Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01 – December 31, 2015

NWMO-TR-2016-18 December 2016

J. Adams[1]

V. Peci[2]

S. Halchuk[1]

P. Street[1]

[1] Canadian Hazards Information Service, Geological Survey of Canada
Natural Resources Canada, Government of Canada

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

NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Seismic Activity in the Northern Ontario Portion of the Canadian Shield
Annual Progress Report for the Period January 01 – December 31, 2015

NWMO TR-2016-18

December 2016

J. Adams[1]
V. Peci[2]
S. Halchuk[1]
P. Street[1]
[1] Canadian Hazards Information Service,
Natural Resources of Canada, Government of Canada

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

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

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

Document History

Title:	Seismic Activity in the Northern Ontario Portion of the Canadian Shield Annual Progress Report for the Period January 01 – December 31, 2015		
Report Number:	NWMO-TR-2016-18		
Revision:	R001	Date:	December 2016
Author Company(s)			
Authored by:	J. Adams, V. Peci, S Halchuck & P. Street		
Verified by:	N. Ackerley		
Approved by:	J. Adams		
Nuclear Waste Management Organization			
Reviewed by:	Richard Crowe		
Accepted by:	Mark Jensen		

Revision Summary		
Revision Number	**Date**	**Description of Changes/Improvements**
R00(1+)	2017-01	Minor edits for typo’s and figure numbering

ABSTRACT

Title: **Seismic Activity in the Northern Ontario Portion of the Canadian Shield Annual Progress Report for the Period January 01 – December 31, 2015**

Report No.: **NWMO-TR-2016-18**

Author(s): J. Adams[1], V. Peci[2], S. Halchuk[1] and P. Street[1]

Company: [1]Canadian Hazards Information Service
[2]V. Peci under contract to the Canadian Hazards Information Service

Date: December 2016

Abstract

The Canadian Hazards Information Service (CHIS), a part of the Geological Survey of Canada (GSC), 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. A key objective of the monitoring program is to observe and document earthquake activity in the Ontario portion of the Canadian Shield. This report summarizes earthquake activity for the year 2015.

CHIS maintains a network of sixteen seismograph stations to monitor low levels of background seismicity in the northern Ontario and eastern Manitoba portions of the Canadian Shield. Core stations are located at: Sioux Lookout (SOLO), Thunder Bay (TBO), Geraldton (GTO), Kapuskasing (KAPO), Eldee (EEO), and Chalk River (CRLO). These are augmented by the CHIS network of temporary stations at: Sutton Inlier (SILO), McAlpine Lake (MALO), Kirkland Lake (KILO), Sudbury (SUNO), Atikokan (ATKO), Experimental Lake (EPLO), Pickle Lake (PKLO), and Pukaskwa National Park (PNPO). The digital data from a temporary station at Victor Mine (VIMO), supported by the diamond mine industry, and a station at Pinawa (ULM), which has funding from the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO), are also used in this study.

All the stations are operated by CHIS and transmit digital data in real-time via satellite to a central acquisition hub in Ottawa. CHIS-staff in Ottawa integrate the data from these stations with those of the Canadian National Seismograph Network and provide monthly reports of the seismic activity in northern Ontario.

During 2015, 51 earthquakes were located. Their magnitude ranged from 1.2 m_N to 3.3 m_N. The largest event, with a magnitude of 3.3 m_N, occurred in the Temiscaming area, while the second largest event 3.1 m_N, occurred in Sudbury. The 51 events located in 2015 compares with the average of 60 per year from the prior 4 years.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

1. INTRODUCTION

The Canadian Hazards Information Service (CHIS), a part of the Geological Survey of Canada (GSC) 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. A key objective of the monitoring program is to observe and document earthquake activity in the Ontario portion of the Canadian Shield. This report summarizes earthquake activity for the year 2015.

To record the seismic activity, CHIS operates sixteen seismic monitoring stations in the Ontario and southeast Manitoba portions of the Canadian Shield (Figure 1). The activity in southeast Manitoba is of interest because the crust is geologically similar to the Ontario part of the Canadian Shield. The core stations supported by the NWMO are located at: Sioux Lookout (SOLO), Thunder Bay (TBO), Geraldton (GTO), Kapuskasing (KAPO), Eldee (EEO), and Chalk River (CRLO). In addition, there is data from the station at Pinawa (ULM), operated by CHIS with funding by the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) (http://www.ctbto.org).

These data are supplemented by a temporary network of CHIS stations at Sutton Inlier (SILO), McAlpine Lake (MALO), Kirkland Lake (KILO), Sudbury (SUNO), Atikokan (ATKO), Experimental Lake (EPLO), Pickle Lake (PKLO), Pukaskwa National Park (PNPO), and Victor Mine (VIMO). The temporary network started as a joint venture established between 2003 and 2005 using equipment partly funded by Industry Canada's FedNor program and partly contributed from the Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS) Consortium, but has been incorporated into CHIS.

All stations record real-time, continuous, digital data, which are transmitted by satellite to the data laboratory in Ottawa and are available for the monitoring of this region, as are all the data from the entire Canadian National Seismograph Network (CNSN) and data from other former POLARIS stations.

Relevant data were requested and read from some US stations, including EYMN, a station near the Canada/US border in Ely, Minnesota, USA. The data is received through CHIS's Antelope data exchange system. Although data from this station is routinely requested for events that have already been identified on a CNSN station, it is not scanned by CHIS for new events. The addition of the U.S. data has mainly helped locate events in the sparsely-seismic Atikokan region.

Beginning around 2009/2010, USArray installed temporary stations in the U.S. just south of the area of interest for this study. The array was rolled eastward, year by year, and was extended into Ontario south of about 47N. During 2014 stations in the array, ceased operating in Michigan but continued to operate into early 2015 in southern Ontario. Instead of removal, in 2013 it was decided to transfer a large subset of the U.S. stations to become a new network, CEUSN (for "Central and Eastern US Network", see http://ceusn.ucsd.edu/). In addition, some previously closed stations were re-installed. Data from the CEUSN stations are often read to improve the locations of the events identified in this report (particularly, the events near the border).

Earthquake size is expressed by magnitude, almost all earthquakes in this series of annual reports will have magnitudes calculated on the Nuttli scale (see section 5), which is used by CHIS for moderate-sized earthquakes in eastern Canada[1]. Magnitudes calculated on the Nuttli scale are formally written m_N or m_{bLg}. The former notation will be used in this report.

The frequency of earthquakes of a given magnitude, is a logarithmic function of magnitude: for example, 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. Thus there is a great benefit to being able to detect the many smaller earthquakes happening in northern Ontario to learn something about the distribution and rate of the less-common higher magnitude earthquakes that could happen in the future and are of interest.

During this twelve-month period 51 earthquakes were located. Their magnitude ranged from 1.2 m_N to 3.3 m_N. The largest event, with a magnitude of 3.3 m_N, occurred in the Temiscaming area, while the second largest event 3.1 m_N, occurred in Sudbury (see Figure 1). The 51 events located in 2015 compares with an average of 60 per year from the prior 4 years.

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 in 1982. Since then, the smaller earthquakes in the study area were located largely as a result of the additional data provided by the dedicated network added after 2003, resulting in a slightly reduced location threshold for the northeastern portion of the region. Earthquakes located in the study area during 2015 and the cumulative seismic activity in eastern Canada since the inception of the program in 1982 are illustrated by a series of maps in Figures 1-8, and the 2015 events are tabulated in Table 1. The year-end station operation statistics are given in Table 2, earthquakes with determined depths are listed in Table 3 and mining-induced seismic events of magnitude 2.5 and greater are tabulated in Table 4.

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 Canadian National Seismograph Network. Each network site, or "station", consists of a small computer and a very sensitive seismograph that can record ground movement of less than 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 the 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.

[1] 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.

CHIS also receives and archives the data from many of the former POLARIS stations. Together, approximately three and a half 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, 5340 earthquakes had been located in Canada during the year 2015. Only 22 of these were over magnitude 2.0 and occurred in the study region.

2.2 OPERATION STATISTICS

Station operation statistics for ULM, SOLO, TBO, GTO, KAPO, EEO, CRLO, SILO, VIMO, MALO, KILO, SUNO, EPLO, ATKO, PKLO, and PNPO are shown in Table 2. Data capture was in excess of 95% for five of the seven core seismograph station, and above 95% for six of the nine temporary stations.

Many of the solar powered sites, including VIMO, MALO, KILO, and SUNO experienced power failure and had poor telecommunications during the winter months, particularly January, February, November and December. SILO was repaired in July after being down since 2010, but dropped out again in September likely due to wildlife attacks at the site. As this site is very remote, no further maintenance trip was made in 2015, and due to the cost of servicing SILO the equipment will probably be removed in the future.

Details of the outages at each station are provided in the Notes section of Table 2.

3. EARTHQUAKES

A total of 51 earthquakes were located in the study area during 2015. The events from the year are listed in Table 1 and plotted in Figure 1. The largest event, with a magnitude of 3.3 m_N, occurred on May 2nd in the active Temiscaming area of Quebec, close to the location of the magnitude 6.2 Timiskaming earthquake of 1935.

Due to increased station density in the northern part of the province beginning in 2003, the magnitude location threshold has decreased in this region of the country from about m_N 3.0, down to approximately m_N 2.0. Although smaller earthquakes (less than magnitude 2.0) can be located with the current network, the accuracy of the event locations decreases with decreasing event magnitude and with increasing distance from the nearby stations of the network. Also, the catalogue of events less than m_N 2.0 is not complete; that is to say, particularly in regions of poorer coverage, it is assumed that events smaller than m_N 2.0 have been missed.

The effects of a lowered threshold can be seen particularly in the James Bay region where 246 events have been located since 2004, which works out to approximately 16 events per year. This compares to the 42 events located in the same region since the beginning of this study in 1982 until the end of 2003, making an average of two events per year. Note that at the greatest deployment of the network (from 2004 to 2009 when the most stations were operational in the region), the number of events recorded in this region peaked at 32 events per year on average. In 2015, nine earthquakes were located in this region, including the third-largest event recorded in the study area this year.

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 came to an end, and stations had to be closed. Eight stations were chosen to be closed initially, with the poorest stations (based on poor uptime statistics, or the high noise levels at the site) chosen, so as to have the smallest effect on the location threshold. Two additional sites were closed in 2010.

The 51 earthquakes from 2015 compares to previous years as follows:

Year	No. of events	No. of stations
2015	51	16
2014	36	16
2013	70	16
2012	57	16
2011	79	16
2010	118	16
2009	82	18
2008	114	26
2007	68	26
2006	83	26
2005	103	26
2004	79	20
2003	45	14
2002	45	7

Although the number of events fluctuates from year to year, it can be seen that the number of located events increased between 2003 and 2005, due to the increase in coverage provided by the FedNor stations, which in turn has lowered the location threshold in the area. In 2012, the rate of seismicity was lower than the average since 2005 (approximately 90 events per year) and lower than in 2011 and 2013. This low rate of seismicity was noticed in other parts of eastern Canada. As neither the network of stations in northern Ontario, nor the method of analysis changed, it suggests that the low 2012 rate was simply part of the natural yearly fluctuation. As noted (Adams et al 2015), the small number of events in 2014 arose from a higher detection threshold, resulting in fewer earthquakes of magnitude 2.0-2.5.

In general, the pattern of activity for 2015 followed that of the previous years, with earthquakes chiefly being reported from James Bay, the Sudbury-Timiskaming area, and from the Severn Highlands.

The second-largest event, with a magnitude of 3.1 m_N, occurred in Sudbury on September 30th (local time = 21:06 on the 29th) and 103 people in Sudbury reported feeling it to CHIS[2]. It was also felt in Sturgeon Falls. The mainshock was followed by three aftershocks that were also felt in Sudbury. It was initially thought to be a mining blast or rockburst, but Professor Marty Hudyma at Laurentian University (pers. comm, 2015) collected data from 17 mine sensors (all less than 15 km distant) to locate it near the Sudbury landfill site, in greenstone metasediments and away from the nickel-bearing rocks and any mining activity. His location is about 1 km southeast of CHIS's revised location, which used only regional seismograph data. CHIS used the RDPM (Regional Depth Phase Modelling; see section 4.2.1) method to estimate the depth of the mainshock. The depth estimates were: SADO 3 km (Figure 10A), BUKO 4 km, and BMRO 4 km from which we chose 3.5 km. The match is precise to about ±1 km, but variations in crustal velocity model may introduce additional errors. Prof Hudyma computed a depth of 1.3

[2] http://www.earthquakescanada.nrcan.gc.ca/recent/2015/20150930.0106/index-en.php

km from his arrival times (significantly more shallow than the calculated RDPM depth), however his stations all lie in the NW hemicircle from the epicentre, and no uncertainty in his depth was available. We conclude that this was a shallow natural earthquake, though it is possible that it was triggered by unloading due to regional mining activity.

Five earthquakes occurred in the Timiskaming region, including the largest 2015 event (3.3 m_N) in the study area on May 2nd. That earthquake plus three others occurred very near to the epicentre of the 1935 magnitude 6.2 Timiskaming earthquake. The May 2nd earthquake gave a RDPM depth of 15 km (Figure 10B), which is a little deeper than the depth for the Timiskaming earthquake (~10 ± 2 km; Bent, 1996). The fifth earthquake occurred on the Ontario side of Ottawa River, which has much less activity than the Quebec side.

No earthquakes occurred in the Cochrane band of seismicity. To the west, the magnitude 2.9 earthquake on August 9th occurred away from the mining areas of Timmins, and gave a RDPM depth of 14.5 km (Figure 10C). This is of similar depth to the earthquakes in the Cochrane band, but is rather deeper than most earthquakes that lie to the west of that band.

One earthquake occurred in the region north of Chapleau, ON, which had been active from September 2012 to March 2013. The 2.5 m_N earthquake on February 12th, 74 km NW of Chapleau, had a RDPM depth of 3.5 km (Figure 10D). It occurred close to a pair of magnitude 3 earthquakes that were given RDPM depths of 8 km in previous reports, but these depths are now under revision. This cluster appears to lie on a linear trend newly-outlined by earthquakes north and east of Chapleau, (Figure 2A)[3].

The 2.4 m_N earthquake on October 10th, 183 km SW from Attawapiskat is in a place with a few prior earthquakes. It is mentioned here only because it appears to be on-strike with the linear band outlined by the earthquakes near Cochrane, which are about 200 km to the SSE.

Eight small earthquakes were located south of Lac Seul, 15 to 100 km NW of Sioux Lookout and station SOLO (Figure 2B). Two of these occurred in a north-south linear band of prior activity, whereas the others were scatted.

One earthquake was located in Minnesota, just south of the Canadian border. It joins a handful the project has located in the U.S. However, as there is no attempt to systematically locate earthquakes south of the border, the actual level of activity in Minnesota is likely similar to that in adjacent Ontario, rather than as shown on the maps.

Figure 3 shows all the earthquakes that have been located in northern Ontario and surrounding areas, since the inception of the northern Ontario seismic program in 1982. A total of 1363 earthquakes are documented during this period.

Figure 4 shows only those events that are magnitude 3 or greater recorded in the study area during the same time period of 34 years (73 events). The pattern of all seismicity echoes the pattern of the larger events, though the Thunder Bay – Atikokan area, which is active with many small earthquakes has not yet experienced an event above magnitude 3.

Figure 5 illustrates the seismic activity in eastern Canada in year 2015. As can be clearly observed, the number of earthquakes documented in northern Ontario represents one of the

[3] Extra figures are inserted as 2A and 2B to keep the numbering of the figures consistent with past reports.

lower densities 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 m_N 2.5 or even lower in some areas and less populated areas like northern Quebec being complete to only about m_N 3.0.

Figure 6 shows all the activity in eastern Canada for the entire monitoring period of 1982 - 2015. 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.

Figure 7 shows the earthquakes located in the study area in 2015 together with some mine blasts for the same year. Many mine blasts are repetitive (same location at similar times each day) and perhaps ten thousand each year are dismissed without being located by the analyst, based on their experience. Events that occur at unusual times or in unusual places are investigated as mining-induced events or as potential earthquakes. It can be difficult or even impossible to distinguish between blasts, earthquakes and mining-induced events solely on the basis of the recorded waveforms. Hence confirmation is sought for unusual events from any nearby mine or quarry, a time-consuming process that is further complicated by possible non-repetitive construction blasts, such as due to road construction. On plots like Figure 7, any proximity of blast and earthquake symbols leads to checking as to whether a blast might have been misidentified as an earthquake.

Three 2015 anecdotes illustrate the effort that blast discrimination takes in the low-seismicity region of Northern Ontario.

A m_N 1.5 event on March 28 was felt or heard by many in Fort Frances, ON. It was initially considered an earthquake because it was located away from most human activities. With the help of Duane Hicks, at the Fort Frances Times newspaper, it was finally attributed to a contractor blasting to create an access road, though the contractor never officially confirmed the blast. The 6:37 p.m. local time does fit with setting up an explosion and firing it before dark, as surface blasting is required to take place in daylight hours.

An event, now classified as “probable blast” on February 15th triggered a quick examination of past catalogued events near Longlac. The events are north of the highway and railway, but close to a pipeline route. Google Earth imagery suggests activity, such as the possible widening of a highway, over a significant fraction of the distance between Geraldton and Longlac in 2012. However, at least one event happened at night-time and has a clean, earthquake-like trace. Like the Lac-des-Iles example below, a systematic evaluation is needed.

Considerable effort was made for 2015 events near the Lac-des-Iles mine run by North American Palladium, 70 km north of TBO. Fortunately, a contact at the mine was able to confirm some events as blasts, including a m_N 3.0 event on July 31st. Ten mining-related events (possible rockbursts) with magnitudes up to mN 2.4 were cataloged in 2015, though it is possible some of those were undocumented blasts. An examination of the catalog for previous years suggests that five events near the mine are flagged as earthquakes, likely in error. Blasts flagged as earthquakes may occur because events are located one by one. Mis-identification issues should be caught during the annual review, but some patterns may only be apparent over multiple years. This example suggests that a clean-up of the earthquake database for Northern Ontario is warranted. As it is unlikely that mines would confirm old blasts or rockbursts, the re-evaluation should involve identifying proximity for mining or other construction activity, reviewing comments made at the time the event was located, and comparing event waveforms to known blast waveforms. It is suggested that this should be done systematically for the entire region, as time permits. The benefit would be a more reliable catalog with a reduced rate of earthquakes.

The Sudbury earthquake of September 30th and its aftershocks occurred quite close to a mining area, but as discussed in above, blasting and mine rockbursts were ruled out. It is possible, however, that the earthquakes were triggered by unloading due to regional mining activity.

Figure 8 shows the earthquakes located in the study area in 2015 together with all known earthquakes. The representation, using red-filled circles for the 2015 earthquakes and open grey 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 2015. For 2015, only one of these "quiet" areas is evident: the Cochrane band. The Chapleau region was also much less active than in 2012-2013.

Depths of moderate-sized events in eastern Canada cannot be directly calculated unless there are at least three stations within 50 km of the epicentre. Station spacing in northern Ontario tends to average from 200 km to 300 km. However, using the Regional Depth Phase Modelling (RDPM) method and the presence of Rg phases, depths of some events have been determined and are discussed below.

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).

As an example, Figure 9 shows the earthquake that occurred 66 km north of Chapleau, ON, on February 12th and which exhibited strong Rg-phases. The presence of this phase for this and many other earthquakes indicates that the depth of the event must have been shallow: less than 5 km (See Section 4.2.1 for further discussion on depth). The RDPM depth for this event is given as 3.5 km (Figure 10D).

Recurrence curves for the study area for the year 2015 and for the period of 1987 to the end of 2015 (29 years of data) are shown in Figure 11 and discussed in more detail in Section 6.

3.1 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.nrcan.gc.ca/stndon/AutoDRM/index-eng.php

Waveform data for individual event files can be accessed at:
http://www.earthquakescanada.nrcan.gc.ca/stndon/NWFA-ANFO/eve/index-en.php

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.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php\

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.

4. LOCATION ACCURACY IN NORTHERN ONTARIO

4.1 PARAMETERS

The minimum requirements to locate an earthquake are 3 stations and 5 phases (P-wave, S-wave). The four basic (independent) parameters calculated for any earthquake location are latitude, longitude, depth and origin time. Additional phases are required in order to estimate the uncertainty of the location. Some events may have aftershocks that are visible on less than 3 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 1 were determined from 3 or more stations.

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 number of stations and phases used in determining the location of each earthquake is included in Table 1.

4.2 LIMITATIONS

Location accuracy in northern Ontario is to a degree hampered by the fact that:

i. Because of socio-geographical constraints several of the original stations were more or less in a straight line, so azimuthal coverage was not ideal; this has been improved by the addition of the newer, temporary stations;
ii. Stations are widely spaced so that phase arrivals may be ambiguous (as a rule the closer the station the sharper the arrival);
iii. Distances larger than 100 km between stations contributes to a lack of phase data for small events ($m_N < 2$);
iv. Some places have more background noise, which can also mask the phase arrivals on nearby stations; and
v. Depths are approximated, as discussed in Section 4.2.1.

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. As a result, caution must be exercised when assessing other derived values, including epicentre and origin time. 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 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. 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. 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 (the Charlevoix, Quebec network being one example), station spacing is seldom less than 50 km. Thus few earthquakes will be recorded within 50 km of more than one station, and depth cannot be directly calculated, but is instead assumed, as is the case in the study area. Where depth of earthquake activity in continental terranes is well known (Charlevoix area for example) earthquake depths seldom exceed 30 km and mostly fall between 10 and 20 km. For eastern Canada, the default depth is generally assumed to be mid-crust (i.e. 18 km) and this is used as the default depth for northern Ontario earthquakes when no other data is available.

There are ways of determining earthquake depth other than direct calculation. The key method has relied 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 thus establishes the earthquake’s depth. However, none of the earthquakes in northern Ontario, in 2015 or in any previous year since the study began in 1982, have been large enough to be recorded clearly at such great distances. A modification of this method, the Regional Depth Phase Modelling (RDPM) method, that uses regional depth phases and does not require close station spacing has been developed by Ma (2004) in conjunction with CHIS seismologists and is now being applied to the larger eastern Canadian earthquakes (generally $m_N > 3$, although depending on the stations and their distribution around the epicentre, the magnitude can be lower). Ma (2004) states, “The regional depth phase sPg and sPmP are very sensitive to focal depth. sPg depth phase develops well generally at distances between about 60 to 120 km for earthquakes, some as small as m_N 1.5. The sPmP depth phase develops well at distances of about 130 to 300 km (actually existing as far as about 600 km). Beyond 300 km, the identification of the phase becomes a problem. With regional depth phase sPmP, we can reliably estimate focal depth by modelling waveforms recorded at stations more than 200 km away for an earthquake with m_N about 2.5. With regional depth phase sPg, we can reliably estimate focal depth by modelling waveforms recorded at stations about 60 km away for an earthquake with a m_N of about 2.0. In short, we can reliably estimate focal depth with the regional depth phase modelling method for moderate and small earthquakes without records from nearby stations in northern Ontario.” (Ma, 2004, p.3).

Further work using RDPM modelling was done by Ma and Atkinson (2006) for earthquakes from the neighbouring regions of the West Quebec seismic zone, and in southern Ontario for 1980 – 2004. It was noted that events deeper than 15 km were limited to specific regions, while the shallower events were found over the entire region. A paper based on the Ma (2004) contract report for CHIS and extended with subsequent work appeared as Ma et al. (2008). Figures 10A through 9D show four applications of RDPM to 2015 events, and each shows the match of the observed to the synthetic waveforms generated for shallower and deeper depths.

A second method of depth determination involves the modelling of the relatively long-period phase Rg. Rg waves are strongly excited by shallow (<5 km depth) events (e.g. Figure 9) and are nearly always present in surface explosions. The presence of a strong Rg-phase for some of the earthquakes indicated that the depths of these events were likely 5 km or shallower, and generally a 5 km depth has been assigned for these events. 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 (2011) suggests that resolution better than 0.5 km can be achieved.

Table 3 lists all the events from 2015 in northern Ontario that had an Rg phase present, and are therefore known to be shallow (most are fixed at 5 km depth, but some with unusually strong Rg are fixed at 1 km depth), as well as four events that were well enough recorded at suitable distance for reliable depths to be determined using the RDPM method. Of the four, two are shallow (3.5 km) and the other two deep, as discussed in Section 3.

4.2.2 Velocity Models

The present velocity model for determining earthquake epicentres in northern Ontario is the standard model of 36 km thick crust for the Canadian Shield. This model uses the following seismic velocities:

Pg 6.2 km/s	(crustal)
Pn 8.2 km/s	(direct longitudinal wave that has passed below the continental layers)
Sn 4.7 km/s	(direct transverse wave that has passed below the continental layers)
Sg 3.57 km/s	(crustal)
Crustal thickness	36 km

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, G. 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 (2006) 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 distribution is poor, and at the current time the excellent station distribution reduces the effects significantly. 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 CALCULATION

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 1. 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 seismographs. 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 ~3 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 log of cumulative frequency versus magnitude plot. To establish the most reliable recurrence curve it is necessary to include earthquakes for the longest period of time possible. The dataset for $m_N > 2.0$ is considered complete since 1987, providing 28 years of data for the less-common larger earthquakes.

Figure 11 shows the magnitude-recurrence plot for the year 2015 earthquakes in black and the plot for the 29-year period of 1987 to 2015 inclusive in red. The standard statistics for the curve fits are given in the boxes. For each dataset the middle line represents the best fit curve, while the outer lines indicate the error bounds.

As can be seen in the combined curve (adapted from Hayek et al., 2007), the data points for all years, including the combined curve, fit the average line reasonably well around magnitude 2 to 3. For larger earthquakes the scatter of the data about the line is larger, because the events are fairly rare and statistical fluctuations give large deviations (note the size of the error bounds on each data point). That is to say, if one m_N 4 event is expected only every 5 years, but only one year of data is considered, then the plot for the year which has that m_N 4 will have a point well above the average line. As the magnitude of the event increases, the rarity of the event increases, and the longer time would need to be considered in order to put the data into proper context. For smaller earthquakes, the data points trend to the left of the line and reach a maximum rate. The point at which the data deviates from the average line represents the magnitude at which the data set is incomplete - earthquakes with magnitudes below this point might be missed because they are below the network detection threshold.

As is found each year, the 2015 curve fit has a much greater uncertainty than the 29-year curve fit. For 2015 a best fit slope of $b = 0.896 \pm 0.19$ was found, versus 1.138 ± 0.04 for the 29-year period curve (compare the black and red uncertainty curves on Figure 11). This small difference in slope gives rise to a 6-fold difference in the rate for $M \geq 6.0$ earthquakes (the ones important for seismic hazard), showing the importance of multi-year monitoring. The data points of the one-year curve (black) are quite similar to the ones of the 29-year curve (red) at magnitudes above 2.1, with the rate for magnitude ≥2.2 events not more than 20% lower than the long-term average. Fluctuations like these are expected, as a single year's worth of data is not considered enough time to generate a statistically-significant rate for this region of relatively low seismicity. Below magnitude 2.1 the 2015 rate is much lower than the 29-year prediction curve, indicating the expected lack of completeness. For magnitude ≥1.2 (the smallest event located in 2015) the 29-year prediction is four times higher than the reported rate, meaning that three-quarters of the earthquakes of M≥1.2 were unreported. Almost all of these would have been of magnitude ≤2.0.

7. MINING-INDUCED ACTIVITY

CHIS does not document mining-induced events or mining activity in a comprehensive manner, as this does not fall within our mandate. The only routinely located mining events are blasts and suspicious events larger than m_N 2.5, or events where there is a request from the mine for information. Literally thousands of blasts are recorded and identified by the project on a yearly basis. Locations were determined for 85 mining-induced seismic events of magnitude 1.1 or greater in the study area in 2015. Sixteen of these mining-induced events recorded in the study area in 2015 were larger than m_N 2.5 and are listed in Table 4.

8. SUMMARY

Data capture was in excess of 95% from five of the seven core seismograph stations, and from six of the nine former POLARIS-FedNor stations. Many of the solar powered sites, experienced power failure and had poor telecommunications during the winter months, especially January, February, November and December. Although SILO operated for nearly two months after being fixed, it has failed again and the equipment will likely be removed during 2017.

The seismic activity in the study area during the calendar year 2015 consisted of 51 earthquakes ranging in magnitude from 1.2 m_N to 3.3 m_N. Twenty-two earthquakes were larger than m_N 2.0, and three were m_N 3.0 or larger. The largest event, 3.3 m_N, occurred in the active Temiscaming area of Quebec on May 2nd.

Based on the logarithmic frequency-magnitude relationship, discussed in Section 6, the distribution of magnitudes indicates that a few earthquakes near m_N 2.1 and many smaller ones remain undetected. The distribution of the majority of the detected earthquakes in this region for 2015 conformed to the pattern of previously observed seismicity.

ACKNOWLEDGEMENTS

The authors would like to thank CHIS staff for helping to develop and maintain the programs used to gather data for this report and POLARIS and UWO for all the additional data from their network. A special thanks to Sylvia Hayek who set up the format of the report and was its lead author until 2012. Also thanks to Richard Crowe and other staff from NWMO for reviewing this report.

REFERENCES

Adams, J., V. Peci, .S. Halchuk and P. Street. 2015. Seismic Activity in the Northern Ontario Portion of the Canadian Shield. Annual Progress Report for the Period January 01 – December 31, 2015. NWMO-TR-2015-21. Toronto, Canada.

Bent, A. L., 1996. An improved source mechanism for the 1935 Timiskaming, Quebec earthquake from regional waveforms, *Pure Appl. Geophys.*, 146, 5-20.

Bent, A. L. 2011. Moment magnitude (Mw) conversion relations for use in hazard assessments in eastern Canada, Seismological Research Letters, v. 82, p. 984-990. doi:10.1785/gssrl.82.6.984.

Bent, A.; and H. Kao. 2006. Crustal structure for eastern and central Canada from an improved neighbourhood algorithm inversion. Seismological Research Letters, v.77, p 297.

Darbyshire, F.A.; and S. Lebedev. 2006. Variations in lithospheric structure and anisotropy beneath the Superior and Grenville Provinces, Ontario. POLARIS Ontario Research Workshop, pp. 19-22.

Hayek, S.J.; J.A. Drysdale, V. Peci, S. Halchuk, J. Adams, and P. Street. 2007. Seismic Activity in Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01 – December 31, 2006. NWMO TR-2007-02. Toronto, Canada.

Ma, S. 2004. Focal depth investigation for earthquakes from 1980 to 2003 in northern Ontario using Regional Depth Phase (sPg, SPmP) Modelling (RDPM) Method and surface waves. Research Contract Report to CHIS, Contract NRCan-04-0601, pp. 1-111.

Ma, S.; and G.M. Atkinson. 2006. Focal Depths for Small to Moderate Earthquakes (mN ≥ 2.8) in Western Quebec, Southern Ontario, and Northern New York. Bulletin of the Seismological Society of America, Vol. 9, No. 2, pp. 609-623

Ma, S; D.W. Eaton and J. Adams. 2008. Intraplate Seismicity of a Recently Deglaciated Shield Terrane: A Case Study from Northern Ontario, Canada. Bulletin of the Seismological Society of America, Dec. 2008; 98: 2828 – 2848.

Ma, S; and D. Motazedian. 2011. Depth Determination of Small Shallow Earthquakes in Eastern Canada from Maximum Power Rg/Sg Spectral Ratio, Journal of Seismology, Vol. 16, No. 2, pp. 107-129.

Motazedian, D., Ma, S. and Crane, S. 2013. Crustal shear-wave velocity models retrieved from Rayleigh wave dispersion data in northeastern North America, Bulletin of the Seismological Society of America, in press., Vol. 103, No. 4, in press.

Musacchio, G.; D.J. White, I. Asudeh, and C.J. Thomson. 2004. Lithospheric structure and composition of the Archean western Superior Province from seismic refraction/wide-angle reflection and gravity modeling. Journal of Geophysical Research 109: No. B3. B03304 10.1029/2003JB002427.

Stevens, A. E. 1994. Earthquakes in the Lake Ontario region: Intermittent scattered activity, not persistent trends. Geoscience Canada, Vol. 21, 105-111.

US Array, Incorporated Research Institutions for Seismology. 2013. http://www.usarray.org/ (accessed May 2013).

Table 1: Located Local Earthquakes, January - December 2015

Date	Time (UT)	Latitude N	Longitude W	#stns/ phases	mN	Region and Comment
2015/01/04	10:30:38	52.41	89.44	6/8	2.2	108 km W from Lansdowne House, ON
2015/01/08	02:14:32	47.82	90.66	3/6	1.5	Minnesota, U.S.
2015/02/03	07:45:09	50.20	92.09	4/7	1.4	17 km NW from Sioux Lookout, ON
2015/02/05	01:12:38	50.67	90.81	6/9	1.6	66 km NW from Allanwater Bridge, ON
2015/02/05	13:30:20	50.08	92.30	4/8	1.3	23 km W from Sioux Lookout, ON
2015/02/12	12:04:28	48.42	83.29	7/13	2.5	65 km N from Chapleau, ON
2015/02/12	23:48:46	53.83	79.65	7/12	3.0	Eastern James Bay
2015/03/02	15:25:09	55.68	84.28	4/6	2.1	75 km NE from Winisk, ON
2015/03/03	05:28:05	46.86	79.45	11/20	2.2	31 km NW from Temiscaming, QC
2015/03/10	18:41:16	49.20	91.52	5/10	1.9	51 km N from Atikokan, ON
2015/04/12	08:48:32	52.37	80.66	4/7	2.2	James Bay
2015/04/30	16:04:50	54.00	82.28	6/10	2.8	James Bay.
2015/05/01	03:29:33	50.01	94.04	3/ 6	1.3	36 km NE from Kenora, ON
2015/05/02	08:34:25	46.83	78.94	26/41	3.3	18 km NE from Temiscaming, QC. Felt
2015/05/06	08:24:34	50.04	94.02	4/7	1.7	39 km NE from Kenora, ON
2015/05/14	02:20:04	50.22	93.27	3/6	1.7	58 km NW from Dryden, ON
2015/05/22	08:35:47	46.39	79.01	9/18	2.3	25 km W from Mattawa, ON
2015/05/27	10:16:28	52.31	80.30	5/9	2.1	James Bay
2015/05/30	01:54:24	52.58	79.55	8/12	2.6	James Bay
2015/06/01	19:15:13	49.85	91.78	5/9	1.9	28 km SE from Sioux Lookout, ON
2015/06/22	05:40:18	46.17	80.69	8/16	1.8	44 km SE from Sudbury, ON
2015/06/23	13:42:24	51.17	93.33	4/8	1.9	31 km NE from Red Lake, ON
2015/08/01	08:53:45	46.32	80.07	7/13	1.8	13 km SW from Sturgeon Falls, ON
2015/08/05	01:00:40	53.78	78.84	5/8	2.3	3 km E from Chisasibi, QC
2015/08/09	13:54:43	48.65	82.29	13/23	2.9	73 km W from Timmins, ON
2015/08/13	01:32:34	53.26	81.23	7/11	2.6	James Bay
2015/08/26	08:09:39	46.81	78.89	9/14	1.9	19 km NE from Temiscaming, QC
2015/08/29	07:00:40	49.11	91.56	4/6	1.6	40 km N from Atikokan, ON
2015/09/02	21:40:54	50.33	88.97	8/14	2.0	35 km E from Collins, ON
2015/09/06	02:20:25	46.27	80.15	6/11	1.7	21 km SW from Sturgeon Falls, ON
2015/09/11	13:45:33	50.35	88.94	6/10	1.8	37 km E from Collins, ON
2015/09/15	02:48:55	49.13	91.53	5/9	1.2	43 km N from Atikokan, ON
2015/09/16	01:43:00	52.37	90.57	3/6	1.6	104 km N from Pickle Lake, ON
2015/09/26	03:27:23	50.28	92.52	5/10	1.7	45 km NW from Sioux Lookout, ON
2015/09/26	23:24:09	53.67	80.73	4/8	2.5	James Bay
2015/09/30	01:06:22	46.51	80.91	14/26	3.1	8 km E from Sudbury, ON. Felt
2015/09/30	01:10:07	46.51	80.90	10/18	2.3	8 km E from Sudbury, ON. Aftershock
2015/09/30	01:14:16	46.51	80.90	9/15	2.0	7 km E from Sudbury, ON. Aftershock
2015/10/02	06:25:58	46.50	80.91	9/18	2.1	7 km E from Sudbury, ON. Aftershock

2015/10/04	21:32:46	46.88	80.18	10/19	2.0	61 km E from Capreol, ON
2015/10/07	04:12:19	49.14	91.56	5/9	1.3	43 km N from Atikokan, ON
2015/10/10	04:26:00	51.55	83.84	5/10	2.4	183 km SW from Attawapiskat, ON
2015/10/10	22:02:00	46.77	78.90	5/8	1.3	17 km E from Temiscaming, QC
2015/10/18	08:17:37	50.33	92.02	4/8	1.6	30 km N from Sioux Lookout, ON
2015/10/24	08:28:10	50.24	92.31	5/9	1.6	31 km NW from Sioux Lookout, ON
2015/10/26	04:10:38	50.19	92.47	5/10	1.6	38 km W from Sioux Lookout, ON
2015/12/20	01:49:24	46.77	78.86	4/7	1.7	19 km E from Temiscaming, QC
2015/12/22	06:27:26	48.43	89.68	3/5	1.5	27 km W from Thunder Bay, ON
2015/12/23	06:29:18	52.74	80.98	6/9	2.2	James Bay
2015/12/25	19:54:11	50.16	92.73	4/8	1.8	44 km N from Dryden, ON
2015/12/26	14:14:39	49.19	92.50	7/13	1.9	69 km S from Dryden, ON

Table 2: NWMO Supported Stations Operating During 2015 (2014 figures given in brackets)

Station		Lat (°N)	Long (°W)	Elev (m)	Uptime (%) 2015 (2014)	Dates of operation as digital stations
ULM	Pinawa	50.2503	95.8750	251	99.8 (100.0)	19941207[1]-
SOLO	Sioux Lookout	50.0213	92.0812	373	97.6 (99.3)	19981104-
TBO	Thunder Bay	48.6473	89.4083	468	86.1 (84.4)	19931005-
GTO	Geraldton	49.7455	86.9610	350	99.8 (97.0)	20010104-
KAPO	Kapuskasing	49.4504	82.5079	210	99.0 (99.9)	19980114-
EEO	Eldee	46.6411	79.0733	398	86.5 (90.3)	19931005-
CRLO	Chalk River	46.0375	77.3801	168	95.8 (98.5)	19941117-
SILO	Sutton Inlier	54.4791	84.9126	195	12.6 (18.5)	20030609-
VIMO	Victor Mine	52.8173	83.7449	78	99.4 (99.6)	20030611-
MALO	McAlpine Lake	50.0244	79.7635	271	98.0 (99.8)	20030620-
KILO	Kirkland Lake	48.4972	79.7232	314	96.0 (97.8)	20030622-
SUNO	Sudbury	46.6438	81.3442	343	88.7 (81.0)	20030623-
EPLO	Experimental Lake	49.6737	93.7258	437	99.8 (96.3)	20040611-
ATKO	Atikokan	48.8231	91.6004	383	73.7 (99.8)	20040609-
PKLO	Pickle Lake	51.4987	90.3522	376	99.8 (99.9)	20040615-
PNPO	Pukaskwa Nat. Park	48.5957	86.2846	219	99.2 (99.3)	20040618-

[1]The date of operation of the core CNSN stations (ULM, SOLO, TBO, GTO, KAPO, EEO and CRLO) is the date since the station was upgraded to be a continuous digital station, not the date when the station was first installed.

Notes: The following summary lists major outages that affected station operation times in 2015.

- Problems with the VSAT dish antenna resulted in the following outages. SOLO data dropped out during intervals from January 4th to 13th due to accumulated snow in the VSAT dish. The transmission power was increased to restore data flow. TBO dropped out from October 25th to December 11th due to faulty components on the VSAT dish antenna, which were replaced by the provider. CRLO was out from October 18th to 27th. Wildlife had pulled cables and misaligned the VSAT dish.

- Main power outages are suspected to have caused the following data outages. TBO dropped out on May 19th, and from June 23rd to 24th. EEO was out on November 7th. CRLO was out from May 13th to 14th and from September 17th to 20th.

- Bad timing resulted in poor data quality and data outages at the following stations. KAPO was affected from April 29th to 30th, on May 24th, on May31st, on June 27th, and from October 14th to 16th. EEO was affected from April 1st to June 9th. A faulty GPS cable was replaced at EEO.

- Repair trips were needed but not scheduled in 2015 for the following stations. SILO dropped out March 15th. ATKO data were intermittent and delayed during intervals starting from April 23rd and ending in August.

- Solar powered sites dropped out due to low battery voltage during parts of winter. VIMO was out from December 29th to 30th. MALO and KILO were out during intervals in January. SUNO was out for extended intervals in January, February and December.

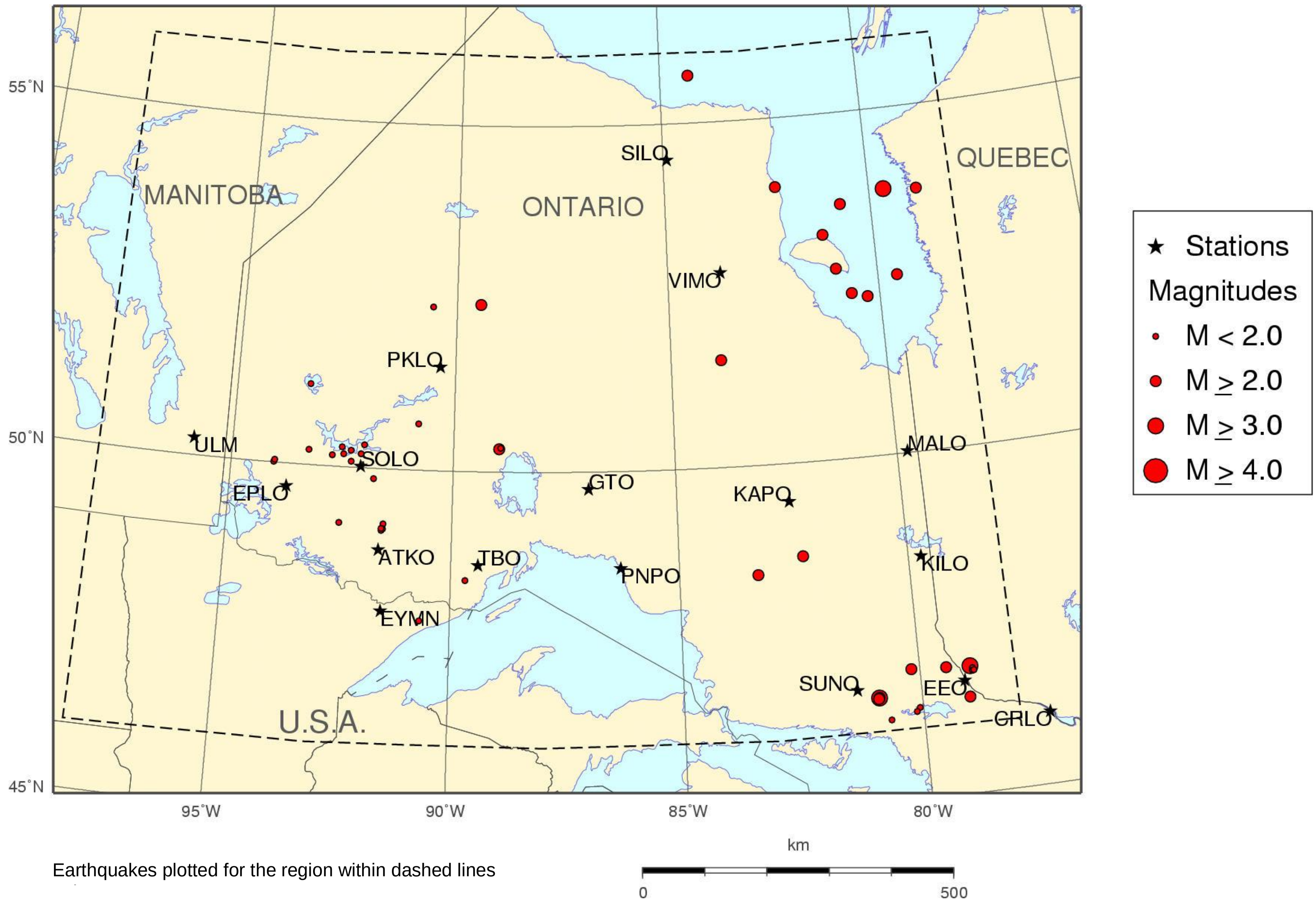
- Some data were missed from VIMO, MALO, KILO, SUNO, EPLO, ATKO, PKLO, and PNPO from June 11th to 12th, on July 28th and July 30th, and from August 29th to 31st. A data acquisition server hung at the data centre. The server was restarted, and the software was rebooted to restore normal operation.

Table 3: Depths Derived using Rg-phases and Regional Depth Phase Method (RDPM) for Moderate-sized Events for 2015

Date	Time (UT) hh:mm:ss	Magnitude (m_N)	Depth (km)	Depth type	Lat N	Long W	Region and Comment
04-Jan	10:30:38	2.2	5	Rg	52.41	89.44	108 km W from Lansdowne House, ON
08-Jan	02:14:32	1.5	5	Rg	47.82	90.66	Minnesota, U.S.
03-Feb	07:45:09	1.4	5	Rg	50.20	92.09	17 km NW from Sioux Lookout, ON
05-Feb	01:12:38	1.6	5	Rg	50.67	90.81	66 km NW from Allanwater Bridge, ON
05-Feb	13:30:20	1.3	5	Rg	50.08	92.30	23 km W from Sioux Lookout, ON
12-Feb	12:04:28	2.5	3.5	RDPM	48.42	83.29	65 km N from Chapleau, ON
10-Mar	18:41:16	1.9	5	Rg	49.20	91.52	51 km N from Atikokan, ON
01-May	03:29:33	1.3	5	Rg	50.01	94.04	36 km NE from Kenora, ON
02-May	08:34:25	3.3	15	RDPM	46.83	78.93	18 km NE from Temiscaming, QC. Felt
06-May	08:24:34	1.7	5	Rg	50.04	94.02	39 km NE from Kenora, ON
14-May	02:20:04	1.7	5	Rg	50.22	93.27	58 km NW from Dryden, ON
01-Jun	19:15:13	1.9	5	Rg	49.85	91.78	28 km SE from Sioux Lookout, ON
22-Jun	05:40:18	1.8	5	Rg	46.17	80.69	44 km SE from Sudbury, ON
23-Jun	13:42:24	1.9	5	Rg	51.17	93.33	31 km NE from Red Lake, ON
01-Aug	08:53:45	1.8	5	Rg	46.32	80.07	13 km SW from Sturgeon Falls, ON
09-Aug	13:54:43	2.9	14.5	RDPM	48.65	82.29	73 km W from Timmins, ON
29-Aug	07:00:40	1.6	1	Rg	49.11	91.56	40 km N from Atikokan, ON
02-Sep	21:40:54	2.0	5	Rg	50.33	88.97	35 km E from Collins, ON
06-Sep	02:20:25	1.7	5	Rg	46.27	80.15	21 km SW from Sturgeon Falls, ON
11-Sep	13:45:33	1.8	5	Rg	50.35	88.94	37 km E from Collins, ON
15-Sep	02:48:55	1.2	5	Rg	49.13	91.53	43 km N from Atikokan, ON
16-Sep	01:43:00	1.6	5	Rg	52.37	90.57	104 km N from Pickle Lake, ON
26-Sep	03:27:23	1.7	5	Rg	50.28	92.52	45 km NW from Sioux Lookout, ON
30-Sep	01:06:22	3.1	3.5	RDPM	46.51	80.91	8 km E from Sudbury, ON. Felt
30-Sep	01:10:07	2.3	1	Rg	46.51	80.90	8 km E from Sudbury, ON. Aftershock
30-Sep	01:14:16	2.0	1	Rg	46.51	80.90	7 km E from Sudbury, ON. Aftershock
02-Oct	06:25:58	2.1	1	Rg	46.50	80.91	7 km E from Sudbury, ON. Aftershock
04-Oct	21:32:46	2.0	5	Rg	46.88	80.18	61 km E from Capreol, ON
07-Oct	04:12:19	1.3	5	Rg	49.14	91.56	43 km N from Atikokan, ON
18-Oct	08:17:37	1.6	5	Rg	50.33	92.02	30 km N from Sioux Lookout, ON
24-Oct	08:28:10	1.6	5	Rg	50.24	92.31	31 km NW from Sioux Lookout, ON
26-Oct	04:10:38	1.6	5	Rg	50.19	92.47	38 km W from Sioux Lookout, ON
22-Dec	06:27:26	1.5	1	Rg	48.43	89.68	27 km W from Thunder Bay, ON
25-Dec	19:54:11	1.8	5	Rg	50.16	92.73	44 km N from Dryden, ON
26-Dec	14:14:39	1.9	5	Rg	49.19	92.50	69 km S from Dryden, ON

Table 4: Mining-Induced Seismic Events m_N 2.5 and Greater, January - December 2015

Date (yyyy/mm/dd)	Mine	Location	Magnitude (m_N)
2015-02-02	Creighton mine	Sudbury	2.8
2015-02-02	Creighton mine	Sudbury	3.0
2015-02-03	Creighton mine	Sudbury	3.0
2015-02-24	Not determined	Sudbury	2.6
2015-03-22	Coleman mine	Sudbury	2.7
2015-03-31	Creighton mine	Sudbury	2.9
2015-04-05	Coleman mine	Sudbury	2.6
2015-04-19	Creighton mine	Sudbury	2.5
2015-07-03	Kidd Creek mine	Timmins	3.1
2015-07-05	Garson mine	Sudbury	2.8
2015-08-05	Creighton mine	Sudbury	3.3
2015-08-05	Creighton mine	Sudbury	3.8
2015-10-28	Not determined	Sudbury	2.6
2015-11-07	Coleman mine	Sudbury	2.5
2015-11-10	Copper Cliff mine	Sudbury	2.8
2015-12-12	Westwood mine	Cadillac	3.0



Earthquakes plotted for the region within dashed lines

Figure 1: Earthquakes in Northern Ontario and Adjacent Areas, 2015

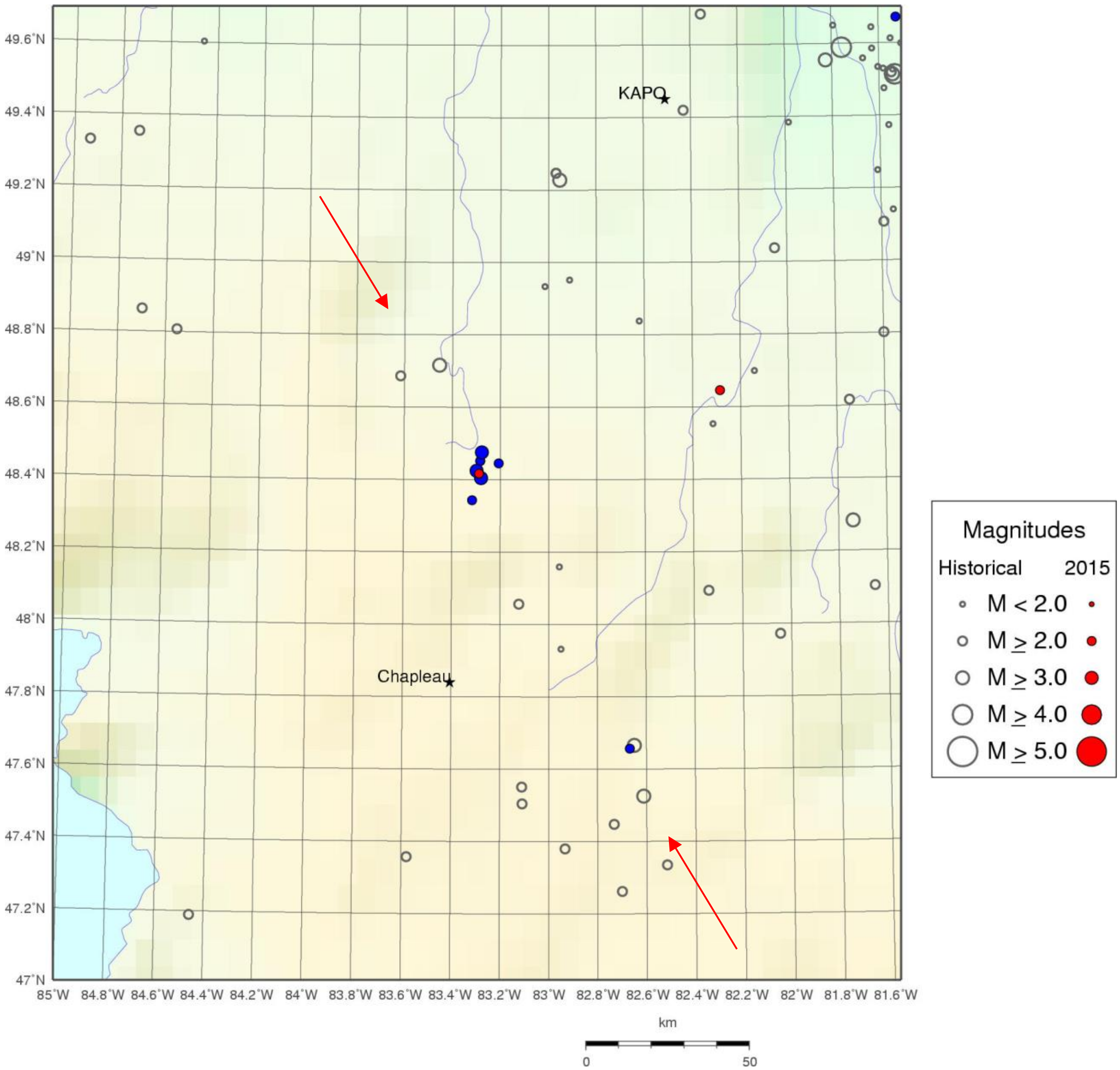


Figure 2A: Earthquakes north and east of Chapleau, showing the 2015 earthquake (red), earthquakes in 2012-2014 (blue), and prior earthquakes (open grey circles). The possible linear trend is indicated between the arrows.

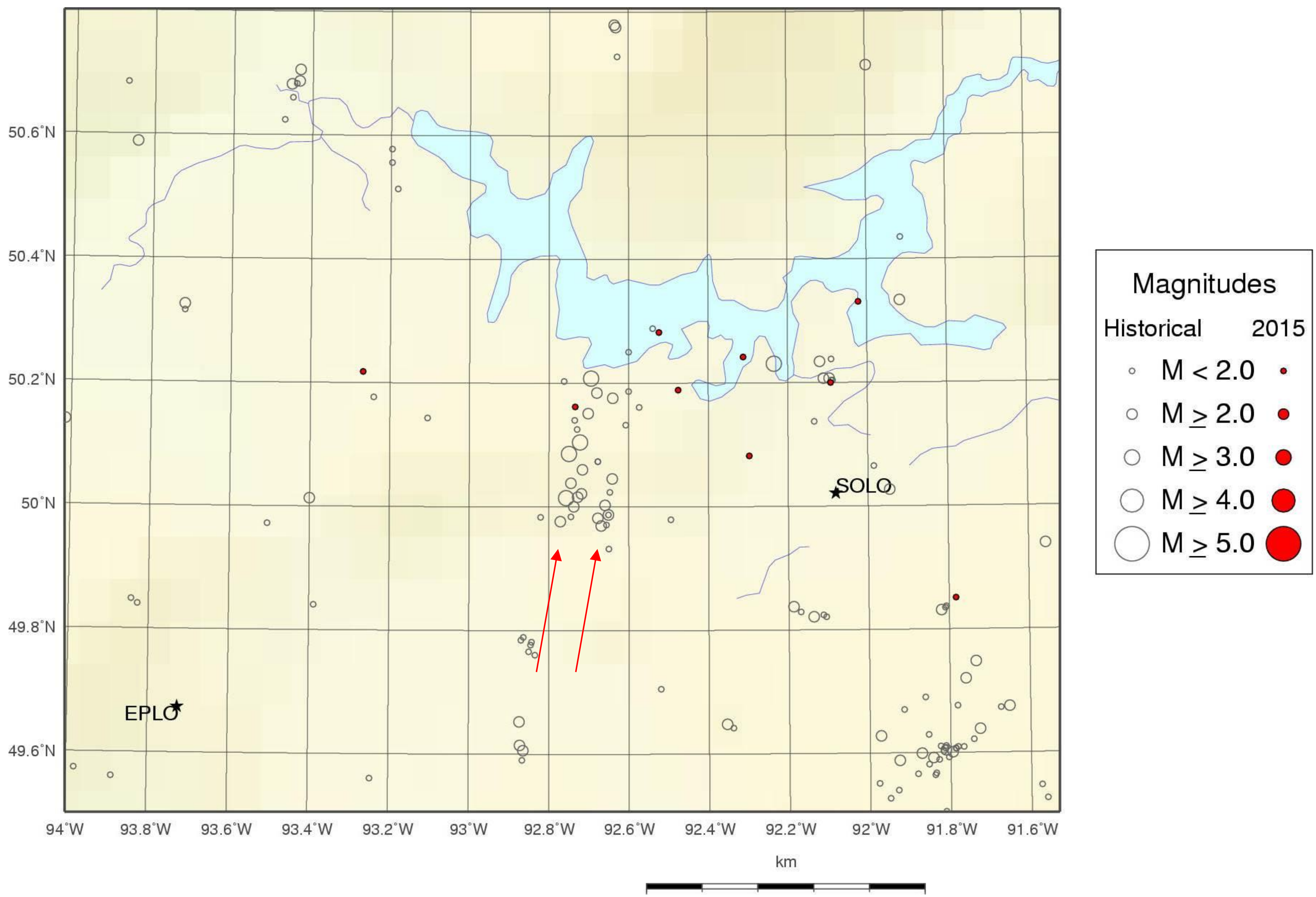
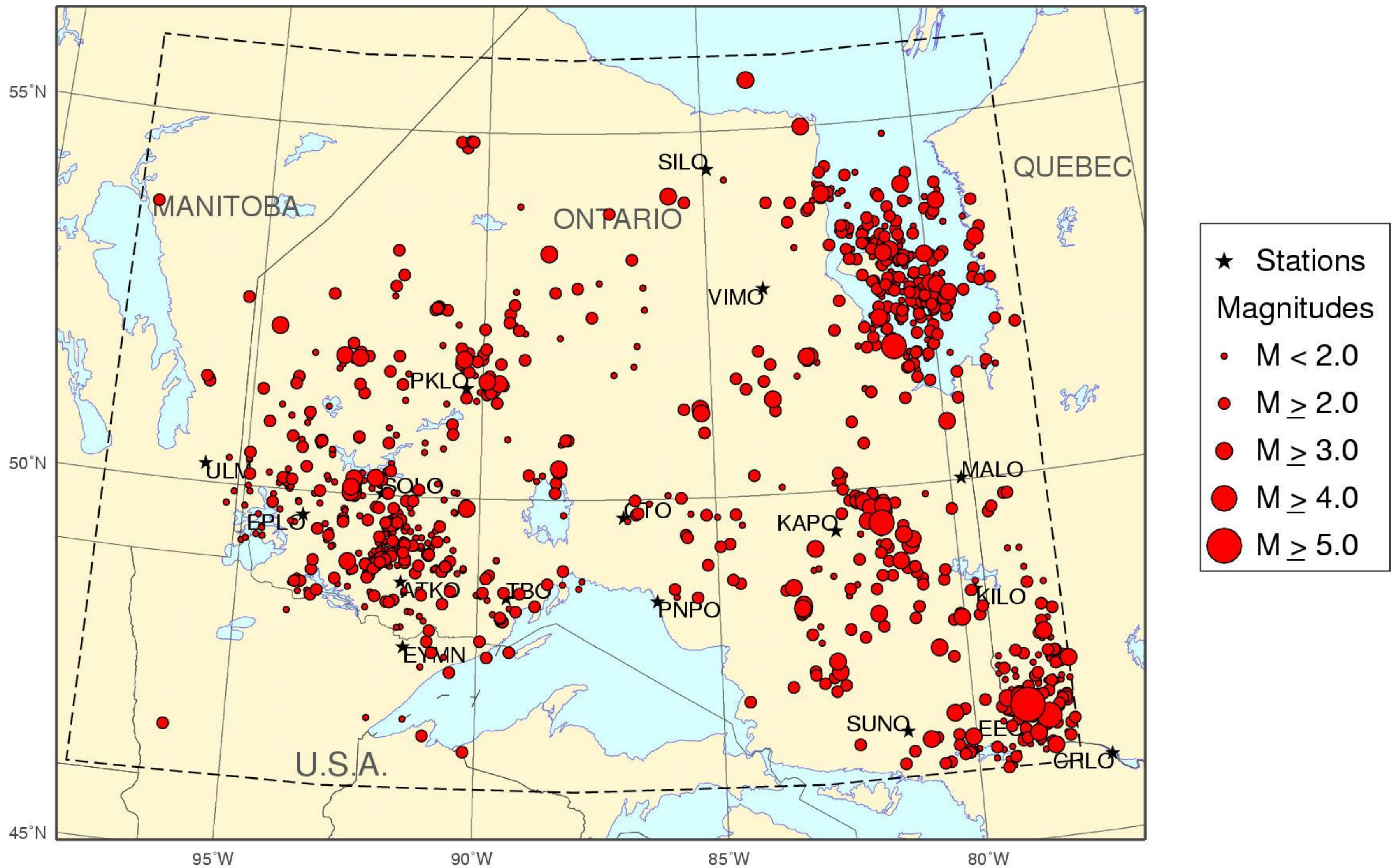
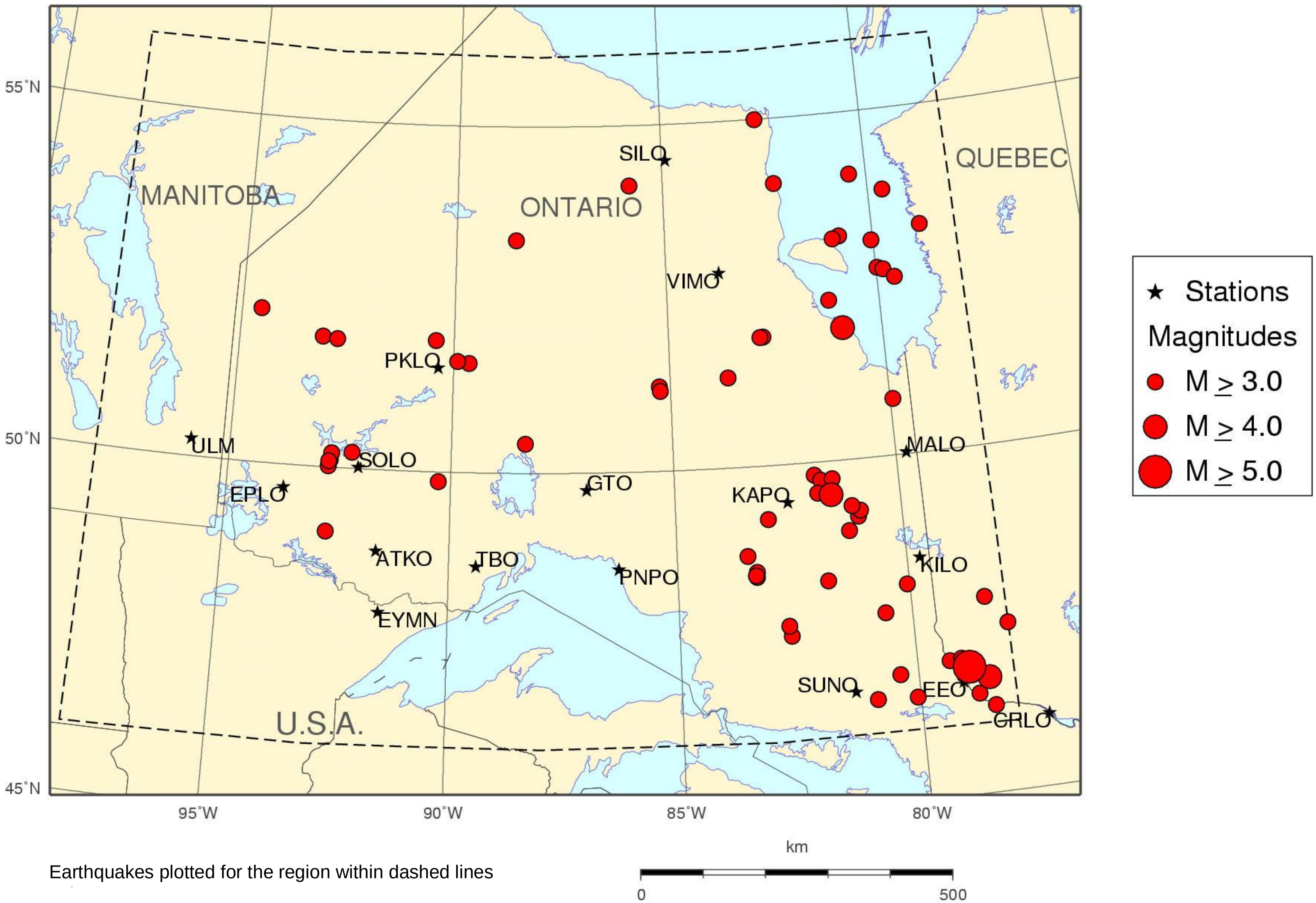


Figure 2B: Earthquakes near Sioux Lookout and station SOLO in 2015 (red) and prior years. Arrows indicate possible linear trends.



Earthquakes plotted for the region within dashed lines

Figure 3: Earthquakes in Northern Ontario and Adjacent Areas, 1982 - 2015



Earthquakes plotted for the region within dashed lines

Figure 4: Earthquakes $m_N \geq 3$ in Northern Ontario and Adjacent Areas, 1982 – 2015

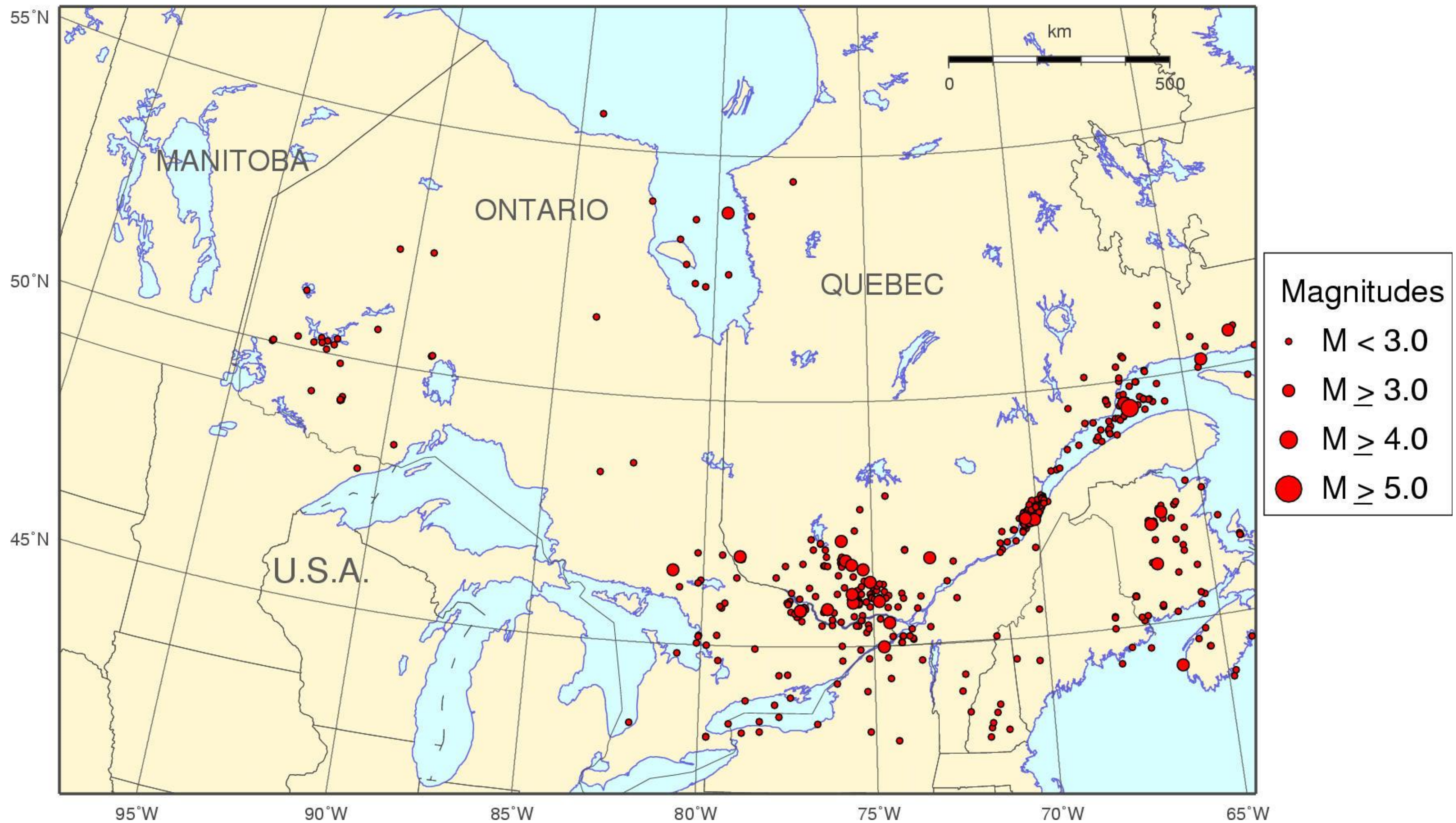


Figure 5: Earthquakes in Eastern Canada, 2015.

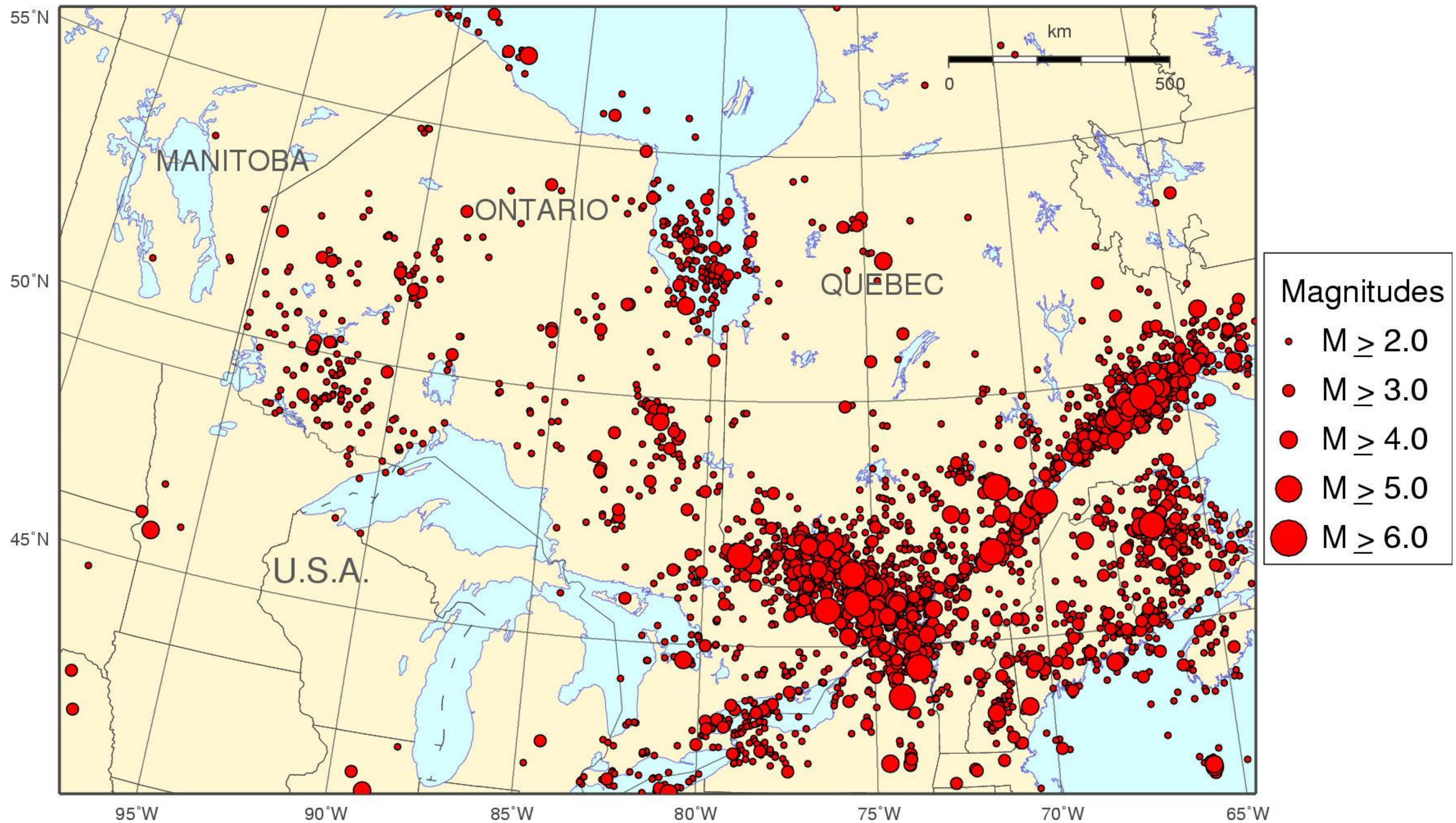
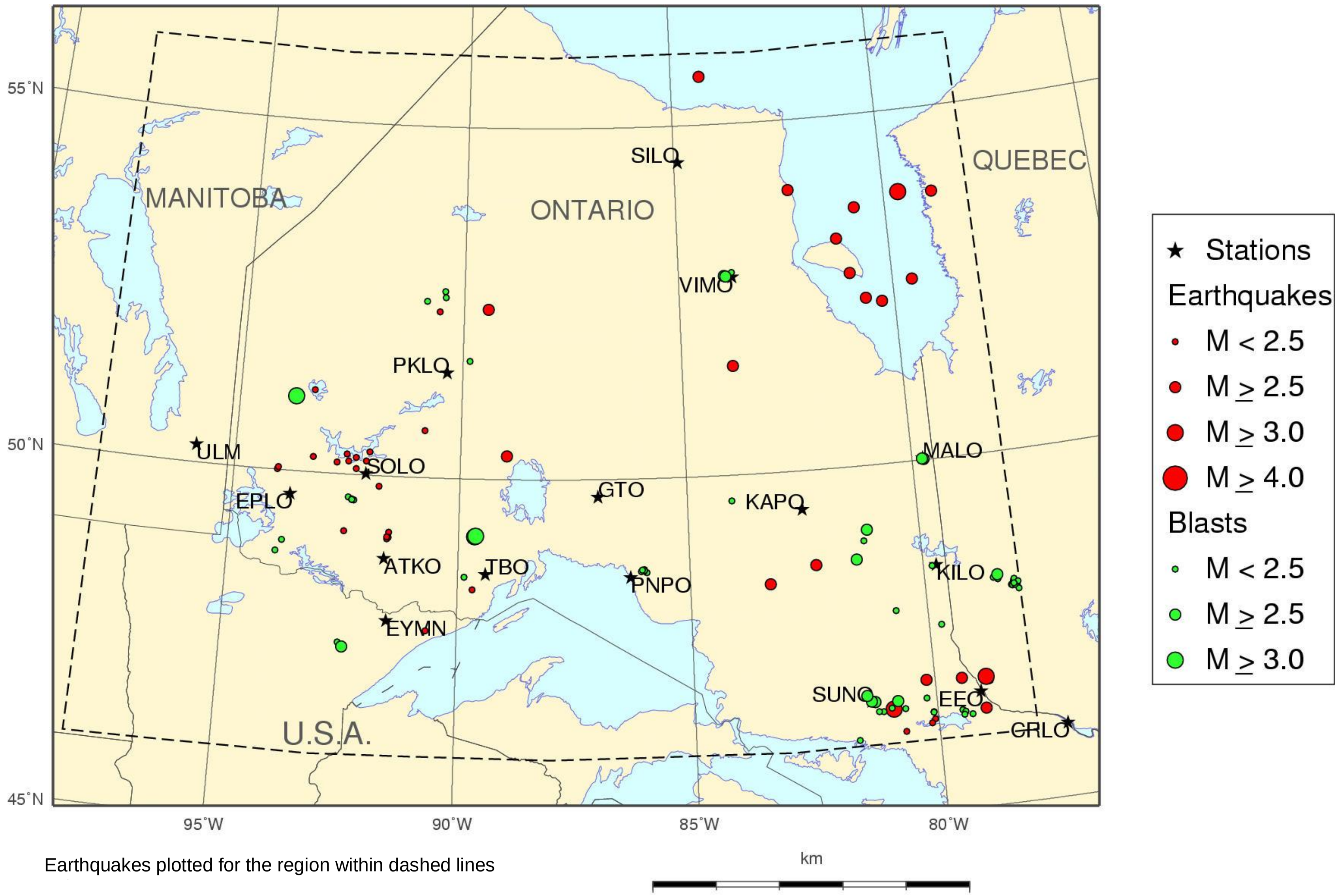


Figure 6: Earthquakes in Eastern Canada, 1982 - 2015



Earthquakes plotted for the region within dashed lines

Figure 7: Earthquakes and Blasts in Northern Ontario and Adjacent Areas, 2015.

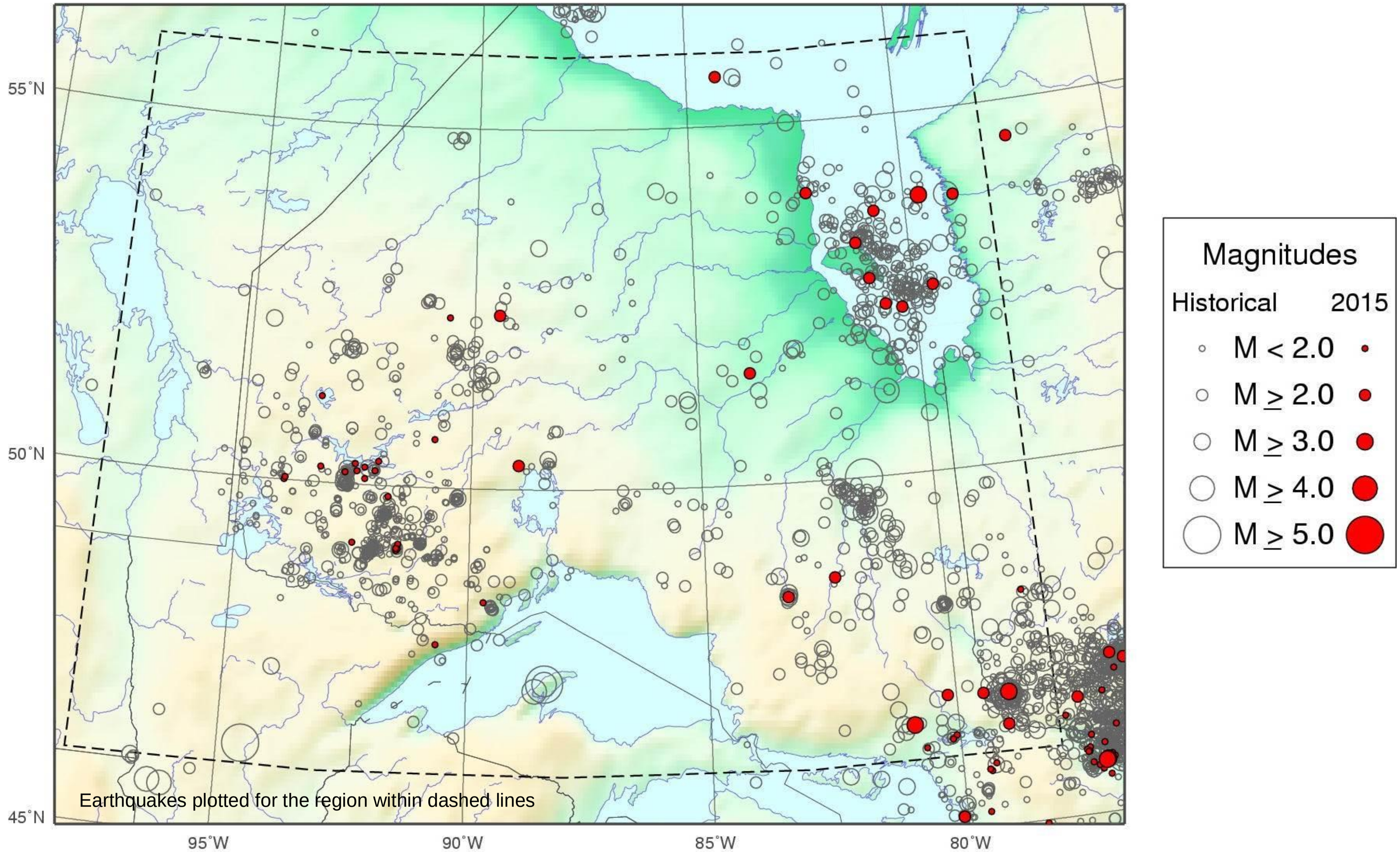


Figure 8: Earthquakes in Northern Ontario and Adjacent Areas for 2015 and prior years

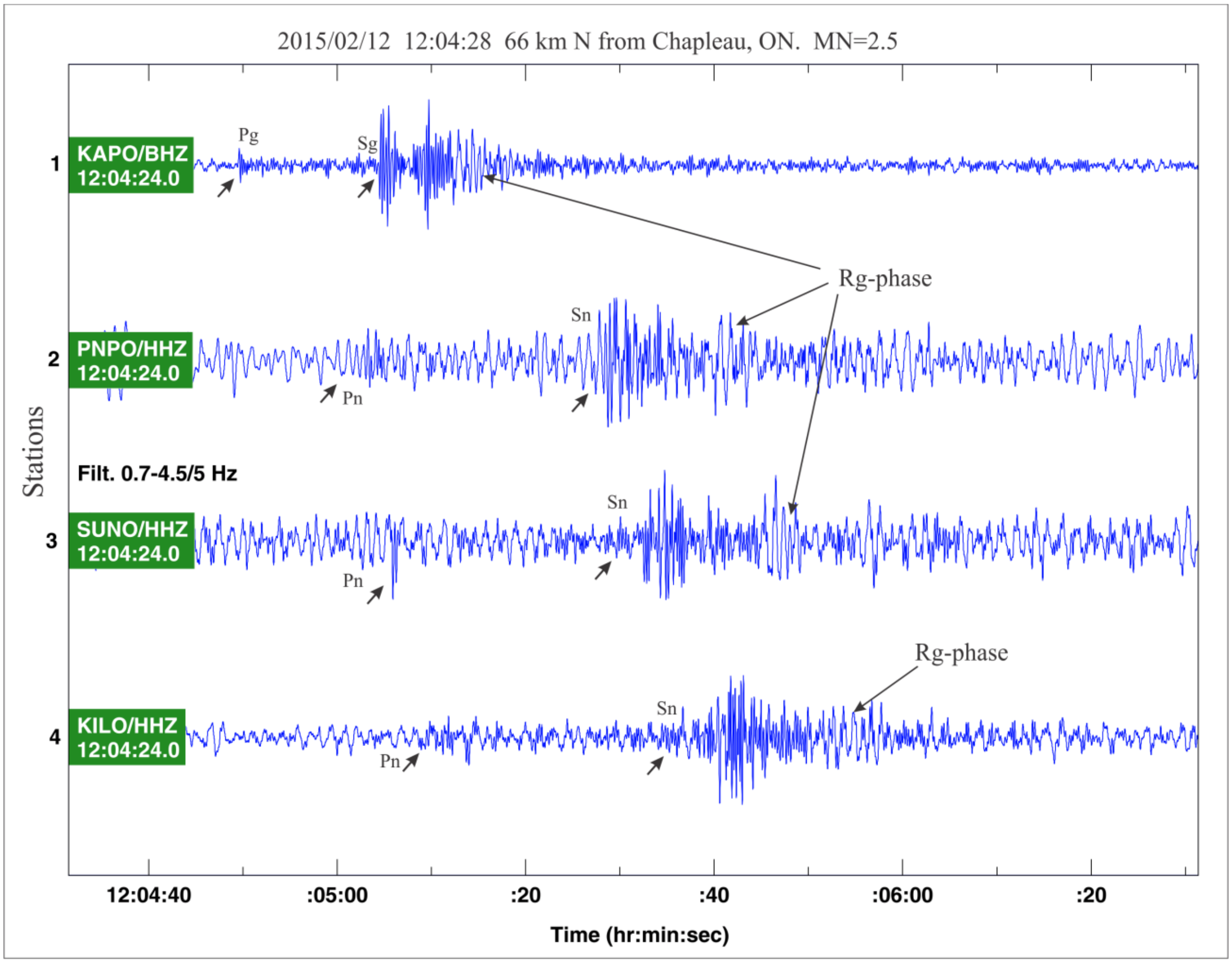


Figure 9: Rg Surface Waves from the m_N 2.5 on 2015/02/12, 66 km north of Chapleau, ON.

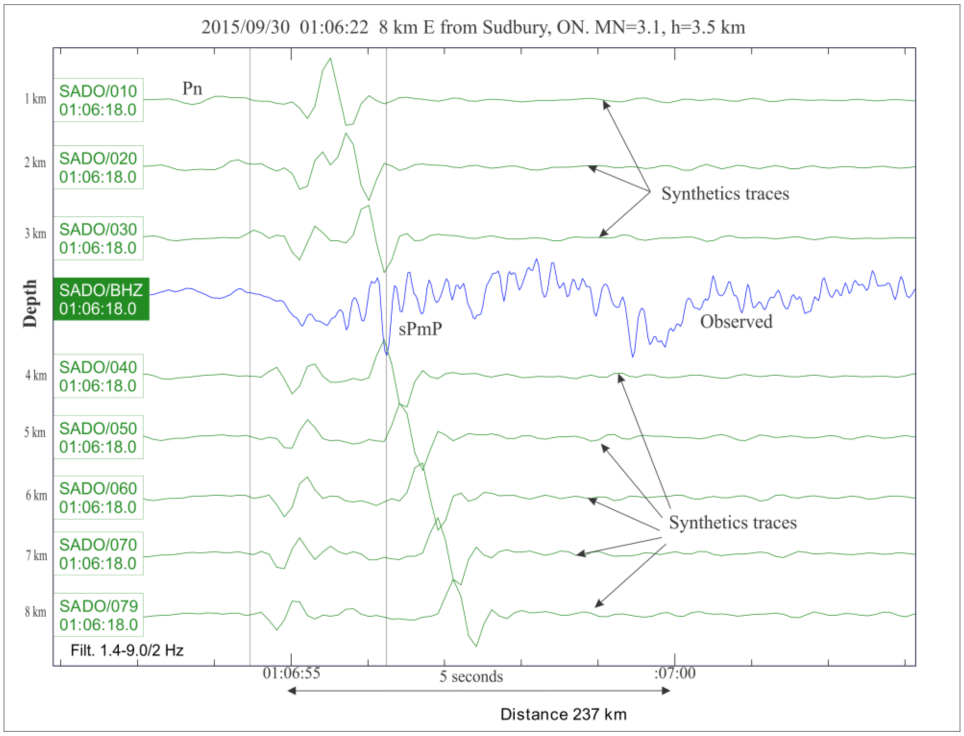


Figure 10A: Observed and Synthetic Waveforms from the m_N 3.1 on 2015/09/30, 8 km east of Sudbury, ON.

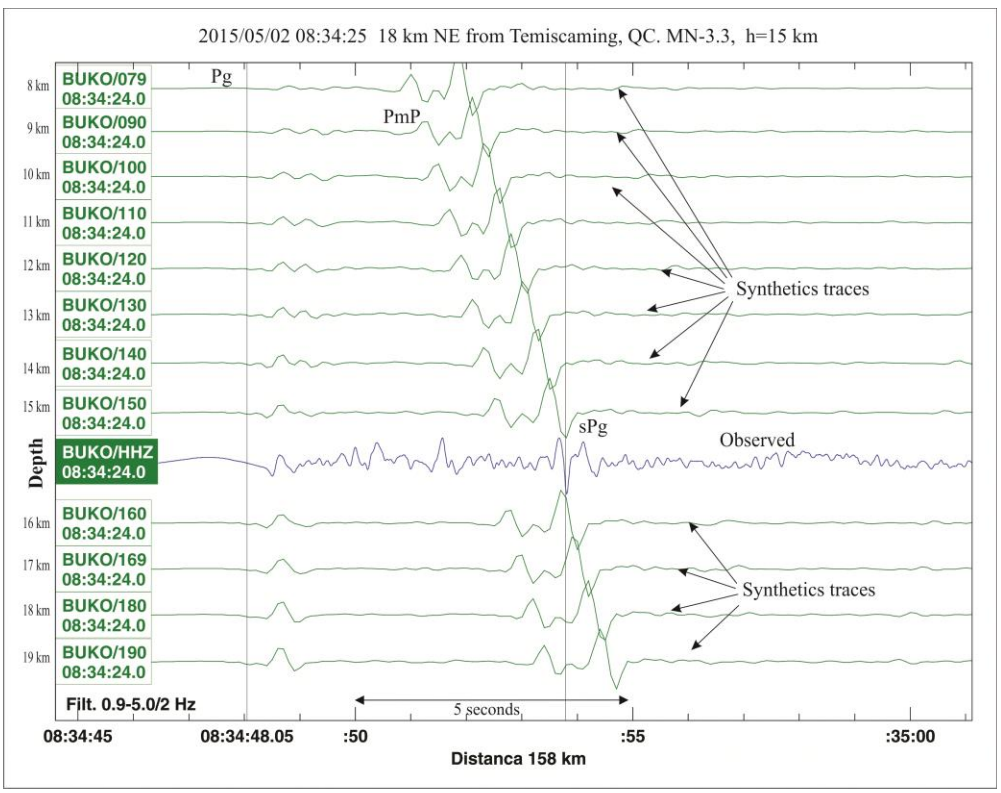


Figure 10B: Observed and Synthetic Waveforms from the m_N 3.3 on 2015/05/02, 18 km northeast of Temiscaming, QC.

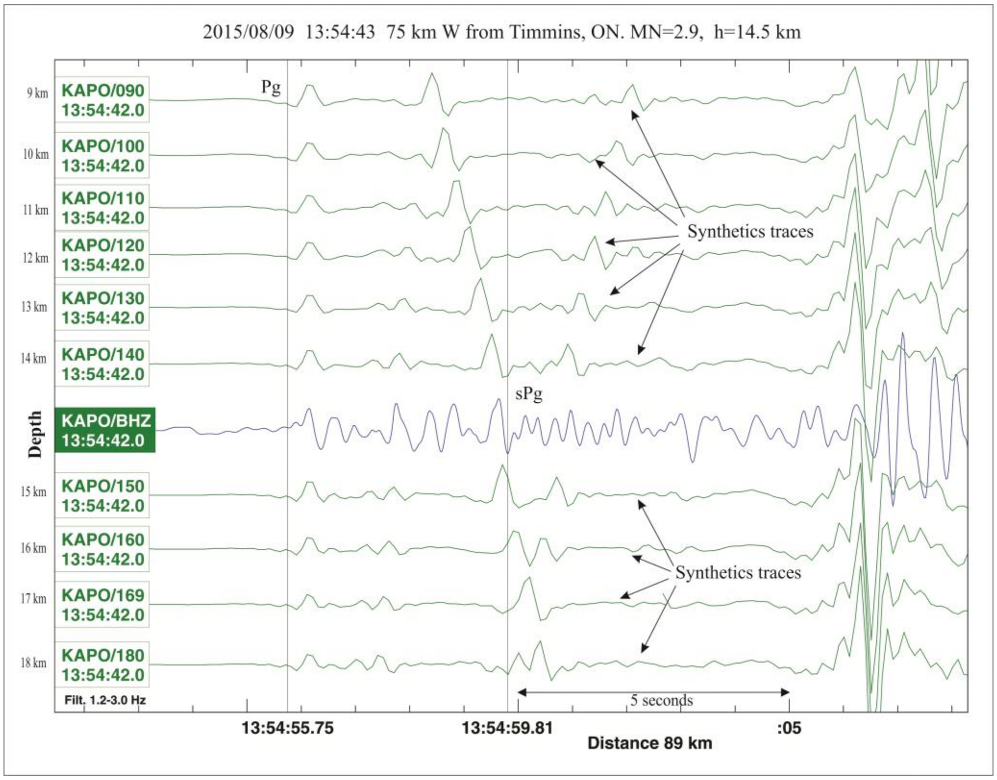


Figure 10C: Observed and Synthetic Waveforms from the m_N 2.9 on 2015/08/09, 75 km west of Timmins, ON.

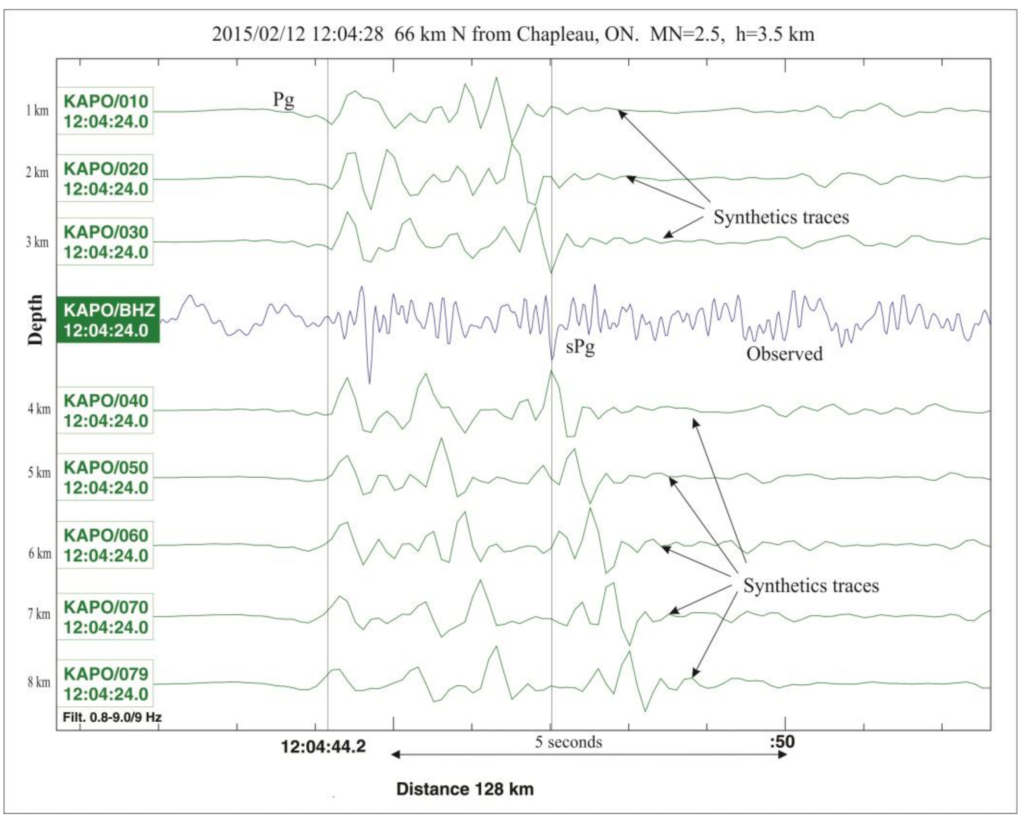


Figure 10D: Observed and Synthetic Waveforms from the m_N 2.5 on 2015/02/12, 66 km north of Chapleau, ON.

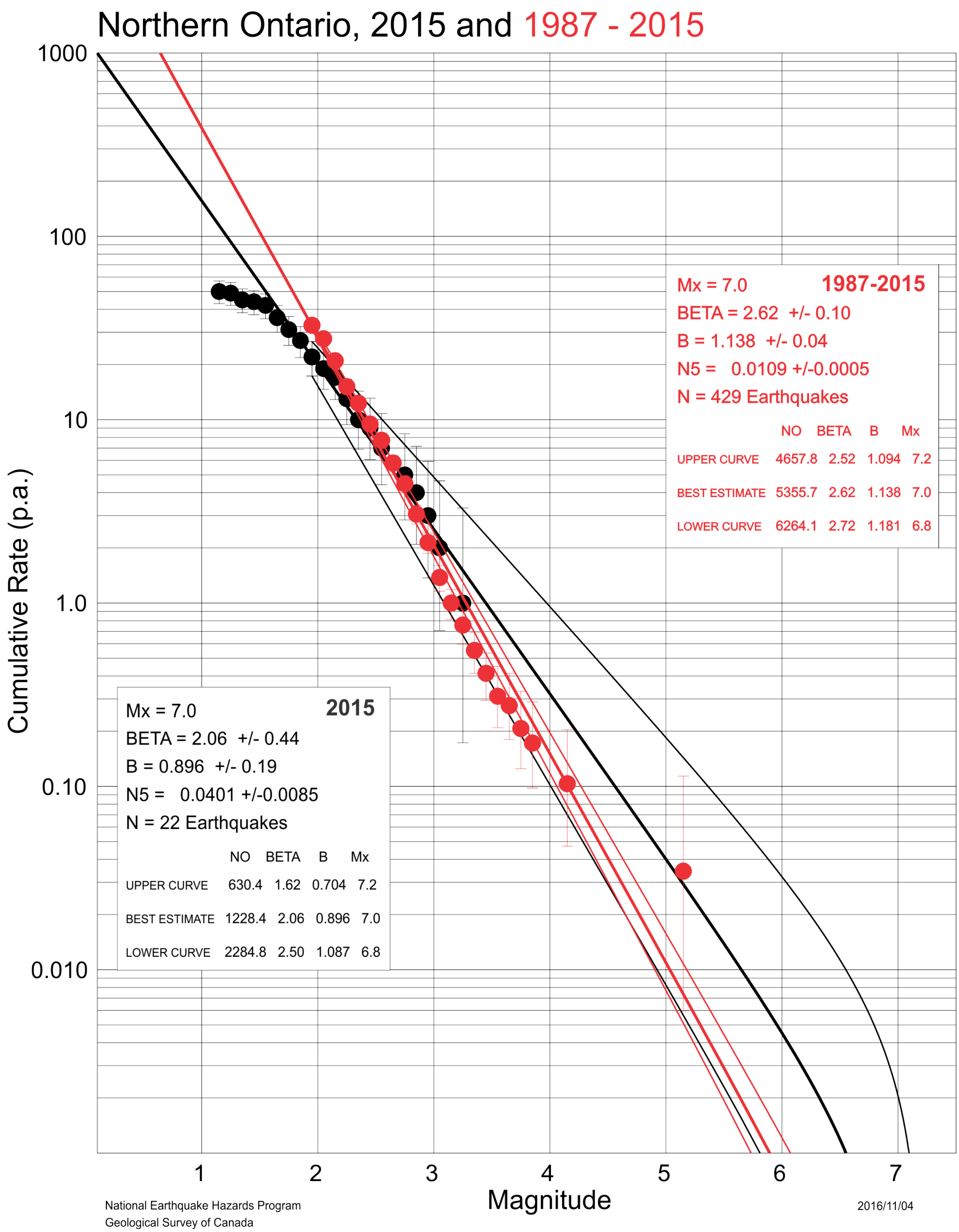


Figure 11: Recurrence Curves for Northern Ontario