Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01 – December 31, 2014

NWMO-TR-2015-21

December 2015

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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, 2014**

Report No.: **NWMO-TR-2015-21**

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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 on-going 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 2014.

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 monitoring program.

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 2014, 36 earthquakes were located. Their magnitude ranged from 1.1 m_N to 3.0 m_N. The largest event, with a magnitude of 3.0 m_N, occurred 190 km northwest of Victor Mine, ON, while the second largest event 2.8 m_N, was located in the James Bay region 95 km north from Moosonee, ON. The 36 events located in 2014 compares with 70 events located in 2013, 57 events in 2012, 79 events in 2011, 118 events in 2010, 82 events in 2009, and 114 events in 2008.

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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 2014.

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), which 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 (http://www.polarisnet.ca), 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 POLARIS initiatives.

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.

Since around 2009/2010, USArray (www.usarray.org) has installed stations in the U.S. just south of the area of interest for this study. The array is being moved eastward, year by year, and during 2014 stations ceased operating in Michigan but continued southern Ontario. Data from these stations could be read to improve the locations of the events identified in this report (particularly the events along the border). The data could also be scanned to look for new events, to lower the threshold in the border regions. Currently this is outside the scope of this contract.

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 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 large earthquakes that could happen in the future and are of engineering design interest.

During this twelve-month period 36 earthquakes were located. Their magnitude ranged from 1.1 m_N to 3.0 m_N. The largest event, with a magnitude of 3.0 m_N, occurred 190 km northwest of Victor Mine, ON, while the second largest event, 2.8 m_N, was located in the James Bay region 95 km north from Moosonee, ON (see Figure 1). The 36 events located in 2014 compares with 70 events located in 2013, 57 events in 2012, 79 events in 2011, 118 events in 2010, 82 events in 2009, and 114 events in 2008.

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 2014 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 1-7, and the 2014 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 3500 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

[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.

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 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, 3441 earthquakes had been located in Canada during the year 2014. Only 17 of these occurred in the study region and were over magnitude 2.

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 97% for five of the seven core seismograph station and above 97% for six of the nine temporary stations.

Many of the solar powered sites, including EPLO, ATKO, 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 at the site. As this site is very remote, no further maintenance trip was made in 2014, and due to the cost of servicing SILO the equipment will probably be removed in 2015.

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

3. EARTHQUAKES

A total of 36 earthquakes were located in the study area during 2014. The events from the year are listed in Table 1 and plotted in Figure 1. The largest event, with a magnitude of 3.0 m_N, occurred 190 km northwest of Victor Mine, ON, on December 3rd.

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, down to approximately m_N 2. Although smaller earthquakes (less than magnitude 2) 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 is not complete; that is to say, particularly in regions of poorer coverage, it is assumed that events smaller than m_N 2 have been missed.

The effects of this lowered threshold can be seen particularly in the James Bay region where 237 events were located since 2004, which works out to approximately 22 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 peak 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 2014, 6 events were located in this region, including the second 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 location threshold may have been somewhat affected for the last four years compared with the previous years, although 2012's low seismicity rate may simply be due to the natural fluctuation of seismicity year to year.

More ex-FedNor stations could be closed in the next few years and this will lead to a threshold closer to pre-2003 (pre-FedNor) levels. At some time, decisions will be required as to (a) whether more low-magnitude earthquake data is still required *and* the remaining FedNor stations be funded, or whether the pre-2003 threshold level would be adequate for the future, and (b) whether a low threshold is required over the entire study area, or a more focussed approach should be used.

The 36 earthquakes from 2014 compare to previous years as follows:

Year	No. of events	No. of stations
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). 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 from 2011, it suggests that the low 2012 rate was simply part of the natural yearly fluctuation. As noted in Section 6, the small number of events in 2014 is chiefly due to fewer earthquakes in the magnitude 2.0-2.5 class.

In general, the pattern of activity for 2014 followed that of the previous years, with earthquakes being reported from James Bay, the area east of Kapuskasing, the area northeast of PKLO, and from the Severn Highlands.

The largest event, with a magnitude of 3.0 m_N, occurred 190 km northwest of Victor Mine, ON, on December 3rd. This is a region of fairly low seismicity, and the December earthquake is the largest yet recorded in the vicinity. The event is further discussed below.
Activity (six events, largest was 1.7 m_N) continued in the region 65 km northwest of Atikokan.

No further activity was reported from the region north of Chapleau, ON, which had been active in 2012-2013. However, the 2.2 m_N earthquake on December 27th, 74 km NW of Hearst is in a place without prior reported earthquakes. It is mentioned here only because it appears to be on-strike with the linear feature outlined by the earthquakes north of Chapleau, which are about 200 km to the SSE.

Figure 2 shows all the earthquakes that have been located in northern Ontario and surrounding area, since the inception of the northern Ontario seismic program in 1982. A total of 1308 earthquakes are documented during this period.

Figure 3 shows only those events that are magnitude 3 or greater recorded in the study area during the same time period of 33 years (70 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 had an event above magnitude 3.

Figure 4 illustrates the seismic activity in eastern Canada in year 2014. As can be clearly observed, the number of earthquakes documented in northern Ontario represents one of the 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 5 shows all the activity in eastern Canada for the entire monitoring period of 1982 - 2014. 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 this earthquake activity in the James Bay region is linked with deep structures reactivated by hot spots.

Figure 6 shows the earthquakes located in the study area in 2014 together with some mine blasts for the same year. Many mine blasts are repetitive (same location at similar times each day) and 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 6 any proximity of blast and earthquake symbols leads to checking as to whether a blast might have been misidentified as an earthquake.

An event on December 19th, in the Hemlo mining region 36 km east of Marathon, happened in an area of recurrent blasting. However the time of day is very different from most blasts in the catalog and the waveform does not show strong Rg waves usually seen for blasts (or shallow earthquakes). The waveform for this event and a preceding blast event are compared in Figure A1, illustrating the difference in waveforms. The absence of strong Rg suggests the December 19th event is at least 3 km deep, and likely 5 km or more. On the basis of the above and analyst's judgement, the December 19th event is retained as an earthquake, though it is possible it was triggered by unloading due to the much shallower mining activity.

Figure 7 shows the earthquakes located in the study area in 2014 together with all known earthquakes. The representation, using red-filled circles for the 2014 earthquakes and open grey circles for the prior activity, makes it easy to judge which 2014 earthquakes happened in regions of prior seismicity, as well as, which areas of past activity did not have an earthquake in 2014. For 2014, only one of these "quiet" areas is evident: the region south of SUNO and EEO and northwest of SUNO; this includes the Chapleau region which was very active in 2012-2013.

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 8 shows an earthquake that occurred southwest of Allanwater Bridge, ON on February 2nd which exhibited strong Rg-phases. The presence of this phase indicates that the depth of the event must have been shallow: less than 5 km in depth. (See Section 4.2.1 for further discussion on depth).

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. The actual and synthetic waveforms from the station at KILO are shown for the m_N 2.7 earthquake which occurred northeast of Kapuskasing, ON on November 6th in Figure 9a. The waveforms from this station indicate a depth of 20 km, which is similar to the depth of nearby earthquakes that lie along what appears to be a deep-seated NW-SE trending structure that is perhaps related to the hotspot trace. Figure 9b shows the actual and synthetic waveforms at VIMO for the m_N 3.0 which occurred in northernmost Ontario, an area with only a sparse record of earthquakes. The waveforms from VIMO indicate a depth of 19 km, which is similar to the depth of the earthquake in Figure 9a, and this may be consistent with deep-seated NW-SE trending structures near Kapuskasing extending this far to the northwest.

Recurrence curves for the study area for the year 2014 and for the period of 1987 to the end of 2014 (28 years of data) are shown in Figure 10 and are 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/index-eng.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 2014 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 2014 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 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.

Also, 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. Similarly 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 2014 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_N3+, although depending on the stations and their distribution around the epicentre, this number can be lower). Ma states, "The regional depth phase sPg and sPmP are very sensitive to focal depth. sPg depth phase develops well generally at distance between about 60 to 120 km for earthquakes, some as small as m_N 1.5. 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 m_N about 2.0. In short, 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).

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 9A and 9B show two applications of RDPM to 2014 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 8) 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 5 km or less can be achieved.

Table 3 lists all the events from 2014 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 might be fixed at 1 km depth), as well as three events which were well enough recorded at suitable distance for reliable depths to be determined using the RDPM method. Of the three, the shallow (3.5 km) February 25th one is consistent with nearby shallow earthquakes that have Rg in the Severn Highlands, and other two deep events were already 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 $m_N > 3$ is considered complete since 1987, providing 28 years of data for the less-common larger earthquakes.

Figure 10 shows the magnitude-recurrence plot for the year 2014 earthquakes in black and the plot for the 28-year period of 1987 to 2014 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.

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 is found each year, the 2014 curve fit has a much greater uncertainty than the 28-year curve fit. For 2014 a best fit slope of $b = 0.969 \pm 0.24$ was found, versus 1.153 ± 0.04 for the 28-year period curve. More importantly, the 2014 curve is lower than the longer-term curve for most of the magnitude range for which earthquakes are represented. Note that the data points of the one-year curve (black) are quite similar to the ones of the 28-year curve (red) at magnitudes near 2.5, with the rate for magnitude 2.5 to 2.7 events not more than 25% 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. However, at magnitude 2.0 the rate is low by a factor of 2, whereas at magnitude 2.0 the 2013 data set (given in that year's report) sits right over the long-term dataset, indicating completeness for 2013 down to magnitude 2.0. Although the 2014 year is likely complete to magnitude 2.5, not 2.0 as in 2013, it is still adequate for future seismic hazard assessments, as such assessments normally consider only earthquakes larger than magnitude 2¾.

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 hundreds of blasts are recorded and identified by the project on a yearly basis. Locations were determined for 50 mining-induced seismic events of magnitude 0.5 or greater in the study area in 2014. Forty-three of these events occurred in the Sudbury Basin, 2 in the Red Lake region, 3 in the Cadillac, QC region, and 2 in the Timmins area. Sixteen of these mining-induced events recorded in the study area in 2014 were larger than m_N 2.5 and are listed in Table 4.

8. SUMMARY

Data capture was in excess of 97% from six 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 2015.

The seismic activity in the study area during the calendar year 2014 consisted of 36 earthquakes ranging in magnitude from 1.1 m_N to 3.0 m_N. Seventeen earthquakes were larger than m_N 2.0, and only one was m_N 3.0 or larger. The largest event, 3.0 m_N, occurred in a remote area of northernmost Ontario on December 3rd.

Based on the logarithmic frequency-magnitude relationship, discussed in Section 6, the distribution of magnitudes indicates that a few earthquakes near m_N 2.5 and many smaller ones remain undetected.

The distribution of the majority of the detected earthquakes in this region for 2014 conformed to the pattern of previous seismicity.

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Table 1: Located Local Earthquakes, January - December 2014

Date	Time (UT)	Latitude	Longitude	#stns/ phases	Magnitude (m_N)	Region and Comment
2014-01-10	16:41:52	53.15N	81.75W	7/11	2.6	James Bay
2014-01-27	10:47:48	49.30N	90.99W	6/12	1.7	77 km NE from Atikokan, ON
2014-02-06	17:41:20	48.72N	89.13W	8/14	2.3	22 km NW from Mackenzie, ON
2014-02-25	07:02:42	49.60N	90.83W	9/18	2.4	86 km SW from Allanwater Bridge,
2014-03-16	10:39:19	50.36N	88.32W	7/12	2.1	81 km E from Collins, ON
2014-03-20	12:10:16	49.60N	90.83W	6/11	1.3	86 km SW from Allanwater Bridge,
2014-03-22	21:47:17	52.46N	89.93W	5/8	2.2	113 km N from Pickle Lake, ON
2014-03-23	07:43:48	49.37N	91.62W	5/10	1.2	69 km N from Atikokan, ON
2014-03-27	21:46:34	49.25N	92.03W	4/8	1.4	64 km NW from Atikokan, ON
2014-03-27	21:49:34	49.27N	92.06W	4/8	1.2	66 km NW from Atikokan, ON
2014-03-28	00:53:07	49.62N	80.04W	6/10	2.2	94 km NE from Cochrane, ON
2014-03-28	10:23:01	50.82N	89.44W	6/10	1.7	60 km N from Collins, ON
2014-04-02	20:18:53	54.35N	82.28W	4/8	2.7	James Bay
2014-04-04	08:03:54	46.77N	79.36W	17/30	1.8	21 km W from Temiscaming, QC
2014-07-05	03:02:50	48.15N	80.07W	10/18	2.6	3 km W from Kirkland Lake, ON
2014-07-07	23:50:29	49.98N	92.74W	5/10	1.7	24 km N from Dryden, ON
2014-07-20	22:40:28	51.31N	81.51W	5/9	2.5	55 km W from Moosonee, ON
2014-07-23	05:17:50	46.65N	79.45W	6/9	1.2	28 km W from Temiscaming, QC
2014-07-24	05:57:16	52.31N	89.22W	7/10	2.1	92 km W from Lansdowne House, ON
2014-10-21	05:00:43	52.14N	81.05W	7/11	2.8	95 km N from Moosonee, ON
2014-10-27	16:16:44	48.88N	80.91W	5/9	2.3	21 km NW from Iroquois Falls, ON
2014-10-28	09:41:16	52.27N	89.09W	3/5	1.5	82 km W from Lansdowne House, ON
2014-11-06	14:59:09	49.67N	81.52W	8/14	2.7	72 km NE from Kapuskasing, ON
2014-11-10	11:08:18	51.76N	82.64W	3/6	1.8	131 km S from Attawapiskat, ON
2014-11-20	08:28:41	49.57N	93.98W	3/5	1.1	42 km SE from Kenora, ON
2014-11-27	17:57:23	52.42N	79.99W	3/6	2.0	James Bay
2014-12-02	09:42:34	49.54N	91.93W	5/8	1.2	59 km S from Sioux Lookout, ON
2014-12-03	07:58:48	54.13N	85.81W	9/18	3.0	190 km NW of Victor Mine, ON
2014-12-05	07:43:27	49.12N	92.78W	6/10	1.6	73 km NE from Fort Frances, ON
2014-12-11	07:21:46	52.05N	92.89W	4/6	2.1	103 km SE from Deer Lake, ON
2014-12-15	19:41:22	49.20N	91.08W	6/12	1.8	63 km NE from Atikokan, ON
2014-12-19	09:25:46	48.67N	85.90W	5/8	1.6	36 km E from Marathon, ON
2014-12-23	10:54:59	52.38N	89.32W	4/6	1.9	99 km W from Lansdowne House, ON
2014-12-27	19:55:41	50.27N	84.15W	4/7	2.2	74 km NW from Hearst, ON
2014-12-29	10:16:46	49.58N	91.53W	6/12	1.7	63 km SE from Sioux Lookout, ON
2014-12-30	06:23:33	49.24N	92.09W	5/9	1.3	65 km NW from Atikokan, ON

Table 2: NWMO Supported Stations Operating During 2014
(2013 figures given in brackets)

Station		Lat (°N)	Long (°W)	Elev (m)	Uptime (%) 2014 (2013)	Dates of operation as digital stations
ULM	Pinawa	50.2503	95.8750	251	100.0 (100.0)	19941207[1]-
SOLO	Sioux Lookout	50.0213	92.0812	373	99.3 (93.5)	19981104-
TBO	Thunder Bay	48.6473	89.4083	468	84.4 (99.6)	19931005-
GTO	Geraldton	49.7455	86.9610	350	97.0 (97.5)	20010104-
KAPO	Kapuskasing	49.4504	82.5079	210	99.9 (99.6)	19980114-
EEO	Eldee	46.6411	79.0733	398	90.3 (96.1)	19931005-
CRLO	Chalk River	46.0375	77.3801	168	98.5 (98.9)	19941117-
SILO	Sutton Inlier	54.4791	84.9126	195	18.5 (0.0)	20030609-
VIMO	Victor Mine	52.8173	83.7449	78	99.6 (99.9)	20030611-
MALO	McAlpine Lake	50.0244	79.7635	271	99.8 (98.0)	20030620-
KILO	Kirkland Lake	48.4972	79.7232	314	97.8 (99.8)	20030622-
SUNO	Sudbury	46.6438	81.3442	343	81.0 (80.6)	20030623-
EPLO	Experimental Lake	49.6737	93.7258	437	96.3 (86.2)	20040611-
ATKO	Atikokan	48.8231	91.6004	383	99.8 (92.1)	20040609-
PKLO	Pickle Lake	51.4987	90.3522	376	99.9 (93.6)	20040615-
PNPO	Pukaskwa Nat. Park	48.5957	86.2846	219	99.3 (94.2)	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 2014.

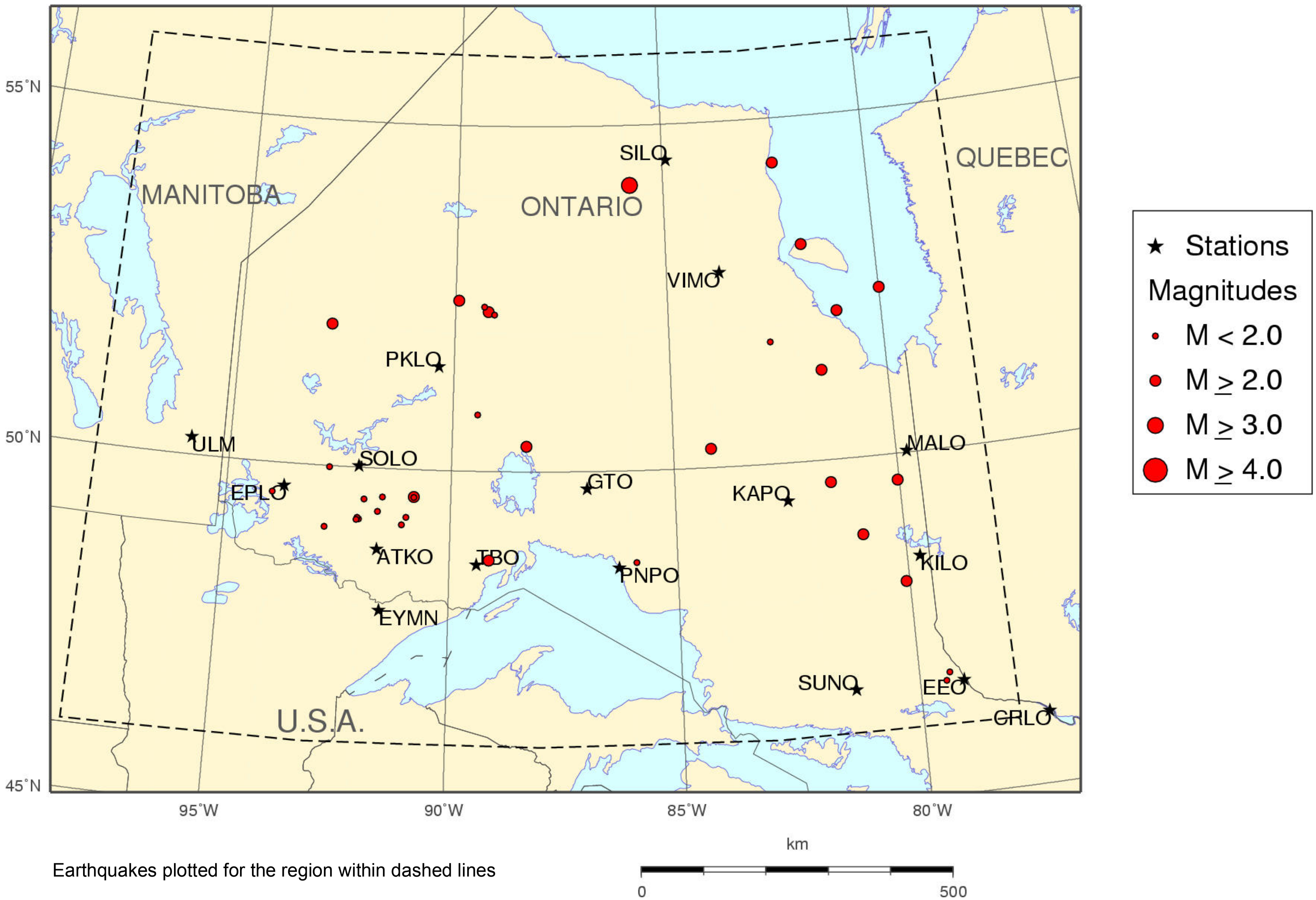
- The cause of the following outages at SOLO, GTO, and EEO are unknown, and data flow returned without any action being taken. SOLO was out from February 21st to 23rd. GTO dropped out from February 27th to March 2nd, and from November 29th to December 2nd. EEO was out during intervals from July 11th to 12th.
- TBO had outages starting from May 25th because the equipment was overheating. Our technologist completed a maintenance trip on July 27th.
- GTO dropped out from May 11th to 12th, from August 26th to 28th, and during intervals in November. Station electronics were remotely reset to restore data flow.
- Main power outages probably caused the following data outages at EEO and CRLO. CRLO dropped out during intervals in March and April and on September 27th and 28th. EEO was out on May 15th.
- EEO was out during intervals in early June when the temperature of the communications modem was changing too rapidly due to A/C air flow. The modem was shielded to provide more stable operation.
- EEO was out during intervals starting in July due to bad timing. The GPS timing was replaced by our technologist on November 9th.
- SILO had dropped out in 2010. Our technologist repaired the station July 16th, 2014. The digitizer, and the transceiver were replaced. Other damage caused by wildlife, including to cables, were also repaired. SILO dropped out again since September 6th. Our technologist suspects a loose connection at the station, possibly due to wildlife. A site trip is required.
- Maintenance at stations VIMO, MALO, and KILO resulted in outages from July 15th to 18th.
- A software problem on a data acquisition computer resulted in some missed data from stations VIMO, MALO, KILO, SUNO, EPLO, ATKO, PKLO, and PNPO on October 23rd, 24th, and 27th.
- Solar powered sites dropped out due to low battery voltage during parts of winter. KILO, SUNO, and EPLO, dropped out during intervals from December, 2013 through February, 2014. SUNO also dropped out starting in late November, 2014, and continuing into December.
- PNPO dropped out during intervals from December 8th to 11th. The transmission power was increased and data availability returned to normal.

Table 3: Depths Derived using Rg-phases and Regional Depth Phase Method (RDPM) for Moderate-sized Events for 2014

Date mm/dd	Time (UT) hh:mm:ss	Magnitude (m_N)	Depth (km)	Depth type Rg/RDPM	Region and Comment
01/27	10:47:48	1.7	5	Rg	77 km NE from Atikokan, ON
02/06	17:41:20	2.3	5	Rg	22 km NW from Mackenzie, ON
02/25	07:02:42	2.4	3.5	RDPM	86 km SW from Allanwater Bridge, ON
03/16	10:39:19	2.1	5	Rg	81 km E from Collins, ON
03/20	12:10:16	1.3	5	Rg	86 km SW from Allanwater Bridge, ON
03/22	21:47:17	2.2	5	Rg	113 km N from Pickle Lake, ON
03/23	07:43:48	1.2	5	Rg	69 km N from Atikokan, ON
03/27	21:46:34	1.4	5	Rg	64 km NW from Atikokan, ON
03/27	21:49:34	1.2	5	Rg	66 km NW from Atikokan, ON
03/28	10:23:01	1.7	5	Rg	60 km N from Collins, ON
07/05	03:02:50	2.6	5	Rg	3 km W from Kirkland Lake, ON
07/07	23:50:29	1.7	5	Rg	24 km N from Dryden, ON
07/23	05:17:50	1.2	5	Rg	28 km W from Temiscaming, QC
07/24	05:57:16	2.1	5	Rg	92 km W from Lansdowne House, ON
10/28	09:41:16	1.5	5	Rg	82 km W from Lansdowne House, ON
11/06	14:59:09	2.7	20	RDPM	72 km NE from Kapuskasing, ON
11/20	08:28:41	1.1	5	Rg	42 km SE from Kenora, ON
12/02	09:42:34	1.2	5	Rg	59 km S from Sioux Lookout, ON
12/03	07:58:48	3.0	19	RDPM	190 km NW of Victor Mine, ON
12/15	19:41:22	1.8	5	Rg	63 km NE from Atikokan, ON
12/23	10:54:59	1.9	5	Rg	99 km W from Lansdowne House, ON
12/29	10:16:46	1.7	5	Rg	63 km SE from Sioux Lookout, ON
12/30	06:23:33	1.3	5	Rg	65 km NW from Atikokan, ON

Table 4: Mining-Induced Seismic Events m_N 2.5 and Greater, January - December 2014

Date (yyyy/mm/dd)	Mine	Location	Magnitude (m_N)
2014-02-02	Creighton Mine	Sudbury	2.8
2014-02-02	Creighton Mine	Sudbury	3.0
2014-02-03	Creighton Mine	Sudbury	3.0
2014-02-24	Not determined	Sudbury	2.6
2014-03-22	Coleman Mine	Sudbury	2.7
2014-03-31	Creighton Mine	Sudbury	2.9
2014-04-05	Coleman Mine	Sudbury	2.6
2014-04-19	Creighton Mine	Sudbury	2.5
2014-07-03	Kidd Creek Mine	Timmins	3.1
2014-07-05	Garson mine	Sudbury	2.8
2014-08-05	Creighton Mine	Sudbury	3.3
2014-08-05	Creighton Mine	Sudbury	3.8
2014-10-28	?Copper Cliff Mine	Sudbury	2.6
2014-11-07	Coleman Mine	Sudbury	2.5
2014-11-10	Copper Cliff Mine	Sudbury	2.8
2014-12-12	Westwood Mine	Cadillac	3.0



Earthquakes plotted for the region within dashed lines

Figure 1: Earthquakes in Northern Ontario and Adjacent Areas, 2014

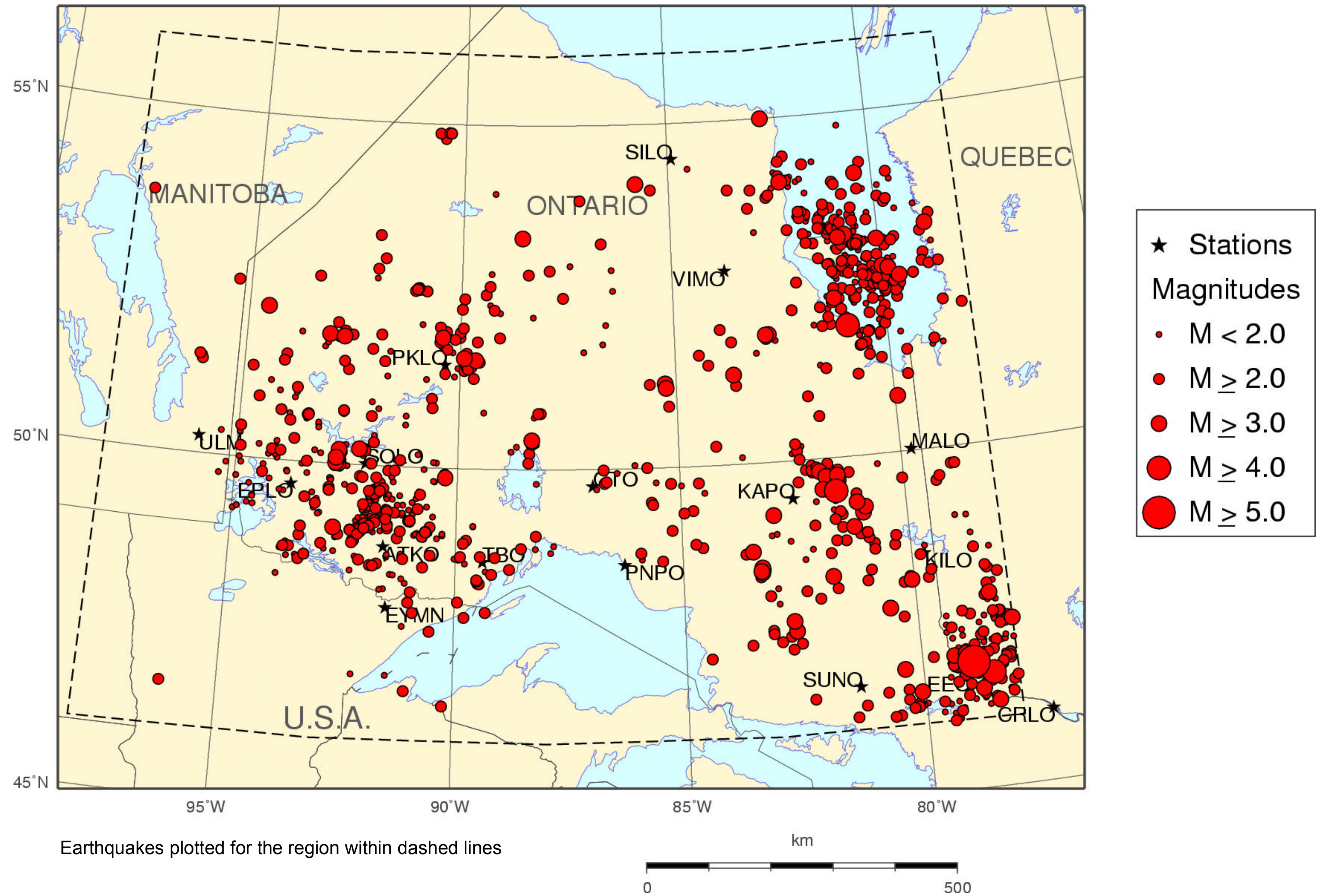
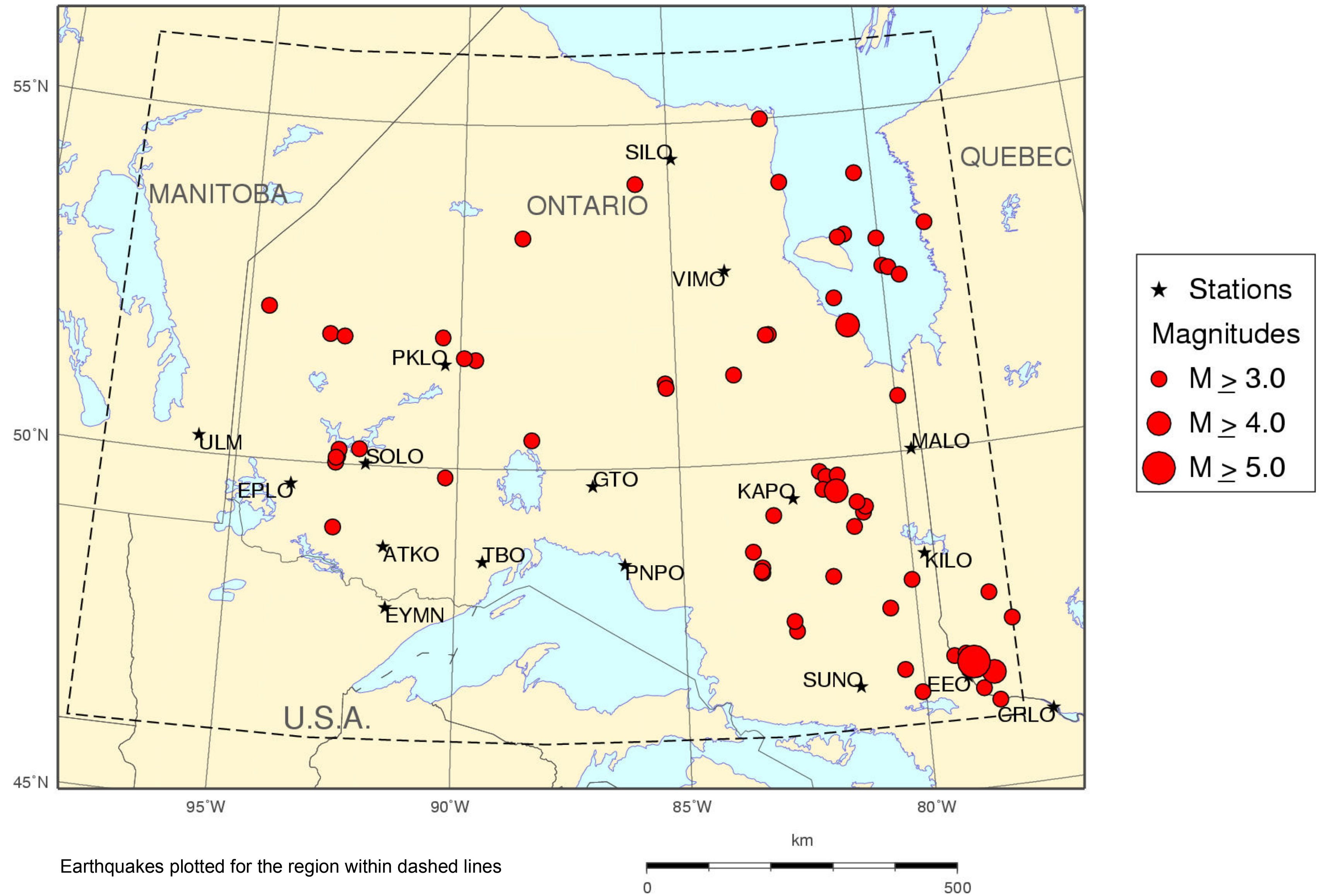


Figure 2: Earthquakes in Northern Ontario and Adjacent Areas, 1982 - 2014



Earthquakes plotted for the region within dashed lines

Figure 3: Earthquakes $m_N \geq 3$ in Northern Ontario and Adjacent Areas, 1982 – 2014

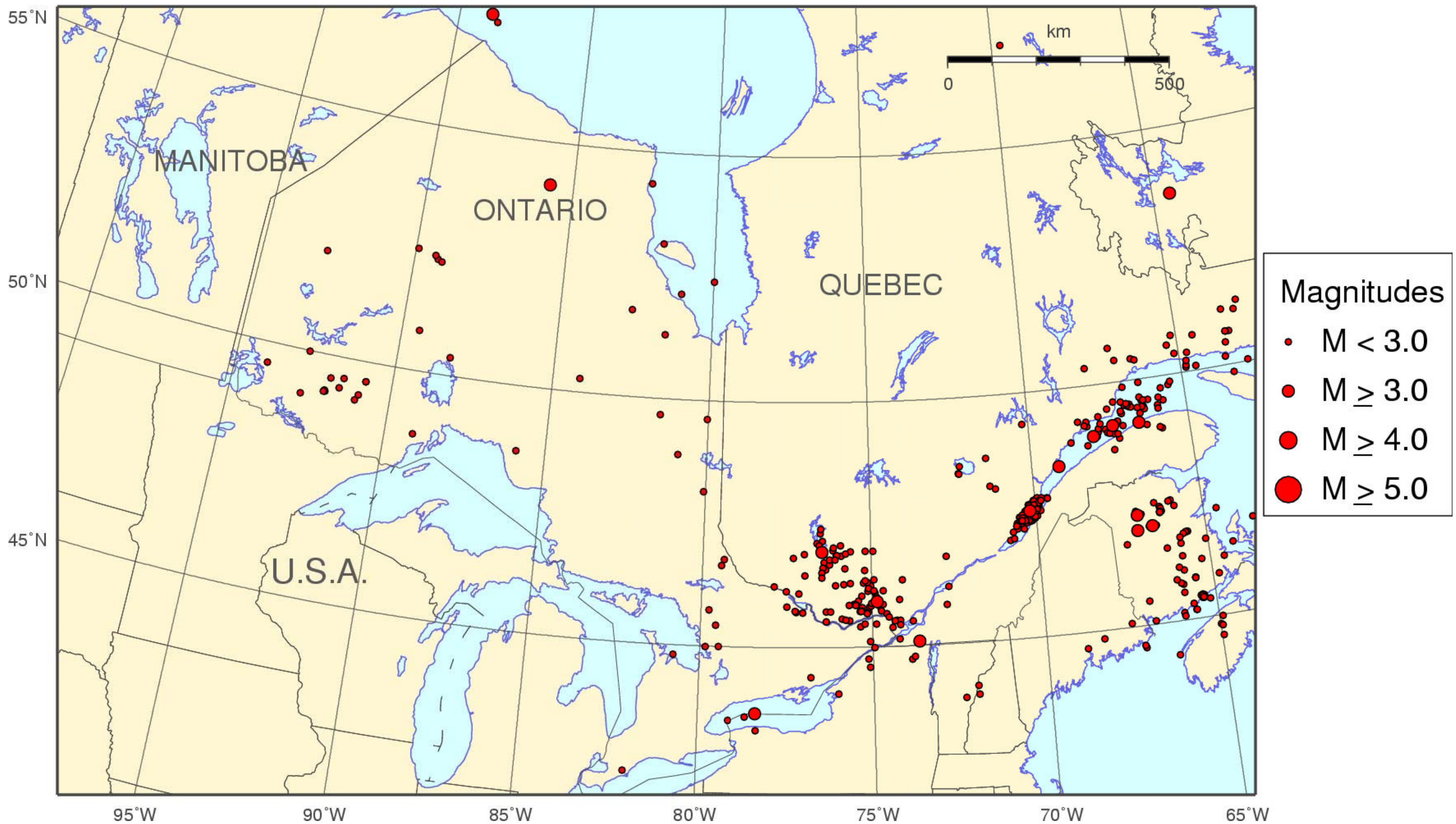


Figure 4: Earthquakes in Eastern Canada, 2014

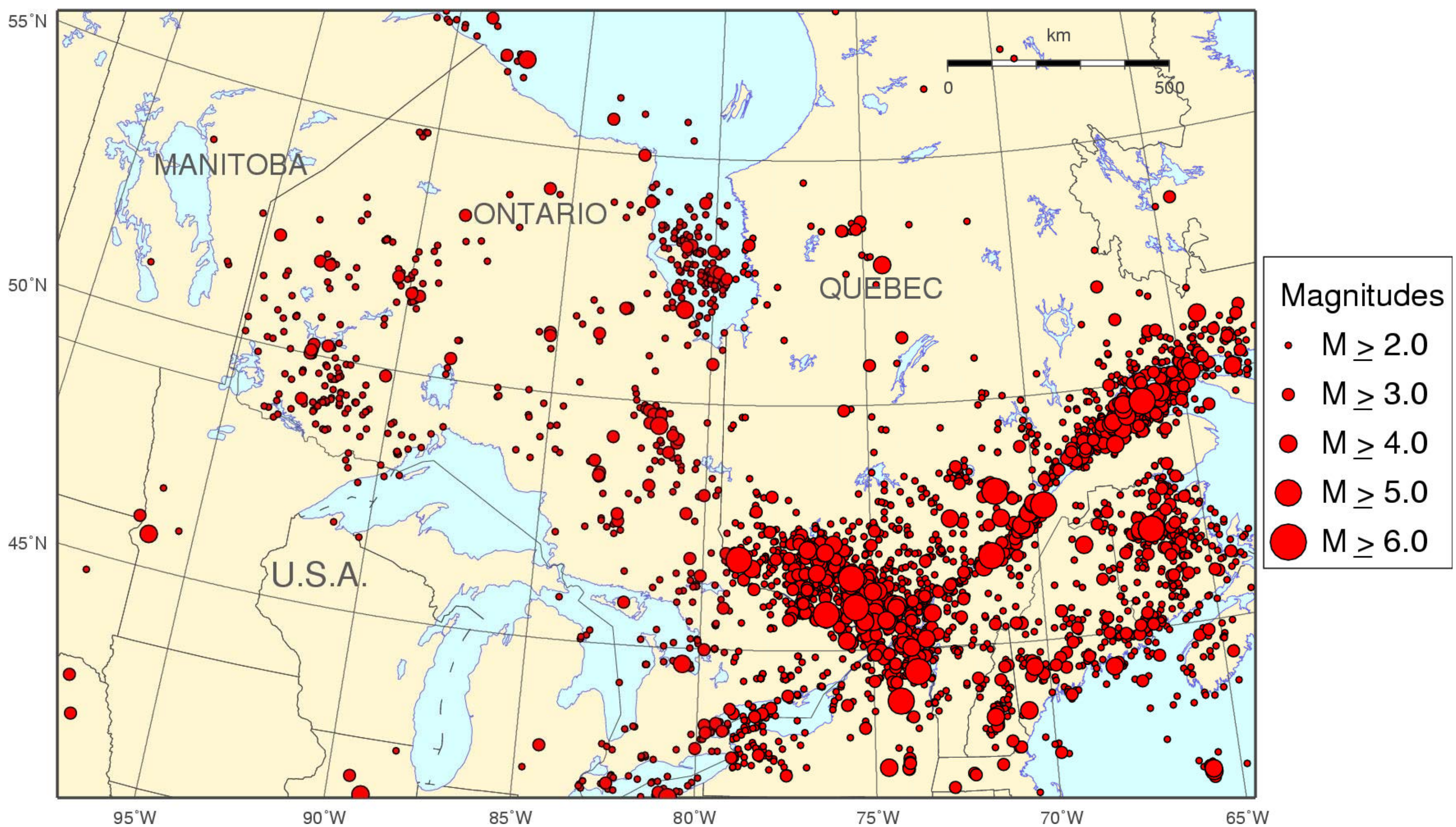


Figure 5: Earthquakes in Eastern Canada, 1982 - 2014

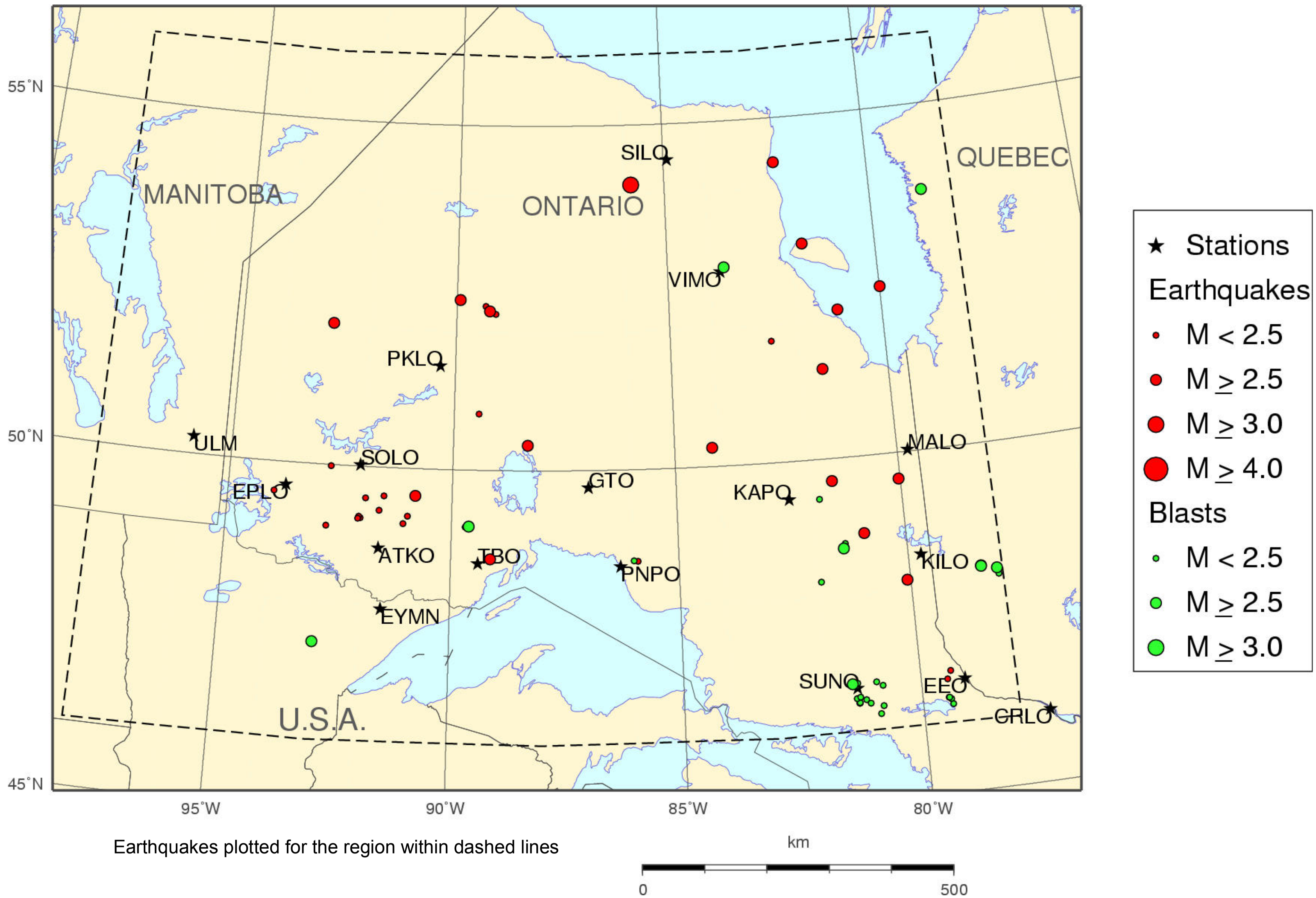


Figure 6: Earthquakes and Blasts in Northern Ontario and Adjacent Areas, 2014

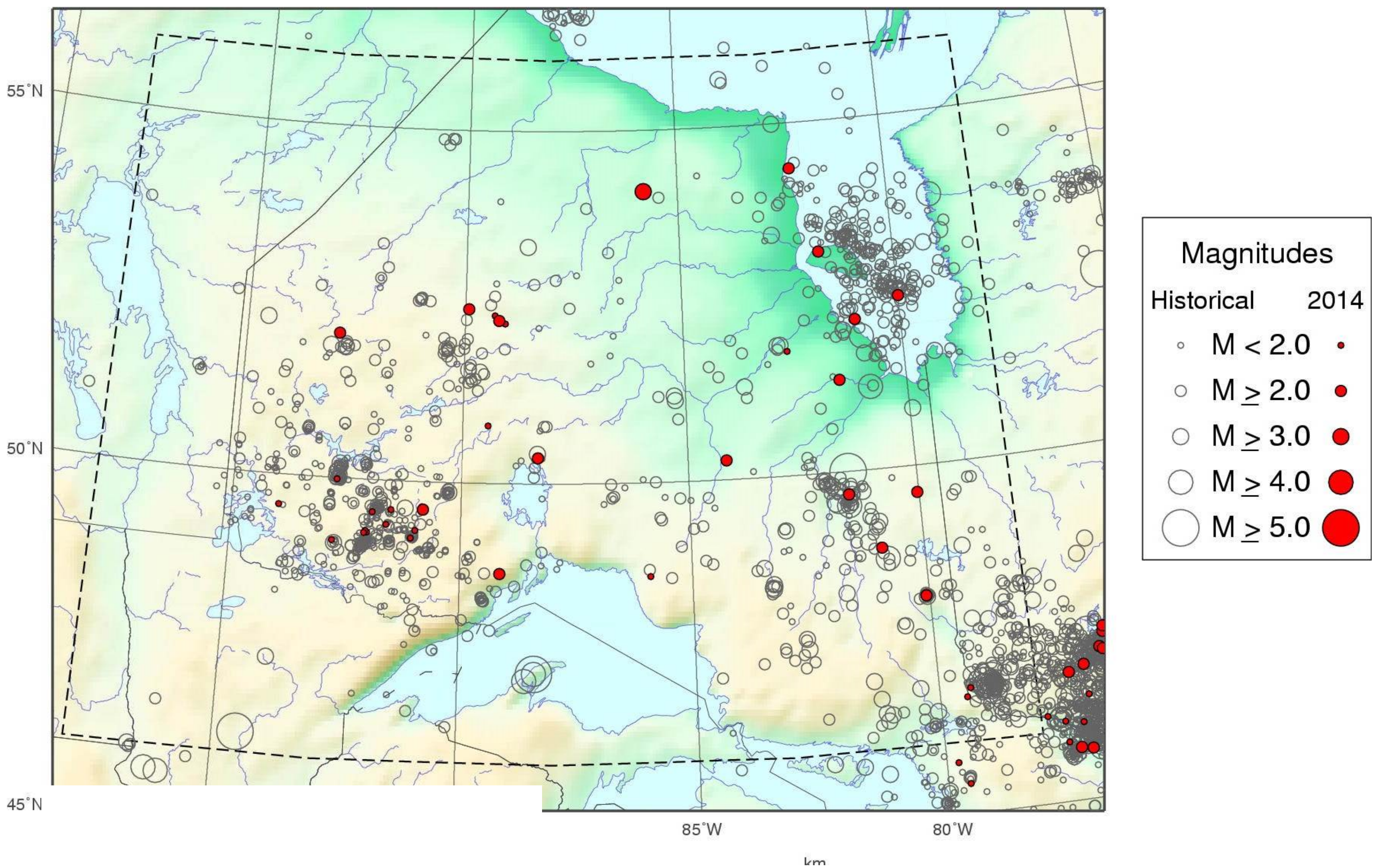


Figure 7: Earthquakes in Northern Ontario and Adjacent Areas for 2014 and prior years

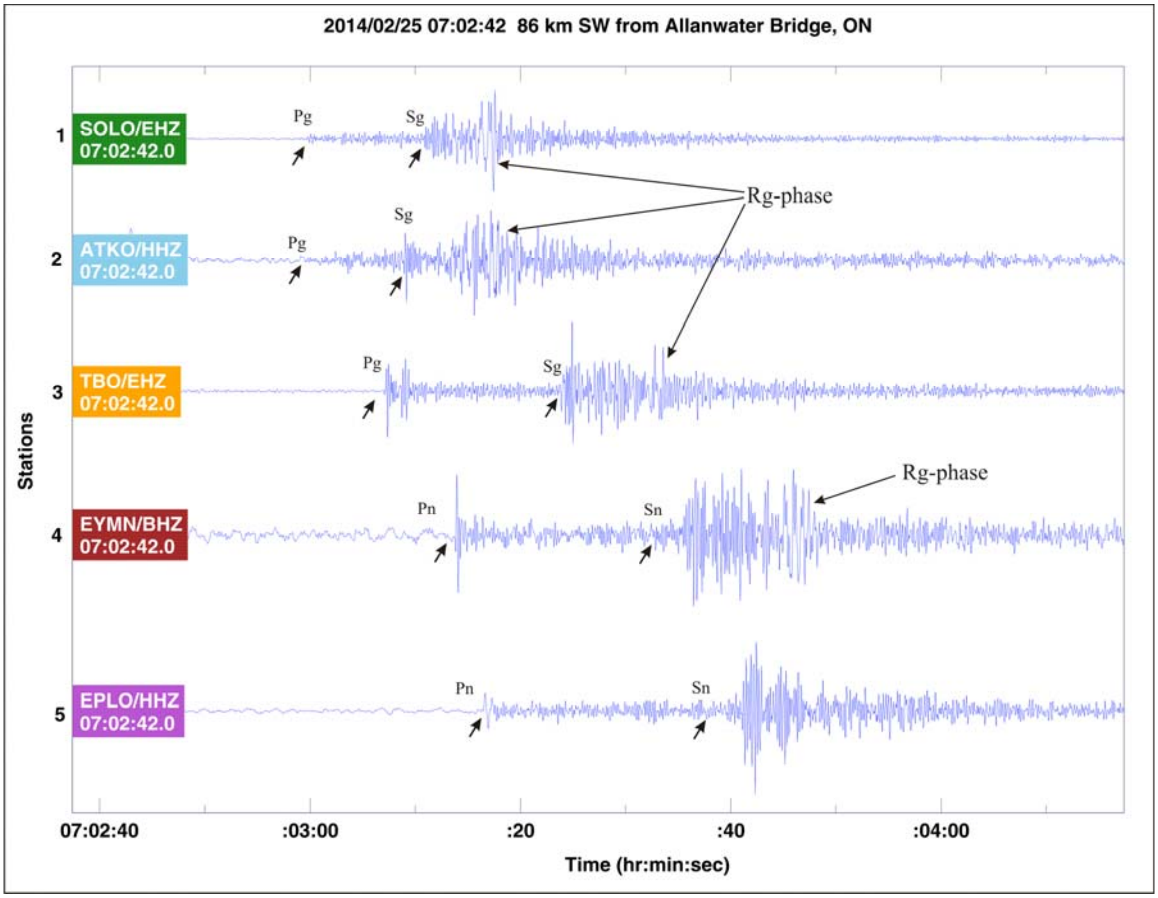


Figure 8: Rg Surface Waves from the m_N 2.4 on 2014/02/25, 86 km southwest of Allanwater Bridge, ON

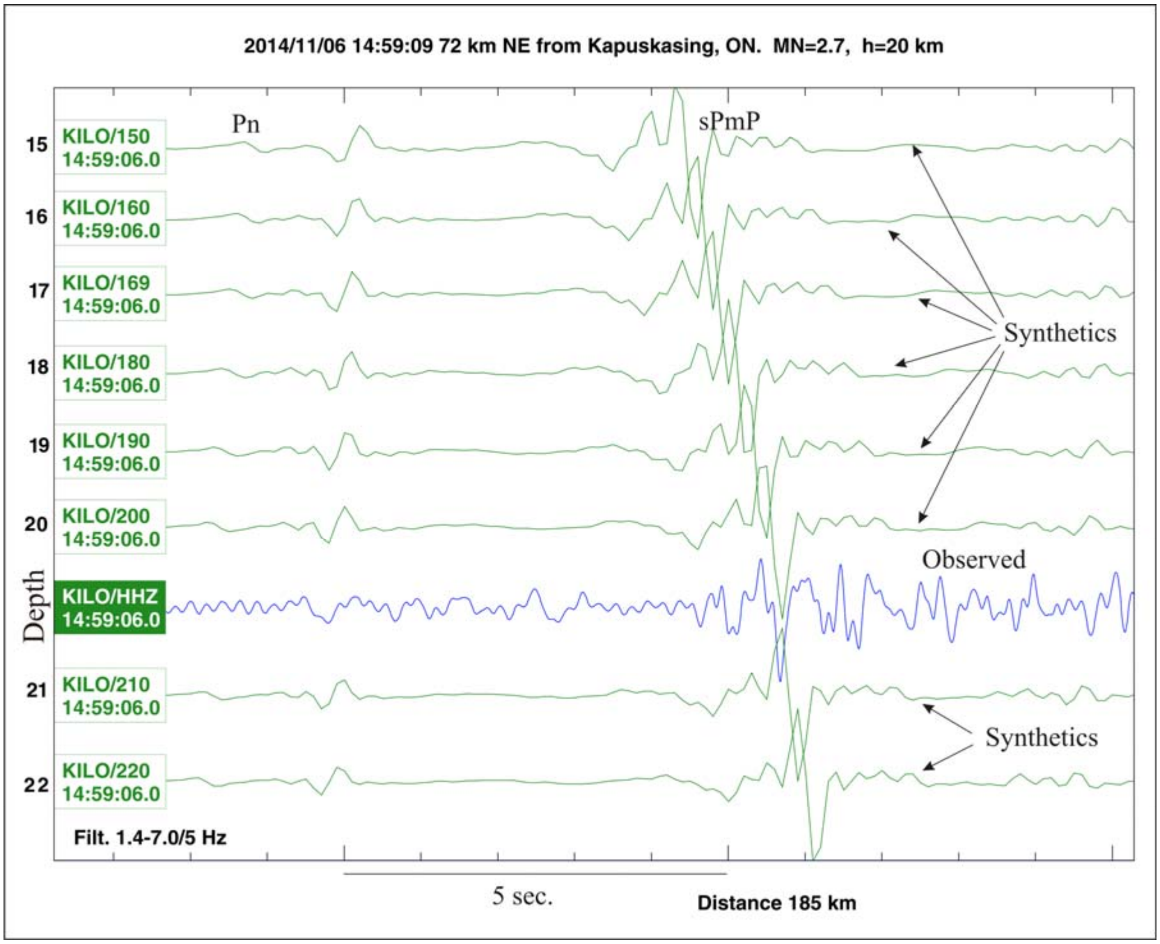


Figure 9A: Observed and Synthetic Waveforms from the m_N 2.7 on 2014/11/06, 72 km northeast of Kapuskasing, ON

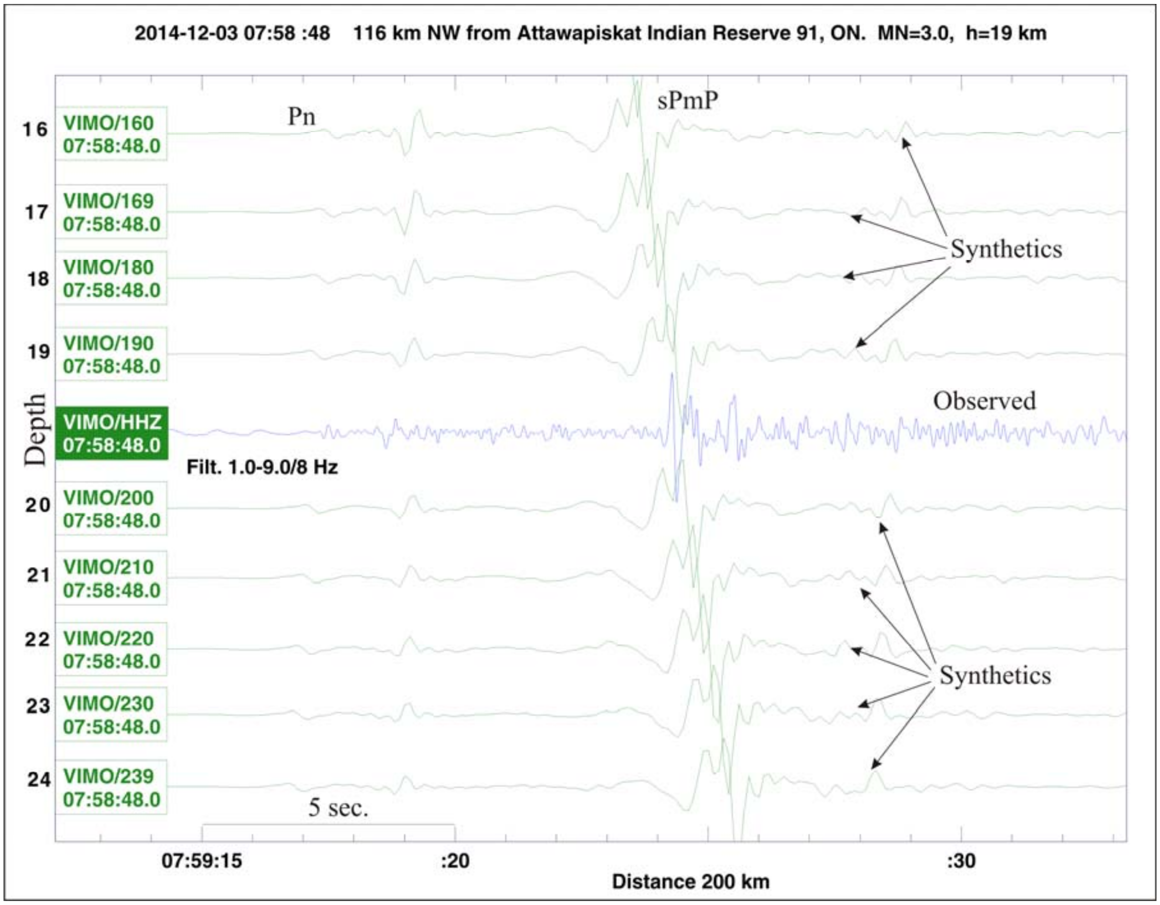


Figure 9B: Observed and Synthetic Waveforms from the m_N 3.0 on 2014/12/03, 116 km northwest of Attawapiskat Indian Reserve 91, ON

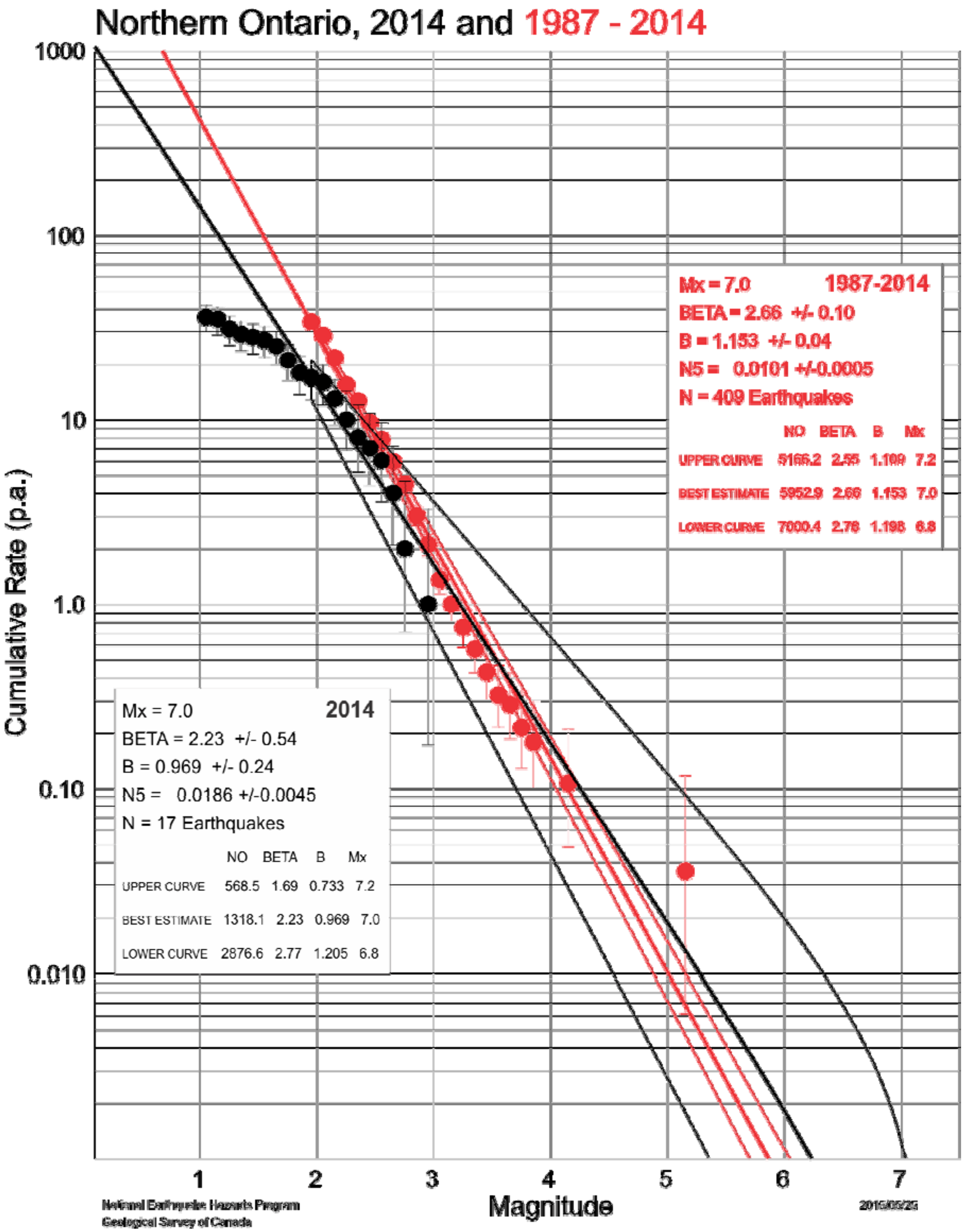
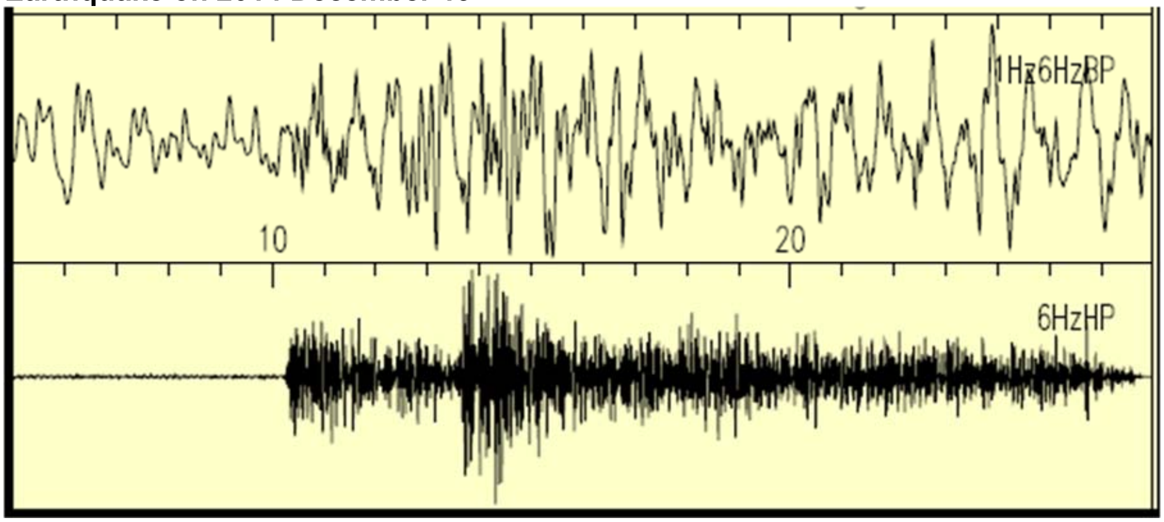


Figure 10: Recurrence Curves for Northern Ontario

Earthquake on 2014 December 19



Blast on 2013 May 22

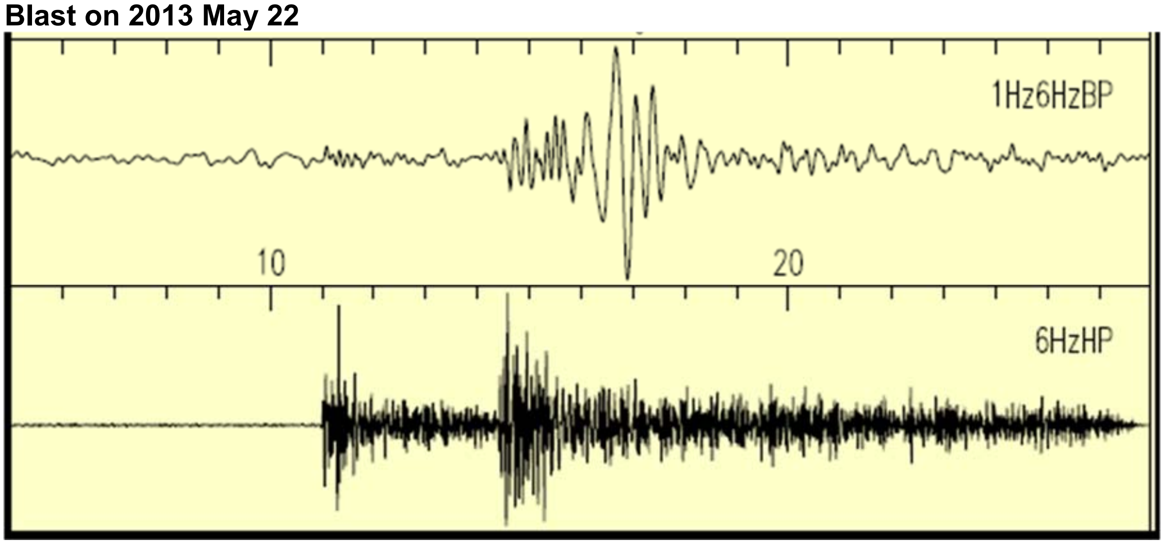


Figure 11. Waveforms at PNPO for the earthquake on December 19th (top) and for a previous nearby blast on 2013 May 22nd (bottom). In each, the lower panel shows high-frequency signals (frequencies below 6 Hz are filtered out) used to read phase arrivals for local earthquakes, while the upper panel shows energy in the 1-6 Hz window that identifies longer-period waves including Rg. The panels are auto-scaled to the maximum amplitude. In the upper panel for the earthquake what is seen is steady background seismic noise amplified to fit the window, while the upper panel for the blast shows clear waveforms for Rg between the 16 and 18 second marks. Therefore note the contrasting absence of Rg from the earthquake record.