Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01 – December 31, 2009

NWMO TR-2010-15

December 2010

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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, 2009**
Report No.: **NWMO TR-2010-15**
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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 2009.

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 2009, 82 earthquakes were located. Their magnitude ranged from 0.5 m_N to 3.4 m_N. The largest events included a m_N 3.4 in Kirkland Lake, ON and a m_N 2.9 in James Bay. The most westerly event in the area being studied was a m_N 1.3, located 54 km south of Kenora, ON. The 82 events located in 2009 compares with 114 events in 2008, 68 events in 2007, 83 events in 2006 and 103 events in 2005.

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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 2009.

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 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

[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.

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 82 earthquakes were located. Their magnitude ranged from 0.5 m_N to 3.4 m_N. The largest events included a m_N 3.4 in Kirkland Lake, ON and a m_N 2.9 in James Bay (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. 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 2009 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 to 6, and the 2009 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 4540 earthquakes had been located in Canada in the year 2009. Only 26 of these occurred in northern Ontario 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, PNPO, NANO, and TIMO are shown in Table 2. Data capture was in excess of 93% for most of the core seismograph station (except EEO) and for 7 of the 11 POLARIS stations (including VIMO). KILO, SUNO and TIMO had data in excess of 79%, while EPLO was only available for 60% of the time.

EEO experienced several problems throughout the year. In January, the region experienced a storm and the station was down for four days due to a local power outage. The data flow did not return when the power was restored and the telecommunications equipment required a remote reset to restore normal operations. Then in July, availability was low due to faulty timing, a problem which was fixed in September with a site visit. Also a satellite communications problem in October required a site reset. KAPO dropped out on August 25th when a passing lightening storm caused a power surge that caused some of the equipment to fail. The site was restored during a site visit on September 18th.

Many of the solar powered sites, particularly KILO, SUNO and TIMO, experienced power failure and had poor telecommunications during the winter months, especially January and December. EPLO data were intermittent since May due to the dish antenna being off alignment. A site trip was required to fix the problem.

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

3. EARTHQUAKES

A total of 82 earthquakes were located in the study area during 2009. The events from the year are listed in Table 1 and plotted in Figure 1. The largest event located this year was m_N 3.4 which occurred on February 24th near Kirkland Lake, Ontario. The second largest event of the year was m_N 2.9 on July 24th in James Bay. Both events occurred in areas of previous seismicity.

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 effect of this lowered threshold can be seen particularly in the James Bay region where 186 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 drew to a close 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. The location threshold appears to have been minimally affected for 2009 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 82 earthquakes from 2009, compare to previous years as follows:

Year	No. of events	No. of stations	
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	
1998	12	7	

The spike in activity in 2000 was due to the m_N 5.2 Temiscamingue event at the beginning of the year, and the numerous aftershocks that followed. The increase in the number of located events between 2003 and 2005 is due to the increase in coverage provided by the FedNor stations, which in turn has lowered the location threshold in the area. Seismic activity in 2005 saw a rise in the number of located events in the James Bay region, with rates of seismicity being slightly higher than average (although continued monitoring at the same level would be required for several more years to determine a more robust average number of events per year), bringing the total number of events for 2005 a bit higher than usual. While 2007 was a quieter year than usual in terms of seismicity, 2008 was somewhat higher with several mini-swarms of micro-activity near Thunder Bay, Sioux Lookout and in the Atikokan region that increased the numbers for the year. 2009 seems to have been a more average year once again.

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 948 earthquakes are documented during this period.

Figure 3 shows only those events that are magnitude 3 or greater during the same time period of 28 years (59 events). The pattern of all the seismicity is consistent with the pattern of the larger events.

Figure 4 illustrates the seismic activity in eastern Canada in the year 2009. As can be clearly observed, the number of earthquakes documented in northern Ontario represents one of the lowest 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 only complete to about m_N 3.0.

Figure 5 shows all the activity in eastern Canada for the entire monitoring period of 1982 - 2009. This figure also shows relatively few earthquakes of magnitude 3 or greater 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 2009 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 EEO are shown for the m_N 3.4 Kirkland Lake earthquake that occurred on February 24th, 2009 in Figure 7. The waveforms from this and other stations indicated a depth of 2.5 to 3 km, which is not considered unusual for this region of Ontario.

Figure 8 shows an earthquake that occurred near Thunder Bay on October 7th, 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 2009 generally conform to areas of past seismicity, except for a small m_N 1.9 event which occurred 46 km north of Hearst, ON and an m_N 2.7 event which occurred 40 km SW of Moose River, ON. Both of these events located close, but outside, the usual zone of seismicity in the Kapuskasing-Cochrane region. Note that 39 events occurred in the Atikokan/Thunder Bay/Sioux Lookout region of northern Ontario, almost half the year's earthquakes. A further 26 events occurred in the James Bay region, which is also one of the more active regions in the study area.

Recurrence curves for the study area for the year 2009 and for the period of 1987 to the end of 2009 (23 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://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 is not ideal; this has been improved by the addition of the newer 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 must be assumed, as is the case in the study area. Where depth of earthquake activity in continental terrains is well known (Charlevoix area for example) earthquake depths seldom exceed 30 km and most occur 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.

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 2009 or in any other 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 (approximately m_N3+) eastern Canadian earthquakes.

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 from 1980 – 2004. It was noted that events deeper than 15 km were limited to specific regions, while the shallower events were found over the entire region. A paper based on Ma (2004) and extended with subsequent work appeared in Ma et al., (2008). Figure 7 shows an application of RDPM to a 2009 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.

Table 3 lists all the events from 2009 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 five events, for which a reliable depth was determined using the RDPM method. Note that the majority of the events occurring in 2009 were too small to determine the depth, even by this 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 23 years of data for the less-common larger earthquakes.

Figure 9 shows the magnitude-recurrence plot for the year 2009 earthquakes in black. It is very similar to the magnitude-recurrence plot for the 23-year period of 1987 to 2009 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 2009 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. The error bounds for the 1-year period encompass the best fit slope for the 23-year period. For the year 2009 a best fit slope of 2.36 +/- 0.37 was found, versus 2.79 +/- 0.12 for the 23-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 69 mining-induced seismic events of magnitude -0.8 or greater in the study area in 2009. Twenty-eight of these events occurred in the Sudbury Basin, including a m_N 3.2 on February 14th. Five events occurred in Timmins, including the largest mining event of 2009, m_N 3.8 recorded on January 6th and a m_N 3.1 on June 16th. A further 8 events were located in the Red Lake region, 9 near Marathon, and 17 in Cadillac, QC. Two events, including a m_N 3.0 on July 3rd, which were felt at Musselwhite mine north of Pickle Lake are also thought to be mining-induced. A total of 14 mining-induced events larger than m_N 2.5 were recorded in the study area in 2009 and are listed in Table 4.

8. SUMMARY

Data capture was in excess of 93% from each of the core seismograph stations except EEO, and for 7 of the 11 POLARIS-type installations. EEO availability was low due to a power failure in January, faulty timing starting in July, and a satellite communications problem in the fall. Many of the solar powered sites, particularly KILO, SUNO and TIMO, experienced power failure and had poor tele-communications during the winter months, especially January and December. EPLO data were intermittent since May due to the dish antenna being off alignment.

The seismic activity in the study area during the calendar year 2009 consisted of 82 earthquakes ranging in magnitude m_N from 0.5 to 3.4. Twenty-six earthquakes were larger than m_N 2.0, and only one of the earthquakes was above m_N 3.0. The largest event, m_N 3.4, was located in Kirkland Lake, ON. The second largest event was a m_N 2.9 located in the James Bay region, one of the more active regions within the study area. 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 all detected earthquakes in this region for 2009 conformed to the pattern of previous seismicity, with the exception of an m_N 1.7 located 46 km north of Hearst and an m_N 2.7 40 km southwest of Moose River. These two events were just outside the usual zone of seismicity in the Kapuskasing-Cochrane region.

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REFERENCES

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

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

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

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

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

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

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

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

Table 1: Located Local Earthquakes, January - December 2009

Date	Time (UT)	Latitude	Longitude	#stns/ phases	Magnitude m_N	Region and Comment
01/04	04:36:48	46.31N	79.62W	11/20	2.2MN	14 km W from North Bay, ON
01/06	01:52:04	48.34N	89.48W	4/ 7	1.5MN	16 km W from Thunder Bay, ON
01/08	17:30:51	53.40N	80.25W	6/10	2.2MN	James Bay.
01/08	21:45:13	53.51N	80.21W	3/ 6	1.4MN	James Bay.
01/09	07:14:11	49.73N	84.97W	6/10	1.9MN	60 km N from Hornepayne, ON
01/12	02:06:40	49.00N	78.97W	4/ 6	1.4MN	17 km NE from Clermont, QC
01/21	09:36:03	49.67N	91.67W	5/ 7	1.2MN	50 km S from Sioux Lookout, ON
01/28	06:53:35	46.33N	79.68W	7/14	1.4MN	16 km W from North Bay, ON
02/07	04:16:29	48.68N	90.03W	3/ 5	1.0MN	61 km NW from Thunder Bay, ON
02/10	23:30:06	49.04N	92.08W	5/10	1.7MN	47 km NW from Atikokan, ON
02/11	00:57:55	49.03N	92.10W	5/10	1.4MN	47 km NW from Atikokan, ON
02/22	09:23:38	54.31N	81.43W	3/ 6	1.8MN	James Bay.
02/24	00:58:36	48.13N	80.05W	19/31	3.4MN	2 km SW from Kirkland Lake, ON
02/24	01:10:10	48.13N	80.05W	7/12	2.0MN	2 km SW from Kirkland Lake, ON
02/24	01:21:43	48.13N	80.05W	3/ 6	1.7MN	2 km SW from Kirkland Lake, ON.
03/05	11:08:58	47.90N	90.90W	4/ 7	1.5MN	110 km SE from Atikokan, ON
03/06	07:29:19	52.56N	80.30W	4/ 6	1.9MN	James Bay.
03/09	04:42:09	53.27N	81.67W	4/ 8	1.7MN	James Bay.
03/12	04:25:23	49.43N	92.09W	9/17	2.3MN	66 km SE from Dryden, ON
03/12	04:28:39	49.46N	92.04W	5/ 9	1.2MN	66 km SE from Dryden, ON
03/13	10:26:44	52.47N	80.10W	4/ 7	1.9MN	James Bay.
03/15	02:45:17	48.16N	79.98W	5/ 9	1.6MN	4 km E from Kirkland Lake, ON
03/29	01:33:07	49.15N	92.06W	6/10	1.5MN	55 km NW from Atikokan, ON
03/30	10:14:38	50.68N	93.87W	4/ 6	1.4MN	44 km S from Red Lake, ON
03/30	11:40:11	53.53N	81.95W	3/ 7	1.8MN	James Bay.
04/12	01:43:10	51.95N	81.71W	5/ 8	1.7MN	98 km NW from Moosonee, ON
04/18	05:08:21	52.65N	80.16W	3/ 5	2.0MN	James Bay.
04/25	13:00:02	46.16N	79.28W	9/17	2.6MN	15 km NE from Powassan, ON
05/06	21:37:08	48.51N	89.33W	6/10	1.7MN	11 km NW from Thunder Bay, ON. F
05/20	15:50:22	53.14N	80.49W	3/ 5	1.5MN	James Bay.
05/24	07:58:21	49.61N	81.55W	5/ 8	1.8MN	68 km E from Kapuskasing, ON
05/25	17:28:41	50.62N	81.77W	12/19	2.7MN	40 km SW from Moose River, ON
05/30	10:44:17	46.87N	79.29W	5/ 7	1.5MN	23 km NW from Temiscaming, QC
06/02	05:10:12	52.22N	80.72W	5/ 9	1.9MN	James Bay.
06/04	01:10:37	48.98N	90.43W	5/10	1.7MN	87 km E from Atikokan, ON
06/15	00:40:05	52.43N	79.99W	5/ 8	1.9MN	James Bay.
06/24	11:24:51	49.53N	91.95W	4/ 8	1.5MN	60 km S from Sioux Lookout, ON
06/28	19:20:58	50.09N	83.57W	5/10	1.9MN	46 km N from Hearst, ON
06/29	13:33:50	52.65N	89.33W	4/ 6	2.2MN	110 km NW from Lansdowne House,
07/11	15:00:20	53.88N	82.58W	3/ 6	2.2MN	James Bay region.
07/19	01:44:22	47.42N	79.43W	6/10	1.7MN	15 km E from Haileybury, ON
07/24	17:46:26	53.07N	80.62W	12/18	2.9MN	James Bay.
07/24	23:39:55	52.83N	80.65W	3/ 5	2.0MN	James Bay.
07/27	15:04:27	48.84N	88.57W	8/14	2.5MN	44 km NE from Mackenzie, ON
08/11	05:11:54	52.46N	79.71W	5/ 8	2.0MN	James Bay.
08/14	02:19:03	49.84N	91.81W	6/11	1.9MN	28 km SE of Sioux Lookout, ON
08/16	17:42:59	52.00N	80.04W	4/ 6	1.7MN	James Bay.
09/03	17:09:38	51.75N	80.18W	4/ 8	2.4MN	James Bay.
09/04	02:18:52	51.87N	80.13W	4/ 8	1.9MN	James Bay.

09/16	17:08:53	51.84N	89.60W	4/ 6	2.1MN	59 km NE from Pickle Lake, ON
09/17	00:50:04	49.65N	92.36W	6/11	2.2MN	37 km E from Dryden, ON
09/19	06:25:09	49.84N	91.81W	7/14	1.9MN	29 km SE from Sioux Lookout, ON
09/27	16:05:12	49.61N	91.79W	6/10	1.5MN	53 km S from Sioux Lookout, ON
10/05	20:35:59	52.89N	80.07W	4/ 6	2.5MN	James Bay.
10/07	20:33:01	48.47N	89.20W	8/16	2.1MN	11 km NE from Thunder Bay, ON
10/11	10:50:39	53.99N	83.56W	6/11	2.7MN	71 km NE of Attawapiskat Indian
11/08	07:26:30	53.05N	80.51W	11/16	2.6MN	James Bay
11/08	14:31:31	50.02N	92.65W	4/ 7	0.9MN	30 km E from Dryden, ON
11/12	09:18:29	49.34N	94.54W	4/ 8	1.3MN	54 km S from Kenora, ON
11/15	21:20:35	52.14N	80.00W	11/18	2.6MN	James Bay.
11/19	09:43:54	49.88N	91.47W	6/10	1.7MN	44 km SE from Sioux Lookout, ON
11/19	11:00:49	49.88N	91.47W	2/ 4	0.8MN	43 km SE from Sioux Lookout, ON
11/19	11:44:59	49.86N	91.48W	4/ 7	1.4MN	43 km SE from Sioux Lookout, ON
11/21	15:07:13	49.84N	91.48W	4/ 7	1.3MN	44 km SE from Sioux Lookout, ON
11/28	17:48:16	54.07N	82.12W	3/ 6	2.1MN	James Bay.
12/02	13:54:05	52.49N	80.15W	3/ 5	1.9MN	James Bay.
12/03	02:15:27	53.46N	81.41W	4/ 8	2.1MN	James Bay.
12/09	02:08:36	49.21N	92.06W	4/ 7	1.2MN	60 km NW from Atikokan, ON
12/11	14:28:07	47.18N	78.37W	5/ 9	1.8MN	75 km NE from Temiscaming, QC
12/14	03:51:37	49.30N	91.35W	4/ 8	1.4MN	65 km N from Atikokan, ON
12/14	08:37:06	49.45N	91.82W	5/ 9	1.5MN	70 km S from Sioux Lookout, ON
12/14	21:18:07	49.47N	91.83W	3/ 4	1.0MN	70 km S from Sioux Lookout, ON
12/15	05:26:39	51.81N	80.59W	4/ 8	1.6MN	55 km N from Moosonee, ON
12/17	21:15:54	47.36N	83.58W	7/13	2.1MN	45 km S from Chapleau, ON
12/20	18:09:35	49.57N	91.88W	4/ 6	0.5MN	70 km S from Sioux Lookout, ON
12/23	16:08:36	48.62N	89.79W	6/11	1.5MN	43 km NW from Thunder Bay, ON
12/24	06:31:27	49.30N	91.32W	4/ 8	1.4MN	65 km N from Atikokan, ON
12/24	06:39:11	49.31N	91.32W	5/ 9	1.5MN	66 km N from Atikokan, ON
12/26	01:01:30	49.00N	92.18W	6/10	2.1MN	50 km NW from Atikokan, ON
12/26	01:12:33	49.00N	92.19W	5/ 8	1.4MN	50 km NW from Atikokan, ON
12/26	01:16:58	48.99N	92.20W	5/ 9	1.5MN	50 km NW from Atikokan, ON
12/26	02:45:20	49.03N	92.21W	5/ 8	1.3MN	50 km NW from Atikokan, ON

Table 2: NWMO Supported Stations Operating During 2009 (2008 figures given in brackets)

Station		Lat (°N)	Long (°W)	Elev (m)	Uptime (%) 2008 (2007)	Dates of operation as digital stations
ULM	Pinawa	50.2503	95.8750	251	95.5 (93.9)	19941207-
SOLO	Sioux Lookout	50.0213	92.0812	373	96.9 (99.9)	19981104-
TBO	Thunder Bay	48.6473	89.4083	468	99.9 (98.9)	19931005-
GTO	Geraldton	49.7455	86.9610	350	99.5 (99.4)	20010104-
KAPO	Kapuskasing	49.4504	82.5079	210	93.1 (96.5)	19980114-
EEO	Eldee	46.6411	79.0733	398	83.3 (94.0)	19931005-
CRLO	Chalk River	46.0375	77.3801	168	99.7 (97.9)	19941117-
SILO	Sutton Inlier	54.4791	84.9126	195	94.2 (98.3)	20030609-
VIMO	Victor Mine	52.8173	83.7449	78	96.0 (99.8)	20030611-
MALO	McAlpine Lake	50.0244	79.7635	271	98.6 (100.0)	20030620-
KILO	Kirkland Lake	48.4972	79.7232	314	80.5 (90.9)	20030622-
SUNO	Sudbury	46.6438	81.3442	343	83.4 (83.7)	20030623-
EPLO	Experimental Lake	49.6737	93.7258	437	59.8 (98.3)	20040611-
ATKO	Atikokan	48.8231	91.6004	383	93.0 (97.5)	20040609-
PKLO	Pickle Lake	51.4987	90.3522	376	100.0 (96.9)	20040615-
PNPO	Pukaskwa Nat. Park	48.5957	86.2846	219	98.5 (85.2)	20040618-
NANO	Aroland	50.3543	86.9684	309	99.6 (98.5)	20050804-
TIMO	Timmins	48.4659	81.3032	392	79.3 (82.1)	20050725-

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 2009. All times given are in UT (Universal Time).

SOLO dropped out from January 4th to 8th due to snow accumulation in the VSAT dish. The station dropped out December 26th and remained out through the end of December. A telecommunications component hung and required a site visit by the provider.

GTO dropped out on January 19th for 20 hours because the station equipment hung and required a power cycle by the local agent. GTO dropped out on June 21st and 23rd due to loss of power.

EEO lost power from January 10th to the 14th due to a bad storm. Data flow did not return when power was restored and the telecommunications equipment required a remote reset to restore normal operation. EEO data quality was bad from July 2nd until September 16th due to bad timing, which also caused some data to drop out. A CHIS technician was at the site on September 16th and restored normal operation. The station dropped out again from September 26th to October 14th and from October 23rd to the 26th, and on the 27th. The satellite communications provider reset their equipment to restore data flow.

The communications at CRLO were upgraded from a serial-based VSAT to an IP-based VSAT on February 18. The statioin dropped out on April 8th due to a main power outage.

The communications at ULM were upgraded from a serial-based VSAT to an IP-based VSAT on March 27. ULM dropped out for a few hours on June 27th and 28th due to loss of power during an electrical storm. The station's timing was bad so the data were not being forwarded from September 5th until the 23rd. A replacement digitizer, which contained a GPS board was shipped and installed to restore normal operation.

KAPO was offline from May 19th until May 20th during resets to the GPS to correct bad timing. The station dropped out August 25th after lightning storms passed through the area and some components appeared to have suffered a power surge. The satellite communications provider replaced a card to clear error codes on the indoor unit, but data remained out. A CHIS technician replaced a power supply to restore normal data flow on September 18th.

Satellite communications dropped out from SOLO, KAPO, and EEO in November. The equipment required a remote reset by the provider. In the case of EEO, a technican replaced some faulty components.

EPLO data were out or intermittent since May 6th and continuing through December, apparently due to the dish antenna being off alignment. A site trip is required.

PNPO data are intermittent since August 14th and continuing through December. The technicians found a faulty VSAT modem affecting data retransmissions. The bandwidth and power have been increased to restore normal data transmission.

The following stations were out or intermittent during the indicated intervals because solar power was insufficient to keep the batteries charged:

VIMO was down in for intervals from January 10th until the 27th. The station dropped out again during intervals throughout December.

KILO was down from December 31, 2008 to January 3, 2009, and from January 4th until February 11th. The station was intermittent from March 29th for two days due to poor communications, and was intermittent again in November and December from lack of power.

SUNO was down from November of 2008 until January 28th, 2009, and again from January 28th until February 2nd. The station was intermittent from February 11th for the rest of the month, and again in November and December.

ATKO was down from December 24, 2008 to January 26, 2009.

TIMO was down from December, 2008 until February 13th, 2009, from March 3rd until the 15th, on April 4th for about a day, and was intermittent throughout December.

NANO data were intermittent on many days in May due to poor communications, and again in December due to lack of power.

MALO dropped out due to low battery voltage during intervals in November and December.

SILO dropped out due to low battery voltage in December, as the limited hours of daylight at this time of year are insufficient to keep the batteries charged.

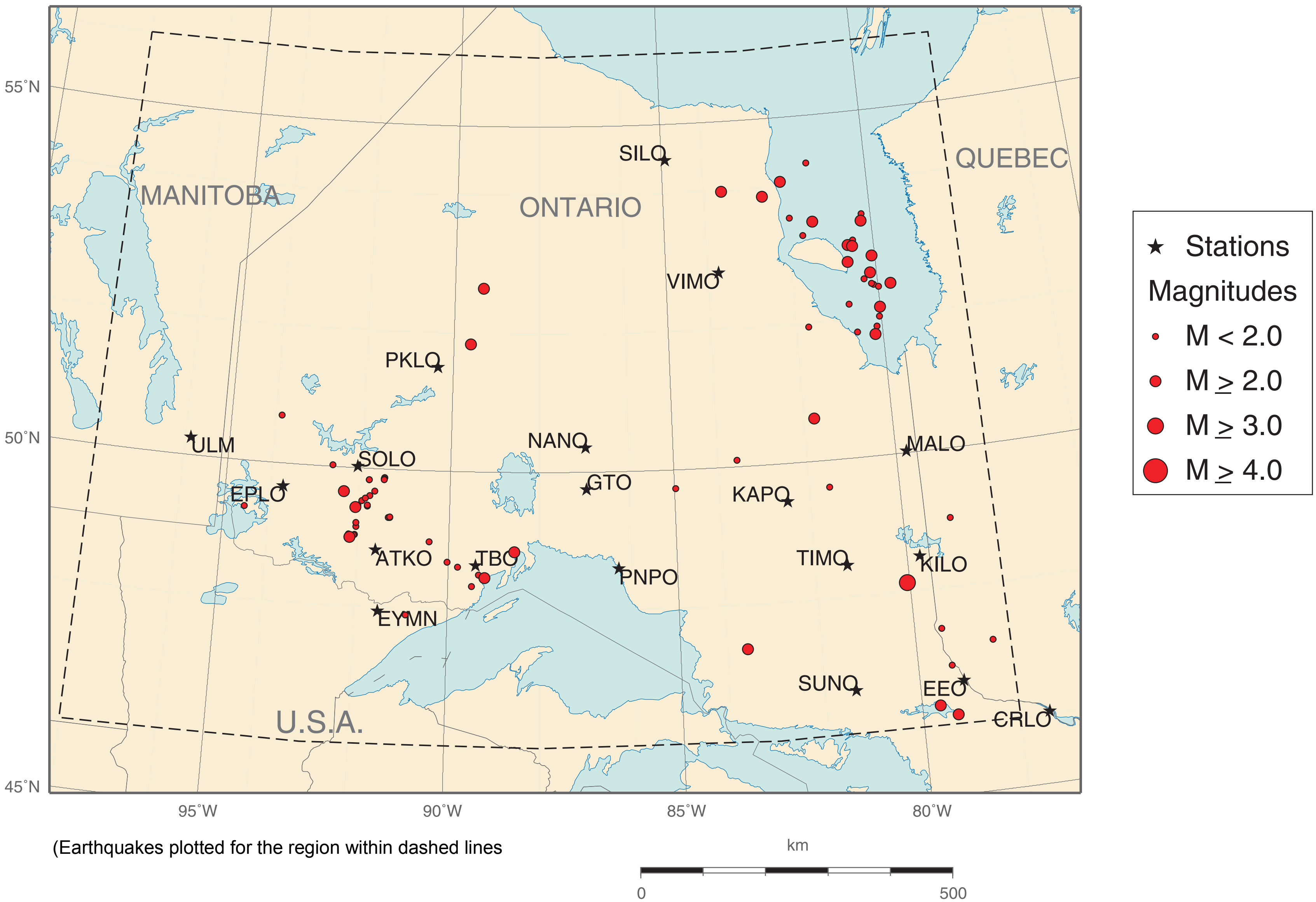
Table 3: Depths Derived using Rg-phases and Regional Depth Phase Method (RDPM) for Moderate-sized Events for 2009

Date mm/dd	Time (UT) hh:mm:ss	Mag (m_N)	Depth (km)	Depth type Rg/RDPM)	Region and Comment
01/04	04:36:48	2.2	5	Rg	14 km W from North Bay, ON
01/06	01:52:04	1.5	5	Rg	16 km W from Thunder Bay, ON
01/21	09:36:03	1.2	5	Rg	50 km S from Sioux Lookout, ON
01/28	06:53:35	1.4	5	Rg	16 km W from North Bay, ON
02/07	04:16:29	1.0	5	Rg	61 km NW from Thunder Bay, ON
02/10	23:30:06	1.7	5	Rg	47 km NW from Atikokan, ON
02/11	00:57:55	1.4	5	Rg	47 km NW from Atikokan, ON
02/24	00:58:36	3.4	3	RDPM	2 km SW from Kirkland Lake, ON
02/24	01:10:10	2.0	3	RDPM*	2 km SW from Kirkland Lake, ON
02/24	01:21:43	1.7	3	RDPM*	2 km SW from Kirkland Lake, ON.
03/12	04:25:23	2.3	1	RDPM	66 km SE from Dryden, ON
03/12	04:28:39	1.2	5	Rg	66 km SE from Dryden, ON
03/15	02:45:17	1.6	5	Rg	4 km E from Kirkland Lake, ON
03/29	01:33:07	1.5	5	Rg	55 km NW from Atikokan, ON
03/30	10:14:38	1.4	5	Rg	44 km S from Red Lake, ON
04/25	13:00:02	2.6	5	Rg	15 km NE from Powassan, ON
05/06	21:37:08	1.7	5	Rg	11 km NW from Thunder Bay, ON. F
06/04	01:10:37	1.7	5	Rg	87 km E from Atikokan, ON
07/27	15:04:27	2.5	2	RDPM	44 km NE from Mackenzie, ON
08/14	02:19:03	1.9	5	Rg	28 km SE of Sioux Lookout, ON
09/16	17:08:53	2.1	5	Rg	59 km NE from Pickle Lake, ON
09/17	00:50:04	2.2	5	Rg	37 km E from Dryden, ON
09/19	06:25:09	1.9	5	Rg	29 km SE from Sioux Lookout, ON
09/27	16:05:12	1.5	5	Rg	53 km S from Sioux Lookout, ON
10/07	20:33:01	2.1	5	Rg	11 km NE from Thunder Bay, ON
11/08	14:31:31	0.9	5	Rg	30 km E from Dryden, ON
11/12	09:18:29	1.3	5	Rg	54 km S from Kenora, ON
11/19	09:43:54	1.7	5	Rg	44 km SE from Sioux Lookout, ON
11/19	11:00:49	0.8	5	Rg	43 km SE from Sioux Lookout, ON
11/19	11:44:59	1.4	5	Rg	43 km SE from Sioux Lookout, ON
11/21	15:07:13	1.3	5	Rg	44 km SE from Sioux Lookout, ON
12/09	02:08:36	1.2	5	Rg	60 km NW from Atikokan, ON
12/14	03:51:37	1.4	5	Rg	65 km N from Atikokan, ON
12/14	08:37:06	1.5	5	Rg	70 km S from Sioux Lookout, ON
12/14	21:18:07	1.0	5	Rg	70 km S from Sioux Lookout, ON
12/20	18:09:35	0.5	5	Rg	70 km S from Sioux Lookout, ON
12/23	16:08:36	1.5	5	Rg	43 km NW from Thunder Bay, ON
12/24	06:31:27	1.4	5	Rg	65 km N from Atikokan, ON
12/24	06:39:11	1.5	5	Rg	66 km N from Atikokan, ON
12/26	01:01:30	2.1	5	Rg	50 km NW from Atikokan, ON
12/26	01:12:33	1.4	5	Rg	50 km NW from Atikokan, ON
12/26	01:16:58	1.5	5	Rg	50 km NW from Atikokan, ON
12/26	02:45:20	1.3	5	Rg	50 km NW from Atikokan, ON

* These events were too small to determine depth directly by the RDPM method. However, due to waveform similarities with the main event just prior to these events, the depth of 3 km for the larger event is assumed for the smaller events as well.

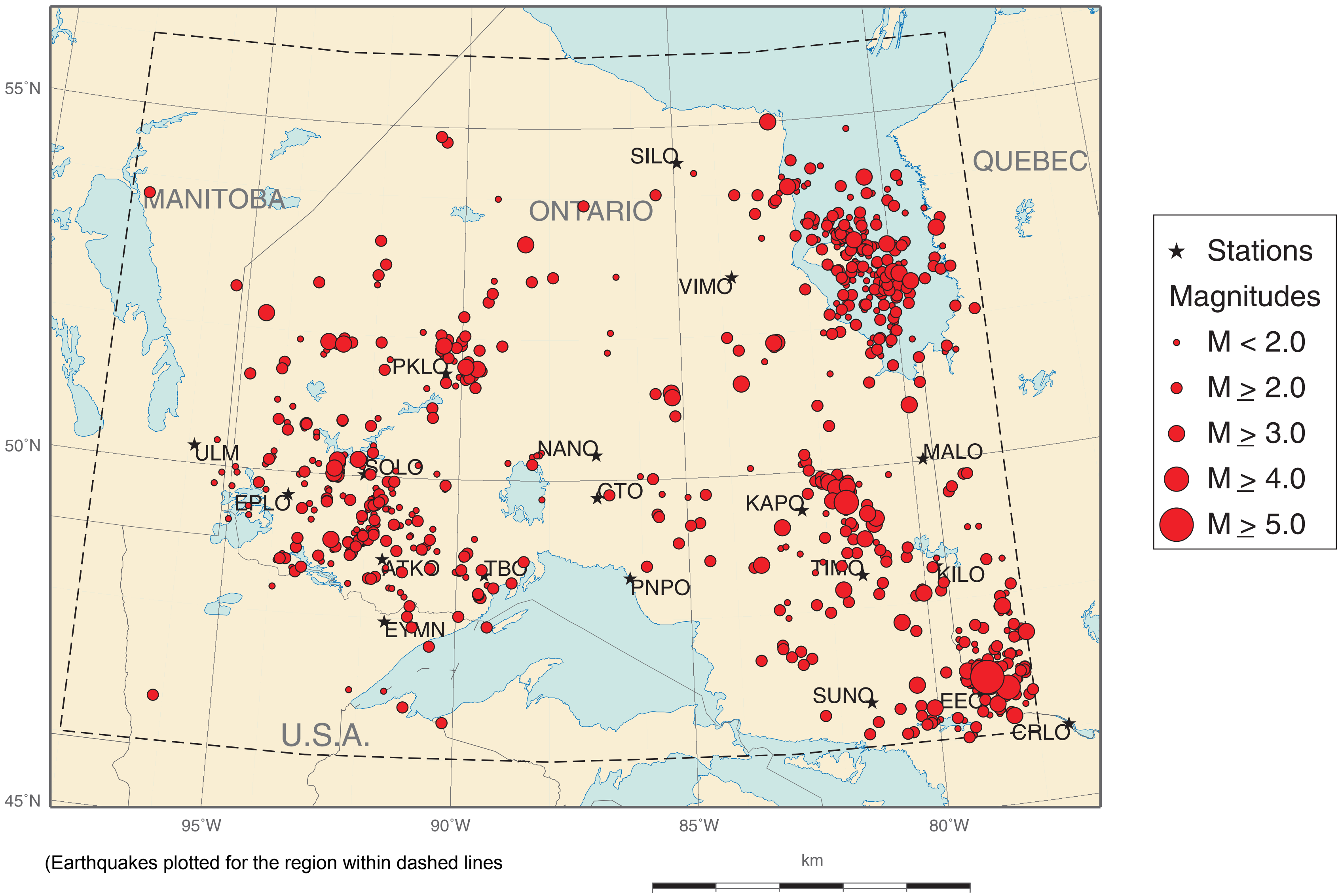
Table 4: Mining-Induced Seismic Events m_N 2.5 and Greater, January - December 2009

Date (yyyy/mm/dd)	Mine	Location	Magnitude
2009/01/06	Kidd Creek Mine	Timmins	3.8 m_N
2009/01/15	Williams Mine	Marathon	3.0 m_N
2009/02/14	Creighton Mine	Sudbury	3.2 m_N
2009/02/15	Creighton Mine	Sudbury	2.9 m_N
2009/02/15	Creighton Mine	Sudbury	2.7 m_N
2009/02/28	LaRonde Mine	Cadillac	2.5 m_N
2009/04/20	Creighton Mine	Sudbury	2.8 m_N
2009/04/28	Garson Mine	Sudbury	2.6 m_N
2009/05/10	Creighton Mine	Sudbury	2.9 m_N
2009/06/16	Kidd Creek Mine	Timmins	3.1 m_N
2009/07/03	Musselwhite Mine	Opapamiskan Lake	3.0 m_N
2009/08/11	Kidd Creek Mine	Timmins	2.6 m_N
2009/10/18	Campbell Mine	Red Lake	2.5 m_N
2009/12/20	Campbell Mine	Red Lake	2.7 m_N



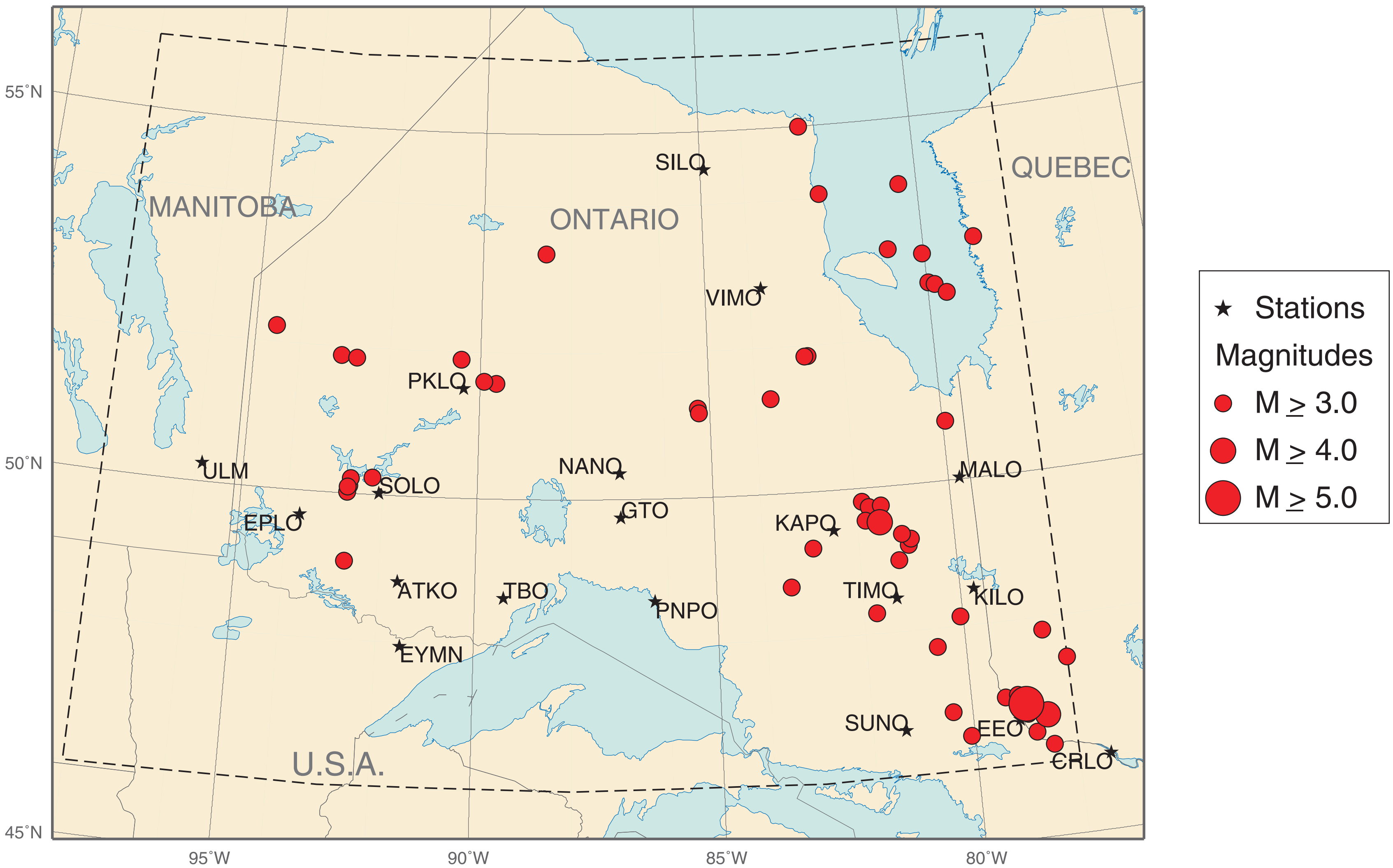
(Earthquakes plotted for the region within dashed lines

Figure 1: Earthquakes in Northern Ontario and Adjacent Areas, 2009



(Earthquakes plotted for the region within dashed lines

Figure 2: Earthquakes in Northern Ontario and Adjacent Areas, 1982 - 2009



(Earthquakes plotted for the region within dashed lines

km

Figure 3: Earthquakes $m_N \geq 3$ in Northern Ontario and Adjacent Areas, 1982 - 2009

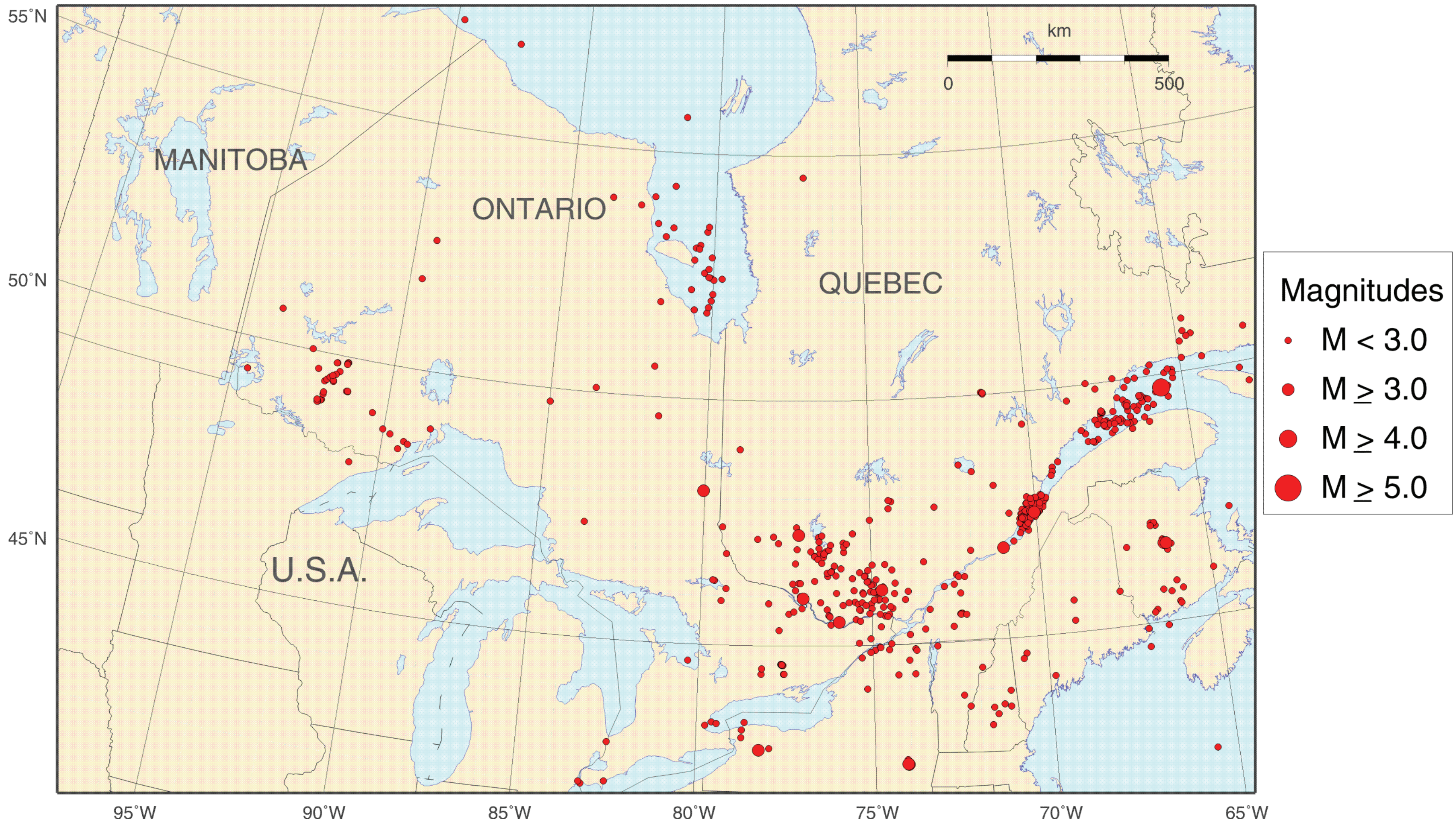


Figure 4: Earthquakes in Eastern Canada, 2009

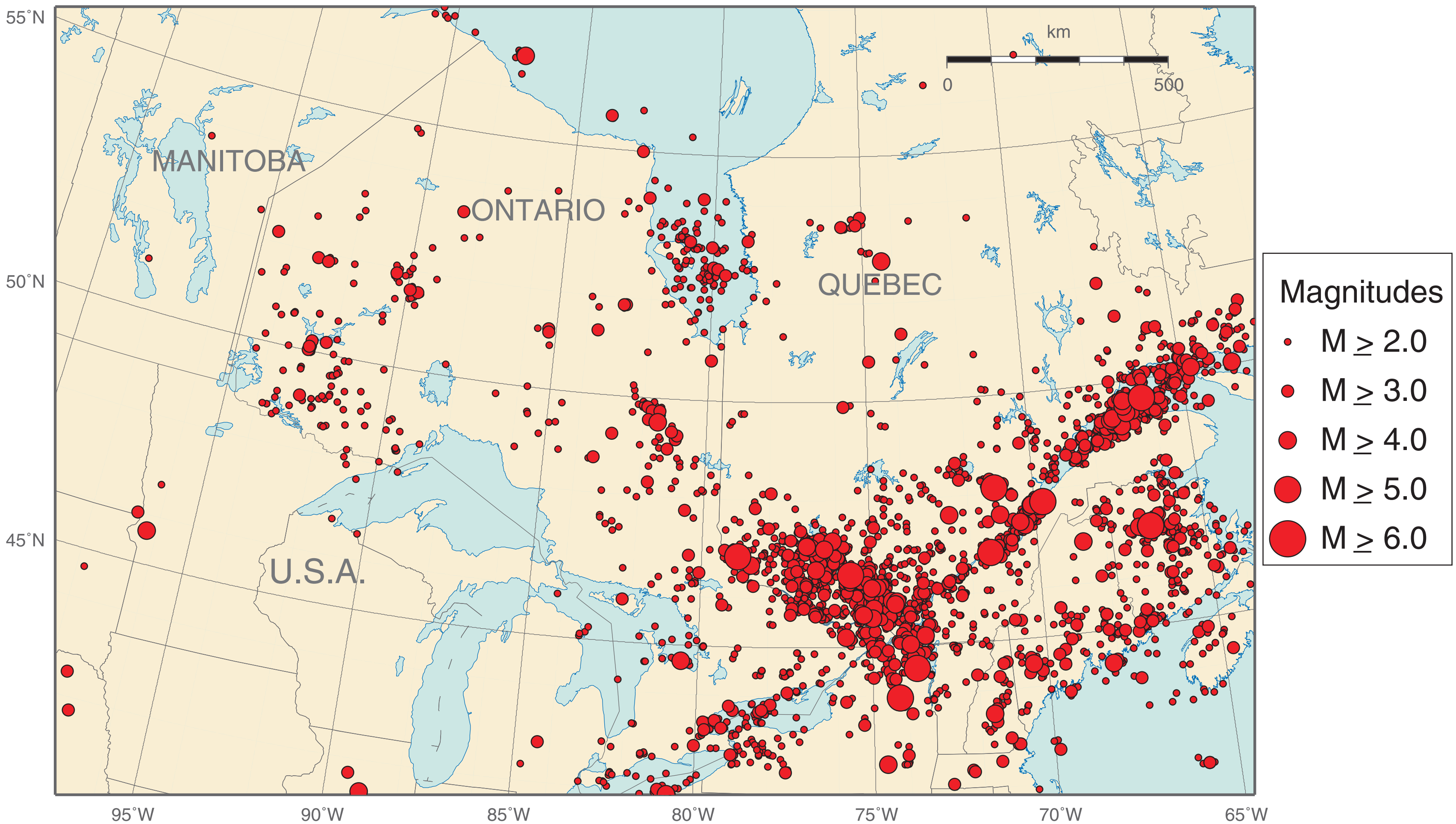


Figure 5: Earthquakes in Eastern Canada, 1982 - 2009

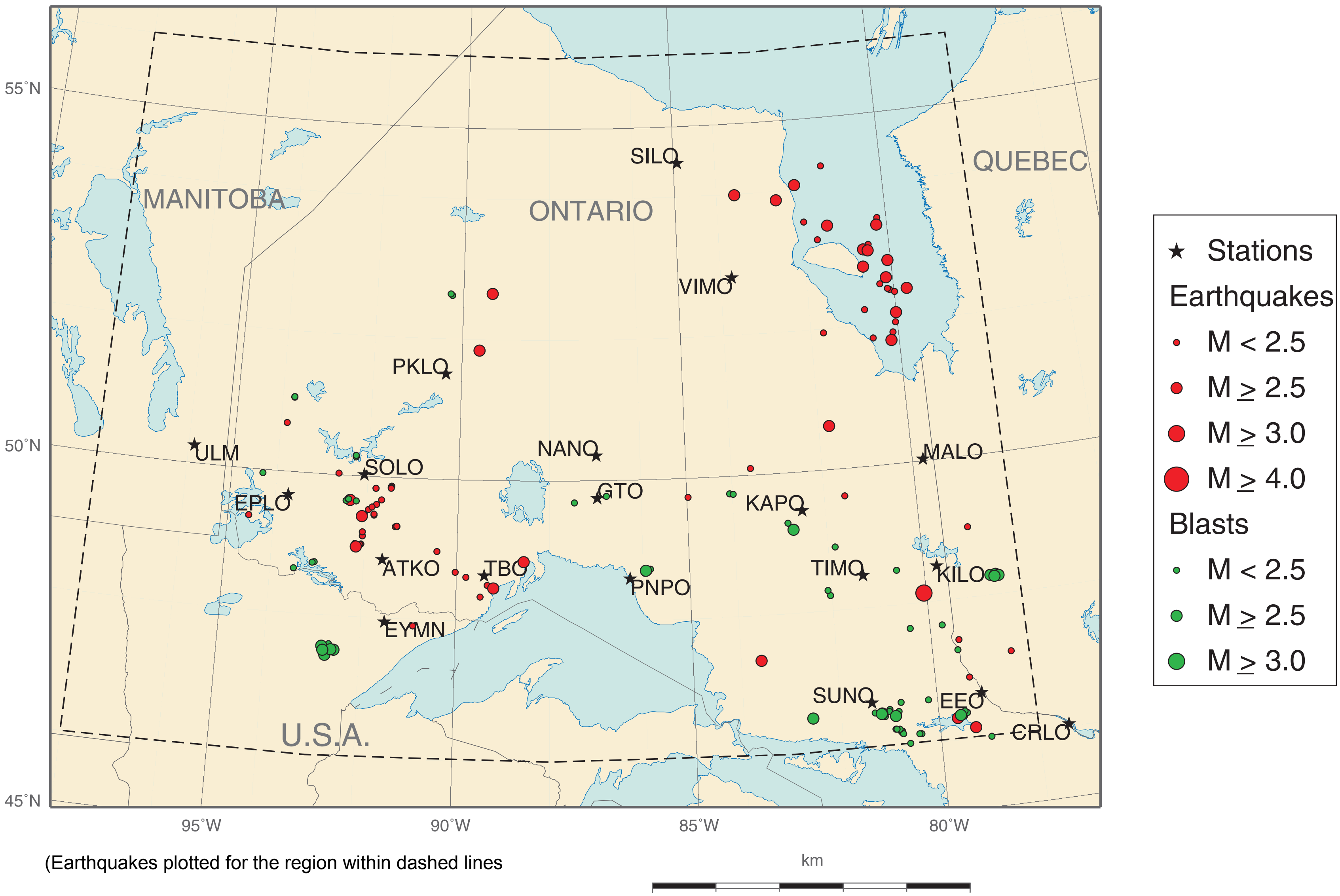


Figure 6: Earthquakes and Blasts in Northern Ontario and Adjacent Areas, 2009

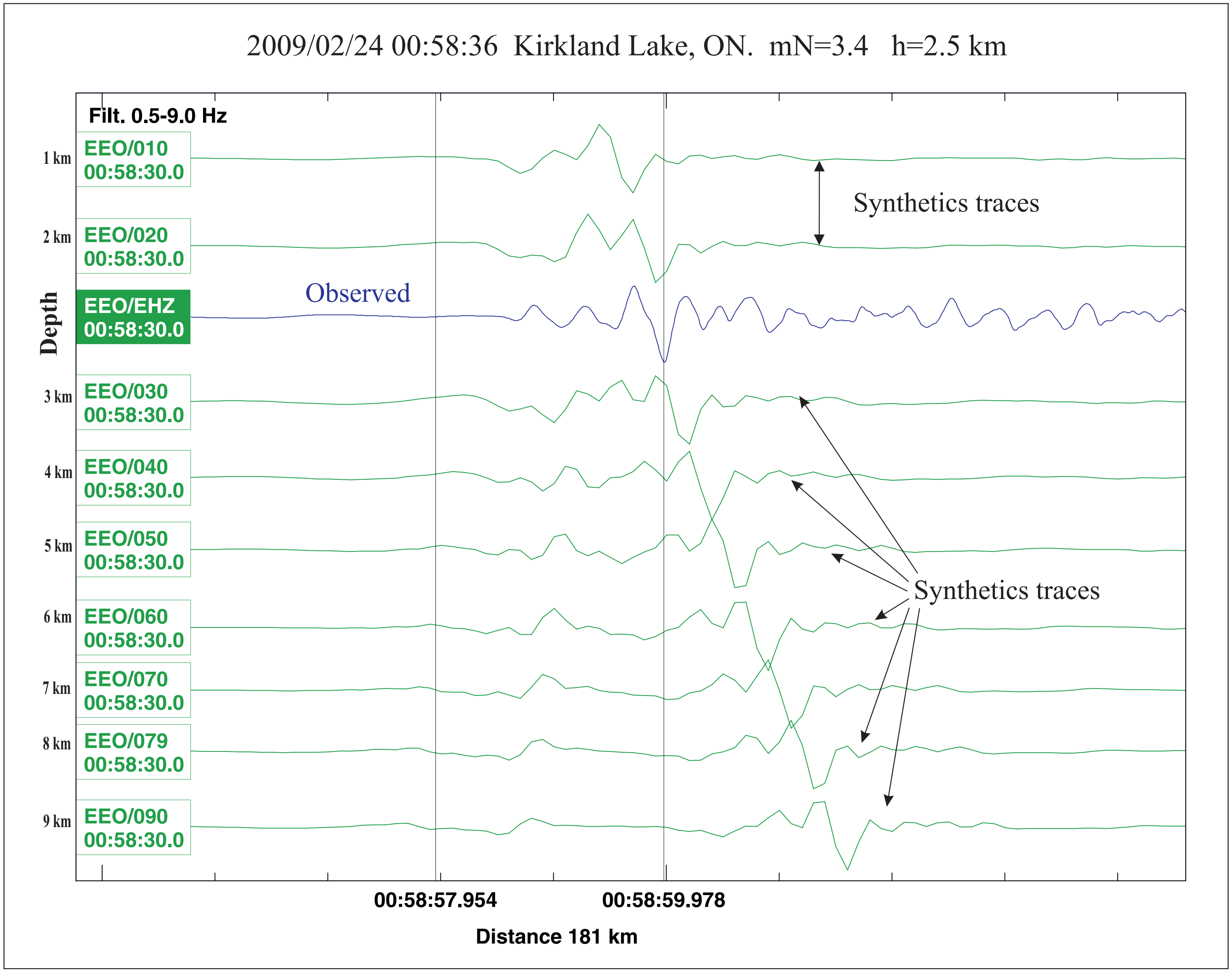


Figure 7: Observed and Synthetic Waveforms from the m_N 3.4 on 2009/02/24 in Kirkland Lake, Ontario

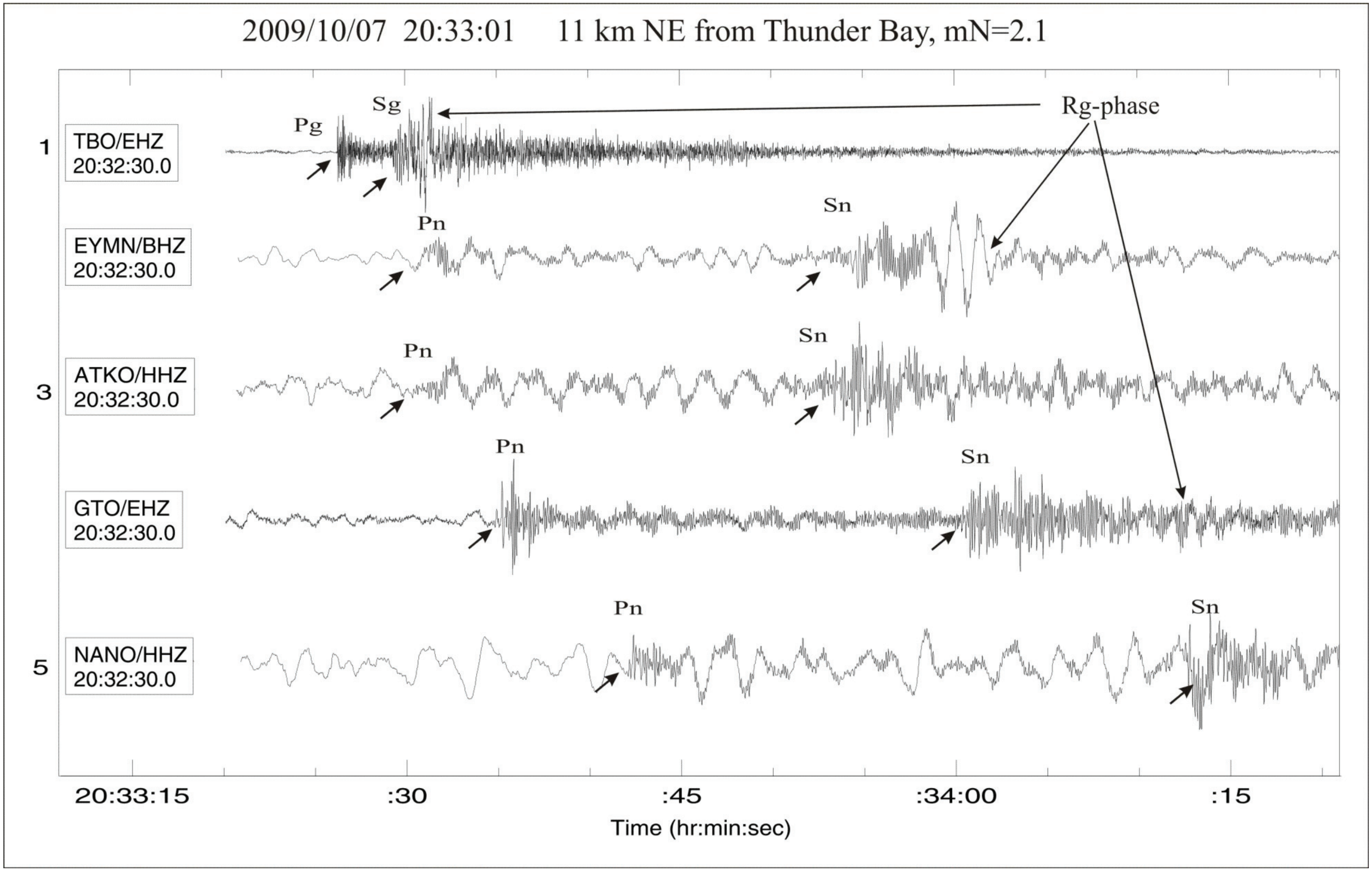


Figure 8: Rg Surface Waves from the m_N 2.1 on 2009/10/07 near Thunder Bay, Ontario

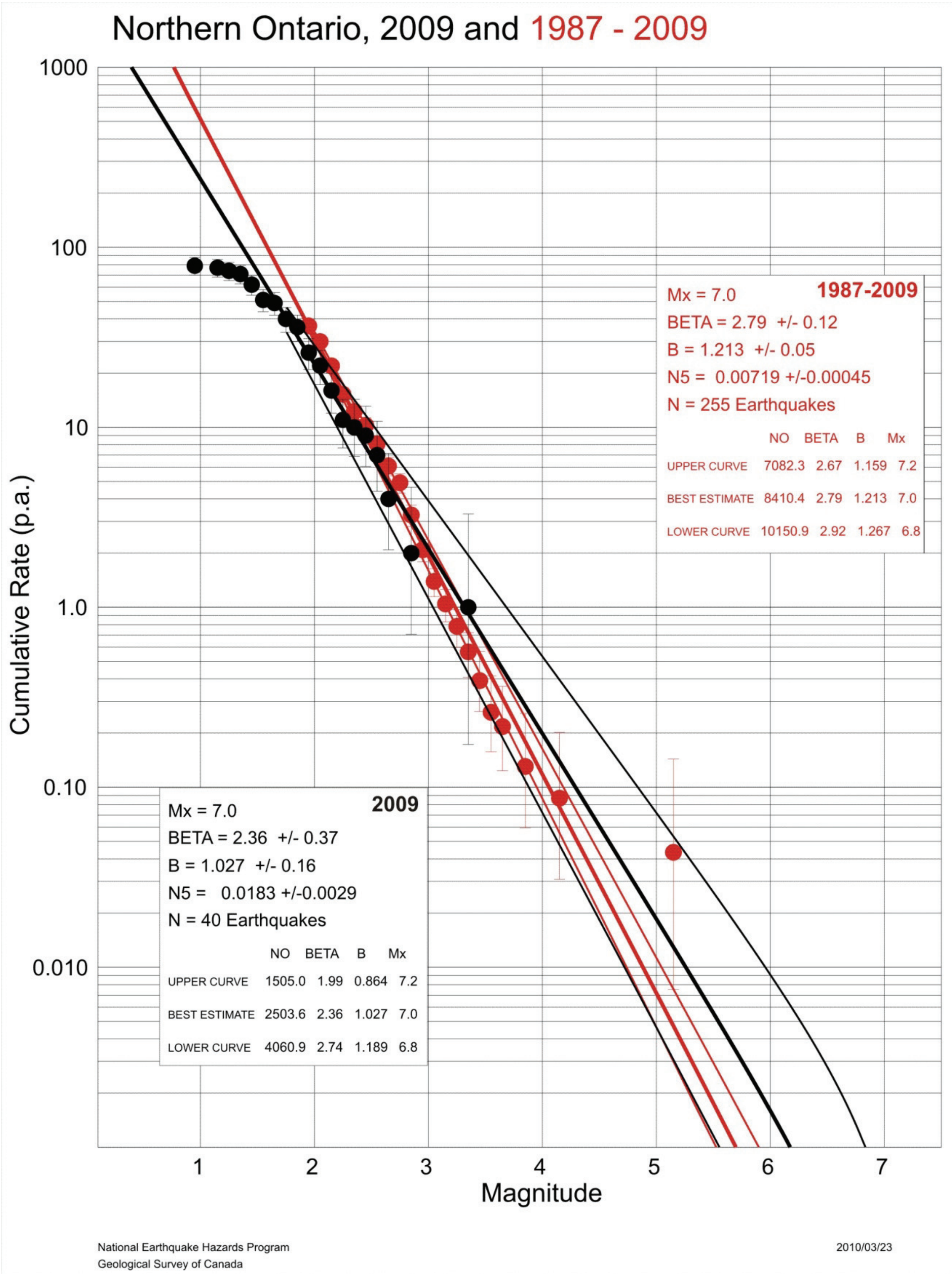


Figure 9: Recurrence Curves for Northern Ontario