Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01 – December 31, 2010

NWMO TR-2011-26 December 2011

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ABSTRACT

Title: **Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01 – December 31, 2010**
Report No.: **NWMO TR-2011-26**
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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 ongoing since 1982 and is currently supported by a number of organizations, including the NWMO. A key objective of the monitoring program is to observe and document earthquake activity in the Ontario portion of the Canadian Shield. This report summarizes earthquake activity for the year 2010.

CHIS maintains a network of eighteen 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), Pukaskwa National Park (PNPO), Aroland (NANO), and Timmins (TIMO). The digital data from a temporary station at Victor Mine (VIMO), supported by the diamond mine industry, and a station at Pinawa (ULM), which has funding from the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) are also used in this study.

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

During 2010, 118 events were located. Their magnitude ranged from 0.7 m_N to 3.2 m_N. The largest events included a m_N 3.2 in the Atikokan region, ON and two m_N 3.1 near Sultan, ON. The most westerly event in the area being studied was a m_N 1.9, located 113 km northeast of Gimli, MB. The 118 events located in 2010 compares with 82 events in 2009, 114 events in 2008, 68 events in 2007 and 83 events in 2006.

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1. INTRODUCTION

The Canadian Hazards Information Service (CHIS), a part of the Geological Survey of Canada (GSC) continues to conduct a seismic monitoring program in the northern Ontario and eastern Manitoba portions of the Canadian Shield. This program has been ongoing since 1982 and is currently supported by a number of organizations, including the NWMO. A key objective of the monitoring program is to observe and document earthquake activity in the Ontario portion of the Canadian Shield. This report summarizes earthquake activity for the year 2010.

To record the seismic activity, CHIS operates eighteen 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), Aroland (NANO), Victor Mine (VIMO) and Timmins (TIMO), 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 Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (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 monitoring of this region, as are all the data from the entire Canadian National Seismograph Network (CNSN) and 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

[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.

earthquakes, 100 magnitude 2.0 earthquakes, 1000 magnitude 1.0 earthquakes, etc. Thus there is a great benefit to being able to detect the many smaller earthquakes happening in northern Ontario to understand 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 118 earthquakes were located. Their magnitude ranged from 0.7 m_N to 3.2 m_N. The largest events included a m_N 3.2 near Allanwater Bridge, ON and two m_N 3.1 near Sultan, ON (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 2010 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 2010 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 5150 earthquakes had been located in Canada in the year 2010. Only 41 of these occurred in the study region <u>and</u> 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, PNPO, NANO, and TIMO are shown in Table 2. Data capture was in excess of 98% for five of the seven core seismograph stations and above 90% for 7 of the 11 POLARIS stations.

ULM and EEO were operational for 89.6% and 76.4%, respectively. ULM was affected by several severe lightning storms, starting in May and continuing throughout the summer, which caused power surges that damaged components at the site. Replacements of faulty parts were required. EEO experienced several power outages throughout the year, but the majority of the downtime was related to a GPS failure, which started July 15th. Data with bad timing were not being forwarded, and the GPS antenna and cable needed to be replaced before timing was restored at the site on October 9th.

Many of the solar powered sites, particularly SILO, VIMO, MALO, KILO, SUNO and TIMO, experienced power failure and had poor telecommunications during the winter months, mostly January and December. EPLO data were intermittent from the beginning of the year until June 13th when the satellite dish antenna was realigned during a site visit. SILO dropped out July 30th due to faulty components at the site. As this site is quite remote, no additional maintenance trips to this site had been scheduled for 2010. The bandwidth at VIMO was too low and was causing data to be intermittent from May to June. An increase of bandwidth fixed the issue, however, in late June the station dropped out, and the VSAT dish had to be repointed by the technicians to restore operation on July 10th.

NANO was closed on June 10th, and TIMO was closed July 3rd. Both stations had been part of the temporary POLARIS FedNor deployment.

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

3. EARTHQUAKES

A total of 118 earthquakes were located in the study area during 2010. The events from the year are listed in Table 1 and plotted in Figure 1. The largest event located this year was a m_N 3.2 which occurred on December 22nd, 43 km S of Allanswater Bridge, Ontario. The second largest events of the year were two earthquakes of m_N 3.1 approximately 15 km apart on March 22nd and December 7th, east of Sultan, ON (approximately 60 km east of Chapleau, ON). Note that these two events, although close together, are not co-located, as can be seen in Figure 7. All three events are located in regions which have had previous seismic activity, although these are the largest recorded events since 1982 in those regions.

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 202 events were located since 2004 (~30 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 have been closed this year. The location threshold appears to have been minimally affected for 2010 compared with the previous years. However, more FedNor stations will be closed in the next few years and this will lead to a threshold closer to pre-2003 (pre-FedNor) levels. At some time, a decision is required as to (a) whether more low-magnitude earthquake data is still required *and* the remaining FedNor stations be funded, or whether the 2003 threshold level was adequate, and (b) whether a lower threshold is required over the entire study area, or a more focussed approach should be used.

The 118 earthquakes from 2010, compare to previous years as follows:

Year	No. of events	No. of stations	
2010	118	16	Removed 2 more stations mid-year
2009	82	18	
2008	114	26	Began removal of FedNor stations (8)
2007	68	26	
2006	83	26	
2005	103	26	
2004	79	20	
2003	45	14	Began installation of FedNor stations
2002	45	7	
2001	35	7	Upgrade of stations to digital completed
2000	73	7	M5.2 Temiscamingue event and aftershocks
1999	32	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 2010, the rate of seismicity was slightly higher, partly due to a mini-swarm of events which started on October 12^{th} and located approximately 65 km northeast of Atikokan, Ontario. The largest of these earthquakes was a m_N 2.9 occurring on October 30^{th}. Note that 27 events occurred 65 km northeast of Atikokan, Ontario, almost a quarter of the year's earthquakes.

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 1066 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 29 years (62 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 2010. 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 - 2010. 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, though this assessment is made mainly on the basis of $m_N > 3$ earthquakes as the location of small earthquakes was very poor until mid-2003. There is not enough data to speculate as to the reason for this higher level of seismicity.

Figure 6 shows the earthquakes located in the study area in 2010 together with some mine blasts for the same year. Many mine blasts are repetitive (same mine 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. 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 TBO are shown for the m_N 3.2 earthquake south of Allanwater Bridge that occurred on December 22nd, 2010 in Figure 8. The waveforms from this and other stations indicated a depth of 3 km, which is not considered unusual for this region of Ontario.

Figure 9 shows an earthquake that occurred near Sultan, Ontario on March 22nd, 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 2010 generally conform to areas of past seismicity, with a few exceptions. One of these exceptions was an event 113 km NE of Gimli, MB, which could not be matched to any construction or mine works, and another one occurred west of VIMO. However, as both of these events occurred in areas which had little coverage prior to 2003, and even now have a higher location threshold than regions to the south and east, seismicity in these regions in the past could simply have been missed.

Recurrence curves for the study area for the year 2010 and for the period of 1987 to the end of 2010 (24 years of data) are shown in Figure 10 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://earthquakescanada.nrcan.gc.ca/stnsdata/autodrm/index_e.php
Individual event files can be accessed at:
http://earthquakescanada.nrcan.gc.ca/stnsdata/nwfa/index_e.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.

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 2010 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).

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 in Ma et al., (2008). Figure 8 shows an application of RDPM to a 2010 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 9) and are nearly always present in surface explosions. The presence of a strong Rg-phase for some of the earthquakes indicated that the depths of these events were likely 5 km or shallower, and generally a 5 km depth has been assigned for these events.

Table 3 lists all the events from 2010 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 eighteen events, for which a reliable depth was determined using the RDPM method. Note that the majority of the events occurring in 2010 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 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.

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 precisions are about 0.1 magnitude units (for the standard error of the mean), the errors in the magnitude are not considered further in the discussion.

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 24 years of data for the less-common larger earthquakes.

Figure 10 shows the magnitude-recurrence plot for the year 2010 earthquakes in black. It is very similar to the magnitude-recurrence plot for the 24-year period of 1987 to 2010 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 2010 curve is slightly 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 2010 a best fit slope of 2.02 +/- 0.27 was found, versus 2.76 +/- 0.12 for the 24-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. 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 75 mining-induced seismic events of magnitude -1.0 or greater in the study area in 2010. Seventeen of these events occurred in the Sudbury Basin, 36 in the Red Lake region, and 22 in the Cadillac, QC region. Only three of these mining-induced events recorded in the study area in 2010 were larger than m_N 2.5 and are listed in Table 4.

8. SUMMARY

Data capture was in excess of 90% from five of the seven core seismograph stations, and for 7 of the 11 POLARIS-type installations. ULM availability was low due to several lightening strikes throughout the summer, which caused components to fail and need replacement. EEO availability was low due to a faulty GPS, which caused timing problems starting in July and continuing into October. Many of the solar powered sites, experienced power failure and had poor telecommunications during the winter months, especially January and December. The satellite dish antenna at EPLO was out of alignment, causing data to be intermittent until June 13th when the dish antenna was realigned. SILO dropped out on July 30th due to faulty components. No maintenance trip was scheduled for 2010 to this site. NANO and TIMO were both closed on June 10th and July 3rd, respectively.

The seismic activity in the study area during the calendar year 2010 consisted of 118 earthquakes ranging in magnitude m_N from 0.5 to 3.2. Forty-one earthquakes were larger than m_N 2.0, and three of the earthquakes were above m_N 3.0. The largest event, m_N 3.2, was located 43 km S of Allanwater Bridge, ON. The two second largest events were m_N 3.1 located approximately 15 km apart east of Sultan, ON. 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 2010 conformed to the pattern of previous seismicity, with a few exceptions: an event 113 km NE of Gimli, MB an event west of VIMO, and a set of events located north and south of Lake Nipigon. It is possible that poorer coverage of these areas in the past (prior to the FEDNOR installation) may have allowed similar small events to go by unnoticed.

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Table 1: Located Local Earthquakes, January - December 2010

Date	Time (UT)	Latitude	Longitude	#stns/ phases	Mag m_N	Region and Comment
01/01	05:32:47	49.36N	91.98W	4/ 7	1.2MN	73 km N from Atikokan, ON
01/07	17:17:46	52.68N	80.44W	5/ 9	2.1MN	James Bay.
01/12	22:40:19	49.93N	86.42W	3/ 6	1.6MN	17 km NE from Longlac, ON
01/17	06:55:23	50.10N	91.31W	8/15	2.2MN	50 km E from Sioux Lookout, ON
01/18	01:13:23	47.14N	78.02W	7/14	1.8MN	90 km NE from Temiscaming, QC
01/18	20:58:51	46.75N	78.89W	7/13	1.6MN	16 km E from Temiscaming, QC
01/21	23:54:48	52.60N	79.97W	8/11	2.4MN	James Bay.
01/26	03:26:37	53.32N	80.95W	7/ 9	2.2MN	James Bay.
01/26	12:01:07	49.10N	92.72W	6/10	1.6MN	75 km S from Dryden, ON
01/31	04:35:05	49.11N	92.70W	3/ 5	0.7MN	75 km S from Dryden, ON
02/04	17:13:42	48.88N	87.84W	3/ 5	1.4MN	55 km W from Terrace Bay, ON
02/05	16:22:16	50.07N	90.55W	4/ 7	1.6MN	33 km SW from Allanwater Bridge, ON
02/06	13:43:56	49.04N	90.31W	4/ 8	1.2MN	100 km E from Atikokan, ON
02/07	02:27:26	53.15N	80.82W	5/ 7	2.3MN	James Bay.
02/07	02:54:29	53.16N	80.82W	4/ 6	1.9MN	James Bay.
02/07	20:05:01	48.79N	87.90W	5/ 9	1.6MN	59 km W from Terrace Bay, ON
02/12	16:45:58	52.06N	80.09W	8/11	2.8MN	James Bay.
02/15	08:54:49	47.49N	78.60W	10/16	1.7MN	79 km E from Haileybury, ON
02/16	01:31:46	49.43N	90.67W	5/ 7	1.3MN	97 km S from Allanwater Bridge, ON
02/17	23:32:02	51.39N	95.98W	3/ 5	1.9MN	113 km NE from Gimli, MB
02/26	15:00:07	50.16N	94.92W	4/ 7	2.1MN	52 km NW from Kenora, ON
02/28	20:24:45	48.84N	88.25W	4/ 8	1.7MN	62 km NE from Mackenzie, ON
03/03	14:17:59	49.28N	93.06W	5/ 7	1.4MN	58 km S from Dryden, ON
03/07	08:12:08	49.10N	91.96W	6/10	1.6MN	45 km NW from Atikokan, ON
03/22	03:03:23	52.44N	79.58W	5/ 7	2.1MN	James Bay.
03/22	04:24:14	47.53N	82.61W	16/25	3.1MN	13 km SE of Sultan, ON
04/01	06:00:28	47.83N	89.79W	9/13	2.2MN	73 km SW from Thunder Bay, ON
04/05	21:24:49	53.68N	81.27W	11/16	2.6MN	James Bay.
04/06	08:52:05	49.83N	91.83W	8/16	2.6MN	28 km S from Sioux Lookout, ON
04/21	06:40:49	52.34N	79.70W	6/ 9	2.1MN	James Bay.
05/04	02:03:31	46.32N	79.68W	4/ 8	0.9MN	16 km W from North Bay, ON
05/04	03:39:51	46.32N	79.65W	9/16	1.6MN	15 km W from North Bay, ON
05/06	06:17:43	47.44N	78.26W	7/13	1.9MN	78 km S from Malartic, QC
05/09	11:28:38	53.45N	80.99W	3/ 5	1.6MN	James Bay.
05/16	13:59:16	49.13N	92.20W	4/ 6	1.2MN	60 km NW from Atikokan, ON
05/16	14:26:59	49.10N	92.25W	3/ 5	1.0MN	60 km NW from Atikokan, ON
05/21	22:18:23	53.80N	80.78W	3/ 5	2.0MN	James Bay.
05/31	01:14:34	48.55N	90.72W	8/14	2.1MN	70 km E from Atikokan, ON
06/11	05:15:09	51.61N	80.64W	9/14	2.1MN	33 km N from Moosonee, ON
06/11	17:59:41	49.03N	88.24W	4/ 8	2.1MN	75 km NE from Mackenzie, ON
06/11	22:29:46	46.80N	78.90W	6/10	1.0MN	19 km NE from Temiscaming, QC
06/12	21:34:34	53.33N	81.39W	3/ 6	2.1MN	James Bay.
06/13	21:49:03	51.15N	94.35W	3/ 6	1.9MN	44 km W from Red Lake, ON
06/19	00:08:23	52.28N	81.17W	7/11	2.3MN	James Bay.
06/23	21:43:48	52.41N	80.78W	10/17	2.9MN	James Bay.
06/29	19:01:14	48.87N	81.07W	4/ 8	2.2MN	17 km S from Cochrane, ON
07/29	00:51:54	46.81N	78.29W	10/17	2.4MN	64 km E from Temiscaming, QC

08/01	12:10:35	50.92N	92.00W	5/ 9	1.8MN	95 km N from Sioux Lookout, ON
08/05	09:17:24	49.00N	92.09W	6/10	1.5MN	45 km NW from Atikokan, ON
08/07	11:08:21	48.56N	90.76W	7/11	1.9MN	70 km E from Atikokan, ON
08/07	14:29:10	46.66N	79.14W	10/17	2.2MN	6 km SW from Temiscaming, QC
08/11	11:19:30	49.65N	90.86W	6/10	1.6MN	83 km SW from Allanwater Bridge, ON
08/20	12:53:06	51.38N	92.58W	5/ 7	2.1MN	88 km NE from Red Lake, ON
08/24	08:29:08	54.14N	82.30W	9/14	2.8MN	James Bay.
09/05	19:31:23	50.74N	91.22W	5/ 9	1.9MN	93 km NE from Sioux Lookout, ON
09/15	00:44:02	48.21N	91.57W	4/ 8	1.4MN	60 km S from Atikokan, ON
09/16	13:14:32	49.01N	92.20W	7/12	1.9MN	52 km NW from Atikokan, ON
09/17	03:56:53	49.02N	92.16W	5/ 9	1.5MN	50 km NW from Atikokan, ON
09/17	20:09:10	47.40N	78.73W	7/10	1.9MN	69 km E from Haileybury, ON
09/23	02:01:43	52.58N	86.42W	4/ 6	1.9MN	80 km SE from Webequie, ON
09/26	00:48:18	48.20N	91.65W	6/11	1.7MN	60 km S from Atikokan, ON
10/05	22:55:07	50.20N	82.24W	3/ 5	1.7MN	73 km N from Kapuskasing, ON
10/07	08:00:58	49.57N	91.84W	6/11	1.7MN	57 km S from Sioux Lookout, ON
10/08	14:01:14	50.45N	94.94W	6/10	2.3MN	75 km NE from Pinawa, MB
10/09	21:45:39	47.22N	79.32W	8/12	1.5MN	35 km SE from Haileybury, ON
10/12	04:04:03	49.20N	91.05W	5/10	1.5MN	65 km NE from Atikokan, ON
10/27	16:25:50	49.04N	92.05W	4/ 7	1.5MN	45 km NW from Atikokan, ON
10/28	02:51:44	48.72N	78.68W	5/ 8	1.4MN	24 km SE from Macamic, QC
10/29	00:05:38	49.23N	91.04W	9/16	2.6MN	68 km NE from Atikokan, ON
10/29	02:57:28	50.08N	94.10W	3/ 6	1.4MN	38 km NE from Kenora, ON
10/30	11:42:13	49.21N	91.05W	8/14	2.2MN	66 km NE from Atikokan, ON
10/30	12:00:28	49.21N	91.05W	11/20	2.9MN	66 km NE from Atikokan, ON
10/30	14:47:50	50.03N	94.08W	3/ 6	1.4MN	35 km NE from Kenora, ON
10/30	16:19:01	49.21N	91.06W	6/11	1.7MN	65 km NE from Atikokan, ON
10/30	17:00:35	49.21N	91.07W	5/10	1.5MN	65 km NE from Atikokan, ON
10/31	01:52:47	49.20N	91.07W	7/12	1.6MN	65 km NE from Atikokan, ON
10/31	04:37:13	50.07N	94.13W	4/ 8	1.5MN	36 km NE from Kenora, ON
10/31	05:56:27	49.21N	91.07W	7/12	1.6MN	65 km NE from Atikokan, ON
10/31	06:08:30	49.21N	91.06W	5/10	1.5MN	65 km NE from Atikokan, ON
10/31	06:41:32	50.81N	88.13W	6/11	2.0MN	100 km NE from Collins, ON
10/31	10:55:10	49.21N	91.07W	10/20	2.7MN	66 km NE from Atikokan, ON
10/31	12:29:18	49.20N	91.06W	5/10	1.2MN	65 km NE from Atikokan, ON
10/31	16:41:14	49.20N	91.06W	5/10	1.4MN	65 km NE from Atikokan, ON
11/02	00:51:39	49.21N	91.05W	9/17	2.2MN	66 km NE from Atikokan, ON
11/02	18:51:53	49.20N	91.06W	5/10	1.7MN	65 km NE from Atikokan, ON
11/05	10:30:02	49.22N	91.02W	5/ 8	1.1MN	65 km NE from Atikokan, ON
11/05	13:42:56	49.20N	91.07W	6/ 9	1.2MN	65 km NE from Atikokan, ON
11/06	15:30:43	46.20N	79.23W	7/13	1.4MN	20 km NE from Powassan, ON
11/06	22:43:46	49.21N	91.08W	5/10	1.4MN	65 km NE from Atikokan, ON
11/07	00:33:17	49.21N	91.06W	5/10	1.2MN	65 km NE from Atikokan, ON
11/11	05:12:11	49.21N	91.08W	5/10	1.2MN	65 km NE from Atikokan, ON
11/14	07:06:11	46.32N	79.66W	8/16	1.4MN	16 km W from North Bay, ON
11/14	22:58:01	49.60N	84.46W	4/ 7	1.8MN	50 km NE from Hornepayne, ON
11/19	15:04:23	49.21N	91.04W	8/15	2.5MN	67 km NE from Atikokan, ON
11/20	10:02:43	46.55N	78.43W	5/ 8	1.6MN	33 km NE from Mattawa, ON
11/20	13:36:44	49.21N	91.05W	4/ 7	0.9MN	65 km NE from Atikokan, ON
11/24	05:54:57	49.71N	86.88W	3/ 6	1.4MN	6 km SE from Geraldton, ON
11/26	14:18:47	50.82N	88.18W	7/11	2.3MN	108 km NE from Collins, ON
11/28	00:14:32	49.20N	91.05W	4/ 8	1.4MN	65 km NE from Atikokan, ON

11/29	02:41:24	49.14N	91.54W	5/ 8	1.3MN	43 km N from Atikokan, ON
12/01	15:11:55	49.19N	91.05W	7/13	1.9MN	64 km NE from Atikokan, ON
12/03	06:19:17	49.02N	92.08W	5/10	1.4MN	45 km NW from Atikokan, ON
12/04	06:01:59	49.00N	92.09W	4/ 8	1.8MN	45 km NW from Atikokan, ON
12/04	18:45:19	49.36N	91.57W	7/12	2.3MN	68 km N from Atikokan, ON
12/04	19:23:33	49.14N	91.56W	4/ 8	1.7MN	44 km N from Atikokan, ON
12/05	04:02:13	49.86N	90.28W	7/12	2.0MN	43 km S from Allanwater Bridge, ON
12/06	02:44:54	51.50N	91.74W	4/ 6	1.7MN	107 km W from Pickle Lake, ON
12/07	07:02:02	47.66N	82.65W	16/28	3.1MN	11 km NE of Sultan, ON
12/10	05:50:33	49.21N	91.08W	4/ 8	1.7MN	65 km NE from Atikokan, ON
12/10	05:51:04	49.22N	91.05W	5/ 8	1.9MN	67 km NE from Atikokan, ON
12/10	06:01:23	49.22N	91.06W	4/ 7	1.0MN	66 km NE from Atikokan, ON
12/10	08:27:44	49.22N	91.06W	4/ 8	1.3MN	66 km NE from Atikokan, ON
12/16	07:01:31	48.13N	80.11W	7/13	2.5MN	6 km W from Kirkland Lake, ON. Felt.
12/17	14:49:11	49.06N	90.69W	7/13	2.4MN	76 km NE from Atikokan, ON
12/21	20:43:15	49.14N	91.53W	6/11	1.8MN	44 km N from Atikokan, ON
12/22	16:30:51	49.86N	90.28W	8/14	3.2MN	43 km S from Allanwater Bridge, ON
12/22	16:36:42	49.84N	90.28W	9/17	2.5MN	45 km S from Allanwater Bridge, ON
12/29	12:09:45	49.13N	91.57W	5/ 9	1.1MN	43 km N from Atikokan, ON

Table 2: NWMO Supported Stations Operating During 2010
(2009 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	89.6 (95.5)	19941207-
SOLO	Sioux Lookout	50.0213	92.0812	373	98.0 (96.9)	19981104-
TBO	Thunder Bay	48.6473	89.4083	468	100.0 (99.9)	19931005-
GTO	Geraldton	49.7455	86.9610	350	99.6 (99.5)	20010104-
KAPO	Kapuskasing	49.4504	82.5079	210	100.0 (93.1)	19980114-
EEO	Eldee	46.6411	79.0733	398	76.4 (83.3)	19931005-
CRLO	Chalk River	46.0375	77.3801	168	98.5 (99.7)	19941117-
SILO	Sutton Inlier	54.4791	84.9126	195	51.3 (94.2)	20030609-
VIMO	Victor Mine	52.8173	83.7449	78	84.7 (96.0)	20030611-
MALO	McAlpine Lake	50.0244	79.7635	271	91.5 (98.6)	20030620-
KILO	Kirkland Lake	48.4972	79.7232	314	92.5 (80.5)	20030622-
SUNO	Sudbury	46.6438	81.3442	343	91.8 (83.4)	20030623-
EPLO	Experimental Lake	49.6737	93.7258	437	66.6 (59.8)	20040611-
ATKO	Atikokan	48.8231	91.6004	383	100.0 (93.0)	20040609-
PKLO	Pickle Lake	51.4987	90.3522	376	100.0 (100.0)	20040615-
PNPO	Pukaskwa Nat. Park	48.5957	86.2846	219	99.8 (98.5)	20040618-
NANO	Aroland	50.3543	86.9684	309	99.9 (99.6)	20050804-20100610
TIMO	Timmins	48.4659	81.3032	392	88.9 (79.3)	20050725-20100703

Notes:
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.

The following summary lists major outages that affected station operation times in 2010. All times given are in UT (Universal Time).

NANO was closed on June 10th.
TIMO was closed on July 3rd after the site was vandalized.

ULM dropped out May 29th during severe thunderstorms. An electrical surge damaged several components. Data flow was restored June 21st. The station dropped out again from July 3rd to July 12th due to a faulty network component after a lightning storm and again on July 20th and 21st due to faulty ports on the new component. ULM dropped out three times in August due to a faulty network component. The component was subsequently replaced.

SOLO dropped out from December 26, 2009 to January 7, 2010. A telecommunications component at the station hung, and required a power cycle by the provider. The station dropped out again on November 30th requiring the satellite communications provider to remotely reset their electronics to restore data flow.

GTO was out during intervals from July 2nd to July 7th due to a faulty VSAT dish component. The provider replaced the unit to restore normal operation.

EEO was out on March 21st during maintenance by the satellite communications provider, and from April 18th to April 19th possibly due to loss of main power. Starting July 15th and continuing through to October 9th, EEO had faulty GPS timing. Data with bad timing were not being forwarded. The GPS antenna and cable were replaced by our technician to restore good timing. EEO dropped out again from October 17th to 19th possibly due to a main power outage.

CRLO dropped out from December 16th to 21st due to a failed power transformer.

SILO, VIMO, MALO, KILO, SUNO, and TIMO, which are solar powered sites, dropped out due to low battery voltage during intervals starting from December 2009, and continuing to February 2010.
VIMO, MALO, KILO, SUNO, and EPLO dropped out again due to low battery voltage during intervals in December 2010.

SILO dropped out from June 28th to July 9th, requiring the technicians to repoint the VSAT dish to restore operation. SILO dropped out July 30th due to faulty components at the site, but as the site is remote, no additional maintenance trip to this site is scheduled for this year.

EPLO data are out or intermittent since May 2009. The satellite dish antenna was realigned during asite trip on June 13th, which restored the station data.

PNPO data were intermittent since August 14, 2009 and continuing to January 13, 2010. The technicians found a faulty VSAT modem affecting data retransmission. The bandwidth and power have been increased to restore normal data transmission.

VIMO data availability was very intermittent from May 17th through to June 14th. The bandwidth was adjusted to improve availability. VIMO dropped out from June 28th to July 10th. The technicians repointed the VSAT dish to restore operation.

KILO dropped out for 8 hours on November 24th, probably due to insufficient solar power.

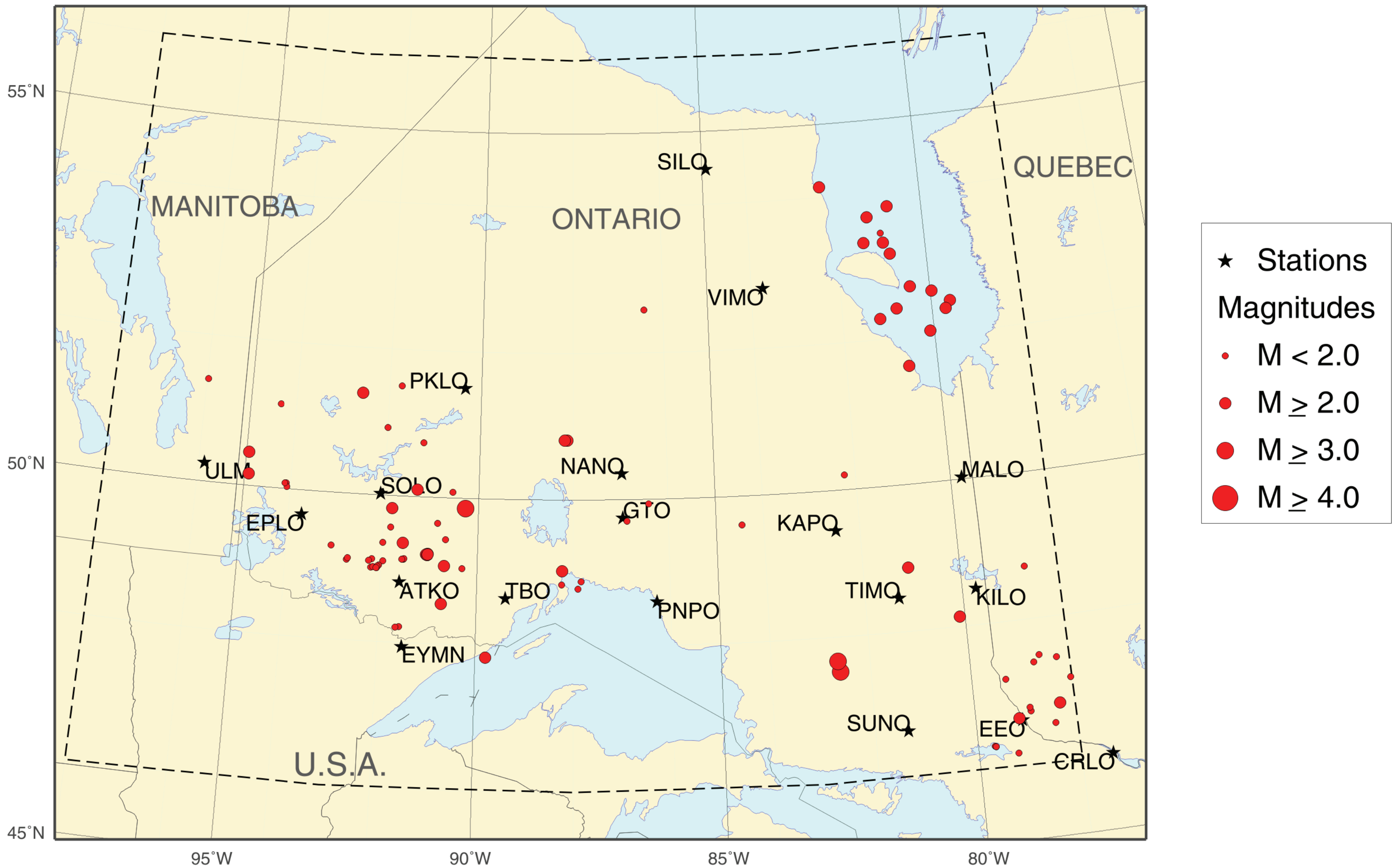
Table 3: Depths Derived using Rg-phases and Regional Depth Phase Method (RDPM) for Moderate-sized Events for 2010

Date mm/dd	Time (UT) hh:mm:ss	Mag (m_N)	Depth (km)	Depth type Rg/RDPM)	Region and Comment
01/01	05:32:47	1.2	5	Rg	73 km N from Atikokan, ON
01/17	06:55:23	2.2	3.5	RDPM	50 km E from Sioux Lookout, ON
01/26	12:01:07	1.6	5	Rg	75 km S from Dryden, ON
01/31	04:35:05	0.7	5	Rg	75 km S from Dryden, ON
02/04	17:13:42	1.4	1	Rg	55 km W from Terrace Bay, ON
02/05	16:22:16	1.6	5	Rg	33 km SW from Allanwater Bridge, ON
02/06	13:43:56	1.2	5	Rg	100 km E from Atikokan, ON
02/07	20:05:01	1.6	1	Rg	59 km W from Terrace Bay, ON
02/16	01:31:46	1.3	5	Rg	97 km S from Allanwater Bridge, ON
02/17	23:32:02	1.9	5	Rg	113 km NE from Gimli, MB
02/26	15:00:07	2.1	5	Rg	52 km NW from Kenora, ON
02/28	20:24:45	1.7	1	Rg	62 km NE from Mackenzie, ON
03/03	14:17:59	1.4	5	Rg	58 km S from Dryden, ON
03/07	08:12:08	1.6	5	Rg	45 km NW from Atikokan, ON
03/22	04:24:14	3.1	3.5	RDPM	70 km SE from Chapleau, ON
04/01	06:00:28	2.2	5	Rg	73 km SW from Thunder Bay, ON
04/06	08:52:05	2.6	2.5	RDPM	28 km S from Sioux Lookout, ON
05/04	02:03:31	0.9	5	Rg	16 km W from North Bay, ON
05/04	03:39:51	1.6	5	Rg	15 km W from North Bay, ON
05/16	13:59:16	1.2	5	Rg	60 km NW from Atikokan, ON
05/16	14:26:59	1.0	5	Rg	60 km NW from Atikokan, ON
05/31	01:14:34	2.1	5	Rg	70 km E from Atikokan, ON
06/11	17:59:41	2.1	5	Rg	75 km NE from Mackenzie, ON
06/23	21:43:47	2.9	15	RDPM	James Bay.
07/29	00:51:54	2.4	14	RDPM	62 km E of Temiscaming, QC
08/05	09:17:24	1.5	5	Rg	45 km NW from Atikokan, ON
08/07	11:08:21	1.9	5	Rg	70 km E from Atikokan, ON
08/11	11:19:30	1.6	5	Rg	83 km SW from Allanwater Bridge, ON
09/05	19:31:23	1.9	5	Rg	93 km NE from Sioux Lookout, ON
09/15	00:44:02	1.4	5	Rg	60 km S from Atikokan, ON
09/16	13:14:32	1.9	5	Rg	52 km NW from Atikokan, ON
09/17	03:56:53	1.5	5	Rg	50 km NW from Atikokan, ON
09/26	00:48:18	1.7	5	Rg	60 km S from Atikokan, ON
10/05	22:55:07	1.7	5	Rg	73 km N from Kapuskasing, ON
10/07	08:00:58	1.7	5	Rg	57 km S from Sioux Lookout, ON
10/08	14:01:14	2.3	5	Rg	75 km NE from Pinawa, MB
10/12	04:04:03	1.5	5	Rg	65 km NE from Atikokan, ON
10/27	16:25:50	1.5	5	Rg	45 km NW from Atikokan, ON
10/29	00:05:38	2.6	3	RDPM	68 km NE from Atikokan, ON
10/30	11:42:13	2.2	3.5	RDPM	66 km NE from Atikokan, ON
10/30	12:00:28	2.9	2.5	RDPM	66 km NE from Atikokan, ON
10/30	16:19:01	1.7	5	Rg	65 km NE from Atikokan, ON
10/30	17:00:35	1.5	5	Rg	65 km NE from Atikokan, ON
10/31	01:52:47	1.6	5	Rg	65 km NE from Atikokan, ON
10/31	05:56:27	1.6	5	Rg	65 km NE from Atikokan, ON
10/31	06:08:30	1.5	5	Rg	65 km NE from Atikokan, ON

10/31	10:55:10	2.7	3	RDPM	66 km NE from Atikokan, ON
10/31	12:29:18	1.2	5	Rg	65 km NE from Atikokan, ON
10/31	16:41:14	1.4	5	Rg	65 km NE from Atikokan, ON
11/02	00:51:39	2.2	2.5	RDPM	66 km NE from Atikokan, ON
11/02	18:51:53	1.7	5	Rg	65 km NE from Atikokan, ON
11/05	10:30:02	1.1	5	Rg	65 km NE from Atikokan, ON
11/05	13:42:56	1.2	5	Rg	65 km NE from Atikokan, ON
11/06	22:43:46	1.4	5	Rg	65 km NE from Atikokan, ON
11/07	00:33:17	1.2	5	Rg	65 km NE from Atikokan, ON
11/11	05:12:11	1.2	5	Rg	65 km NE from Atikokan, ON
11/14	07:06:11	1.4	5	Rg	16 km W from North Bay, ON
11/19	15:04:23	2.5	3	RDPM	67 km NE from Atikokan, ON
11/20	13:36:44	0.9	5	Rg	65 km NE from Atikokan, ON
11/24	05:54:57	1.4	5	Rg	6 km SE from Geraldton, ON
11/26	14:18:47	2.3	4	RDPM	108 km NE from Collins, ON
11/28	00:14:32	1.4	5	Rg	65 km NE from Atikokan, ON
11/29	02:41:24	1.3	5	Rg	43 km N from Atikokan, ON
12/01	15:11:55	1.9	3	RDPM	64 km NE from Atikokan, ON
12/03	06:19:17	1.4	5	Rg	45 km NW from Atikokan, ON
12/04	06:01:59	1.8	5	Rg	45 km NW from Atikokan, ON
12/04	18:45:19	2.3	5	Rg	68 km N from Atikokan, ON
12/04	19:23:33	1.7	5	Rg	44 km N from Atikokan, ON
12/05	04:02:13	2.0	5	Rg	43 km S from Allanwater Bridge, ON
12/07	07:02:02	3.1	4	RDPM	59 km E from Chapleau, ON
12/10	05:50:33	1.7	5	Rg	65 km NE from Atikokan, ON
12/10	05:51:04	1.9	5	Rg	67 km NE from Atikokan, ON
12/10	06:01:23	1.0	5	Rg	66 km NE from Atikokan, ON
12/10	08:27:44	1.3	5	Rg	66 km NE from Atikokan, ON
12/16	07:01:31	2.5	2.0	RDPM	6 km W from Kirkland Lake, ON.
12/17	14:49:11	2.4	3.5	RDPM	76 km NE from Atikokan, ON
12/21	20:43:15	1.8	5	Rg	44 km N from Atikokan, ON
12/22	16:30:51	3.2	3	RDPM	43 km S from Allanwater Bridge, ON
12/22	16:36:42	2.5	2.5	RDPM	45 km S from Allanwater Bridge, ON
12/29	12:09:45	1.1	5	Rg	43 km N from Atikokan, ON

Table 4: Mining-Induced Seismic Events m_N 2.5 and Greater, January - December 2010

Date (yyyy/mm/dd)	Mine	Location	Magnitude
2010/06/12	LaRonde Mine	Cadillac	2.6 m_N
2010/07/02	LaRonde Mine	Cadillac	2.5 m_N
2019/09/24	Coleman Mine	Sudbury	2.6 m_N

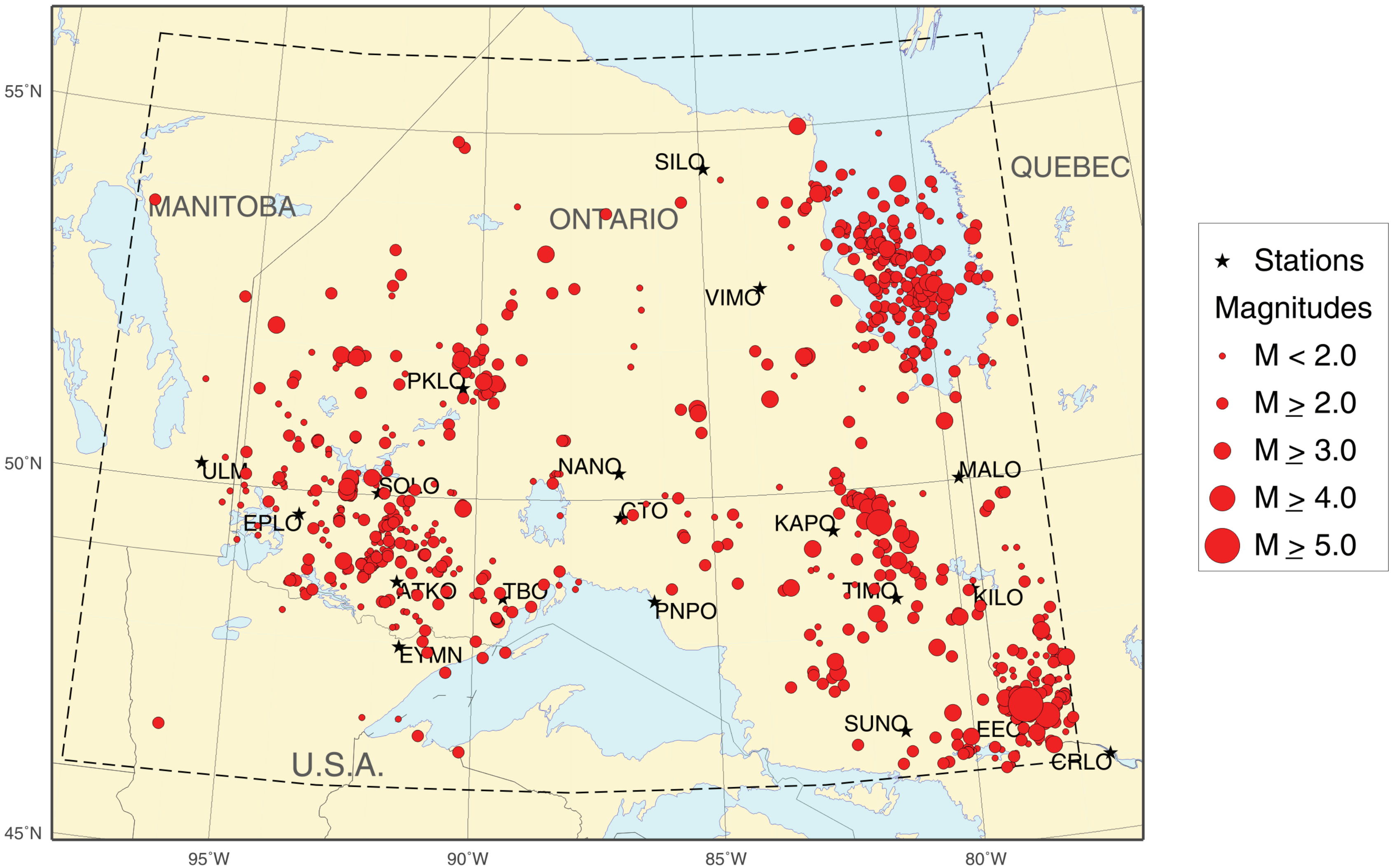


(Earthquakes plotted for the region within dashed lines

km

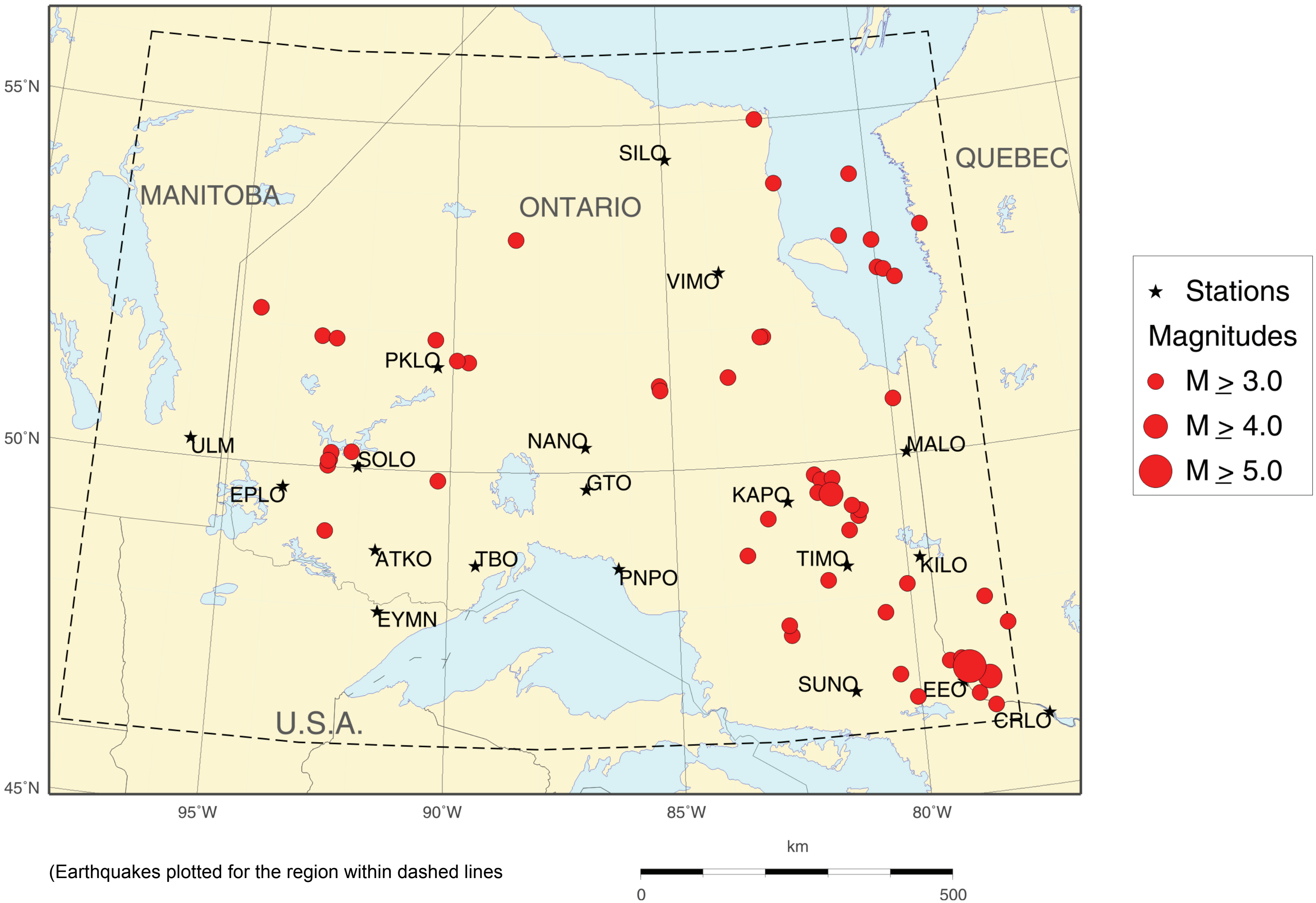
0 500

Figure 1: Earthquakes in Northern Ontario and Adjacent Areas, 2010



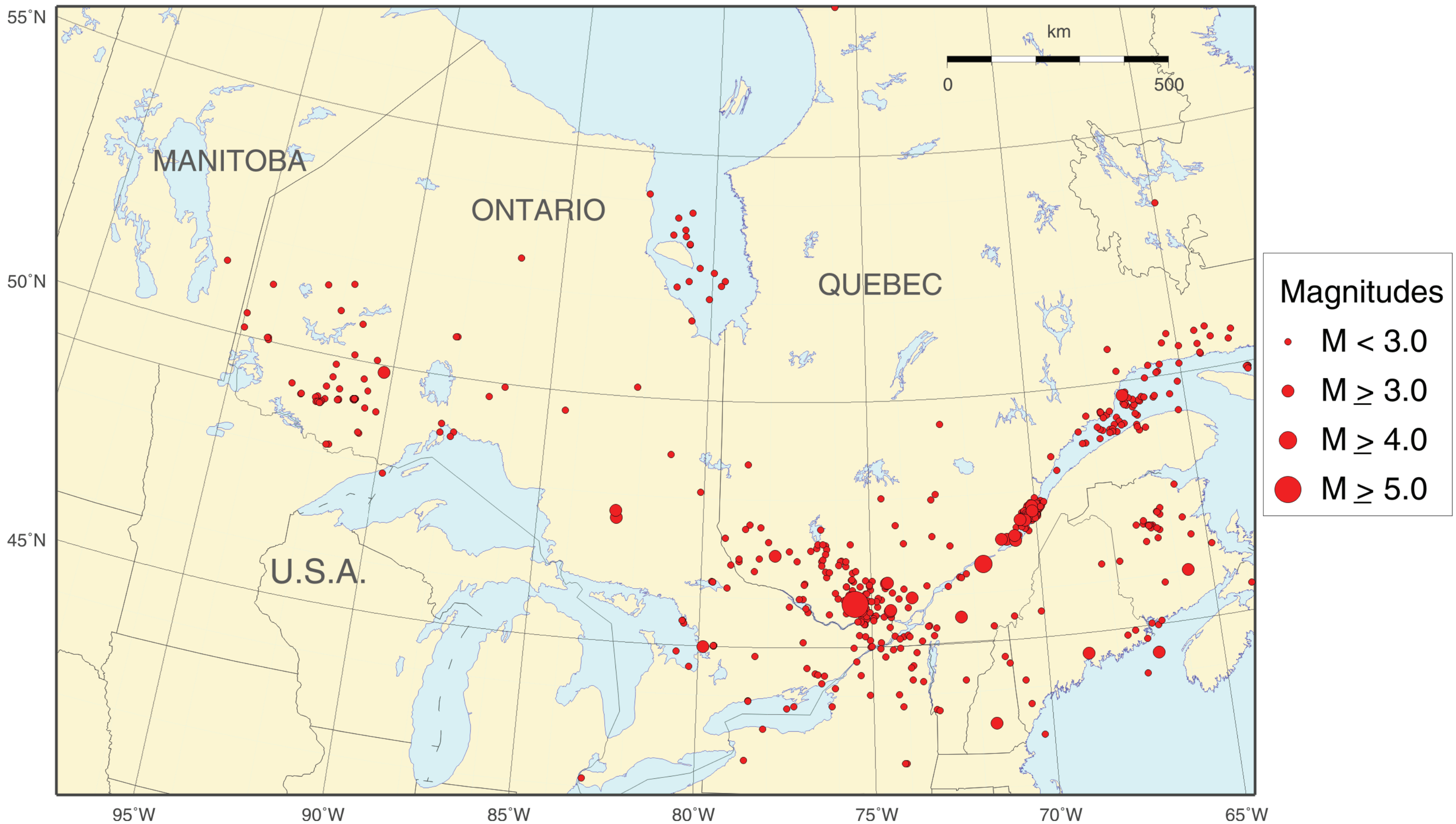
(Earthquakes plotted for the region within dashed lines

Figure 2: Earthquakes in Northern Ontario and Adjacent Areas, 1982 - 2010



(Earthquakes plotted for the region within dashed lines

Figure 3: Earthquakes $m_N \geq 3$ in Northern Ontario and Adjacent Areas, 1982 – 2010



(Earthquakes plotted for the region within dashed lines

Figure 4: Earthquakes in Eastern Canada, 2010

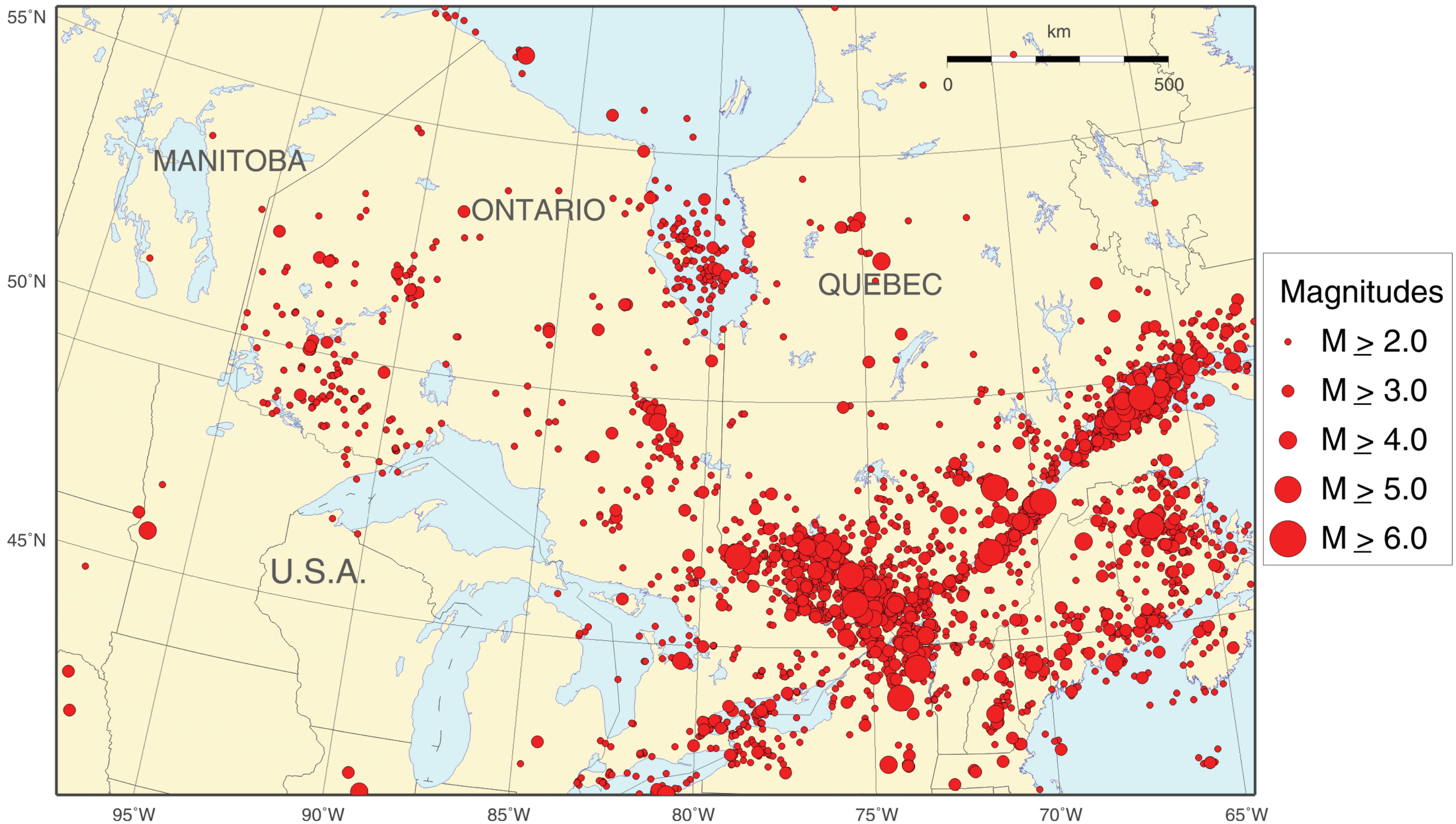
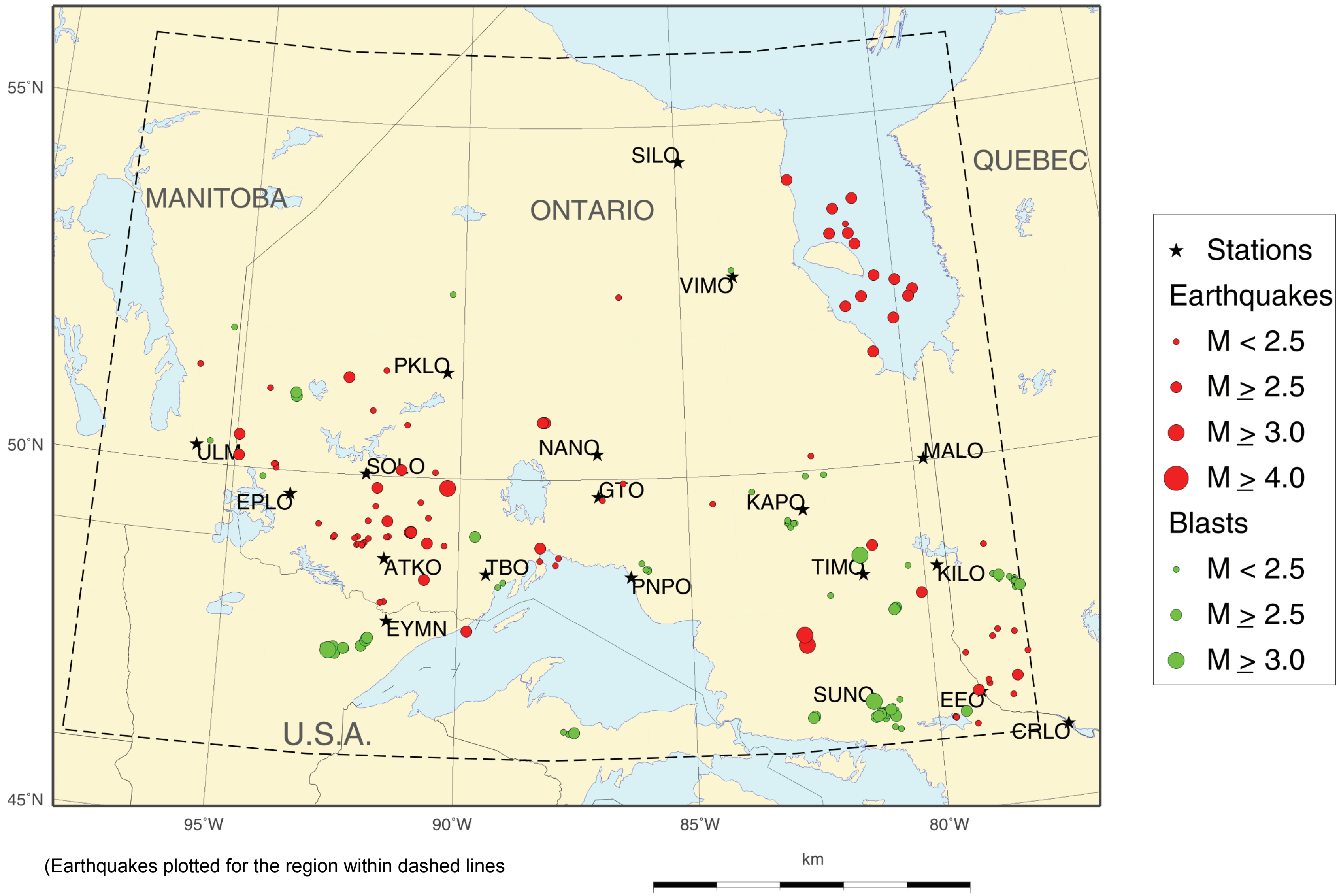


Figure 5: Earthquakes in Eastern Canada, 1982 - 2010



(Earthquakes plotted for the region within dashed lines

km

Figure 6: Earthquakes and Blasts in Northern Ontario and Adjacent Areas, 2010

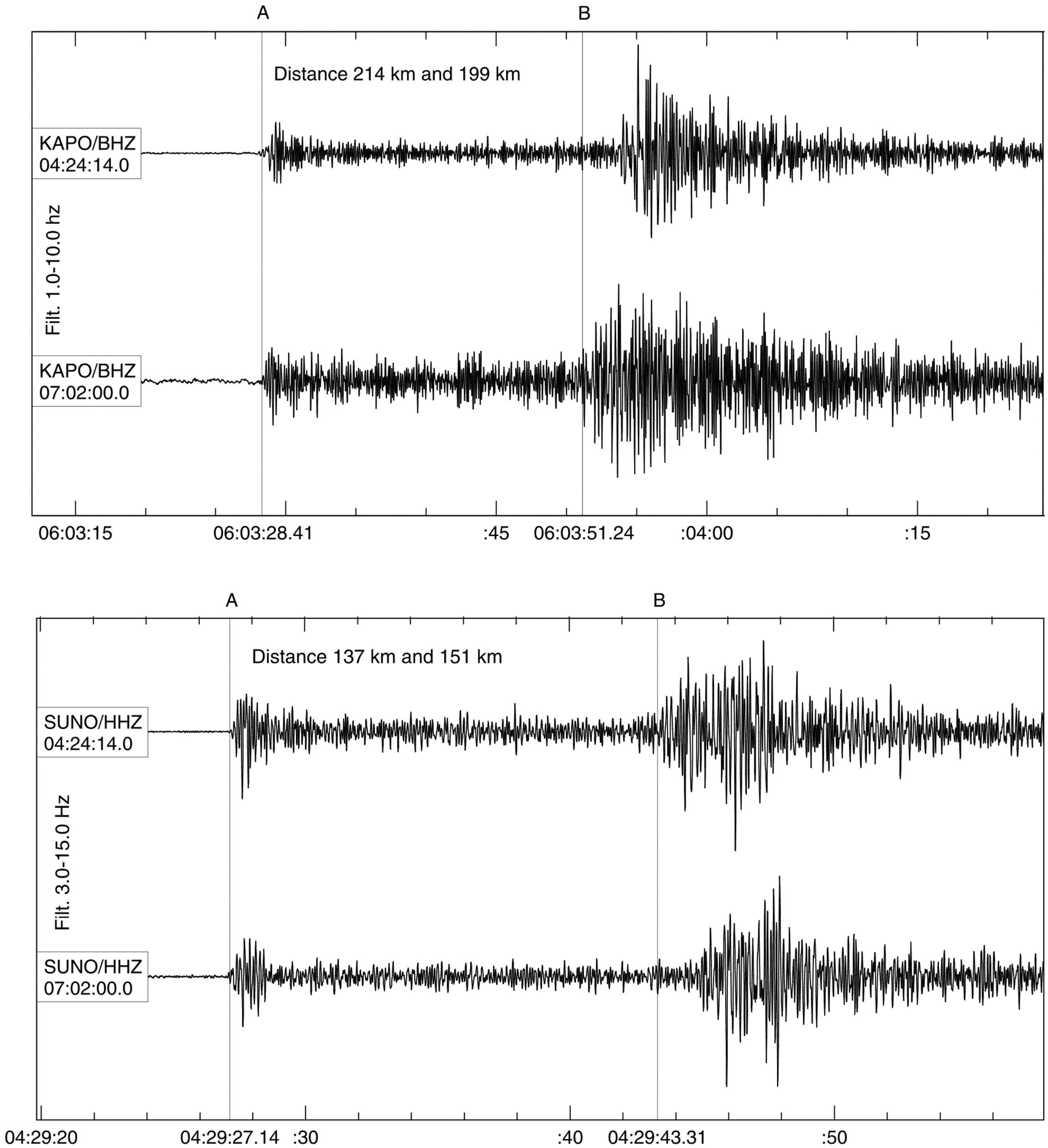


Figure 7: Comparisons of the waveforms of the two m_N 3.1 events near Sultan, ON

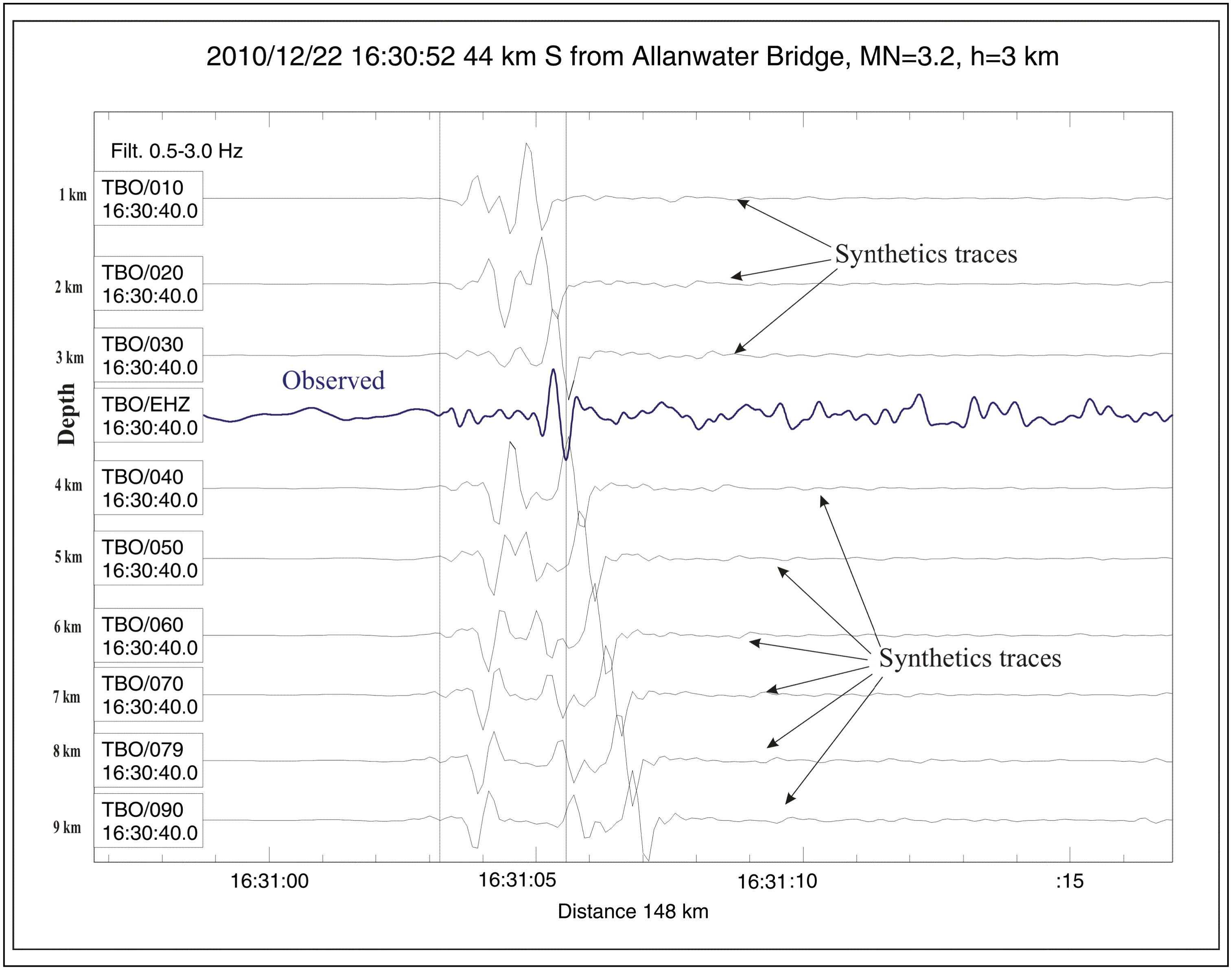


Figure 8: Observed and Synthetic Waveforms from the m_N 3.2 on 2010/12/22 43 km south of Allanwater Bridge, ON

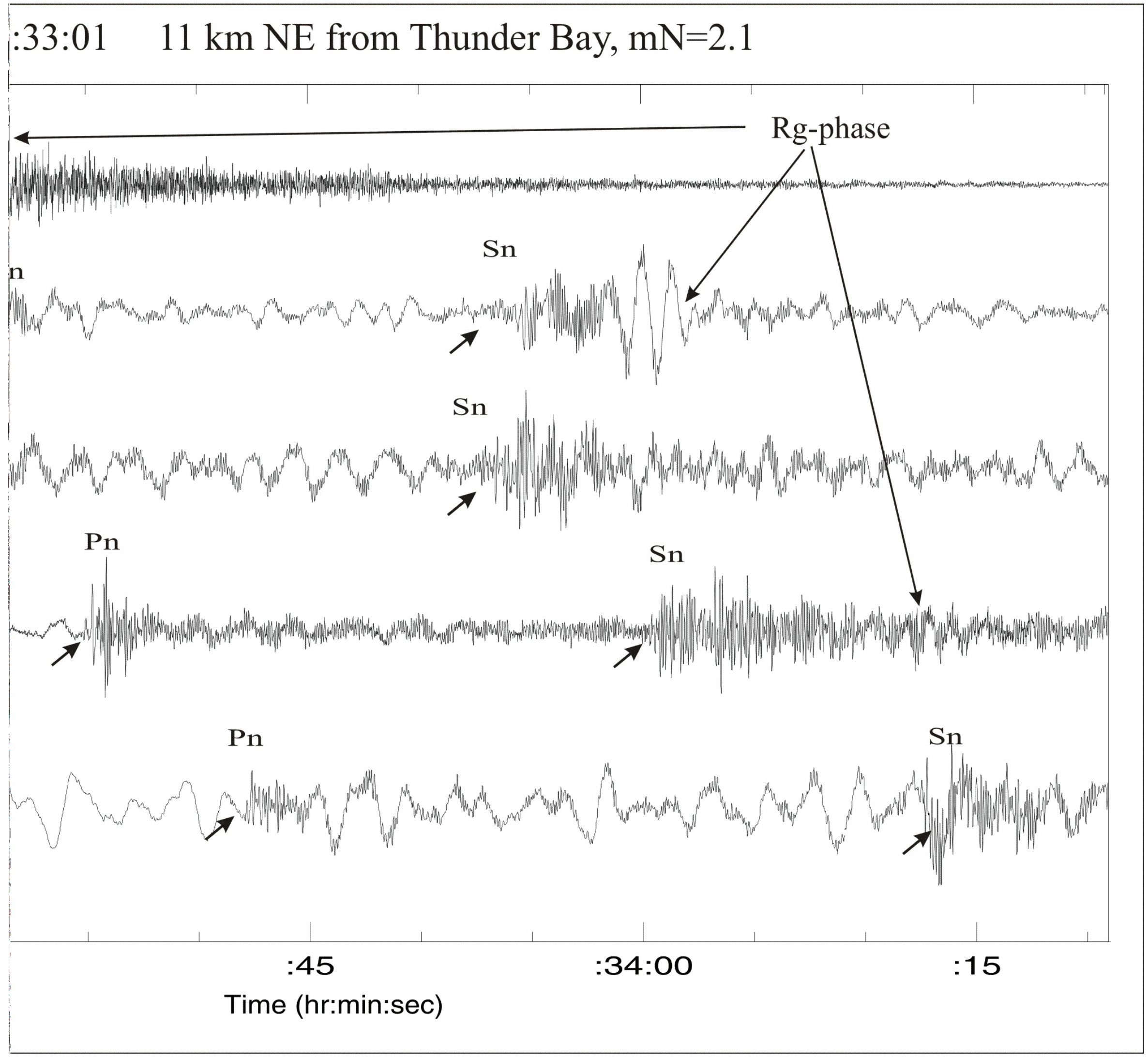


Figure 9: Rg Surface Waves from the m_N 3.1 on 2010/03/22 near Sultan, Ontario

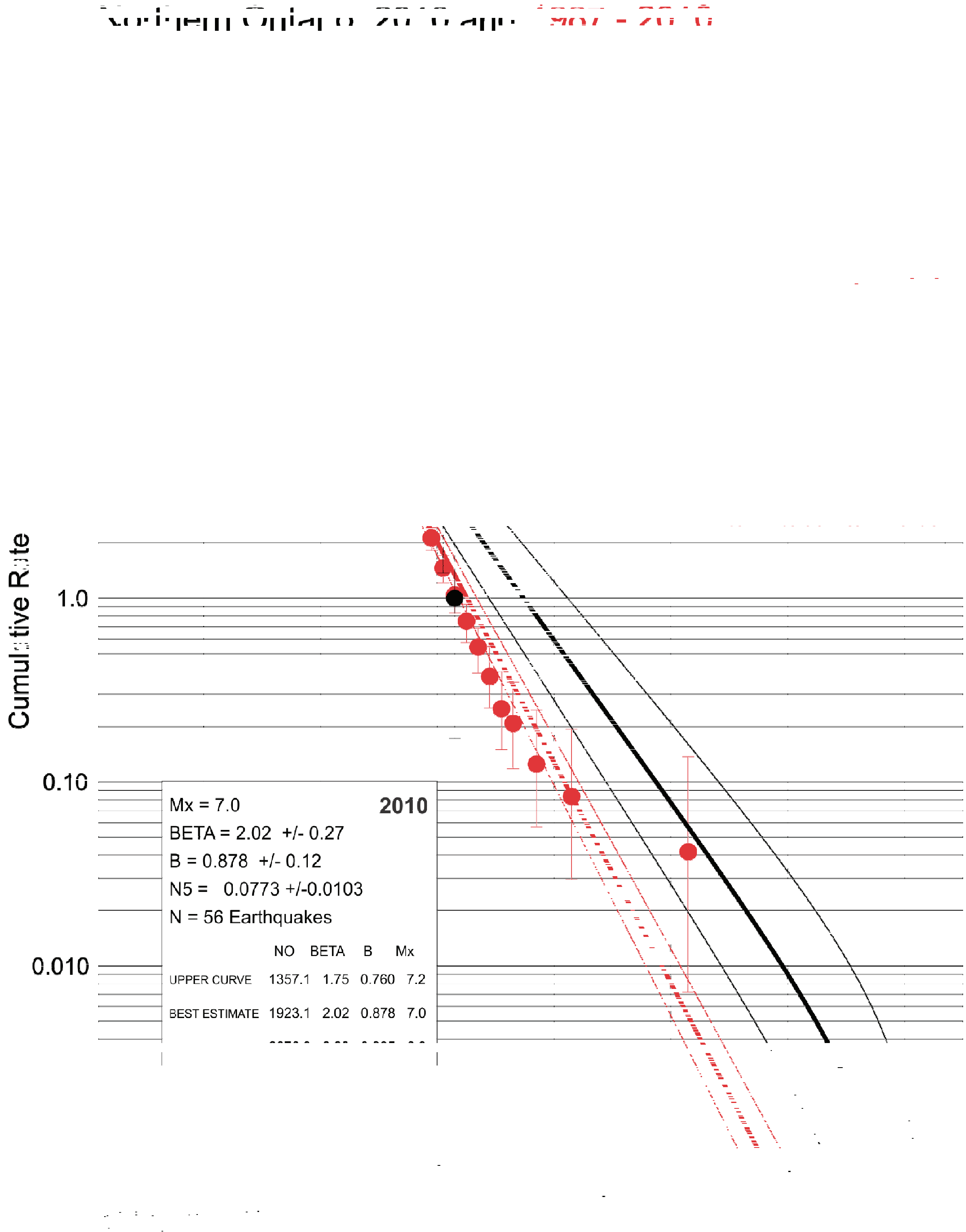


Figure 10: Recurrence Curves for Northern Ontario