Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Report for the Period January 01 – December 31, 2011

NWMO TR-2012-26 **December 2012**

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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, 2011**
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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 2011.

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 2011, 79 events were located. Their magnitude ranged from 0.9 m_N to 3.0 m_N. The largest events included three m_N 3.0 events: two in James Bay, and one 81 km east of Collins, ON. The most westerly events in the area being studied were two small events (m_N 2.0 and 2.1), located 113 km northeast of Gimli, MB. The 79 events located in 2011 compares with 118 events located in 2010, 82 events in 2009, 114 events in 2008, 68 events in 2007 and 83 events in 2006.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

1. INTRODUCTION

The Canadian Hazards Information Service (CHIS), a part of the Geological Survey of Canada (GSC) continues to conduct a seismic monitoring program in the northern Ontario and eastern Manitoba portions of the Canadian Shield. This program has been 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 2011.

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 are joint ventures that were established from 2003 to 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 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 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 79 earthquakes were located. Their magnitude ranged from 0.9 m_N to 3.0 m_N. The largest events included two m_N 3.0 in James Bay, and one m_N 3.0 located 81 km east of Collins, ON, just north of Lake Nipigon (see Figure 1).

The CNSN is able to locate all earthquakes of magnitude 3.5 and above anywhere within Canada, except in some pockets of the high Arctic. This was lowered to approximately magnitude 3 with the installation of the core stations across northern Ontario 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 2011 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 2011 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 4360 earthquakes had been located in Canada during the year 2011. Only 33 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 98% for five of the seven core seismograph station and above 90% for 6 of the 9 POLARIS stations.

KAPO and EEO were operational for 94.5% and 89.7% respectively. The majority of the outages at KAPO were due the failure of the digitizer at the site, which needed to be replaced. EEO had a series of problems, starting with a power outage and very small aperture terminal (VSAT) electronics that needed to be replaced to restore good data transmission. Note that problems continue at the site, although data is being received.

Many of the solar powered sites, particularly VIMO, MALO, KILO, and SUNO, experienced power failure and had poor telecommunications during the winter months, mostly January and December. SILO dropped out in 2010 due to faulty components at the site. As this site is quite remote, no additional maintenance trips to this site have been made in 2011.

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

3. EARTHQUAKES

A total of 79 earthquakes were located in the study area during 2011. The events from the year are listed in Table 1 and plotted in Figure 1. The largest events located this year were three magnitude 3 events: two m_N 3.0 in James Bay on January 10th and August 22nd (which was reported to be felt by people in the region), and a m_N 3.0 on August 8th, located 81 km east of Collins, ON, just north of Lake Nipigon. Note that the latter event locates in an area which has not seen much significant seismicity in the past.

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.

The effects of this lowered threshold can be seen particularly in the James Bay region where 214 events were located since 2004 (~27 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 (2 events per 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 first, based on poor uptime statistics, or the high noise levels at the site. Two additional sites were closed last year. The location threshold appears to have been minimally affected for 2011 compared with the previous years.

The 79 earthquakes from 2011 compare to previous years as follows:

Year	No. of events	No. of stations
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
2001	35	7
2000	73[1]	7

1. Includes magnitude 5.2 Temiscaming event and aftershocks.

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 2011, the rate of seismicity was average for the past eight years. In general, there was no unusual or swarm activity in 2011.

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 1145 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 30 years (65 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 2011. 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 - 2011. 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 2011 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 construction blasts.

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 3.0 earthquake in James Bay that occurred on August 22nd, 2011 in Figure 7. The waveforms from this station indicate a depth of 16.5 km, which is consistent with previous depths found for events in the James Bay region.

Figure 8 shows an earthquake that occurred just north of Lake Nipigon, 81 km east of Collins, Ontario on August 8th, 2011 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 2011 generally conform to areas of past seismicity. The magnitude 3 north of Lake Nipigon was the largest event to have occurred in this region of sparse seismicity since the beginning of this study in 1982. There was also a pair of events located 113 km NE of Gimli, Manitoba, where only one similar event occurred last year. These three earthquakes in Manitoba could not be matched to any known construction or mine works. 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 2011 and for the period of 1987 to the end of 2011 (25 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. Similarly a station which stops recording or which is noisy will have the same effect on the location uncertainty.

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 with most 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_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 the regional depth phase modelling method for moderate and small earthquakes without records from nearby stations in northern Ontario." (Ma, 2004, p.3).

Further work using RDPM modelling was done by Ma and Atkinson (2006) for earthquakes from the neighbouring regions of the West Quebec seismic zone, and in southern Ontario for 1980 – 2004. It was noted that events deeper than 15 km were limited to specific regions, while the shallower events were found over the entire region. A paper based on the Ma (2004) contract report 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 "0-5 km" can be achieved.

Table 3 lists all the events from 2011 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 six events, for which a reliable depth was determined using the RDPM method. Note that the majority of the events occurring in 2011 were too small to determine the depth 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 conducted 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.

The consequences for the earthquake locations in this report are still being assessed. 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 precision is about 0.1 magnitude units (the standard error of the mean), errors in magnitude are not considered further in the 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 25 years of data for the less-common larger earthquakes.

Figure 9 shows the magnitude-recurrence plot for the year 2011 earthquakes in black. It is very similar to the magnitude-recurrence plot for the 25-year period of 1987 to 2011 inclusive shown 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 2011 curve is higher than the longer-term curve, but with a much greater uncertainty. 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 are well over a year. For the year 2011 a best fit slope of b = 0.865 ± 0.14 was found, versus 1.188 ± 0.05 for the 25-year period curve.

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. 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 96 mining-induced seismic events of magnitude 0.9 or greater in the study area in 2011. Forty-one of these events occurred in the Sudbury Basin, 35 in the Red Lake region, 15 in the Cadillac, QC region, 4 in the Timmins area, and one near Musselwhite Mine. Twenty-five of these 2012 mining-induced events 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 2011 consisted of 79 earthquakes ranging in magnitude from 0.9 to 3.0. Forty-one earthquakes were larger than m_N 2.0, and three of the earthquakes were m_N 3.0. Of these m_N 3.0 events, two were located in James Bay, and one was located 81 km east of Collins, ON, just north of Lake Nipigon. 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 2011 conformed to the pattern of previous seismicity. However, the event north of Lake Nipigon was the largest event to have occurred in this region of generally sparse seismicity since the start of this study in 1982.

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Table 1: Located Local Earthquakes, January - December 2011

Date	Time (UT)	Latitude	Longitude	#stns/ phases	Magnitude (m_N)	Region and Comment
2011-01-01	04:28:53	49.84N	90.32W	4/ 7	1.3	46 km S from Allanwater Bridge, ON
2011-01-01	07:56:30	49.85N	90.29W	8/14	2.7	44 km S from Allanwater Bridge, ON
2011-01-02	04:12:07	49.86N	90.30W	6/11	2.4	44 km S from Allanwater Bridge, ON
2011-01-04	08:37:45	49.02N	90.32W	4/ 7	1.2	100 km E from Atikokan, ON
2011-01-04	09:52:43	50.35N	94.96W	3/ 6	1.5	70 km E from Pinawa, MB
2011-01-06	08:13:54	49.86N	90.30W	7/12	1.5	43 km S from Allanwater Bridge, ON
2011-01-07	16:37:55	49.34N	91.55W	9/13	2.2	66 km N from Atikokan, ON
2011-01-10	08:38:24	53.19N	80.97W	13/23	3.0	James Bay.
2011-01-10	09:18:51	51.38N	95.97W	6/10	2.0	113 km NE from Gimli, MB
2011-01-11	09:31:11	49.03N	90.88W	5/ 9	1.5	62 km NE from Atikokan, ON
2011-01-12	01:42:44	49.86N	90.30W	6/10	1.4	43 km S from Allanwater Bridge, ON
2011-01-20	18:14:51	48.64N	85.44W	9/15	2.2	60 km SE from Manitouwadge, ON
2011-01-20	18:21:29	49.85N	90.29W	7/12	2.0	44 km S from Allanwater Bridge, ON
2011-01-21	16:46:15	52.54N	79.92W	4/ 7	1.8	James Bay.
2011-01-28	00:42:21	49.85N	90.28W	8/13	1.7	43 km S from Allanwater Bridge, ON
2011-01-28	20:19:37	49.30N	91.19W	7/13	1.8	69 km NE from Atikokan, ON
2011-02-02	14:27:43	49.06N	93.44W	4/ 8	1.4	47 km N from Fort Frances, ON
2011-02-03	21:22:04	49.03N	90.89W	4/ 7	1.0	62 km NE from Atikokan, ON
2011-02-06	19:13:13	48.67N	92.23W	5/10	1.5	46 km W from Atikokan, ON
2011-02-10	19:34:43	49.06N	90.69W	8/15	2.2	76 km NE from Atikokan, ON
2011-02-12	10:14:51	49.05N	90.60W	4/ 8	1.2	81 km NE from Atikokan, ON
2011-02-13	01:09:09	53.35N	81.43W	3/ 4	2.1	James Bay.
2011-02-14	22:15:02	46.29N	79.32W	6/10	1.5	12 km E from North Bay, ON
2011-02-16	08:09:56	49.14N	91.54W	8/14	2.1	43 km N from Atikokan, ON
2011-02-20	19:08:36	49.41N	93.16W	7/13	2.2	47 km SW from Dryden, ON
2011-02-27	09:17:50	49.51N	91.81W	5/ 9	1.9	64 km S from Sioux Lookout, ON
2011-02-27	12:20:03	49.47N	91.96W	5/ 9	1.5	66 km S from Sioux Lookout, ON
2011-03-04	14:23:20	52.96N	87.43W	3/ 5	1.8	6 km SW from Webequie, ON
2011-03-04	20:43:01	48.86N	84.70W	6/ 9	2.4	32 km S from Hornepayne, ON
2011-03-05	15:16:18	50.75N	88.27W	4/ 6	1.6	98 km NE from Collins, ON
2011-03-11	00:41:11	49.14N	91.54W	6/11	1.8	44 km N from Atikokan, ON
2011-03-20	04:46:14	52.61N	80.30W	7/13	2.7	James Bay.
2011-03-24	19:55:30	48.62N	93.72W	5/ 9	1.9	24 km W from Fort Frances, ON
2011-03-25	01:06:20	49.16N	91.48W	5/ 9	1.1	47 km N from Atikokan, ON
2011-03-27	05:48:46	47.19N	84.46W	8/15	2.3	75 km N from Sault Ste. Marie, ON
2011-03-29	05:29:31	49.40N	91.59W	5/10	1.6	73 km N from Atikokan, ON
2011-03-29	08:03:24	49.40N	91.60W	5/10	1.4	72 km N from Atikokan, ON
2011-03-31	01:50:18	49.15N	91.53W	5/10	1.2	45 km N from Atikokan, ON
2011-03-31	02:14:17	49.14N	91.55W	5/ 9	1.4	44 km N from Atikokan, ON
2011-04-01	04:31:05	54.87N	90.37W	4/ 6	2.1	120 km N from Kitchenuhmaykoosib, ON

2011-04-01	04:32:26	54.88N	90.42W	4/ 5	2.3	120 km N from Kitchenuhmaykoosib, ON
2011-04-01	05:58:49	54.87N	90.37W	12/19	2.8	120 km N from Kitchenuhmaykoosib, ON
2011-04-02	08:08:04	49.15N	91.54W	5/10	1.3	45 km N from Atikokan, ON
2011-04-03	16:15:28	49.13N	91.54W	7/11	2.0	43 km N from Atikokan, ON
2011-04-03	20:03:12	52.21N	88.31W	3/ 6	1.8	30 km W from Lansdowne House, ON
2011-04-03	20:24:50	47.68N	91.13W	3/ 6	1.2	124 km S from Atikokan, ON
2011-04-15	11:21:57	51.46N	84.24W	4/ 6	2.0	200 km N from Hearst, ON
2011-04-17	00:17:17	52.55N	79.95W	6/10	2.2	James Bay.
2011-04-27	11:00:23	50.37N	94.96W	4/ 7	1.5	70 km E from Pinawa, MB
2011-05-08	19:22:29	49.56N	93.89W	3/ 5	1.4	50 km SE from Kenora, ON
2011-05-15	13:27:09	49.61N	90.88W	6/ 8	1.3	87 km SW from Allanwater Bridge, ON
2011-05-17	03:06:37	51.44N	96.04W	4/ 8	2.1	112 km NE from Gimli, MB
2011-05-18	11:27:51	49.86N	90.30W	3/ 7	1.3	44 km S from Allanwater Bridge, ON
2011-05-20	04:49:12	49.04N	90.31W	4/ 8	1.2	100 km E from Atikokan, ON
2011-05-22	14:13:12	49.55N	91.98W	5/ 8	1.0	57 km S from Sioux Lookout, ON
2011-05-26	02:58:53	49.35N	94.68W	3/ 6	1.3	55 km S from Kenora, ON
2011-05-30	05:25:32	49.30N	91.22W	5/ 9	0.9	68 km NE from Atikokan, ON
2011-06-04	03:00:37	49.85N	93.84W	4/ 8	1.5	43 km E from Kenora, ON
2011-06-04	03:02:25	49.84N	93.83W	4/ 8	1.6	43 km E from Kenora, ON
2011-06-14	17:59:59	49.98N	86.71W	6/11	2.1	25 km NW from Longlac, ON
2011-06-17	01:27:56	49.83N	81.90W	9/12	2.1	60 km NE from Kapuskasing, ON
2011-06-20	19:07:22	49.87N	90.33W	6/11	1.6	43 km S from Allanwater Bridge, ON
2011-07-11	11:19:31	49.33N	91.21W	5/ 9	1.5	71 km NE from Atikokan, ON
2011-08-08	08:39:53	50.42N	88.33W	8/13	3.0	81 km E from Collins, ON
2011-08-22	16:50:42	52.31N	81.19W	7/11	3.0	James Bay. Felt.
2011-09-04	08:12:05	52.66N	80.79W	7/ 9	2.4	James Bay.
2011-09-04	10:27:13	54.24N	80.28W	3/ 5	2.1	105 km NW from Chisasibi, QC
2011-09-12	12:31:10	51.31N	91.68W	4/ 7	1.6	105 km W from Pickle Lake, ON
2011-09-22	18:28:57	49.20N	92.03W	4/ 8	1.4	59 km NW from Atikokan, ON
2011-09-28	09:18:25	53.24N	80.93W	8/11	2.5	James Bay.
2011-09-30	15:51:21	49.77N	81.22W	6/ 9	2.4	80 km N from Cochrane, ON
2011-10-05	19:33:26	53.68N	79.72W	4/ 6	2.6	57 km W from Chisasibi, QC
2011-10-10	18:38:20	52.19N	82.20W	12/17	2.8	85 km S from Attawapiskat, ON
2011-10-14	20:04:35	50.09N	88.41W	9/16	2.2	78 km E from Collins, ON
2011-10-22	08:00:01	53.07N	80.55W	6/10	2.4	James Bay.
2011-10-27	15:57:21	50.61N	91.22W	3/ 6	1.5	81 km NE from Sioux Lookout, ON
2011-10-28	03:15:18	49.25N	91.75W	5/10	1.5	57 km N from Atikokan, ON
2011-11-08	09:35:01	49.60N	90.88W	4/ 7	1.0	88 km SW from Allanwater Bridge, ON
2011-12-27	12:03:15	47.44N	78.36W	7/11	1.7	77 km S from Malartic, QC

Table 2: NWMO Supported Stations Operating During 2011 (2010 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	99.7 (89.6)	19941207[1]-
SOLO	Sioux Lookout	50.0213	92.0812	373	98.0 (98.0)	19981104-
TBO	Thunder Bay	48.6473	89.4083	468	99.8 (100.0)	19931005-
GTO	Geraldton	49.7455	86.9610	350	99.7 (99.6)	20010104-
KAPO	Kapuskasing	49.4504	82.5079	210	94.5 (100.0)	19980114-
EEO	Eldee	46.6411	79.0733	398	89.7 (76.4)	19931005-
CRLO	Chalk River	46.0375	77.3801	168	99.4 (98.5)	19941117-
SILO	Sutton Inlier	54.4791	84.9126	195	0.0 (51.3)	20030609-
VIMO	Victor Mine	52.8173	83.7449	78	98.4 (84.7)	20030611-
MALO	McAlpine Lake	50.0244	79.7635	271	88.3 (91.5)	20030620-
KILO	Kirkland Lake	48.4972	79.7232	314	93.3 (92.5)	20030622-
SUNO	Sudbury	46.6438	81.3442	343	87.3 (91.8)	20030623-
EPLO	Experimental Lake	49.6737	93.7258	437	96.4 (66.6)	20040611-
ATKO	Atikokan	48.8231	91.6004	383	97.4 (100.0)	20040609-
PKLO	Pickle Lake	51.4987	90.3522	376	100.0 (100.0)	20040615-
PNPO	Pukaskwa Nat. Park	48.5957	86.2846	219	98.3 (99.8)	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 2010. All times given are in UT (Universal Time).

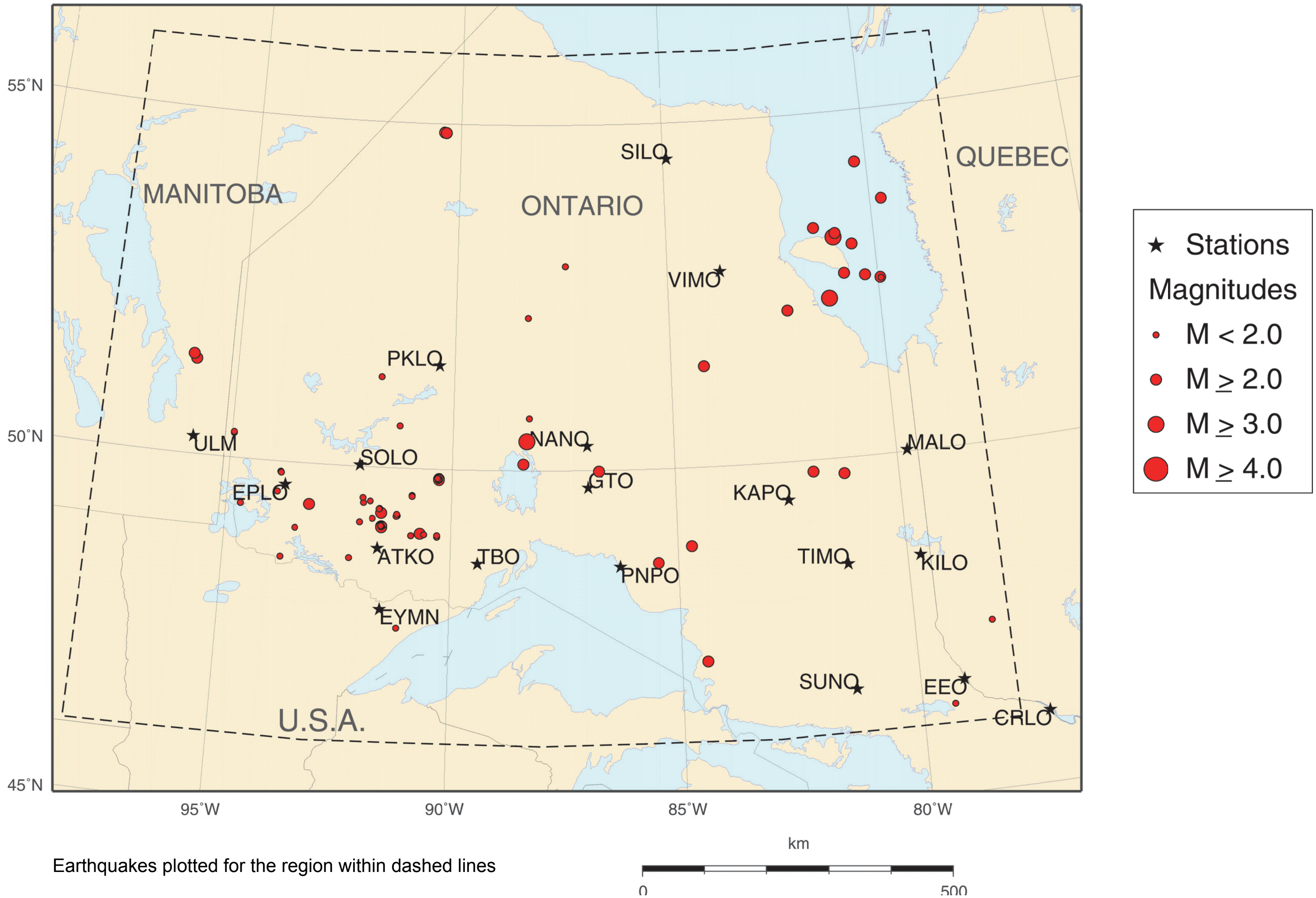
- ULM, SOLO, TBO, GTO, KAPO, EEO, CRLO and VIMO dropped out for 16 hours starting October 6th because the satellite communications service provider experienced an attitude control issue with their satellite.
- VIMO, MALO, KILO, and SUNO, which are solar powered sites, dropped out due to low battery voltage during intervals starting in late 2010 and continued into February, 2011. Then starting in October 2011, KILO dropped out due to low battery voltage, joined by MALO in November. By December SUNO, EPLO, ATKO and PNPO started to drop out as well due to low battery voltage.
- SOLO was out from February 22nd to the 28th. The communications provider replaced a faulty component on the VSAT dish.
- SILO remains out since July 30, 2010 due to faulty station components. No additional maintenance trip to this site was scheduled for 2011.
- KAPO dropped out on April 17th for a day for unknown reasons. Data flow resumed without any action being taken. KAPO dropped out again from October 17th to 20th. The satellite communications electronics at the site were power cycled to restore communications. On November 20th the digitizer failed, and was replaced December 17th.
- EEO was out from January 16th to 18th. The VSAT antenna indoor electronics had to be reset locally to restore normal communications. The station was out from February 22nd for a day, possibly due to a main power outage. Data flow returned without any action being taken. EEO dropped out during intervals from May 15th to June 14th. The satellite communications provider replaced VSAT electronics at the site to restore good data transmission. The station began dropping out again during intervals while reporting data packet errors starting June 23. The problem continues. Our satellite communications provider has found no fault with their equipment. A site visit will be required.
- CRLO dropped out from July 18th to 19th apparently due to a power outage.

Table 3: Depths Derived using Rg-phases and Regional Depth Phase Method (RDPM) for Moderate-sized Events for 2011

Date mm/dd	Time (UT) hh:mm:ss	Magnitude (m_N)	Depth (km)	Depth type Rg/RDPM	Region and Comment
01/01	04:28:53	1.3	5	Rg	46 km S from Allanwater Bridge, ON
01/01	07:56:30	2.7	2	RDPM	44 km S from Allanwater Bridge, ON
01/02	04:12:07	2.4	3	RDPM	44 km S from Allanwater Bridge, ON
01/04	08:37:45	1.2	5	Rg	100 km E from Atikokan, ON
01/04	09:52:43	1.5	5	Rg	70 km E from Pinawa, MB
01/06	08:13:54	1.5	5	Rg	43 km S from Allanwater Bridge, ON
01/07	16:37:55	2.2	5	Rg	66 km N from Atikokan, ON
01/10	09:18:51	2.0	5	Rg	113 km NE from Gimli, MB
01/11	09:31:11	1.5	5	Rg	62 km NE from Atikokan, ON
01/12	01:42:44	1.4	5	Rg	43 km S from Allanwater Bridge, ON
01/20	18:14:51	2.2	3	RDPM	60 km SE from Manitouwadge, ON
01/20	18:21:29	2.0	5	Rg	44 km S from Allanwater Bridge, ON
01/28	00:42:21	1.7	5	Rg	43 km S from Allanwater Bridge, ON
01/28	20:19:37	1.8	5	Rg	69 km NE from Atikokan, ON
02/02	14:27:43	1.4	5	Rg	47 km N from Fort Frances, ON
02/03	21:22:04	1.0	5	Rg	62 km NE from Atikokan, ON
02/06	19:13:13	1.5	5	Rg	46 km W from Atikokan, ON
02/10	19:34:43	2.2	5	Rg	76 km NE from Atikokan, ON
02/12	10:14:51	1.2	5	Rg	81 km NE from Atikokan, ON
02/16	08:09:56	2.1	5	Rg	43 km N from Atikokan, ON
02/20	19:08:36	2.2	5	Rg	47 km SW from Dryden, ON
03/05	15:16:18	1.6	5	Rg	98 km NE from Collins, ON
03/11	00:41:11	1.8	5	Rg	44 km N from Atikokan, ON
03/25	01:06:20	1.1	5	Rg	47 km N from Atikokan, ON
03/29	05:29:31	1.6	5	Rg	73 km N from Atikokan, ON
03/29	08:03:24	1.4	5	Rg	72 km N from Atikokan, ON
03/31	01:50:18	1.2	5	Rg	45 km N from Atikokan, ON
03/31	02:14:17	1.4	5	Rg	44 km N from Atikokan, ON
04/02	08:08:04	1.3	5	Rg	45 km N from Atikokan, ON
04/03	16:15:28	2.0	5	Rg	43 km N from Atikokan, ON
04/27	11:00:23	1.5	5	Rg	70 km E from Pinawa, MB
05/08	19:22:29	1.4	5	Rg	50 km SE from Kenora, ON
05/17	03:06:37	2.1	5	Rg	112 km NE from Gimli, MB
05/20	04:49:12	1.2	5	Rg	100 km E from Atikokan, ON
05/26	02:58:53	1.3	5	Rg	55 km S from Kenora, ON
06/04	03:00:37	1.5	5	Rg	43 km E from Kenora, ON
06/04	03:02:25	1.6	5	Rg	43 km E from Kenora, ON
06/14	17:59:59	2.1	5	Rg	25 km NW from Longlac, ON
08/08	08:39:53	3.0	1	RDPM	81 km E from Collins, ON
08/22	16:50:42	3.0	16	RDPM	James Bay. Felt.
09/22	18:28:57	1.4	5	Rg	59 km NW from Atikokan, ON
10/14	20:04:35	2.2	3	RDPM	78 km E from Collins, ON
10/27	15:57:21	1.5	5	Rg	81 km NE from Sioux Lookout, ON
10/28	03:15:18	1.5	5	Rg	57 km N from Atikokan, ON

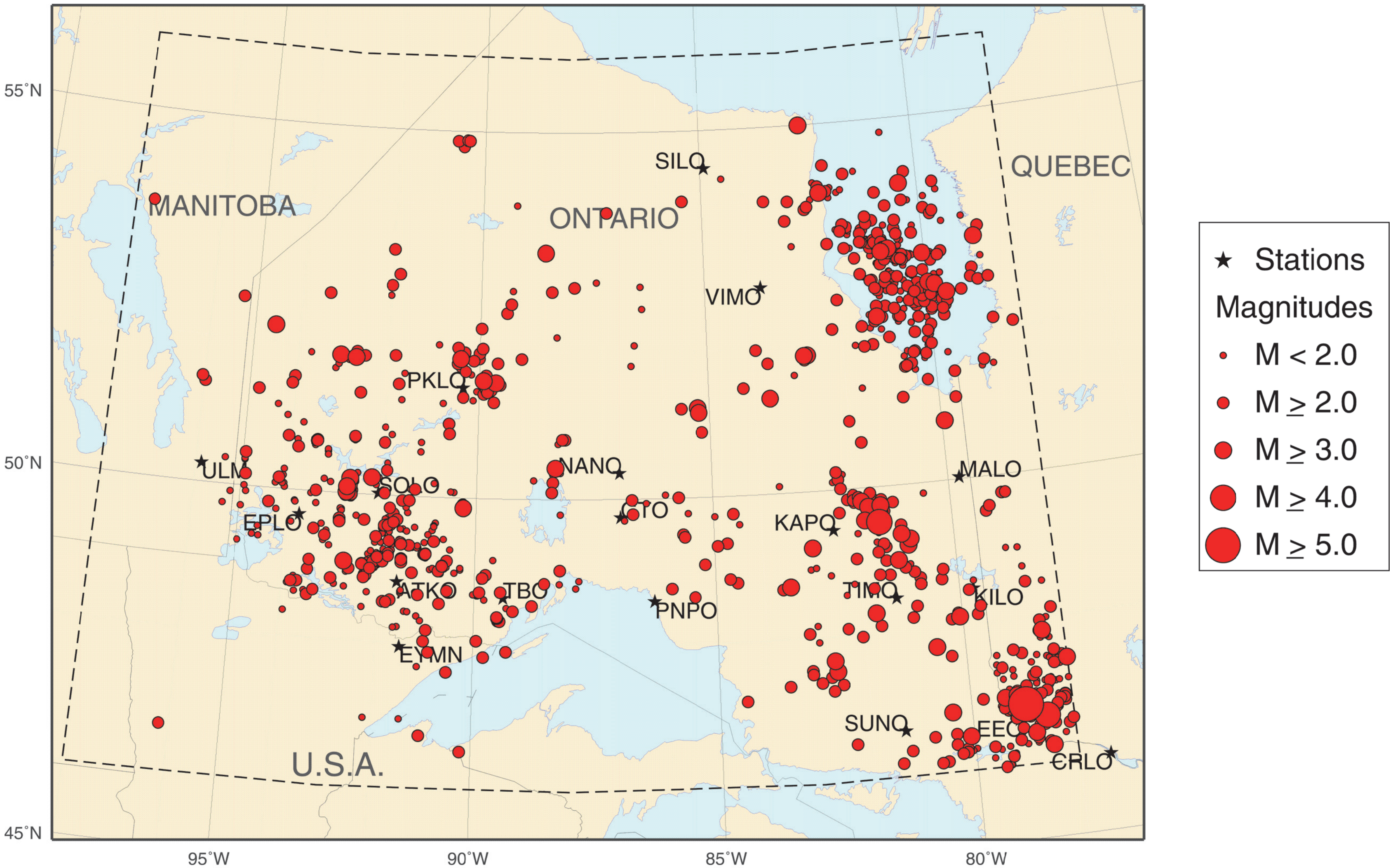
Table 4: Mining-Induced Seismic Events m_N 2.5 and Greater, January - December 2011

Date (yyyy/mm/dd)	Mine	Location	Magnitude
2011/01/27	Coleman Mine	Sudbury	2.9 m_N
2011/01/27	Coleman Mine	Sudbury	2.8 m_N
2011/03/18	Coleman Mine	Sudbury	3.3 m_N
2011/04/06	Coleman Mine	Sudbury	3.7 m_N
2011/04/22	Near Musselwhite Mine	Opapamiskan Lake	2.7 m_N
2011/05/12	Coleman Mine	Sudbury	2.7 m_N
2011/06/06	Laronde mine	Cadillac	2.9 m_N
2011/06/18	Campbell Mine	Red Lake	2.5 m_N
2011/07/06	Creighton Mine	Sudbury	3.0 m_N
2011/07/17	Garson Mine	Sudbury	2.7 m_N
2011/08/09	LaRonde Mine	Cadillac	3.4 m_N
2011/08/21	Creighton Mine	Sudbury	3.3 m_N
2011/08/21	Creighton Mine	Sudbury	2.5 m_N
2011/08/21	Kidd Creek	Timmins	3.3 m_N
2011/09/13	Kidd Creek	Timmins	3.8 m_N
2011/09/17	Campbell Mine	Red Lake	2.5 m_N
2011/09/30	LaRonde Mine	Cadillac	3.1 m_N
2011/10/05	Lockerby Mine	Sudbury	2.6 m_N
2011/10/09	Creighton Mine	Sudbury	2.7 m_N
2011/10/19	LaRonde Mine	Cadillac	3.0 m_N
2011/11/25	Creighton Mine	Sudbury	3.2 m_N
2011/12/12	LaRonde Mine	Cadillac	2.8 m_N
2011/12/14	Campbell Mine	Red Lake	3.0 m_N
2011/12/15	Campbell Mine	Red Lake	2.5 m_N
2011/12/15	Campbell Mine	Red Lake	2.7 m_N



Earthquakes plotted for the region within dashed lines

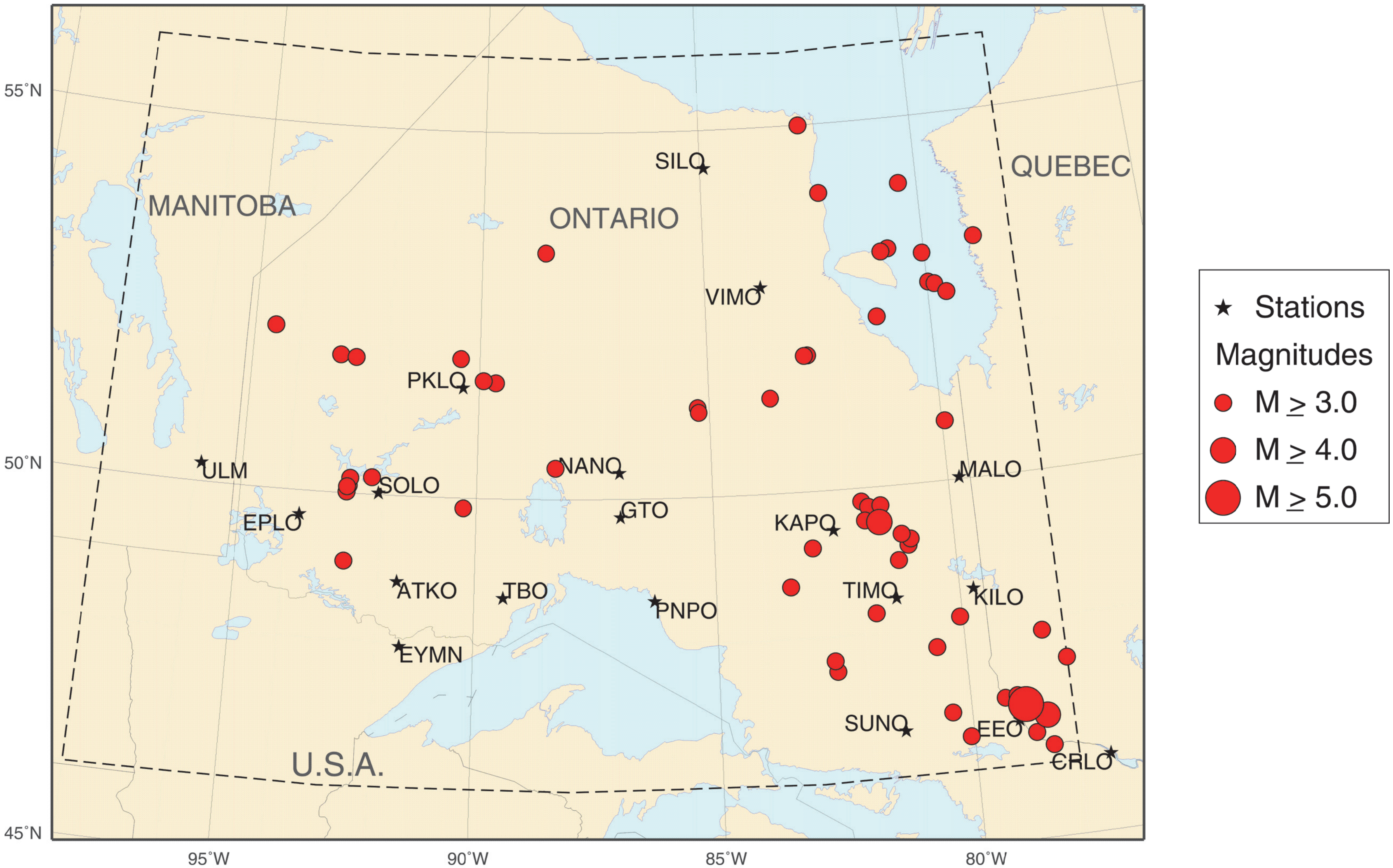
Figure 1: Earthquakes in Northern Ontario and Adjacent Areas, 2011



Earthquakes plotted for the region within dashed lines

km
0
500

Figure 2: Earthquakes in Northern Ontario and Adjacent Areas, 1982 - 2011



Earthquakes plotted for the region within dashed lines

km
0
500

Figure 3: Earthquakes $m_N \geq 3$ in Northern Ontario and Adjacent Areas, 1982 – 2011

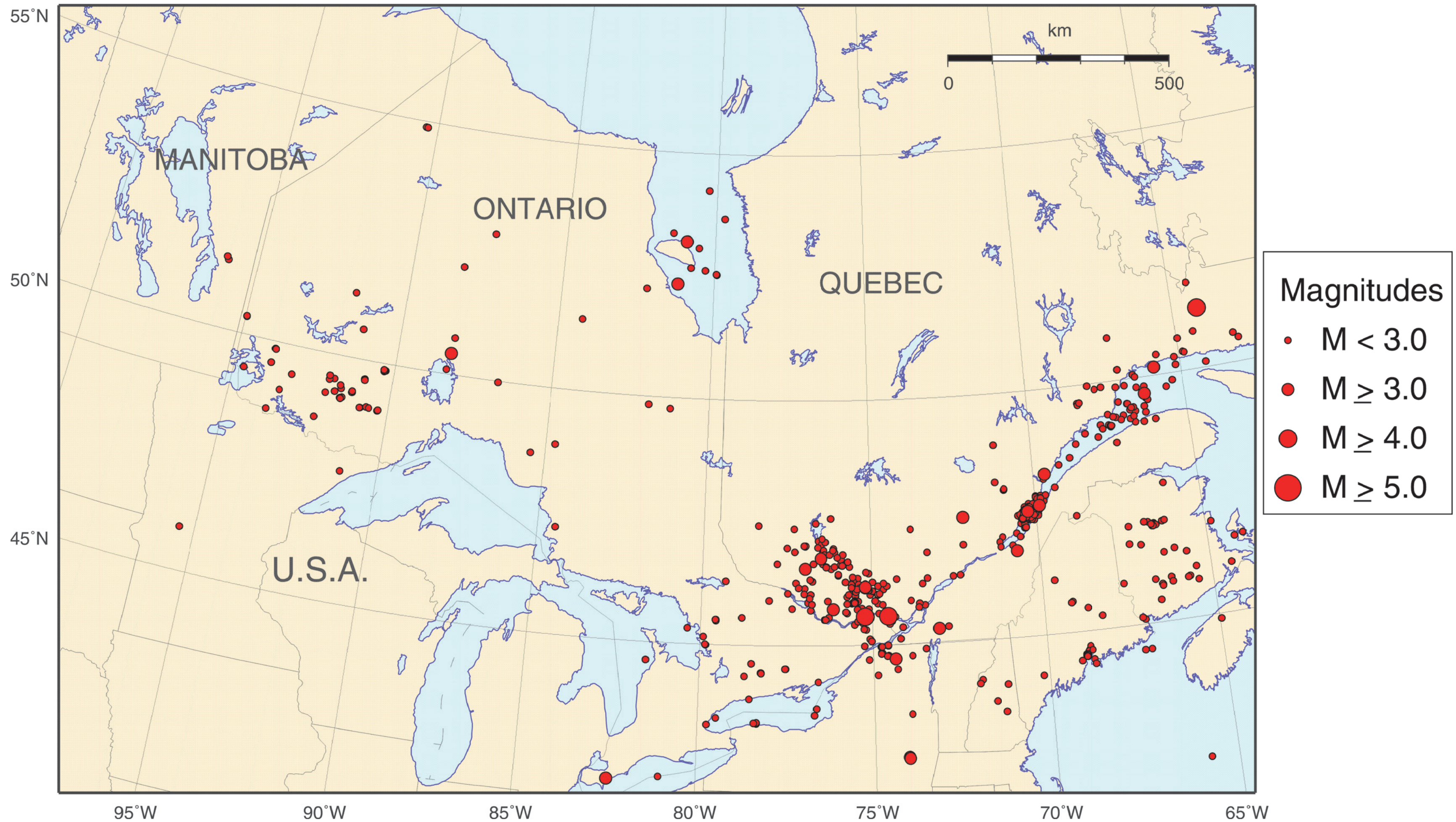


Figure 4: Earthquakes in Eastern Canada, 2011

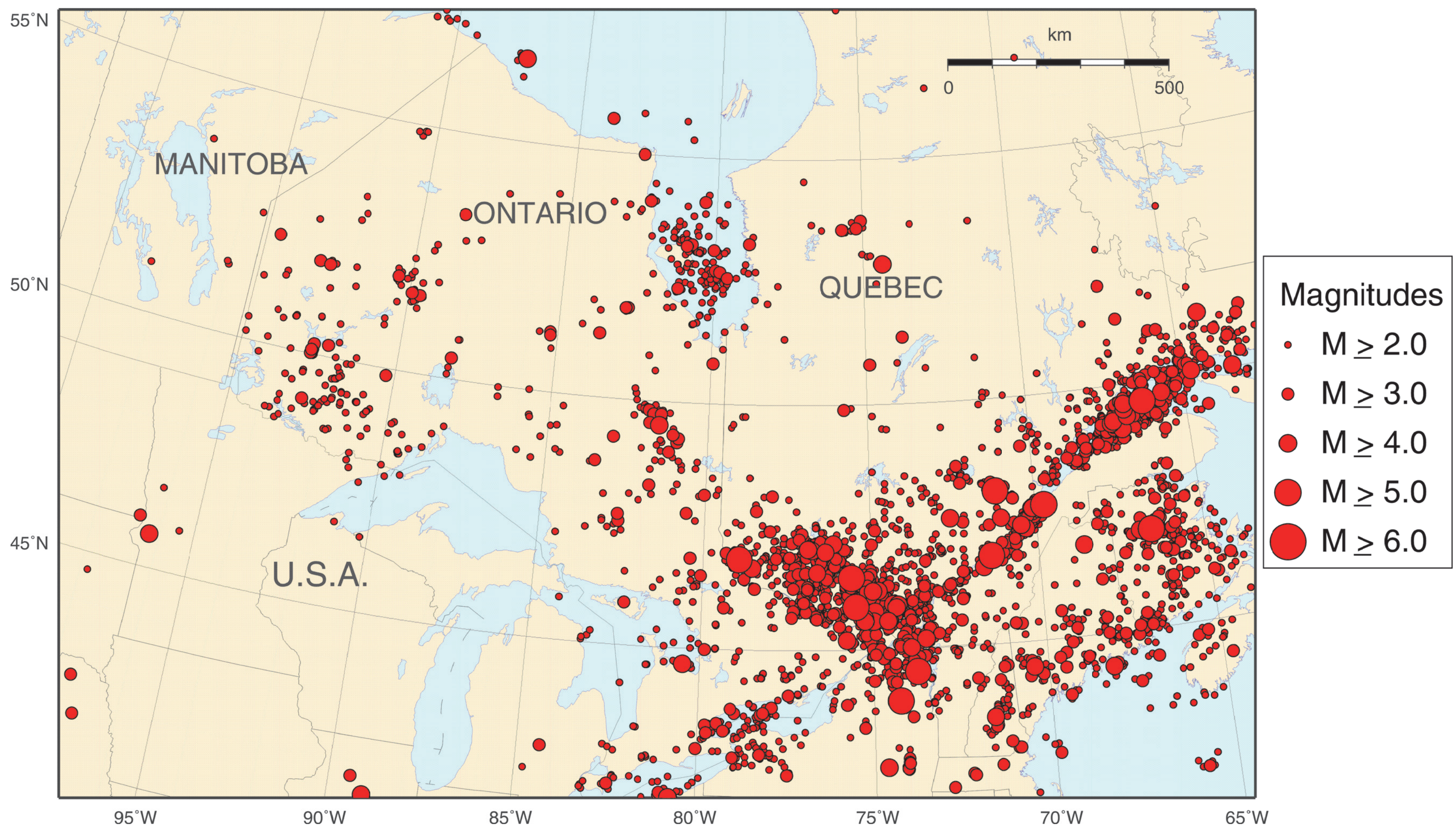
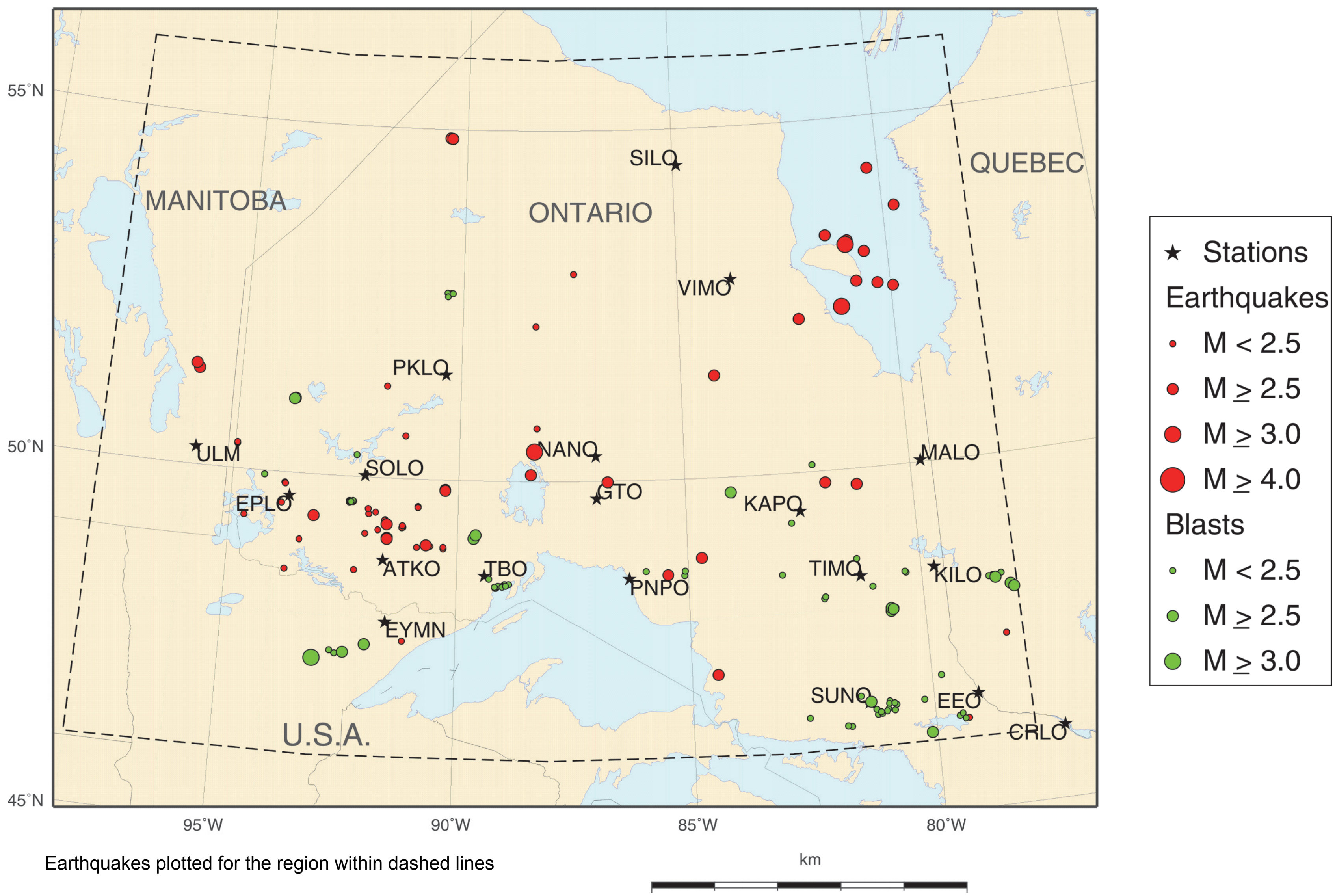


Figure 5: Earthquakes in Eastern Canada, 1982 - 2011



Earthquakes plotted for the region within dashed lines

Figure 6: Earthquakes and Blasts in Northern Ontario and Adjacent Areas, 2011

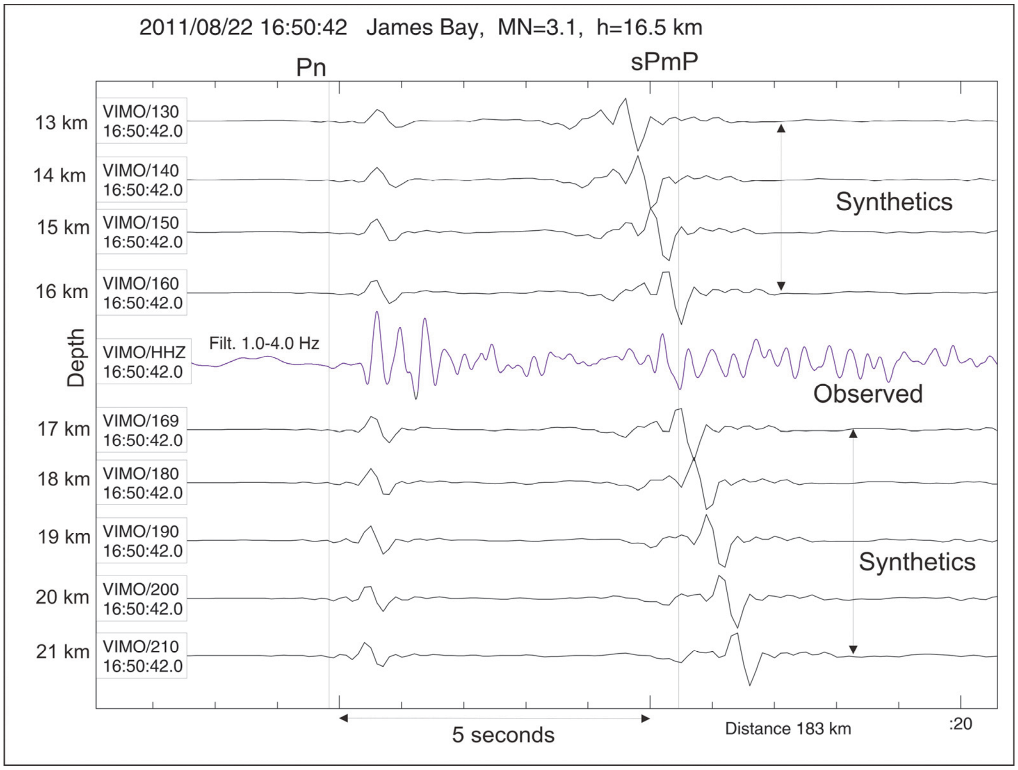


Figure 7: Observed and Synthetic Waveforms from the m_N 3.1 on 2011/08/22 in James Bay

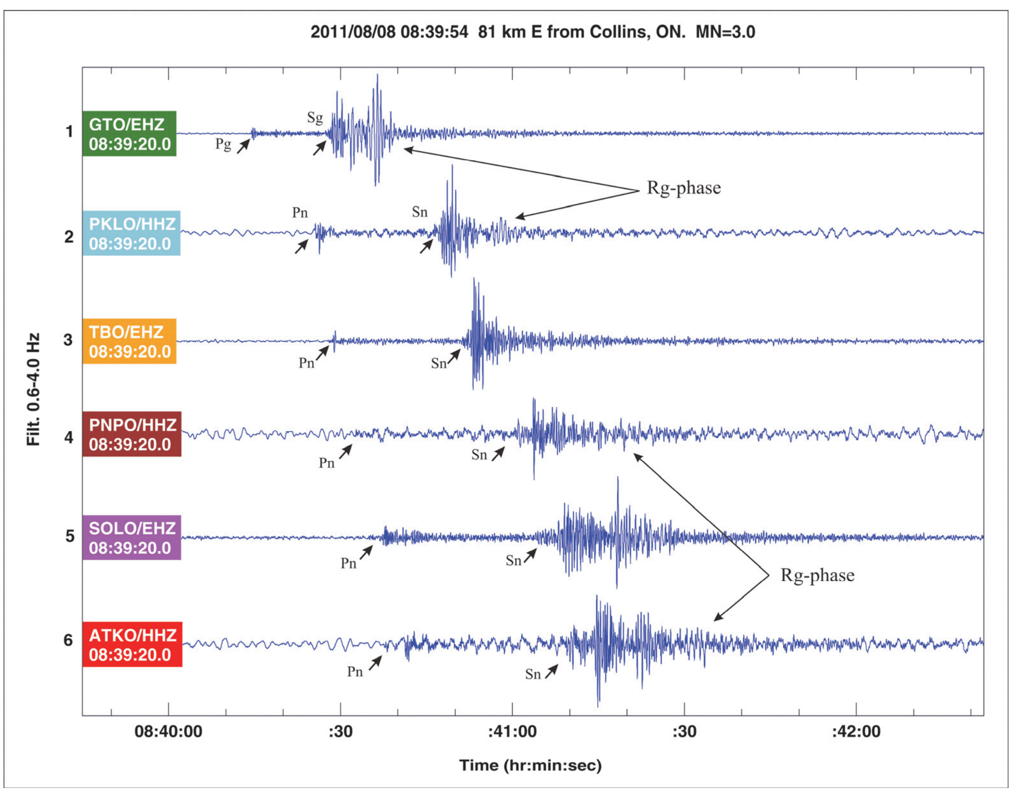


Figure 8: Rg Surface Waves from the m_N 3.0 on 2011/08/08 81km E of Collins, ON

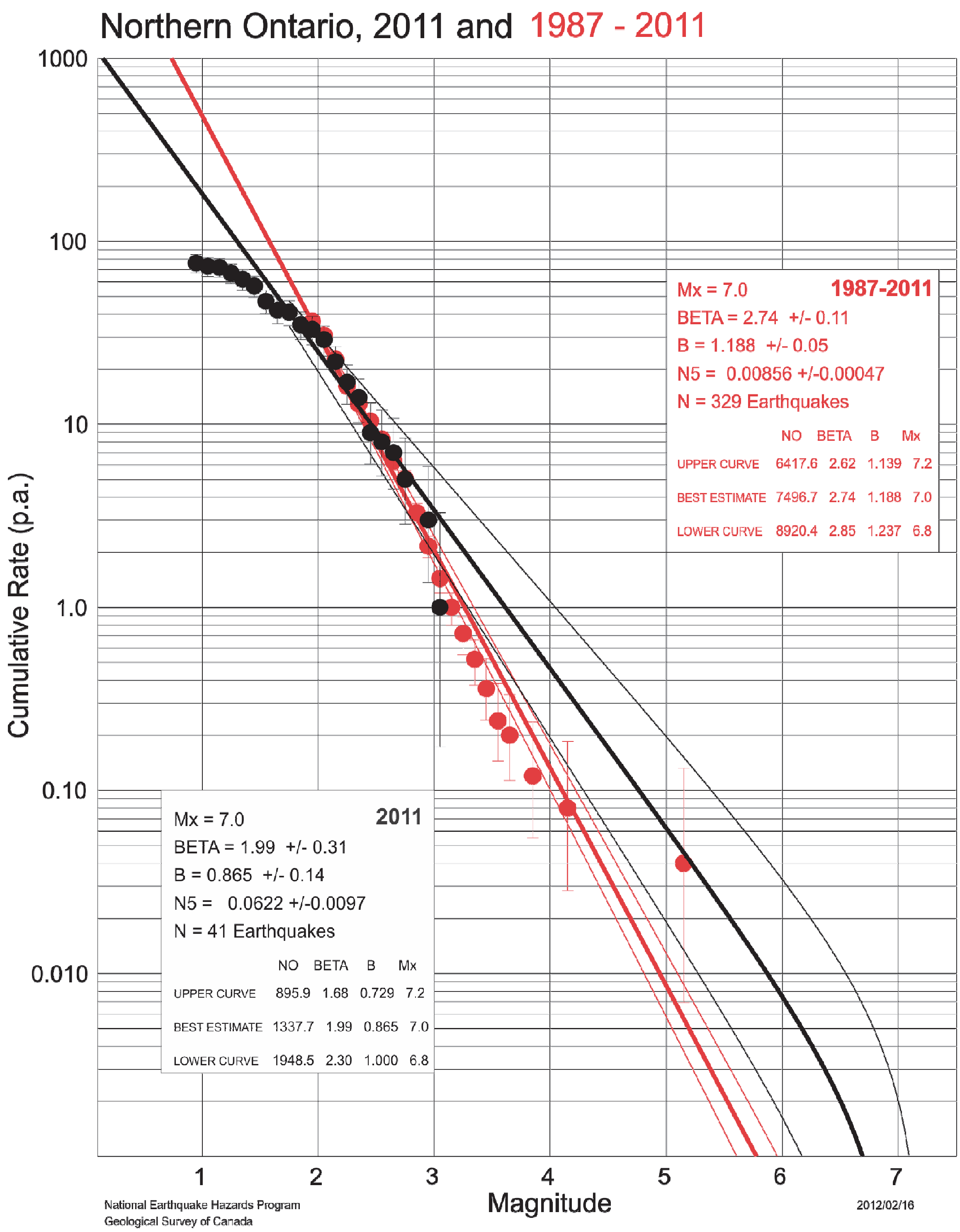


Figure 9: Recurrence Curves for Northern Ontario