SEISMICITY STUDIES FOR LONG-TERM SEISMIC HAZARD ASSESSMENT IN THE NORTHERN ONTARIO PART OF THE CANADIAN SHIELD

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ABSTRACT :

A seismic monitoring program began in 1982 to document earthquake activity of the northern Ontario portion of the Canadian Shield in order to quantify seismic hazard in this nearly-aseismic region. The goal is to provide seismic hazard estimates for high-reliability structures (probabilities needed at ~10^{-4} p.a. and lower). Over the past 25 years, more than 740 earthquakes were located in the region with m_N magnitudes ranging from 0.5 to 4.3. The detailed monitoring has: (i) dropped the completeness threshold for magnitude of events from 3.5 to <2.0; (ii) established the rate of Mw > 4 events as 0.03 per annum for a 1.2 million square kilometre area; (iii) estimated the b-value as 1.2; (iv) used Rg-phases and a Regional Depth Phase Method to determine earthquake depths; (v) identified a non-random distribution of events and confirmed that much activity occurs as shallow swarms; and (vi) identified regions where the earthquake depths are shallow (< 6 km) and others where the depths are deep (5-17 km). The results feed into future seismic hazard analyses in the following way: (i) the local b-value and rates of activity can be compared with average global rates for Stable Continental Cores; (ii) seismic hazard in the regions of shallow earthquakes is higher than if default depths of 10 or 18 km were used; and (iii) regions of deep earthquakes suggest reactivated fault zones more likely to generate large earthquakes.

KEYWORDS: seismic hazard, earthquake, b-value, Canadian Shield, stable continent

1. INTRODUCTION

In 1982, Atomic Energy of Canada Limited approached the Geological Survey of Canada (GSC) to conduct a seismic monitoring program in the northern Ontario and eastern Manitoba portions of the Canadian Shield. The goal of this work, which continues today through support from NWMO (Nuclear Waste Management Organization), is to determine the seismicity rates and patterns in this relatively-aseismic region, and to provide seismic hazard estimates for high-reliability structures, including potential nuclear waste repositories.

To record the seismic activity, Canadian Hazards Information Service (CHIS; a part of the GSC) currently operates twenty-six seismograph stations in the Ontario and southeast Manitoba portions of the Canadian Shield. This represents a significant increase from the three stations that were originally in place before the commencement of this program. The additional stations have lowered the magnitude threshold for earthquakes that can be located. Since the frequency of smaller earthquakes is far greater than, but proportional to, the frequency of larger events, the location of smaller earthquakes provides valuable information on the rate of the larger, rare events, and is a partial substitute for a long historical record (which is lacking for northern Ontario).

Earthquake size is expressed by magnitude. Almost all earthquakes discussed have magnitudes calculated on the Nuttli scale, which is used by CHIS for moderate-sized earthquakes in eastern Canada. Magnitudes calculated on the Nuttli scale are formally written m_N or m_{bLg} (note: moment magnitude, $Mw \approx m_N - 0.5$ units).

2. SEISMOGRAPH NETWORK

Prior to 1982, only three analogue seismograph stations (all since closed) existed in the study area: LHC (Lakehead, ON) in the southwestern region of Ontario, and SUD (Sudbury, ON) and KLC (Kirkland Lake, ON) in the eastern side of the province. In support of the new monitoring program, 6 new Canadian National Seismograph Network (CNSN) stations were installed across the middle of the province, and into Manitoba to replace the existing stations. Initially, all but EEO (Eldee, ON) were analogue, however, they were upgraded over the course of the years to continuous, digital, real-time stations.

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 vibratory cultural noise such as traffic, heavy industry and trains. Natural background noises, such as waves on nearby lakes or oceans, 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. However, the placement of these stations was also limited by the practical aspects of accessibility to roads and power.

In 2003 FEDNOR (http://www.ic.gc.ca/epic/site/fednor-fednor.nsf/en/home), a Government of Canada initiative, sponsored six new stations in northern Ontario chiefly for deep-Earth studies in collaboration with the POLARIS initiative (http://www.polarisnet.ca). These stations use Nanometrics Libra satellite technology, solar panels to provide power, and a temporary vault and so are not restricted to places with road access and near powerlines. Over the course of three years, 18 Libra stations were installed for the FEDNOR program, with the data being sent in real-time via satellite to the Canadian National Data Centre in Ottawa, operated by CHIS. See Figure 1 for a map of the stations.

CHIS receives, processes and archives all of the data (including other POLARIS stations). The data are available in SEED, GSE, CA and INT format. The continuous digital data is accessible through the CHIS web site at http://earthquakescanada.nrcan.gc.ca/stnsdata/index_e.php. Descriptions of these formats are available on the website.

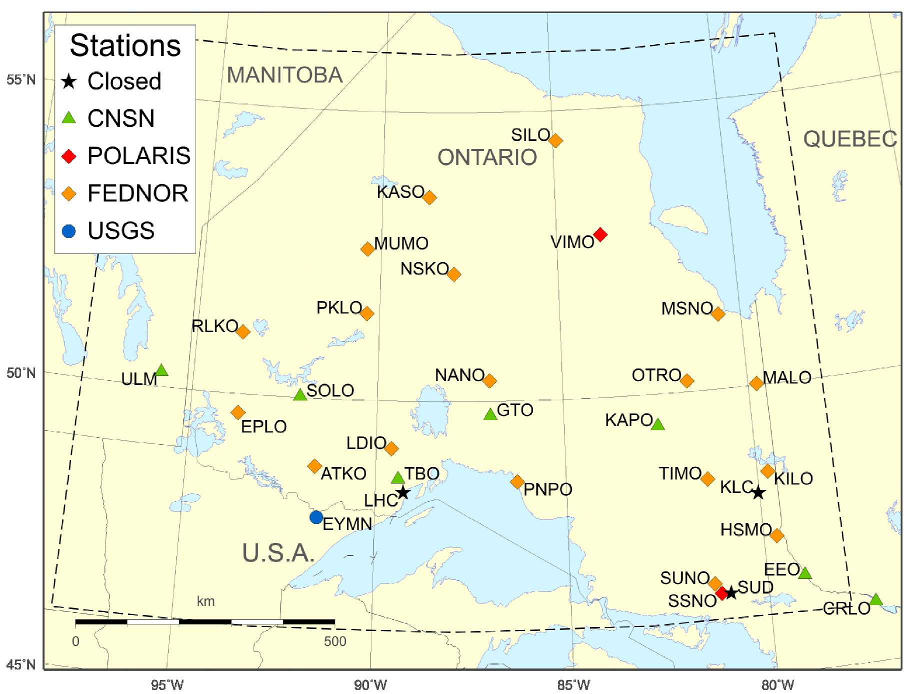

Figure 1. Map of stations prior to 1982 (stars), and as at mid-2008. Dotted box shows study region.

3. SEISMICITY

Prior to the start of this study in 1982, only a handful of earthquakes had been located in northern Ontario west of 83 degrees. Over the past 25 years, more than 750 earthquakes with magnitudes ranging from 0.5 to 5.2 were located in the study area (Fig. 2). Annual reports on the seismicity have been produced, the most recent of which is Hayek et al. (2007). It should be noted that the discrimination of small natural earthquakes from human activity (mine and quarry blasting, and mine-induced seismicity) is very difficult in this region as there are about 10 to 100 human events for every natural earthquake.

The largest event, M5.2 on 2000/01/01 was located in the Temiscamingue region of Quebec, bordering the eastern side of Ontario. The second-largest event, M4.3 on 1982/08/13 was located just 36 km from the M5.2 event. Temiscamingue is part of the Western Quebec seismic zone (Basham et al., 1985), which was already known to be more seismically-active compared to the surrounding areas and has historically had several larger, felt (and sometimes damaging) events. The third-largest event since 1982 was a M4.2 on 2006/12/07 in the Kapuskasing-Cochrane region, to the NW of the two larger events. It was also in an area which had reported earthquakes prior to 1982. Initially it was believed to represent typical sparse activity noted in the eastern portion of the province from Kapuskasing to Sudbury. However, the increase in seismographs allowed for the many smaller events in the Kapuskasing-Cochrane region to be detected and located. As well, the increase and the improved network configuration helped increase the accuracy of these locations. As a result, a picture of increased seismicity compared to the region to the south and west has emerged. The seismicity occurs in a linear trend from NW to SE, in-line with the Western Quebec seismic zone, suggesting the possibility that these two zones may be related. Adams and Basham (1991) attributed part of the Western Quebec earthquakes to the passage of a hot spot, the path of which had passed earlier under Cochrane. In this way Kapuskasing-Cochrane seismicity may be an extension of the Western Quebec seismic zone.

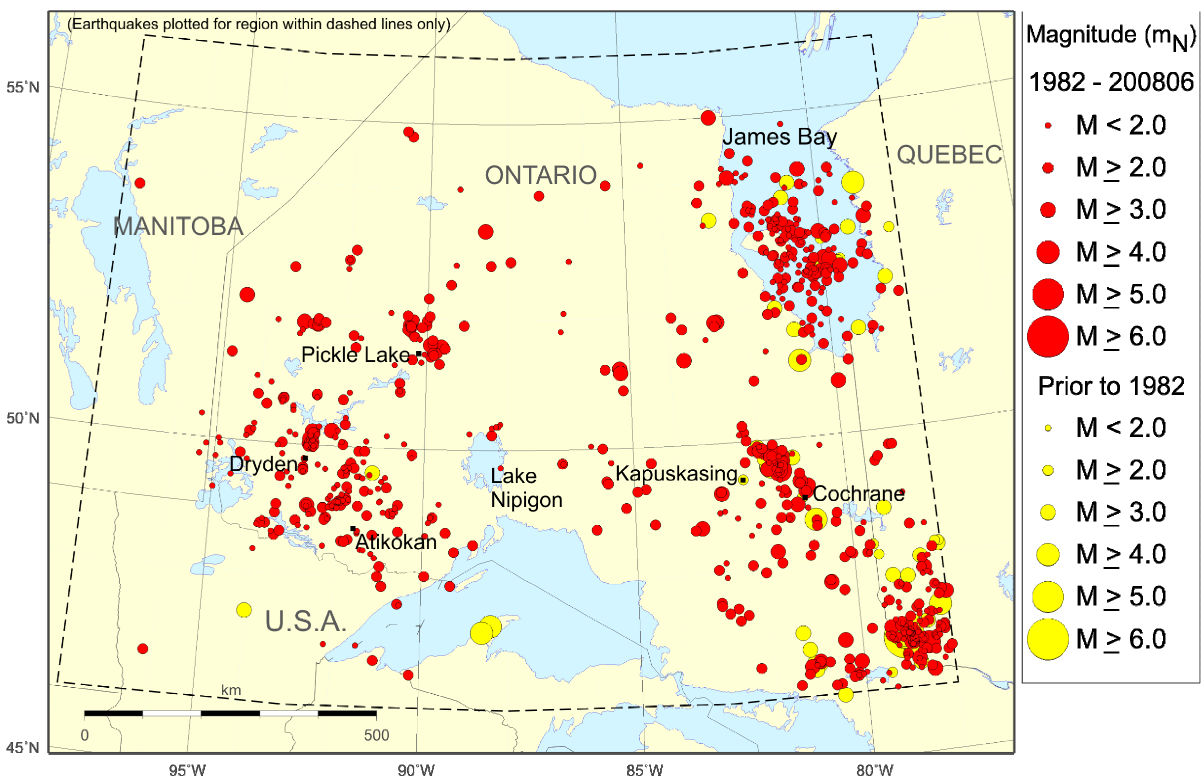

Figure 2. Map of earthquakes located in region before and since 1982 (when study began)

Basham et al. (1985) also recognized a cluster of seismic activity under James Bay that has become more clearly defined since 1982 and especially since 2003. Other regions of enhanced seismicity in the previously-considered "aseismic" shield, have also emerged, such as the activity across the Severn Highlands (Atikokan-Dryden-Pickle Lake region), northwest of Lake Superior. Note that the Atikokan region experienced its first recorded magnitude 3 only in 2008, and hence nearly all the activity up until then would have remained undetected had it not been for the stations installed for this project. This region is also notable for earthquake swarms, such as those that have occurred near Pickle Lake and Dryden, Ontario (Ma et al., 2008).

4. EARTHQUAKE OCCURRENCE RATES FOR THE STABLE PART OF THE CANADIAN SHIELD

The annual frequency of earthquakes of a given magnitude (M) is an inverse logarithmic function of magnitude, so a magnitude-recurrence curve can be established by fitting the earthquakes of a region on a log(cumulative frequency) versus magnitude plot. Because the seismicity rates in northern Ontario are quite low, this requires the use of either a large region, a longer data collection period, or a decrease in the location threshold, in order to acquire enough data to create a reliable recurrence curve. As the quality of the network has improved with time, the detection threshold has dropped. Therefore, to establish the recurrence curve for northern Ontario, the data from the most recent years were used for the lower magnitudes, whereas the older data was used for the higher magnitudes, as shown on Figure 3. To estimate the rate for the stable part of the shield, and to exclude the Temiscamingue part of the Western Quebec zone, the southern boundary for the earthquakes considered was set to 47.5ºN. Of 570 earthquakes considered, 297 passed the completeness criteria.

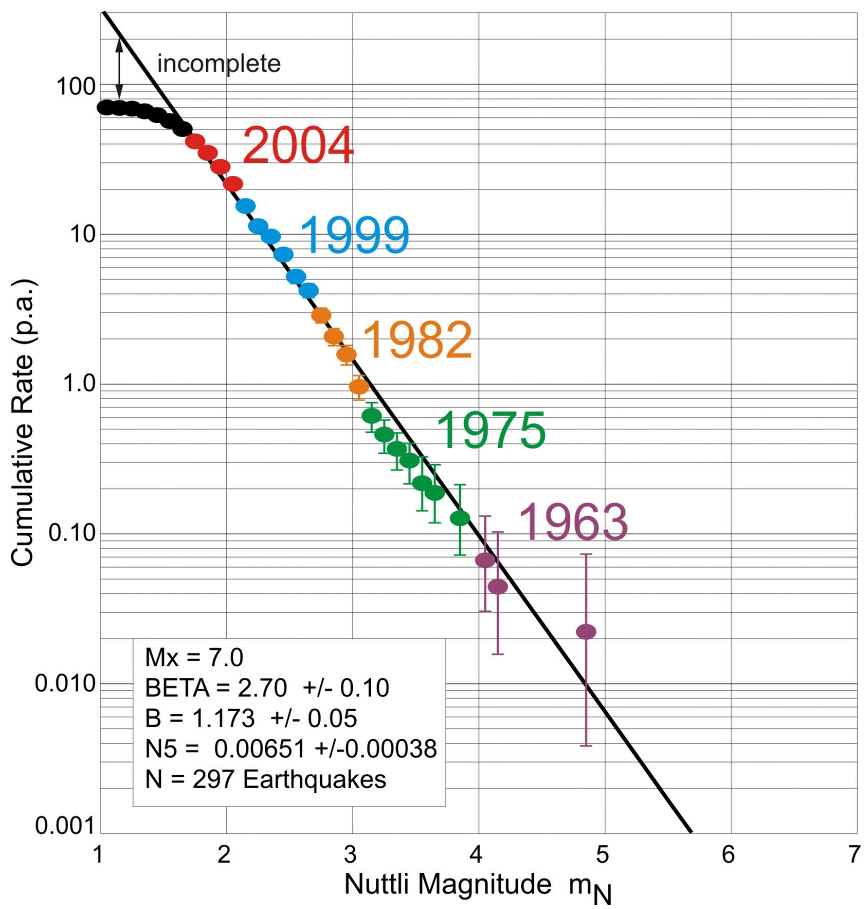

Figure 3. Magnitude-recurrence curve, with completeness years for each magnitude class

As can be seen from Figure 3, most of the data fits the curve fairly well. For larger earthquakes, the scatter of data is larger because the events are fairly rare, and statistical fluctuations give large deviates (note the size of the error bounds on each data point). That is to say, if one M 5 event is expected only every 100 years, but only ten years of data is considered, then the point for a period which had a M 5 will plot well above the fitted curve. As the magnitude of the event increases, the probability of the event decreases, and the longer the historical record needed to put the event into its proper context.

For the smallest earthquakes, the data points trend to the left of the curve and reach a maximum rate. The point at which the data deviates from the curve represents the magnitude at which the data set is incomplete – some or many earthquakes with magnitudes below this point might be missed because they are below the network detection threshold. For most of northern Ontario this occurs at approximately 1.8 m_N for the most recent years.

From this curve, the b-value is determined to be 1.2, which means that the rate of earthquakes larger than, say, magnitude 3 is about fourteen times the rate for magnitude 4. This is a higher than typical value (0.9) for earthquakes, and is also higher than the global rate for stable continental cores (SCC) of 0.87 (Fenton et al, 2006). A high b-value will produce lower seismic hazard (for the same rate of moderate earthquakes), so verifying that this value is reliable (and that the estimate is not biased by extraneous factors, such as inhomogeneous magnitudes or clustered seismicity) will be important for future seismic hazard assessments.

The rate of occurrence of a 4.5 m_N (~4.0 Mw) event over the 1.2 million square kilometre area is 0.03 per annum. Note that for the recurrence curve, the Nuttli magnitude (m_N) is used, whereas in general, for hazard purposes, Mw is normally considered: empirically a 4.5 m_N translates approximately to a 4.0 Mw event.

5. EARTHQUAKE DEPTHS IN THE CANADIAN SHIELD

As more events were located, it was noted that many of the events in the southwestern part of northern Ontario displayed a strong Rg-phase (Fig. 4). The Rg-phase is only apparent in shallow earthquakes (depths less than about 5 km). However, the station density, although increased, was not enough to make reliable direct calculations of depth. For larger events, like a magnitude 5.5 event, it is often possible to use the teleseismic waves at distant stations to calculate the depth of an event, but with our largest event being M5.2, this method could not be applied to the northern Ontario events.

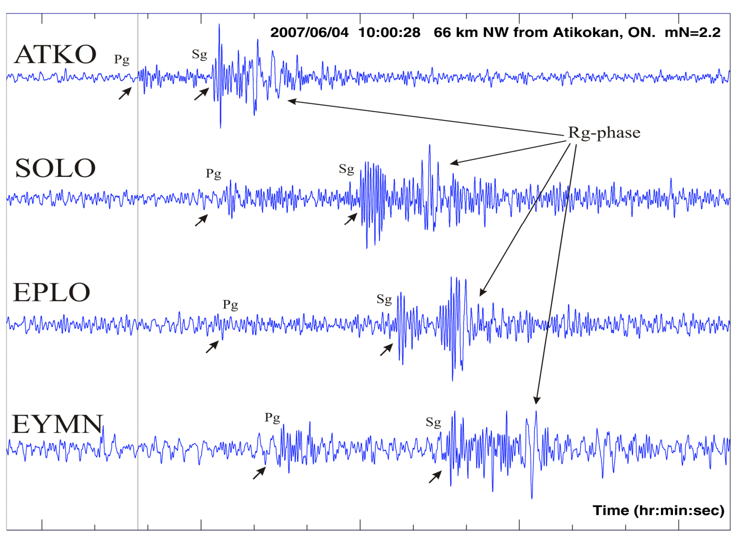

Figure 4. Rg-phases for a m_N 2.2 event in northern Ontario

However, in 2003 Shutian Ma while working at the GSC developed/adapted the Regional Depth Phase Modelling (RDPM) method (e.g. as applied in Ma and Atkinson, 2006 and Ma et al., 2008) that uses the regional depth phases of moderate-sized earthquakes (M3-4) recorded on stations at regional distances (60 to 400 km) to determine the depth (see Figure 5). Using the RDPM method, as well as the identification of Rg-phases, the depths of 250 events have been calculated or inferred (only 30 were large enough to use the RDPM method), as shown on Figure 6. The deepest event found so far occurred near Cochrane and was at 22 km.

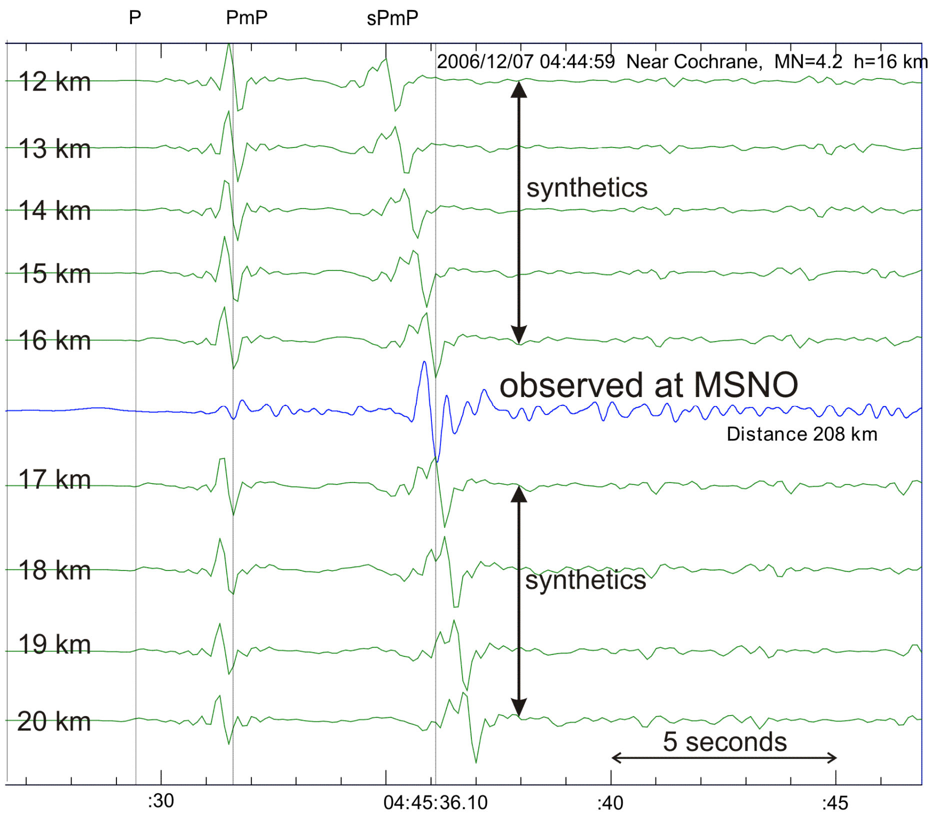

Figure 5. Region Depth Phase Modelling method: comparison of synthetic traces at different depths compared to the actual recorded trace from a m_N 4.2 event in the Kapuskasing-Cochrane region

The results thus far indicate that almost all of the earthquakes in the Severn Highlands, including the swarms near Dryden and Pickle Lake appear to be shallow (depth <6 km, and perhaps most being ≤3 km). By contrast the activity in regions of James Bay, Kapuskasing-Cochrane, and in the Western Quebec seismic zone can range from shallow to deeper (often around 10-20 km). A similar but more extensive study was done by Ma et al. (2008), with similar conclusions.

6. PATTERNS OF EARTHQUAKE ACTIVITY

In addition to the regional rate and depths of the events, there is the important issue as to whether the seismicity is a) clustered in the short-term, b) clustered in the long-term, or c) evenly distributed across the Canadian shield. Ma et al. (2008) have shown that "a" is correct for the last 20 years of data, and this is evident from the distribution of events on Figure 2.. Choice "c" is often used in seismic hazard calculations in the absence of definitive evidence, and indeed the data are inadequate to judge whether "b" is correct instead ("long-term"

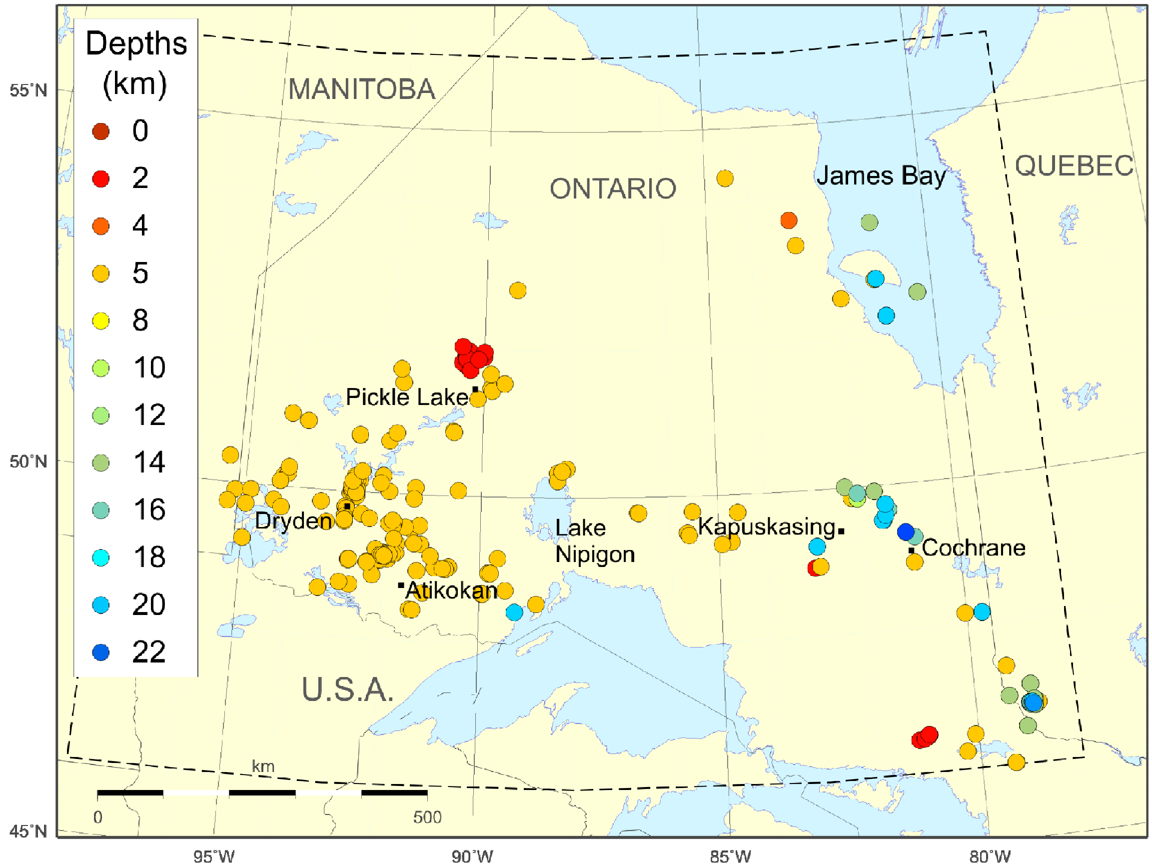

Figure 6. Earthquakes with depths determined by the RDPM method or by the presence of an Rg phase

means about 10,000 – 100,000 years, the target for the seismic hazard probability). Some arguments against "c" and for "b" have been given by Ma et al (2008), who causally link earthquake activity with either deep structures reactivated by hot spots (such as Kapuskasing-Cochrane and James Bay) or elevated topography plus a thick, high-velocity upper mantle root. Conversely lower levels of activity may occur in regions of low topography underlain by a lower-velocity upper mantle root. For example, most of the earthquakes in the Severn Highlands occur beneath topography with a surface elevation greater than 350 m that is above a high-velocity root, whereas the adjacent, topographically-lower region of Lake Nipigon has fewer earthquakes and is underlain by low-velocity mantle. Time will tell if these are robust conclusions or not.

7. IMPLICATIONS FOR SEISMIC HAZARD

The seismicity level is very low and the local b-value is quite high, which implies a low chance of strong earthquakes. However, the reliability of the b-value estimate needs to be confirmed.

Seismic hazard in regions of shallow (<5 km) earthquakes is higher than for regions with earthquakes at depths like 10 or 18 km – depths used as default depths in the absence of more accurate depth information. So in the western part of northern Ontario, most of the events are closer to the surface, and hence will be closer to any structures on or near the surface. The regions of deeper earthquakes suggest reactivated fault zones that may be more likely to generate large earthquakes.

The Fenton et al. (2006) study of global SCC earthquakes suggested that the largest earthquakes possible in SCCs are not less than Mw 6.8, and possibly larger. This means that the absence of large earthquakes during the historical record can not be taken as a zero chance that they will occur in the future. In particular, the old method of adding 0.5 units to the largest historical earthquake (~ Mw4.5 giving ~Mw5.0) would seriously underestimate the potential.

8. CONCLUSION

Enhanced seismic monitoring in the study region has decreased the location threshold in northern Ontario since 1982 from approximately magnitude 3.5 in 1982 when the study began, down to magnitude <2. Several regions that had previously been considered to be essentially aseismic, have been shown to actually have an elevated number of earthquakes compared to the surrounding regions, including James Bay, Dryden, Pickle Lake, and Atikokan, Ontario. Furthermore, the increased station density and better distribution allowed more precise locations of events, helping to define certain regions,. For example the linear Kapuskasing-Cochrane region, is, potentially an extension of the Western Quebec seismic zone. Also, the events near Pickle Lake and Dryden were confirmed as swarms confined to a small area, compared to the activity near Atikokan, which is spread over a larger geographic region.

The more than 740 earthquakes located in northern Ontario over the past 25 years have made it possible to construct a recurrence curve, which shows that the rate of earthquakes Mw ≥4.0 is 0.03 per annum for the 1.2 million square kilometer area, and the b-value is 1.2. However, this local b-value may be an overestimate, given the average global rates for Stable Continental Cores.

Using the presence of Rg-phases on events, as well as the RDPM method for moderate-sized events, it was shown that earthquakes in the south-western part of northern Ontario (in particular Dryden, Pickle Lake and Atikokan) tend to be shallow – this increases the hazard for the area, as previously most of the events were assumed to occur at mid-crust (18 km). Thus far, the deeper events appear to be limited to the Temiscaming region in the west Quebec seismic zone and the Kapuskasing-Cochrane and James Bay regions (the second possibly being an extension of the first). The deeper earthquakes suggest reactivated fault zones which are more likely to generate larger earthquakes.

REFERENCES

Adams, J. and P.W. Basham, 1991. The seismicity and seismotectonics of eastern Canada. Chapter 14 Neotectonics of North America, Decade of North American Geology volume DMV-1, p. 261-276.

Basham, P.W., D.H. Weichert, F.M. Anglin, and M.J. Berry, 1985. New probabilistic strong seismic ground motion maps of Canada. Bulletin of the Seismological Society of America, v. 75, p. 563 - 595.

Fenton, C., J. Adams, and S. Halchuk, 2006. Seismic hazards assessment for radioactive waste disposal sites in of low seismic activity. Geotechnical and Geological Engineering, v. 24, p. 579-592.

Hayek, S., J.A. Drysdale, V. Peci, S. Halchuk, J. Adams and P. Street, 2007. Seismic activity in northern Ontario portion of the Canadian Shield: Annual progress report for the period January 01- December 31, 2006. Report TR-2007-02, Nuclear Waste Management Organization, Toronto, 42 pp plus electronic appendix.

Ma, S. and G.M. Atkinson, 2006. Focal Depths for Small to Moderate Earthquakes (m_N ≥2.8) in Western Quebec, Southern Ontario, and Northern New York. Bulletin of the Seismological Society of America, v. 96, p. 609 - 623.

Ma, S., D.W. Eaton, and J. Adams, 2008. Intraplate seismicity of a recently deglaciated shield terrane: A case study from northern Ontario, Canada. Bulletin of the Seismological Society of America, v. 98 (in press).