SEISMIC ACTIVITY IN THE NORTHERN ONTARIO PORTION OF THE CANADIAN SHIELD: ANNUAL PROGRESS REPORT FOR THE PERIOD JANUARY 01 - DECEMBER 31, 2008

NWMO TR-2009-05 **July 2009**

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ABSTRACT

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Report No.: **NWMO TR-2009-05**
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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 2008.

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 2008.

During this twelve-month period 114 earthquakes were located. Their magnitude ranged from 0.1 m_L to 3.2 m_N. The largest events included a m_N 3.2 in the Atikokan region, a m_N 3.0 in the Kapuskasing-Cochrane region and a 2.9 m_N north of Red Lake, Ontario. The most westerly event in the area being studied was a m_N 2.8 event located just west of Deer Lake, ON. The 114 events located in 2008 compares with 68 events in 2007, 83 events in 2006, 103 events in 2005, and 79 events in 2004.

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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 2008.

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. Eight of these FedNor stations were closed during 2008. 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 data from this station is routinely requested for events that have already been identified on a CNSN station, it is not scanned by CHIS for new events. The addition of the U.S. data has mainly helped locate events in the sparsely-seismic Atikokan region.

Earthquake size is expressed by magnitude. Almost all earthquakes in this series of annual reports will have magnitudes calculated on the Nuttli scale (see section 5), which is used by CHIS for moderate-sized earthquakes in eastern Canada[1]. Magnitudes calculated on the Nuttli scale are formally written m_N or m_{bLg}. The former notation will be used in this report.

The frequency of earthquakes of a given magnitude is a logarithmic function of magnitude: for each magnitude 4.0 earthquake in a region, one can expect approximately 10 magnitude 3.0 earthquakes, 100 magnitude 2.0 earthquakes, 1000 magnitude 1.0 earthquakes, etc. Thus

[1] The Richter or local magnitude mL is used for small events when amplitudes are not available from at least one station that is farther than 50 km from the epicentre.

there is a great benefit to being able to detect the many smaller earthquakes happening in northern Ontario 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 114 earthquakes were located. Their magnitude ranged from 0.1 m_L to 3.2 m_N. The largest of these events included a m_N 3.2 in the Atikokan region, a m_N 3.0 in the Kapuskasing-Cochrane region, and a m_N 2.9 that was 60 km north of Red Lake, 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 2008 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 2008 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 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 4400 earthquakes had been located in Canada in the year 2008. Only 54 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, 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 96%

for most of the core seismograph station except EEO and ULM, and in excess of 90% for 13 of the 19 POLARIS stations (including VIMO). OTRO, SUNO, PNPO and TIMO had data in excess of 80%, while NSKO and MSNO were below 60%. EEO availability was low due to a faulty power supply in January, and to faulty components on the local VSAT, which were replaced by the satellite communications service provide in June. ULM had several problems throughout the year: a snow storm in March, timing errors in May (which required resetting the GPS), and a power failure at the end of November. However the majority of the downtime occurred over the summer due to a couple of lightening storms which resulted in several components requiring replacement. Many of the solar powered sites, particularly NSKO and MSNO, experienced power failure and had poor telecommunications during the winter months.

Five of the temporary FedNor stations were closed in August: MUMO, LDIO, RLKO, KASO and NSKO. The last two were often not operational as they were located in very remote, difficult to access sites, and they had difficulty acquiring enough solar power to run for about half the year. When they were operational, the background noise (likely due to the soil conditions) was not optimal for recording very low level activity. MUMO and LDIO were located at mine sites and hence had a lot of background noise. Also the proximity of LDIO to TBO made it somewhat redundant. RLKO had been vandalized several times and hence had not had much operational time.

Then in late September and early October the closure of three more stations occurred: MSNO, OTRO and HSMO. The first two sites were fairly noisy, likely due to soil conditions, and HSMO was located in the near several other good sites and was hence considered less valuable.

Thus, overall, the stations chosen to be closed first from the FedNor project have had little impact on the overall threshold of located events in the northern Ontario region.

3. EARTHQUAKES

A total of 114 earthquakes were located in the study area during 2008. The events from 2008 are listed in Table 1 and plotted in Figure 1. The largest event located this year was a m_N 3.2 which occurred on April 2nd in the Atikokan region. This was the first recorded event above magnitude 3 in this region. The second largest event of the year was a m_N 3.0 on March 21st in the Kapuskasing-Cochrane region, historically one of the more active regions of northern Ontario.

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. The effects of this can be seen particularly in the James Bay region where 160 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 114 earthquakes from 2008, compare to previous years as follows:

Year	No. of events	No. of stations	
2008	114	26	Began removal of FedNor 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	

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 was a quieter year than usual in terms of seismicity.

Conversely, 2008 has been more active than usual, with several swarms. The first small swarm in 2008 occurred around the Atikokan region throughout March and April (13 events). In October a swarm of activity very close to Thunder Bay was felt by nearby residents, even though the largest event was only a m_N 2.3 (also 13 events). And finally a suite of 14 events occurred approximately 50 km south of Sioux Lookout in the months of November and December. Thirty-five events were also recorded throughout the year in the James Bay region. These four regions alone account for 75 of the 114 events in 2008, or 66% of the year's seismicity.

As noted in the previous section (Section 2), in 2008 eight of the POLARIS FedNor installations were closed and moved to other parts of the country. The stations (OTRO, KASO, NSKO, RLKO, MSNO, MUMO, LDIO and HSMO) were chosen due to poor uptime statistics, or the high noise levels at the site. Therefore, the location threshold appears to have been unchanged compared with the previous year. However, more FedNor stations will be closed in the next few years and this will lead to a threshold closer to pre-2003 (pre-POLARIS 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.

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 867 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 27 years (58 events). The pattern of all the seismicity echoes the pattern of the larger events, including the Atikokan region where the first event larger than m_N 3.0 has been recorded this past year.

Figure 4 illustrates the seismic activity in eastern Canada in year 2008. 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 - 2008. 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 2008 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 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 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 EYMN are shown for the m_N 3.2 Atikokan earthquake that occurred on April 2nd, 2008 in Figure 7. These waveforms indicated a depth of 4 km for this event, which is not considered unusual for this region of Ontario. Figure 8 shows an earthquake that occurred 70 km NW of Thunder Bay 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. Figure 9 shows the comparison of waveforms for two events in the Cochrane-Kapuskasing region on October 13th only minutes apart. The first event was large enough to find a depth of 4.5 km using the RDPM method. The second event was not, but due to the similarities of the waveforms, the depth of the second event was assumed to be the same as the depth of the first. (See Section 4.2.1 for further discussion on depth).

The earthquake epicentres of 2008 generally conform to areas of past seismicity, although the most westerly event with 2.8 m_N on August 19th at 09:10 UT occurred in an area with very few recorded earthquakes. In fact, the nearest event recorded to this event in the past was a 3.2 m_N located 64 km to the S-E on February 7th, 1986. It is difficult to say whether this lack of pervious seismicity is due to a lower seismicity rate, or whether this is just an artefact of the location being at edge of the study area and network where the location threshold starts to increase.

Recurrence curves for the study area for the year 2008 and for the period of 1987 to the end of 2008 (22 years of data) are shown in Figure 10 and are discussed in more detail in Section 6.

Data for all stations are available in continuous data archive files at CHIS. All the archived data can be accessed on-line on the CHIS AutoDRM web site at http://earthquakescanada.nrcan.gc.ca/stnsdata/autodrm/index_e.php 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 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 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 2008 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 extended with subsequent work appeared in Ma et al., (2008). Figure 7 shows an application of RDPM to a 2008 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 a 5 km depth has been assigned for these events.

Table 3 lists all the events from 2008 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, plus one, for which a reliable depth was determined using the RDPM method. Note that the majority of the events occurring in 2008 were too small to determine the depth, even by these methods.

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.

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. Although 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, 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>3 is considered complete since 1987, providing 22 years of data for the less-common larger earthquakes.

Figure 10 shows the magnitude-recurrence plot for the year 2008 earthquakes in black. It is very similar to the magnitude-recurrence plot for the 22-year period of 1987 to 2008 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 2008 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 22-year period. For the year 2008 a best fit slope of 2.64 +/- 0.30 was found, versus 2.83 +/- 0.13 for the 22-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 77 mining-induced seismic events of magnitude -0.3 or greater in the study area in 2008. Thirty-eight of these events occurred in the Sudbury Basin, including a m_N 3.8 on September 11th, a m_N 3.4 on October 6th, and a m_N 3.1 on December 5th. A further 14 events were located in the Red Lake region, including a m_N 3.0 on August 10th, and a m_N 3.2 on October 3rd. Seven events were recorded in the Kirkland Lake area, one of which was a m_N 3.1, two events near Marathon, and 16 near the Cadillac/Rouyn-Noranda area in Quebec, including a m_N 3.3 at Laronde mine on July 20th. A total of 18 mining-induced events larger than m_N 2.5 were recorded in the study area in 2008 and are listed in Table 4.

8. SUMMARY

Data capture was in excess of 96% from each of the core seismograph stations except EEO and ULM, which were both around 94% complete. For the POLARIS type installations, data capture exceeded 90% for 13 of the 19 POLARIS type installations, and exceeded 80% for all but two of the stations (NSKO and MSNO). EEO had a faulty power supply in January, and failed components in the summer that required replacement, while ULM was subject to a snow storm in March, timing errors in May, several lightening strikes during the summer (which caused damage to some equipment that then needed to be replaced), and a power failure in November. 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 NSKO and MSNO in particular seemed to have trouble recovering until mid-way through the year. RLKO appeared to have good up-times, however the data received from the station since then early last year has been purely digital noise. Hence, RLKO, along with 7 other FedNor stations (MSNO, NSKO, KASO, MUMO, OTRO, LDIO and HSMO) were closed between August and October of 2008. Most of these were closed due to poor station quality, and hence the location threshold does not appear to have been affected.

The seismic activity in the study area during the calendar year 2008 consisted of 114 earthquakes ranging in magnitude from 0.1 to 3.2. Fifty-four earthquakes were larger than m_N 2.0, and two of the earthquakes were m_N 3.0 and larger. The largest event, m_N 3.2, was located in the Atikokan region, and was the first ever recorded event in this region larger than magnitude 3. The second largest event was a m_N 3.0 located in the Cochrane-Kapuskasing region, which has had a fair amount of seismicity in the past. 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 2008 conformed to the pattern of previous seismicity, with the exception of the m_N 2.8 event 83 km W of Deer Lake, Ontario, along the Manitoba/Ontario border. Not many events have previously been recorded in this area, although it is unclear as to whether this is because it is truly less active, or whether the lack of recorded seismicity is due to it being at the edge of the network, in an area not well covered by seismometers in the past.

ACKNOWLEDGEMENTS

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Table 1: Located Local Earthquakes, January - December 2008

Date	Time (UT)	Latitude	Longitude	#stations/ phases	Mag	Region and Comment
01/05	02:22:22	50.27N	94.10W	4/ 8	1.5 m_N	55 km NE from Kenora, ON
01/06	02:12:51	52.54N	80.24W	5/ 8	1.9 m_N	James Bay.
01/08	17:12:36	52.25N	81.25W	5/ 6	2.0 m_N	James Bay
01/15	15:48:12	52.26N	80.27W	5/ 7	2.2 m_N	James Bay
01/22	13:26:53	47.03N	79.06W	10/18	2.2 m_N	35 km N from Temiscaming, QC
02/05	06:06:54	46.86N	78.94W	9/14	1.2 m_N	19 km NE from Temiscaming, QC
02/23	08:23:25	51.91N	91.86W	7/12	2.1 m_N	125 km NW from Pickle Lake, ON
03/08	07:07:10	49.15N	92.04W	8/14	2.2 m_N	55 km NW from Atikokan, ON
03/08	12:15:30	49.09N	92.18W	6/13	1.9 m_N	55 km NW from Atikokan, ON
03/08	16:03:34	49.10N	92.17W	5/ 9	1.5 m_N	56 km NW from Atikokan, ON
03/09	04:47:09	49.15N	92.02W	7/12	1.9 m_N	53 km NW from Atikokan, ON
03/09	19:24:50	46.31N	78.76W	8/15	1.6 m_N	5 km SW from Mattawa, ON
03/10	04:36:42	48.99N	90.76W	10/18	2.5 m_N	68 km NE from Atikokan, ON
03/12	14:44:14	49.08N	92.20W	5/ 9	1.8 m_N	56 km NW from Atikokan, ON
03/13	09:44:53	49.15N	92.02W	5/ 9	1.5 m_N	54 km NW from Atikokan, ON
03/21	18:08:53	49.74N	81.48W	15/24	3.0 m_N	79 km NE from Kapuskasing, ON
03/25	02:07:20	49.38N	81.99W	4/ 8	1.8 m_N	26 km E from Kapuskasing, ON
03/26	00:26:38	49.04N	92.04W	5/10	1.8 m_N	45 km NW from Atikokan, ON
03/28	08:44:17	48.98N	78.72W	4/ 8	1.6 m_N	34 km E from Clermont, QC
03/30	08:49:32	52.57N	80.18W	6/12	2.0 m_N	James Bay.
04/02	00:19:58	49.08N	92.74W	5/ 9	2.0 m_N	Atikokan region, ON. Foreshock.
04/02	01:10:32	49.06N	92.74W	6/ 9	1.8 m_N	Atikokan region, ON. Foreshock.
04/02	01:27:23	49.07N	92.73W	8/15	3.2 m_N	Atikokan region, ON
04/05	18:44:34	53.97N	82.47W	3/ 6	1.5 m_N	115 km N from Attawapiskat, ON
04/07	03:08:59	47.00N	78.69W	6/ 9	1.1 m_N	45 km NE from Temiscaming, QC
04/09	22:40:28	48.13N	79.65W	5/ 7	1.2 m_N	30 km E from Kirkland Lake, ON
04/17	05:40:23	51.69N	80.22W	6/ 9	1.9 m_N	James Bay.
04/20	12:31:11	49.15N	92.04W	5/ 8	1.5 m_N	53 km NW from Atikokan, ON
04/20	21:04:17	49.15N	92.00W	6/10	1.8 m_N	52 km NW from Atikokan, ON
04/21	03:15:24	50.07N	90.49W	6/10	1.8 m_N	30 km SW from Allanwater Bridge,
04/25	06:08:48	50.05N	86.01W	3/ 4	1.4 m_N	46 km NE from Longlac, ON
04/27	01:34:47	47.74N	78.37W	4/ 7	1.3 m_N	47 km S from Malartic, QC
05/14	21:41:47	52.05N	80.38W	4/ 8	2.5 m_N	James Bay.
06/01	19:22:10	52.23N	80.09W	4/ 7	1.8 m_N	James Bay.
06/02	00:01:56	52.34N	79.96W	5/ 8	2.0 m_N	James Bay.
06/04	22:05:35	52.34N	81.35W	4/ 7	1.8 m_N	James Bay.
06/09	17:24:20	52.37N	79.94W	5/ 9	2.4 m_N	James Bay.
06/09	18:28:07	52.90N	80.82W	5/ 9	1.9 m_N	James Bay.
06/18	8:28:38	46.55N	78.59W	8/15	2.2 m_N	30 km N from Mattawa, ON
06/19	23:16:58	49.14N	81.55W	3/ 5	1.4 m_N	40 km W from Cochrane, ON
06/26	21:15:27	52.45N	80.10W	4/ 6	2.0 m_N	James Bay
06/30	18:22:41	53.07N	80.57W	7/11	2.1 m_N	James Bay
07/01	10:05:16	51.79N	80.45W	5/ 9	2.0 m_N	James Bay.
07/01	22:19:33	49.69N	81.45W	5/ 7	1.8 m_N	78 km NE from Kapuskasing, ON
07/05	7:11:24	53.27N	80.99W	6/11	2.2 m_N	James Bay
07/09	13:05:21	53.37N	80.89W	3/ 6	1.9 m_N	James Bay
07/13	3:55:02	48.80N	80.89W	9/16	2.1 m_N	14 km NW from Iroquois Falls, ON
07/14	3:16:06	46.03N	79.43W	12/20	2.0 m_N	7 km W from Powassan, ON
07/14	17:17:48	49.11N	81.59W	6/10	2.1 m_N	42 km W from Cochrane, ON
07/15	1:21:16	52.84N	80.66W	4/ 8	1.9 m_N	James Bay.
07/21	22:31:40	46.84N	78.93W	3/ 5	0.9 m_N	20 km NE from Temiscaming, QC
08/04	2:55:47	46.81N	78.90W	6/10	1.2 m_N	19 km NE from Temiscaming, QC

08/12	12:47:20	52.87N	80.32W	4/ 8	2.0 m_N	James Bay.
08/13	9:59:50	53.54N	80.86W	3/ 6	1.8 m_N	James Bay.
08/19	3:12:09	53.07N	79.70W	5/ 8	2.3 m_N	James Bay.
08/19	9:10:35	52.56N	95.30W	11/15	2.8 m_N	83 km W from Deer Lake, ON
08/21	4:18:38	49.64N	81.63W	3/ 5	1.7 m_N	64 km NE from Kapuskasing, ON
08/31	15:45:31	53.41N	80.59W	4/ 8	2.3 m_N	James Bay.
09/03	5:48:22	52.25N	79.70W	5/ 8	2.1 m_N	James Bay.
09/10	20:20:37	52.70N	81.17W	4/ 9	2.2 m_N	James Bay.
09/13	13:07:18	48.97N	90.71W	3/ 6	1.6 m_N	70 km E from Atikokan, ON
09/26	9:42:04	52.06N	80.08W	10/18	2.8 m_N	James Bay.
09/30	6:53:12	48.91N	89.84W	8/15	2.5 m_N	70 km NW from Thunder Bay, ON
10/01	14:24:08	48.72N	89.90W	4/ 7	2.2 m_N	55 km NW from Thunder Bay, ON
10/01	15:00:14	53.35N	81.11W	5/ 9	2.3 m_N	James Bay.
10/01	15:42:04	53.32N	81.11W	4/ 7	2.2 m_N	James Bay.
10/10	9:23:53	52.77N	80.53W	3/ 6	1.7 m_N	James Bay.
10/13	2:38:26	49.52N	81.47W	7/12	2.4 m_N	60 km NW from Cochrane, ON
10/13	2:45:40	49.53N	81.46W	7/12	2.1 m_N	60 km NW from Cochrane, ON
10/13	18:55:22	48.33N	89.51W	4/ 7	1.8 m_N	16 km SW from Thunder Bay, ON
10/19	4:05:07	48.33N	89.48W	8/15	2.3 m_N	14 km SW from Thunder Bay, ON. F
10/19	20:41:46	48.40N	89.55W	3/ 6	0.1 m_L	15 km W from Thunder Bay, ON
10/19	21:47:27	48.35N	89.53W	4/ 7	1.6 m_N	15 km W from Thunder Bay, ON
10/20	6:20:03	52.71N	78.62W	6/12	2.6 m_N	35 km S from Wemindji, QC
10/21	11:58:09	47.37N	78.27W	8/15	2.2 m_N	86 km S from Malartic, QC
10/23	16:54:15	48.34N	89.50W	5/ 8	2.3 m_N	14 km SW from Thunder Bay, ON. F
10/24	13:10:33	48.33N	89.48W	5/ 9	2.1 m_N	14 km SW from Thunder Bay, ON
10/25	7:58:22	52.54N	80.14W	7/13	2.6 m_N	James Bay
10/27	4:23:38	48.35N	89.51W	4/ 7	1.7 m_N	15 km W from Thunder Bay, ON
11/03	21:04:54	46.85N	78.92W	5/ 9	1.6 m_N	20 km NE from Temiscaming, QC
11/07	18:02:03	52.83N	80.32W	3/ 6	1.9 m_N	James Bay.
11/09	9:24:09	48.37N	89.52W	6/12	2.1 m_N	15 km W from Thunder Bay, ON. Fe
11/09	9:31:22	48.37N	89.52W	5/ 9	2.1 m_N	15 km W from Thunder Bay, ON. Fe
11/09	9:44:44	48.37N	89.53W	5/ 9	1.8 m_N	15 km W from Thunder Bay, ON. Fe
11/09	9:48:50	48.37N	89.53W	6/10	2.1 m_N	15 km W from Thunder Bay, ON. Fe
11/09	10:57:49	48.37N	89.52W	5/ 9	1.8 m_N	15 km W from Thunder Bay, ON. Fe
11/11	1:44:07	49.61N	91.79W	6/12	1.7 m_N	53 km S from Sioux Lookout, ON
11/11	3:13:30	49.60N	91.81W	7/11	2.1 m_N	53 km S from Sioux Lookout, ON
11/13	9:18:51	49.61N	91.77W	6/10	1.3 m_N	53 km S from Sioux Lookout, ON
11/19	3:41:01	48.38N	89.53W	4/ 8	2.0 m_N	16 km W from Thunder Bay, ON
11/19	22:08:35	49.58N	81.63W	4/ 6	1.6 m_N	61 km E from Kapuskasing, ON
11/19	22:09:55	49.53N	81.60W	3/ 5	1.5 m_N	62 km E from Kapuskasing, ON
11/21	8:07:02	53.64N	79.77W	5/ 8	2.2 m_N	James Bay
11/28	16:26:48	53.44N	81.00W	5/10	2.1 m_N	James Bay.
11/28	21:24:01	49.60N	91.79W	8/13	2.4 m_N	54 km S from Sioux Lookout, ON
11/28	23:17:03	49.61N	91.82W	6/11	1.8 m_N	52 km S from Sioux Lookout, ON
11/30	4:17:20	49.61N	91.81W	6/11	1.7 m_N	52 km S from Sioux Lookout, ON
11/30	13:26:18	49.29N	90.54W	6/11	1.8 m_N	100 km NE from Atikokan, ON
12/02	0:23:37	53.84N	82.63W	3/ 5	2.1 m_N	100 km N from Attawapiskat, ON
12/04	4:40:51	49.62N	91.74W	4/ 7	1.0 m_N	53 km S from Sioux Lookout, ON
12/04	4:43:18	49.60N	91.82W	5/ 8	1.5 m_N	53 km S from Sioux Lookout, ON
12/04	4:43:55	49.59N	91.83W	4/ 7	1.4 m_N	54 km S from Sioux Lookout, ON
12/06	0:07:46	49.59N	91.84W	7/13	2.3 m_N	54 km S from Sioux Lookout, ON
12/06	0:12:45	49.58N	91.85W	6/12	1.7 m_N	53 km S from Sioux Lookout, ON
12/06	6:31:44	49.64N	91.73W	4/ 6	2.1 m_N	53 km S from Sioux Lookout, ON
12/08	2:38:19	51.54N	94.03W	8/15	2.9 m_N	60 km N from Red Lake, ON
12/10	15:50:00	51.45N	94.08W	8/12	2.3 m_N	50 km NW from Red Lake, ON
12/13	19:29:13	48.69N	91.23W	4/ 6	1.4 m_N	30 km E from Atikokan, ON

12/14	0:41:27	50.20N	92.76W	5/ 9	1.4 m_N	48 km N from Dryden, ON
12/18	19:10:14	52.84N	80.91W	4/ 7	2.1 m_N	James Bay.
12/18	21:52:59	47.07N	78.40W	6/10	1.6 m_N	66 km NE from Temiscaming, QC
12/21	0:30:09	49.61N	91.78W	3/ 5	0.8 m_N	53 km S from Sioux Lookout, ON
12/28	18:25:03	49.59N	91.80W	5/10	1.5 m_N	54 km S from Sioux Lookout, ON
12/31	21:18:23	46.89N	79.00W	6/12	1.8 m_N	21 km N from Temiscaming, QC

Table 2: NWMO Supported Stations Operating During 2008
(2007 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	93.9 (99.3)	19941207-
SOLO	Sioux Lookout	50.0213	92.0812	373	99.9 (98.3)	19981104-
TBO	Thunder Bay	48.6473	89.4083	468	98.9(95.1)	19931005-
GTO	Geraldton	49.7455	86.9610	350	99.4 (99.9)	20010104-
KAPO	Kapuskasing	49.4504	82.5079	210	96.5 (99.5)	19980114-
EEO	Eldee	46.6411	79.0733	398	94.0 (87.7)	19931005-
CRLO	Chalk River	46.0375	77.3801	168	97.9 (89.7)	19941117-
MUMO	Musselwhite Mine	52.6128	90.3914	316	100.0 (99.9)	20030615-20080817
SILO	Sutton Inlier	54.4791	84.9126	195	98.3 (95.6)	20030609-
VIMO	Victor Mine	52.8173	83.7449	78	99.8 (99.8)	20030611-
OTRO	Otter Rapids	50.1818	81.6286	109	88.7 (82.9)	20030618-20081003
MALO	McAlpine Lake	50.0244	79.7635	271	98.1 (100.0)	20030620-
KILO	Kirkland Lake	48.4972	79.7232	314	90.9 (99.9)	20030622-
SUNO	Sudbury	46.6438	81.3442	343	83.7 (93.2)	20030623-
RLKO	Red Lake	51.0704	93.7585	362	99.9 (99.9)	20041119-20080815
EPLO	Experimental Lake	49.6737	93.7258	437	98.3 (92.7)	20040611-
ATKO	Atikokan	48.8231	91.6004	383	97.5 (99.9)	20040609-
PKLO	Pickle Lake	51.4987	90.3522	376	96.9 (99.3)	20040615-
LDIO	Lac des Iles Mine	49.1750	89.5955	500	97.3 (96.8)	20040616-20080813
PNPO	Pukaskwa Nat. Park	48.5957	86.2846	219	85.2 (94.8)	20040618-
KASO	Kasabonika Lake	53.5279	88.6414	192	100.0 (68.1)	20050803-20080820
NSKO	Neskantaga	52.1965	87.9305	241	58.7 (40.1)	20050729-20080823
NANO	Aroland	50.3543	86.9684	309	98.5 (99.3)	20050804-
MSNO	Moosonee	51.2913	80.6151	15	53.7 (99.9)	20050723-20080930
TIMO	Timmins	48.4659	81.3032	392	82.1 (92.4)	20050725-
HSMO	Haileybury	47.3708	79.6657	306	95.9 (98.1)	20050720-20081005

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 2008. All times given are in UT (Universal Time).

ULM dropped out from March 30th until the 31st due to a snow storm causing poor communication links. On May 20th to 23rd the timing was off and the station's GPS required a reset. Then on July 24th a lightening storm caused several components to be failed, and the station was restored 6 days later when the satellite communications provider replaced components and cards on the VSAT DIU. August 9th to 15th the station dropped out again and a technician was required to replace cards on the indoor unit, and components on the dish. Another lightening storm on September 1st caused an outage of another 5 days until the technician was able to replace the VSAT components and restore data flow. And on November 29th, a power outage caused the station to drop out, and a reset by the local contact was required to restore the data flow on December 1st.

TBO dropped out on July 14th due to VSAT problems. The technician from the telecommunications service provider restored the data flow on July 18th.

GTO dropped out from January 15th for a day, and the digitizer was power cycled to restore the data flow. Then on April 1st until the 2nd, the data from GTO was experiencing timing problems.

KAPO was out on February 23rd to the 25th due to a local power outage. On August 21st KAPO was accidentally left offline until the 22nd while investigating a timing problem. And on September 14th, the station dropped out due to a power outage. Ontario Power Generation replaced a fuse on the pole to restore power, but the data were being rejected due to bad timing until September 23rd when the station GPS antenna and cable were replaced.

EEO had dropped out late in 2007, a problem which continued until January 11th, 2008. The satellite communications service provider replaced a faulty power supply on the local VSAT DIU. Then EEO was out from June 7th until the 17th, when components were replaced on the local VSAT again. There was a minor drop out on December 29th for 18 hours due to a local power outage.

CRLO was down from August 28th until September 4rth due to a faulty VSAT, which was repaired by the satellite communications service provider.

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

- OTRO was out from late in 2007 until January 8th; January 9th until February 2nd; again February 18th to 26th. The station continued to be intermittent from April unitl August.
- KILO dropped out on January 2nd until the 10th, and then again on the 19th. The station was working well from then on until November 27th, when it again suffered from insufficient power right through until the end of the year.
- MALO dropped out on January 6th until the 10th.
- EPLO was out from late in 2007 until January 4th.
- LDIO went down on January 1st and returned two days later.
- TIMO was out from late in 2007 until January 31st, and then again at the end of the year from November 26 through the end of December.
- SUNO was down since late 2007 until January 10th, and again from the 15th until the 30th. At the end of the year it dropped out again on November 25th, right through until the end of 2008.
- NSKO data were intermittent or out from January 26th and remained down until May 26th. The sation was intermittent from June 12th until the 17th.
- MSNO data were out from January 18th until June 2nd, and again on June 7th.
- SILO began dropping out on November 30th. The problem continued until December 6th.
- ATKO began having problems December 24th, which continued through the end of the year.

Eight sites were closed in 2008. LDIO was closed August 13th. RLKO, although it had good uptime statistics, the data quality continued to be bad since early last year due to equipment failure at the site. The site was permanently closed on August 15th, 2008. MUMO was closed shortly after on August 17th, KASO on the 20th and NSKO on the 23rd. MSNO was closed September 30th, followed by OTRO on October 3rd, and HSMO on October 5th.

PKLO, NANO and HSMO data were intermittent on several days in January during the interval 15 to 22 UTC due to communication problems. The same problem continued into February in March, but also affected EPLO, ATKO, and LDIO.

HSMO had availability problems from April 3rd to May 14th, PNPO dropped out from April 29th and returned on June 21st, MALO and PKLO were out or intermittent from June 10th to 16th, and VIMO was out from June 16th to 18th.

Table 3: Depths Derived using Rg-phases and Regional Depth Phase Method (RDPM) for Moderate-sized Events for 2008

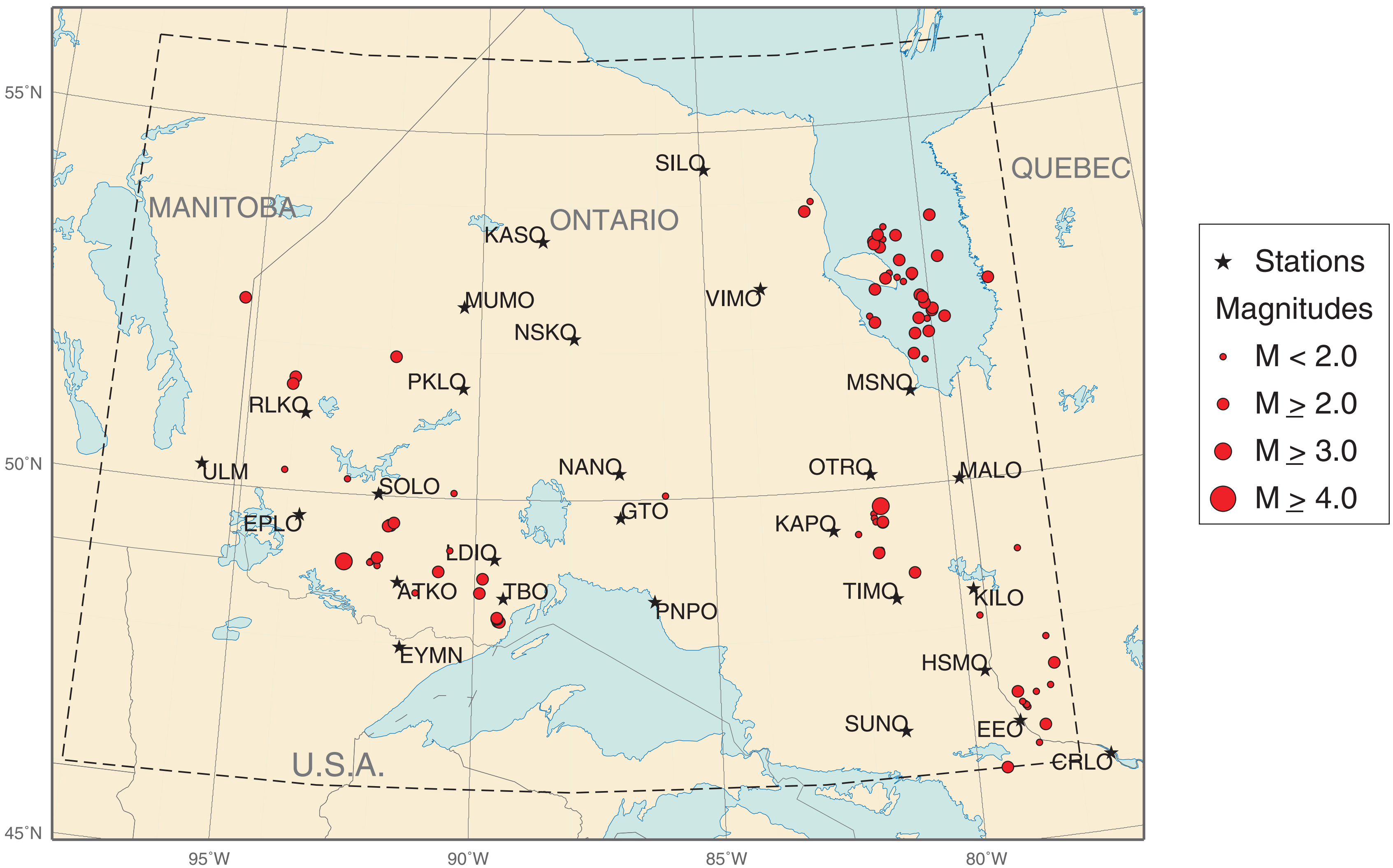
Date mm/dd	Time(UTC) hh:mm:ss	Mag	Depth (km)	Depth type	Region and Comment
01/05	02:22:22	1.5 m_N	5	Rg	55 km NE from Kenora, ON
02/23	08:23:25	2.1 m_N	5	Rg	125 km NW from Pickle Lake, ON
03/08	07:07:10	2.2 m_N	5	Rg	55 km NW from Atikokan, ON
03/08	16:03:34	1.5 m_N	5	Rg	56 km NW from Atikokan, ON
03/09	04:47:09	1.9 m_N	5	Rg	53 km NW from Atikokan, ON
03/10	04:36:42	2.5 m_N	5	Rg	68 km NE from Atikokan, ON
03/12	14:44:14	1.8 m_N	5	Rg	56 km NW from Atikokan, ON
03/13	09:44:53	1.5 m_N	5	Rg	54 km NW from Atikokan, ON
03/21	18:08:53	3.0 m_N	16	RDPM	79 km NE from Kapuskasing, ON
04/02	00:19:58	2.0 m_N	5	Rg	Atikokan region, ON. Foreshock.
04/02	01:10:32	1.8 m_N	5	Rg	Atikokan region, ON. Foreshock.
04/02	01:27:23	3.2 m_N	4	RDPM	Atikokan region, ON
04/20	12:31:11	1.5 m_N	5	Rg	53 km NW from Atikokan, ON
04/20	21:04:17	1.8 m_N	5	Rg	52 km NW from Atikokan, ON
04/21	03:15:24	1.8 m_N	5	Rg	30 km SW from Allanwater Bridge,
07/14	03:16:06	2.0 m_N	5	Rg	7 km W from Powassan, ON
09/13	13:07:18	1.6 m_N	5	Rg	70 km E from Atikokan, ON
09/30	06:53:12	2.5 m_N	4	RDPM	70 km NW from Thunder Bay, ON
10/01	14:24:08	2.2 m_N	5	Rg	55 km NW from Thunder Bay, ON
10/13	02:38:26	2.4 m_N	4.5	RDPM	60 km NW from Cochrane, ON
10/13	02:45:40	2.1 m_N	4.5	RDPM*	60 km NW from Cochrane, ON
10/13	18:55:22	1.8 m_N	1	Rg	16 km SW from Thunder Bay, ON
10/19	04:05:07	2.3 m_N	1	Rg	14 km SW from Thunder Bay, ON. Felt.
10/19	20:41:46	0.1 m_L	1	Rg	15 km W from Thunder Bay, ON
10/19	21:47:27	1.6 m_N	1	Rg	15 km W from Thunder Bay, ON
10/23	16:54:15	2.3 m_N	1	Rg	14 km SW from Thunder Bay, ON. Felt.
10/24	13:10:33	2.1 m_N	1	Rg	14 km SW from Thunder Bay, ON
10/27	04:23:38	1.7 m_N	1	Rg	15 km W from Thunder Bay, ON
11/09	09:24:09	2.1 m_N	1	Rg	15 km W from Thunder Bay, ON. Felt.
11/09	09:31:22	2.1 m_N	1	Rg	15 km W from Thunder Bay, ON. Felt.
11/09	09:44:44	1.8 m_N	1	Rg	15 km W from Thunder Bay, ON. Felt.
11/09	09:48:50	2.1 m_N	1	Rg	15 km W from Thunder Bay, ON. Felt.
11/09	10:57:49	1.8 m_N	1	Rg	15 km W from Thunder Bay, ON. Felt.
11/11	01:44:07	1.7 m_N	5	Rg	53 km S from Sioux Lookout, ON
11/11	03:13:30	2.1 m_N	5	Rg	53 km S from Sioux Lookout, ON
11/13	09:18:51	1.3 m_N	5	Rg	53 km S from Sioux Lookout, ON
11/19	03:41:01	2.0 m_N	1	Rg	16 km W from Thunder Bay, ON
11/28	21:24:01	2.4 m_N	4	RDPM	54 km S from Sioux Lookout, ON
11/28	23:17:03	1.8 m_N	5	Rg	52 km S from Sioux Lookout, ON
11/30	04:17:20	1.7 m_N	5	Rg	52 km S from Sioux Lookout, ON
11/30	13:26:18	1.8 m_N	5	Rg	100 km NE from Atikokan, ON
12/04	04:40:51	1.0 m_N	5	Rg	53 km S from Sioux Lookout, ON
12/04	04:43:18	1.5 m_N	5	Rg	53 km S from Sioux Lookout, ON
12/04	04:43:55	1.4 m_N	5	Rg	54 km S from Sioux Lookout, ON
12/06	00:07:46	2.3 m_N	5	Rg	54 km S from Sioux Lookout, ON
12/06	00:12:45	1.7 m_N	5	Rg	53 km S from Sioux Lookout, ON
12/06	06:31:44	2.1 m_N	5	Rg	53 km S from Sioux Lookout, ON

12/13	19:29:13	1.4 m_N	5	Rg	30 km E from Atikokan, ON
12/14	00:41:27	1.4 m_N	5	Rg	48 km N from Dryden, ON
12/21	00:30:09	0.8 m_N	5	Rg	53 km S from Sioux Lookout, ON
12/28	18:25:03	1.5 m_N	5	Rg	54 km S from Sioux Lookout, ON

* This event was too small to determine depth directly by the RDPM method, however, due to waveform similarities with larger event just prior to this event, the depth of 4.5 km for the larger event is assumed for this smaller event as well.

Table 4: Mining-Induced Seismic Events m_N 2.5 and Greater, January - December 2008

Date (mm/dd)	Mine	Location	Mag
01/01	Copper Cliff South Mine	Sudbury	2.6 m_N
01/15	Mouska Mine	Rouyn-Noranda	2.6 m_N
04/09	Thayer Lindsey	Sudbury	2.9 m_N
04/25	Campbell Mine	Red Lake	2.8 m_N
06/23	Garson Mine	Sudbury	2.6 m_N
07/12	Macassa Mine	Kirkland Lake	3.1 m_N
07/13	Macassa Mine	Kirkland Lake	2.6 m_N
07/18	Campbell Mine	Red Lake	2.6 m_N
07/20	Laronde Mine	Cadillac	3.3 m_N
08/09	Campbell Mine	Red Lake	2.5 m_N
08/10	Campbell Mine	Red Lake	3.0 m_N
08/12	Stobie Mine	Sudbury	2.5 m_N
08/13	Stobie Mine	Sudbury	2.8 m_N
09/09	Garson Mine	Sudbury	2.9 m_N
09/11	Copper Cliff North	Sudbury	3.8 m_N
10/03	Campbell Mine	Red Lake	3.2 m_N
10/06	Fraser Mine	Sudbury	3.4 m_N
12/05	Garson Mine	Sudbury	3.1 m_N



(Earthquakes plotted for the region within dashed lines

Figure 1: Earthquakes in Northern Ontario and Adjacent Areas,

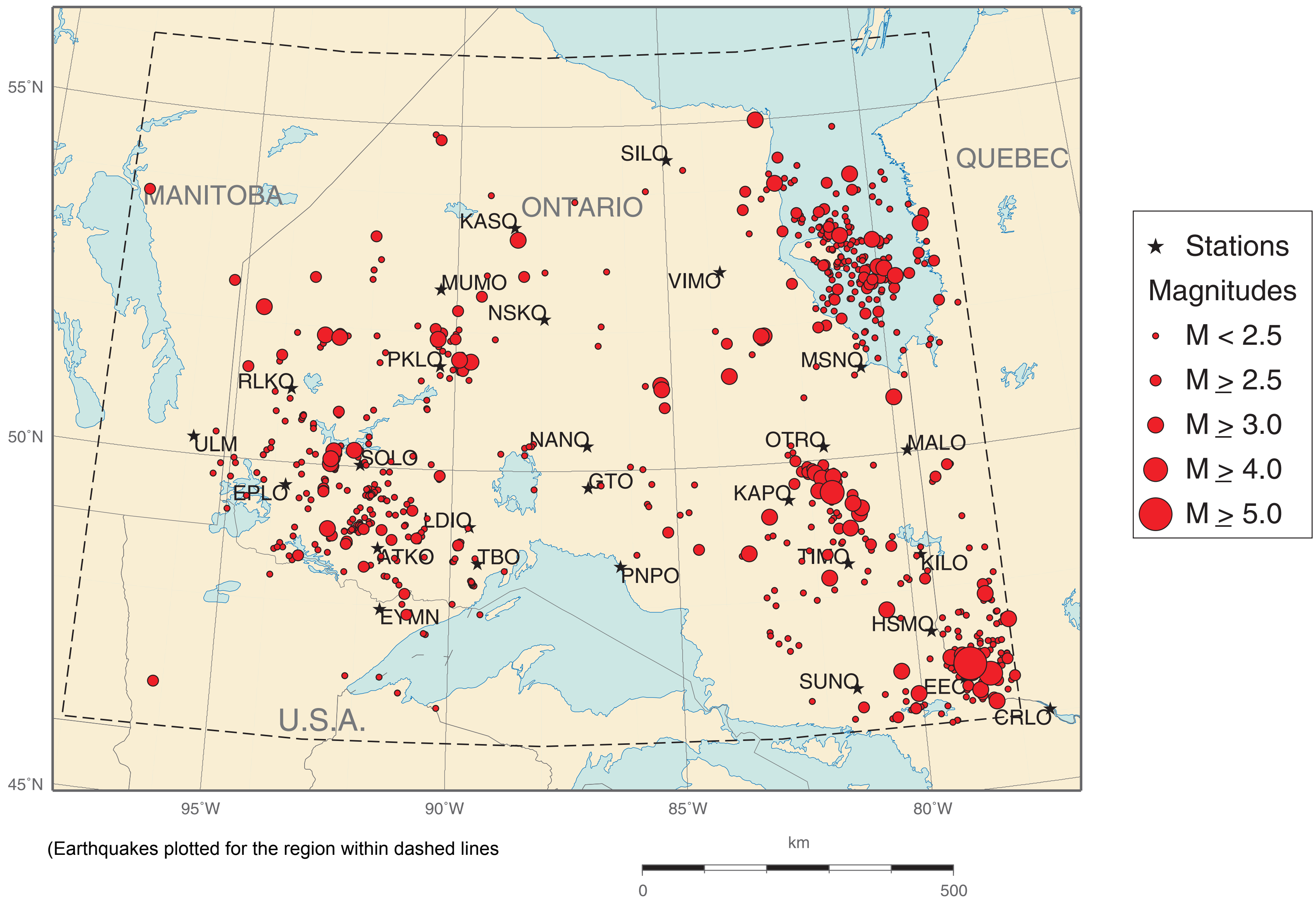
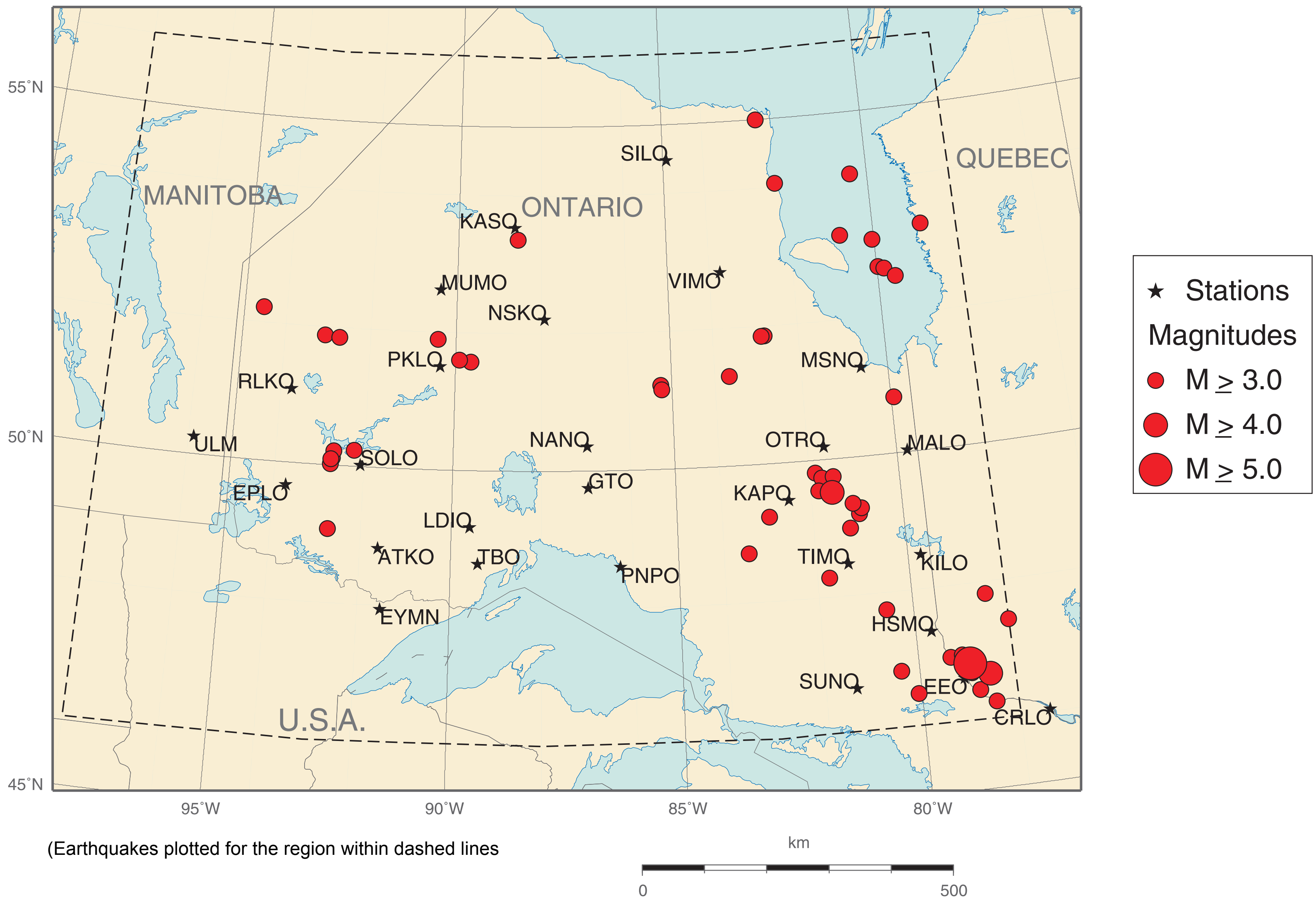


Figure 2: Earthquakes in Northern Ontario and Adjacent Areas, 1982 -



(Earthquakes plotted for the region within dashed lines

Figure 3: Earthquakes M>3 in Northern Ontario and Adjacent Areas, 1982

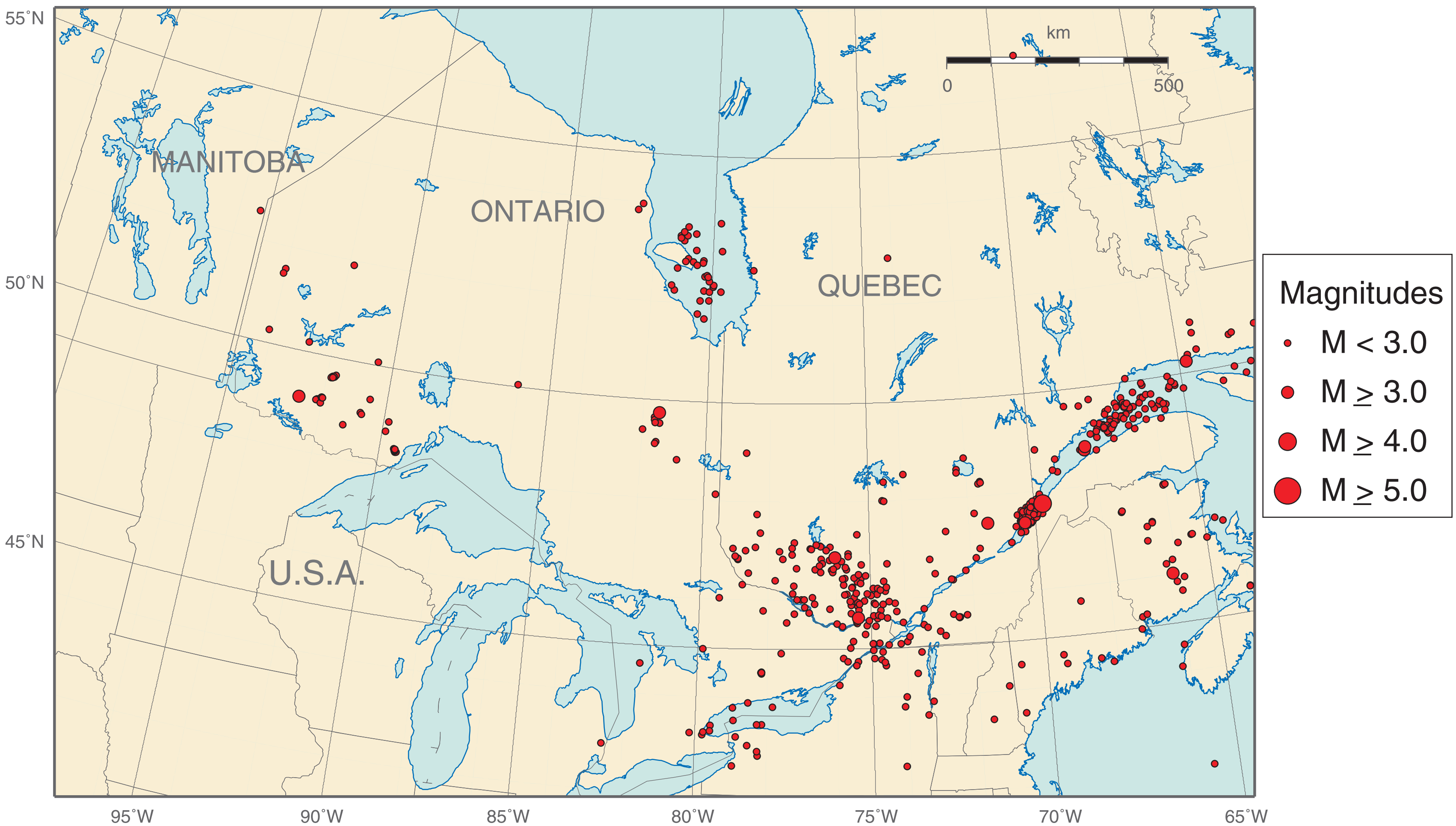


Figure 4: Earthquakes in Eastern Canada, 2008

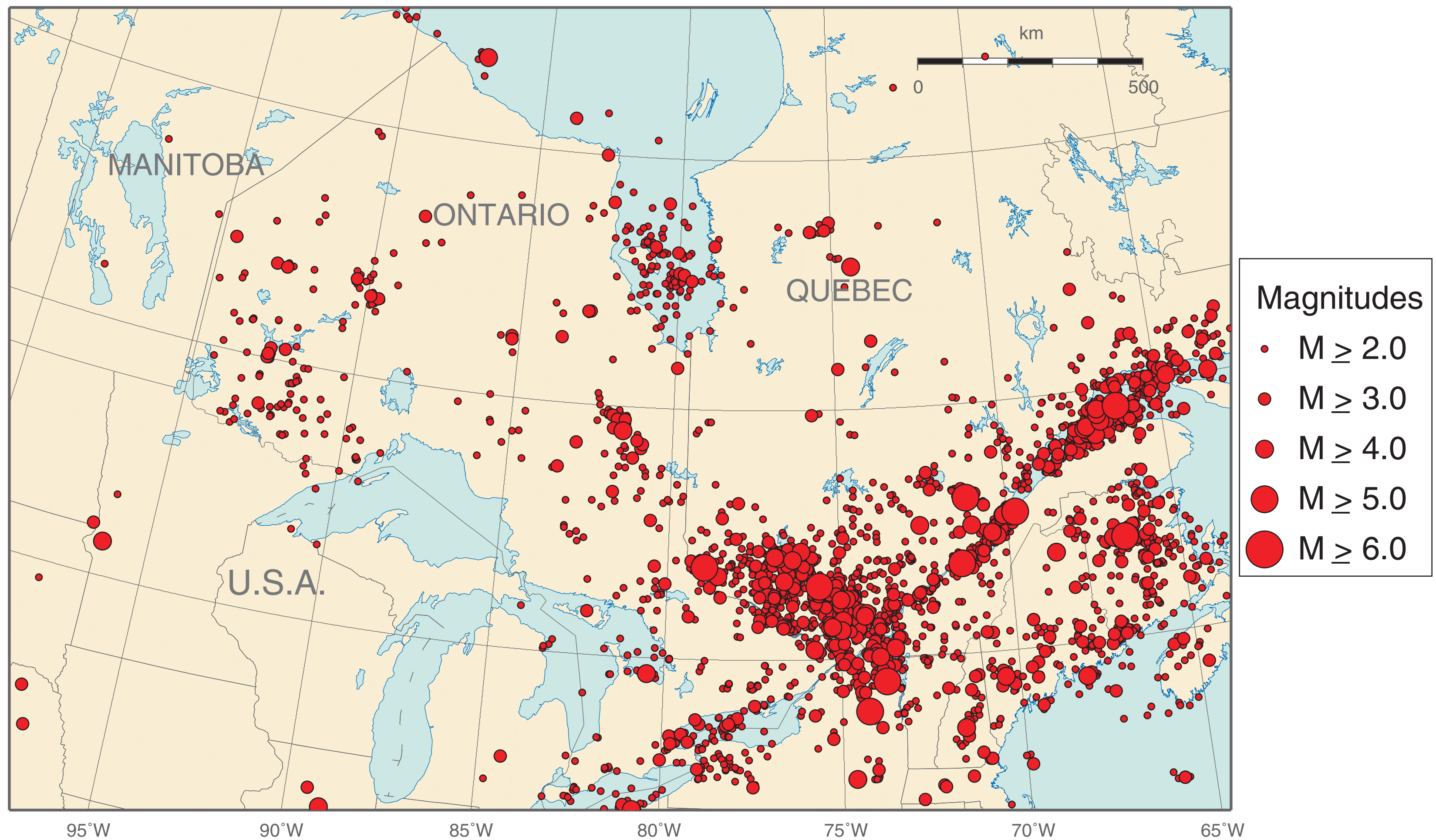


Figure 5: Earthquakes in Eastern Canada, 1982 - 2008

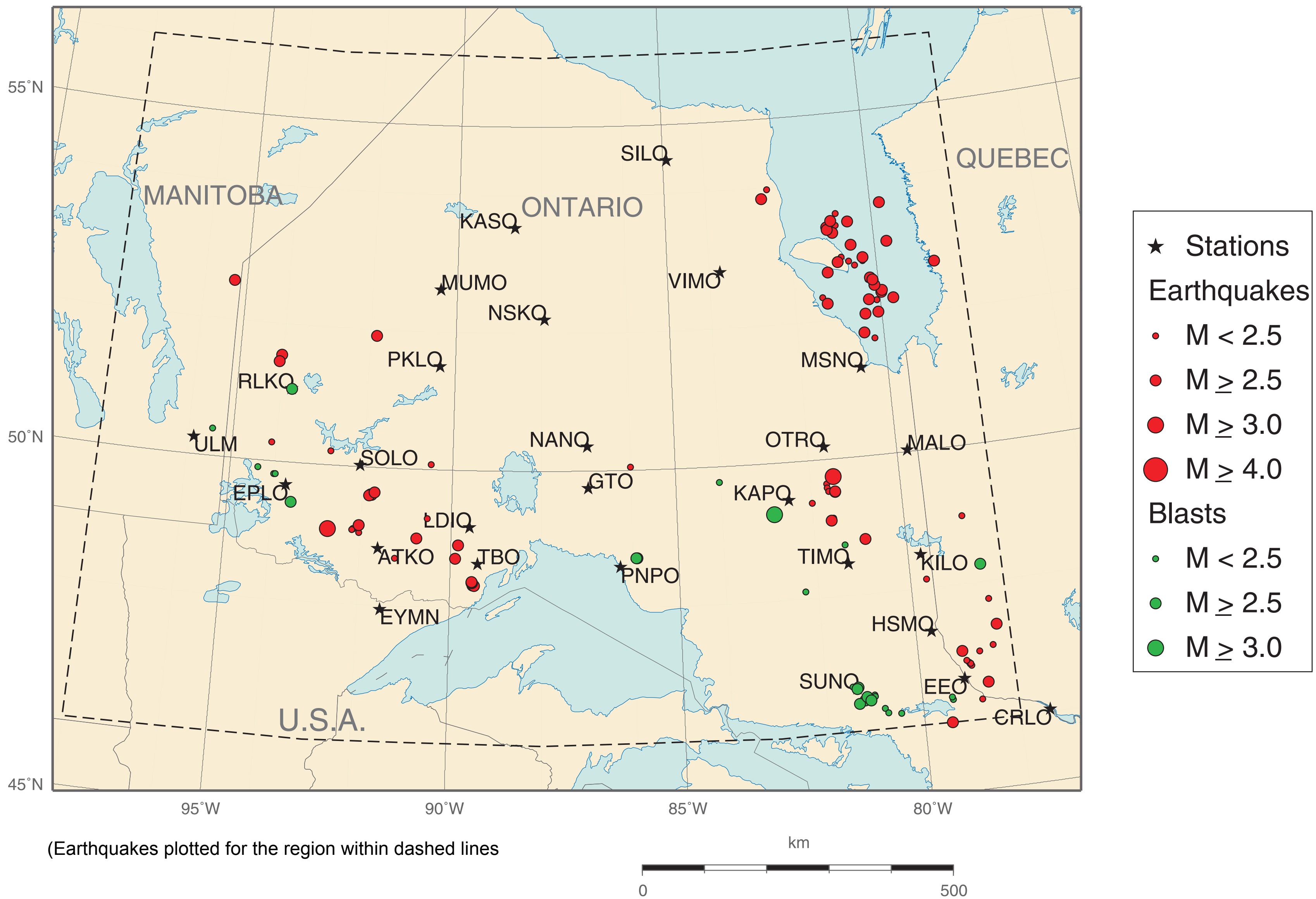


Figure 6: Earthquakes and Blasts in Northern Ontario and Adjacent

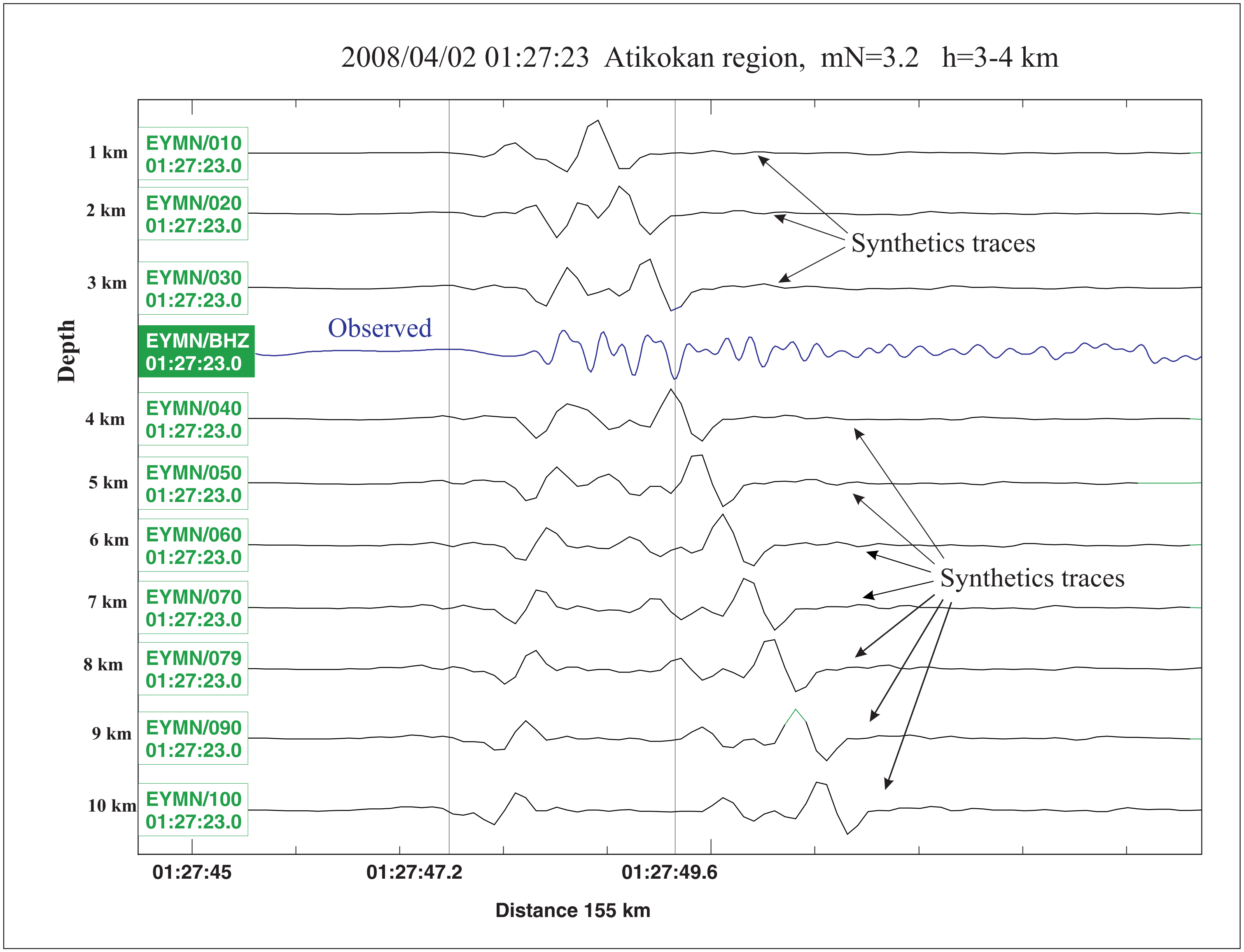


Figure 7: Observed and Synthetic Waveforms from the m_N 3.2 on 2008/04/02 in the Atkikokan Region of Ontario

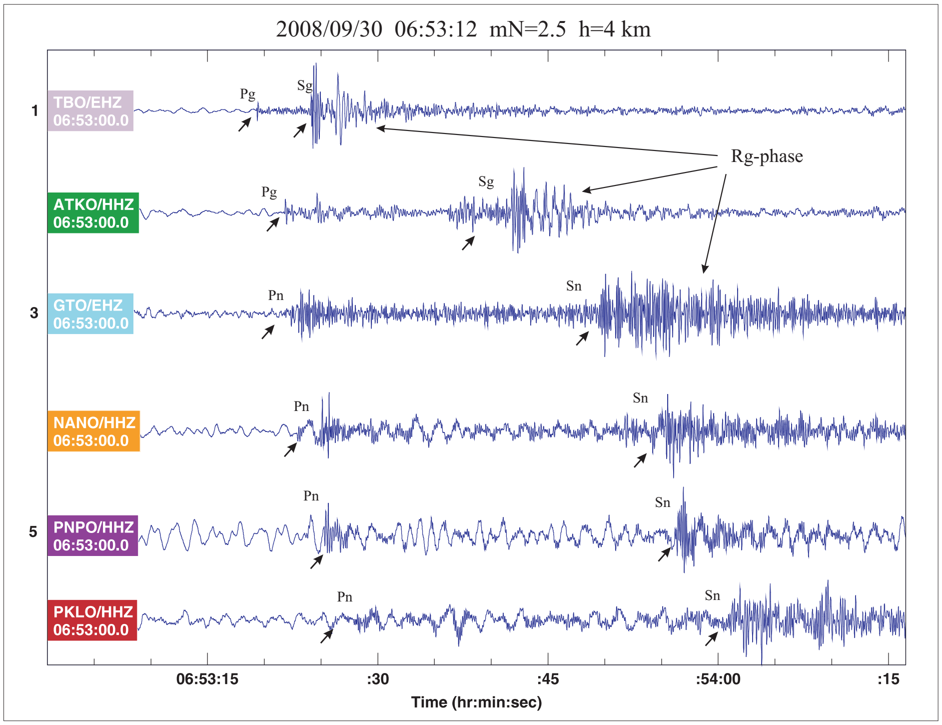


Figure 8: Rg Surface Waves from the mN 2.5 on 208/09/30 NW of Thunder Bay, ON

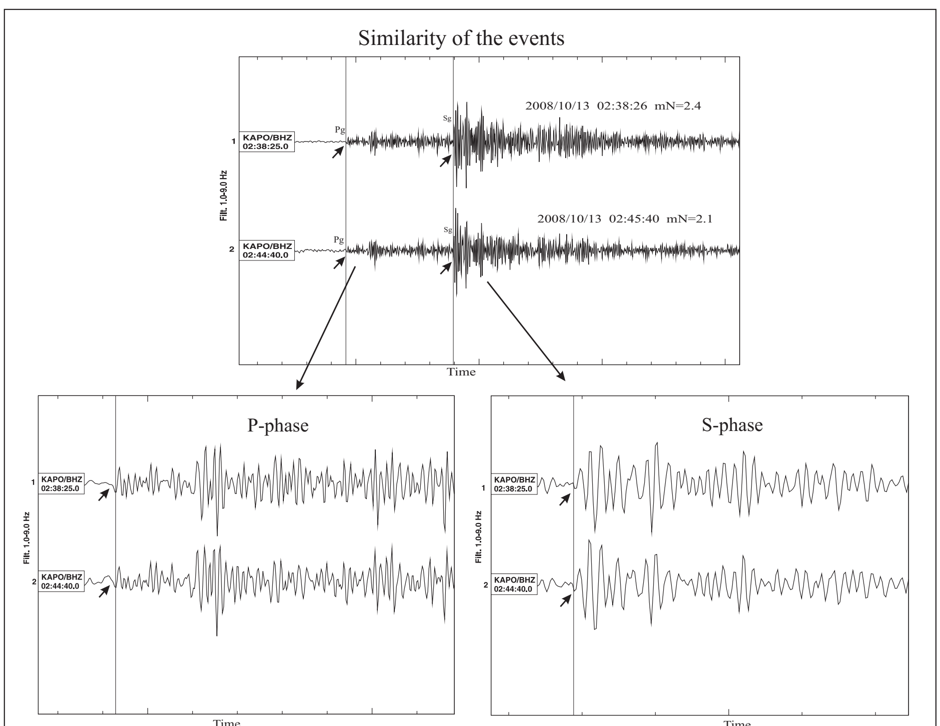


Figure 9: Comparison of two October 13th events in the Cochrane-Kapuskasing region

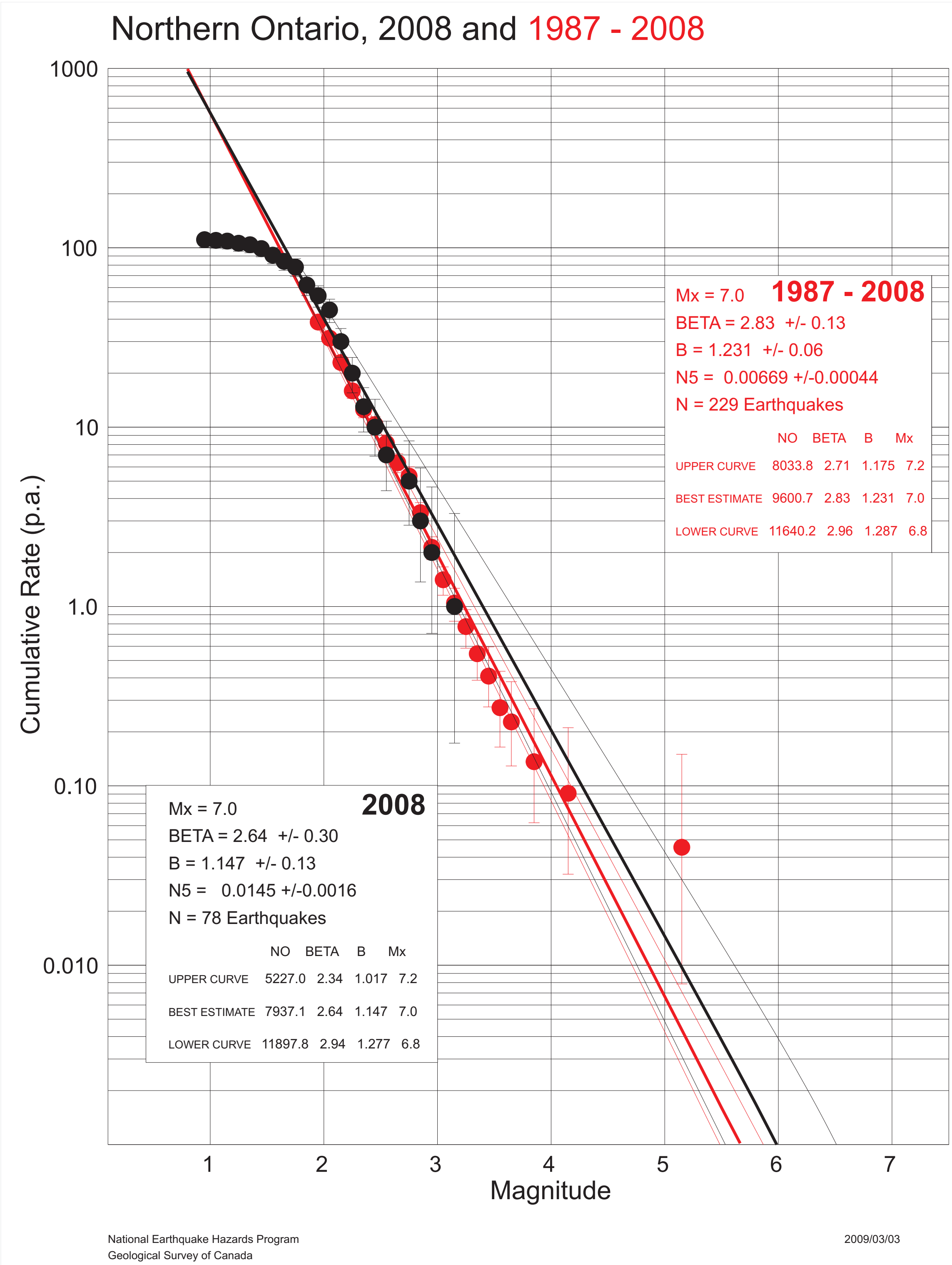


Figure 10: Recurrence Curves for Northern Ontario