# Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Report for the Period January 01 – December 31, 2012

**NWMO TR-2013-24** **December 2013**

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## ABSTRACT

**Title:** **Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Report for the Period January 01 – December 31, 2012**
**Report No.:** **NWMO TR-2013-24**
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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 2012.

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 project.

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 seismic activity in northern Ontario.

During 2012, 57 events were located. Their magnitude ranged from 1.1 $m_N$ to 4.2 $m_N$. The largest event with a magnitude of 4.2 occurred 69 km N of Moosonee, ON. The most westerly events in the area being studied was a small, $m_N$ 1.9 event, located 115 km northeast of Gimli, MB. This is the same location that saw two similar sized events last year. The pattern of seismicity for 2012 is similar to the seismicity patterns of the previous years. The 57 events located in 2012 compares with the 79 events located 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 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 2012.

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 POLARIS Consortium (http://www.polarisnet.ca).

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 data from the Canadian National Seismograph Network (CNSN) and 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 the Earthworm 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.

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

[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.

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 57 earthquakes were located. Their magnitude ranged from 1.1 $m_N$ to 4.2 $m_N$. The largest event of $m_N$ 4.2 was located in the James Bay region, 69 km north of Moosonee, Ontario, while the second largest, $m_N$ 3.9 occurred 64 km N of Chapleau, Ontario (see Figure 1).

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 2012 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 1-6, and the 2012 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 4000 earthquakes are located in Canada every year. CHIS operates approximately 150 instruments, called seismographs, across the country to detect and locate these events. Together, these instruments make up the 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.

CHIS also receives and archives all the data from the 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, approximately 5270 earthquakes had been located in Canada during the year 2012. Only 29 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 95% for six of the seven core seismograph station and above 90% for 5 of the 9 POLARIS stations.

EEO was operational for only 85.7% of the time, due mainly to an intermittent transmission failure that could not be identified. This problem was only resolved with the upgrade of the station from serial-based to IP-based very small aperture terminal (VSAT). Note that several stations received a similar type of upgrade, as the satellite provider is phasing-out the serial-based service.

Many of the solar powered sites, including MALO, EPLO, ATKO, PNPO and SUNO, experienced power failures and had poor telecommunications during the winter months, particularly January, February, November and December. SILO dropped out in 2010 due to faulty components at the site. As this site is quite remote, no maintenance trip to this site was made in 2012.

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

## 3. EARTHQUAKES

A total of 57 earthquakes were located in the study area during 2012. The events from the year are listed in Table 1 and plotted in Figure 1. The largest events located this year were a $m_N$ 4.2 event on May 2nd in the James Bay region, 69 km north of Moosonee, and a $m_N$ 3.9 event on September 22nd, 64 km north of Chapleau, Ontario (both of which were reported to be felt by people in the region). Note that the latter event was located in an area which did not have significant seismicity in the past, although there have been several smaller events in this region, including a $m_N$ 3.0 in 2012, within the last two years.

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 $m_N$ 2.0. 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 this lowered threshold can be seen particularly in the James Bay region where 220 events were located since 2004, which works out to approximately 24 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 2012, only six events were located in this region, but this does include the largest event recorded in the study area this year: the $m_N$ 4.2 recorded on May 2nd in the southern end of James Bay, 69 km N of Moosonee, ON.

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 first, with the poorest stations (based on poor uptime statistics, or the high noise levels at the site) chosen first 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 two 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 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 are 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 lower threshold is required over the entire study area, or a more focussed approach should be used.

The 57 earthquakes from 2012, compare to previous years as follows:

| Year | No. of events | No. of stations |
|---|---|---|
| 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 this is simply part of the natural yearly fluctuation.

In general, the pattern of activity for 2012 followed that of the previous years. Although there was no significant swarm activity within the region in 2012, there were five events in each of the following regions: (a) ~17 km northwest of Sioux-Lookout, (b) ~50 km northwest of Atikokan, and (c) ~135 km northwest of Pickle Lake. Also, six events were recorded in the region ~65 km north of Chapleau, including the $m_N$ 3.9. Note that several magnitude threes had also been recorded in this region in the previous year. A comparison of the waveforms, however, indicates that the events in the Chapleau series are from various distinct locations within the general region.

Three events occurred north of GTO in an area that has only seen very sparse activity in the past: the first on April 29th was a $m_N$ 2.3 and located 55 km NE of Webequie, ON (318 km NE of PKLO, 204km W of VIMO); the second on September 8th was a $m_N$ 1.9 located 80 km southeast of Lansdowne House (225 km E of PKLO, 218 km N of GTO), while the third was a $m_N$ 2.1 event occurring 34 km northeast of Lansdowne House (218 km NE of PKLO, 264 km W of VIMO). This region had recorded only minor dispersed seismicity in the past, with no event recorded prior to the start of this study in 1982. The events were both near the location threshold, with magnitudes of $m_N$ 2.3, 1.9 and 2.1, respectively.

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 1202 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 31 years (68 events). The pattern of all the seismicity echoes the pattern of the larger events.

Figure 4 illustrates the seismic activity in eastern Canada in year 2012. 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 about $m_N$ 3.0.

Figure 5 shows all the activity in eastern Canada for the entire monitoring period of 1982 - 2012. 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 2012 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.

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).

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 VIMO are shown for the $m_N$ 4.2 earthquake which occurred 69 km north of Moosonee, Ontario on May 2nd, 2012 in Figure 7. The waveforms from this station indicate a depth of 17.0 km, which is consistent with previous depths found for events in the James Bay region.

Figure 8 shows an earthquake that occurred northwest of Sioux Lookout on June 27th, 2012 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).

The earthquake epicentres of 2012 generally conform to areas of past seismicity. The magnitude 4.2 which occurred 69 km north of Moosonee, was only one of four events with magnitude greater than 4 to have occurred in the study region since 1982. The $m_N$ 3.9 and 3.0 events which were located at 64 km and 72 km north of Chapleau respectively, are part of a mini-swarm of events that continues on into 2013. This region had seen only a few events prior to 2012, and none prior to 1982, most likely due to the poor coverage of this region prior to the commencement of this northern Ontario project, the low rate of larger events in the region (magnitude 3.5+), as well as the quality of the data available prior to the installation the continuous, digital network (circa 1990 - 2000).

A $m_N$ 2.3, 1.9 and 2.1 were located north of GTO on April 29th, September 8th and November 18th respectively. This general region has seen very sparse and dispersed activity in the past, most of it being recorded since the installation of the FedNOR stations. No event with magnitude greater than 3 has been recorded in this region.

There was also a small event located 113 km NE of Gimli, MB, where only a few similar events have been recorded in the last two years. However, as these events occurred in areas which had little coverage prior to 2003, and even now have a higher location threshold than regions to the east, seismicity in these regions in the past could simply have been missed.

Recurrence curves for the study area for the year 2012 and for the period of 1987 to the end of 2012 (26 years of data) are shown in Figure 9 and are discussed in more detail in Section 6.

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

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.

## 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.

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. 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 spacings are 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 2011 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, 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 60km to 120km 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 Ma (2004) and extended with subsequent work appeared as Ma et al., (2008). Figure 7 shows an application of RDPM to a 2011 event and 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 2012 in northern Ontario that had an Rg phase present, and are therefore known to be shallow (fixed at 5 km depth), as well as the twelve events, which were well enough recorded at suitable distance for a reliable depth to be determined using the RDPM method.

### 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 station) 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 (is for the standard error of the mean), errors in magnitude are not considered further in this discussion.

## 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 26 years of data for the less-common larger earthquakes.

Figure 9 shows the magnitude-recurrence plot for the year 2012 earthquakes in black and the plot for the 26-year period of 1987 to 2012 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.

The 2012 curve is higher than the longer-term curve, but with a much greater uncertainty. For the year-2012 a best fit slope of b = 0.845 ± 0.16 was found, versus 1.163 ± 0.05 for the 26-year period curve. Note that the data points of the one-year curve (black) are very similar to the ones of the 26-year curve (red) at the lower magnitudes, but the coincidental occurrence of $m_N$ 4.2 and $m_N$ 3.9 earthquakes (in different places) in 2012 skews the year-2012 recurrence curve. This is as expected, as a single year's worth of data is not considered enough time to generate a statistically-significant curve for this region of relatively low seismicity in which the repeat time for events larger than 4 is close to a decade. 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).

## 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 104 mining-induced seismic events of magnitude -0.2 or greater in the study area in 2012. Fifty-one of these events occurred in the Sudbury Basin, 22 in the Red Lake region, 25 in the Cadillac, QC region, 3 in the Timmins area, and 3 near Kirkland Lake. Fifteen of these mining-induced events recorded in the study area in 2012 were larger than $m_N$ 2.5 and are listed in Table 4.

## 8. SUMMARY

The seismic activity in the study area during the calendar year 2012 consisted of 57 earthquakes ranging in magnitude from 1.1 to 4.2. Twenty-nine earthquakes were larger than $m_N$ 2.0, and three of the earthquakes were $m_N$ 3.0 or larger. Of these, the largest event, $m_N$ 4.2, was located 69 km north of Moosonee, and the $m_N$ 3.9 and 3.0 were both located north of Chapleau, in a region which has seen several events around magnitude 3 in the last couple of years. Based on the logarithmic frequency-magnitude relationship, mentioned in Section 1, the distribution of magnitudes indicates that a few earthquakes near $m_N$ 2.0 and many smaller remain undetected.

The distribution of the majority of the detected earthquakes in this region for 2012 conformed to the pattern of previous seismicity. However, the three events north of GTO indicate that there is sparse on-going activity between the regions of recurring low-level seismicity.

## ACKNOWLEDGEMENTS

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### Table 1: Located Local Earthquakes, January - December 2012

| Date | Time (UT) | Latitude | Longitude | #stns/ phases | Magnitude ($m_N$) | Region and Comment |
|---|---|---|---|---|---|---|
| 2012-01-12 | 00:28:31 | 49.44N | 91.21W | 3/ 6 | 1.2 | 83 km N from Atikokan, ON |
| 2012-01-25 | 02:09:08 | 50.20N | 94.50W | 3/ 6 | 1.1 | 43 km N from Kenora, ON |
| 2012-01-25 | 08:45:14 | 52.57N | 91.11W | 7/10 | 2.1 | 137 km NW from Pickle Lake, ON |
| 2012-01-26 | 09:42:12 | 49.63N | 94.66W | 3/ 6 | 1.4 | 27 km SW from Kenora, ON |
| 2012-01-27 | 20:11:35 | 51.43N | 95.95W | 4/ 6 | 1.9 | 115 km NE from Gimli, MB |
| 2012-01-29 | 19:32:40 | 46.67N | 78.98W | 3/ 6 | 1.4 | 11 km SE from Temiscaming, QC |
| 2012-02-01 | 15:58:52 | 52.56N | 90.83W | 4/ 6 | 2.1 | 133 km N from Pickle Lake, ON |
| 2012-02-02 | 08:34:43 | 49.12N | 91.94W | 4/ 7 | 1.3 | 48 km NW from Atikokan, ON |
| 2012-02-08 | 05:54:43 | 47.66N | 82.67W | 6/ 8 | 2.0 | 60 km E from Chapleau, ON |
| 2012-02-11 | 16:11:28 | 52.54N | 90.99W | 6/ 8 | 1.9 | 131 km NW from Pickle Lake, ON |
| 2012-02-12 | 13:52:16 | 52.61N | 91.03W | 8/13 | 2.7 | 139 km NW from Pickle Lake, ON |
| 2012-02-13 | 17:01:26 | 52.60N | 91.05W | 5/ 9 | 2.2 | 139 km NW from Pickle Lake, ON |
| 2012-03-04 | 05:04:31 | 52.58N | 91.06W | 6/12 | 2.3 | 138 km NW from Pickle Lake, ON |
| 2012-03-10 | 06:20:14 | 49.13N | 91.90W | 5/10 | 1.3 | 47 km NW from Atikokan, ON |
| 2012-03-11 | 10:27:06 | 48.96N | 92.23W | 4/ 8 | 1.2 | 50 km NW from Atikokan, ON |
| 2012-03-16 | 16:25:46 | 48.19N | 78.42W | 5/10 | 2.7 | 25 km NW from Malartic, QC |
| 2012-03-22 | 03:51:37 | 48.19N | 78.34W | 3/ 6 | 1.4 | 16 km W from Malartic, QC |
| 2012-04-10 | 07:08:35 | 49.92N | 94.37W | 4/ 8 | 1.7 | 12 km N from Kenora, ON |
| 2012-04-21 | 09:27:48 | 51.45N | 80.48W | 5/ 7 | 2.2 | 23 km NE from Moosonee, ON |
| 2012-04-29 | 19:15:37 | 53.27N | 86.68W | 4/ 7 | 2.3 | 55 km NE from Webequie, ON |
| 2012-05-02 | 00:03:40 | 51.90N | 80.93W | 6/12 | 4.2 | 69 km N from Moosonee, ON. Felt. |
| 2012-05-06 | 10:20:57 | 49.29N | 94.89W | 4/ 6 | 1.1 | 68 km SW from Kenora, ON |
| 2012-05-17 | 08:19:26 | 48.14N | 79.97W | 4/ 7 | 1.9 | 5 km E from Kirkland Lake, ON |
| 2012-06-01 | 08:37:20 | 47.55N | 78.26W | 6/10 | 2.0 | 81 km S from Malartic, QC |
| 2012-06-04 | 08:02:32 | 49.26N | 93.08W | 4/ 7 | 1.3 | 60 km S from Dryden, ON |
| 2012-06-05 | 08:58:36 | 49.45N | 94.57W | 3/ 6 | 1.2 | 42 km S from Kenora, ON |
| 2012-06-13 | 07:11:37 | 53.40N | 80.90W | 4/ 6 | 2.2 | James Bay. |
| 2012-06-26 | 14:37:49 | 47.19N | 78.18W | 4/ 7 | 1.4 | 88 km NE from Temiscaming, QC |
| 2012-06-27 | 06:00:37 | 50.23N | 92.12W | 9/18 | 2.7 | 18 km NW from Sioux Lookout, ON |
| 2012-06-28 | 02:43:26 | 50.21N | 92.11W | 7/14 | 2.6 | 17 km NW from Sioux Lookout, ON |
| 2012-06-30 | 02:59:32 | 52.70N | 79.99W | 6/ 9 | 2.4 | James Bay. |
| 2012-07-02 | 04:44:01 | 50.21N | 92.10W | 8/15 | 2.4 | 17 km NW from Sioux Lookout, ON |
| 2012-07-06 | 00:10:37 | 49.76N | 85.21W | 4/ 8 | 2.2 | 68 km NW from Hornepayne, ON |
| 2012-07-09 | 20:56:11 | 52.59N | 80.35W | 5/ 7 | 2.7 | James Bay |
| 2012-07-12 | 07:02:16 | 52.48N | 79.72W | 13/19 | 2.9 | James Bay |

| | | | | | | |
|---|---|---|---|---|---|---|
| 2012-07-14 | 12:34:10 | 46.13N | 79.43W | 6/11 | 1.5 | 10 km NW from Powassan, ON |
| 2012-07-20 | 09:41:24 | 49.06N | 90.61W | 4/ 8 | 1.3 | 83 km NE from Atikokan, ON |
| 2012-07-27 | 21:11:10 | 46.82N | 78.90W | 6/10 | 1.7 | 19 km NE from Temiscaming, QC |
| 2012-07-29 | 13:25:20 | 49.12N | 91.95W | 6/12 | 2.0 | 47 km NW from Atikokan, ON |
| 2012-07-29 | 16:01:16 | 49.13N | 91.95W | 6/10 | 1.7 | 48 km NW from Atikokan, ON |
| 2012-08-13 | 03:20:16 | 50.20N | 92.09W | 5/ 9 | 1.7 | 17 km NW from Sioux Lookout, ON |
| 2012-08-22 | 07:04:53 | 46.84N | 78.89W | 5/ 8 | 1.3 | 19 km NE from Temiscaming, QC |
| 2012-08-24 | 23:00:50 | 50.20N | 92.09W | 5/ 9 | 1.5 | 17 km NW from Sioux Lookout, ON |
| 2012-08-25 | 17:47:57 | 50.32N | 93.72W | 3/ 6 | 1.8 | 75 km NE from Kenora, ON |
| 2012-08-28 | 01:32:22 | 46.30N | 79.62W | 6/11 | 1.8 | 13 km W from North Bay, ON |
| 2012-08-31 | 04:57:12 | 49.85N | 90.29W | 7/13 | 2.4 | 44 km S from Allanwater Bridge, ON |
| 2012-09-05 | 07:55:05 | 50.33N | 93.72W | 5/10 | 2.1 | 76 km NE from Kenora, ON |
| 2012-09-06 | 15:56:10 | 49.23N | 91.57W | 6/11 | 2.2 | 55 km N from Atikokan, ON |
| 2012-09-08 | 19:41:57 | 51.70N | 87.12W | 4/ 8 | 1.9 | 80 km SE of Lansdowne House, ON |
| 2012-09-22 | 13:39:16 | 46.21N | 78.67W | 6/10 | 1.5 | 13 km S from Mattawa, ON |
| 2012-09-22 | 16:10:40 | 48.40N | 83.28W | 9/13 | 3.9 | 64 km N from Chapleau, ON. Felt. |
| 2012-10-17 | 02:32:38 | 48.48N | 83.28W | 7/11 | 3.0 | 72 km N from Chapleau, ON |
| 2012-10-18 | 06:36:04 | 49.98N | 92.49W | 4/ 7 | 1.4 | 33 km NE from Dryden, ON |
| 2012-11-18 | 20:35:46 | 52.49N | 87.60W | 5/ 8 | 2.1 | 34 km NE of Lansdowne House, ON |
| 2012-11-19 | 05:51:17 | 48.45N | 83.21W | 4/ 6 | 2.0 | 65 km N from Chapleau, ON |
| 2012-11-22 | 01:52:12 | 48.45N | 83.28W | 10/13 | 2.6 | 69 km N from Chapleau, ON |
| 2012-11-22 | 01:52:08 | 48.45N | 83.28W | 4/ 5 | 2.3 | 69 km N from Chapleau, ON |

## Table 2: NWMO Supported Stations Operating During 2012 (2011 figures given in brackets)

| Station | | Lat (°N) | Long (°W) | Elev (m) | Uptime (%) 2010 (2009) | Dates of operation as digital stations |
|---|---|---|---|---|---|---|
| ULM | Pinawa | 50.2503 | 95.8750 | 251 | 100.0 (99.7) | 19941207[1]- |
| SOLO | Sioux Lookout | 50.0213 | 92.0812 | 373 | 99.0 (98.0) | 19981104- |
| TBO | Thunder Bay | 48.6473 | 89.4083 | 468 | 96.8 (99.8) | 19931005- |
| GTO | Geraldton | 49.7455 | 86.9610 | 350 | 99.3 (99.7) | 20010104- |
| KAPO | Kapuskasing | 49.4504 | 82.5079 | 210 | 97.8 (94.5) | 19980114- |
| EEO | Eldee | 46.6411 | 79.0733 | 398 | 85.7 (89.7) | 19931005- |
| CRLO | Chalk River | 46.0375 | 77.3801 | 168 | 98.1 (99.4) | 19941117- |
| SILO | Sutton Inlier | 54.4791 | 84.9126 | 195 | 0.0 (0.0) | 20030609- |
| VIMO | Victor Mine | 52.8173 | 83.7449 | 78 | 99.9 (98.4) | 20030611- |
| MALO | McAlpine Lake | 50.0244 | 79.7635 | 271 | 91.2 (88.3) | 20030620- |
| KILO | Kirkland Lake | 48.4972 | 79.7232 | 314 | 93.7 (93.3) | 20030622- |
| SUNO | Sudbury | 46.6438 | 81.3442 | 343 | 86.3 (87.3) | 20030623- |
| EPLO | Experimental Lake | 49.6737 | 93.7258 | 437 | 81.5 (96.4) | 20040611- |
| ATKO | Atikokan | 48.8231 | 91.6004 | 383 | 88.1 (97.4) | 20040609- |
| PKLO | Pickle Lake | 51.4987 | 90.3522 | 376 | 92.2 (100.0) | 20040615- |
| PNPO | Pukaskwa Nat. Park | 48.5957 | 86.2846 | 219 | 90.7 (98.3) | 20040618- |

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

Notes:
The following summary lists major outages that affected station operation times in 2012. All times given are in UT (Universal Time).

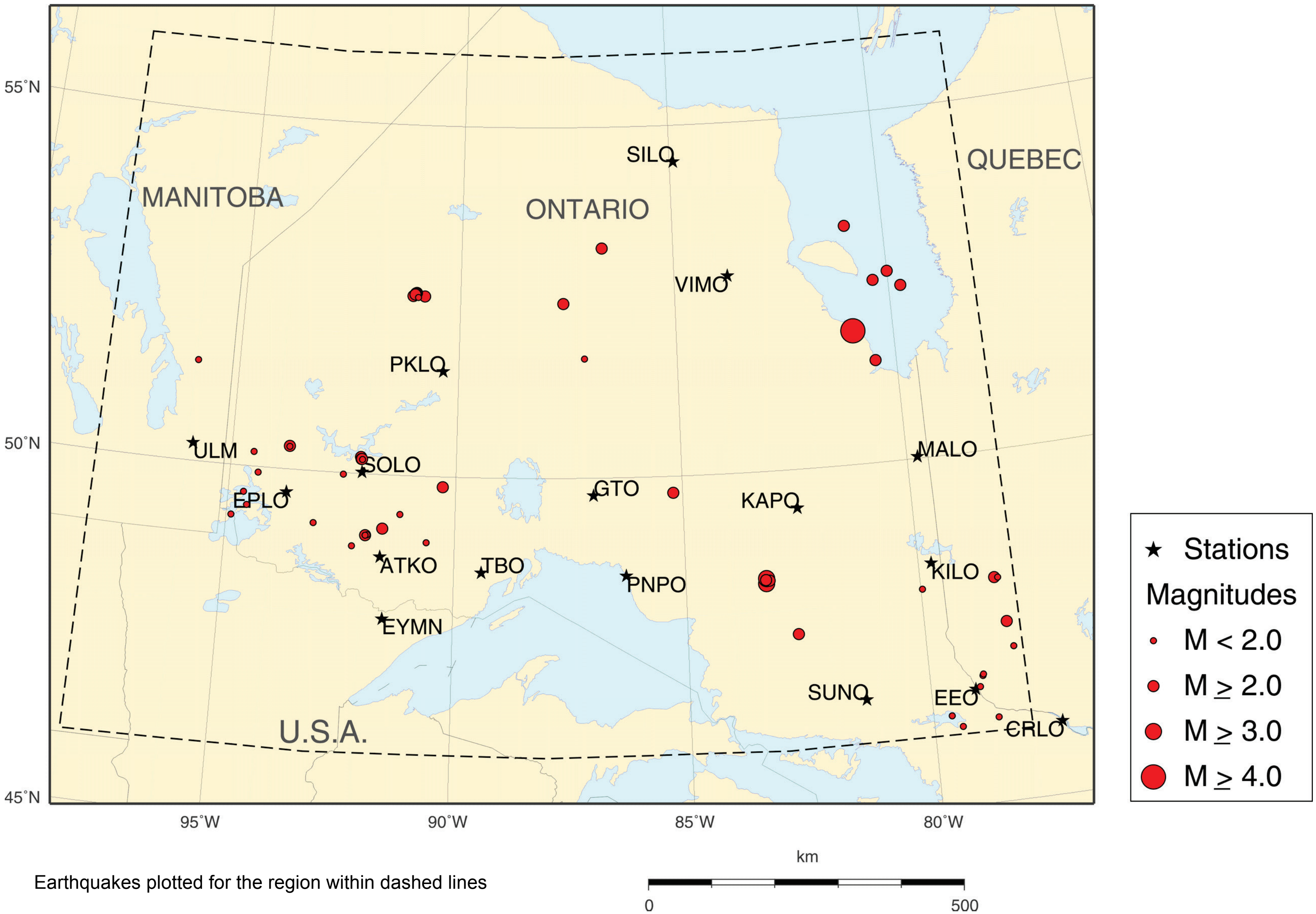
- SILO remains out since July 30, 2010 due to faulty station components. No maintenance trip to this site was made during 2012.
- MALO, KILO, SUNO, EPLO, ATKO, and PNPO, which are solar powered sites, dropped out due to low battery voltage during intervals during January to March. And again in November and December, MALO, SUNO, EPLO, ATKO, PKLO and PNPO began to drop out due to low battery voltage.
- TBO and KAPO communications were upgraded from serial-based to IP-based VSAT in January, resulting in an outage during the work.
- SOLO, GTO and EEO were out in October during upgrades of the satellite communications to IP-based VSAT.
- EEO has been dropping out during intervals while reporting data packet errors since June 2011. The satellite communications provider replaced VSAT electronics at the site to restore good data transmission, however, the problem continued. The satellite communications provider found no fault with their equipment. This problem was fixed in October with the upgrade of the satellite communications (see previous note).
- CRLO dropped out from March 4th to 8th, and May 3rd, 4th, 22nd and 23rd due to power outages.
- TBO was out from June 14th to 22nd due to a loss of main power.
- GTO dropped out from October 17th to 19th when a UPS failed.
- SOLO was out during intervals in December due to snow on the VSAT dish.

**Table 3: Depths Derived using Rg-phases and Regional Depth Phase Method (RDPM) for Moderate-sized Events for 2012**

| Date mm/dd | Time (UT) hh:mm:ss | Magnitude ($m_N$) | Depth (km) | Depth type Rg/RDPM | Region and Comment |
|---|---|---|---|---|---|
| 01/25 | 08:45:14 | 2.1 | 5 | Rg | 137 km NW from Pickle Lake, ON |
| 01/27 | 20:11:35 | 1.9 | 5 | Rg | 115 km NE from Gimli, MB |
| 02/01 | 15:58:52 | 2.1 | 5 | Rg | 133 km N from Pickle Lake, ON |
| 02/08 | 05:54:43 | 2.0 | 5 | Rg | 60 km E from Chapleau, ON |
| 02/11 | 16:11:28 | 1.9 | 5 | Rg | 131 km NW from Pickle Lake, ON |
| 02/12 | 13:52:16 | 2.7 | 1 | RDPM | 139 km NW from Pickle Lake, ON |
| 03/04 | 05:04:31 | 2.3 | 1 | RDPM | 138 km NW from Pickle Lake, ON |
| 03/10 | 06:20:14 | 1.3 | 5 | Rg | 47 km NW from Atikokan, ON |
| 03/16 | 16:25:46 | 2.7 | 4 | RDPM | 25 km NW from Malartic, QC |
| 04/10 | 07:08:35 | 1.7 | 5 | Rg | 12 km N from Kenora, ON |
| 05/02 | 00:03:40 | 4.2 | 17 | RDPM | 69 km N from Moosonee, ON. Felt. |
| 05/06 | 10:20:57 | 1.1 | 5 | Rg | 68 km SW from Kenora, ON |
| 05/17 | 08:19:26 | 1.9 | 1 | Rg | 5 km E from Kirkland Lake, ON |
| 06/27 | 06:00:37 | 2.7 | 3 | RDPM | 18 km NW from Sioux Lookout, ON |
| 06/28 | 02:43:26 | 2.6 | 3 | RDPM | 17 km NW from Sioux Lookout, ON |
| 07/02 | 04:44:01 | 2.4 | 3 | RDPM | 17 km NW from Sioux Lookout, ON |
| 07/06 | 00:10:37 | 2.2 | 1 | RDPM | 68 km NW from Hornepayne, ON |
| 07/12 | 07:02:16 | 2.9 | 14 | RDPM | James Bay |
| 07/29 | 13:25:20 | 2.0 | 5 | Rg | 47 km NW from Atikokan, ON |
| 07/29 | 16:01:16 | 1.7 | 5 | Rg | 48 km NW from Atikokan, ON |
| 08/13 | 03:20:16 | 1.7 | 5 | Rg | 17 km NW from Sioux Lookout, ON |
| 08/24 | 23:00:50 | 1.5 | 5 | Rg | 17 km NW from Sioux Lookout, ON |
| 08/25 | 17:47:57 | 1.8 | 5 | Rg | 75 km NE from Kenora, ON |
| 08/28 | 01:32:22 | 1.8 | 5 | Rg | 13 km W from North Bay, ON |
| 08/31 | 04:57:12 | 2.4 | 3 | RDPM | 44 km S from Allanwater Bridge, |
| 09/05 | 07:55:05 | 2.1 | 5 | Rg | 76 km NE from Kenora, ON |
| 09/06 | 15:56:10 | 2.2 | 1 | RDPM | 55 km N from Atikokan, ON |
| 09/22 | 16:10:40 | 3.9 | 8 | RDPM | 64 km N from Chapleau, ON. Felt. |
| 10/18 | 06:36:04 | 1.4 | 5 | Rg | 33 km NE from Dryden, ON |

**Table 4: Mining-Induced Seismic Events $m_N$ 2.5 and Greater, January - December 2012**

| Date (yyyy/mm/dd) | Mine | Location | Magnitude ($m_N$) |
|---|---|---|---|
| 2012/01/05 | Laronde Mine | Cadillac | 2.7 |
| 2012/02/25 | Coleman Mine | Sudbury | 2.7 |
| 2012/03/14 | Campbell Mine | Red Lake | 2.7 |
| 2012/03/14 | Campbell Mine | Red Lake | 2.6 |
| 2012/04/02 | Macassa Mine | Kirkland Lake | 2.6 |
| 2012/04/16 | Laronde Mine | Cadillac | 3.3 |
| 2012/06/30 | Campbell Mine | Red Lake | 3.1 |
| 2012/07/29 | Laronde Mine | Cadillac | 2.6 |
| 2012/08/03 | Campbell Mine | Red Lake | 2.6 |
| 2012/08/03 | Laronde Mine | Cadillac | 3.0 |
| 2012/08/18 | Creighton Mine | Sudbury | 3.1 |
| 2012/09/05 | Laronde Mine | Cadillac | 2.9 |
| 2012/11/02 | Laronde Mine | Cadillac | 2.8 |
| 2012/11/10 | Coleman Mine | Sudbury | 3.0 |
| 2012/11/15 | Lockerby Mine | Sudbury | 3.0 |




Earthquakes plotted for the region within dashed lines

**Figure 1: Earthquakes in Northern Ontario and Adjacent Areas, 2012**

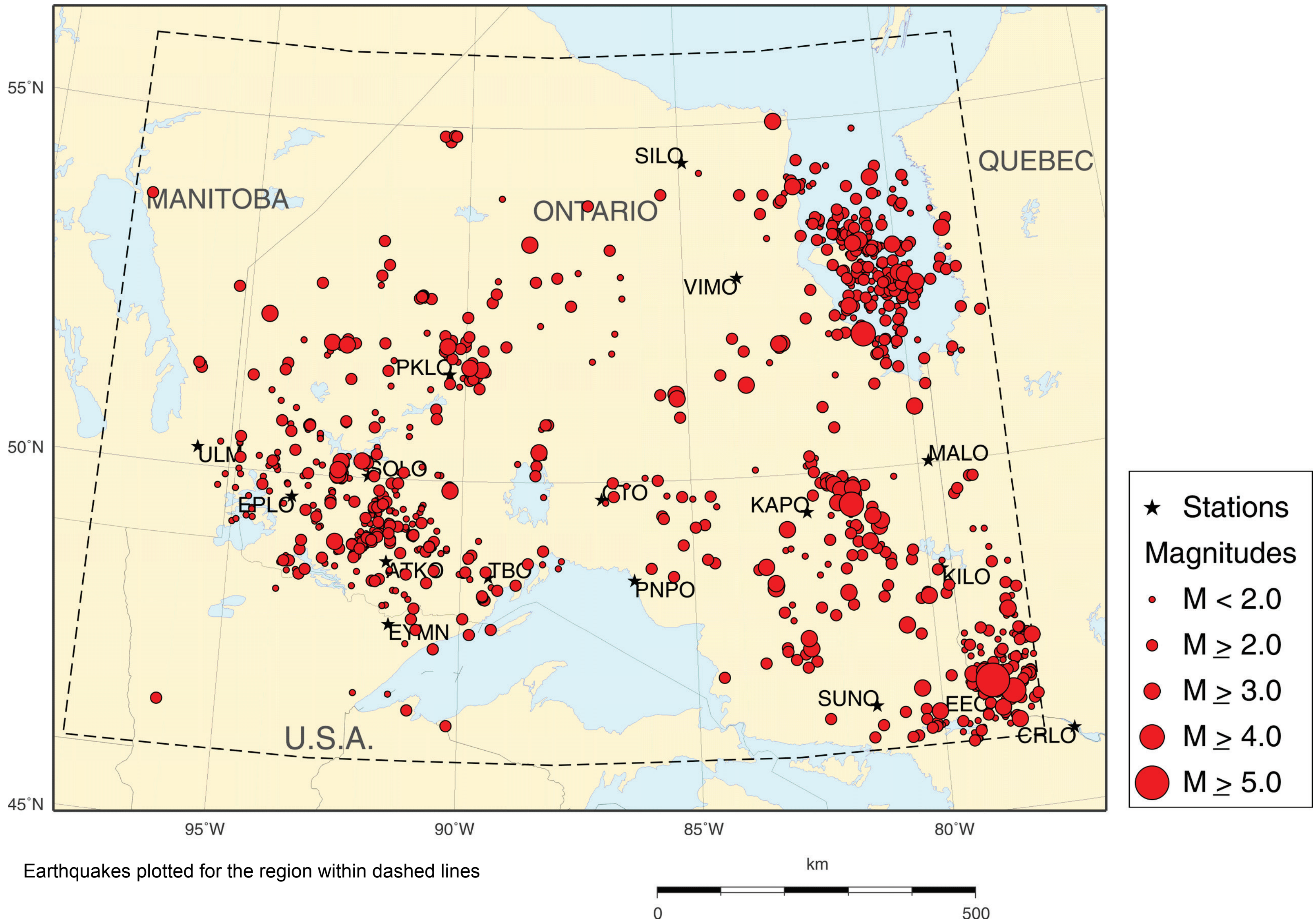
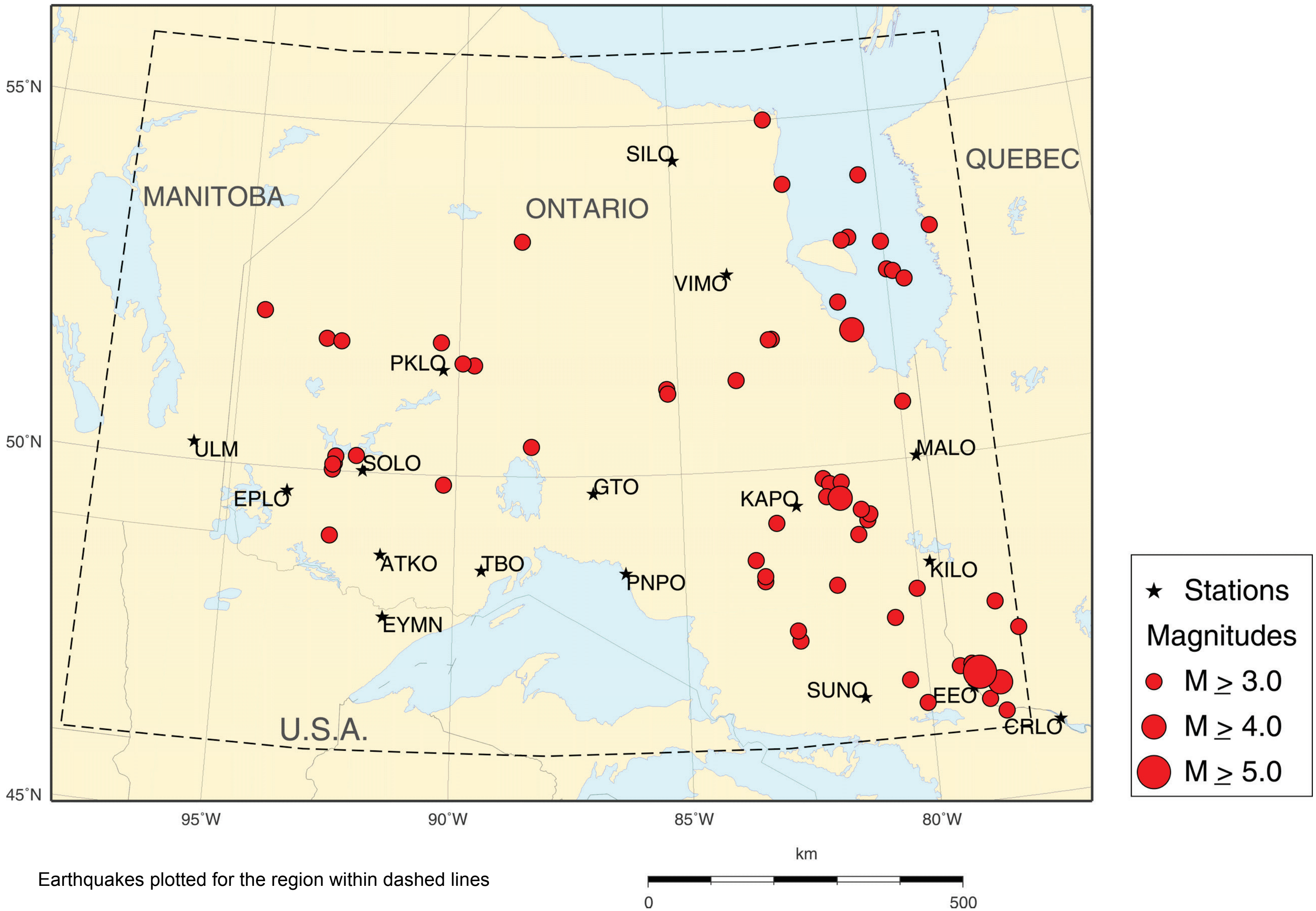



**Figure 2: Earthquakes in Northern Ontario and Adjacent Areas, 1982 - 2012**




Earthquakes plotted for the region within dashed lines

**Figure 3: Earthquakes $m_N \geq 3$ in Northern Ontario and Adjacent Areas, 1982 – 2012**

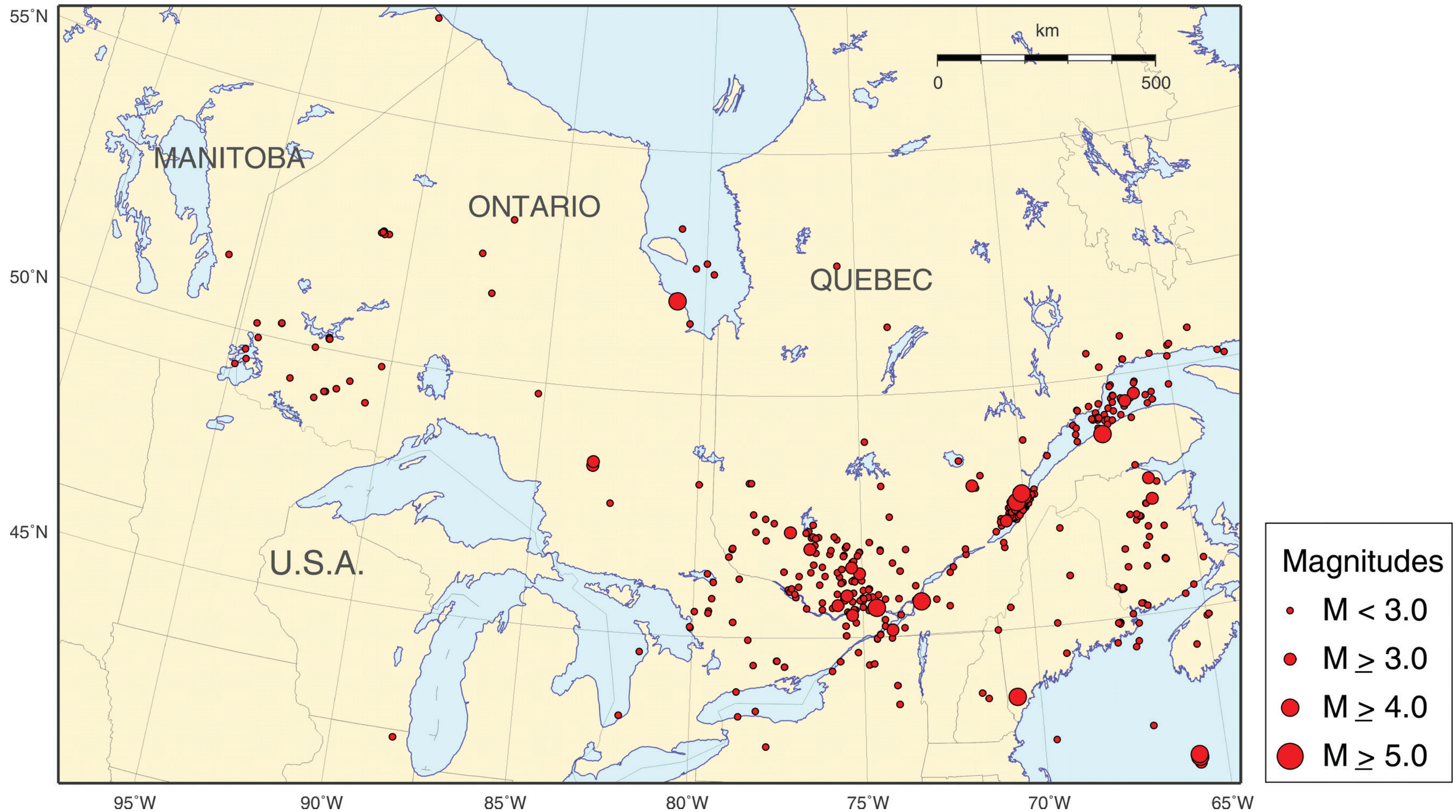



**Figure 4: Earthquakes in Eastern Canada, 2012**

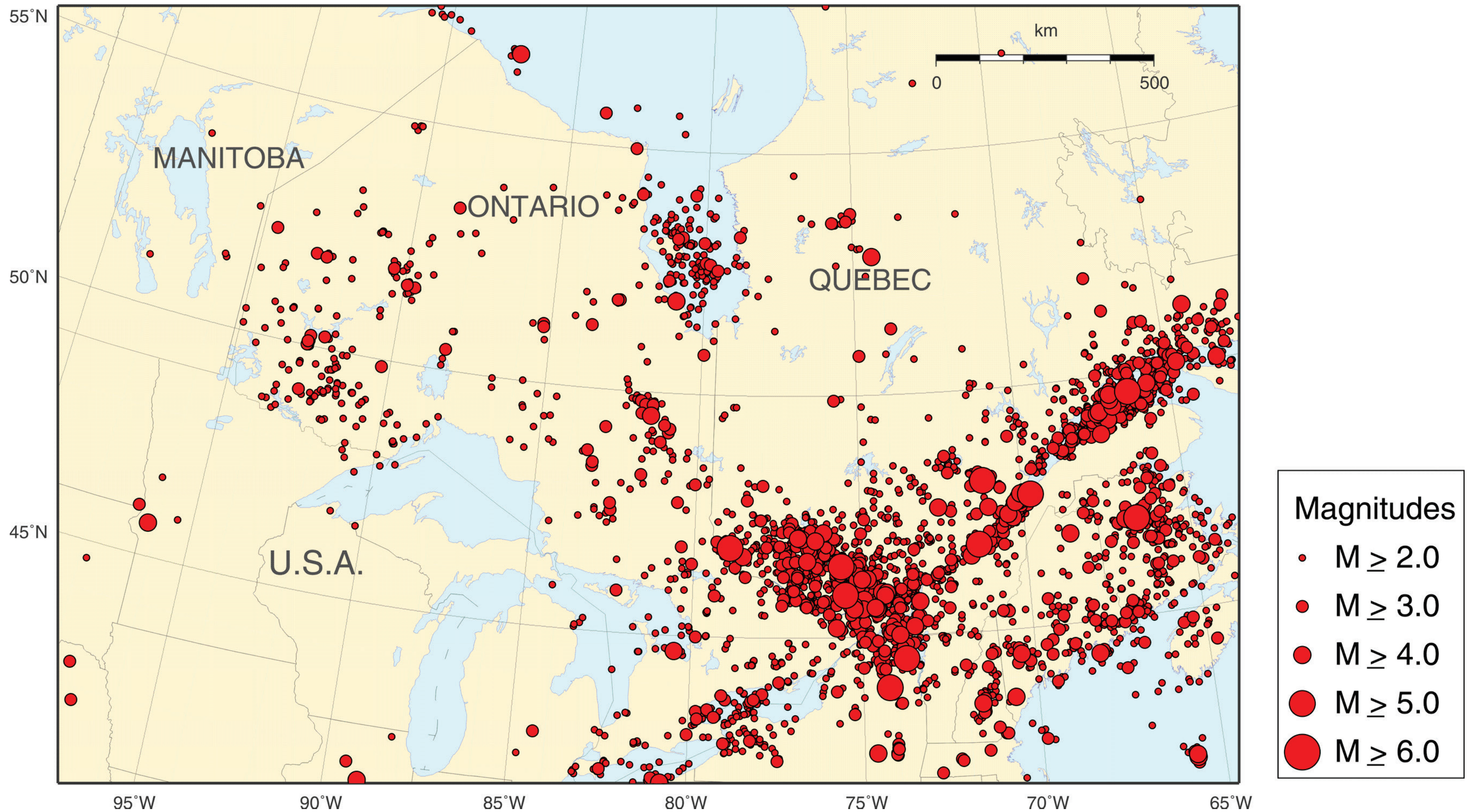
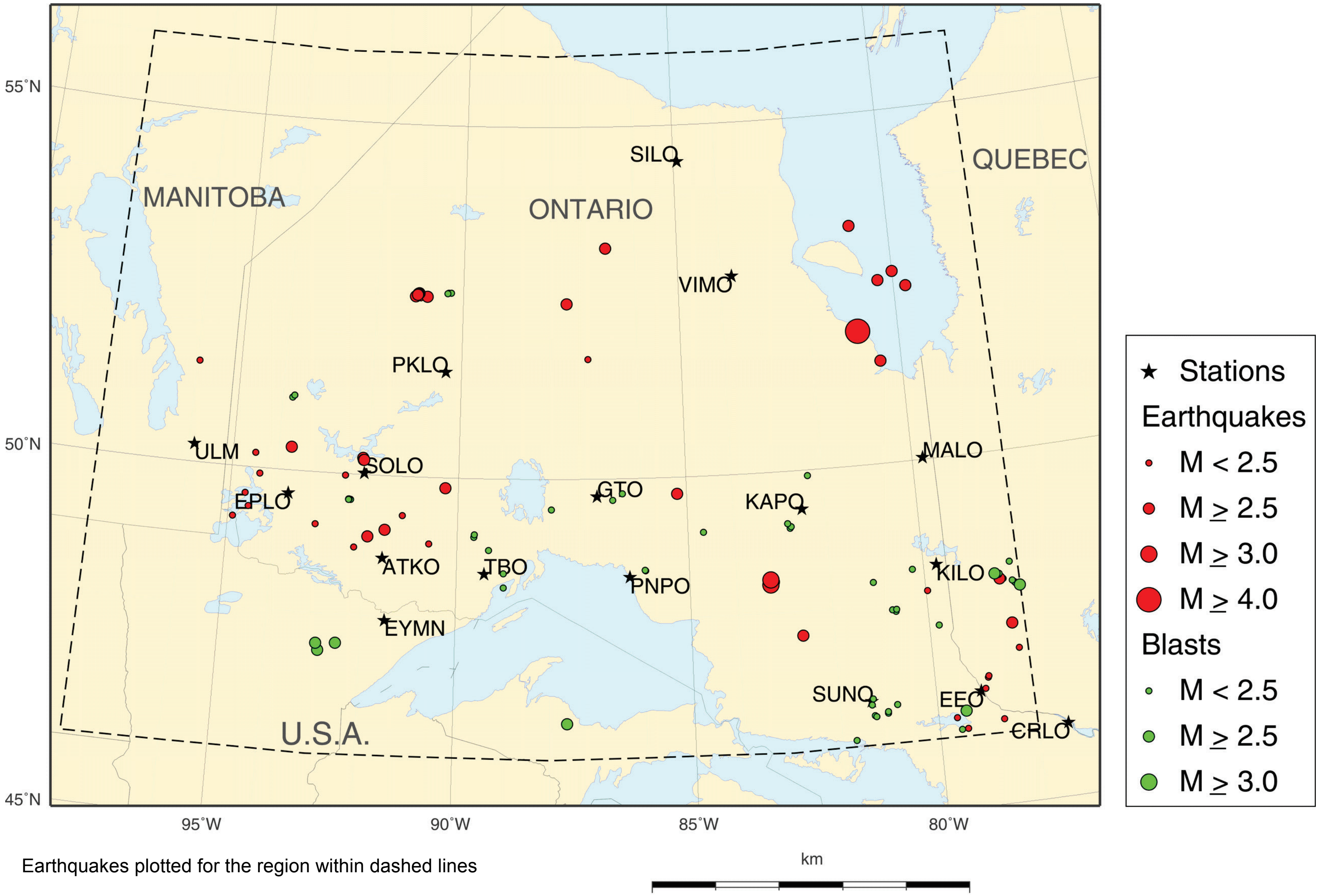



**Figure 5: Earthquakes in Eastern Canada, 1982 - 2012**




Earthquakes plotted for the region within dashed lines

**Figure 6: Earthquakes and Blasts in Northern Ontario and Adjacent Areas, 2012**

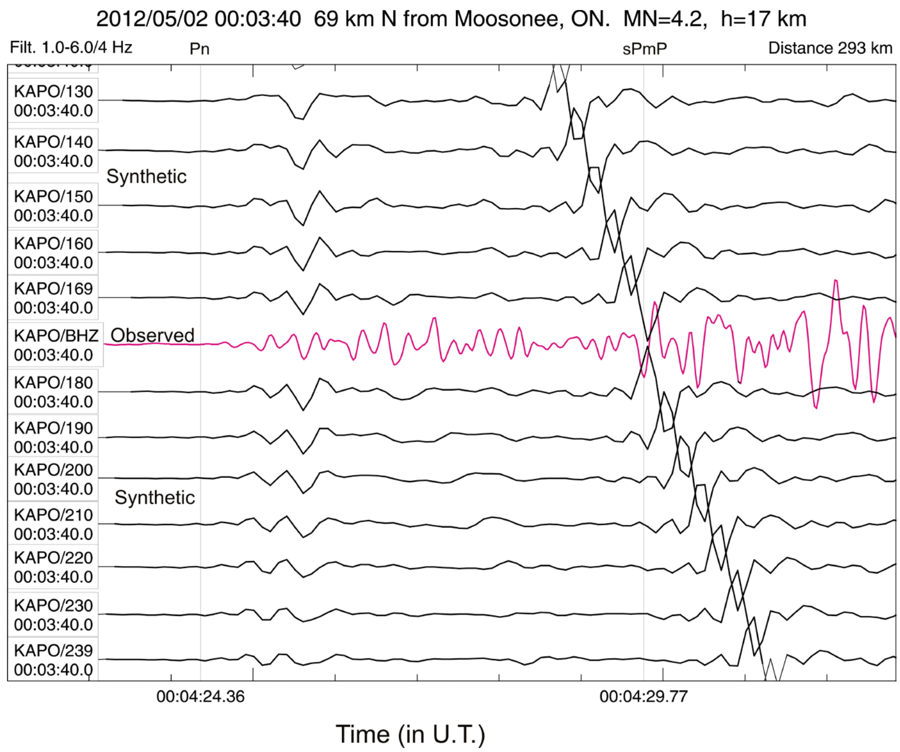



**Figure 7: Observed and Synthetic Waveforms from the $m_N$ 4.2 on 2012/05/02, 69 km north of Moosonee, ON**

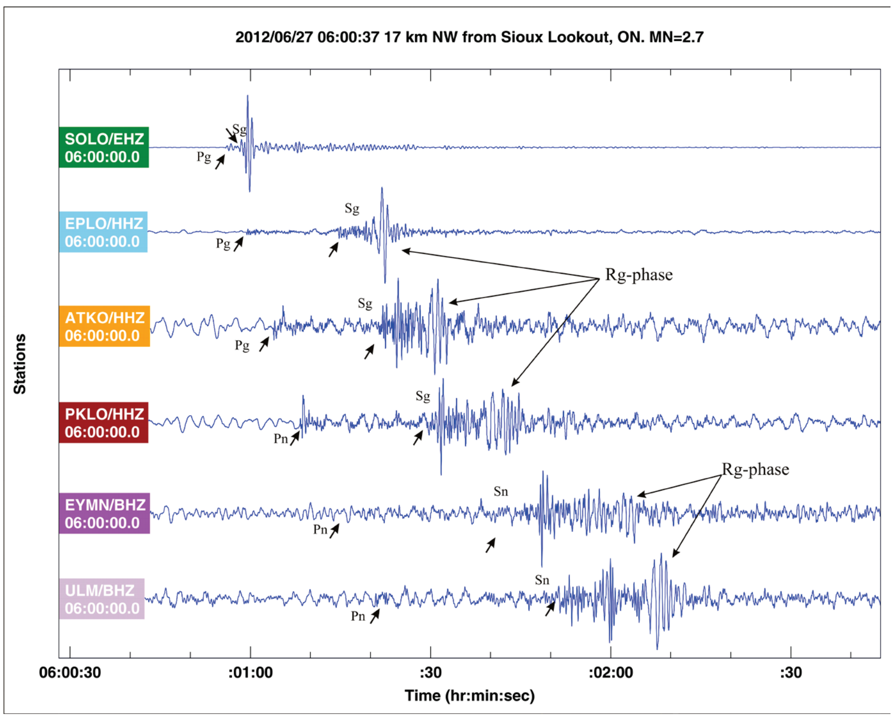



**Figure 8: Rg Surface Waves from the $m_N$ 2.7 on 2012/06/27, 18 km northwest of Sioux Lookout, ON**

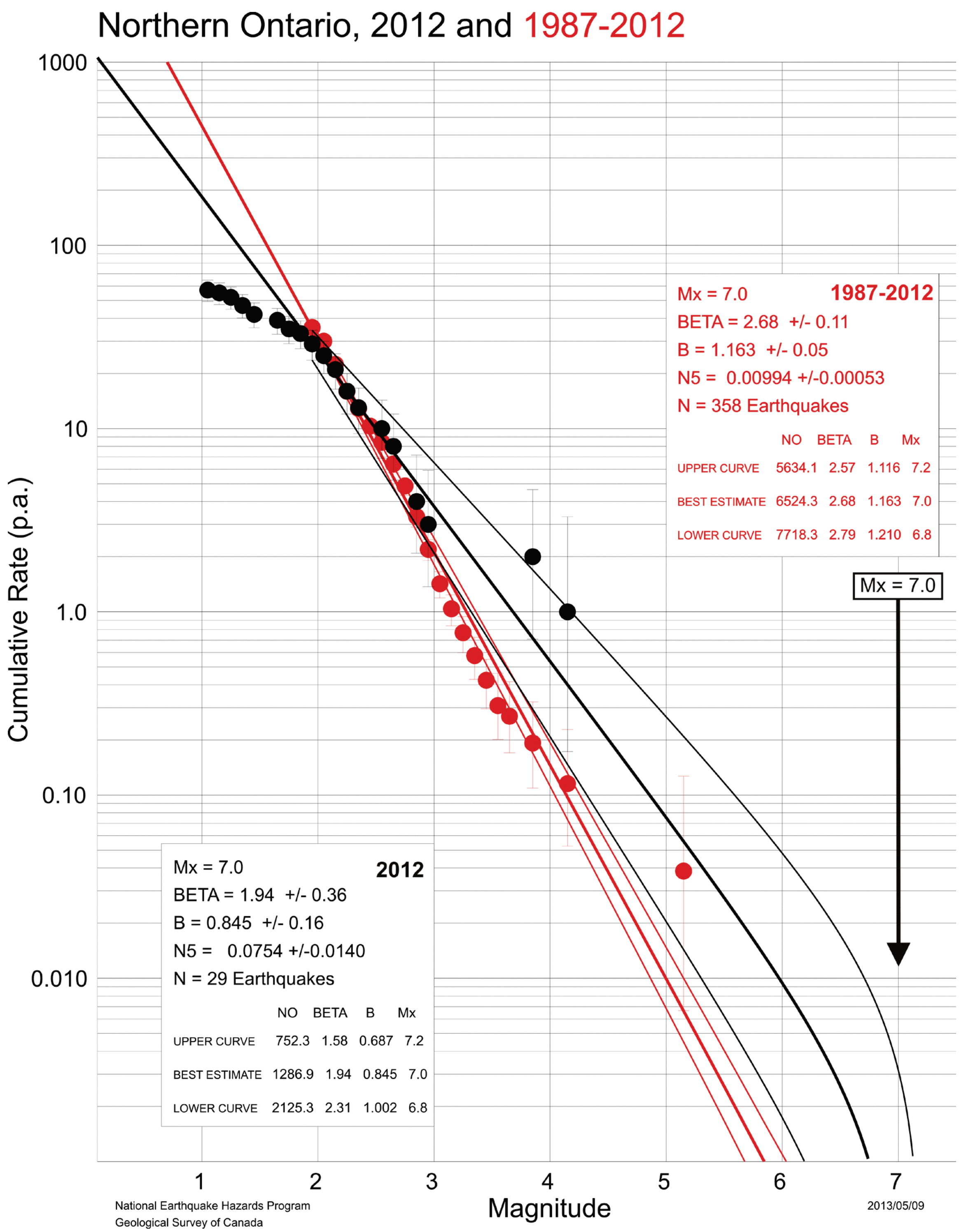



**Figure 9: Recurrence Curves for Northern Ontario**