SEISMIC ACTIVITY IN NORTHERN ONTARIO PORTION OF THE CANADIAN SHIELD: ANNUAL PROGRESS REPORT FOR THE PERIOD JANUARY 01 - DECEMBER 31, 2007

NWMO TR-2008-08 **December 2008**

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ABSTRACT

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Report No.: **NWMO TR-2008-08**

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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 2007.

CHIS maintains a network of twenty-six 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 POLARIS and FedNor networks of temporary stations at: Musselwhite Mine (MUMO), Sutton Inlier (SILO), Otter Rapids (OTRO), McAlpine Lake (MALO), Kirkland Lake (KILO), Sudbury (SUNO), Atikokan (ATKO), Red Lake (RLKO), Experimental Lake (EPLO), Pickle Lake (PKLO), Lac-des-Iles (LDIO), Pukaskwa National Park (PNPO), Kasabonika Lake (KASO), Neskantaga (NSKO), Aroland (NANO), Moosonee (MSNO), Timmins (TIMO), and Haileybury (HSMO). The digital data from a temporary station at Victor Mine (VIMO), partially funded 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. This report summarizes seismic monitoring results for the year 2007.

During this twelve-month period 68 earthquakes were located. Their magnitude (m_N) ranged from 1.1 to 3.0. The largest events included a m_N 3.0 and a m_N 2.8 in James Bay, and two m_N 2.9s and a m_N 2.8 in the Cochrane-Kapuskasing region of Ontario. The most westerly event in the area being studied was a m_N 1.4 event located just west of Kenora, ON. The 68 events located in 2007 compares with 83 events in 2006, 103 events in 2005, 79 events in 2004, and 45 located events in 2003 and 2002. The general increase in located events is a reflection of the lower location threshold since the progressive addition of FedNor stations from 2003 to 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 2007.

To record the seismic activity, CHIS operates twenty-six 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). Stations at Musselwhite Mine (MUMO), Sutton Inlier (SILO), Otter Rapids (OTRO), McAlpine Lake (MALO), Kirkland Lake (KILO), Sudbury (SUNO), Atikokan (ATKO), Red Lake (RLKO), Experimental Lake (EPLO), Pickle Lake (PKLO), Lac-des-Iles (LDIO), Pukaskwa National Park (PNPO), Kasabonika Lake (KASO), Neskantaga (NSKO), Aroland (NANO), Moosonee (MSNO), Timmins (TIMO), and Haileybury (HSMO) are joint ventures established from 2003 to 2005 using equipment partly funded by Industry Canada's FedNor program and partly contributed from the POLARIS Consortium (http://www.polarisnet.ca). Kasabonika Lake, Neskantaga, and Aroland are First Nations communities. All stations are digital stations, with data transmitted by satellite to the data laboratory in Ottawa. In addition, data from the digital station at Pinawa (ULM), operated by CHIS with funding by the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) (http://www.ctbto.org) and data from Victor Mine (VIMO), another POLARIS station, are also continuously available for monitoring of this region, as is all the data from the entire Canadian National Seismograph Network (CNSN).

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 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. Magnitudes calculated on the Nuttli scale are formally written m_N or m_{bLg}. The former will be used in this report.

The frequency of earthquakes of a given magnitude is a logarithmic function of magnitude: for each magnitude 4.0 earthquake in a region one can expect approximately 10 magnitude 3.0 earthquakes, 100 magnitude 2.0 earthquakes, 1000 magnitude 1.0 earthquakes, etc. Thus there is a great benefit to being able to detect the many smaller earthquakes happening in northern Ontario so as 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 68 earthquakes were located. Their magnitude (m_N) ranged from 1.1 to 3.0. The largest of these events included a m_N 3.0 and a m_N 2.8 in James Bay, and two m_N 2.9s and a m_N 2.8 in the Cochrane-Kapuskasing region of Ontario (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 north-eastern portion of the region. Earthquakes located in the study area during 2007 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 year 2007 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 OPERATION

2.1 CANADIAN NATIONAL SEISMOGRAPH NETWORK

More than 3000 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 4300 earthquakes had been located in Canada in the year 2007. Only 25 of these occurred in northern Ontario and were over magnitude 2.

2.2 STATION OPERATION STATISTICS

Station operation statistics for ULM, SOLO, TBO, GTO, KAPO, EEO, CRLO, MUMO, SILO, VIMO, OTRO, MALO, KILO, SUNO, RLKO, EPLO, ATKO, PKLO, LDIO, PNPO, KASO, NSKO, NANO, MSNO, TIMO, and HSMO are shown in Table 2. Data capture was in excess of 95% for most of the core seismograph station (including ULM) except EEO and CRLO, and in excess of 92% for all POLARIS stations (including VIMO) except KASO, NSKO and OTRO. EEO availability was low due to failure of the DIU (Digital Indoor Unit) late in the year, which needed to be replaced by the satellite provider. CRLO had several problems throughout the year: timing failed early in the year for several days; in May there were communication problems; and in the summer several local power outages cost the station several days of data each. Many of the solar powered sites, particularly the more northern ones like SILO, OTRO, KASO, NSKO, SUNO, TIMO, PNPO and LDIO, experienced power failure and had poor telecommunications during the winter months. KASO, NSKO and OTRO had difficulty recovering from the power loss and were down until well into 2007. Although RLKO appears to have good uptimes, the site was vandalized again, and the data received by the data centre since April 2007 is purely digital noise.

3. EARTHQUAKES

A total of 68 earthquakes were located in the study area during 2007. The events from 2007 are listed in Table 1 and plotted in Figure 1. The largest event located this year was a m_N 3.0 which occurred on June 18th in James Bay. And in the same region there was also a m_N 2.8 on December 31st.

The other three largest events of the year occurred in the Cochrane-Kapuskasing area: a m_N 2.8 on May 23rd, and two m_N 2.9s on July 10th within 10 seconds of each other. This small region has experienced earthquakes in the past, with over 60 events located here since 1982. Seven of those events were located in the past year, 10 in 2006, and 12 in 2005. However, only 10 of the 63 events since 1982 have been felt. The largest known events in this region include a magnitude 5 event in December of 1928. (See Hayek et al. (2007) for further details.)

Due to increased station density in the northern part of the province, the magnitude location threshold has decreased in this region of the country from about m_N 3, down to approximately m_N 2.0. The effects of this can be seen particularly in the James Bay region where 125 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 the extreme north-west of Ontario are less well monitored than the rest of northern Ontario, so the lack of earthquakes located there need not represent a lack of natural seismicity.

The 68 earthquakes from 2007, compare to previous years as follows:

Year	No. of events	No. of stations	
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 all stations to digital is completed
2000	73	7	← M5.2 Temiscamingue events and aftershocks
1999	32	7	
1998	12	7	
1997	15	7	
1996	25	7	
1995	20	7	
1994	21	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 James Bay region which seems to have been a bit 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). This brought the total number of events for 2005 a bit higher than usual, while 2007 seems to have been a relatively quiet year (see Section 6).

Note that in 2008 some of the POLARIS FedNor installations will be closed and moved to other parts of the country. At that point, the location threshold will return towards the pre-2003 level. Certain stations can be removed with little effect on the current threshold as they are either noisy, or have had poor operational up-times. The aim is, of course, to close these stations first, while trying to keep the better stations running longer. However, at some time, a decision is required as to (a) whether more low-magnitude earthquake data is still required or the 2003 threshold level was adequate, and (b) whether a lower threshold is required over the entire study area, or a more focussed approach may be used.

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 759 earthquakes are documented during this period.

Figure 3 shows only those events that are magnitude 3 or greater recorded during the same time period of 26 years (58 events). The pattern of all the seismicity echoes the pattern of the larger events except in the Atikokan region where no event larger than m_N 2.8 has occurred since 1987.

Figure 4 illustrates the seismic activity in eastern Canada in year 2007. 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 m_N 2.0 in some areas, and less populated areas like northern Quebec being only complete down to about m_N 3.0.

Figure 5 shows all the activity in eastern Canada for the entire monitoring period of 1982 - 2007. 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 coverage for 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 2007 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 (see Section 6).

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 real 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 Method (RDPM) and the presence of Rg phases, depths of some events have been determined. The actual and synthetic waveforms from the station at KAPO are shown for the 2.8 earthquake east of Kapuskasing in Figure 7. These waveforms indicated a depth of 17 km for this event, thought to be typical for events in Cochrane-Kapuskasing source region, but atypical for most of northern Ontario which appears to have more shallow depth events. Figure 8 shows an earthquake in the Atikokan region of Ontario 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.

The earthquake epicentres of 2007 generally conform to areas of past seismicity, except for three small events that were located east of Collins, near the north end of Lake Nipigon:

2007/03/09	**08:48 UT**	**1.6 m_N**	**38 km E from Collins, ON**
2007/03/29	**15:54 UT**	**2.0 m_N**	**76 km E from Collins, ON**
2007/05/20	**08:04 UT**	**1.6 m_N**	**88 km E from Collins, ON**

The magnitudes of all three events are close to the location threshold for this area; however, it is clear that the first event is distinct from the last two, whose sources are likely much closer to each other than the solutions indicate (see Figure 9). Only four events have been recorded previously in this region since 2004 with magnitudes ranging from 1.4 to 1.7, all during non-daylight hours. There is no known blasting source in this region; outside of daylight hours, only underground mines are allowed to blast. Nothing is recorded here prior to 2004, although the detection threshold in the region would have been such that events of this size would likely not have been locatable before 2003 when the FedNor stations came on-line.

Recurrence curves for the study area from the year 2007 are similar to the curve from 1987 to the end of 2007 (21 years of data) in Figure 10 and are discussed in more detail in Section 6.

A digital plot of the traces from the seismic stations used in this study, and an epicentre map for each of the earthquakes occurring in 2007 is included in Appendix A. Traces from some of the monitoring stations relevant to the event are shown for each earthquake. The traces have been passed through a Butterworth bandpass filter with corners at 3 and 15 Hz prior to plotting. This filter enhances the phases used for locating the earthquake, while filtering out most of the noise. However, some lower frequency phases (like Rg) may also be filtered out. 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 and 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 pegged to the location of the larger, better-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 stations;
ii. Stations are widely spaced so that phase arrival may be ambiguous (as a rule the closer the station the sharper the arrival);
iii. Larger distances between stations contributes to a lack of phase data for small events ($m_N < 2$);
iv. Some locations 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.

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 array 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. 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. None of the 2007 events in the study area were large enough to calculate a depth from the phase arrival data alone.

However, 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. This method is not applicable to northern Ontario as all the earthquakes, since the study began in 1982, have been too small 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. Ma states, "The regional depth phase sPg and sPmP are very sensitive to focal depth. sPg depth phase develops well generally at distance between about 60 to 120 km for earthquakes, some as small as m_N 1.5. sPmP depth phase develops well at distances of about 130 to 300 km (actually existing as far as about 600 km). Beyond 300 km, the identification of the phase becomes a problem. With regional depth phase sPmP, we can reliably estimate focal depth by modelling waveforms recorded at stations more than 200 km away for an earthquake with m_N about 2.5. With regional depth phase sPg, we can reliably estimate focal depth by modelling waveforms recorded at stations about 60 km away for an earthquake with m_N about 2.0. In short, we can reliably estimate focal depth with regional depth phase modelling method for moderate and small earthquakes without records from nearby stations in northern Ontario." (Ma, 2004, p.3).

Further work using RDPM modelling was done by Ma and Atkinson (2006) for earthquakes from the neighbouring regions of the West Quebec seismic zone, and in southern Ontario 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 the Ma (2004) contract report and subsequent work is in preparation by Dr. Ma. Figure 7 shows an application of RDPM toa 2007 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 a 5 km depth has been assigned for these events. Note that because of the filter used (Butterworth bandpass filter with corners at 3 and 15 Hz), none of the waveform plots in Appendix A show the Rg wave, even where it is clear in the unfiltered data.

Table 3 lists all the events from 2007 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 one event for which a reliable depth was determined using the RDPM method. Note that the majority of the events occurring in 2007 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 explostions 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.

Preliminary work by Bent and Kao (2006) at CHIS 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 effect of using a poor velocity model is 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.

4.3 SYNOPSIS

Without knowing the depth of many of the earthquakes that have occurred in northern Ontario, caution must be applied in assessing the other derived values (epicentre and origin time), as there can be trade-offs of these parameters against depth. Earthquake detection and location in northern Ontario is complete down to approximately magnitude 2.0 since the progressive addition from 2003 to 2005 of the FedNor stations. Though smaller earthquakes can be located with the current network, the accuracy of these event locations decreases with decreasing event magnitude and with increasing distance from nearby stations of the network. Hence caution must be exercised when dealing with the uncertainties associated with these earthquake locations, especially in relating these events to specific geological features or trends. 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.

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, magnitudes are based on the Nuttli magnitude scale, a variation on the Richter scale. 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>3 is considered complete since 1987, providing 21 years of data for the less-common larger earthquakes.

Figure 10 shows the magnitude-recurrence plot for the year 2007 earthquakes in black. It is very similar to the magnitude-recurrence plot for the 21-year period of 1987 to 2007 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 2007 curve is perhaps slightly lower 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. The error bounds for the 1-year period encompass the best fit slope for the 21-year period. For the year

2007 a best fit slope of 2.75 +/- 0.55 was found, versus 2.70 +/- 0.13 for the 21-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 86 mining-induced seismic events of magnitude 0.5 or greater in the study area in 2007. Thirty of these events occurred in the Sudbury Basin, including two m_N 3.0, one on October 7th and another on November 28th. Four mining related events were located in the Red Lake region, 21 near Marathon, 6 at Kirkland Lake, 25 near the Cadillac/Rouyn-Noranda area in Quebec, including a magnitude 3.0 at Mouska mine on February 10th. A total of 9 mining-induced events larger than m_N 2.5 were recorded in the study area in 2007 and are listed in Table 4.

8. SUMMARY

Data capture was in excess of 95% from each of the core seismograph stations except EEO and CRLO, and exceeded 92% for most of the POLARIS type installations except for OTRO, KASO and NSKO. EEO had a failed DIU late in the year which required replacement, while CRLO suffered from lost timing, communication problems and several power outages in the region.
All the solar powered sites experience intervals of low power during the winter, and telecommunication problems hampered data capture from many of these stations as well. Stations KASO, NSKO and OTRO seemed to have trouble recovering until mid-way through the year. Due to their remote location, it was not possible to have them serviced in 2007. RLKO appeared to have good up-times, however the site was vandalized yet again this April, and the data received from the station since then has been purely digital noise.

The seismic activity in the study area during the calendar year 2007 consisted of 68 earthquakes ranging in magnitude from 1.1 to 3.0. Twenty-five earthquakes were larger than m_N 2.0, and only one of the earthquakes was m_N 3.0. Two of the largest events were located in the James Bay region, including the m_N 3.0 and a smaller m_N 2.8, while two m_N 2.9s and a m_N 2.8 were located in the Cochrane-Kapuskasing region. 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 larger than m_N 1.0 remain undetected.

The distribution of all detected earthquakes in this region for 2007 conformed to the pattern of previous seismicity, with the exception of three small magnitude events east of Collins, near the north end of Lake Nipigon, were prior to 2004 no events had been recorded.

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The authors would like to thank CHIS staff for helping to develop and maintain the programs used to gather data for this report, POLARIS for all the additional data from their network, and the mining companies for assistance in verifying events related to mining. A special thanks to Tom Lam from the NWMO for his feedback on this report.

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Table 1: Located Local Earthquakes, January - December 2007

Date mm/dd	Time(UTC) hh:mm:ss	Lat (°N)	Long (°W)	#station/ phases	Mag	Region and Comment
01/07	14:05:44	53.36N	81.30W	3/ 6	1.4 m_N	James Bay.
01/08	05:25:33	46.83N	78.75W	7/12	1.4 m_N	30 km NE from Temiscaming, QC
01/14	11:37:05	51.88N	80.04W	4/ 9	2.2 m_N	James Bay.
01/22	07:23:54	53.43N	81.04W	5/ 9	1.8 m_N	James Bay.
01/26	21:40:04	54.00N	89.24W	3/ 4	1.7 m_N	45 km NE from Kitchenuhmaykoosib, ON
02/04	14:37:01	48.43N	89.26W	8/13	2.5 m_N	5 km NE from Thunder Bay, ON
02/04	16:35:36	47.46N	78.41W	3/ 5	1.4 m_N	77 km S from Malartic, QC
02/09	08:28:46	49.72N	94.97W	4/ 6	1.4 m_N	40 km W from Kenora, ON
02/17	04:00:20	50.88N	90.63W	4/ 8	1.8 m_N	72 km SW from Pickle Lake, ON
02/17	04:05:56	50.87N	90.62W	7/12	2.2 m_N	73 km SW from Pickle Lake, ON
02/18	13:35:05	53.90N	87.19W	4/ 8	2.4 m_N	100 km N from Webequie, ON
02/25	01:07:10	52.86N	92.01W	6/10	2.1 m_N	145 km E from Deer Lake, ON
02/25	01:08:44	52.86N	92.01W	3/ 5	1.9 m_N	145 km E from Deer Lake, ON
02/25	07:34:52	52.71N	81.14W	6/10	1.9 m_N	James Bay.
03/01	23:48:13	52.83N	89.30W	5/ 7	1.8 m_N	116 km S from Kitchenuhmaykoosib, ON
03/02	11:22:24	49.37N	81.56W	5/ 9	1.5 m_N	52 km NW from Cochrane, ON
03/03	11:07:19	46.04N	79.32W	6/11	1.3 m_N	30 km S from North Bay, ON
03/09	08:48:51	50.22N	88.72W	4/ 8	1.6 m_N	53 km E from Collins, ON
03/13	08:33:10	46.04N	79.33W	7/14	1.5 m_N	30 km S from North Bay, ON
03/14	07:50:21	46.83N	78.91W	6/11	1.5 m_N	17 km NE from Temiscaming, QC
03/20	23:26:47	47.55N	78.23W	7/10	1.6 m_N	67 km S from Malartic, QC
03/25	08:21:32	53.12N	79.62W	5/ 7	2.2 m_N	James Bay.
03/29	15:54:19	50.23N	88.39W	4/ 7	2.0 m_N	76 km E from Collins, ON
03/29	17:02:42	52.88N	87.92W	3/ 4	2.0 m_N	40 km W from Webequie, ON
04/08	03:36:27	51.52N	78.75W	3/ 5	1.5 m_N	84 km SW from Eastmain, QC
04/08	04:06:07	48.84N	82.62W	5/ 7	1.9 m_N	63 km S from Kapuskasing, ON
04/08	19:35:19	49.70N	92.52W	7/11	1.9 m_N	24 km E from Dryden, ON
04/09	06:29:32	48.99N	90.71W	4/ 7	1.4 m_N	72 km NE from Atikokan, ON
04/11	10:50:51	51.94N	80.17W	4/ 7	1.7 m_N	James Bay.
04/14	22:13:31	48.88N	92.23W	5/ 9	1.6 m_N	47 km W from Atikokan, ON
04/20	06:14:54	51.64N	80.53W	6/ 9	2.0 m_N	38 km N from Moosonee, ON
04/25	04:42:21	52.68N	78.86W	5/ 8	2.0 m_N	34 km S from Wemindji, QC
05/02	00:08:08	51.74N	79.71W	4/ 8	1.7 m_N	James Bay.
05/08	06:14:20	51.55N	89.55W	4/ 7	2.1 m_N	46 km E from Pickle Lake, ON
05/08	13:11:44	52.52N	79.90W	5/ 8	2.2 m_N	James Bay.
05/20	08:04:59	50.36N	88.29W	4/ 7	1.6 m_N	88 km E from Collins, ON
05/23	00:42:39	49.59N	81.48W	6/11	2.8 m_N	63 km E from Kapuskasing, ON
05/29	04:22:02	52.87N	80.25W	4/ 8	1.9 m_N	100 km W from Wemindji, QC
06/04	10:00:28	49.05N	92.36W	6/10	2.2 m_N	66 km NW from Atikokan, ON
06/14	03:43:01	51.88N	93.72W	3/ 6	1.8 m_N	86 km S from Deer Lake, ON
06/18	04:38:39	52.56N	79.58W	7/11	3.0 m_N	James Bay.
06/19	11:05:33	52.81N	80.83W	3/ 5	1.7 m_N	James Bay.
06/24	09:30:13	48.91N	80.96W	6/11	1.9 m_N	18 km S from Cochrane, ON
07/07	13:45:11	53.12N	80.51W	5/ 8	2.2 m_N	James Bay.
07/08	00:10:55	53.51N	81.67W	3/ 6	1.7 m_N	James Bay.
07/10	19:25:32	49.87N	81.93W	6/10	2.9 m_N	62 km NE from Kapuskasing, ON.
07/10	19:25:43	49.87N	81.93W	4/ 7	2.9 m_N	63 km NE from Kapuskasing, ON
07/27	22:01:32	46.83N	78.89W	7/14	1.6 m_N	19 km NE from Temiscaming, QC
08/13	09:54:59	49.33N	91.38W	5/10	2.1 m_N	67 km N from Atikokan, ON
09/06	05:49:37	47.82N	78.49W	8/15	2.1 m_N	44 km SW from Malartic, QC

09/10	**15:42:28**	**46.83N**	**78.92W**	**7/14**	**1.7 m_N**	**19 km NE from Temiscaming, QC**
10/01	**09:25:00**	**48.76N**	**92.90W**	**6/11**	**1.7 m_N**	**41 km NE from Fort Frances, ON**
10/05	**01:23:04**	**53.02N**	**91.85W**	**5/ 7**	**2.1 m_N**	**195 km E from Pickle Lake, ON**
10/10	**22:57:19**	**49.64N**	**92.34W**	**5/ 9**	**1.9 m_N**	**40 km E from Dryden, ON**
10/13	**06:07:35**	**53.83N**	**80.79W**	**5/ 8**	**1.9 m_N**	**James Bay.**
10/24	**18:17:23**	**47.62N**	**90.54W**	**3/ 6**	**2.2 m_N**	**Western Lake Superior.**
10/29	**23:08:01**	**53.19N**	**80.80W**	**4/ 7**	**1.8 m_N**	**James Bay.**
10/29	**23:10:13**	**53.09N**	**80.79W**	**3/ 5**	**1.6 m_N**	**James Bay.**
11/01	**19:44:37**	**52.83N**	**80.75W**	**3/ 6**	**2.3 m_N**	**James Bay.**
11/15	**05:52:31**	**47.72N**	**78.31W**	**7/11**	**1.7 m_N**	**48 km S from Malartic, QC**
11/21	**21:03:12**	**52.49N**	**80.44W**	**4/ 7**	**2.4 m_N**	**James Bay.**
12/01	**16:49:32**	**49.53N**	**81.58W**	**4/ 6**	**1.5 m_N**	**63 km E from Kapuskasing, ON**
12/02	**06:58:05**	**46.84N**	**78.92W**	**11/18**	**1.7 m_N**	**20 km NE from Temiscaming, QC**
12/05	**05:24:53**	**49.09N**	**90.65W**	**3/ 5**	**1.2 m_N**	**80 km NE from Atikokan, ON**
12/13	**02:20:50**	**54.20N**	**82.40W**	**3/ 6**	**1.7 m_N**	**142 km N from Attawapiskat, ON**
12/13	**15:01:52**	**46.67N**	**79.20W**	**9/17**	**1.4 m_N**	**9 km SW from Temiscaming, QC**
12/30	**09:00:12**	**47.24N**	**79.10W**	**4/ 6**	**1.1 m_N**	**46 km SE from Haileybury, ON**
12/31	**02:49:42**	**52.47N**	**80.22W**	**11/16**	**2.8 m_N**	**James Bay.**

Table 2: NWMO Supported Stations Operating During 2007 (2006 figures given in brackets)

Station	Lat (°N)	Long (°W)	Elev (m)	Uptime (%) 2007 (2006)	Dates of operation as digital stations
ULM Pinawa	50.2503	95.8750	251	99.3 (98.9)	19941207-
SOLO Sioux Lookout	50.0213	92.0812	373	98.3 (99.7)	19981104-
TBO Thunder Bay	48.6473	89.4083	468	95.1 (96.8)	19931005-
GTO Geraldton	49.7455	86.9610	350	99.9 (91.2)	20010104-
KAPO Kapuskasing	49.4504	82.5079	210	99.5 (98.4)	19980114-
EEO Eldee	46.6411	79.0733	398	87.7 (95.7)	19931005-
CRLO Chalk River	46.0375	77.3801	168	89.7 (99.4)	19941117-
MUMO Musselwhite Mine	52.6128	90.3914	316	99.9 (99.7)	20030615-
SILO Sutton Inlier	54.4791	84.9126	195	95.6 (96.3)	20030609-
VIMO Victor Mine	52.8173	83.7449	78	99.8 (99.8)	20030611-
OTRO Otter Rapids	50.1818	81.6286	109	82.9 (95.1)	20030618-
MALO McAlpine Lake	50.0244	79.7635	271	100.0 (99.8)	20030620-
KILO Kirkland Lake	48.4972	79.7232	314	99.9 (99.8)	20030622-
SUNO Sudbury	46.6438	81.3442	343	93.2 (95.9)	20030623-
RLKO Red Lake	51.0704	93.7585	362	99.9 (73.2)	20041119-
EPLO Experimental Lake	49.6737	93.7258	437	92.7 (98.6)	20040611-
ATKO Atikokan	48.8231	91.6004	383	99.9 (99.7)	20040609-
PKLO Pickle Lake	51.4987	90.3522	376	99.3 (99.7)	20040615-
LDIO Lac des Iles Mine	49.1750	89.5955	500	96.8 (99.5)	20040616-
PNPO Pukaskwa Nat. Park	48.5957	86.2846	219	94.8 (99.5)	20040618-
KASO Kasabonika Lake	53.5279	88.6414	192	68.1 (74.6)	20050803-
NSKO Neskantaga	52.1965	87.9305	241	40.1 (61.8)	20050729-
NANO Aroland	50.3543	86.9684	309	99.3 (91.6)	20050804-
MSNO Moosonee	51.2913	80.6151	15	99.9 (62.3)	20050723-
TIMO Timmins	48.4659	81.3032	392	92.4 (100.0)	20050725-
HSMO Haileybury	47.3708	79.6657	306	98.1 (99.4)	20050720-

Notes:
The installation 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 uptimes in 2007. All times given are in UT (Universal Time).

ULM communications were mistakenly taken offline April 24th. The plan was to upgrade the telecommunications at a nearby site. Unfortunately, the satellite service technicians went to the wrong site and disabled the serial-based VSAT circuit at ULM instead. The technicians restored communications the next day.
May 16th a cable was accidentally disconnected during a vault inspection at ULM causing a data outage for a day.

SOLO was out from December 13th to the 18th. A local contractor was performing work near the VSAT, and powered off the electronics which were mistakenly left off.

TBO timing was bad from February 2nd to 8th due to the digitizer clock failing. The station was power cycled to restore normal operation. TBO dropped out from June 19th for two days when the power supply did not switch back to main power from UPS power after an outage of the main power supply. The UPS was bypassed to restore normal operation, and was replaced during a site trip later in the year.

TBO was out on October 18 for several hours due to a power outage; then again on the 26th for several days when the UPS overheated due to an electric heater malfunction; and again on the 31st when high winds took down local power lines. When power was restored, there were also problems found with the VSAT DIU. The satellite communications provider replaced the unit and data flow resumed November 06 at 22:51. The satellite service provider performed some additional maintenance on November 07 causing some data outages from 18:40 to 20:32.

KAPO was out on January 3rd for several hours due to a power outage. Ontario Power performed maintenance on a transformer to restore power. KAPO was out from July 2nd for a day when the breaker tripped and was reset by the local contact.

EEO was out from June 28th to July 18th. The satellite communications provider had to replace a board in the DIU to restore normal operation. EEO was out again from September 22nd to October 11th. The satellite communications service provider replaced the Digital Indoor Unit to restore operation.
Then EEO was out or intermittent on several days in November and December while reporting outroute communication errors until it dropped out on December 30 and remained out through the end of the month.

CRLO timing was bad from February 02 at 21:27 to February 07 at 17:41 when the digitizer clock failed. The station was power cycled to restore normal operation. CRLO data were out from May 8th to 12th, and during several smaller intervals in May due to communication problems and maintenance. In June, CRLO dropped out for a day after a power outage during a lightening storm. The equipment required a power cycle by the local contact to restore data flow. August 3rd CRLO dropped out due to a power outage. The digitizer settings incorrectly reset to default values, so data were not being handled properly when power was restored to the site. The digitizer configuration was reset and normal data flow resumed on August 31 at 13:26.

The following stations were out or intermittent during the specified intervals because solar power was insufficient to maintain battery charge:

NSKO was out from September 25, 2006 to July 12, 2007. After returning July 12th, the station dropped out again July 21st until August 16th.

KASO data dropped out or were intermittent since November 05, 2006 because solar power was insufficient to maintain battery charge. Data availability improved starting April 26, 2007. There continued to be intervals which occurred daily during which data were intermittent.
SILO from January 9 to 12 and from March 5, 8 to 9, 28 to April 12;

OTRO from January 1 to 8, 11 to 14, 18 to 25, 27; February 1 to 16; April 8 to 9; November 25 and 28, 30 until end of year.
SUNO from January 4 to 9 and 19 to 20 and then from December 13 until end of year.
PNPO from December 31 at 22:19 to January 1; March 21 to 22, 29 to April 19, and April 23 to June 18.
TIMO from January 14 to 18, 19 to 20; November 6 to 7, 20; December 4 to 8, 10 and 12 to end of year.
LDIO from March 3, 5, 7 and 30; April 1, 2 to 3, 4 to 13, 16 to 18; May 2, 15, 19 to 20, 21, 22, 29.
HSMO from April 7 to 25; May 3-11; and intermittent from June 17 to July 20.
EPLO from December 6 until end of year.

Table 3: Depths Derived using Rg-phases and Regional Depth Phase Method (RDPM) for Moderate-sized Events for 2007

Date mm/dd	Time(UTC) hh:mm:ss	Mag (m_N)	Depth (km)	Depth type (Rg/RDPM)	Region and Comment
01/08	05:25:33	1.4	5	Rg	30 km NE from Temiscaming, QC
02/09	08:28:46	1.4	5	Rg	40 km W from Kenora, ON
02/17	04:00:20	1.8	5	Rg	72 km SW from Pickle Lake, ON
02/17	04:05:56	2.2	5	Rg	73 km SW from Pickle Lake, ON
03/01	23:48:13	1.8	5	Rg	116 km S from Kitchenuhmaykoosib
03/03	11:07:19	1.3	5	Rg	30 km S from North Bay, ON
03/13	08:33:10	1.5	5	Rg	30 km S from North Bay, ON
03/29	15:54:19	2.0	5	Rg	76 km E from Collins, ON
04/08	19:35:19	1.9	5	Rg	24 km E from Dryden, ON
04/09	06:29:32	1.4	5	Rg	72 km NE from Atikokan, ON
04/14	22:13:31	1.6	5	Rg	47 km W from Atikokan, ON
05/08	06:14:20	2.1	5	Rg	46 km E from Pickle Lake, ON
05/20	08:04:59	1.6	5	Rg	88 km E from Collins, ON
05/23	00:42:39	2.8	16	RDPM	72 km E from Kapuskasing, ON
06/04	10:00:28	2.2	5	Rg	66 km NW from Atikokan, ON
06/24	09:30:13	1.9	5	Rg	18 km S from Cochrane, ON
08/13	09:54:59	2.1	5	Rg	67 km N from Atikokan, ON
10/01	09:25:00	1.7	5	Rg	41 km NE from Fort Frances, ON
10/10	22:57:19	1.9	5	Rg	40 km E from Dryden, ON

Table 4: Mining-Induced Seismic Events m_N 2.5 and Greater, January - December 2007

Date (mm/dd)	Mine	Location	Mag
01/02	Copper Cliff South Mine	Sudbury	2.5 m_N
02/10	Mouska Mine	Rouyn-Noranda	3.0 m_N
02/20	Laronde Mine	Cadillac	2.7 m_N
03/02	Laronde Mine	Cadillac	2.8 m_N
03/04	Laronde Mine	Cadillac	2.5 m_N
06/14	Fraser Mine	Sudbury	2.7 m_N
10/07	Creighton Mine	Sudbury	3.0 m_N
11/28	Coleman-McCreedy Mine	Sudbury	3.0 m_N
12/05	Creighton Mine	Sudbury	2.7 m_N

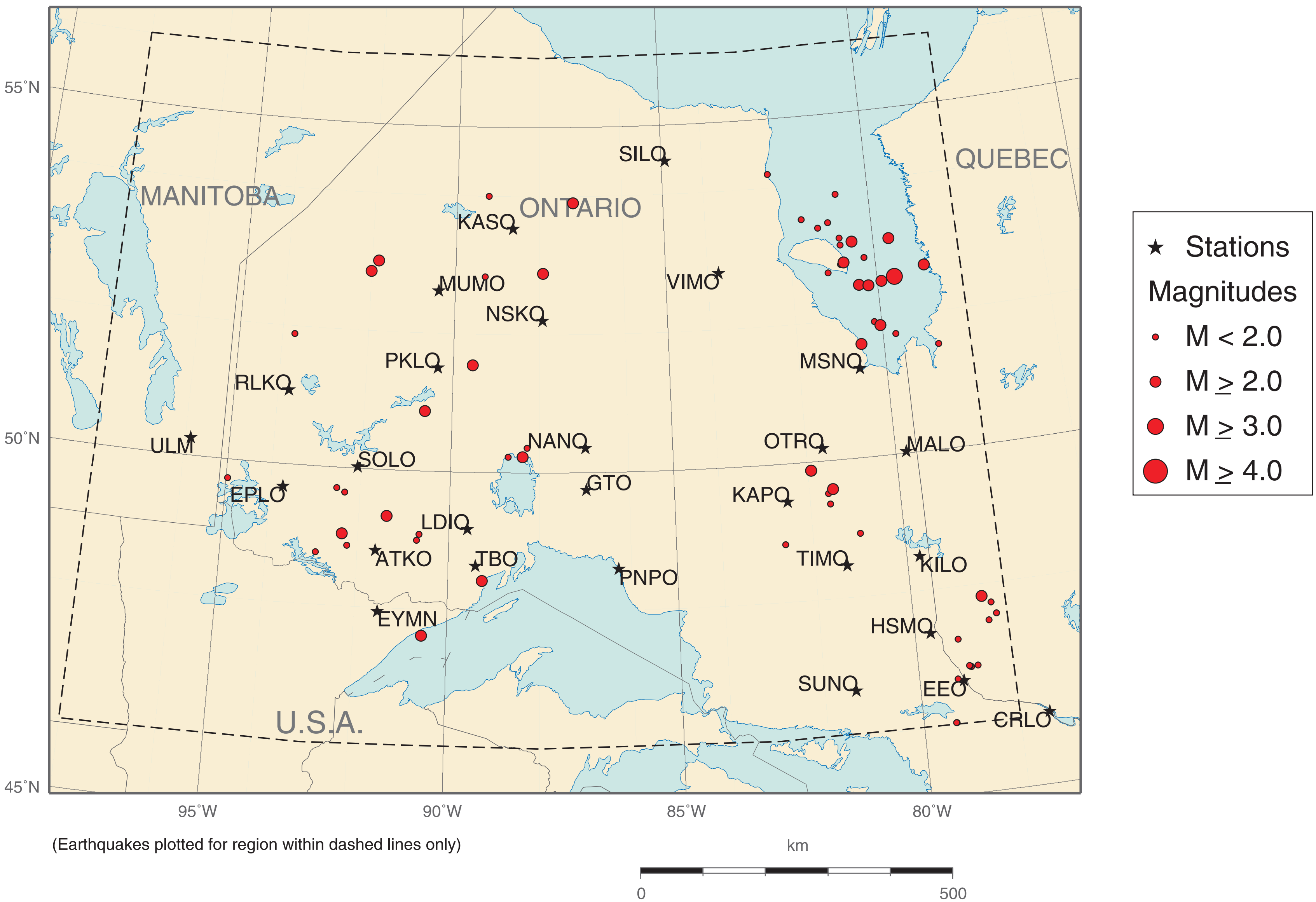


Figure 1: Earthquakes in Northern Ontario and Adjacent Areas, 2007

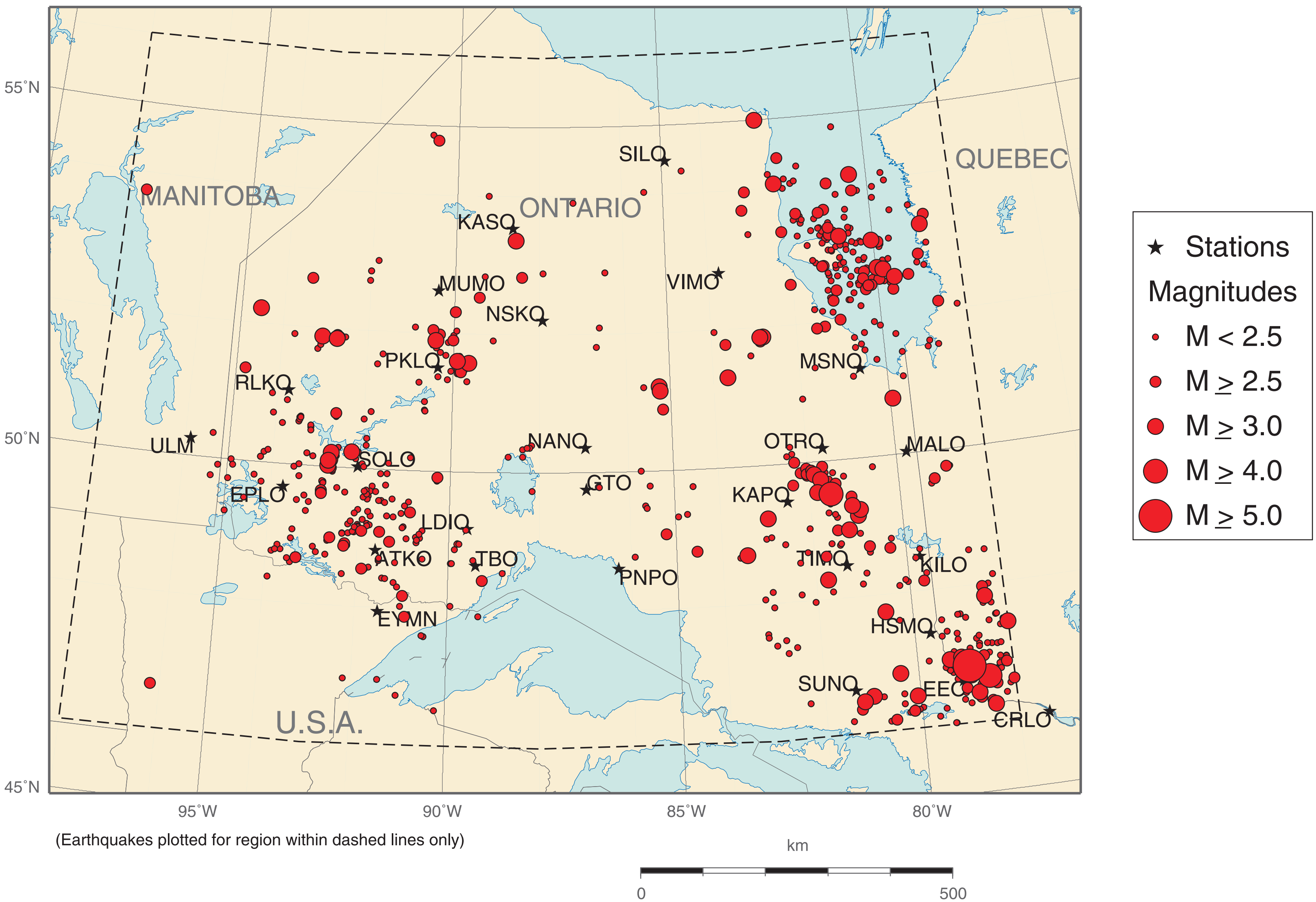


Figure 2: Earthquakes in Northern Ontario and Adjacent Areas, 1982 - 2007

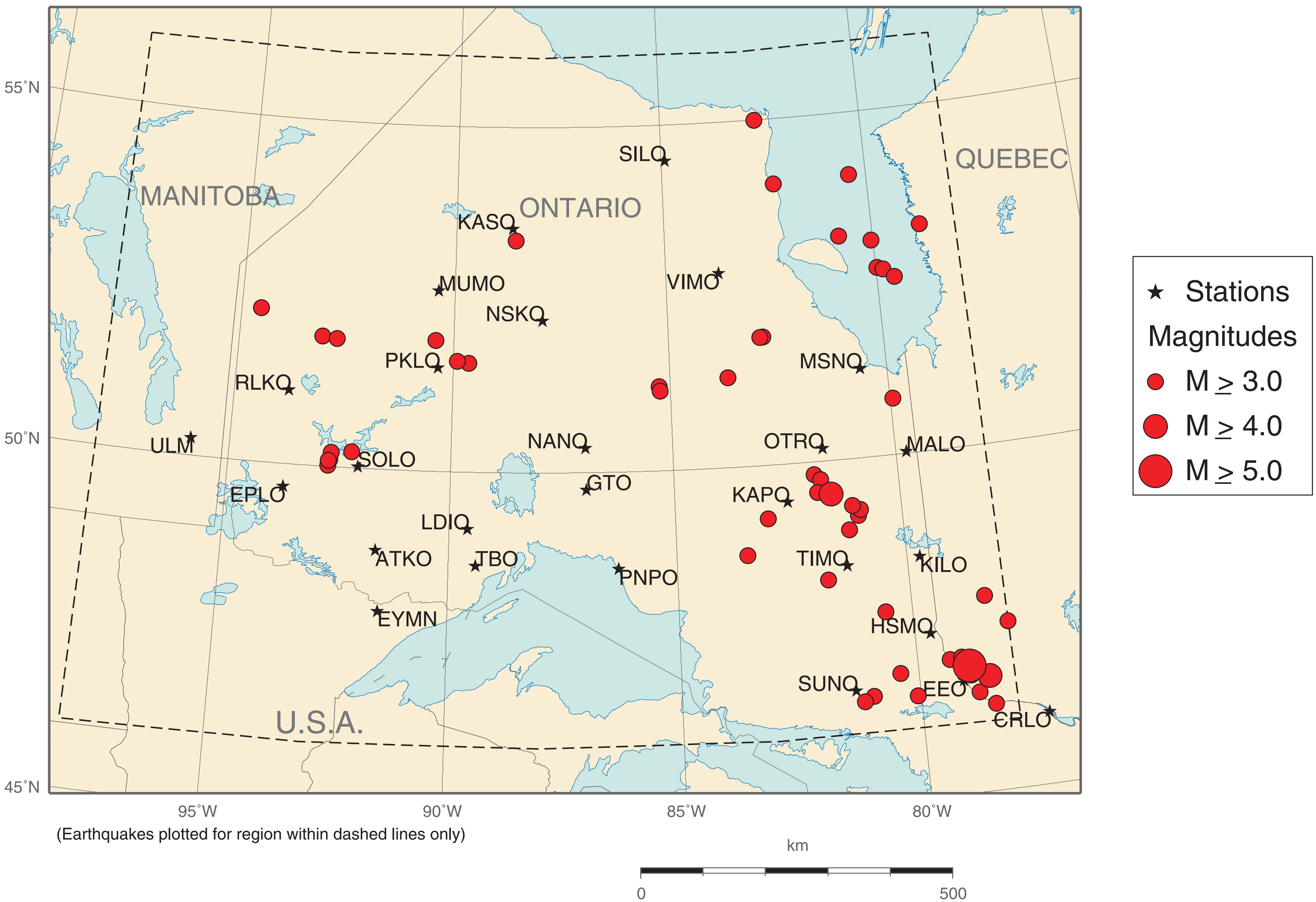


Figure 3: Earthquakes $m_N \geq 3$ in Northern Ontario and Adjacent Areas, 1982 - 2007

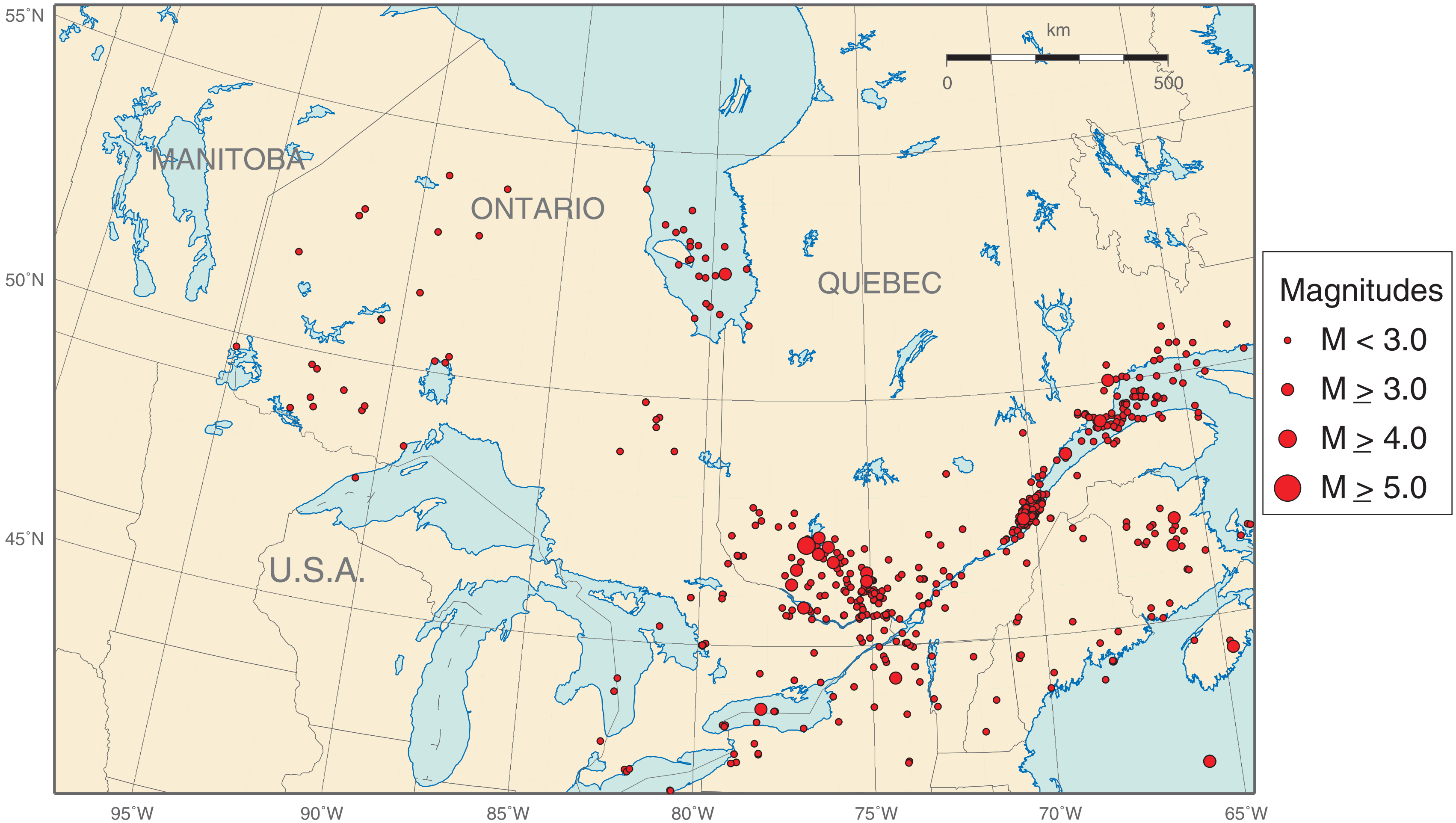


Figure 4: Earthquakes in Eastern Canada, 2007

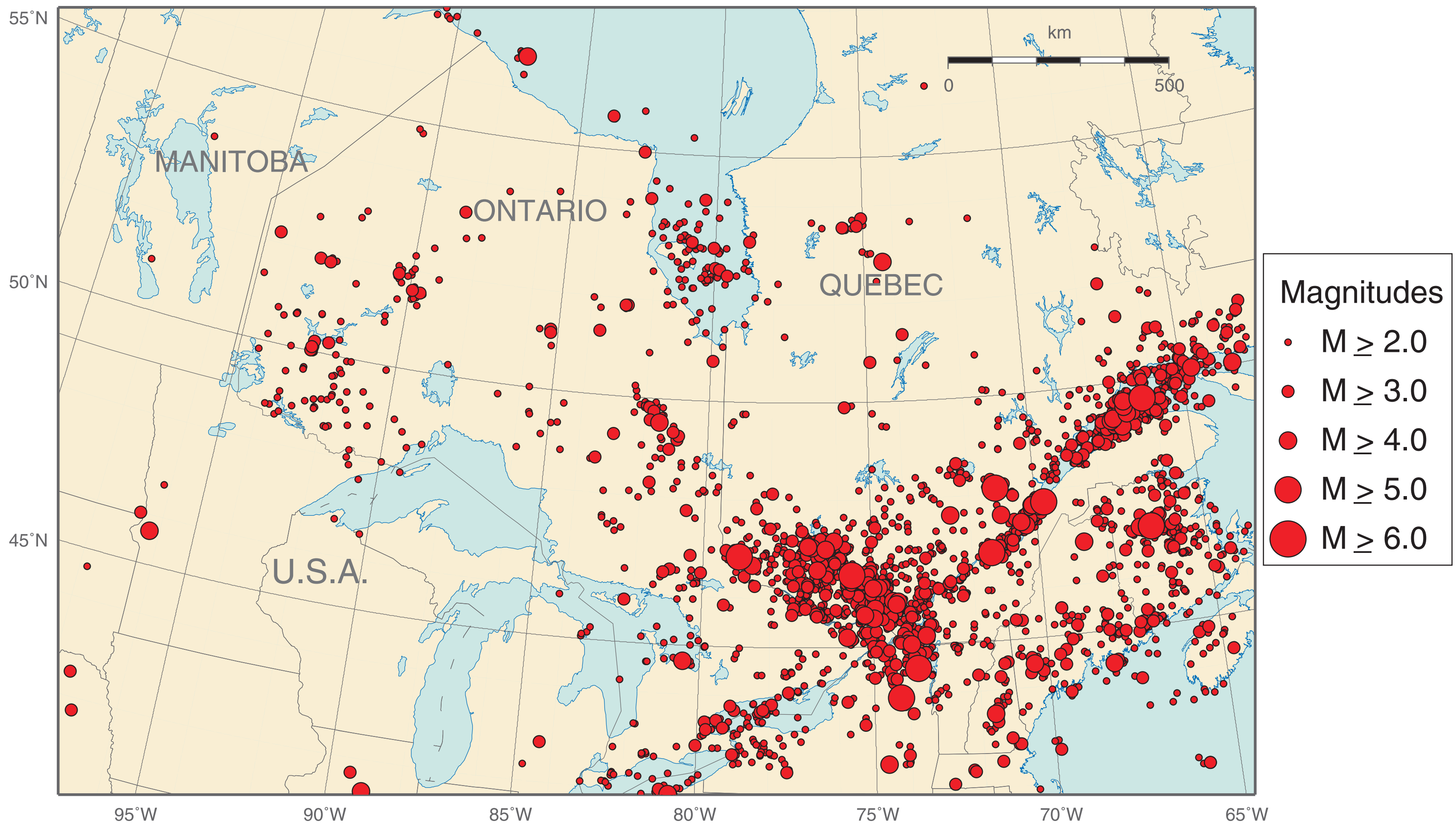
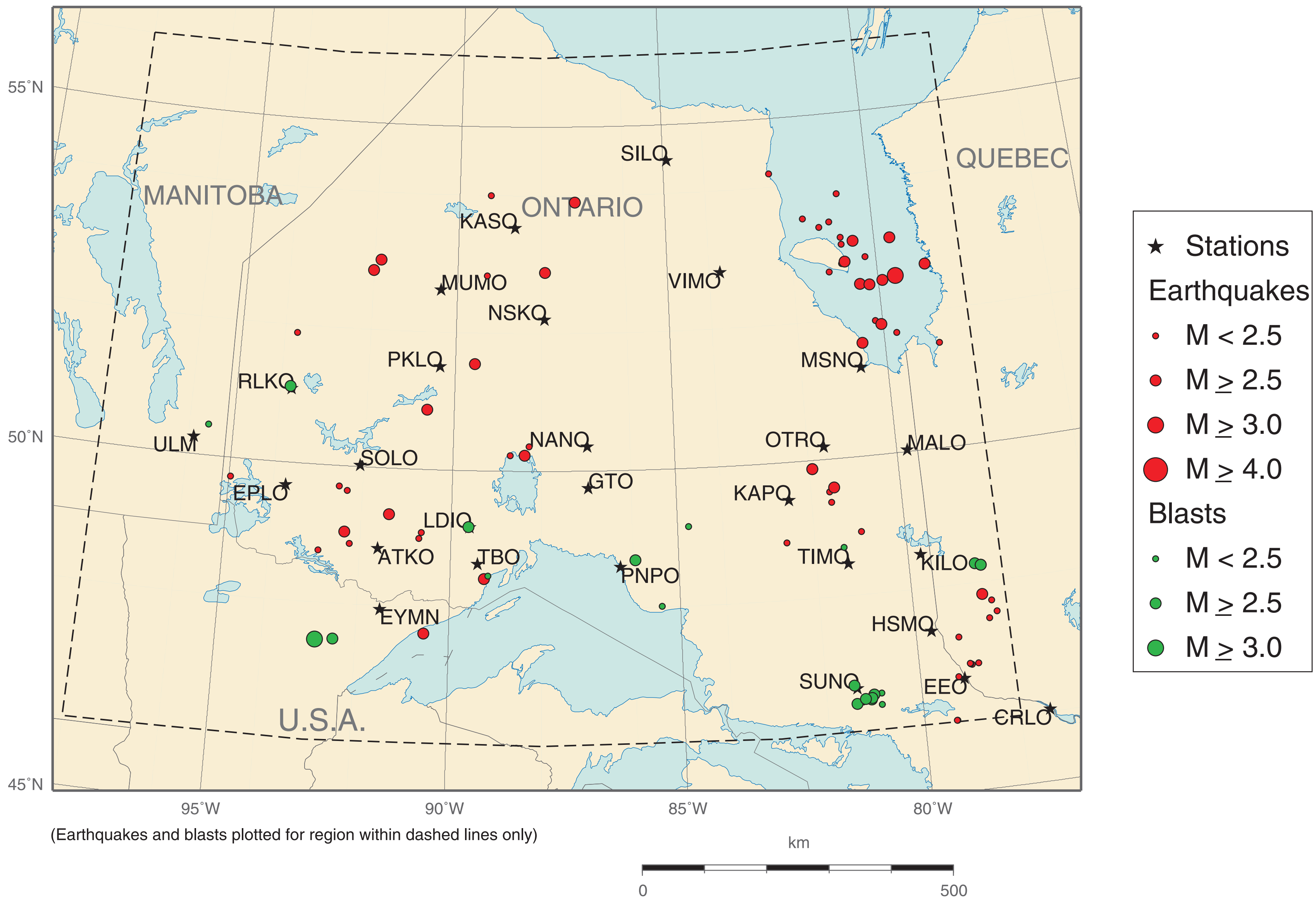


Figure 5: Earthquakes in Eastern Canada, 1982 - 2007



(Earthquakes and blasts plotted for region within dashed lines only)

Figure 6: Earthquakes and Blasts in Northern Ontario and Adjacent

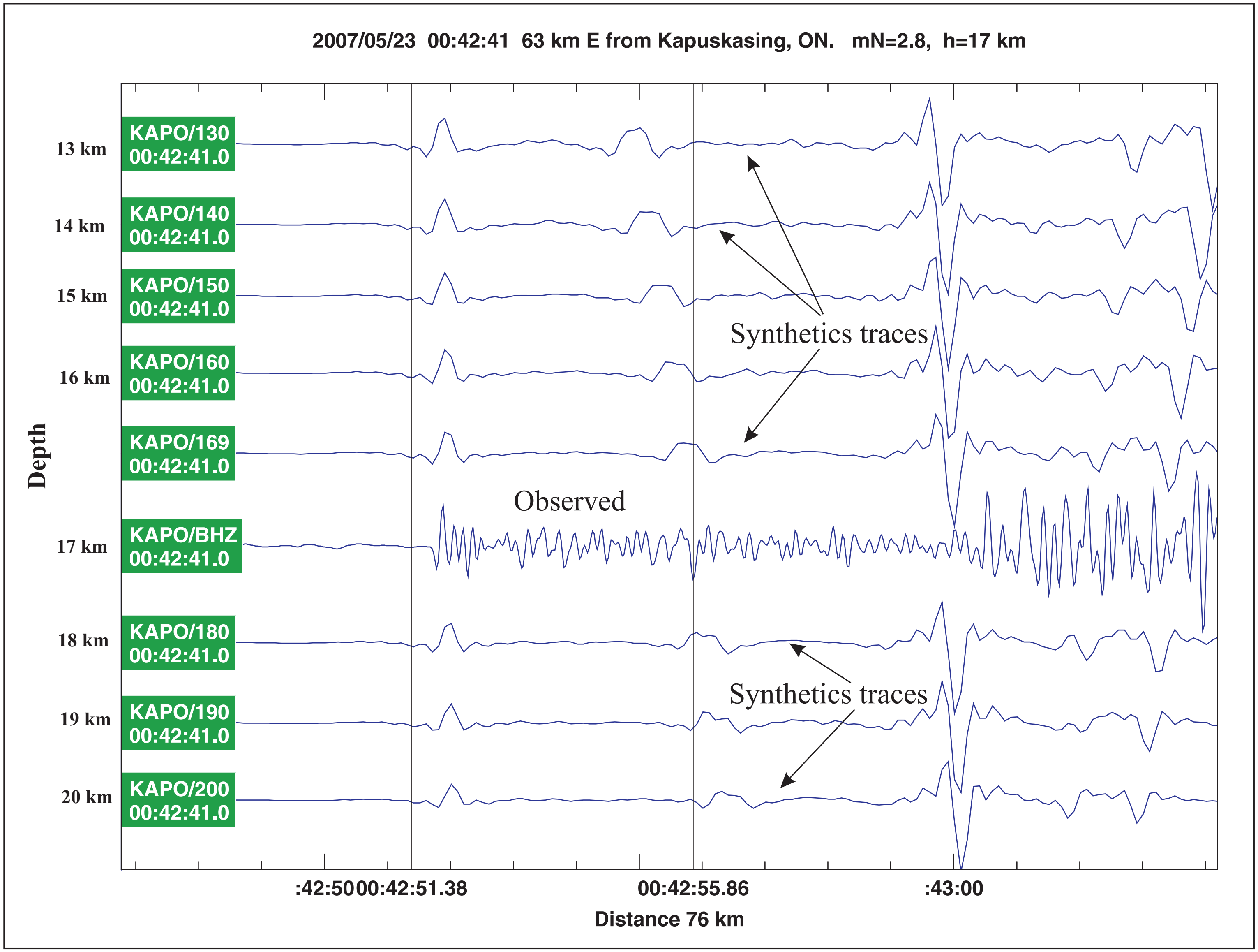


Figure 7: Observed and Synthetic Waveforms from the m_N 2.8 on 2007/05/23 in the Cochrane-Kapuskasing Region of Ontario

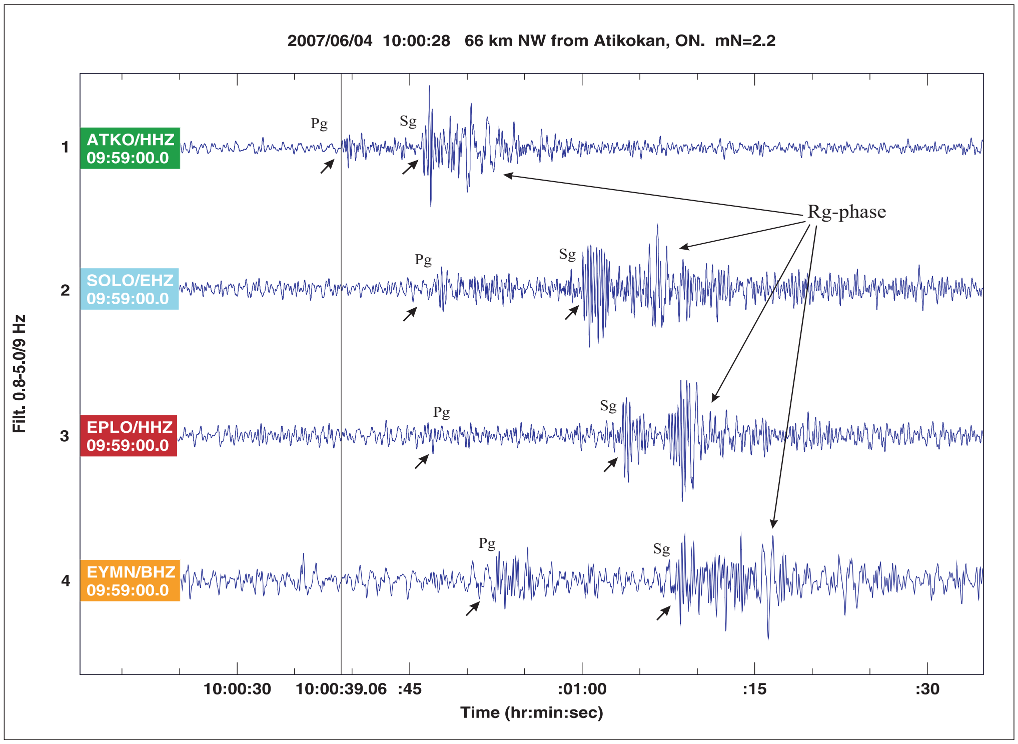


Figure 8: Rg Surface Waves from the m_N 2.2 on 2007/06/04 NW of Atikokan, ON

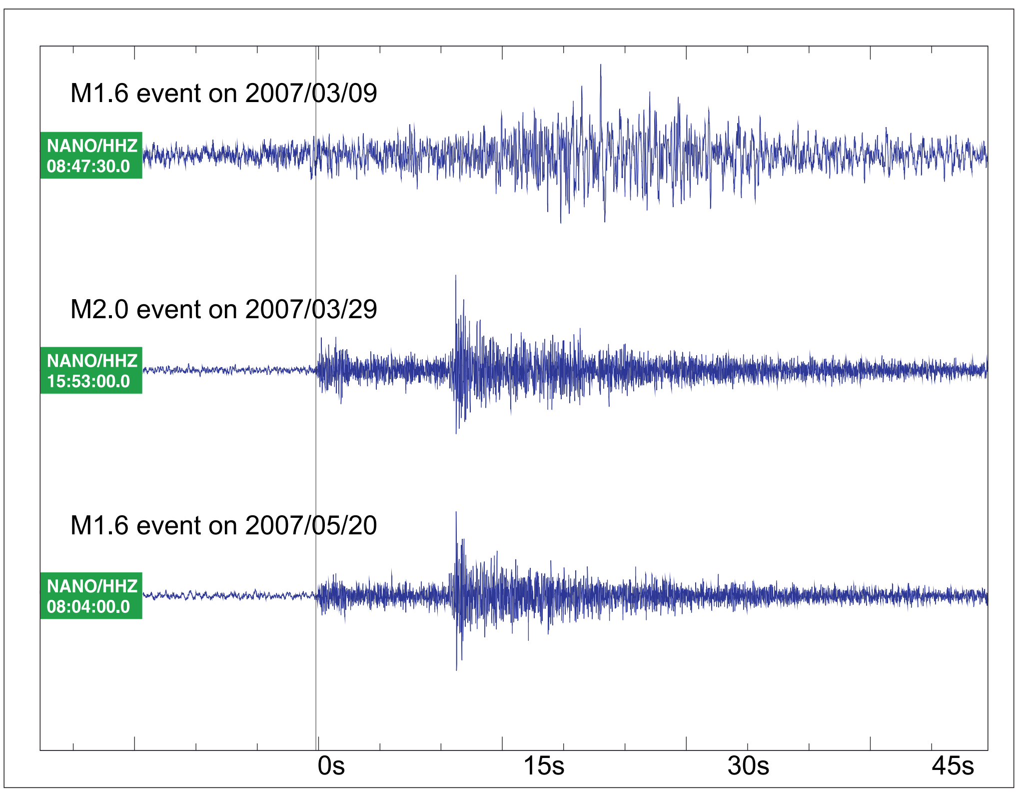


Figure 9: Comparison of the Waveforms of the Events near Collins, ON

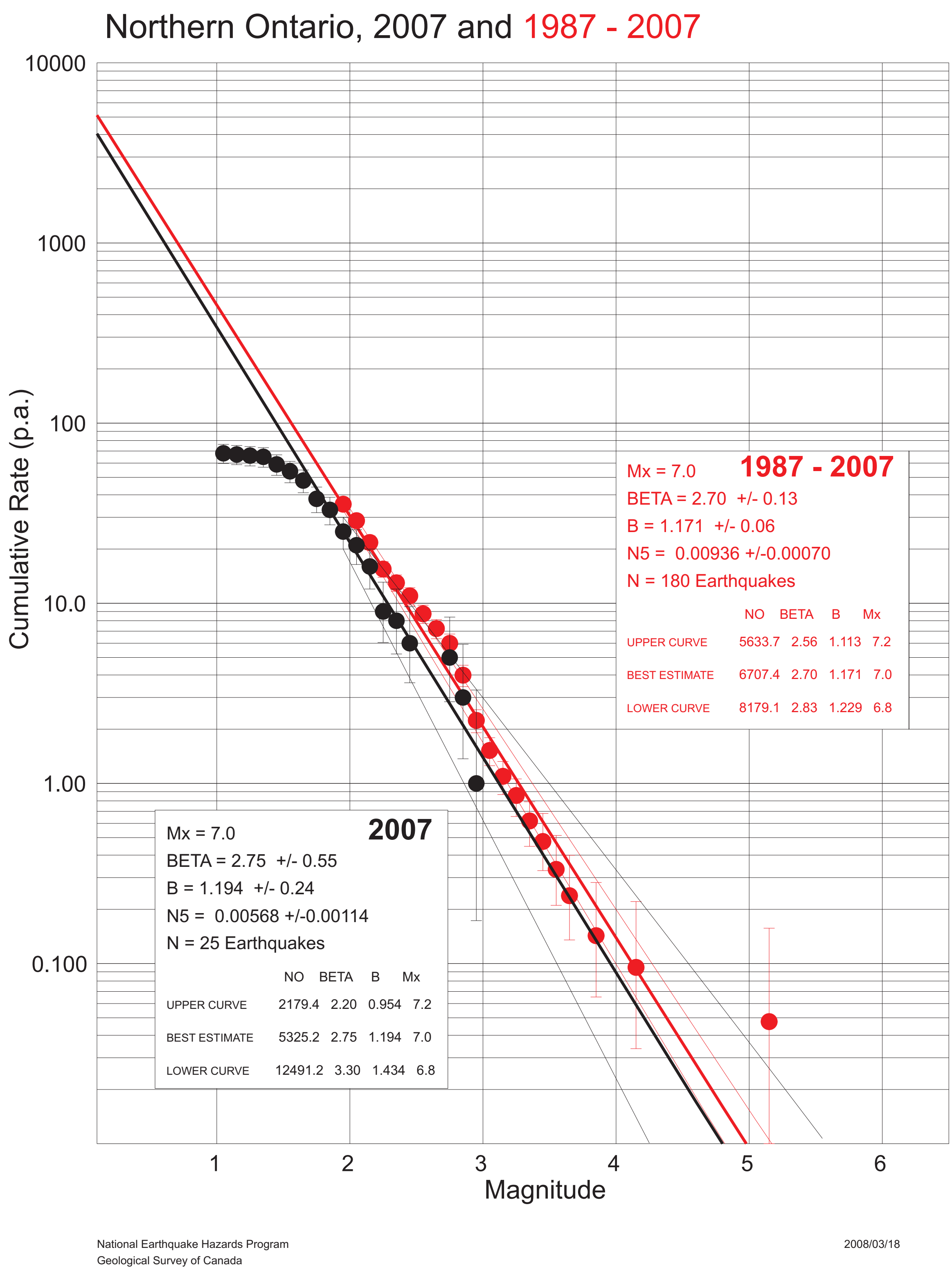


Figure 10: Recurrence Curves for Northern Ontario

APPENDIX A: EARTHQUAKE EPICENTRES AND RECORDED SEISMIC WAVEFORMS

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(INFORMATION WILL BE PROVIDED UPON REQUEST)