GEOLOGICAL SURVEY OF CANADA
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Seismic Hazard Earthquake Epicentre File (SHEEF) used in the fourth generation seismic hazard maps of Canada

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Natural Resources Canada
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Open files are products that have not gone through the GSC formal publication process.

ABSTRACT

Canada's Fourth Generation seismic hazard model is the basis for the seismic design provisions in the 2005 National Building Code of Canada (NBCC). The seismic hazard earthquake epicentre file (SHEEF) was compiled in the early 1990s as a consistent catalogue to be used in the final calculations of the NBCC hazard. Canadian and American sources were consulted, and aftershock sequences were removed in three selected regions.

RÉSUMÉ

Le modèle d'aléa sismique de quatrième génération du Canada est à la base des dispositions de conception parasismique du *Code national du bâtiment du Canada* (CNB) de 2005. Le fichier SHEEF (seismic hazard earthquake epicentre file), soit un catalogue uniforme des épicentres de séisme et des aléas sismiques produit au début des années 1990, a servi à effectuer les calculs définitifs des aléas du CNB. Des sources canadiennes et américaines ont été consultées et les séquences de répliques de trois régions particulières ont été éliminées.

INTRODUCTION

The Geological Survey of Canada (GSC) has produced a new seismic hazard model and from this a suite of new seismic hazard maps for Canada (Adams and Halchuk, 2003). GSC Open File 4459 "Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada" covered the development of (and rationale for) the hazard model, provided the detailed model, and gave results for selected cities and localities across Canada. Open File 4459 formed the basis for the Canadian National Committee on Earthquake Engineering's (CANCEE) final recommendations for the seismic design provisions in the 2005 edition of the National Building Code of Canada (NBCC). Additional background information on the seismic provisions intended for NBCC2005 appeared in the April 2003 special issue of the Canadian Journal of Civil Engineering. The final NBCC2005 calculated seismic hazard values for a 10-km-spaced grid covering all of Canada and surrounding coastal waters were presented in Halchuk and Adams (2008).

The present open file is being issued to place on record and make available the earthquake catalogue that was used to develop the model and hence perform the calculations for the Fourth Generation seismic hazard maps of Canada. The earthquake epicentre solutions are provided in the Canadian Earthquake Epicentre File (CEEF) format. Sample solution lines are given in Table 1, while a detailed explanation of the format is provided in the accompanying CEEFformat.txt file.

METHOD

The prime source of information for Canadian earthquake epicentre and magnitude information is the Geological Survey of Canada's (GSC) Canadian Earthquake Epicentre File (CEEF), which has been maintained and added to since the early years of the 20th century. In anticipation of the 1985 revision to the National Building Code of Canada, this file was reviewed to ensure that it contained the most accurate information. Revised solutions, determined by various researchers at the GSC were included from the time period of 1937 to 1977 (Appendix C in Basham et al., 1982).

Considerable work by John Adams, Janet Drysdale, Robert Wetmiller and about a dozen students led to a complete revision to post-1939 eastern earthquakes. Published reports include Adams and Staveley (1985), Adams et al. (1989), Adams and Simmons (1991), Adams and Penney (1993), Adams and Wahlstrom (1995). For the published reports and all other earthquakes, the basic instrumental readings were entered into the database and used to redetermine the epicentres and Nuttli magnitudes for each event. The body of work was known informally as the "JD database" and has since been integrated with the main earthquake database. The "JD-solutions" were adopted into SHEEF. Additional revisions were made to western epicentres by Robert Horner and Garry Rogers, compiled by Dieter Weichert, and adopted into SHEEF.

EXTENT OF THE SHEEF CATALOGUE

The eastern and western regions that define the area covered by SHEEF are shown in Figure 1. Earthquakes beyond the country's boundaries are included, as they still have the potential to cause damage within Canada. Differences in ground motion attenuation between eastern and western Canada meant that earthquakes at different distances outside the country had to be considered. This distance was set at a minimum of 200 km for the southwestern and northwestern boundaries and 300 km for the southeastern boundary. In northwestern and southwestern Canadian border regions the GSC's catalogue (which had been augmented by various U.S. agency solutions) was considered accurate and complete enough out to the 200 km limit to be used as the prime source of epicentre information. In the southeastern border region the then-recently-completed NCEER catalogue (Seeber and Armbruster, 1991) was adopted as the definitive source for the northeastern United States. These revised events were included in the region extending from the Canada/US border southward to 37.5N and westward to 87.5W (Figure 2). The NCEER catalogue, which was complete to the end of 1984, was supplemented by the Weston Observatory catalogue (Ebel, pers comm.) for the time period of 1984-1988 inclusive. In eastern Canada earthquakes were included until the end of 1990, while in western Canada they were included to the end of 1991. The total number of earthquakes in SHEEF is 13,683.

"DE-CLUSTERING"

There is some debate over the inclusion or removal of aftershocks in the determination of magnitude recurrence relations (Basham et al, 1982) and thence the hazard. Basham et al wrote:

> "On the one hand, the inclusion of aftershocks violates the assumption of Poissonian distribution often used to model earthquake occurrence; on the other, large aftershocks can contribute risk (*sic*) in their own right. Further, it is often difficult to decide if earthquakes have occurred as mainshock-aftershock sequences, or as swarms with many events of similar magnitude. Examples of swarm-like activity … are the earthquakes of Byam Martin Channel, Baffin Island and Miramichi, New Brunswick. In general, the effect on magnitude recurrence of including aftershocks is a small change in the recurrence slope. This may be a small increase if many small aftershocks pass the completeness test, or a small descrease (*sic*) if only large aftershocks of the larger historical earthquakes pass the completeness test."

GSC scientists involved in the Fourth Generation model concurred with this assessment and further noted that in some places in eastern Canada aftershock activity seemed to continue for decades, or perhaps even centuries, far longer than the time scales considered for California declustering algorithms (eg Reasenberg, 1985).

As a compromise for the whole of Canada, the GSC decided to remove aftershocks from only three regions: around the Miramichi (New Brunswick), Byam Martin channel (western Arctic) and Nahanni (Northwest Territories) clusters, all of which had unusually active (swarm-like) mainshock-aftershock sequences. For each of the regions an area for the aftershock zone was developed (Figure 3). All activity prior to the mainshocks, the three or four largest events in the area and all activity more than ten years after the mainshocks were kept in SHEEF. The time periods for the aftershocks removed from Miramichi (1982-1990) and Nahanni (1985-1990) were shorter than 10 years because the dataset was complete only to the end of 1990. In all, 203 events were removed from the Byam Martin region (list provided in the file byammartin_rem.txt), 197 from Miramichi (miramichi_rem.txt) and 682 from Nahanni (nahanni_rem.txt). Figure 3 shows maps of these removed aftershocks.

DUPLICATES

A set of possible duplicate events were identified by K. Goda (*pers. comm.*, 2009). The list of duplicate candidates was divided into two eras: pre-1992 (marking the time period covered by the SHEEF catalog), and 1992-2008 (the time period during which the earthquakes are extracted directly from the CHIS database). Each candidate duplicate pair or triplet was examined, and legitimate separate earthquakes (two events separated by several degrees, part of swarm or aftershock activity where several events occurred in the same minute) were noted and retained.

In the SHEEF portion of the catalog, a total of 27 duplicates were identified. These appear to have entered the SHEEF catalog as the result of the combination of the various catalogs. The duplicates that have been removed are in the file duplicates_to_1991.ceef.txt. Should it be necessary to replicate the exact NBCC 2005 or 2010 calculations the earthquakes in file duplicates_to_1991.ceef.txt should be added back into SHEEF.

In terms of seismic hazard, only those earthquakes which were used to determine the magnitude recurrence curves for the various source zones of the Fourth Generation seismic hazard models will be of interest. In other words, the earthquakes which fall within source zones and pass completeness can potentially have an effect on hazard. Of the 27 duplicates, 10 meet these criteria and are spread over 9 different source zones. Magnitude recurrence curves were recalculated for each zone with the duplicate solutions removed. The resulting magnitude recurrence numbers were inserted into the hazard models for short period and long period calculations. Hazard values were compared for locations directly over each affected source zone to see the difference between the duplicate and no-duplicate calculations. Differences were for the most part, as expected, minimal. Of these, the differences in the Bas-Saint-Laurent region would be of greatest concern. Hazard in this region would decrease by as much as 10% when the duplicate events are removed. These changes were not implemented in the models used to determine the National Building Code of Canada 2010 hazard models. The approved changes to these models were limited to the ground motion relations. The corrected catalog will be used in the determination of hazard for the 2015 edition of the building code.

In the 1992-2008 era, a total of 103 likely duplicates were identified. The vast majority (95) of these duplicate events were located in western Canada and occurred as the result of different methods that were used to update earthquake solutions in the database. The duplicates were removed and duplicate events from this era can be found in the file duplicates1992_2008.ceef.txt. Although these duplicates have not been used in any hazard calculations by the GSC and no longer appear in the database, they are included here for the reference of researchers who may have used the dataset prior to the release of this open file.

MAGNITUDES

Those events with magnitudes of less than 2.5 were excluded from SHEEF because only earthquakes with magnitudes greater than 2¾ were to be considered for the determination of magnitude recurrence relations. Historical seismograph station spacing was such that the magnitude completeness threshold was less than 2.5 in only a few small regions around the country. Additionally, the events smaller than 2.5 may have a magnitude bias relative to larger events resulting from the method used to determine their size.

The preferred magnitude in SHEEF will vary considerably depending on agency, location and date (Figure 4). In western Canada M_L (local "Richter" magnitude) is the predominant magnitude, while in eastern Canada it is m_N (Nuttli body wave (m_{bLg}) magnitude). For offshore Canada the M_L is known to be different from onshore M_L. Other magnitudes provided by various agencies include body wave (m_b), surface wave (M_S), coda duration (M_C). Older events may be identified by M (magnitude type undefined) OT (other, usually based on intensity data) or the magnitude type may be left blank. In the catalogue, two-letter codes are used to identify the preferred magnitude type – these are defined in the supplementary file CEEFformat.txt.

Adams and Halchuk (2003) note:

> "The eastern earthquakes chiefly have m_{bLg} magnitudes, so within the hazard program we converted them to moment magnitudes using the Atkinson (1993) relation for $m_N \leq 5.5$ and Boore and Atkinson (1987) for larger events, in order to use the Atkinson and Boore (1995) strong ground motion relations. The western earthquakes have a mix of magnitudes, depending on availability and quality, and are assigned in order of preference, moment magnitude for the largest, surface-wave magnitude for the next and so on; since the definition (or calibration) of these different scales are generally perceived to blend the scales smoothly into one another, we consider them equivalent to moment magnitudes in order to apply the Boore et al. (1993; 1994) and Youngs et al. (1997) relations."

Note that no explicit conversion equations (e.g. m_b to M_W) were applied; western magnitudes were used as if they were M_W and all eastern magnitudes were presumed to be m_N, with the conversion taking place in the hazard code, as mentioned above.

EARTHQUAKE DEPTHS

The vast majority of earthquake locations in SHEEF have assigned depths. The sparse spacing of Canadian seismograph stations has until recently made it impossible to accurately determine depth. Even with the current distribution of stations depth can only be determined in a few locations. Some commonly assigned depths are 0, 1, 5, 10, 18, 20, 30, 33, 35 km. Many solutions prior to 1969 do not have any depth assigned. A one-letter code (see CEEFformat.txt) indicates how the depth was determined or assigned. Note that individual earthquake depths were not used in the Fourth Generation seismic hazard models; instead the population of determined depths were used to assign regional depths to the source zones in just the east (Adams and Halchuk, 2003):

> "For the east, best depths and upper and lower bounds are intended to indicate the likely range of earthquake depths. However in order to assign appropriate weights to the various values, for some zones (e.g. SGL), the terms lower and upper refer merely to alternative values, not relative depths. The weights are 0.5, 0.25, and 0.25.

Depth values in the western zones where the BJF relations are used (shallow crustal zones) have no physical meaning in the hazard calculation, despite our knowledge of earthquake depths there. Instead the value is a parameter in the Boore et al. (1993, 1994) equations and its value depends on the period for which ground motions are being estimated. For the subcrustal in-plate zones, for which the Youngs et al. relation is used, we decided on a single depth of 50 km near the depths of the large earthquakes that presumably occur at or near the change of subduction angle of the Juan de Fuca plate."

ACCURACY AND PRECISION OF LOCATIONS

The accuracy and precision of the earthquake locations varies considerably over time and space. Trailing zeros in the date, latitude, longitude, and depth of a solution do not indicate a higher level of precision. They are an artifact of the data storage format. Location accuracy also varies significantly. In the Lake Ontario region, for example, Stevens (1995) found that uncertainty in early- and pre-instrumental earthquakes prior to 1930 was at least ±50 km. The uncertainty reduced to ±30 km from 1930-1970, and ±10 km from 1970-1991.

THE CASCADIA EARTHQUAKE OF 1700

The location of the epicentre of the January 26, 1700 magnitude 9 (estimated) subduction zone earthquake is not known. The fault rupture along the Cascadia subduction zone is estimated to have been more than 1000 km long and the epicentre might have been anywhere along it. For inclusion in the SHEEF, the epicentre was placed at the intersection of the current Canada – United States border with the landward extent of the rupture zone (e.g. Adams and Halchuk, 2003, figure 6).

SHEEF DATA AND SUPPLEMENTARY FILES THAT ACCOMPANY THIS REPORT

SHEEF– the list of solution lines in Canadian Earthquake Epicentre File (CEEF) format
CEEFformat.txt – description of CEEF format by column number

byammartin_rem.txt – list of aftershocks removed from the Byam-Martin, NU region
miramichi_rem.txt – list of aftershocks removed from the Miramichi, NB region
nahanni_rem.txt – list of aftershocks removed from the Nahanni, NT region

duplicates_to_1991.ceef.txt – list of 27 events identified as duplicates and removed from the SHEEF catalog in late 2009. These events should be put back in the SHEEF catalog to reproduce the file used in the Fourth Generation hazard models.

duplicates1992_2008.ceef.txt – list of 103 events identified as duplicates in late 2009. These duplicates have not been used in any hazard calculations by the GSC and no longer appear in the database.

SHEEFsimp.txt – SHEEF catalogue in "simplified" format, containing just the essentials (date, time, agency, latitude, longitude, depth, depth flag, magnitude, magnitude type). For agency, depth flag, and magnitude type explanations, see the file CEEFformat.txt

SHEEF199192to2008.txt – a SHEEF-compatible list of additional, more recent solutions (not used in the Fourth Generation hazard models) from the end of the original SHEEF to the end of 2008. **Note** - no review of events outside of Canada has been done for this time period.

SHEEFpostermap.pdf – poster sized map displaying the epicentres in SHEEF.

SUMMARY

The seismic hazard earthquake epicentre file (SHEEF) was compiled in the early 1990s as a consistent catalogue to be used in the final calculations of the 2005 National Building Code of Canada seismic hazard. Canadian and American sources were consulted, and aftershock sequences were removed in three selected regions.

ACKNOWLEDGEMENTS

The creation of an earthquake catalogue is a complex undertaking, and has involved many of my colleagues over and above those whose names appear as authors on this and the related Open Files. Katsu Goda's close examination of the catalog lead to the identification of numerous duplicates and highlighted errors in the methods of updating the modern catalog. His thoroughness is much appreciated. John Adams was instrumental not only in the compilation of SHEEF but also in his extensive review and improvement of this report. I would also particularly thank Peter Basham, Janet Drysdale, Robert Horner, Garry Rogers, Dieter Weichert, and Robert Wetmiller.

All of the figures were generated using the freely available GMT (Generic Mapping Tools) software package, developed by P. Wessel and W.H.F Smith. My sincere thanks for their development and maintenance of this versatile product.

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TABLES

Table 1. Sample SHEEF solution lines (CEEF format)

FIGURE CAPTIONS

Figure 1. Earthquakes in the SHEEF catalogue. All earthquakes with a magnitude of 2.5 or greater are included in the east (red outline) to the end of 1990 and in the west (blue outline) to the end of 1991.

Figure 2. Region in the northeastern United States for which earthquakes were extracted from the NCEER catalogue for use in SHEEF.

Figure 3. Aftershock sequences removed from SHEEF. Events were removed from (a) the Miramichi region from 1982-1990), (b) the Byam Martin region from 1972-1981 and (c) the Nahanni region from 1985-1990. Most aftershocks in the Miramichi region were pegged to the mainshock location, and so plot at 47.0 °N 66.6 °W.

Figure 4. Type of magnitude that is associated with the preferred magnitude in SHEEF.

Table 1. Sample SHEEF solution lines (CEEF format)
Explanation of column values is provided in the accompanying file CEEFformat.txt

```
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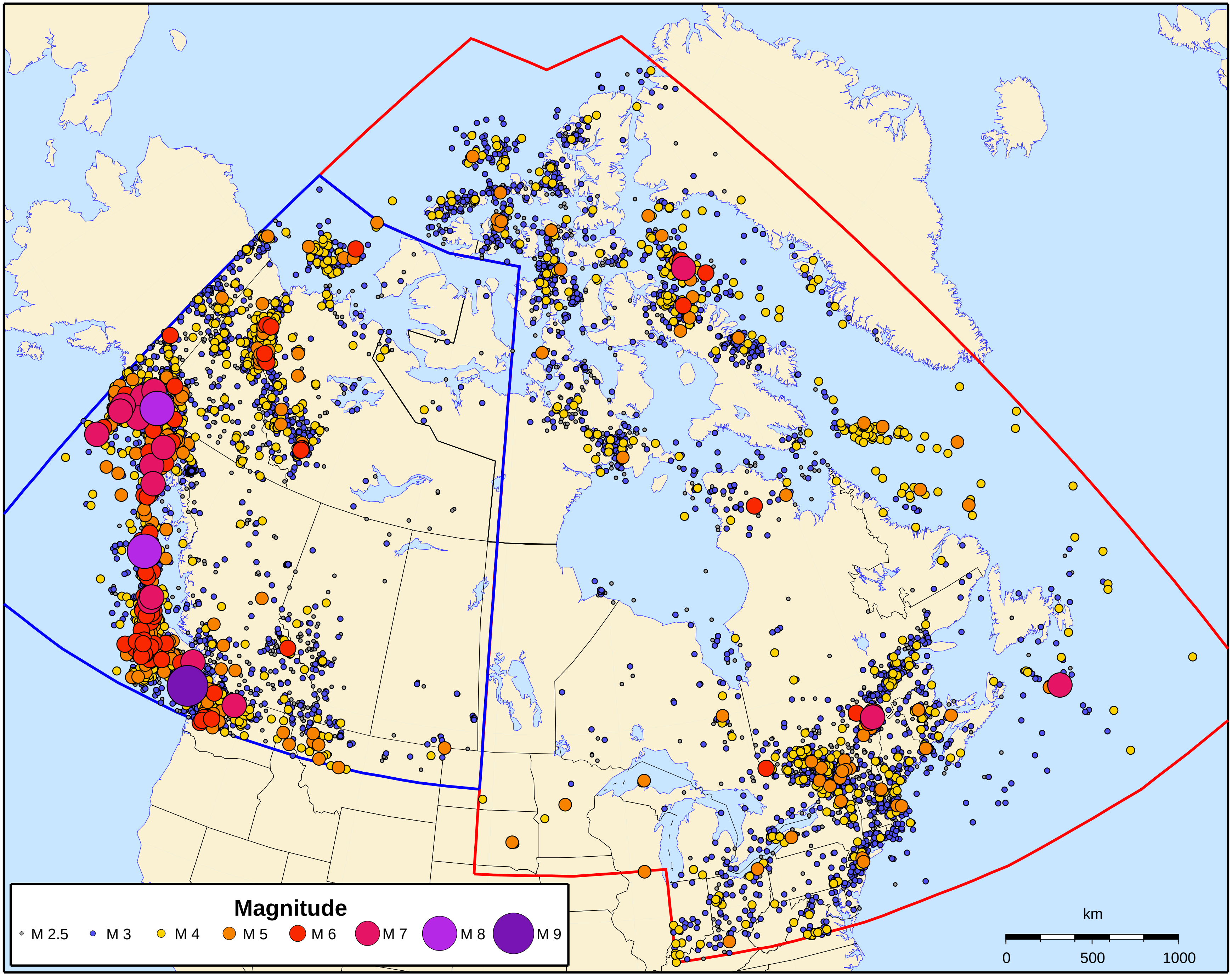

Figure 1. Earthquakes in the SHEEF catalog. All earthquakes with a magnitude of 2.5 or greater are included in the east (red outline) to the end of 1990 and in the west (blue outline) to the end of 1991.

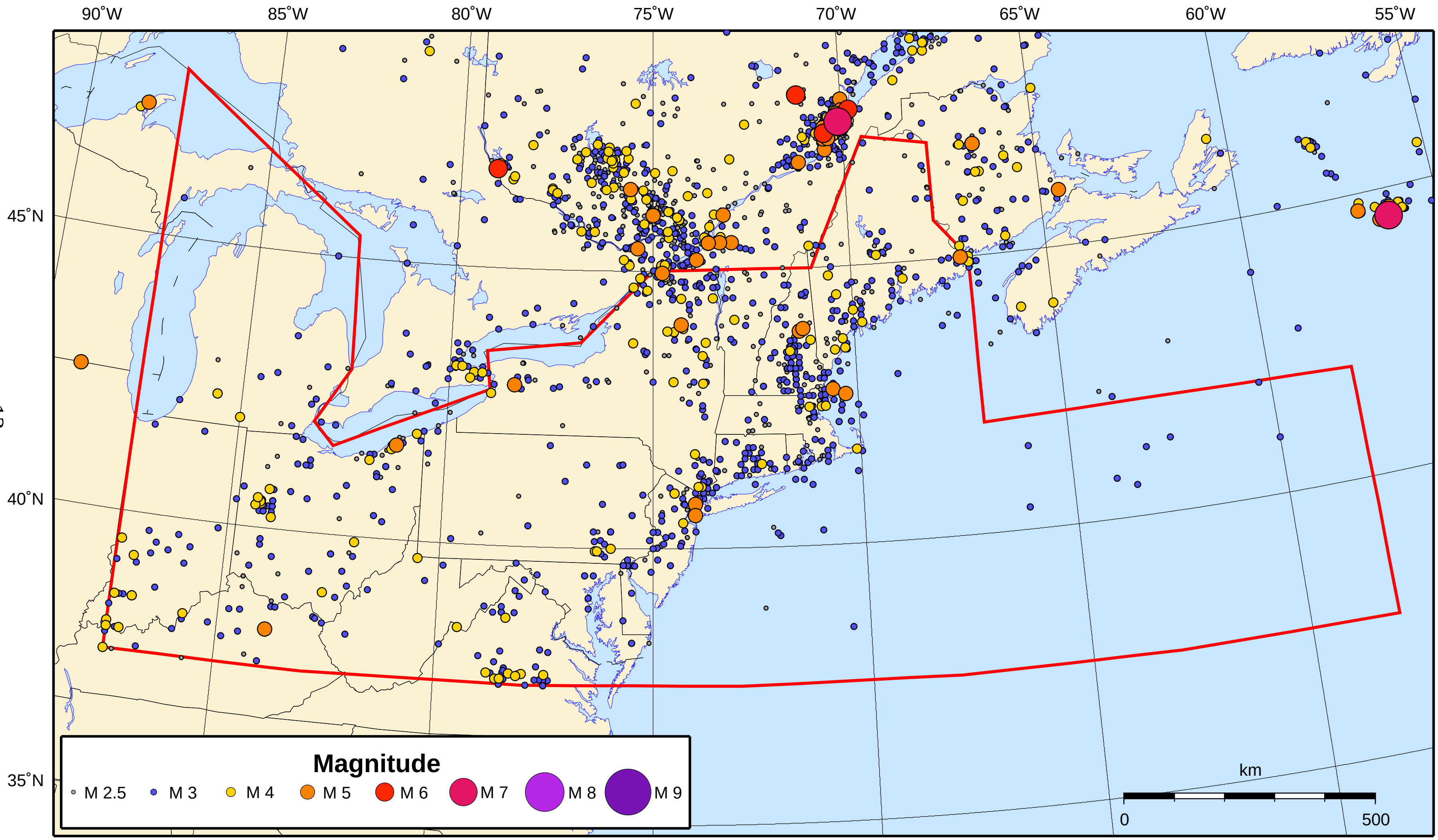

Figure 2. Region in the northeastern United States for which earthquakes were extracted from the NCEER catalog for use in SHEEF.

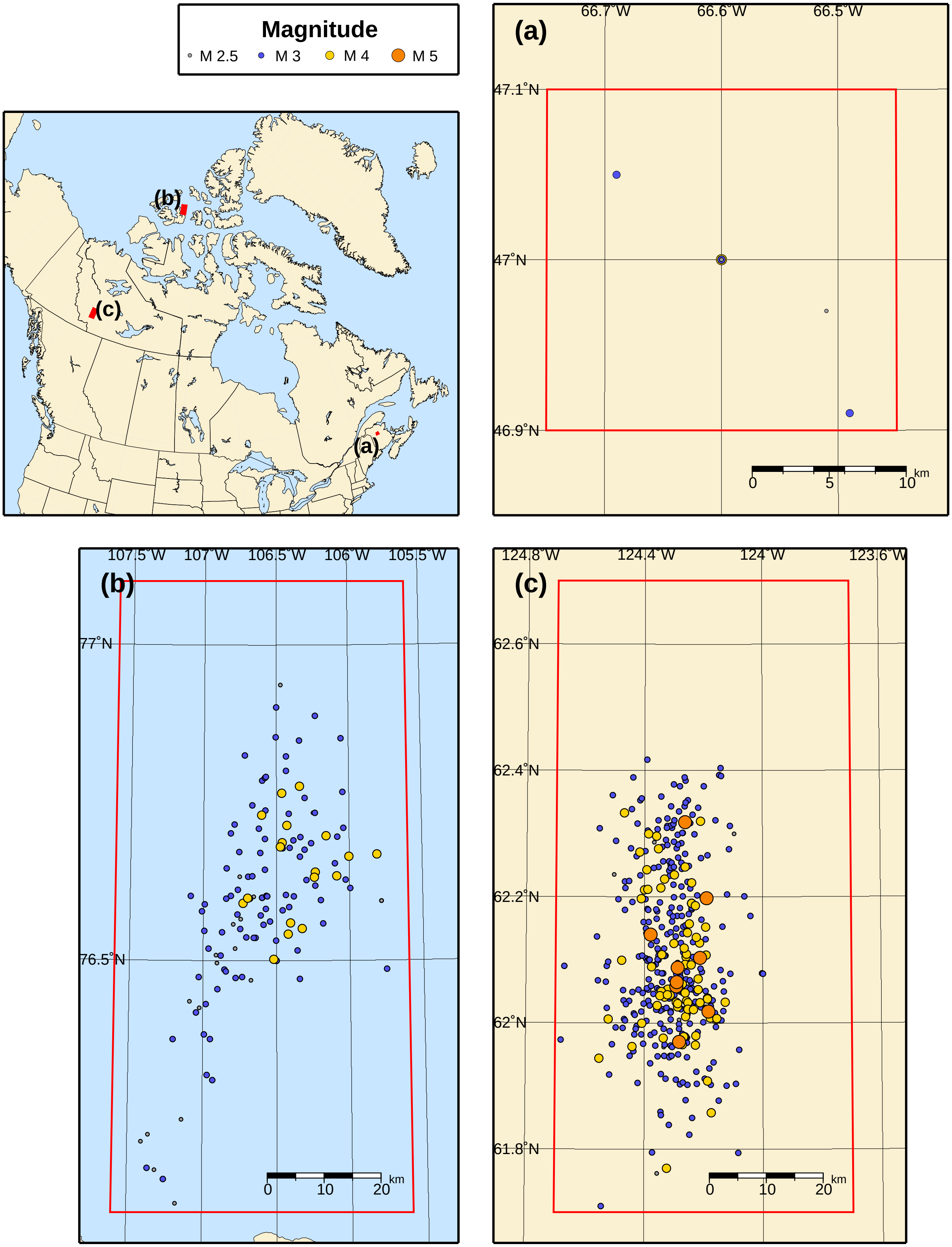

Figure 3. Aftershock sequences removed from SHEEF. Events were removed from (a) the Miramichi region from 1982-1990, (b) the Byam Martin region from 1972-1981 and (c) the Nahanni region from 1985-1990. Most aftershocks in the Miramichi region were pegged to the mainshock location, and so plot at 47.0 °N 66.6 °W.

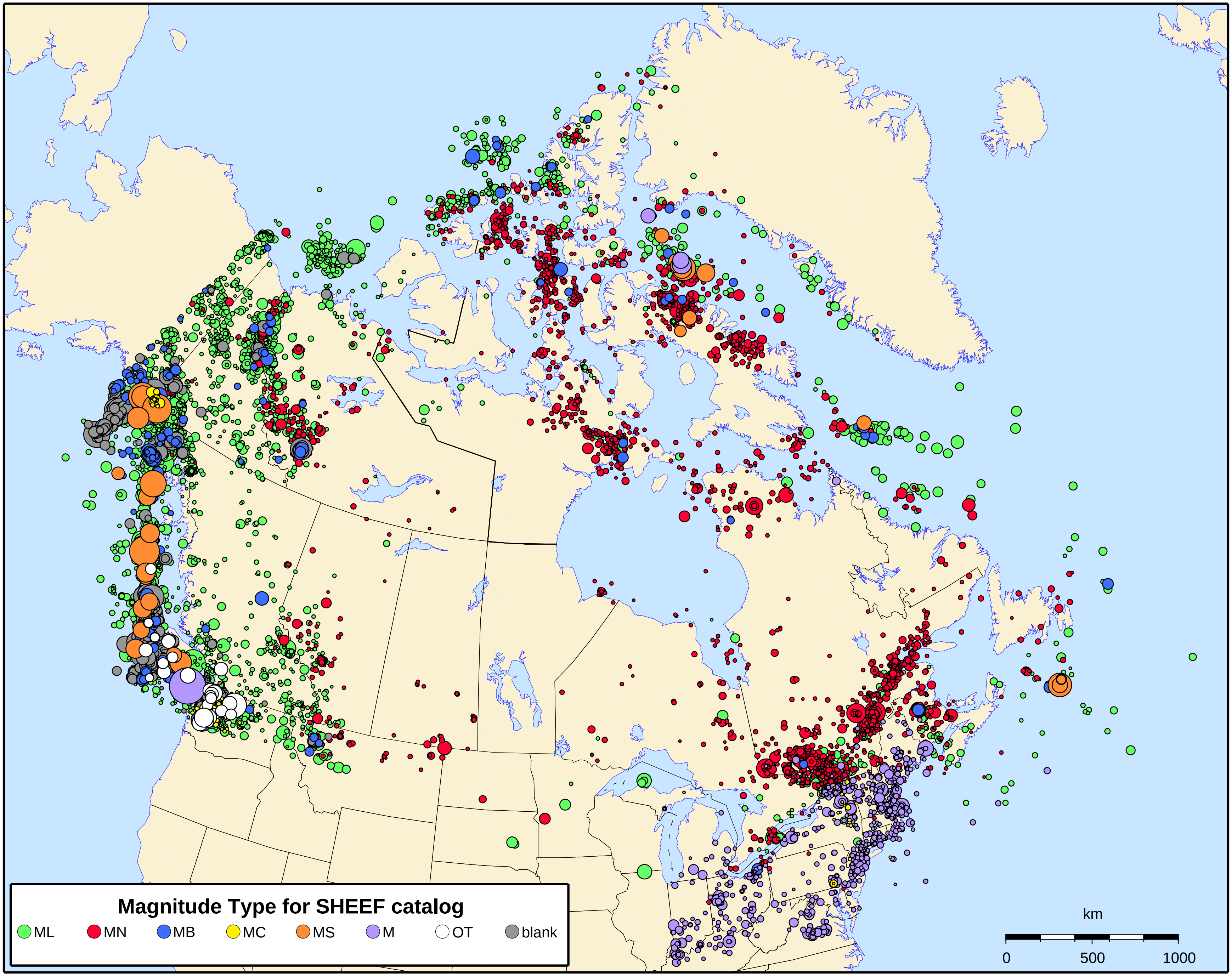

Figure 4. Type of magnitude that is associated with the preferred magnitude in SHEEF.