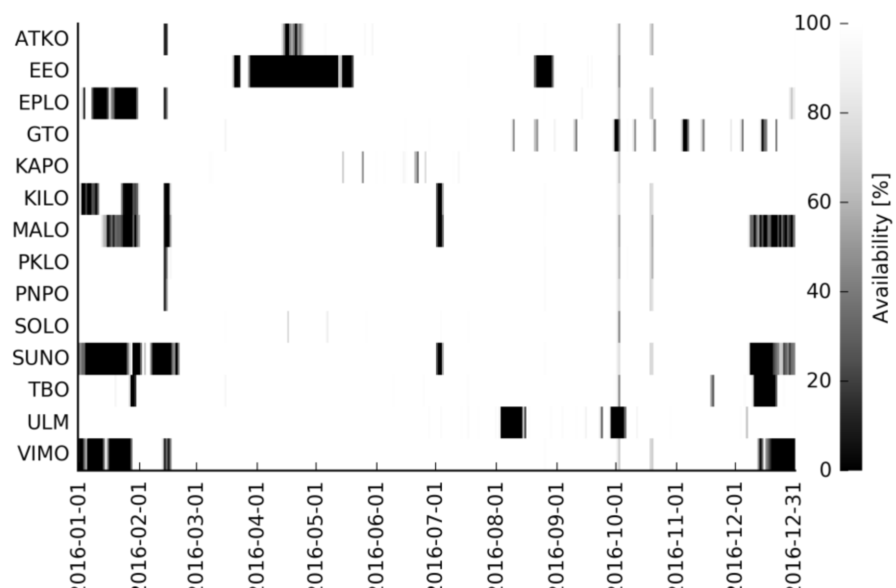


Figure 2: Daily data availability for CN network in northern Ontario, 2016. See Table 1 for definition of availability.

The following list summarizes major outages that affected data availability in 2016 (see Table 1 and Figure 2).

- SILO remains out since March 2015. Our technologist suspects damage due to wildlife. A repair trip is required to check loose connections and the alignment of the satellite dish antenna. No trip is currently scheduled. Instead, due to the cost of servicing SILO, the equipment will probably be removed in the future.
- TBO dropped out January 27–30 due to snow accumulation on the VSAT dish antenna.
- VIMO, MALO, KILO, SUNO, and EPLO, which are solar powered sites, dropped out due to low battery voltage during intervals in January and February.
- VIMO, MALO, KILO, EPLO, ATKO, PKLO, and PNPO, which use Nanometrics Libra I VSAT communications, dropped out for varying intervals starting February 14 due to a "week number rollover" bug in the Trimble GPS receiver. A firmware upgrade was released and applied to compensate for the problem.
- EEO dropped out from March 28 to May 20. Our satellite service provider accessed the site after snow melt and replaced components to restore data flow.
- ATKO data dropped out during intervals from April 14 to May 26. Our technologists repointed the satellite dish antenna, and modified the transmission parameters to restore data flow.
- KAPO timing was bad stating May 7. The vault had flooded. A site maintenance trip on June 22 repaired the GPS timing problem, but data quality were still bad due to a faulty sensor. A replacement sensor was installed on July 10.
- CRLO timing was bad from June 10. A maintenance trip on June 24 temporarily improved timing, but timing was bad again since July 8. Another maintenance trip on August 29 was required to restore normal operation.
- MALO, KILO, and SUNO stations were out July 2–5 due to a problem at our satellite hub.
- ULM was out August 3–16. The problem was eventually determined to be a faulty port on the serial-to-IP converter.
- EEO dropped out August 21–31. Our technologist replaced a switch at the station.
- ULM dropped out from September 28 to October 6. Our local agent power cycled the station equipment to restore operation. The Ethernet switch was subsequently replaced.
- Our satellite service provider had problems with its orbiting satellite due to a technical anomaly. This resulted in a communications outage of approximately 17 hours October 2–3 for the CN network stations in Table 1.
- VIMO, MALO, KILO, SUNO, EPLO, ATKO, PKLO and PNPO: out October 19–20. An acquisition system required a reboot to restore normal data flow.
- TBO dropped out November 19–20 due to suspected power outage.
- ULM dropped out December 7 due to snow accumulation on the VSAT dish antenna.
- TBO dropped out December 10–22 due to snow accumulation on the VSAT dish antenna.
- GTO dropped out for a few days each month starting in August. The station was remotely power cycled each time to restore operation. A serial-to-IP converter is believed to be the culprit.
- VIMO, MALO, SUNO, and EPLO (solar powered sites) dropped out due to low battery voltage during intervals in December.

3. EARTHQUAKES

This section focuses on the natural tectonic seismicity of northern Ontario, placing the earthquakes detected in 2016 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 2016 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. Although earthquakes smaller than 2.0 m_N can be located with the current network, the accuracy of the event locations can be affected and the catalogue of events less than 2.0 m_N 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 station coverage means that the portions of the study area that are in Manitoba, Minnesota 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.

In 2008, the POLARIS-FedNor project ended, and stations had to be closed. Eight stations were chosen to be 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 the location threshold may have been somewhat increased for the last five years compared with the previous five years.

The 54 earthquakes of 2016 is compared to previous years in Table 2 and Figure 3.

The rate of seismicity (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 location threshold (magnitude of completeness) of the seismograph network changes. The location threshold of a seismograph network 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.

The selective decommissioning of FedNor stations in 2008–2009 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. Nonetheless, it is becoming clear that in fact the network magnitude of completeness has increased. In particular the rate of declustered seismicity (all magnitudes) dropped from 74.7/year to 49.5/year between the 6-year periods 2004–2009 and 2011–2016. The rate is still significantly greater than the 26.0/year observed just prior to the FedNor deployment (1997–2002), not to mention the 6.0/year of 1983-1988.

Table 2: Earthquake and station counts in northern Ontario, 2000–2016

year	known earthquakes	declustered [a,e] (mainshocks)	suspected [b,e] earthquakes	nominal [c] stations	available [d,e] stations
2016	54	48	9	16	14.0
2015	50	46	8	16	14.3
2014	34	33	4	16	14.8
2013	69	56	13	16	14.3
2012	57	48	11	16	14.0
2011	79	66	3	16	14.4
2010	118	90	9	16	15.3
2009	82	67	9	18	16.5
2008	114	83	8	26	21.8
2007	67	63	4	26	24.2
2006	83	75	1	26	24.0
2005	100	85	4	26	22.2
2004	79	75	8	20	16.9
2003	45	35	7	14	10.7
2002	45	39	5	7	6.9
2001	35	29	5	7	6.9
2000	72	36	5	7	6.0

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

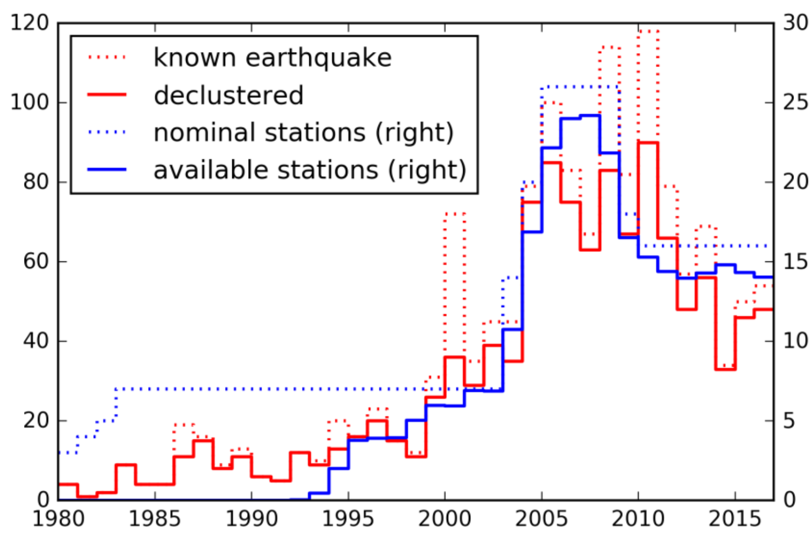


Figure 3: Earthquake and station counts in northern Ontario, 1980–2016. See Table 2 for explanation of terms. Note that “available stations” is only computable from the digital archive starting in 1994.

3.2 EVENTS OF INTEREST

In general, the geographic distribution of seismic activity for 2016 followed that of the previous years, with earthquakes chiefly being reported from James Bay, the Sudbury-Timiskaming area, and from the Severn Highlands. See Figure 4 for a map and Table 3 for a detailed listing of all earthquakes in the study area in 2016. The smallest earthquakes catalogued were 1.1 $m_{N.}$

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, 1409 earthquakes have been documented.

Table 3 includes the best estimate of depth for each event in the study area in 2016. 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 cannot be estimated in this way. In 2016, eight events had depths estimated by Regional Depth Phase Modelling (RDPM) and 16 more were assigned 2±3 km depths based on the observation of crustal Rayleigh phases. 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 examples from 2016.

The largest earthquake in the study area was a 3.1 m_N event on 2016-05-22 in the middle of James Bay. In all 14 of the 53 earthquakes (and 5 of 9 suspected earthquakes) recorded in the study area in 2016 were in James Bay. Three James Bay events had depths estimated by RDPM: two at 13 km and one at 17.5 km (see Table 3).

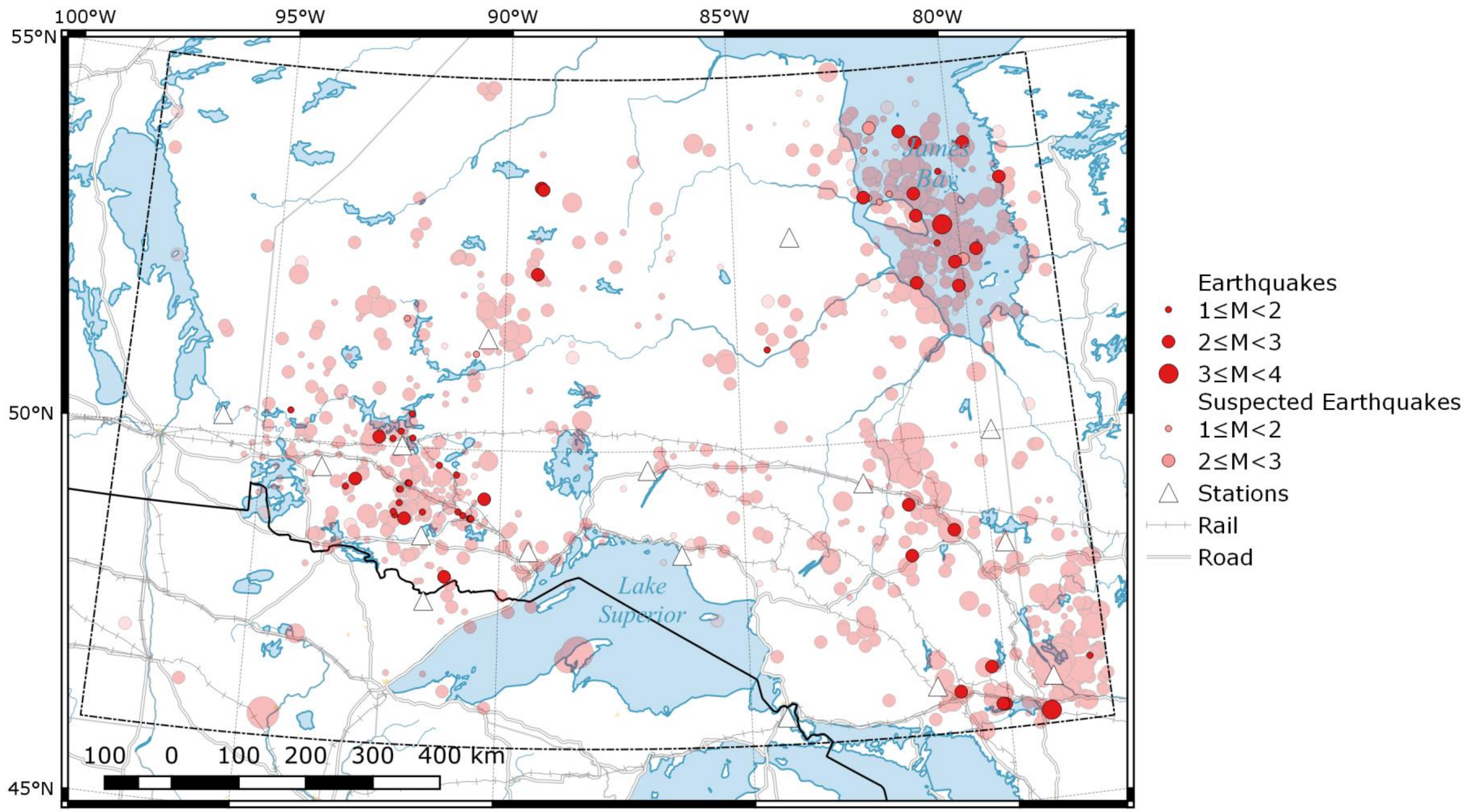


Figure 4: Earthquakes in northern Ontario, 2016. Earthquakes 1900–2015 are plotted semi-transparently. Events and stations are plotted for the region within dashed lines only. The study area is outlined with a dash-dotted line. Only stations with data available in 2016 are shown.

Table 3: Earthquakes in northern Ontario, 2016

time [a] [UTC]	mag. [m_N]	lat. [°N]	lon. [°W]	dep. [km]	S [b]	P [b]	felt	D [c]	comment
2016-01-09 18:36	1.6	49.5216	91.9198	2	5	10		R	61 km S from Sioux Lookout, ON
2016-01-09 18:36	1.6	49.5216	91.9198	2	5	10		R	61 km S from Sioux Lookout, ON
2016-01-25 09:39	1.4	49.7767	91.2918	5	5	10		F	59 km SE from Sioux Lookout, ON
2016-01-31 19:54	2.9	46.3234	80.0569	2	16	28		V	12 km SW from Sturgeon Falls, ON
2016-02-01 09:45	2.2	46.3298	80.1110	2	9	16		M	16 km W from Sturgeon Falls, ON
2016-03-14 05:44	2.2	49.3439	90.3363	5	9	17		F	101 km S from Allanwater Bridge, ON
2016-03-14 22:43	2.0	53.2786	80.9120	18	3	6		F	James Bay
2016-03-16 08:41	1.8	49.5186	91.8966	5	6	12		F	61 km S from Sioux Lookout, ON
2016-03-24 16:02	1.5	49.4319	92.0933	2	5	10		R	65 km SE from Dryden, ON
2016-03-29 01:17	2.2	48.2807	91.0968	2	5	8		R	67 km SE from Atikokan, ON
2016-03-30 14:10	1.8	50.2114	92.1228	2	4	7		R	17 km NW from Sioux Lookout, ON
2016-03-31 15:36	1.4	49.4322	92.0717	5	5	9		F	67 km SE from Dryden, ON
2016-04-02 22:08	2.2	52.4624	79.6519	18	6	10		F	James Bay
2016-04-05 06:43	2.0	52.3133	80.1443	18	4	7		F	James Bay
2016-04-12 09:55	2.2	50.1208	92.5761	2	7	14		R	42 km W from Sioux Lookout, ON
2016-04-22 14:06	1.4	49.1597	90.8672	2	5	9		R	71 km NE from Atikokan, ON
2016-05-05 21:43	2.1	52.3825	89.3111	2	3	6		R	91 km W from Lansdowne House, ON
2016-05-13 02:21	2.6	49.0435	91.9662	3.5	9	18		V	42 km NW from Atikokan, ON
2016-05-13 02:45	1.2	49.0451	91.9329	5	3	6		F	40 km NW from Atikokan, ON
2016-05-22 02:45	3.1	52.8318	80.3399	17.5	10	18		V	James Bay
2016-05-23 02:15	2.5	53.9014	79.6935	13	4	7		V	55 km W from Chisasibi, QC
2016-05-23 03:48	1.3	49.0826	92.1623	5	5	10		F	55 km NW from Atikokan, ON
2016-05-25 01:03	2.4	53.3870	78.9616	18	4	7		F	44 km N from Wemindji, QC
2016-06-06 13:00	2.7	53.2840	82.0412	18	7	13		F	James Bay
2016-06-09 10:19	2.8	53.5440	89.2597	10.5	11	21		V	52 km SE from Kitchenuhmaykoosib, ON
2016-06-09 11:33	1.9	53.5266	89.2633	10.5	3	5		M	55 km SE from Kitchenuhmaykoosib, ON
2016-06-13 18:28	2.0	53.9616	80.7688	18	3	5		F	James Bay
2016-06-23 02:34	2.3	49.1137	81.6107	18	9	14		F	44 km W from Cochrane, ON
2016-07-04 05:11	2.0	53.5208	89.2153	10.5	5	9		M	55 km SE from Kitchenuhmaykoosib, ON
2016-07-08 21:48	1.8	53.5439	80.3166	18	3	6		F	James Bay
2016-07-09 20:35	1.4	49.1386	91.5958	2	6	10		R	43 km N from Atikokan, ON
2016-07-23 08:43	2.6	48.7246	80.7295	11	10	19		V	6 km SW from Iroquois Falls, ON
2016-08-06 06:29	2.3	54.1285	81.1214	18	3	6		F	James Bay
2016-08-15 08:16	2.8	52.0800	81.0233	13	11	18		V	James Bay
2016-08-28 12:22	1.9	50.1083	92.2842	2	4	8		R	21 km W from Sioux Lookout, ON
2016-09-12 03:43	1.6	50.1282	91.8713	5	7	11		F	11 km NE from Sioux Lookout, ON
2016-09-28 03:30	2.0	52.9811	80.9043	18	3	5		F	James Bay
2016-10-01 05:27	1.9	49.2482	92.0810	2	6	11		R	65 km NW from Atikokan, ON
2016-10-01 19:43	1.9	52.5891	80.4921	18	3	6		F	James Bay
2016-10-14 18:23	3.0	46.1758	79.1887	5.5	23	39	✓	V	20 km NE from Powassan, ON.
2016-10-17 12:37	1.5	49.6567	90.9255	5	5	9		F	85 km SW from Allanwater Bridge, ON
2016-10-21 02:30	2.4	48.4280	81.6273	18	12	20		F	22 km W from Timmins, ON
2016-10-30 11:22	1.7	50.4533	91.9078	2	4	7		R	44 km N from Sioux Lookout, ON
2016-11-18 11:10	1.9	49.1267	92.1933	2	8	14		R	59 km NW from Atikokan, ON
2016-11-19 18:36	1.1	49.0555	91.9186	2	4	7		R	40 km NW from Atikokan, ON
2016-11-19 19:35	1.1	49.0620	91.9071	2	4	7		R	41 km NW from Atikokan, ON
2016-11-23 20:41	2.2	49.5377	93.0170	2	7	13		R	29 km SW from Dryden, ON
2016-11-25 14:03	2.0	46.5447	80.9022	1	8	13	✓	F	9 km NE from Sudbury, ON
2016-11-26 17:10	1.9	46.8374	78.3210	18	8	12		F	61 km E from Temiscaming, QC
2016-12-12 15:06	2.5	46.8404	80.2566	18	8	15		F	54 km E from Capreol, ON
2016-12-23 15:48	1.6	49.0785	90.6240	5	6	11		F	81 km NE from Atikokan, ON
2016-12-24 02:39	1.6	49.0712	90.6108	5	7	12		F	82 km NE from Atikokan, ON
2016-12-25 08:16	2.4	51.9879	80.1148	18	6	11		F	James Bay
2016-12-26 03:17	1.7	49.0755	90.5983	5	9	15		F	83 km NE from Atikokan, ON

Note:

[a] Times given are Coordinated Universal Time (UTC), not local times.

[b] "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):

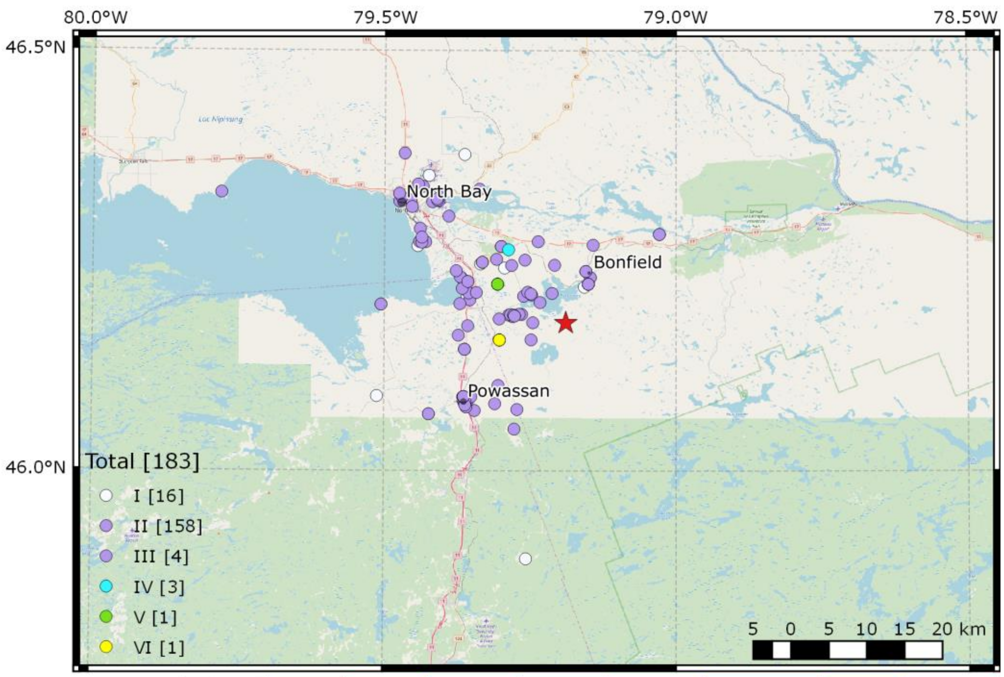
F – operator assigned
V – RDPM
R – Rg observed; assigned shallow depth
M – fixed depth based on waveform similarity

The second largest earthquake in northern Ontario in 2016 was a 3.0 m_N event 26 km ESE of North Bay on 2016-10-14. The event was felt in North Bay and several nearby small towns; 183 "Did you feel it?" reports were collected by CHIS[3] with 167 indicating that the event was felt. The felt area was roughly triangular, from North Bay to Bonfield to Powassan, as shown in Figure 5. The epicentral error in this region is likely less than 5 km, so the fact that all of the felt reports were to the north and west of the epicentre can be attributed to low population density towards Algonquin Park to the southeast.

Using RDPM the depth of the event near North Bay was estimated to be 5.5 km, the average of estimates from two stations (see Section 4.2.1). This is rather shallow relative to the Kipawa seismic zone just to the north, but typical of the depths observed in southern Ontario (Ma & Atkinson, 2006) and the southern part of northern Ontario (Ma, Eaton, & Adams, 2008).

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 the earthquakes, mining explosions and mining-induced events catalogued near Sudbury in 2016 along with the seismicity of previous years, back to 1982.

Just one event near Sudbury in 2016 was believed to be a natural earthquake, a 2.0 m_N event on 2016-11-25 (solid red circle between Stobie and Garson mines in Figure 6). The event was also recorded at 11 stations of the Sudbury Regional Seismic Network (SRSN) stations operated by



INTENSITY	I	II - III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy

Figure 5: "Did you feel it?" reports for 3.0 m_N earthquake near North Bay on 2016-10-14. Note that when converting from the individual community-derived intensities shown here to the modified Mercalli intensity (MMI) scale, reports are normally averaged over small areas, a process that smooths outliers away.

[3] http://www.earthquakescanada.nrcan.gc.ca/recent/2016/20161014.1823/dyfi-en.php

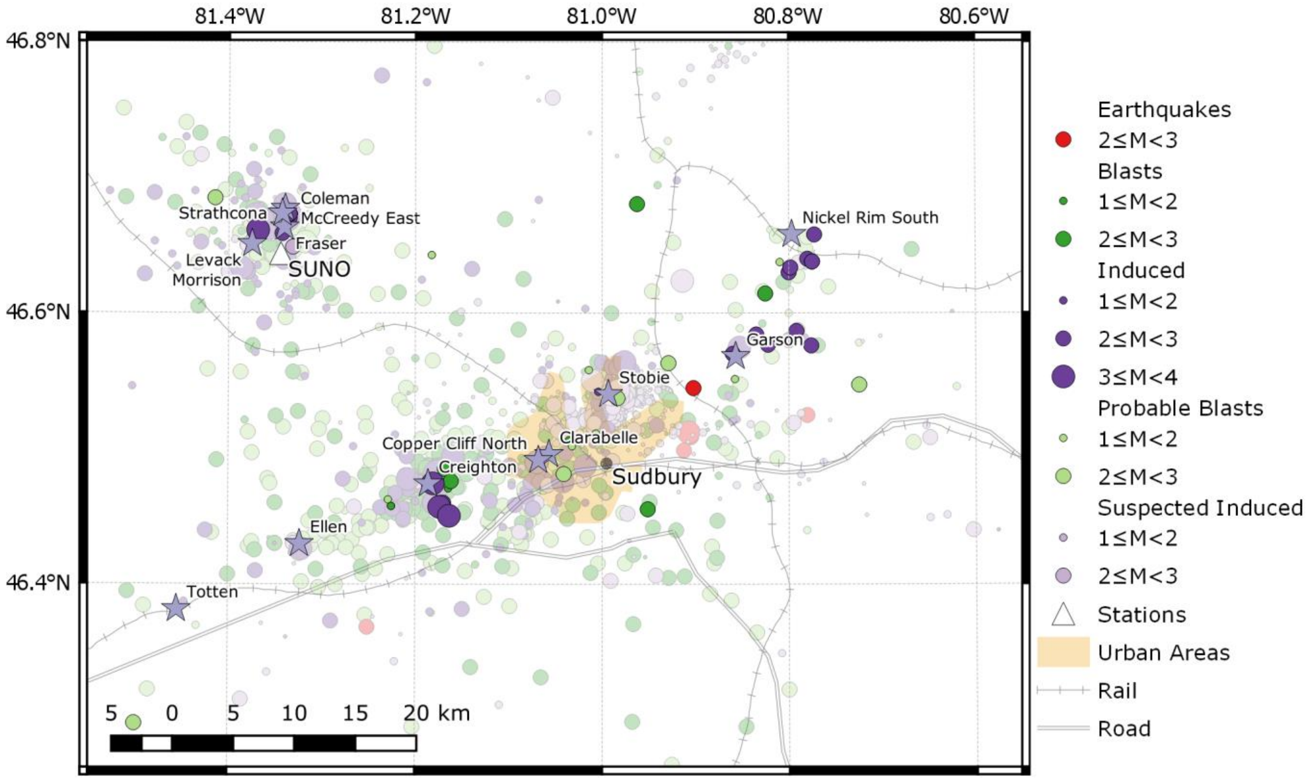


Figure 6: Seismic events near Sudbury, 1982–2016. Events prior to 2016 are partially transparent. Producing mines from the Atlas of Canada (Lands and Minerals Sector; National Energy Board, 2017) are shown as purple stars. Urban areas, major roads and railways are from Natural Earth (Schneider, Friedl, & Potere, 2010; Natural Earth, 2009).

Professor Martin Hudyma at Laurentian University (personal communication, 2016). It was reported as felt at Garson but not Stobie. The epicentre obtained using waveforms from the regional network was 4 km away from Garson and 6 km away from Stobie (the SRSN epicentre was a little further away from Stobie). There is significant waveform similarity between the 2016 event and those observed in 2015. This appears to be a continuation of the sequence first noted in 2015 (nearby transparent red circles in Figure 6), which started with a 3.1 m_N event. The cluster is located near the Sudbury landfill, but is believed to be related to a pre-existing dormant fault structure, not the landfill itself.

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. On plots like Figure 6 any proximity of blast and earthquake symbols leads to checking as to whether a blast might have been misidentified as an earthquake.

The Sudbury earthquake of 2015-09-10 and its aftershocks occurred quite close to a mining area, but as discussed in above, blasting and mine rockbursts can be ruled out. Although it is possible that the earthquakes were triggered by unloading due to regional mining activity, these events are currently categorized as natural tectonic earthquakes.

The third largest earthquake in northern Ontario in 2016 was a 2.9 m_N event 12 km SW of Sturgeon Falls on 2016-01-31 (see Figures 6 and 8). This event is believed to have been quite shallow; the depth was estimated at 2 km based on a single clear depth phase at SADO, and supported by a strong Rg phase at EEO.

No earthquakes occurred in the Timiskaming/Témiscaming region, in the Kipawa and Cochrane South seismic zones of the 2015 National Seismic Hazard Map (NSHM) (Halchuk, Allen, Adams, & Rogers, 2014). A small, 1.9 m_N, event occurred 60 km east of Témiscaming (see Figure 8); it was assigned the regional default depth of 18 km.

Two earthquakes occurred in the band of seismicity near Cochrane (see Figure 8). This band of seismicity is designated the Cochrane North seismic zone in the 2015 NSHM. The larger of the two, a 2.6 m_N event on 2016-07-23, was large enough for the depth to be estimated using RDPM at 11 km. This is consistent with the depths observed previously in the Cochrane band.

To the southwest, a 2.4 m_N earthquake on 2016-10-21 occurred away from the mining areas of Timmins, but was too small for the depth to be estimated using RDPM.

No new earthquakes have been observed in the region north and east of Chapleau that was active from 2012–2013 and in 2015 (see Figure 9).

The Severn Highlands seismic zone of the 2015 NSHM continued to produce small earthquakes (see Figure 10). Six small earthquakes or suspected earthquakes were located south of and under Lac Seul, within 50 km of, and to the north and west of Sioux Lookout and station SOLO. The largest of these, a 2.2 m_N earthquake on 2016-04-12 and the smallest, a 1.5 m_N suspected earthquake on 2016-01-20 were close to the “Dryden swarm” of 2002–2003 (Ma, Eaton, & Adams, 2008).

One earthquake was located close to the Ontario/Minnesota border, with magnitude 2.2 m_N on 2016-03-29, possibly part of a linear cluster striking NNW and crossing the border (see Figure 10). A shallow depth was assigned because Rg was observed. No earthquakes were located in Minnesota in 2016. 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 the maps.

Low-level seismic activity continued in a cluster 40–60 km to the northeast of Atikokan and station ATKO (see Figure 10). In all, 6 events added to this cluster in 2016. A depth of 3.5 km was estimated for the largest of these, 2.6 $m_{N,}$ using RDPM, while for two others Rg was observed, suggesting a depth less than 5 km.

Three earthquakes were recorded in a previously inactive area, 50 km SE of Kitchenuhmaykoosib, and 240 km NNE of station PKLO (see Figure 7). The first and larges event, with magnitude 2.8 m_N on 2016-06-09, was estimated to be at a depth of 10.5 km by RDPM. A 1.9 m_N aftershock an hour later and a 2.0 m_N on 2016-07-04 was assigned the same depth based on waveform similarity.

Figure 4 shows the earthquakes located in the study area in 2016 together with all known earthquakes since 1982. The representation, using red-filled circles for the 2015 earthquakes and partially transparent circles for the prior activity, makes it easy to judge which 2015 earthquakes happened in regions of prior seismicity as well as which areas of past activity did not have an earthquake in 2016. For 2016, a few “quiet” areas were evident: the Kipawa cluster, the northern end of the Cochrane band and the cluster immediately northeast of Pickle Lake.

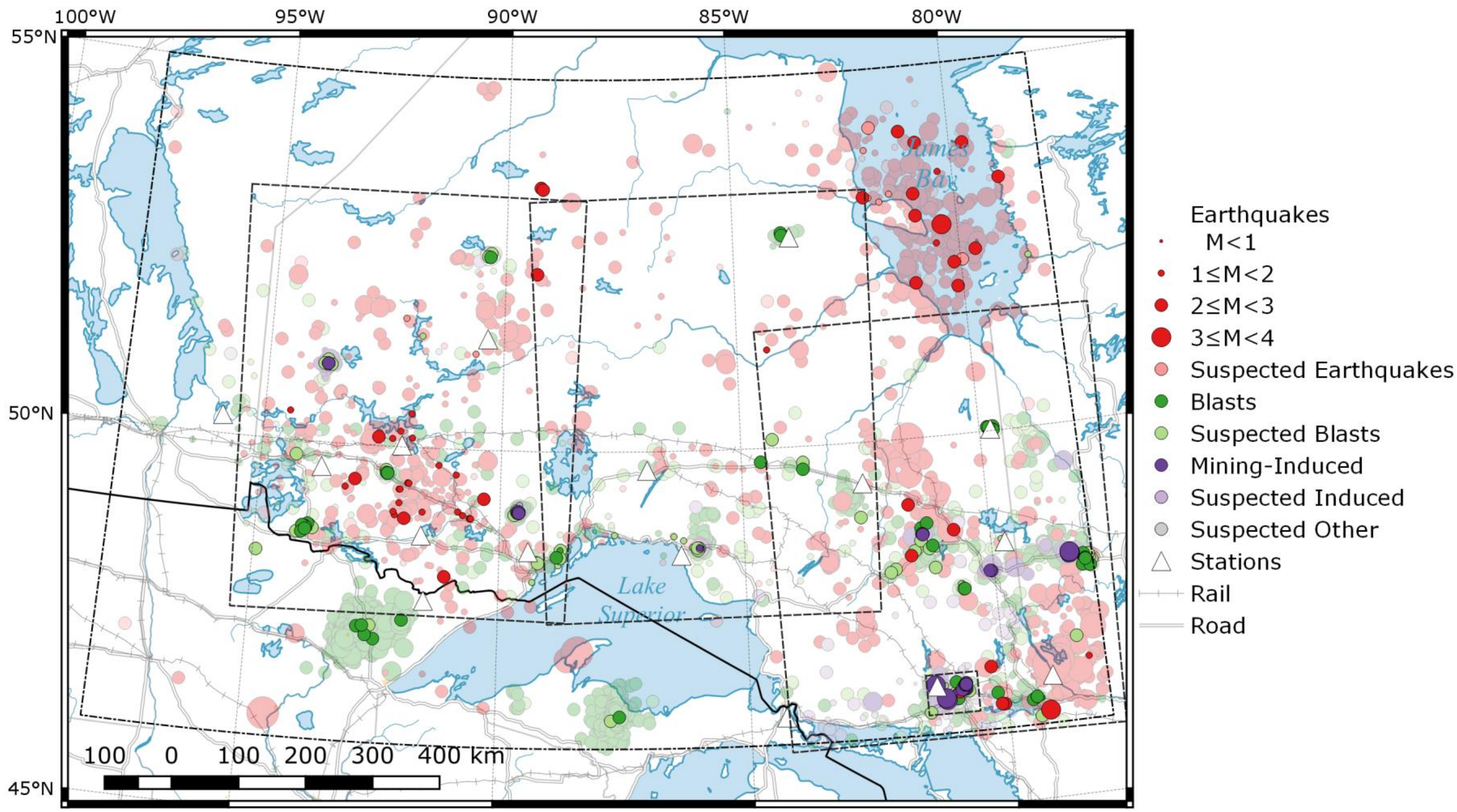


Figure 7: Seismic events in northern Ontario, 2016. Events 1900–2015 are plotted semi-transparently. Events and stations are plotted in the study area only. The study area is outlined with a dash-dotted line. Areas mapped in more detail in Figures 6–8 are outlined with a dashed line. Only stations with data available in 2016 are shown.

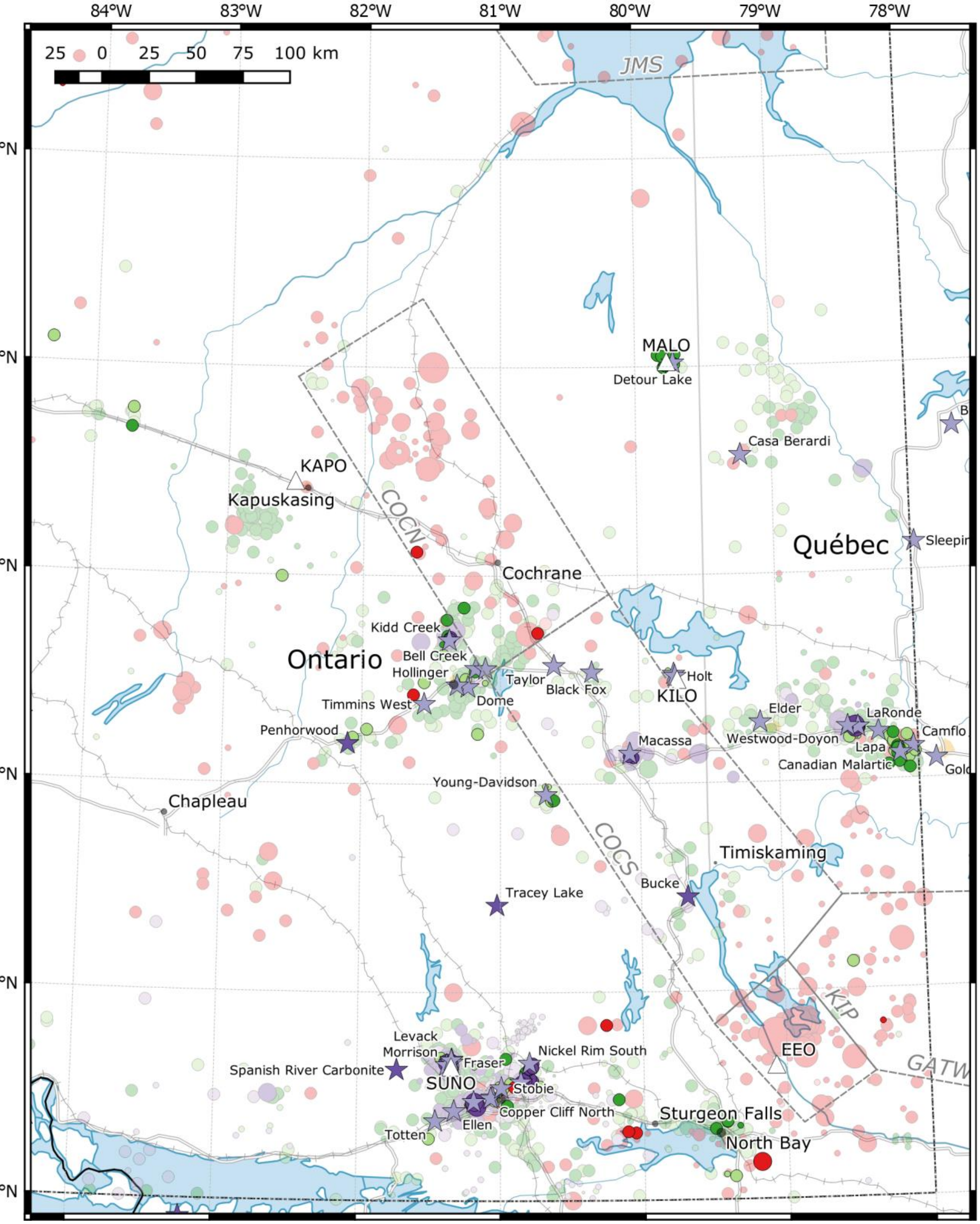


Figure 8: Seismic events north of Lake Huron, 2016. Legend and notes as for Figure 7. In addition, mines from the Atlas of Canada (Lands and Minerals Sector; National Energy Board, 2017) are shown as purple stars and seismic zones of the 2015 national seismic hazard model (Halchuk, Allen, Adams, & Rogers, 2014) are outlined with dashed lines. Seismic zone abbreviations: JMS – James Bay, COCN – Cochrane North, COCN – Cochrane South, KIP – Kipawa, GATW – Gatineau West.

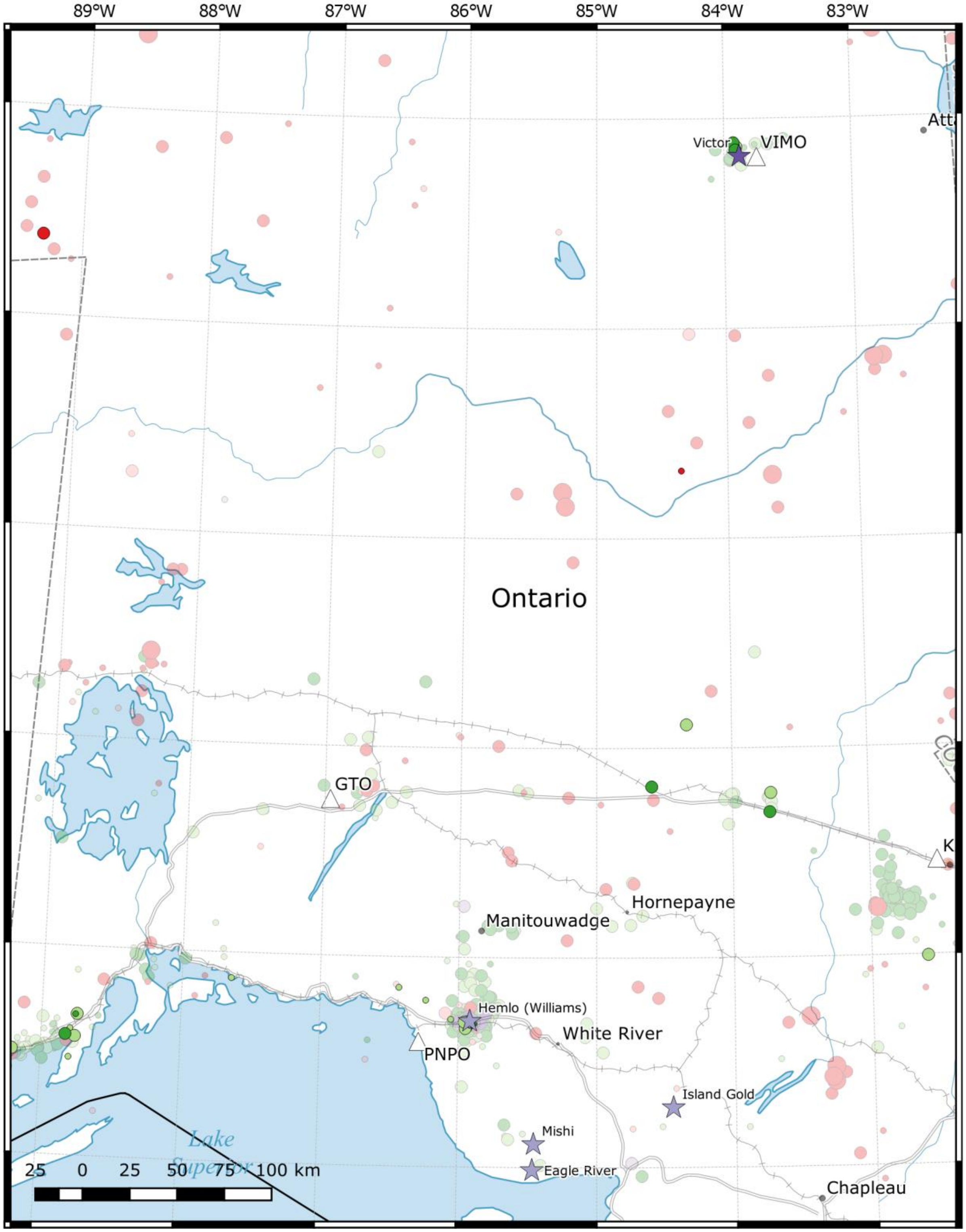


Figure 9: Seismic events northeast of Lake Superior, 2016. Legend and notes as for Figure 8.

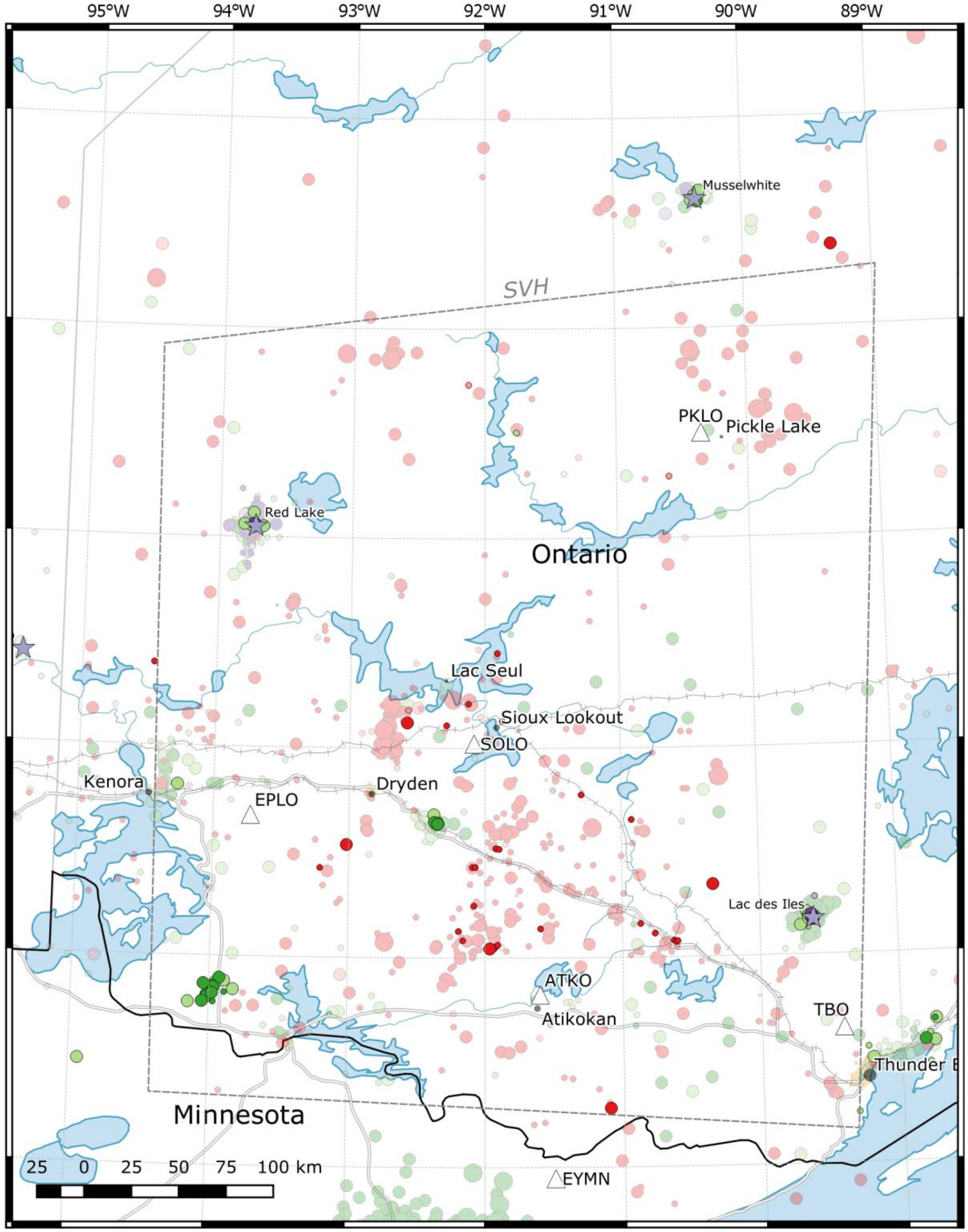


Figure 10: Seismic events in the Severn Highlands, 2016. Legend and notes as for Figure 8. Seismic zone abbreviations: SVH – Severn Highands.

As in the past, a strong Rg-phase was present on many events. Rg-phases are a feature of shallow earthquakes, mine blasts, and mining-induced events. For many of these events over the past years, no known operating mines are located nearby, and the time of day on some of these events are not within daylight hours when surface mines, construction crews or quarries would be blasting. These facts support that the events are earthquakes, but with a shallow source (see Section 4.2.1).

Figure 11 is effectively a summary of the northern Ontario seismic monitoring project thus far, showing earthquakes in the period 1982–2016.

Figure 12 shows earthquakes of magnitude 3 or greater recorded in the study area during the period 1982–2016 (75 events in 35 years). The pattern of all seismicity echoes the pattern of the larger events, though the Thunder Bay – Atikokan area that is active with many small earthquakes has not yet had an event above magnitude 3.

Figure 13 illustrates the seismic activity in eastern Canada in year 2016. The rates of seismicity in northern Ontario are some of the lowest in eastern Canada. This figure also indicates the generally low level of seismic activity in southern Ontario. 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 all the activity in eastern Canada for the entire monitoring period of 1982–2016. This figure also shows relatively few earthquakes of magnitude greater than 3 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 southern Hudson Bay) appears to be more active than the onshore region. Ma et al. (2008) suggest that the reason for the 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 for all stations are available in continuous data archive files at CHIS. All the archived data can be accessed on-line on the CHIS AutoDRM web site at:

http://www.earthquakescanada.ca/stndon/AutoDRM/.

The data are available 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. Descriptions of all these formats are also available on the web sites.

Catalog entries for 2015 and all previous earthquakes and blasts are available at:

http://www.earthquakescanada.ca/stndon/NEDB-BNDS/.

The same tool can access preliminary solutions for earthquakes more recent than the ones documented in the 2015 report, however that list may not be complete and the 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 CSV format.

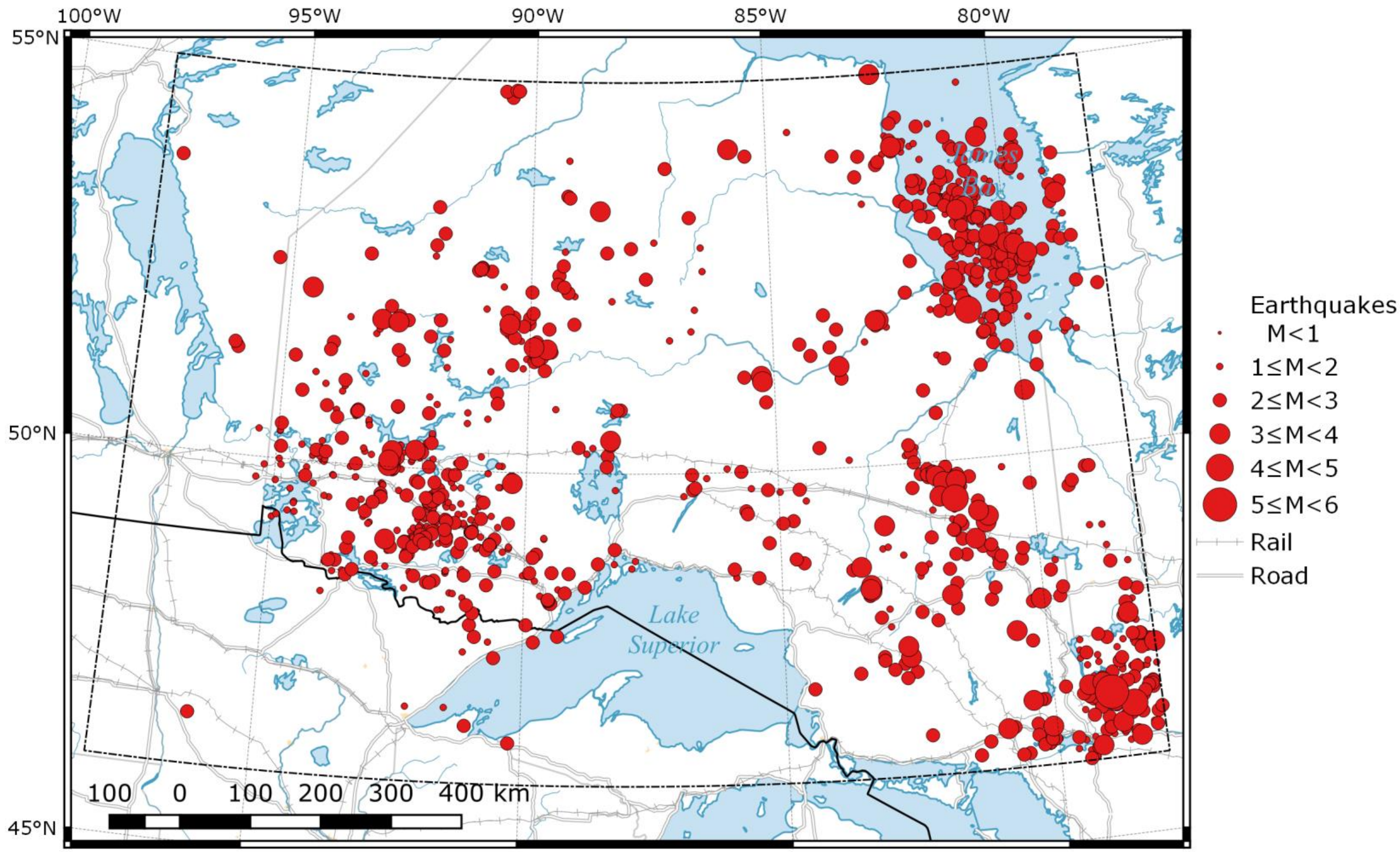


Figure 11: Earthquakes in northern Ontario, 1982–2016. Events and stations are plotted for the region within dashed lines only.

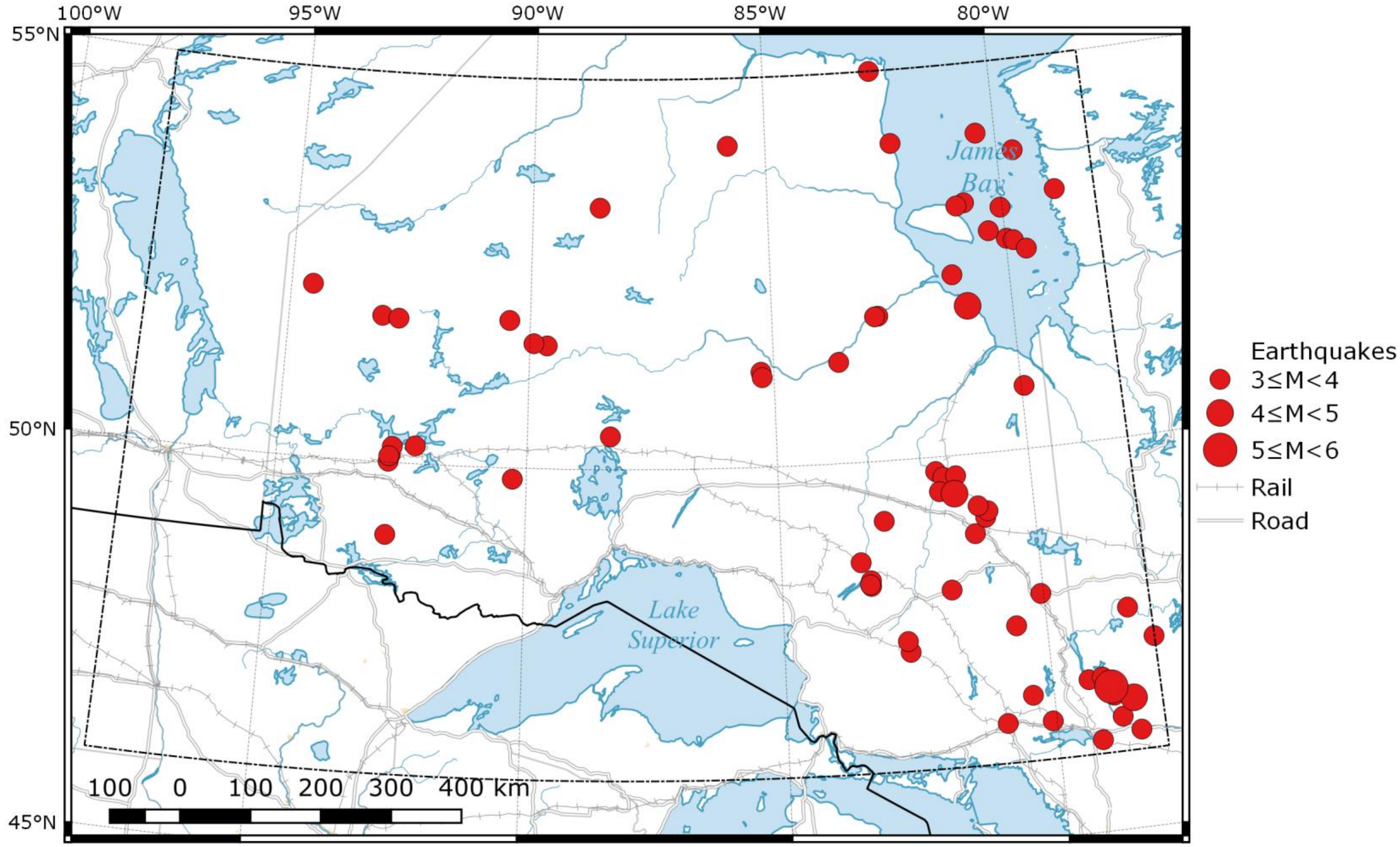


Figure 12: Earthquakes mN ≥ 3 in northern Ontario, 1982–2016. Events and stations are plotted for the region within dashed lines only.

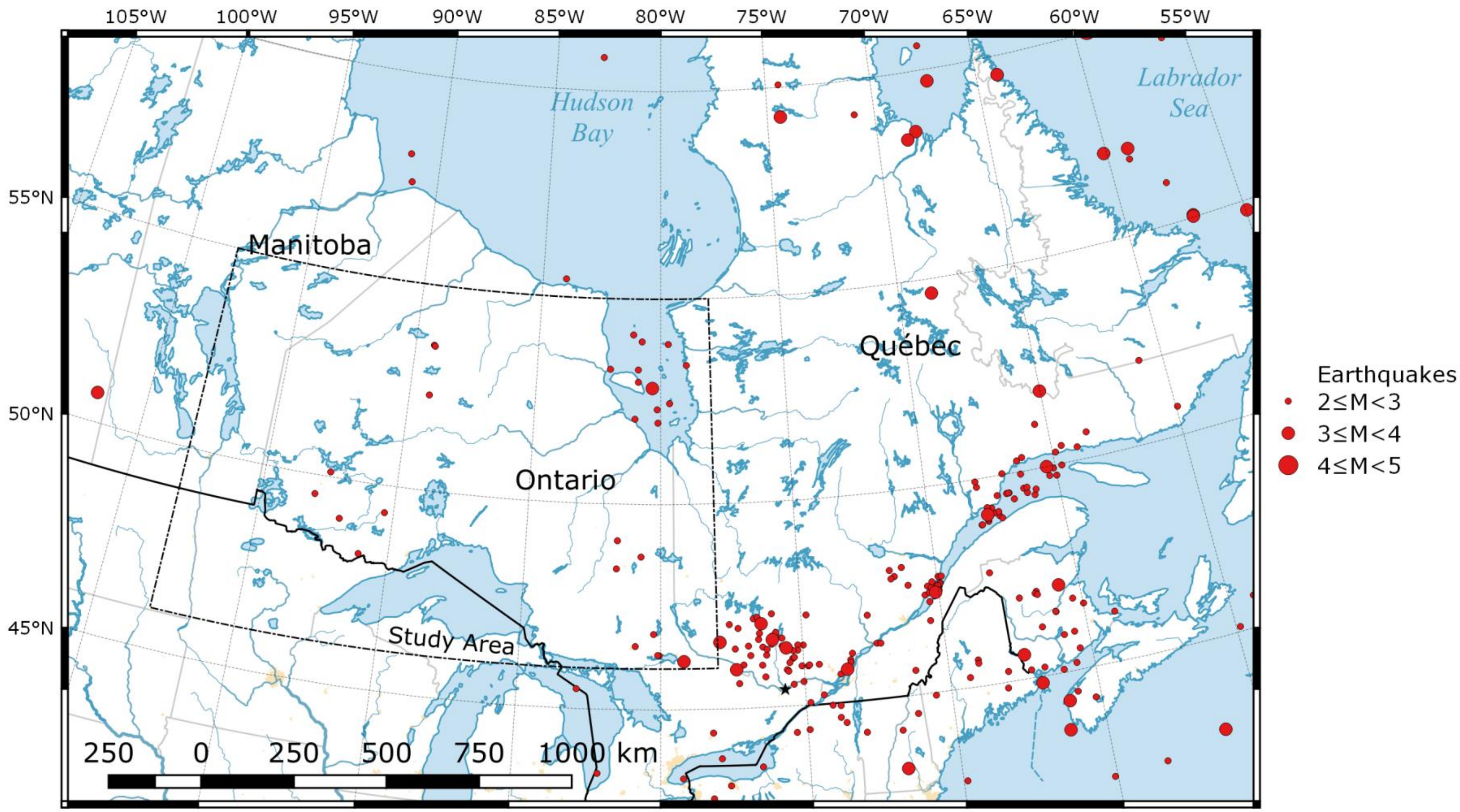


Figure 13: Earthquakes in eastern Canada, 2016

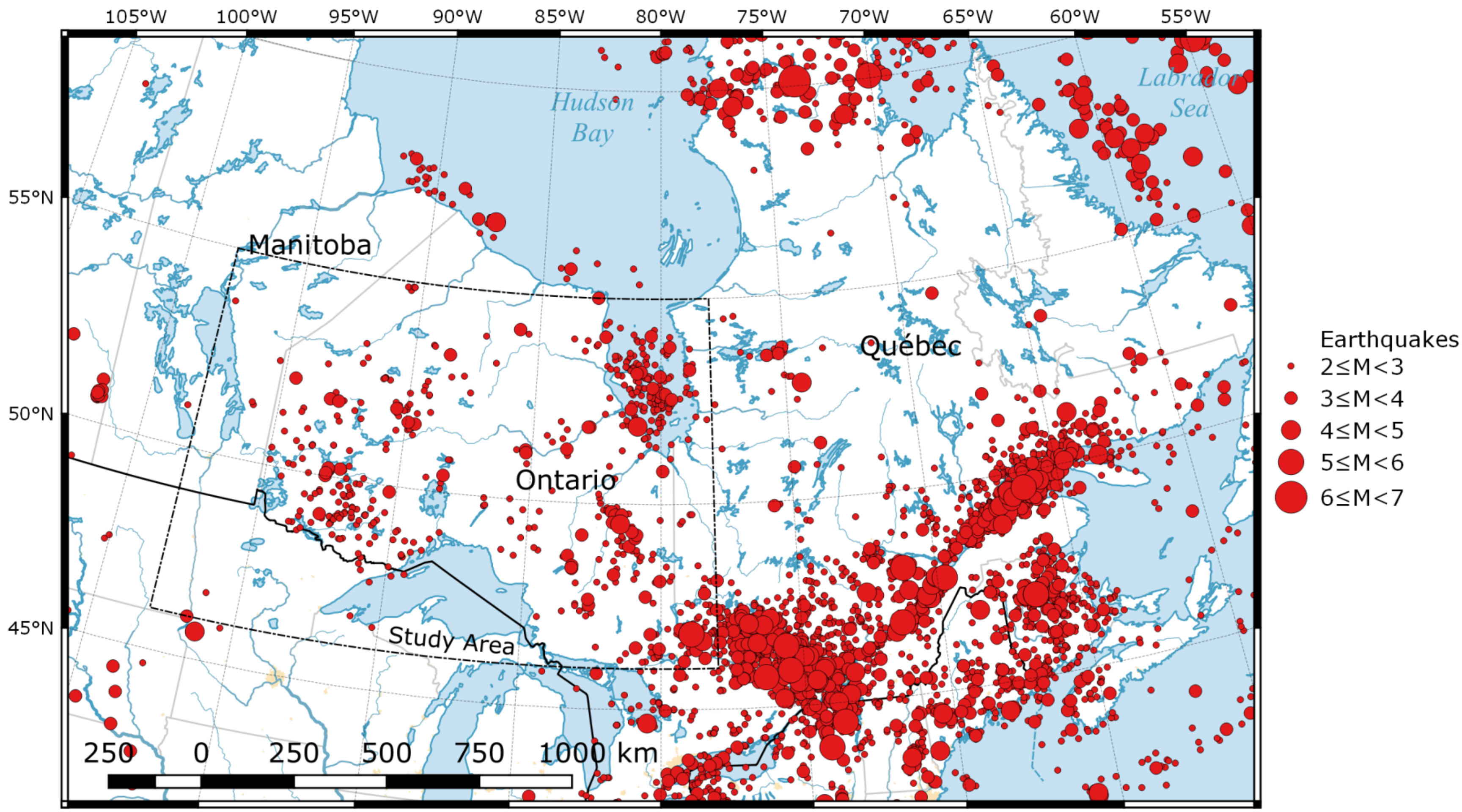


Figure 14: Earthquakes in eastern Canada, 1982–2016

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 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, except in the Appalachians, southern Ontario and the southern part of northern Ontario, where the default is assumed to be shallower, at 5 km, unless other information is available.

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 2016 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 states, “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, p. 3) RDPM has been and is now being applied to the larger eastern Canadian earthquakes. It is generally useful down to $m_N > 3$, although depending on station quality and azimuthal distribution, the magnitude can be lower. Different regional depth phases are useful in different distance ranges, as summarized in Table 4 (Ma, 2004).

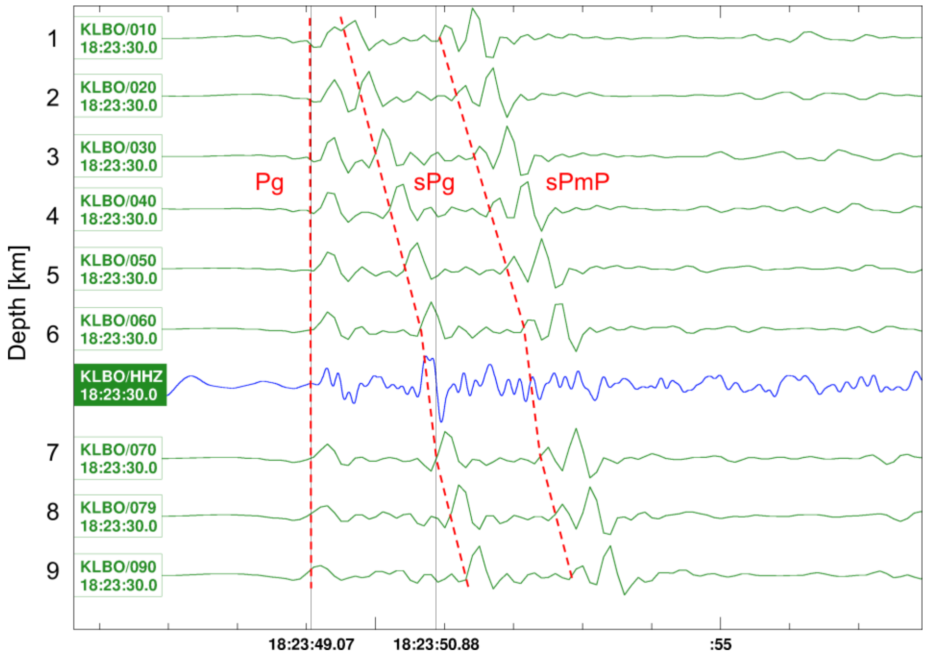
Table 4: Regional depth phases and their ranges of utility

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

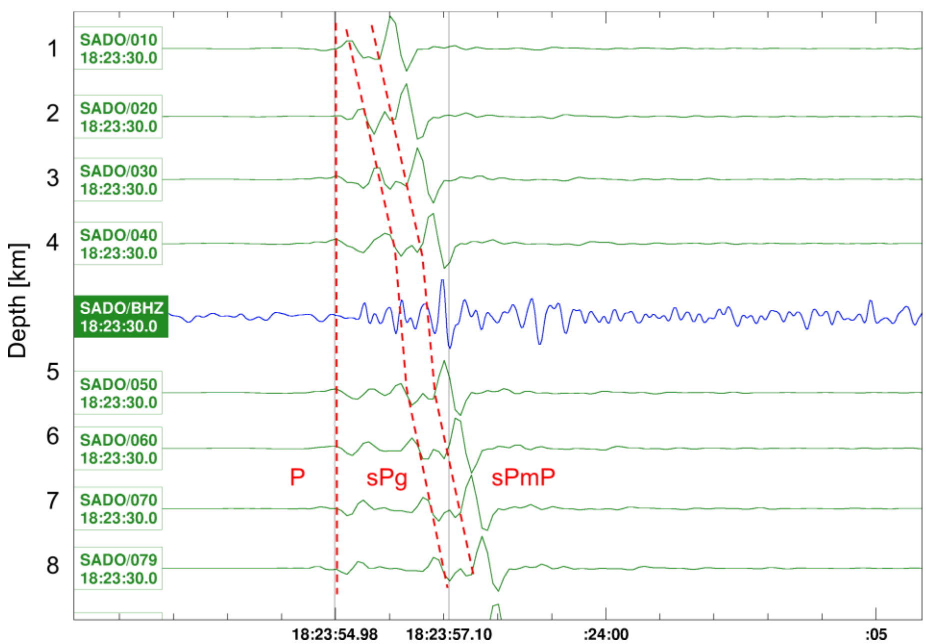
Extensive work using RDPM modelling was done for earthquakes in neighbouring regions, the West Quebec seismic zone and southern Ontario (Ma & Atkinson, 2006). A further paper based on Ma (2004) focused on the Severn Highlands of northern Ontario (Ma, Eaton, & Adams, 2008). In both cases, it was noted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

Table 5 lists the events in northern Ontario in 2016 which had depths estimated by RDPM.

Figure 15 shows an application of RDPM to a shallow 3.0 m_N earthquake, while Figure 16 shows an application of RDPM to a confirmed 3.1 m_N mining event, also necessarily shallow. In each case, the match of the observed to the synthetic waveforms is not perfect. This is because these events are at the low end of the range of magnitudes for which RDPM is possible. Nonetheless, these examples suggest that reference and depth phases can be picked to within ±0.2 s. Assuming that phases are correctly identified and modeled velocities are within ±10% of actual velocities, this corresponds to an uncertainty of ±1 km for depth estimates for shallow events.

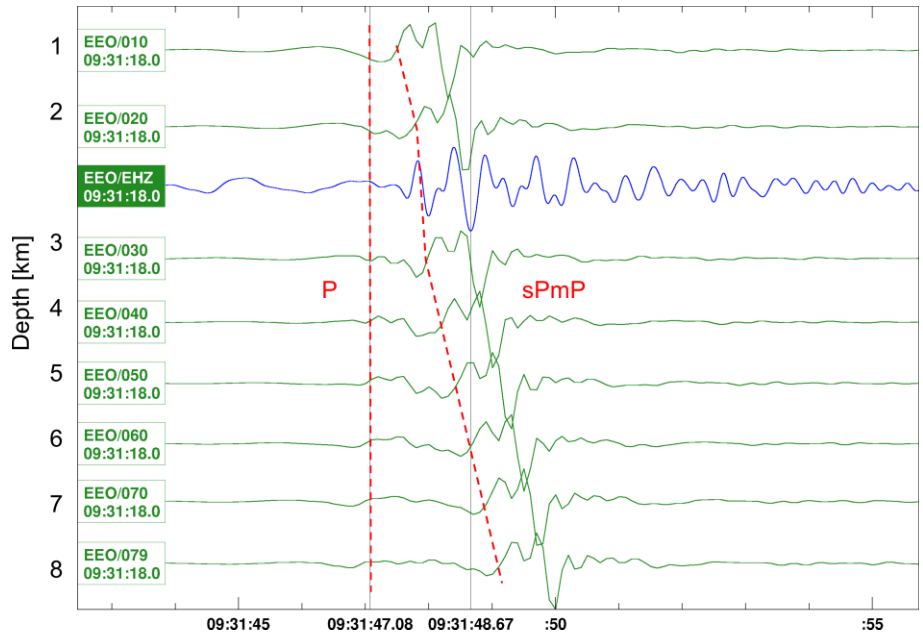


a) Waveforms at station KLBO, 121 km SW of epicentre, filtered using 1–6 Hz fifth order bandpass. Best fit depth 6.0 km. sPg is better developed than sPmp.

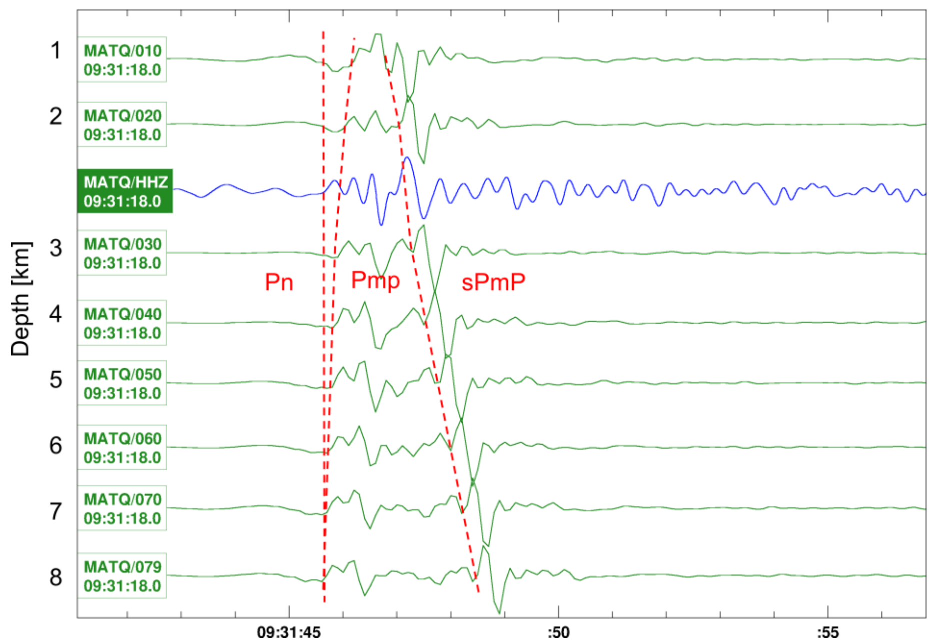


b) Waveforms at station SADO, 156 km S of epicentre, filtered using 1.2–6 Hz fifth order bandpass. Best fit depth 5.0 km. sPmP is better developed than sPg.

Figure 15: RDPM for 3.0 m_N earthquake near North Bay on 2016-10-14. Synthetic waveforms are in green; observed waveforms are in blue. Arrivals of labelled phases in synthetic waveforms are shown as dashed red lines, and approximate. Origin time was 2016-10-14 18:23:34 UTC. Average of two depth estimates is 5.5 km.



a) Waveforms at station EEO, 185 km from epicentre, filtered using 0.5–3.5 Hz 6th order bandpass. Best fit depth 2.5 km.



b) Waveforms at station MATQ, 178 km from epicentre, filtered using 0.7–3.5 Hz 6th order bandpass. Best fit depth 2.5 km.

Figure 16: RDPM for 3.1 m_N mining-induced event at Laronde Mine on 2016-07-24. Synthetic waveforms are in green; observed waveforms are in blue. Arrivals of labelled phases in synthetic waveforms are shown as dashed red lines, and approximate. Origin time was 2016-07-24 09:31:19 UTC. Average of two depth estimates is 2.5 km below sea level. Confirmed depth 2.87 km below surface.

Starting in the summer of 2016 mine operators began to provide confirmed depths for some events in their mines when requested by CHIS. In all, two mining events in 2016 had depth estimates obtained via RDPM and confirmed depths from mine operators (see Table 5). The mining event of Figure 16 is particularly interesting because the depth estimate from RDPM of 2.5 km (below sea level) is quite close to the depth provided by the mine operator of 2.87 km (below the surface, which is 320 m above sea level).

A second 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. A paper based on work using the period of the maximum power Rg/Sg spectral ratio to determine depths of small shallow events in eastern Canada by Ma and Motazedian (2012) suggests that resolution better than 0.5 km can be achieved by modeling Rg amplitudes but this 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

Table 5: Depths estimated using RDPM or observation of Rg-phases, 2016

time [UTC]	mag. [m_N]	lat. [°N]	lon. [°W]	depth [km] est. [a]	depth [km] act. [b]	felt	# c	comment
2016-01-10 22:49	3.3	46.4504	81.1636	2.0	-	✓	1	Mining related event, Sudbury, ON
2016-06-14 00:47	3.3	46.4743	81.1809	1.5	-	✓	3	Mining related event, Sudbury, ON
2016-09-15 21:30	3.2	48.2608	78.4470	2.5	-		1	Mining related event, Laronde Mine, QC
2016-05-22 02:45	3.1	52.8318	80.3399	17.5			2	James Bay
2016-07-24 09:31	3.1	48.2452	78.4460	2.5	2.87		2	Mining related event, Laronde Mine, QC
2016-12-30 09:31	3.1	46.6610	81.3688	2.5	2.80		2	Mining related event, Sudbury, ON
2016-10-14 18:23	3.0	46.1758	79.1887	5.5		✓	2	20 km NE from Powassan, ON
2016-01-31 19:54	2.9	46.3234	80.0569	2.0			1	12 km SW from Sturgeon Falls, ON
2016-06-09 10:19	2.8	53.5440	89.2597	10.5			2	52 km SE from Kitchenuhmaykoosib, ON
2016-08-15 08:16	2.8	52.0800	81.0233	13			2	James Bay
2016-05-13 02:21	2.6	49.0435	91.9662	3.5			2	42 km NW from Atikokan, ON
2016-07-23 08:43	2.6	48.7246	80.7295	11			2	6 km SW from Iroquois Falls, ON
2016-05-23 02:15	2.5	53.9014	79.6935	13			1	55 km W from Chisasibi, QC
2016-03-29 01:17	2.2	48.2807	91.0968	2				67 km SE from Atikokan, ON
2016-04-12 09:55	2.2	50.1208	92.5761	2				42 km W from Sioux Lookout, ON
2016-11-23 20:41	2.2	49.5377	93.0170	2				29 km SW from Dryden, ON
2016-05-05 21:43	2.1	52.3825	89.3111	2				91 km W from Lansdowne House, ON
2016-08-28 12:22	1.9	50.1083	92.2842	2				21 km W from Sioux Lookout, ON
2016-10-01 05:27	1.9	49.2482	92.0810	2				65 km NW from Atikokan, ON
2016-11-18 11:10	1.9	49.1267	92.1933	2				59 km NW from Atikokan, ON
2016-03-30 14:10	1.8	50.2114	92.1228	2				17 km NW from Sioux Lookout, ON
2016-10-30 11:22	1.7	50.4533	91.9078	2				44 km N from Sioux Lookout, ON
2016-01-09 18:36	1.6	49.5216	91.9198	2				61 km S from Sioux Lookout, ON
2016-01-09 18:36	1.6	49.5216	91.9198	2				61 km S from Sioux Lookout, ON
2016-03-24 16:02	1.5	49.4319	92.0933	2				65 km SE from Dryden, ON
2016-04-22 14:06	1.4	49.1597	90.8672	2				71 km NE from Atikokan, ON
2016-07-09 20:35	1.4	49.1386	91.5958	2				43 km N from Atikokan, ON
2016-11-19 18:36	1.1	49.0555	91.9186	2				40 km NW from Atikokan, ON
2016-11-19 19:35	1.1	49.0620	91.9071	2				41 km NW from Atikokan, ON

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

[a] Estimated depths are below sea level.

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

[c] The number of RDPM depth phases used ("**#**") is given when applicable.

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 (with respect to sea level).

Table 5 lists the events from 2016 in northern Ontario with depth estimates based on either RDPM or the observation of Rg. In all eight earthquakes and five mining-induced events had depths estimated using RDPM. Of the eight earthquakes, three were shallow (< 6 km depth) and five were closer to mid-crustal depths, between 10 and 20 km depth. Shallow depths were assigned for 16 earthquakes based on the observation of Rg.

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 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.

Table 6: Parameters of velocity model CN01

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

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 17 shows the magnitude-recurrence plot for 2016 and 1982–2016. Note that many of the 2016 data points are hidden beneath those for 1982–2016.

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).

As expected, the curve fit for a single year has much greater uncertainty than the long-term curve fit. For 2016, the best-fit slope was found to be 1.02 ± 0.2, versus 1.131 ± 0.04 for 1982–2016 (30 years). The difference in slope may seem small – it results in only 2-fold difference in the rate for M≥6.0 earthquakes (the ones important for seismic hazard) – but when uncertainties are taken into account this becomes a 16-fold difference. This example underlines the value of long-term seismic monitoring.

The earthquake occurrence rates estimated from the single year 2016 are quite similar (within 20%) those estimated over thirty years, over a broad range of magnitudes, from 2.1 to 3.0. This is better correspondence than seen in previous years, when random fluctuations resulted in greater discrepancies.

Below magnitude 1.8 and down to the minimum magnitude observed of 1.1, the occurrence rates deviate significantly from the long-term straight-line fit. This suggests that the northern Ontario catalogue for 2016 is complete down to approximately magnitude 1.8.

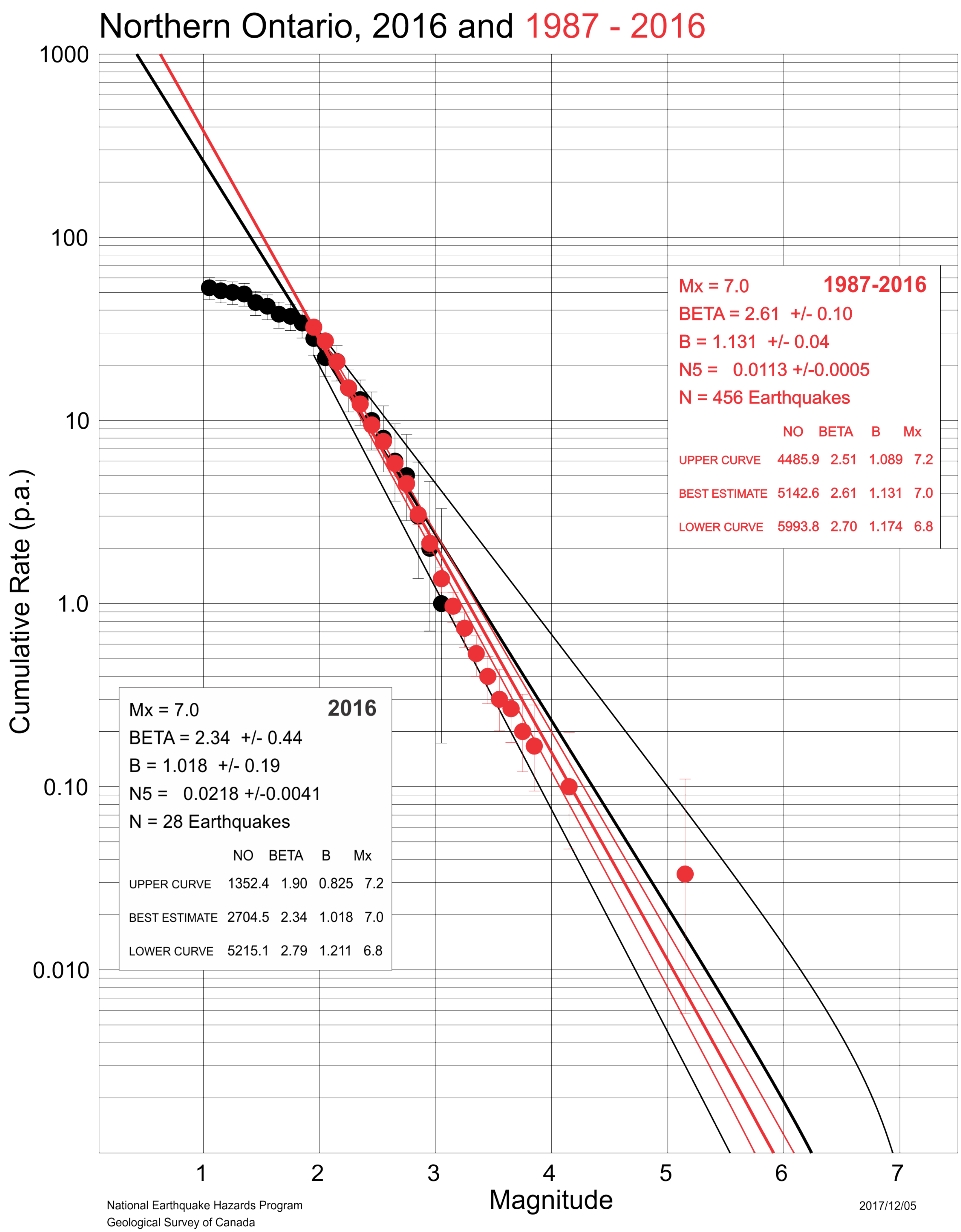


Figure 17: Recurrence curves for Northern Ontario, 2016 and 1987–2016. Yearly earthquake occurrence rates in 0.1 magnitude unit wide bins are shown as points, while fitted curves are shown as lines. Standard fit statistics are given in boxes, including the fitted slope b (or equivalently β) and the assumed maximum magnitude Mx. For each dataset, the middle line represents the best-fit curve, while the outer lines indicate the error bounds.

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 the top 12 events of all event types in 2016, ranging in magnitude between 3.0 and 3.3 m_N, 10 were mining-related events associated with Creighton and Morrison Mines near Sudbury and LaRonde Mine near Val d'Or.

In all, 123 known and 13 suspected mining induced events were located in the study area in 2016. These events ranged in magnitude from of magnitude 0.8 to 3.3 m_N. Thirty-eight of these mining-induced events recorded in the study area in 2016 were larger than 2.5 m_N: 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.

Two mining-induced events in 2016 had confirmed depths; to demonstrate the utility of this information, the depths were also estimated using RDPM. The RDPM waveforms for one event are shown in Figure 16. Although the actual observed arrivals are not nearly as clear as the synthetic ones, the identification of sPmP can be made with some degree of confidence, allowing an depth estimate of 2.5 km below sea level, close to the confirmed depth below surface of 2.8 km. For both events, the depth estimated via RDPM compares favourably to that reported by the mine operator. The error associated with a depth estimate from RDPM appears mainly to arise from the problem of picking and identifying the depth phases in the observed waveforms, rather than from modeling errors in the synthetic waveforms. It is hoped that by collecting more information about mining events from mine operators a "ground truth" dataset can be assembled. This data could prove instrumental in the assessment of existing methods and the development of new methods of estimation of depths of shallow earthquakes.

Table 7: Mining-induced events $m_N \geq 2.5$, 2016

time [UTC]	mag. [m_N]	lat. [°N]	lon. [°W]	dep.[a] [km]	felt	depth type	mine	notes
2016-01-02 22:16	3.1	48.2510	78.4420	1		F	LaRonde	
2016-01-07 22:22	2.8	46.6700	81.3350	1		F	Coleman	Triple event. SUNO & KLBO down.
2016-01-10 22:37	3.2	46.4570	81.1740	1	✓	F	Creighton	SUNO & KLBO down.
2016-01-10 22:49	3.3	46.4504	81.1636	2.0	✓	V	Creighton	SUNO & KLBO down.
2016-01-13 10:38	3.0	48.2510	78.4420	1		F	LaRonde	
2016-02-19 11:54	2.8	48.2505	78.4542	1		F	LaRonde	
2016-02-25 07:15	3.0	48.2510	78.4420	1		F	LaRonde	Confirmed by Westwood Mine operator
2016-02-29 08:09	2.5	46.4600	81.1730	1		F	Creighton	Event type not confirmed by mine operator.
2016-04-06 21:34	2.6	48.2510	78.4420	1		F	LaRonde	
2016-05-02 21:29	3.1	48.2510	78.4420	1		F	LaRonde	
2016-05-12 09:56	2.9	49.1670	89.6130	1		F	Lac-des-Iles	Double event (blast, rockburst). Part of the Ontario Mine Rescue Competition.
2016-05-13 10:01	2.6	48.2510	78.4420	1		F	LaRonde	
2016-05-16 22:51	2.6	49.1670	89.6130	1		F	Lac-des-Iles	
2016-05-22 05:30	2.8	49.1670	89.6130	1		F	Lac-des-Iles	
2016-05-22 06:25	2.6	46.4570	81.1740	1		F	Creighton	Triple event (blast, rockbursts).
2016-06-04 16:13	2.6	48.1236	80.0470	1		F	Kirkland Lake Gold	
2016-06-06 07:20	2.9	46.4570	81.1740	1		F	Creighton	
2016-06-06 08:38	2.5	46.4570	81.1740	1		F	Creighton	
2016-06-09 00:33	2.6	48.2510	78.4420	1		F	LaRonde	
2016-06-10 18:40	2.7	46.4570	81.1740	1		F	Creighton	
2016-06-14 00:47	3.3	46.4743	81.1809	1.5	✓	V	Creighton	
2016-06-14 07:31	2.5	46.4570	81.1740	1		F	Creighton	
2016-06-20 18:14	2.7	46.6587	81.3427	1		F	Morrison	
2016-06-24 10:07	2.6	46.5842	80.8349	1		F	Nickel Rim South	Double event (blast, rockburst).
2016-06-28 08:39	2.7	46.6487	81.3313	1		F		Probable mining related event
2016-07-24 09:31	3.1	48.2452	78.4460	2.5		V	LaRonde	
2016-09-15 21:30	3.2	48.2608	78.4470	2.5		V	LaRonde	
2016-09-24 12:11	2.9	49.1854	89.6288	1		F	Lac-des-Iles	
2016-09-24 15:14	2.7	49.1894	89.6234	1		F	Lac-des-Iles	
2016-10-19 15:06	2.7	48.2510	78.4420	2.84		F	LaRonde	
2016-11-01 21:32	2.5	48.2510	78.4420	2.90		F	LaRonde	
2016-11-18 22:16	2.5	46.6730	81.3350	1		F	Coleman	
2016-11-20 23:06	2.6	48.2510	78.4420	2.84		F	LaRonde	VLDQ down.
2016-11-25 23:10	2.9	46.6400	80.7800	1		F	Nickel Rim South	
2016-12-09 09:58	2.6	46.6380	80.7750	1		F	Nickel Rim South	Triple event (blast, rockbursts). SUNO, BUKO KLBO down.
2016-12-14 10:31	2.6	48.2471	78.4500	2.75		F	LaRonde	
2016-12-30 09:31	3.1	46.6610	81.3688	2.80		F	Morrison	SUNO KLBO BUKO down.

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

[a] A fixed "F" depth type of 1 is the default value used for mining events when no other depth estimate is available.

8. SUMMARY

Data availability was in excess of 95% from five of the seven core seismograph stations, but just three of the eight temporary stations. Solar powered sites struggle in the winter months, particularly December and January. The station SILO has stopped operating and there is no plan to fix it; VIMO and MALO are similarly vulnerable. Refurbishment efforts in 2017 and 2018 are expected to bring data availability at all other stations in northern Ontario back to close to 100%.

During this twelve-month period, 54 earthquakes were located, close to the average of 49.8/year over the previous 5 years. The magnitudes of the earthquakes located in 2016 ranged from 1.1 to 3.1 m_N. The largest earthquake, with a magnitude of 3.1 m_N, occurred under James Bay; the second largest, with a magnitude of 3.0 m_N was felt widely in North Bay. There were 10 other events between magnitude 3.0 and 3.3 m_N, but they were all confirmed to be mining-related events at Creighton and Morrison Mines near Sudbury and LaRonde Mine near Val d'Or.

Based on the logarithmic frequency-magnitude relationship discussed in Section 6, the distribution of magnitudes indicates the catalogue for 2016 is complete down to approximately magnitude 1.8 m_N.

The distribution of the majority of the detected earthquakes in this region for 2016 conformed to the pattern of previous seismicity.

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