SEISMIC ACTIVITY IN NORTHERN ONTARIO PORTION OF THE CANADIAN SHIELD: ANNUAL PROGRESS REPORT FOR THE PERIOD JANUARY 01 - DECEMBER 31, 2006

NWMO TR-2007-02 October 2007

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ABSTRACT

Title: **SEISMIC ACTIVITY IN NORTHERN ONTARIO PORTION OF THE CANADIAN SHIELD - ANNUAL PROGRESS REPORT FOR THE PERIOD JANUARY 01 - DECEMBER 31, 2006**
Report No.: **NWMO TR-2007-02**
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Company: Canadian Hazards Information Service, Geological Survey of Canada
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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 2006.

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 2006.

During this twelve-month period 83 earthquakes were located. Their magnitude (m_N) ranged from 1.2 to 4.2. The largest of these events included a m_N 3.7, a m_N 3.4 and a m_N 4.2 in the Cochrane-Kapuskasing region of Ontario. There was also a m_N 4.1 seismic event in the Sudbury region, but this has been associated with mining activity. The most westerly event in the area being studied was a m_N 2.2 event located near Kenora, ON. The 83 events located in 2006 compares with 103 events in 2005, 79 events in 2004, 45 located events in 2003 and 45 again in 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 2006.

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 monitored 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 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 will happen in the future and are of engineering design interest.

During this twelve-month period 83 earthquakes were located. Their magnitude (m_N) ranged from 1.2 to 4.2. The largest of these events included a m_N 3.7, a m_N 3.4 and a m_N 4.2 in the Cochrane-Kapuskasing region of Ontario (see Figure 1).

The CNSN is able to locate all earthquakes of magnitude 3.5 and above, even in the sparsely populated areas of northern Ontario. 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 2006 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 2006 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 (CNSN). 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 in the National Seismology Data Centre. At the time of writing this report, approximately 3900 earthquakes were located in Canada in the year 2006. Only 33 of these occurred in northern Ontario and were over magnitude 2.

2.2 STATION OPERATION

Station operation statistics for ULM, VIMO, SOLO, TBO, GTO, KAPO, EEO, CRLO, MUMO, SILO, 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 each of the core seismograph station except GTO, and in excess of 92% for all POLARIS stations, including VIMO, except RLKO, KASO, NSKO and MSNO. GTO availability was low due to failure of the GPS antenna late in the year, which needed to be replaced. Many of the solar powered sites, particularly the more northern ones like SILO, OTRO, KASO, NSKO and

MSNO, as well as SUNO and EPLO, experienced power failure and had poor telecommunications during January and December. KASO, NSKO and MSNO had difficulty recovering from the power loss and were down until April or May. KASO and NSKO continued to have problems later in the year as well. RLKO went down in July due to equipment failure and NANO dropped out in September as a result of vandalism. Both stations were serviced in October and have been working well since that time.

3. EARTHQUAKES

3.1 SEISMICITY IN THE NORTHERN ONTARIO REGION

A total of 83 earthquakes were located in the study area during 2006, compared to 103 in 2005, 79 in 2004, 45 in 2003, and another 45 in 2002. 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.

The events from 2006 are listed in Table 1 and plotted in Figure 1. The earthquake epicentres generally conform to areas of past seismicity. A m_N 1.8 event, located approximately 190 km north-west of Pickle Lake, ON in the western part of the province, occurred in an area where events have not been previously recorded. However, it would not have been possible to locate such a small magnitude event in past years in this area without the additional FedNor stations.

The largest event located this year, was the m_N 4.2, which occurred on December 7th in the Cochrane-Kapuskasing region of Ontario. There was also a m_N 3.7 on January 3rd and a m_N 3.4 on March 4th in the same general region. This small region has experienced earthquakes in the past, with almost 60 events located here since 1982. Twelve of those events were located in 2005, and another 10 in 2006. However, only 10 of the 60 events since 1982 have been felt. The largest known events in this region include a magnitude 5 event in December of 1928, located approximately 90 km S of Moose River, ON, and a magnitude 4.4 event on November 1944 located in the region of Iroquois Falls, ON (see Section 3.2 for further discussion).

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 2.5 or even better in many areas. The effects of this can be seen particularly in the James Bay region where 102 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 (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 likely go up again towards the pre-2003 level. Some stations can be removed with little effect to the current threshold as the stations 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, an analysis is required as to whether more low-level data is required or whether the 2003 threshold level was adequate. And whether a lower threshold is required over the whole study area, or whether a more focussed approach may be used.

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).

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 691 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 25 years (57 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 1982.

Figure 4 illustrates the seismic activity in eastern Canada in year 2006. 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 - 2006. 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 2006 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).

The Cochrane-Kapuskasing region was fairly active in 2006 with 6 events, including two large felt events with magnitudes of 4.2 and 3.4. Figure 7 shows a plot of all known earthquakes in the region since 1928. Note that the older events are less accurately located due to the limited number of stations in the region in the past, and some events are based solely on felt reports (see section 3.2 below). The actual and synthetic waveforms from the station at Moosonee, ON are shown for the 4.2 earthquake in Figure 8. These waveforms were used to determine the depth of this event.

Figure 9 shows an earthquake near Red Lake, ON which exhibited strong Rg-phases. The presence of this phase can be used to determine that the depth of the event must have been shallow: less than 5 km in depth.

Recurrence curves for the Northern Ontario area for the year 2006 are compared to the curve from 1987 to the end of 2006 (20 years of data) in Figure 10 and discussed in more detail in section 6 and Appendix A.

Another seismic event, the magnitude 4.1 in Sudbury, ON, turned out to be a rockburst in the Creighton Mine. This is one of the largest rockbursts to have occurred within Canada, and probably the largest to have occurred in the Sudbury region. With the additional POLARIS stations in place, it provided lots of near-field data (less than 1 km from epicentre) for a large event (see Figures 11 and 12).

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 2006 is included in Appendix B. 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.

3.2 SEISMICITY IN THE COCHRANE-KAPUSKASING REGION

A map with the earthquakes located in the Cochrane-Kapuskasing area before 1982 (yellow) and after 1982 (red) are shown in Figure 7. (See Table 5 for list of events.) Only 10 seismic events were located in this region prior to 1982, one of which is the first, and largest, known earthquake from this region: magnitude 5.0 in 1928. The time, location and magnitude of this event are all estimated from a Toronto Star Weekly (December 1, 1928) article, which reported that “earth tremors so violent as to rock camp buildings and toss bushmen from their bunks occurred last evening in the vicinity of Island Falls.” The event was not recorded by any of the seismographs in operation at the time; most of the network was set up to record distant earthquakes and may have filtered out the more high frequencies of a local earthquake. The teleseismic signal from a distant earthquake, which possibly occurred at the same time, may have further obscured any signal of the local earthquake.

Only one other earthquake for this region is based only on felt reports, and that was a magnitude 2.3 event in 1956 near Kapuskasing that was reportedly felt over only a 10 mile radius. All the other events listed are based on seismograph records, with more than one station recording the event.

Since 1982 a further 60 events have been located, 9 of which were reported felt. The dramatic increase in number of located events is directly related to the number and quality of stations that are now in operation in northern Ontario. The largest event recorded in this region since 1982 was the m_N 4.2 recorded this past year on December 7. The smallest event recorded in the region was a m_N 1.3, which was only possible to locate because it occurred during the middle of the night when all was quiet, and with the additional FedNor stations in place.

It had been suggested in the early 1980s that this region may be an extension of the Western Quebec Seismic Zone (1983 Forsyth, et al.), a hypothesis supported by the number of felt events (i.e. m_N 3 and 4) relative to the rest of northern Ontario that have been recorded.

Recently-acquired information shows that the earthquake cluster is elongated in the NW-SE direction and that eight of the earthquakes are relatively deep (8-15 km by the RPDM method; Ma, 2004), significantly deeper than most of the earthquakes to the south and west. The five 2006 events in the cluster ranged from 6-17 km in depth. The elongation and greater depth suggest a tectonic relationship to crustal-scale faults, though whether those faults are related to the hotspot that passed under the region about 130 million years ago, or to an extension of the Ottawa-Bonnechere graben from the north end of Lake Timiskaming, is not yet known. More speculatively, such clusters of contemporary earthquakes may represent on-going aftershocks to large prehistoric earthquakes, in which case the clusters should probably be considered as potential seismic sources that could produce large earthquakes.

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. Distance 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 2006 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. As Ma says, "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 8 shows an example of 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 2006 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 eleven events for which a reliable depth was determined using the RDPM method.

4.2.2 Velocity Models

The present velocity model for determining earthquake epicentres in northern Ontario is the standard model of 36 km thick crust for the Canadian Shield. This model uses the following seismic velocities:

Pg 6.2 km/s	(crustal)
Pn 8.2 km/s	(direct longitudinal wave that has passed below the continental layers)
Sn 4.7 km/s	(direct transverse wave that has passed below the continental layers)
Sg 3.57 km/s	(crustal)
Crustal thickness	36 km

A Lithoprobe seismic experiment carried out throughout northern Ontario in the summer of 1996 yielded a suite of small magnitude 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 effects 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 decrease 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(cumulative frequency) - magnitude plot. To establish the most reliable recurrence curve it is necessary to include earthquakes for the longest period of time possible. As the quality of the network has improved with time, the detection threshold has dropped. Therefore to establish the recurrence curve for northern Ontario we considered that the data set for M>2 was complete since 2004, but that the dataset for M>3 was complete since 1987, thereby giving an additional 17 years of data for the less-common larger earthquakes (see Appendix A).

Figure 10 shows the magnitude-recurrence plots for the year 2006 earthquakes (in red) compared to the 20-year period of 1987 to 2006 inclusive (in black). The standard statistics for the curve fits are given in the boxes. For each dataset the heavy line represents the best fit curve, while the thin dashed lines represent the error bounds. The best fit slope of 2.48 +/- 0.23 for the year 2006 data was fixed to the slope derived for the 3 year period of 2004-2006 (see Appendix A). A single year's worth of data is not considered long enough to generate a statistically-significant curve. The slopes derived from the 3-year and 20-year periods differ slightly, but the difference is not significant. In fact, the error bounds for the 3-year period encompasses the best fit slope for the 20-year period. Furthermore, the cumulative rate of magnitude 2.0 and larger earthquakes recorded for 2006 is not significantly different than the 3-year average. The data does indicate that for 2006 there were more than the 20-year average number of magnitude 3 and 4 events in the region, as can be seen by the three data points above the curves in the magnitude 3 to 4 range. That is because the average rates of occurrence of these events is less than 1 per year, so the 2006 data plots above the line.

The monitoring is believed to be complete to magnitude 2.0 from the year 2004 onwards. That is, all the earthquakes of magnitude 2.0 or larger in the region since 2004 have been located, although events smaller than magnitude 2.0 have likely been missed. This is why at the smallest located magnitude (1.2), the data falls significantly below the calculated curve - only one quarter of the magnitude 1.2 events expected over the year have been located.

Figures in Appendix B show the data for the individual years 2002 through 2006 superimposed on the best-fit slope derived from the 2004-2006 data. No events below magnitude 1 were located in the northern Ontario region prior to 2004 and the 2002 data in particular shows that the dataset is not complete below magnitude 2.0. Additionally, the individual data sets for the years 2004, 2005, and 2006 have been superimposed on each other and the 3-year average.

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 107 mining-induced seismic events of magnitude -0.3 or greater in the study area in 2006. Forty-nine of these events occurred in the Sudbury Basin, including a m_N 4.1 on November 29th that had several aftershocks, one of which was a m_N 3.1 which occurred 16 minutes after the main shock. Twenty mining related events were located in the Red Lake region, 2 near Marathon, 7 at Kirkland Lake, 28 in Cadillac Quebec and one event at Lac-des-Iles mine 90 km N of Thunder Bay. A total of 7 mining-induced events larger than m_N 2.5 were recorded in the study area in 2006 and are listed in Table 4.

The m_N 4.1 seismic event in Sudbury is the largest known mining related event to have occurred within Canada. It was widely felt throughout Sudbury and the neighbouring regions, and had numerous aftershocks (see Figure 11). Previously, a m_N 4.0, also in the Sudbury region, had been recorded on July 1984. However, it was the three preceding m_N 3 events – 3.4, 3.5 and 3.3 respectively – on June 20, 1984 that claimed the lives of four miners (Cajka, 1984).

Using the Regional Depth Phase Modelling (RDPM) method, an average focal depth of 2.5 km (± 2km) was found using four seismic stations (EEO, BUKO, SADO and CRLO) for the main event (see Figure 12) and the m_N 3.1 aftershock. The main event was confirmed to be located in the hanging wall of the Creighton mine, at a level of 7263 ft, or 2214 m (pers. comm. Steve Audette, Creighton mine Ground Control) just outside the workings of the mine. The events were located with the mine's seismic system, and the aftershocks were confirmed to be located within 50-100 m of the main shock. Some of the aftershocks fell directly within the confines of the mine. This seismic event with a well constrained depth provided good ground truth for the depth found using the Regional Depth Phase Method.

Details of this seismic event and the related aftershocks can be found in a paper by Gail Atkinson that is currently in preparation (Atkinson, 2007).

8. SUMMARY

Data capture was in excess of 96% from each of the core seismograph station (except GTO), and exceeded 92% for most of the POLARIS type installations (except for RLKO, KASO, NSKO and MSNO). GTO lost timing in October and needed to have the GPS antenna and cable replaced. 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. However, it is uncertain why the stations KASO, NSKO and MSNO had such low uptimes. Due to their remote location, it was not possible to have them serviced in 2006. RLKO went down due to equipment failure in July, but has been working well since it was serviced in October.

The seismic activity in the study area during the calendar year 2006 consisted of 83 earthquakes ranging in magnitude from 1.2 to 4.2. Thirty-three earthquakes were larger than m_N 2.0, and three of the earthquakes were m_N 3.0 or larger. Those three largest events were located in the Cochrane-Kapuskasing region, and were magnitude 4.2, 3.7 and 3.4. 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 2006 conformed to the pattern of previous seismicity, with the exception of a small magnitude 1.7 event 188 km north-west of Pickle Lake, ON.

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Table 1: Located Local Earthquakes, January - December 2006

Date mm/dd	Time(UTC) hh:mm:ss	Lat (°N)	Long (°W)	#station/ phases	Mag	Region and Comment
01/03	11:05:10	49.33N	81.08W	26/38	3.7 m_N	29 km N from Cochrane, ON. Felt.
01/29	10:36:33	49.19N	91.76W	4/ 8	1.3 m_N	50 km NW from Atikokan, ON
01/29	20:21:59	49.17N	91.82W	6/11	2.1 m_N	50 km N from Atikokan, ON
02/03	03:43:26	50.36N	88.23W	3/ 6	1.5 m_N	87 km E from Collins, ON
02/14	04:03:03	46.76N	79.09W	10/19	1.9 m_N	Temiscaming, QC
02/14	04:27:45	46.36N	79.09W	11/20	2.0 m_N	28 km E from North Bay, ON
02/17	00:25:19	51.53N	79.08W	6/10	1.4 m_N	James Bay region.
02/22	07:46:42	49.53N	81.54W	6/10	1.9 m_N	65 km E from Kapuskasing, ON
02/25	16:00:32	48.60N	79.71W	6/11	1.5 m_N	47 km SW from La Sarre, QC
03/04	02:13:10	49.51N	81.54W	10/15	3.4 m_N	65 km E of Kapuskasing, ON. Felt.
03/04	18:20:03	46.86N	78.86W	10/19	2.9 m_N	21 km NE from Temiscaming, QC
03/08	01:38:26	47.54N	78.25W	6/11	2.2 m_N	63 km S from Malartic, QC
03/09	10:55:39	52.85N	80.40W	5/ 8	1.5 m_N	James Bay.
03/23	19:25:10	53.52N	79.54W	7/10	1.8 m_N	James Bay.
04/01	23:20:46	52.58N	80.33W	27/45	2.7 m_N	James Bay.
04/01	23:32:35	52.45N	80.34W	10/17	2.1 m_N	James Bay. Aftershock.
04/08	10:29:54	54.32N	84.51W	3/ 5	1.9 m_N	85 km N of Attawapiskat Indian Reserve.
04/13	23:57:10	52.87N	81.41W	5/ 8	1.8 m_N	James Bay.
04/27	12:00:29	53.35N	82.99W	4/ 6	1.3 m_N	60 km NW from Attawapiskat, ON
05/01	00:59:02	54.08N	81.77W	6/10	1.9 m_N	James Bay.
05/20	17:29:39	49.22N	81.47W	6/10	2.1 m_N	37 km NW from Cochrane, ON
05/22	07:42:19	49.15N	92.02W	6/11	1.8 m_N	53 km NW from Atikokan, ON
05/22	10:14:02	48.16N	82.96W	6/ 9	1.9 m_N	52 km NE from Chapleau, ON
06/05	17:44:23	49.85N	82.05W	7/12	2.5 m_N	55 km NE from Kapuskasing, ON
06/13	21:38:51	49.15N	92.09W	5/ 8	1.7 m_N	56 km NW from Atikokan, ON
06/24	12:29:37	51.21N	85.61W	9/14	2.1 m_N	190 km NE from Geraldton, ON
07/10	11:31:00	53.10N	80.29W	4/ 7	1.9 m_N	James Bay.
07/13	10:53:35	53.31N	80.93W	9/15	2.0 m_N	James Bay.
07/14	08:40:21	53.14N	81.22W	4/ 8	1.7 m_N	James Bay.
07/26	07:37:11	52.72N	92.02W	5/ 8	1.7 m_N	188 km NW of Pickle Lake, ON
08/06	01:32:54	52.48N	79.70W	4/ 6	1.3 m_N	James Bay.
08/06	22:47:20	52.52N	80.45W	3/ 6	1.6 m_N	James Bay.
08/08	11:57:39	52.91N	80.83W	3/ 5	1.7 m_N	James Bay.
08/16	09:11:36	49.32N	91.25W	8/14	1.5 m_N	69 km NE from Atikokan, ON
08/18	08:34:34	49.02N	90.65W	4/ 8	1.5 m_N	80 km NE from Atikokan, ON
08/20	09:25:05	49.94N	91.42W	13/24	2.3 m_N	43 km E from Sioux Lookout, ON
08/22	01:32:19	52.17N	81.35W	6/ 9	1.8 m_N	James Bay.
08/23	22:57:41	49.01N	90.94W	7/13	1.8 m_N	57 km NE from Atikokan, ON
08/28	01:15:07	53.59N	81.26W	6/ 9	2.7 m_N	James Bay.
08/28	14:49:29	53.02N	80.66W	3/ 5	1.7 m_N	James Bay.
08/31	09:28:32	51.11N	79.64W	8/13	2.1 m_N	70 km E from Moose Factory, ON
09/04	14:41:31	50.56N	93.20W	4/ 6	1.8 m_N	70 km SE from Red Lake, ON
09/09	11:39:39	48.95N	82.91W	5/ 9	1.8 m_N	65 km SW from Kapuskasing, ON
09/10	23:21:01	50.58N	93.20W	4/ 7	1.6 m_N	66 km SE from Red Lake, ON
09/13	21:24:39	49.65N	92.87W	13/24	2.5 m_N	14 km S from Dryden, ON
09/14	22:59:15	50.51N	93.18W	4/ 5	1.6 m_N	57 km SE from Red Lake, ON
09/16	10:56:42	49.59N	92.87W	7/12	1.7 m_N	20 km S from Dryden, ON
09/16	23:03:06	51.36N	81.65W	3/ 5	1.7 m_N	65 km W from Moosonee, ON
09/28	07:20:32	53.98N	82.06W	3/ 6	1.4 m_N	James Bay.

10/05	**16:33:49**	**49.59N**	**91.93W**	**5/ 9**	**2.1 m_N**	**53 km S from Sioux Lookout, ON**
10/05	**16:38:19**	**49.63N**	**91.85W**	**4/ 8**	**1.7 m_N**	**50 km S from Sioux Lookout, ON**
10/06	**12:53:05**	**52.13N**	**81.11W**	**4/ 7**	**1.9 m_N**	**James Bay.**
10/09	**09:36:54**	**52.76N**	**80.94W**	**9/16**	**2.1 m_N**	**James Bay.**
10/09	**17:41:24**	**50.77N**	**92.63W**	**8/13**	**2.4 m_N**	**85 km E from Red Lake, ON**
10/14	**18:11:58**	**48.54N**	**88.82W**	**8/14**	**2.4 m_N**	**11 km E from Mackenzie, ON**
10/15	**19:08:39**	**49.16N**	**91.04W**	**9/15**	**1.9 m_N**	**65 km NE from Atikokan, ON**
10/17	**23:05:05**	**47.38N**	**79.31W**	**11/19**	**2.1 m_N**	**Lorrainville, QC. Felt**
10/19	**21:58:24**	**49.61N**	**92.87W**	**9/15**	**2.5 m_N**	**18 km S from Dryden, ON**
10/19	**22:15:34**	**49.61N**	**92.86W**	**10/15**	**2.8 m_N**	**20 km S from Dryden, ON**
10/19	**23:07:40**	**51.01N**	**94.12W**	**5/ 9**	**1.9 m_N**	**30 km W from Red Lake, ON**
10/21	**06:52:08**	**49.67N**	**91.91W**	**5/ 8**	**1.3 m_N**	**44 km S from Sioux Lookout, ON**
10/21	**12:35:12**	**50.78N**	**92.63W**	**10/16**	**2.7 m_N**	**85 km E from Red Lake, ON**
10/21	**21:05:10**	**50.73N**	**92.63W**	**5/ 9**	**1.5 m_N**	**86 km SE from Red Lake, ON**
10/24	**06:46:41**	**50.29N**	**92.54W**	**6/12**	**1.7 m_N**	**47 km NW of Sioux Lookout, ON**
10/25	**20:13:05**	**49.81N**	**94.39W**	**6/12**	**2.2 m_N**	**4 km E from Kenora, ON**
10/28	**14:55:39**	**51.67N**	**89.86W**	**4/ 7**	**2.0 m_N**	**34 km NE from Pickle Lake, ON**
10/30	**23:46:41**	**49.72N**	**94.22W**	**4/ 8**	**1.6 m_N**	**20 km SE from Kenora, ON**
11/02	**14:45:17**	**49.06N**	**92.35W**	**7/12**	**2.0 m_N**	**64 km NW from Atikokan, ON**
11/07	**02:12:13**	**52.91N**	**81.48W**	**4/ 7**	**2.2 m_N**	**James Bay.**
11/23	**12:44:46**	**49.84N**	**93.39W**	**3/ 6**	**1.3 m_N**	**40 km W from Dryden, ON**
11/26	**03:04:03**	**49.97N**	**93.51W**	**5/ 8**	**1.5 m_N**	**53 km NW from Dryden, ON**
11/28	**03:53:23**	**47.73N**	**78.49W**	**5/10**	**1.6 m_N**	**52 km SW from Malartic, QC**
12/01	**22:55:15**	**48.55N**	**82.32W**	**4/ 8**	**1.8 m_N**	**70 km W from Timmins, ON**
12/05	**23:20:19**	**52.46N**	**81.18W**	**10/16**	**2.2 m_N**	**James Bay.**
12/06	**20:24:17**	**49.79N**	**85.54W**	**4/ 7**	**1.9 m_N**	**71 km E from Longlac, ON**
12/06	**21:25:26**	**49.38N**	**91.81W**	**5/10**	**2.0 m_N**	**72 km N from Atikokan, ON**
12/07	**04:44:59**	**49.51N**	**81.53W**	**10/15**	**4.2 m_N**	**62 km NW of Cochrane, ON. Felt.**
12/07	**04:59:09**	**49.52N**	**81.55W**	**6/11**	**2.6 m_N**	**63 km NW from Cochrane, ON.**
12/14	**09:58:25**	**50.11N**	**82.45W**	**4/ 8**	**1.8 m_N**	**77 km N from Kapuskasing, ON**
12/17	**04:01:53**	**52.81N**	**80.95W**	**4/ 8**	**1.6 m_N**	**James Bay.**
12/26	**17:23:13**	**53.28N**	**81.80W**	**4/ 7**	**2.1 m_N**	**James Bay.**
12/27	**17:51:02**	**52.38N**	**79.64W**	**8/12**	**2.6 m_N**	**James Bay.**
12/30	**00:43:22**	**48.49N**	**78.31W**	**3/ 5**	**1.2 m_N**	**20 km SW from Amos, QC**

Table 2: NWMO Supported Stations Operating During 2006
(2005 figures given in brackets)

Station	Lat (°N)	Long (°W)	Elev (m)	Uptime (%) 2006 (2005)	Operation dates of digital stations
ULM Pinawa	50.2503	95.8750	251	98.9 (99.3)	19941207-
SOLO Sioux Lookout	50.0213	92.0812	373	99.7 (98.6)	19981104-
TBO Thunder Bay	48.6473	89.4083	468	96.8 (96.0)	19931005-
GTO Geraldton	49.7455	86.9610	350	91.2(100.0)	20010104-
KAPO Kapuskasing	49.4504	82.5079	210	98.4 (99.8)	19980114-
EEO Eldee	46.6411	79.0733	398	95.7 (99.8)	19931005-
CRLO Chalk River	46.0375	77.3801	168	99.4 (99.6)	19941117-
MUMO Musselwhite Mine	52.6128	90.3914	316	99.7 (99.9)	20030615-
SILO Sutton Inlier	54.4791	84.9126	195	96.3 (99.8)	20030609-
VIMO Victor Mine	52.8173	83.7449	78	99.8 (94.0)	20030611-
OTRO Otter Rapids	50.1818	81.6286	109	95.1 (92.6)	20030618-
MALO McAlpine Lake	50.0244	79.7635	271	99.8 (99.9)	20030620-
KILO Kirkland Lake	48.4972	79.7232	314	99.8 (99.9)	20030622-
SUNO Sudbury	46.6438	81.3442	343	95.9 (99.6)	20030623-
RLKO Red Lake	51.0704	93.7585	362	73.2 (87.0)	20041119-
EPLO Experimental Lake	49.6737	93.7258	437	98.6 (99.9)	20040611-
ATKO Atikokan	48.8231	91.6004	383	99.7 (99.8)	20040609-
PKLO Pickle Lake	51.4987	90.3522	376	99.7 (99.8)	20040615-
LDIO Lac des Iles Mine	49.1750	89.5955	500	99.5 (99.8)	20040616-
PNPO Pukaskwa Nat. Park	48.5957	86.2846	219	99.5 (99.7)	20040618-
KASO Kasabonika Lake	53.5279	88.6414	192	74.6 (96.8)	20050803-
NSKO Neskantaga	52.1965	87.9305	241	61.8 (97.2)	20050729-
NANO Aroland	50.3543	86.9684	309	91.6 (99.4)	20050804-
MSNO Moosonee	51.2913	80.6151	15	62.3 (98.0)	20050723-
TIMO Timmins	48.4659	81.3032	392	100.0 (98.8)	20050725-
HSMO Haileybury	47.3708	79.6657	306	99.4 (99.5)	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 2006. All times given are in UT (Universal Time).

The following POLARIS and FedNor stations were down during the indicated times in January due to loss of power at these solar powered sites:

SILO was down from January 10th to 19th;
OTRO started the year down, came back on January 6th, and then was down again from the 12th to the 21st;
SUNO from January 9th to 23rd;
RLKO from the end of 2005 until January 21st;
EPLO was out from January 13th the 17th;
KASO went down January 5th, and did not recover until the beginning of May;
NSKO went down in January, and did not recover until April 22nd; and
MSNO went down on January 4rth, and recovered only at the end of May.

Almost all POLARIS and FedNor stations had poor telecommunications throughout the months of January and February. Retransmission requests for missed data were issued and data was backfilled to varying degrees.

CRLO was out from April 18 at 20:47 to April 20 at 14:57. The satellite communications service provider replaced the VSAT DIU to restore data flow.

TBO dropped out on May 12 several hours due to a power outage in the area caused by high winds.

A lightning storm and a power surge damaged the VSAT at ULM on May 23rd. Faulty components on the VSAT dish and inside electronics had to be replaced, and power and data flow were restored on May 25th. Lightning caused more power outages on May 28th, but this time only outroute communications were damaged. A few minor outages on May 30th and 31st during the repair of the outroute by satellite service provider.

CRLO and EEO were down on July 18th and 26th intervals due to heavy storms affecting power in the area. CRLO recovered most of the data, but EEO needed a full reset to restore data flow.

RLKO dropped out July 18 due to equipment failure and did not return until October 3rd when the site was serviced and new equipment was installed.

EEO was out from August 2nd to 4th, and again from the 20th to the 28th, due to power outages at the site.

NSKO began experiencing failures again in August. Station never properly recovered for the rest of the year.

ULM dropped out during September 7th to the 9th due to faulty VSAT components. The station was subsequently taken offline for testing in September to trouble shoot outroute communication problems at the Toronto teleport. A faulty card on our splitter was replaced.

TBO dropped out from September 3rd to the 13th due to bad timing. The GPS antenna and cable were replaced to restore data flow.

EEO data were out or intermittent on September 6th and required a replacement window on the VSAT feedhorn.

SILO, KASO and NSKO data were delayed and intermittent during intervals on September 14th to 18th due to communication problems. NSKO was already experiening problems, and KASO also never properly recovered for the rest of the year.

NANO failed on October 5th due to vandalism, and only came back up a month later when it was serviced.

SOLO had outages due to snow on the dish on October 12th for 8 hours, and due to a power outage for 5 hours on October 29th.

EEO also lost 11 hours due to snow on the VSAT dish on October 12th, and had a power outage on the 14th with 14 hours of lost data. Then on the 22nd of October EEO experienced some outroute communications errors, that went on for a day before it got fixed.

GTO data quality was bad from October 19 at 19:42 through to November 20 at 19:28 due to bad timing. The GPS antenna and cable were replaced to restore good timing.

KAPO dropped out from November 18 at 18:42 to November 24 at 16:29. The site required repairs to the power lines to the equipment building. The station dropped out again from December 10 at 05:39 to December 11 at 23:22. The local contact power cycled the site to restore data flow.

In December, the POLARIS and FedNor stations were again suffering from the loss of power to some of the solar powered sites, and from poor telecommunications. In particular, SILO, OTRO and SUNO were down for several days each during the month of December.

Table 3: Depths Derived using Rg-phases and Regional Depth Phase Method for Moderate-sized Events for 2006

Date mm/dd	Time(UTC) hh:mm:ss	Mag (m_N)	Depth (km)	Depth type (Rg/RDPM)	Region and Comment
01/03	11:05:10	3.7	15	RDPM	29 km N from Cochrane, ON. Felt.
01/29	10:36:33	1.3	5	Rg	50 km NW from Atikokan, ON
01/29	20:21:59	2.1	5	Rg	50 km N from Atikokan, ON
03/04	02:13:10	3.4	12.5	RDPM	65 km E from Kapuskasing, ON. Felt.
04/01	23:20:46	2.7	10	RDPM	James Bay.
04/08	10:29:54	1.9	5	Rg	85 km N from Attawapiskat Indian Reserve, ON
04/27	12:00:29	1.3	5	Rg	60 km NW from Attawapiskat, ON
05/22	07:42:19	1.8	5	Rg	53 km NW from Atikokan, ON
06/05	17:44:23	2.5	6	RDPM	55 km NE from Kapuskasing, ON
06/13	21:38:51	1.7	5	Rg	56 km NW from Atikokan, ON
08/16	09:11:36	1.5	5	Rg	69 km NE from Atikokan, ON
08/18	08:34:34	1.5	5	Rg	80 km NE from Atikokan, ON
08/20	09:25:05	2.3	5	Rg	43 km E from Sioux Lookout, ON
08/23	22:57:41	1.8	5	Rg	57 km NE from Atikokan, ON
08/28	01:15:07	2.7	11	RDPM	James Bay.
09/09	11:39:39	1.8	5	Rg	65 km SW from Kapuskasing, ON
09/13	21:24:39	2.5	4	RDPM	14 km S from Dryden, ON
09/16	10:56:42	1.7	5	Rg	20 km S from Dryden, ON
10/05	16:33:49	2.1	5	Rg	53 km S from Sioux Lookout, ON
10/05	16:38:19	1.7	5	Rg	50 km S from Sioux Lookout, ON
10/09	17:41:24	2.4	5	Rg	85 km E from Red Lake, ON
10/14	18:11:58	2.4	5	Rg	11 km E from Mackenzie, ON
10/15	19:08:39	1.9	5	Rg	65 km NE from Atikokan, ON
10/17	23:05:05	2.1	5	Rg	Lorrainville, QC. Felt.
10/19	21:58:24	2.5	5.5	RDPM	18 km S from Dryden, ON
10/19	22:15:34	2.8	5	RDPM	20 km S from Dryden, ON
10/19	23:07:40	1.9	5	Rg	30 km W from Red Lake, ON
10/21	12:35:12	2.7	5	RDPM	85 km E from Red Lake, ON
10/24	06:46:41	1.7	5	Rg	47 km NW from Sioux Lookout, ON
10/25	20:13:05	2.2	5	Rg	4 km E from Kenora, ON
10/28	14:55:39	2.0	5	Rg	34 km NE from Pickle Lake, ON
10/30	23:46:41	1.6	5	Rg	20 km SE from Kenora, ON
11/02	14:45:17	2.0	5	Rg	64 km NW from Atikokan, ON
11/23	12:44:46	1.3	5	Rg	40 km W from Dryden, ON
12/06	20:24:17	1.9	5	Rg	71 km E from Longlac, ON
12/06	21:25:26	2.0	5	Rg	72 km N from Atikokan, ON
12/07	04:44:59	4.2	16	RDPM	62 km NW from Cochrane, ON. Felt.
12/07	04:59:09	2.6	17	RDPM	63 km NW from Cochrane, ON. Aftershock.

Table 4: Mining-Induced Seismic Events m_N 2.5 and Greater, January - December 2006

Date (mm/dd)	Mine	Location	Mag
03/28	**Copper Cliff South**	**Sudbury**	**2.5 m_N**
05/25	**Laronde**	**Val-d'Or**	**2.5 m_N**
05/28	**Fraser Mine**	**Sudbury**	**2.5 m_N**
06/11	**Copper Cliff North**	**Sudbury**	**2.8 m_N**
08/14	**Copper Cliff North**	**Sudbury**	**2.8 m_N**
11/29	**Creighton**	**Sudbury**	**4.1 m_N**
11/29	**Creighton**	**Sudbury**	**3.1 m_N**

Table 5: Earthquakes located in the Cochrane-Kapuskasing Region, 1928 - 2006

Date yyyy/mm/dd	Time(UTC) hh:mm:ss	Lat (°N)	Long (°W)	#station/ phases	Mag	Region and Comment
1928/12/01	00:00:00	50.00N	81.50W	0/ 0	5.0 m_L	90 km S of Moose River, ON. Felt.
1944/11/05	19:07:53	48.72N	80.80W	3/ 6	4.4 m_N	28 km S of Cochrane, ON
1956/12/01	14:00:00	49.42N	82.43W	0/ 0	2.3 m_L	Kapuskasing, ON. Felt.
1969/06/04	09:36:02	49.67N	81.45W	8/12	3.1 m_N	74 km NW from Cochrane, ON
1970/04/13	04:56:53	49.75N	81.88W	4/ 4	2.6 m_N	55 km NE from Kapuskasing, ON
1970/04/25	00:46:27	49.70N	81.22W	6/12	3.1 m_N	72 km N from Cochrane, ON
1978/12/03	22:27:25	49.08N	81.07W	6/14	2.7 m_N	4 km W from Cochrane, ON
1980/04/13	22:40:23	49.59N	81.76W	30/42	4.1 m_N	53 km E of Kapuskasing, ON. Felt.
1980/07/31	10:10:04	49.90N	82.04W	9/12	3.0 m_N	60 km NE from Kapuskasing, ON
1981/05/15	06:30:03	49.71N	81.94W	5/ 6	2.5 m_N	48 km NE from Kapuskasing, ON
1982/10/28	00:05:45	49.85N	82.17W	4/ 7	2.6 m_N	50 KM NE from Kapuskasing, ON
1983/05/28	02:30:28	49.85N	82.03W	3/ 4	2.0 m_N	60 KM NE from Kapuskasing, ON
1983/05/30	13:10:17	50.14N	82.33W	3/ 7	2.4 m_N	80 KM N from Kapuskasing, ON
1983/07/22	02:06:36	49.81N	82.03W	4/ 8	2.5 m_N	50 KM NE from Kapuskasing, ON
1983/08/16	08:20:49	49.69N	82.35W	3/ 5	2.8 m_N	30 KM N from Kapuskasing, ON
1983/09/19	23:52:30	49.83N	81.62W	3/ 5	2.3 m_N	80 KM NE from Kapuskasing, ON
1986/09/25	17:19:48	48.98N	81.19W	5/11	3.1 m_N	17 km SW from Cochrane, ON
1987/06/06	14:24:25	49.04N	82.05W	3/ 4	2.1 m_N	51 km SE from Kapuskasing, ON
1987/12/20	07:52:48	48.66N	80.34W	8/13	2.7 m_N	28 km SE from Iroquois Falls, ON
1989/04/06	13:15:28	49.82N	81.87W	16/31	3.1 m_N	60 km NE from Kapuskasing, ON
1989/11/19	20:29:29	48.62N	81.75W	5/ 9	2.6 m_N	35 km NW from Timmins, ON
1990/12/22	13:24:56	49.46N	81.09W	8/14	2.8 m_N	43 km N from Cochrane, ON
1991/11/24	07:04:50	49.74N	81.73W	11/23	3.0 m_N	61 KM NE from Kapuskasing, ON
1992/08/11	19:50:44	48.72N	80.78W	4/10	2.5 m_N	48 KM NE from Timmins, ON
1994/01/15	04:25:17	49.30N	81.09W	5/ 7	2.5 m_N	27 km N from Cochrane, ON. Felt.
1994/12/25	21:31:22	49.75N	81.71W	17/25	2.8 m_N	64 km NE from Kapuskasing, ON
1995/01/05	11:30:56	49.17N	81.43W	3/ 5	2.0 m_N	32 km W from Cochrane, ON
1995/12/06	22:52:49	49.55N	81.83W	30/43	3.5 m_N	47 km E of Kapuskasing, ON. Felt.
1996/04/12	02:40:00	48.99N	81.45W	16/24	2.6 m_N	33 km W of Cochrane, ON. Felt.
1996/04/20	01:43:03	49.18N	80.97W	23/37	3.3 m_N	12 km N of Cochrane, ON. Felt.
1996/04/21	16:20:57	49.18N	80.97W	2/ 3	2.2 m_N	12 km N from Cochrane, ON
1996/08/16	04:56:46	49.24N	82.95W	29/46	3.7 m_N	42 km SW from Kapuskasing, ON
1996/08/18	13:41:47	49.25N	82.97W	2/ 3	2.2 m_N	43 km SW from Kapuskasing, ON
1996/08/22	20:19:06	49.25N	82.97W	8/12	2.8 m_N	43 km SW from Kapuskasing, ON
1999/02/01	22:22:05	49.26N	80.94W	15/24	3.4 m_N	22 km N of Cochrane, ON. Felt.
2000/07/24	08:14:16	50.24N	82.37W	4/ 8	2.2 m_N	90 km N from Kapuskasing, ON
2000/11/05	16:14:03	49.67N	81.47W	6/11	2.7 m_N	75 km E from Kapuskasing, ON
2001/01/09	16:23:58	50.00N	82.34W	6/10	2.5 m_N	65 km N from Kapuskasing, ON
2001/07/28	03:48:18	48.48N	79.81W	7/12	2.1 m_N	45 km NE from Kirkland Lake, ON
2002/10/13	03:07:37	49.91N	81.60W	11/16	2.5 m_N	80 km NE from Kapuskasing, ON
2002/10/16	19:10:07	49.88N	82.00W	12/19	2.8 m_N	60 km NE of Kapuskasing, ON. Felt.
2004/05/17	19:25:19	48.63N	80.79W	5/ 8	2.2 m_N	18 km SW from Iroquois Falls, ON
2004/05/26	04:21:22	49.90N	82.00W	3/ 5	1.9 m_N	63 km NE from Kapuskasing, ON
2004/09/02	08:51:59	49.86N	80.56W	5/ 9	1.4 m_N	94 km N from Cochrane, ON
2004/10/11	08:33:50	49.62N	81.47W	12/17	2.3 m_N	70 km NW from Cochrane, ON
2004/10/31	04:23:29	48.70N	82.14W	3/ 6	1.7 m_N	65 km NW from Timmins, ON
2004/12/07	16:07:33	49.25N	81.61W	7/13	1.7 m_N	48 km NW from Cochrane, ON
2005/01/27	10:31:08	49.66N	81.46W	11/19	2.0 m_N	73 km NW from Cochrane, ON
2005/02/21	11:06:26	48.77N	81.42W	4/ 7	1.5 m_N	34 km N from Timmins, ON

2005/03/28	**12:59:49**	**49.76N**	**81.22W**	**4/ 6**	**1.8 m_N**	**78 km N from Cochrane, ON**
2005/04/17	**18:48:28**	**49.82N**	**81.45W**	**14/23**	**2.1 m_N**	**84 km NE from Kapuskasing, ON**
2005/04/20	**07:03:30**	**49.48N**	**81.58W**	**6/10**	**1.4 m_N**	**61 km NW from Cochrane, ON**
2005/06/01	**00:56:54**	**48.80N**	**80.30W**	**8/13**	**2.0 m_N**	**28 km E from Iroquois Falls, ON**
2005/06/11	**07:40:23**	**48.78N**	**81.40W**	**14/23**	**2.0 m_N**	**36 km N from Timmins, ON**
2005/07/05	**02:47:21**	**49.56N**	**81.67W**	**4/ 6**	**1.7 m_N**	**58 km E from Kapuskasing, ON**
2005/07/18	**11:36:27**	**49.73N**	**81.55W**	**7/12**	**1.7 m_N**	**73 km NE from Kapuskasing, ON**
2005/07/30	**11:29:02**	**48.80N**	**81.60W**	**9/15**	**2.0 m_N**	**42 km NW from Timmins, ON**
2005/10/25	**00:01:44**	**49.65N**	**81.79W**	**9/13**	**1.9 m_N**	**53 km NE from Kapuskasing, ON**
2005/12/19	**04:47:21**	**49.60N**	**81.50W**	**5/ 8**	**1.3 m_N**	**70 km E from Kapuskasing, ON**
2006/01/03	**11:05:10**	**49.33N**	**81.08W**	**26/38**	**3.7 m_N**	**29 km N from Cochrane, ON. Felt.**
2006/02/22	**07:46:42**	**49.53N**	**81.54W**	**6/10**	**1.9 m_N**	**65 km E from Kapuskasing, ON**
2006/02/25	**16:00:32**	**48.60N**	**79.71W**	**6/11**	**1.5 m_N**	**47 km SW from La Sarre, QC**
2006/03/04	**02:13:10**	**49.51N**	**81.54W**	**10/15**	**3.4 m_N**	**65 km E of Kapuskasing, ON. Felt.**
2006/05/20	**17:29:39**	**49.22N**	**81.47W**	**6/10**	**2.1 m_N**	**37 km NW from Cochrane, ON**
2006/06/05	**17:44:23**	**49.85N**	**82.05W**	**7/12**	**2.5 m_N**	**55 km NE from Kapuskasing, ON**

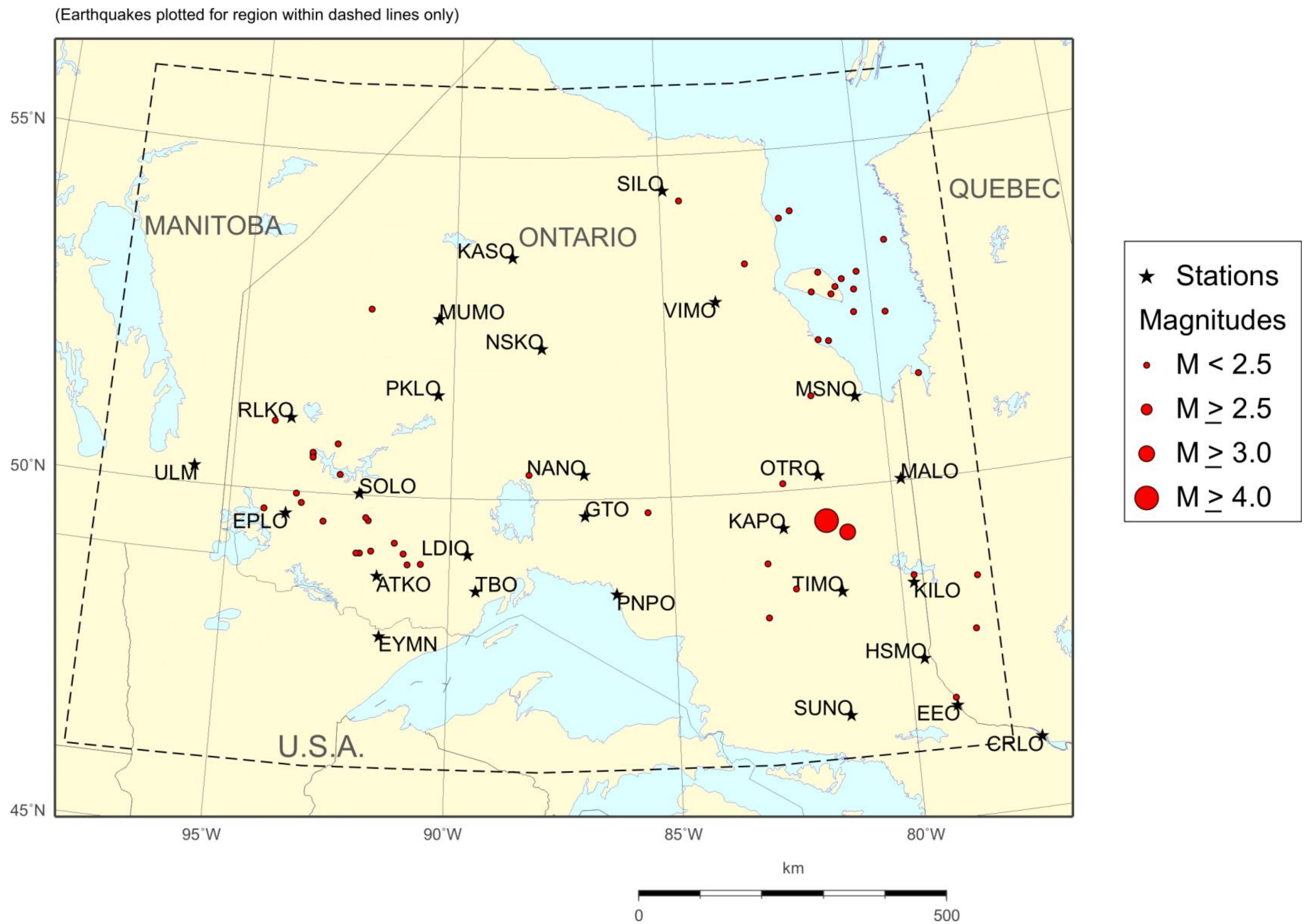


Figure 1: Earthquakes in Northern Ontario and Adjacent Areas, 2006

(Earthquakes plotted for region within dashed lines only)

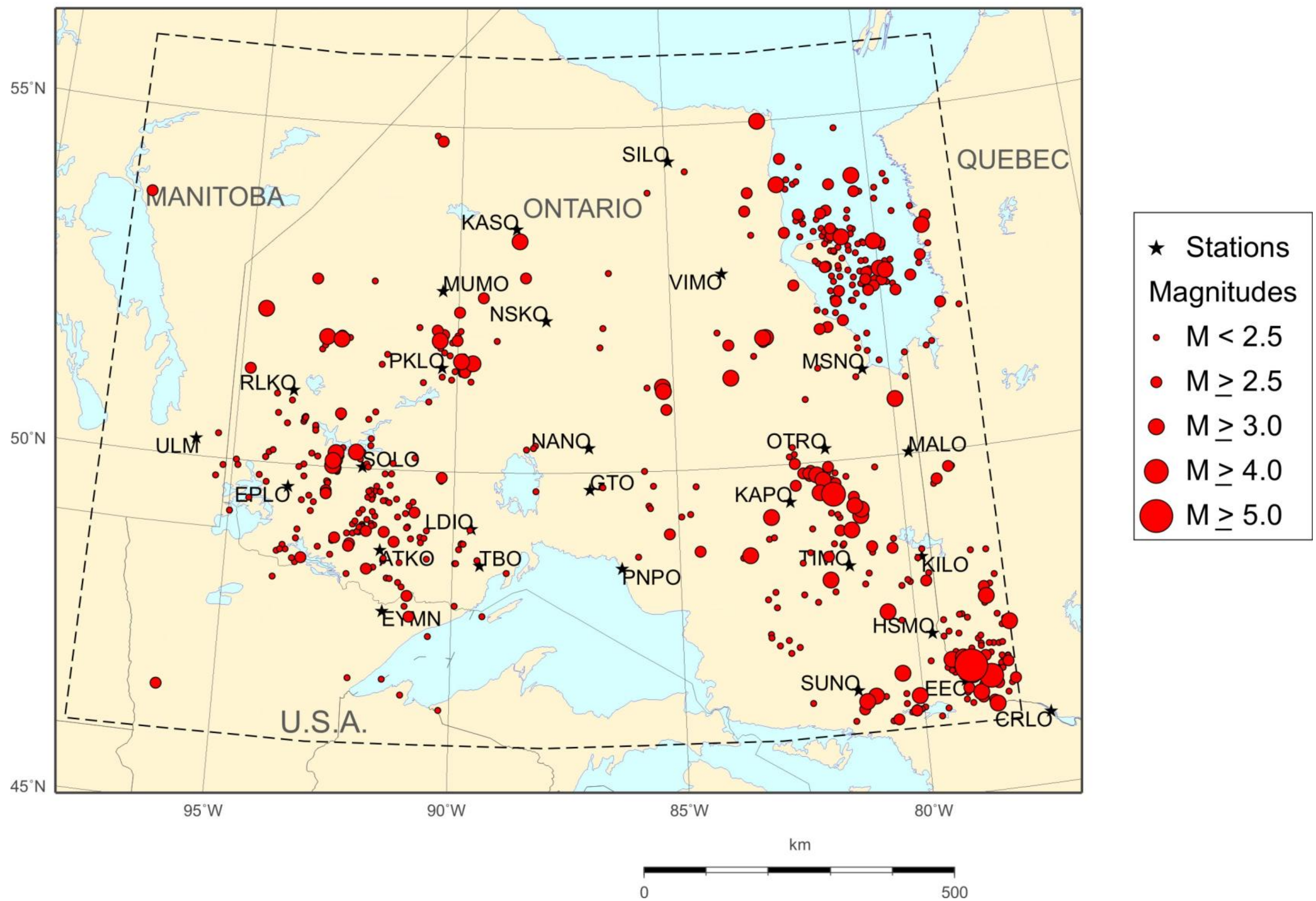


Figure 2: Earthquakes in Northern Ontario and Adjacent Areas, 1982-2006

(Earthquakes plotted for region within dashed lines only)

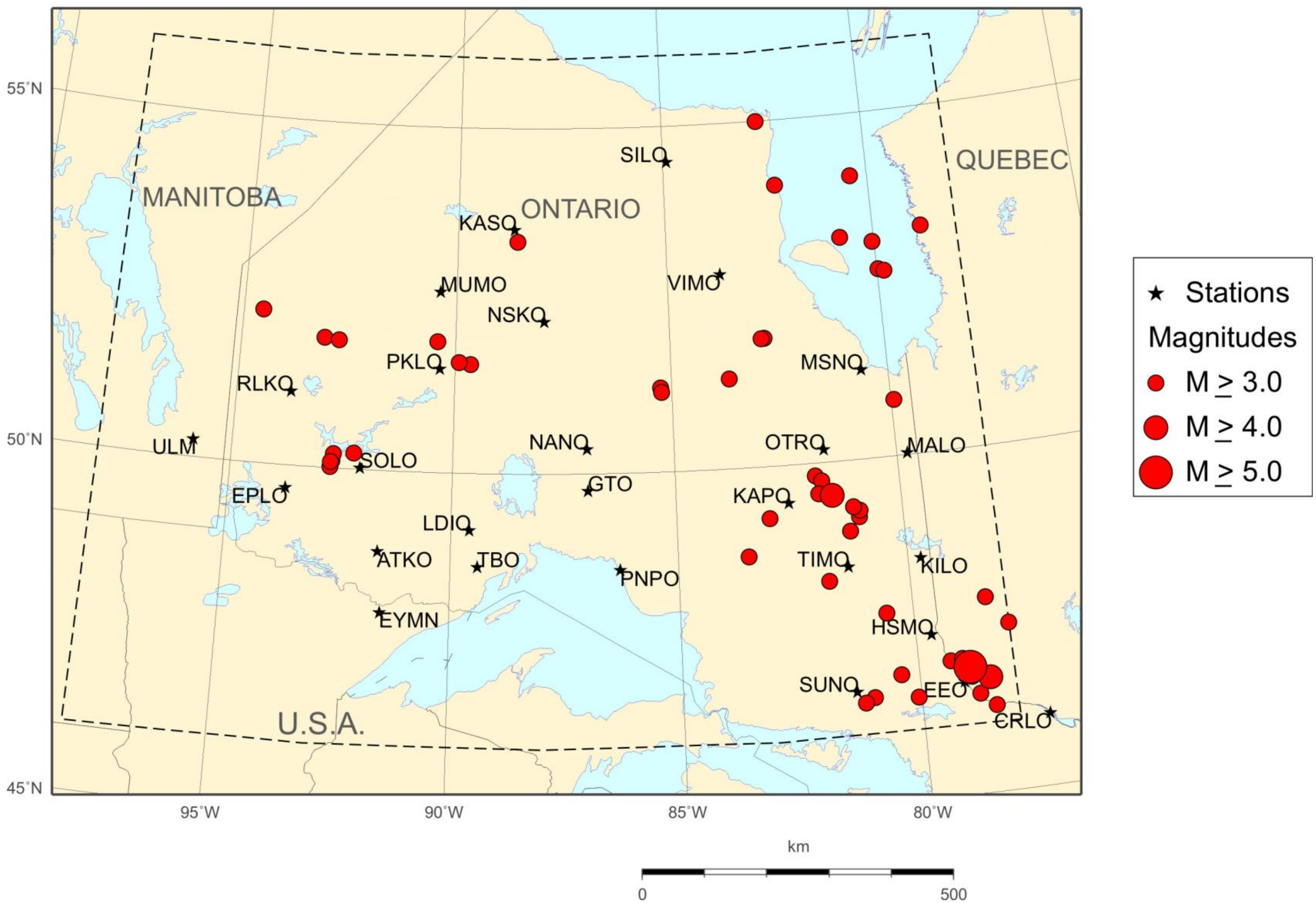


Figure 3: Earthquakes m_N>3 in Northern Ontario and Adjacent Areas, 1982-2006

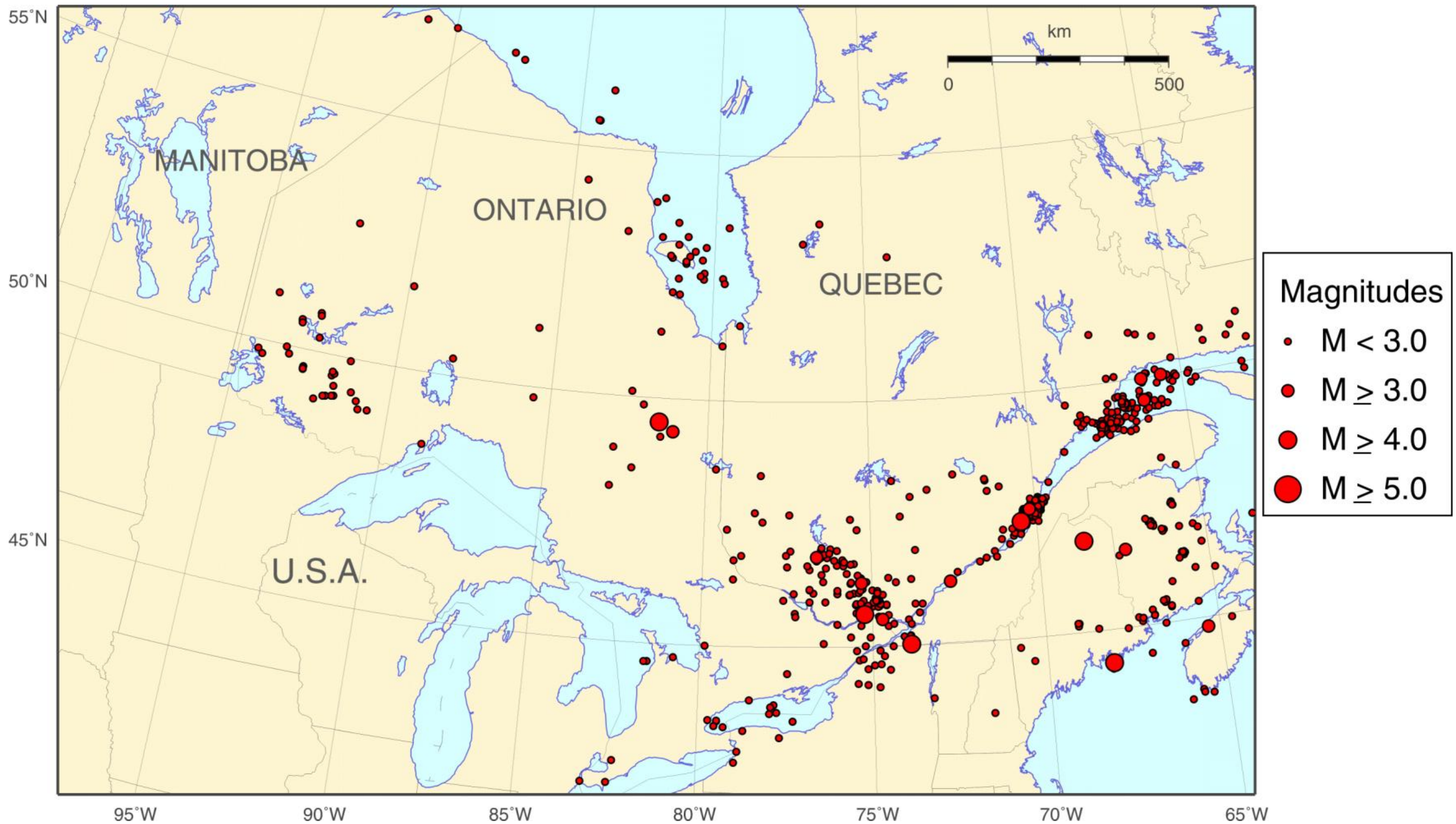


Figure 4: Earthquakes in Eastern Canada, 2006

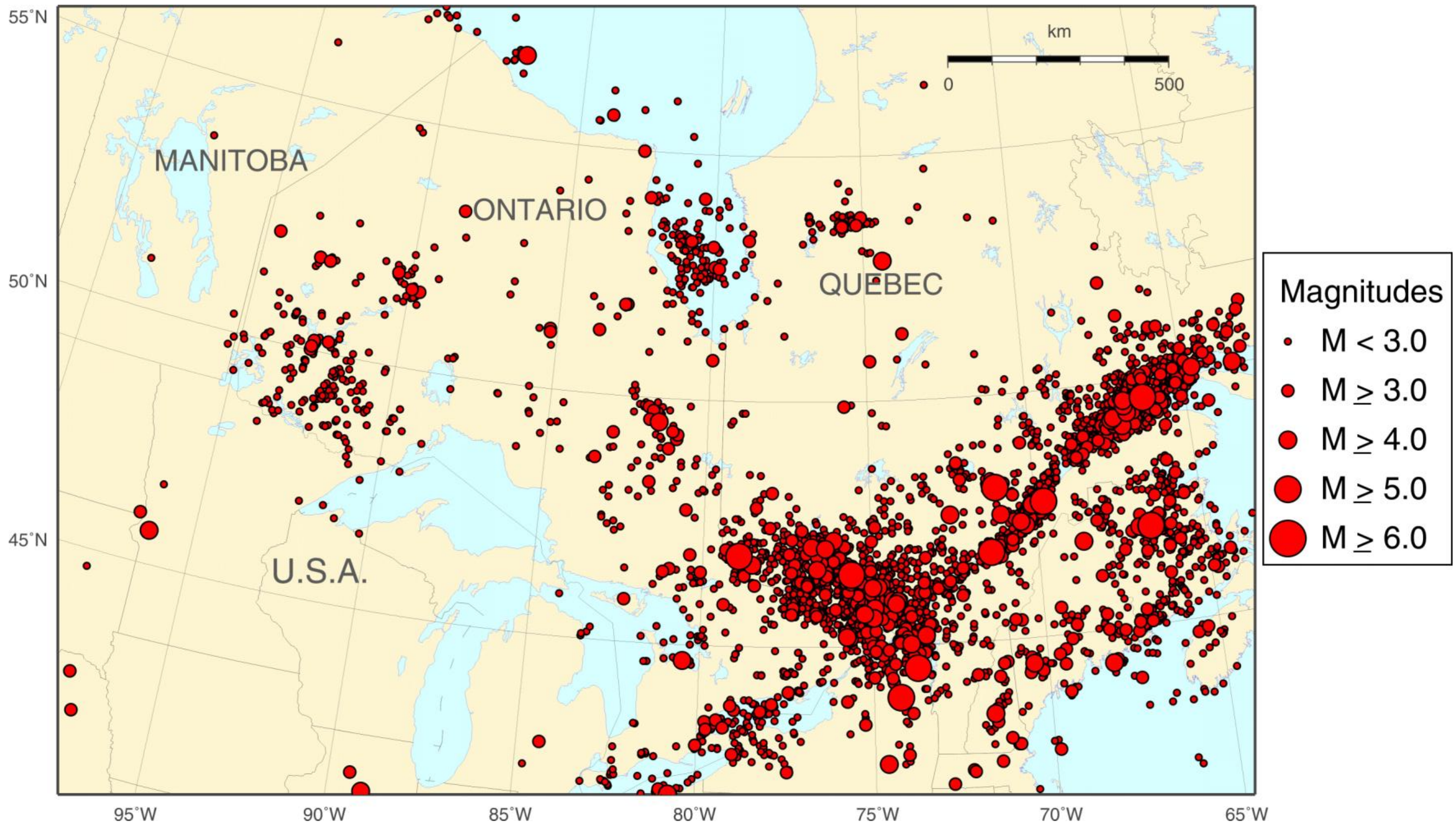


Figure 5: Earthquakes in Eastern Canada, 1982-2006

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

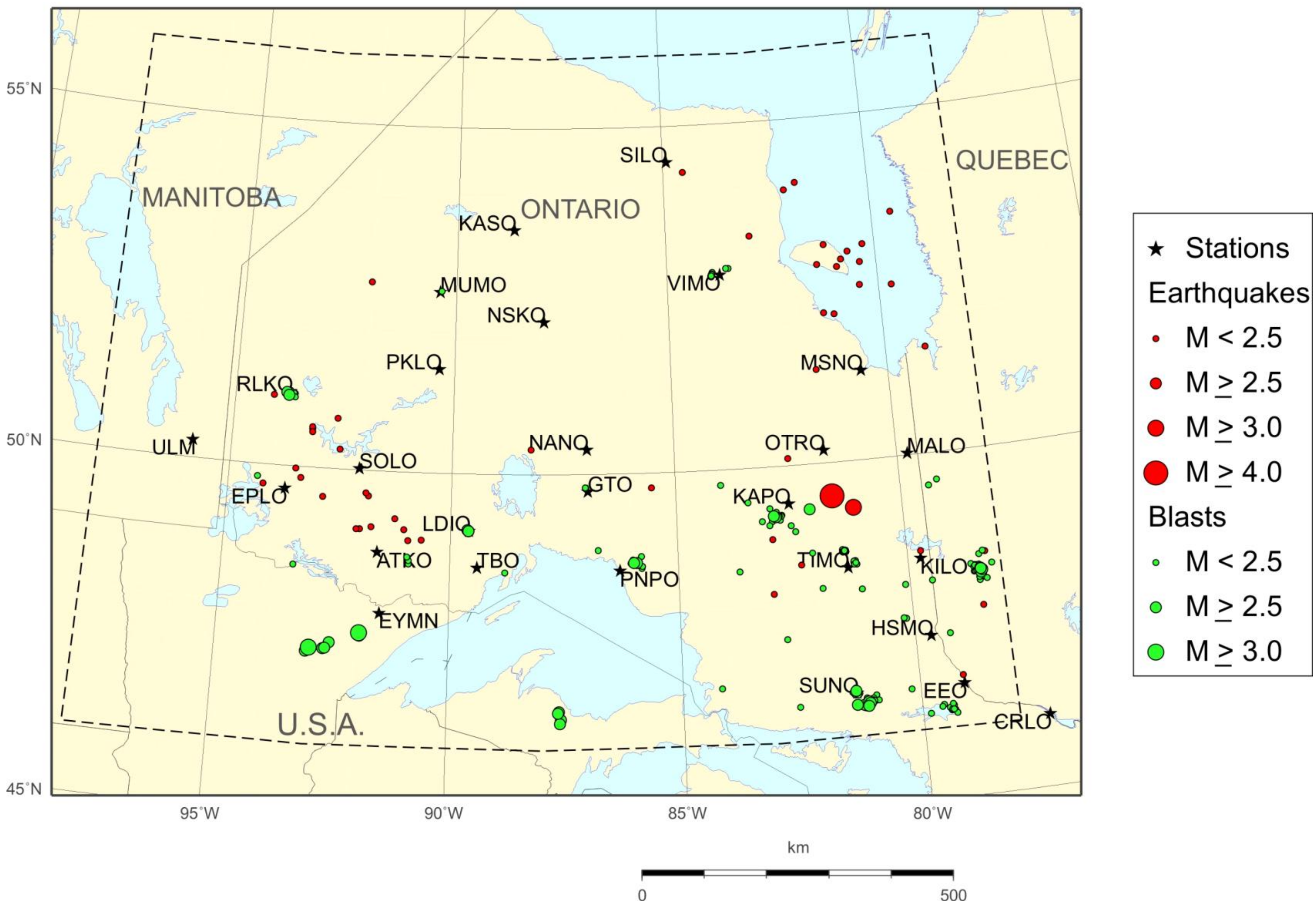


Figure 6: Earthquakes and Blasts Northern Ontario, 2006

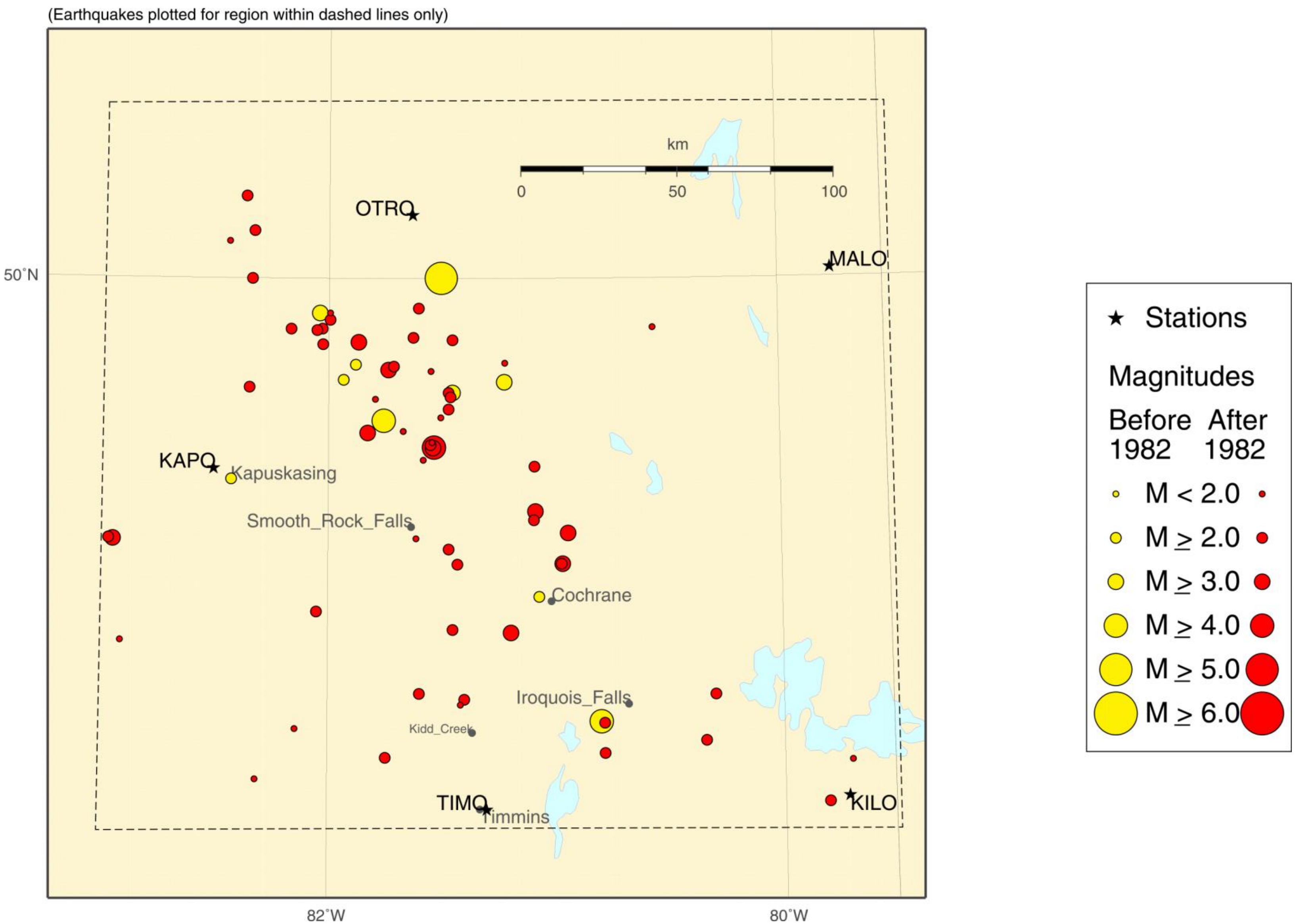


Figure 7: Earthquakes in the Cochrane-Kapuskasing Area since 1928

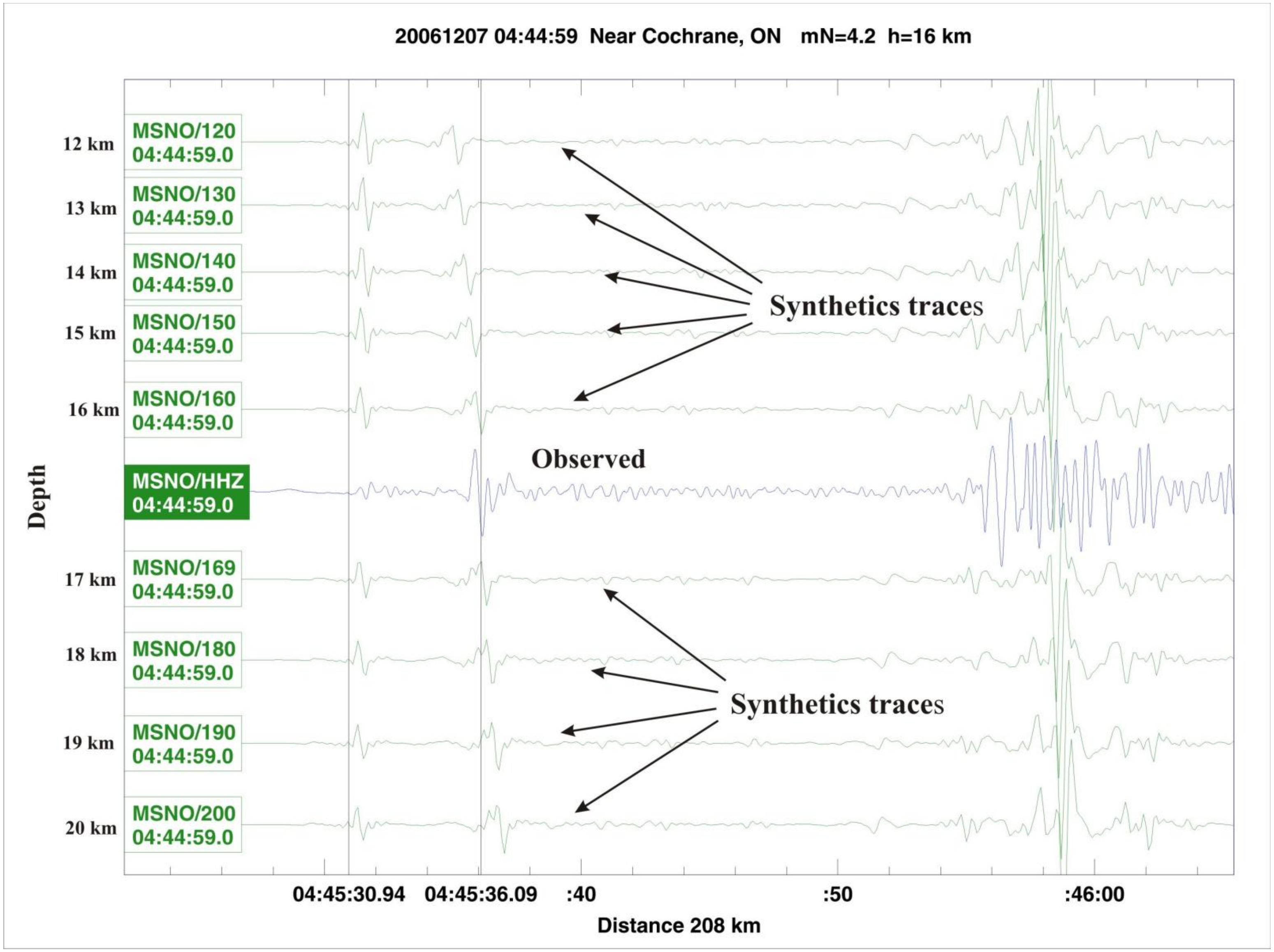


Figure 8: Observed and Synthetic Waveforms from the m_N 4.2 on 2006/12/07 near Cochrane, Ontario

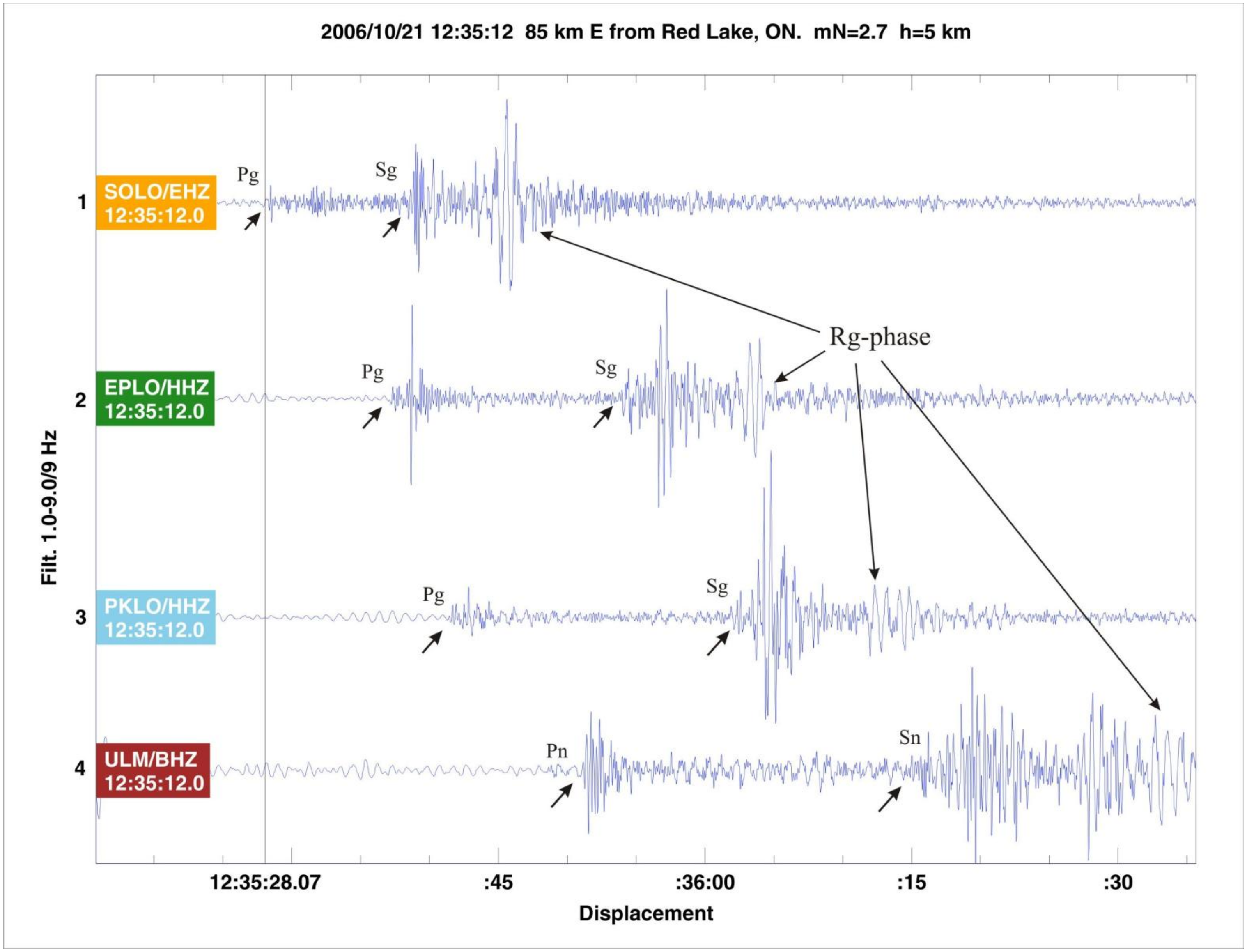


Figure 9: Rg Surface Waves from the m_N 2.7 on 2006/10/21 East of Red Lake, Ontario

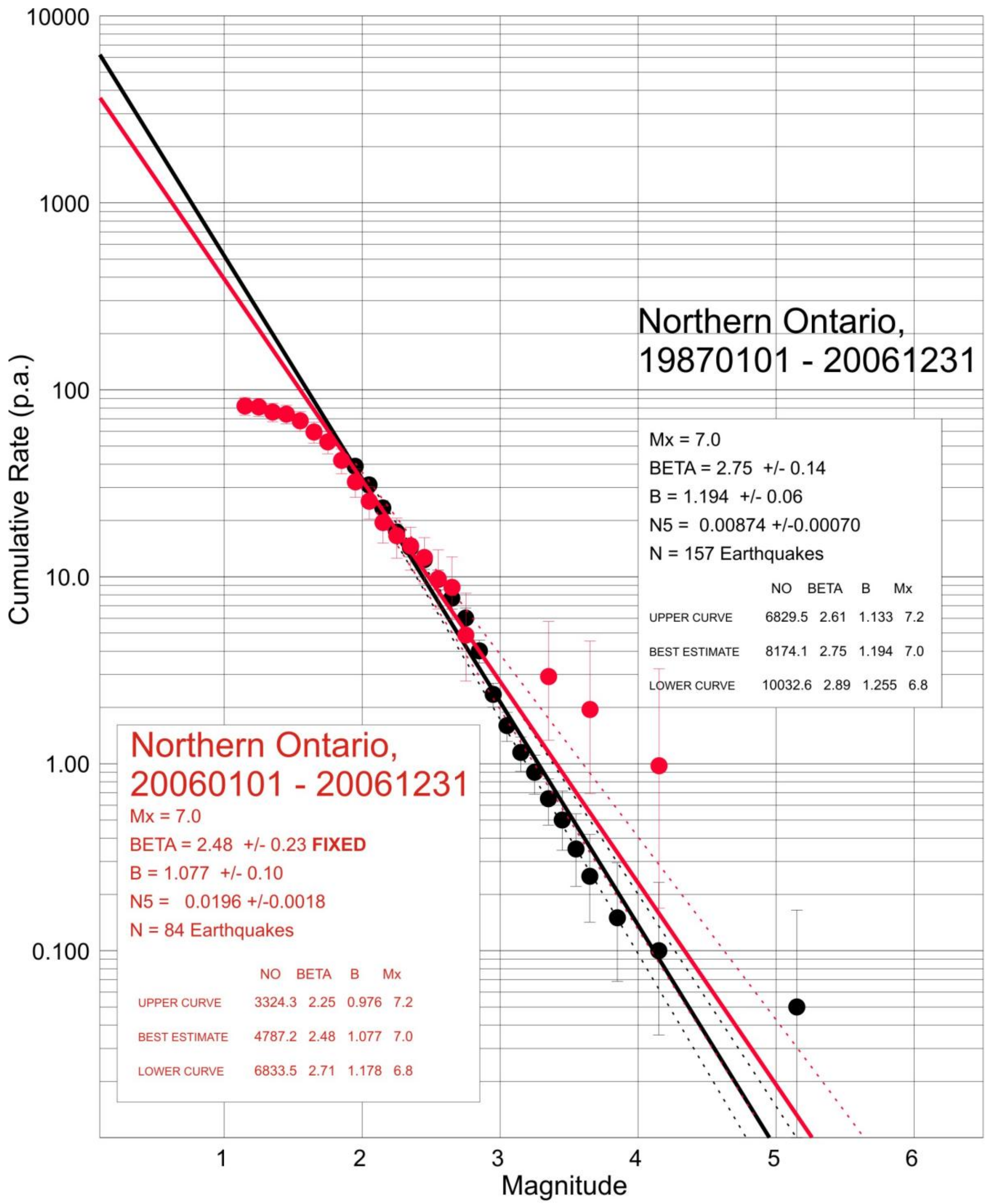


Figure 10: Recurrence Curves for Northern Ontario

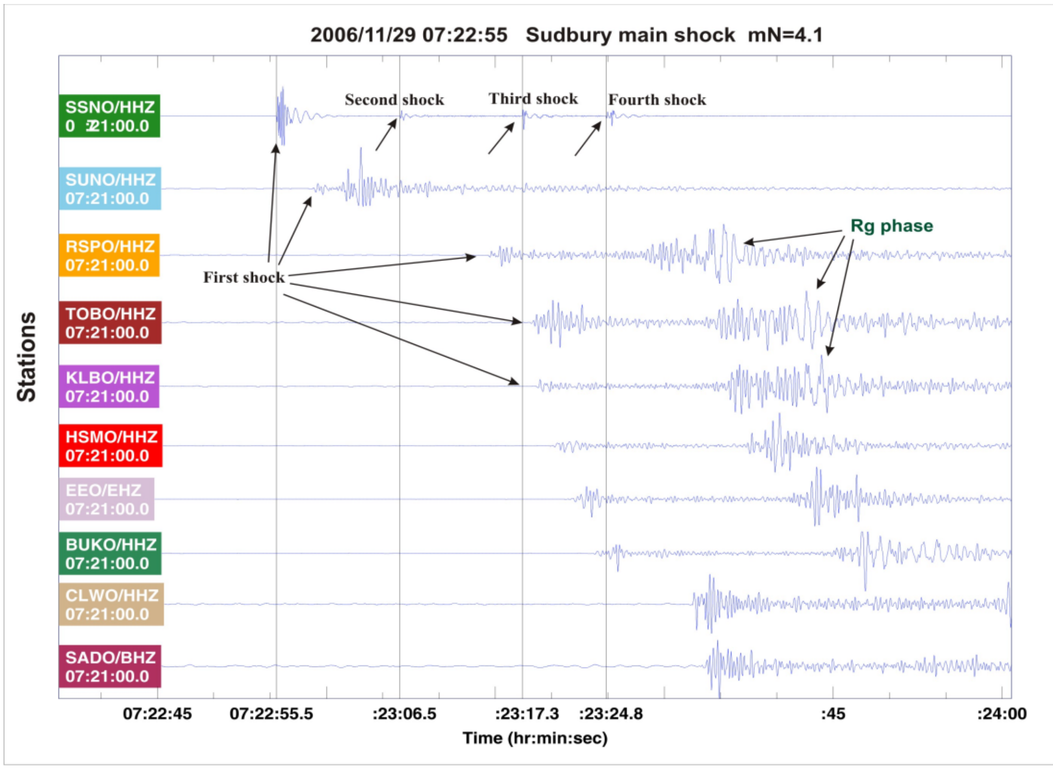


Figure 11: Sudbury m_N 4.1 Mining Event on 2006/11/29

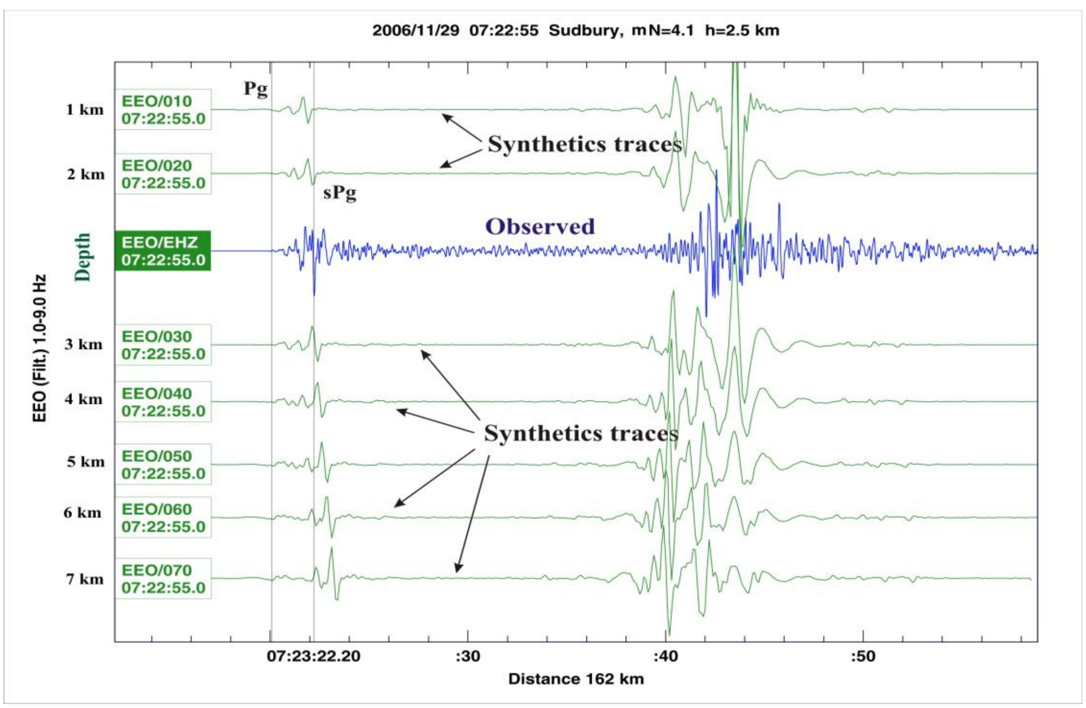


Figure 12: Regional Depth Phases for Sudbury m_N 4.1 Mining Event

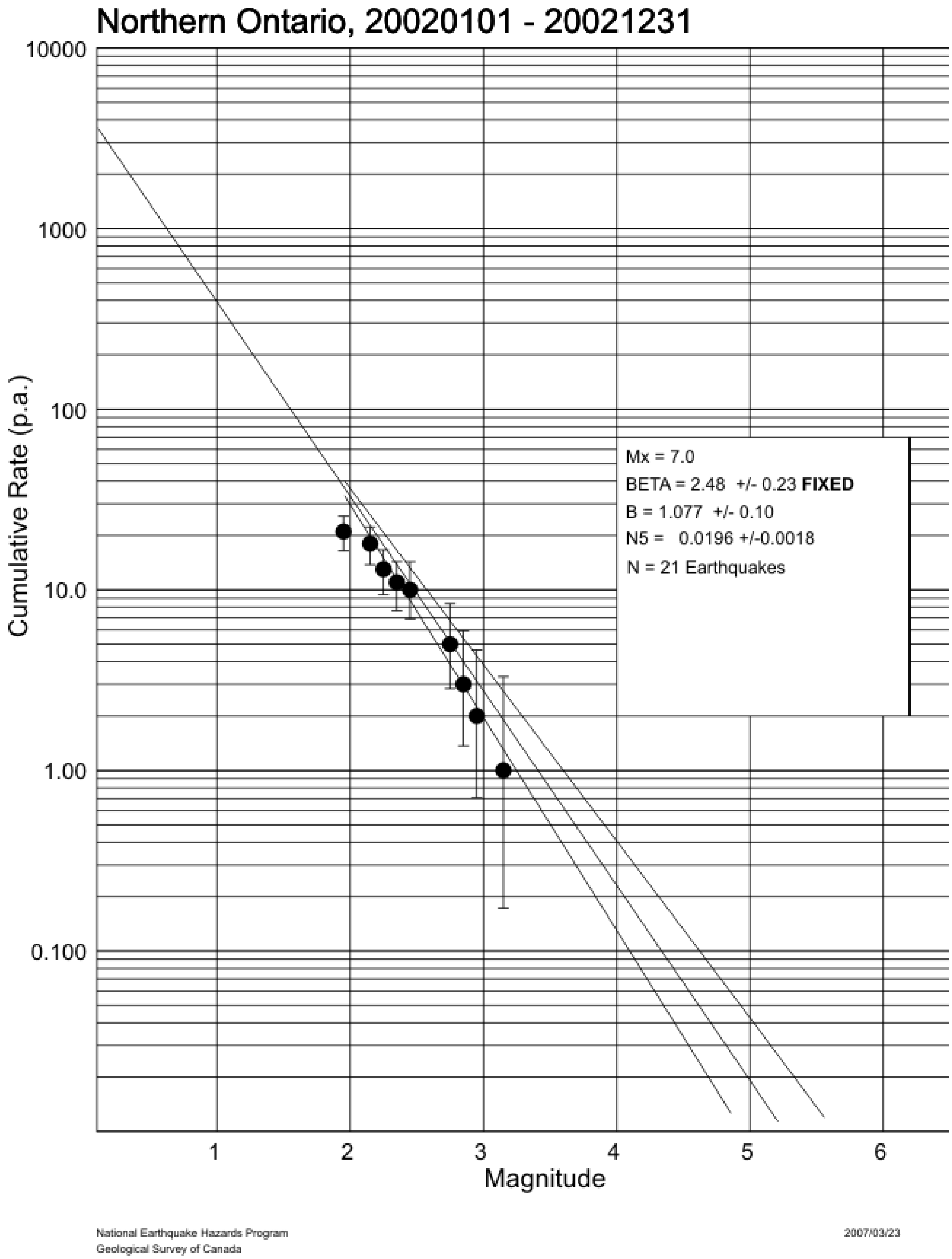
APPENDIX A: RECURRENCE CURVES FOR 2002 - 2006

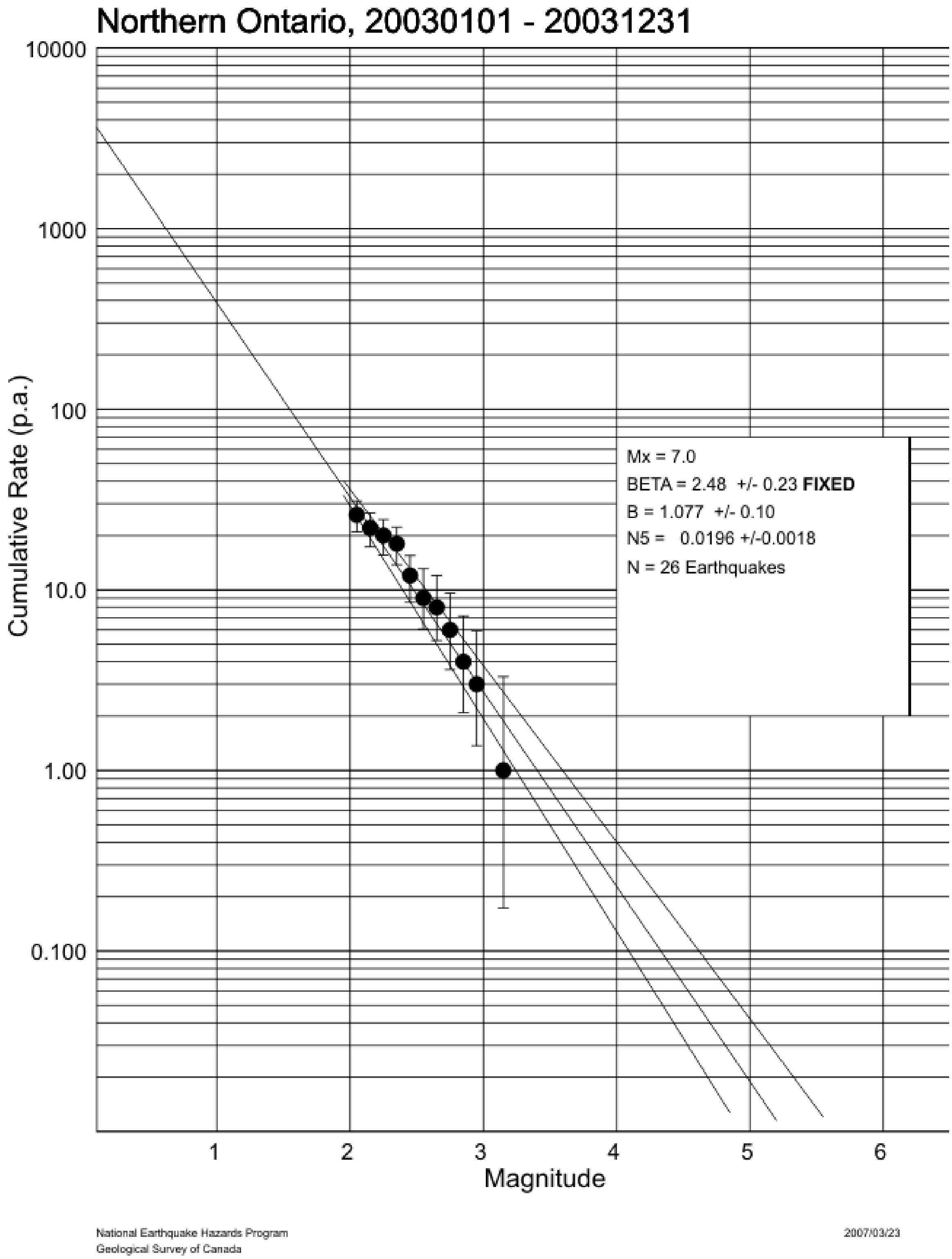
CONTENTS

Following is a set of magnitude recurrence curves for each year from 2002 to 2006, as well as a combined curve for years 2004 to 2006 superimposed on the curves for 2004, 2005 and 2006. A maximum earthquake of magnitude 7 is considered for this region.

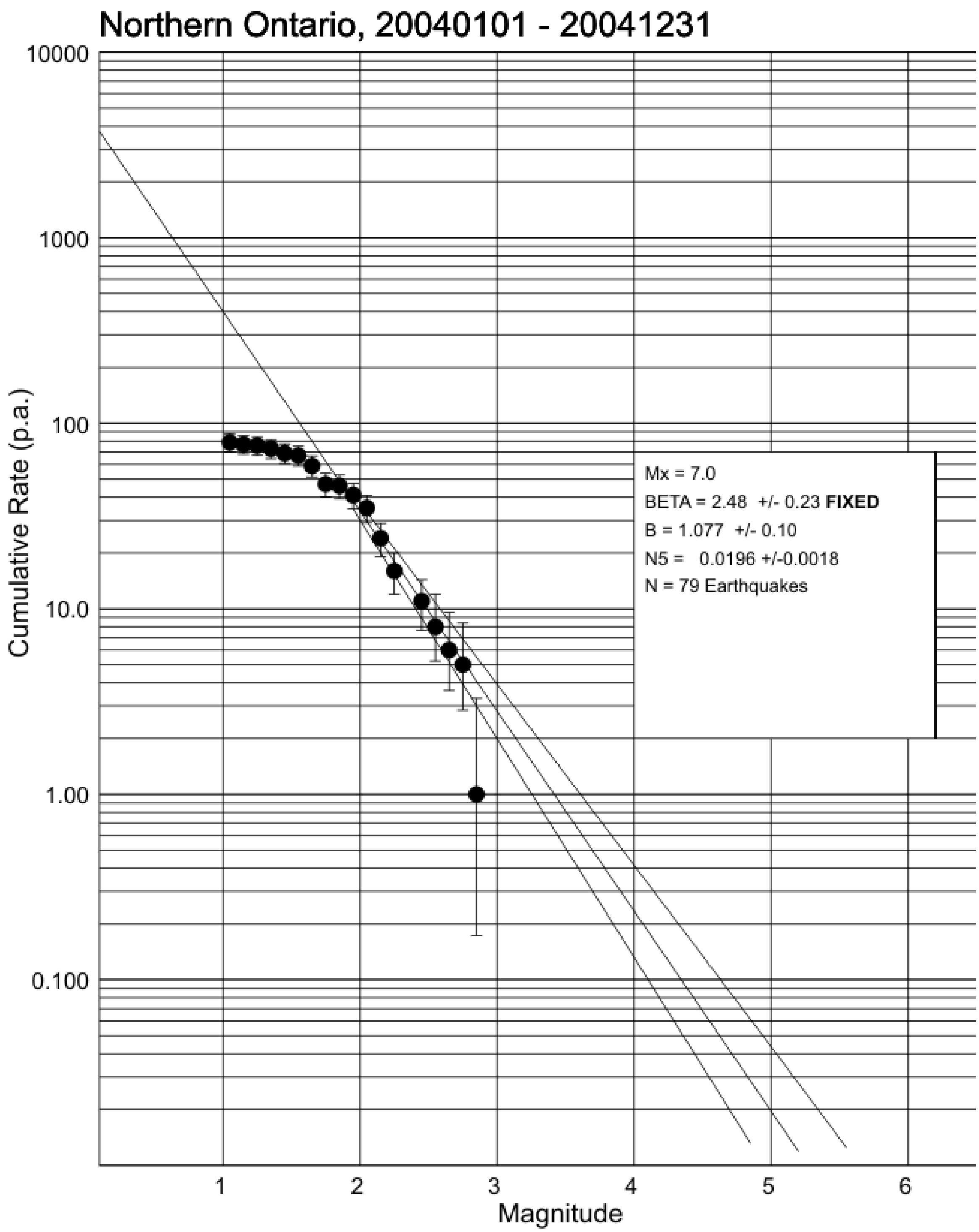
As can be seen in the combined curve, the data points for all years, including the combined curve, fit the average line reasonably well around magnitude 2 to 3. For larger earthquakes the scatter of the data about the line is larger, because the events are fairly rare and statistical fluctuations give large deviations (note the size of the error bounds on each data point). That is to say, if one m_N 4 event is expected only every 5 years, but only one year of data is considered, then the plot for the year which has that m_N 4 will have a point well above the average line. As the magnitude of the event increases, the rarity of the event increases, and the longer time would need to be considered in order to put the data into proper context.

For smaller earthquakes, the data points trend to the left of the line and reach a maximum rate. The point at which the data deviates from the average line represents the magnitude at which the data set is incomplete - earthquakes with magnitudes below this point might be missed because they are below the network detection threshold.


Northern Ontario, 20020101 - 20021231
10000
1000
100
10.0
1.00
0.100
Cumulative Rate (p.a.)
1
2
3
4
5
6
Magnitude
Mx = 7.0
BETA = 2.48 +/- 0.23 FIXED
B = 1.077 +/- 0.10
N5 = 0.0196 +/-0.0018
N = 21 Earthquakes
National Earthquake Hazards Program
Geological Survey of Canada
2007/03/23

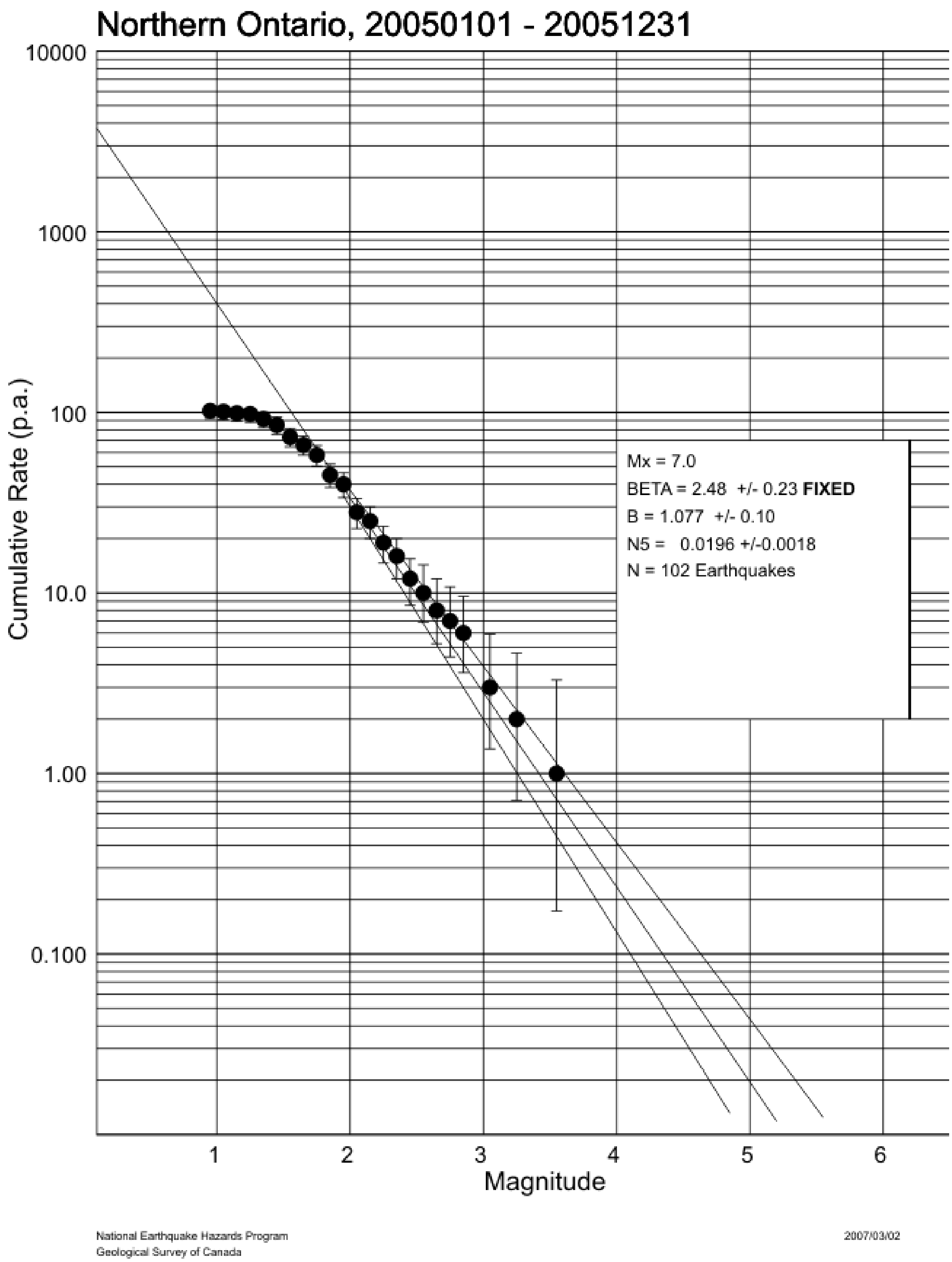


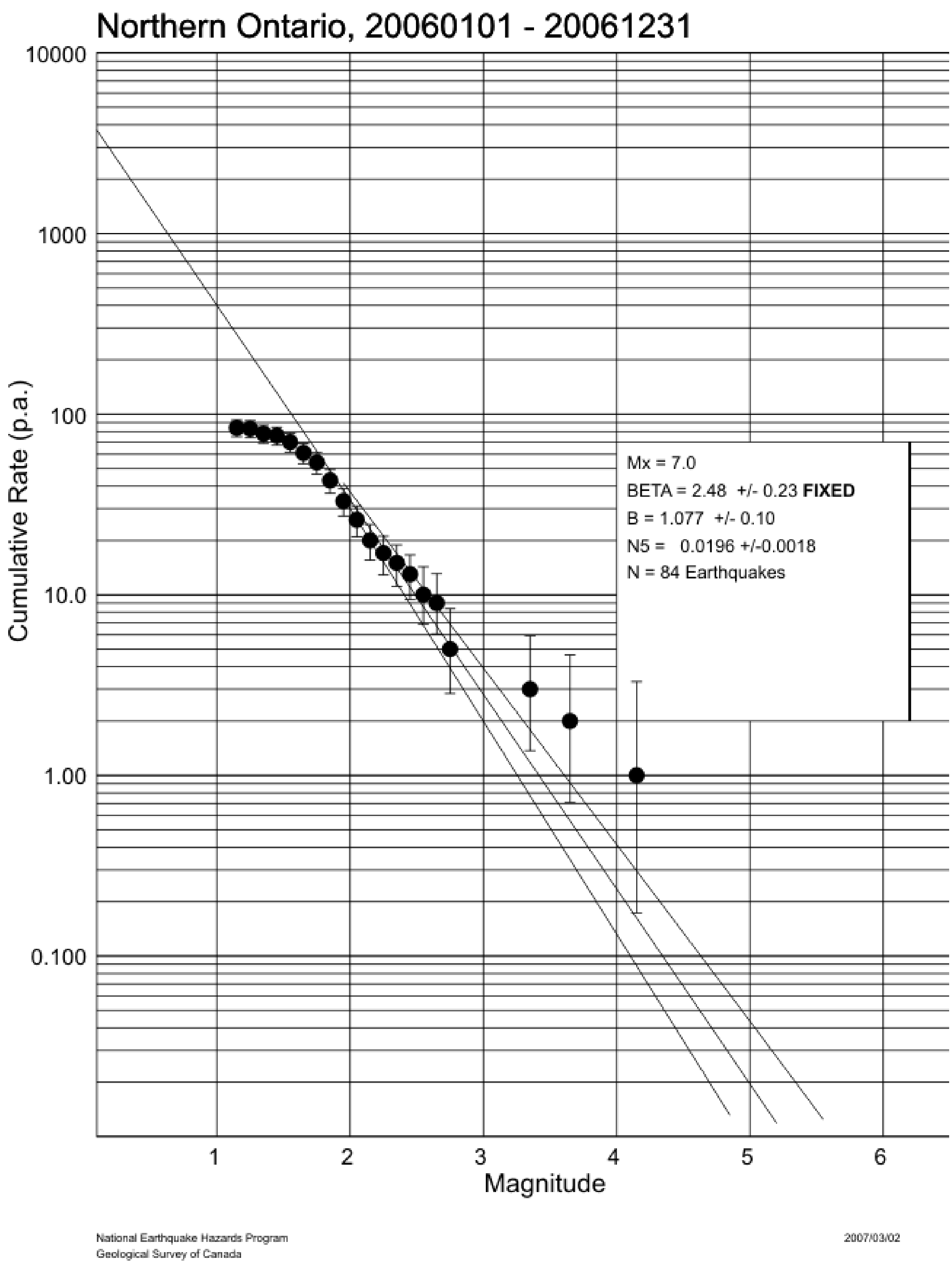
Northern Ontario, 20030101 - 20031231
10000
1000
100
10.0
1.00
0.100
Cumulative Rate (p.a.)
1
2
3
4
5
6
Magnitude
Mx = 7.0
BETA = 2.48 +/- 0.23 **FIXED**
B = 1.077 +/- 0.10
N5 = 0.0196 +/-0.0018
N = 26 Earthquakes
National Earthquake Hazards Program
Geological Survey of Canada
2007/03/23

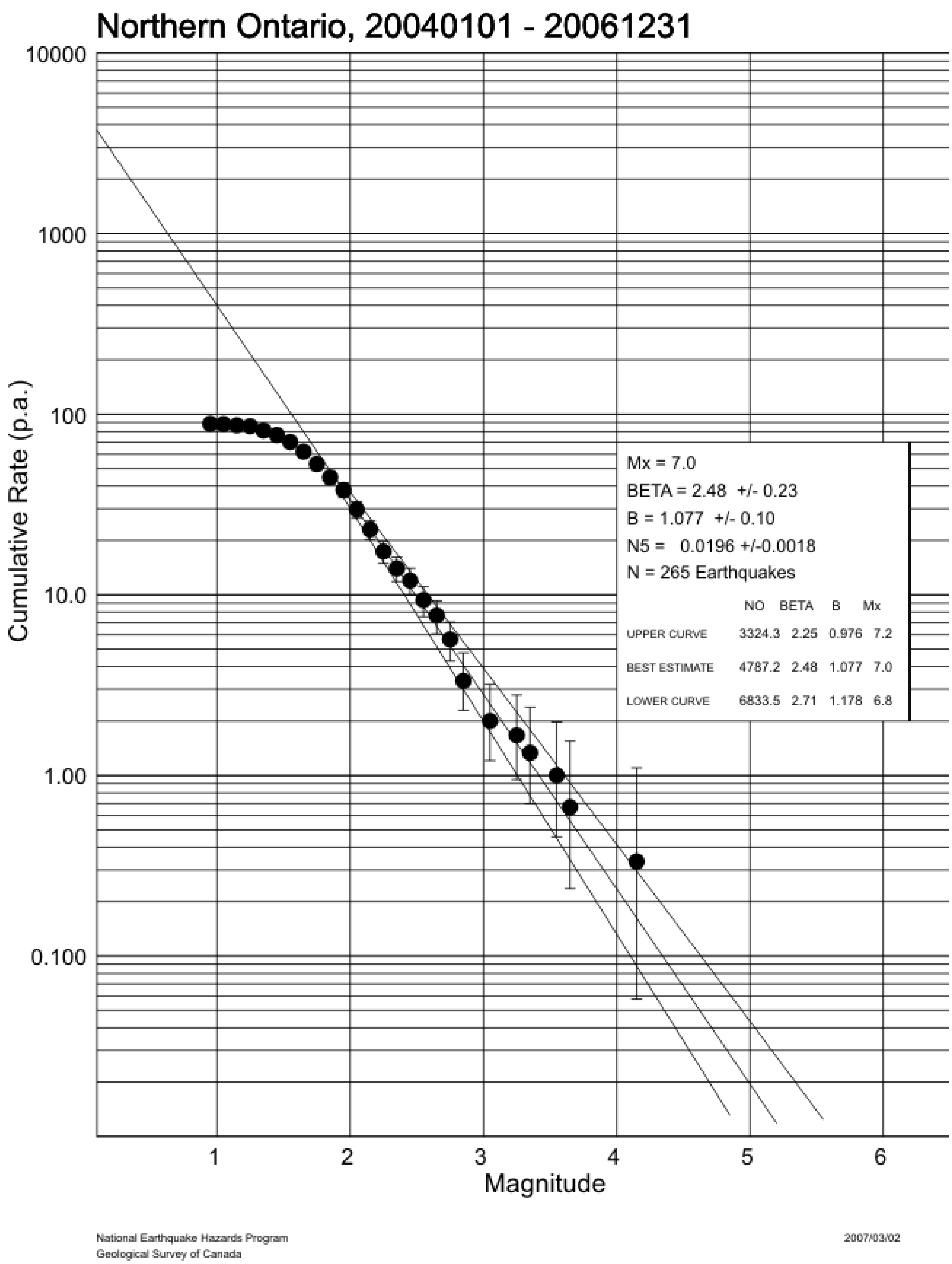


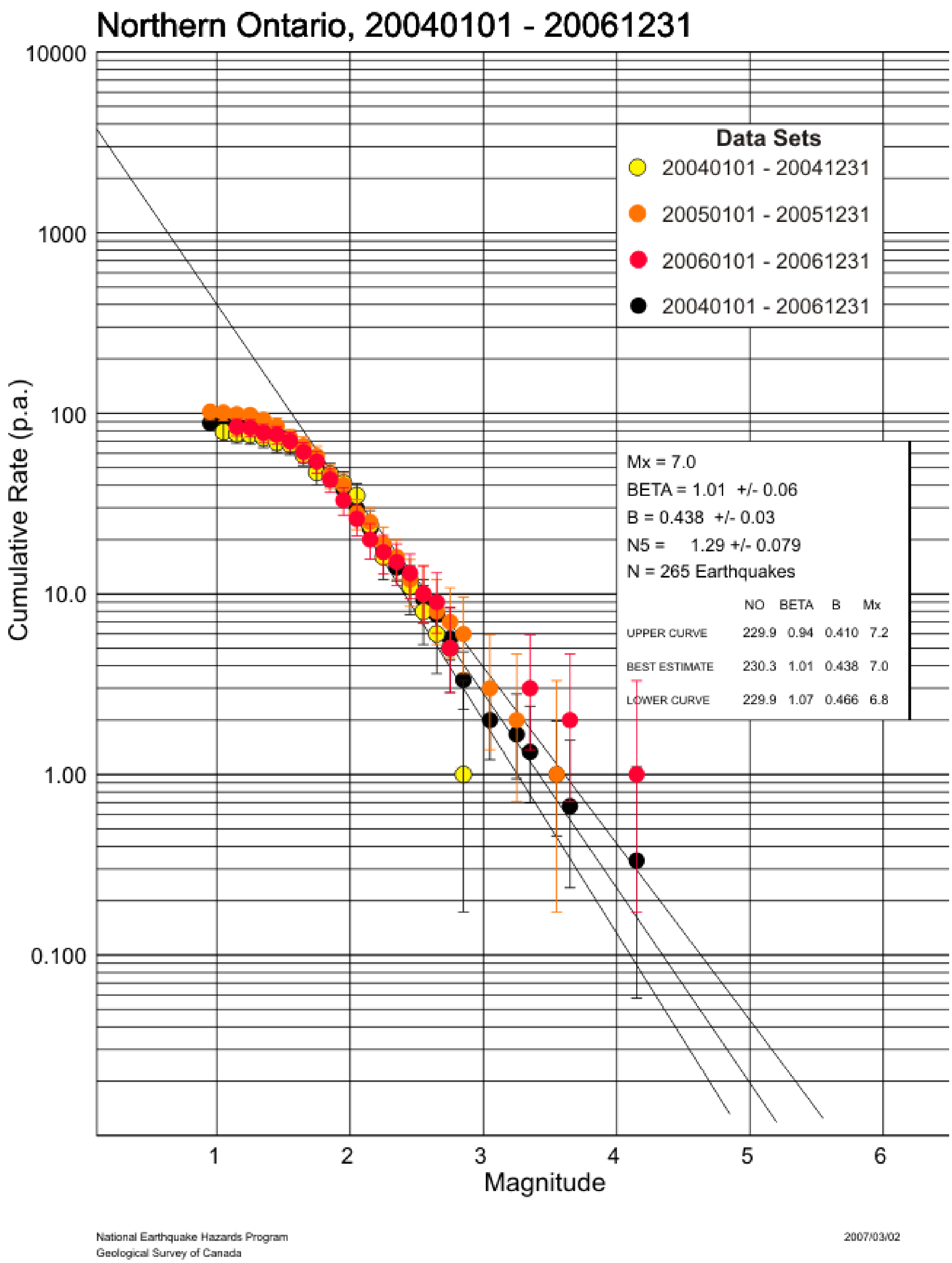
National Earthquake Hazards Program
Geological Survey of Canada

2007/03/02


Northern Ontario, 20050101 - 20051231
10000
1000
100
10.0
1.00
0.100
Cumulative Rate (p.a.)
1
2
3
4
5
6
Magnitude
Mx = 7.0
BETA = 2.48 +/- 0.23 **FIXED**
B = 1.077 +/- 0.10
N5 = 0.0196 +/-0.0018
N = 102 Earthquakes
National Earthquake Hazards Program
Geological Survey of Canada
2007/03/02


Northern Ontario, 20060101 - 20061231
10000
1000
100
10.0
1.00
0.100
Cumulative Rate (p.a.)
1
2
3
4
5
6
Magnitude
Mx = 7.0
BETA = 2.48 +/- 0.23 FIXED
B = 1.077 +/- 0.10
N5 = 0.0196 +/-0.0018
N = 84 Earthquakes
National Earthquake Hazards Program
Geological Survey of Canada
2007/03/02


Northern Ontario, 20040101 - 20061231
Cumulative Rate (p.a.)
10000
1000
100
10.0
1.00
0.100
1
2
3
4
5
6
Magnitude
Mx = 7.0
BETA = 2.48 +/- 0.23
B = 1.077 +/- 0.10
N5 = 0.0196 +/-0.0018
N = 265 Earthquakes
NO BETA B Mx
UPPER CURVE 3324.3 2.25 0.976 7.2
BEST ESTIMATE 4787.2 2.48 1.077 7.0
LOWER CURVE 6833.5 2.71 1.178 6.8
National Earthquake Hazards Program
Geological Survey of Canada
2007/03/02


Northern Ontario, 20040101 - 20061231
10000
1000
100
10.0
1.00
0.100
Cumulative Rate (p.a.)
1
2
3
4
5
6
Magnitude
Data Sets
20040101 - 20041231
20050101 - 20051231
20060101 - 20061231
20040101 - 20061231
Mx = 7.0
BETA = 1.01 +/- 0.06
B = 0.438 +/- 0.03
N5 = 1.29 +/- 0.079
N = 265 Earthquakes
NO BETA B Mx
UPPER CURVE 229.9 0.94 0.410 7.2
BEST ESTIMATE 230.3 1.01 0.438 7.0
LOWER CURVE 229.9 1.07 0.466 6.8
National Earthquake Hazards Program
Geological Survey of Canada
2007/03/02

APPENDIX B: EARTHQUAKE EPICENTRES AND RECORDED SEISMIC WAVEFORMS

CONTENTS

(INFORMATION WILL BE PROVIDED UPON REQUEST)