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Abstract

The Nuttli (M_N) scale is the most frequently used magnitude scale in eastern Canada. It is based on the amplitude of the Lg phase and therefore is not appropriate for distances of less than 50 km where the Lg phase is not developed. The original Richter, M_L, scale developed for use in California and known to be inappropriate for eastern North America, is used in eastern Canada only when the Lg phase is highly attenuated or non-existent, generally for earthquakes occurring in oceanic crust or small earthquakes that are not recorded at distances of greater than 50 km. This study focuses on the latter by establishing a magnitude relation between M_N calculated at appropriate distances and M_N or M_L calculated at close distances. The magnitude relation would enable magnitudes for very small earthquakes to be calculated from a larger number of stations and a magnitude recurrence relation to be established over a wider magnitude range. It would also enable a direct comparison of earthquakes from a particular region recorded only locally with those recorded over a wider distance range. Data from earthquakes occurring within several regions of eastern Canada for which M_N was reported as the preferred magnitude but where amplitude and period data from local stations were also measured and archived, M_L and M_N from stations at less than 50 km from the epicenter were calculated and compared to the published or event magnitudes. In most regions M_L underestimates the magnitude by more than 1 magnitude unit whereas the M_N (<50 km) values were only about 0.1-0.2 units smaller than the presumed magnitude of the earthquake indicated by M_N calculated at appropriate distances. A series of conversion relations were developed and the effects of initial magnitude type, complexity of conversion relation and global vs. regional corrections were compared. The effect of using hypocentral distance instead of epicentral distance for earthquakes at less than 50 km was evaluated but except for the closest and deepest events, the effect is not significant. Additionally, because precise depths are rarely determined for small earthquakes in eastern Canada hypocentral distances for most regions would be approximations only. For distances from approximately 10 km to 50 km it is recommended that M_N be calculated and that 0.11 be added to the value. These magnitudes can then be combined with M_N magnitudes from distances of greater than 50 km to determine the event magnitude. At distances of less than 10 km the conversion relations are not reliable and there appears to be more regional variation. Unless there are no stations at distances of 10 km or greater, magnitudes should not be calculated from such close distances. When there is no alternative, the same procedure as for 10-50 km distances should be followed but it should be noted that the magnitudes might not be equivalents to regional $M_{N.}$ For routine seismicity analysis, stations at extremely close distances are rarely essential for magnitude determination. However, in special cases usually related to focused studies of a particular location data from these distances may be crucial. In conjunction with the study of magnitudes determined from close distances, the practice in eastern Canada of using only the M_N equation for greater distances of the two equations proposed by Nuttli (1973) for all distances in eastern Canada was re-evaluated and found to be a better choice than the two-equation option. However, it was also demonstrated that attenuation relation is not ideal for eastern Canada as there is a discrepancy between magnitudes calculated at distances greater and less than 4°.

Introduction

Ideally the same magnitude scale would be used to measure all earthquakes. The reality is that many different magnitude scales are used and there are scientifically sound reasons for selecting one over the other. Among these are regional differences in geology or velocity structure, variations in the frequency content of waves from earthquakes of different sizes, the fact that some magnitude scales are based on phases that are not recorded at all distances and the ease or speed at which a particular magnitude may be calculated when responding to a felt or significant earthquake.

The Nuttli (1973) M_N scale is the primary magnitude scale for day-to-day use in eastern Canada. Note that in some older publications M_N may appear as m_N but the former is more consistent with current upper vs. lower case usage. Teleseismic magnitudes, such as M_S and m_b, are calculated only for the larger earthquakes. Moment magnitude, M_W, while calculated more frequently than it was in the past, is still difficult to calculate for the smallest earthquakes (less than M_N 4.0) and generally takes longer to determine than M_N making it less than ideal for use in urgent situations. The original Richter (1935) M_L scale is known to be inappropriate for eastern North America and is used only when there are no other practical options. More specifically, it is used for earthquakes for which there is no Lg phase and which are too small to be recorded teleseismically. These earthquakes almost all fall into one of two categories: earthquakes occurring in oceanic crust and earthquakes for which the magnitudes are calculated from data recorded at less than 50 km from the epicenter. This study focuses on the latter case. I note that Richter neither calibrated the M_L scale for nor intended it to be used at very close distances.

When different magnitude scales are used for earthquakes occurring in the same region a conversion relation between them or to another magnitude scale is needed to objectively compare their relative sizes. The present study was initially intended to focus on three data sets: routine locations from the Charlevoix Seismic Zone northeast of Quebec City where the permanent Canadian National Seismograph Network (CNSN) is sufficiently dense to routinely determine precise epicenters and often hypocenters of very small (< M_N 1) earthquakes, the aftershock sequence of the 2010 Val-des-Bois earthquake (Atkinson and Assatourians, 2010) in the Western Quebec Seismic Zone, which includes the Ottawa-Montreal region, and the McAdam, New Brunswick swarm (Bent et al., 2017). In an attempt to better understand the significantly different conversion relations for the McAdam swarm in relation to the two Quebec seismic zones, the study region was subsequently expanded in stages to include all of eastern Canada. In the regions added at this later stage of the study the data set was restricted to events where period-amplitude-magnitude data were available from at least one station at an epicentral distance of less than 5 km. A 5 km distance cut-off was selected as that is roughly where the conversion relations and/or the magnitudes themselves appear to break down and where the data set was in most need of enhancement. Data from stations in the 5-50 km range were included for these additional events when available from the pick file but no effort was made to search for events where the closest station was in that distance range. Earthquakes used in the analysis are shown in Figure 1. For readers unfamiliar with the term, a pick file is the database file for an earthquake containing the origin time, location and magnitude as well as the phase data used to derive those parameters.

Using the data set described above a series of magnitude conversion relations were developed. All involved comparing single-station M_L or M_N recorded at distances of less than 50 km to the event or catalog M_N calculated from regional (> 50 km) distances. For each magnitude type both constant and linear relations were determined for distances of 10-50 km for all regions combined and for specific regions when there were sufficient data. Magnitude residuals comparing converted station magnitudes to the event magnitudes from the Canadian National Earthquake Database (CNED, 2017, see Data and Resources) were calculated. The statistical F-test was used to determine the significance of any differences. Considering all factors, recommendations for including magnitudes at close distances in routine seismic monitoring were developed.

While very small earthquakes rarely pose a hazard to humans and are often not felt, how to use amplitude-period data recorded at close distances has implications beyond trying to determine magnitudes for earthquakes too small to be recorded at regional distances. Expanding the range over which reliable magnitudes are calculated may lead to improved seismic hazard estimates if they are based on magnitude recurrences rates. Additionally, being able to determine rapid and reliable magnitudes from close distances has applications to aftershock studies, earthquake early warning and monitoring of volcanoes and regions where induced seismicity is of concern.

Magnitudes in Eastern Canada

The Nuttli (1973) M_N magnitude scale is the most commonly calculated magnitude for earthquakes occurring in eastern Canada. While the original scale consisted of two equations the equation for distances greater than 4° is used regardless of the distance based on the recommendation of Wetmiller and Drysdale (1982). Details on the use of M_N in eastern Canada are discussed further in Bent (2011a) and Bent and Greene (2014). While those two studies raise some issues questioning whether M_N is the most appropriate choice, it nevertheless, remains the primary magnitude scale in current use and in the earthquake catalog. The most important factor to consider for the present study is that M_N is based on amplitudes of the Lg phase and thus is not defined for distances of less than 50 km. While GSC seismic analysts may calculate M_N from stations at less than 50 km, they exclude the resulting magnitudes from the event magnitude calculation, which is defined as the mean of all individual station magnitudes not explicitly excluded. We also note that M_N in eastern Canada is calculated at generally higher frequencies than the range near 1 Hz that Nuttli (1973) intended. While this has resulted in some complications converting M_N to M_W (see Bent and Greene, 2014), it is not considered to be a significant issue for the current study. The earthquakes evaluated cover a fairly narrow range of magnitudes where all amplitude measurements have been made at high frequencies and a comparison of frequency used in the magnitude calculations vs. magnitude and distance reveals that the extremely high frequencies (short periods) are pervasive and not confined to the smallest or closest earthquakes (Figures 2a and 2b).

While M_L (Richter, 1935), which was developed for use in California, is known to be a less than ideal choice for eastern North America, it is used when all else fails as it can almost always be calculated. In eastern Canada, the original M_L distance relations are used with no modifications for the different crustal structure between eastern and western North America. Two differences, however, are that the vertical component is used whereas the scale was defined for the horizontal component and the waveforms are used as is and not converted to a Wood-Anderson equivalent. The Richter scale as published in 1935 was not calibrated for distances less than 25 km. Richter (1935) noted that the scale was not as well calibrated between 25 and 50 km as at it was at greater distances, mostly because of a lack of data. He also commented that he did not foresee extending the scale to distances of less than 25 km where a better way to determine magnitudes might be by comparing the seismograms to those of earthquakes from a similar epicenter that had magnitudes well determined by measurements at more distant stations. In part, this comment was motivated by the problem of clipped records at close distances but even with modern instruments the approach may provide the best magnitude estimates when such data are available. However, in regions of sparse seismicity this method may not be viable as there may be no recordings of larger earthquakes with which to compare the smaller ones.

With respect to the use of the M_L scale in eastern Canada, the distance corrections are obtained from a look-up table, which has the same correction for all distances from 5 km down to 0 km. As such, if the same amplitude and period data are entered for distances of 2 km and 5 km, the resulting magnitude will be the same. Tests with the McAdam data extrapolating the trend of the distance correction for 5-15 km to shorter distances led to an average station magnitude change of 0.1 units suggesting that this may not be a significant issue. However, apart from that test, there is no numerical or analytical study to prove that the extrapolation is valid. The M_N scale, which is a straightforward equation, can easily be applied at all distances but that does not necessarily imply that the distance correction is valid outside the range for which it was intended. In a slight diversion from the primary focus of this paper, evidence is presented that suggests the attenuation relation used in the M_N calculations may need to be modified.

M_N: One Equation or Two

The justification for using only a single equation to calculate M_N in eastern Canada comes from Wetmiller and Drysdale (1982), a short abstract for a presentation made at the Annual Meeting of the Eastern Section of the Seismological Society of America. This work and the supporting data never appeared as a full length publication making it difficult to evaluate the validity of their conclusions. However, it is an easy task to determine whether more consistent results are obtained with a single equation or with the two equation approach preferred by Nuttli (1973).

$M_N = 3.75 + 0.90\log\Delta + \log(A/T)$ for $0.5° \le \Delta \le 4°$
$M_N = 3.30 + 1.66\log\Delta + \log(A/T)$ for $4° \le \Delta \le 30°$

Δ is distance in degrees, A is amplitude in µm and T is period in seconds.

Earthquakes from the beginning of 2006 through late 2016 were extracted from the Canadian National Earthquake Database (CNED, 2017). The dataset consisted of earthquakes east of 110° W for which M_N was listed as the preferred magnitude (8111 events). It was then reduced to events for which at least three station magnitude (amplitude-period) readings at each of the two distance ranges (479 events; Figure 3) were used to calculate the catalog magnitude. As a rule, events in the south were eliminated because they lacked magnitudes at distant stations and in the north because there were too few close magnitudes. Nevertheless, the spatial distribution of the resulting data set is reasonably representative of seismic activity in eastern Canada.

Individual station magnitudes were recalculated and mean network magnitudes for each event were calculated for the following groups of stations: close stations, distant stations and all stations. For each group magnitudes were calculated as follows: Nuttli's preferred two equations, distant equation only and close equation only. Event magnitude is defined as the mean of all individual station magnitudes and not the mean of the close group and distant group. It therefore may be weighted more heavily by one distance range than another depending on the earthquake.

When both equations are used the mean station magnitudes from the close stations are, on average, 0.35 magnitude units greater than the mean station magnitudes calculated from more distant stations. When only the distant equation is used, the difference is reduced to 0.16. If only the close equation is used, the difference is 0.44. To satisfy the author's curiosity, one more set of calculations was run this time using the distance equation for close stations and the close equation for distance stations. The mean difference was -0.25. Thus, using the single distant equation does lead to more consistent results and Wetmiller and Drysdale (1982) made the best choice given the above options. However, the difference between the two groups is still significant. These results suggest that the attenuation relation is inappropriate for eastern Canada and/or that practices, such as calculating magnitudes at higher frequencies than those for which the scale was intended, are affecting the results.

Using the two equation M_N, the average event magnitude is 0.13 magnitude units greater than those in the CNED (2017, Data and Resources), which is potentially large enough to affect the magnitude recurrence curves used in seismic hazard calculations (for example, Bent, 2011a). Thus, the choice of magnitude equation and attenuation has a potential impact beyond a simple indication of earthquake size and there is value in pursuing this issue further.

$M_{Lg(f)}$ (Herrmann and Kijko, 1983) has been proposed as an alternate magnitude scale for routine use in eastern Canada (Bent and Greene, 2014). It is similar to M_N but was developed based on the theoretical properties of the Lg wave and designed to better handle measurements made at high frequencies. Tests using the $M_{Lg(f)}$ scale show that its relation to M_W, unlike the M_N conversion relation, is not time dependent making it a better choice for a long-term catalog. Tests to date using the $M_{Lg(f)}$ scale were based on the attenuation relation used by the United States Geological Survey (USGS) for m_{bLg} measurements in the eastern US (Q=1400; J. Dewey written communication, 2012). $M_{Lg(f)}$ magnitudes were calculated for the data set discussed above and mean close and far magnitudes were calculated and compared. A similar discrepancy between close and far magnitudes was observed providing further evidence that the attenuation relation may be inappropriate. Whether M_N is retained as the preferred magnitude for eastern Canada or whether $M_{Lg(f)}$ or another scale is adopted it would be desirable to investigate attenuation to determine the most regionally appropriate value.

Comparison of Magnitudes at Close and Greater Distances

An earlier study (Bent and Vadnais, 2016) evaluated all earthquakes in the Charlevoix Seismic Zone occurring over a six month period (January-June 2012) for which M_N was noted as the official event magnitude type. The Charlevoix Seismic Zone northeast of Quebec City is one of the most active seismic zones in eastern Canada and the seismograph station density is higher than in most other regions of eastern Canada. These two factors combined make it an ideal region for comparing earthquakes of different magnitudes and for comparing the same earthquakes at local and regional distances. Their study concluded that M_L at distances of less than 50 km underestimated the earthquake size, assuming that M_N determined at the correct distance range is an appropriate measure of size, by 1.2 magnitude units. Similar conclusions had been obtained in an earlier study by Lamontagne (1999). M_N calculated at distances of less than 50 km underestimated the regionally derived M_N value by 0.2 magnitude units and as such appears to be a better choice for close range magnitudes. I note, however, that the M_N magnitudes would not be true M_N's as Lg is not developed at these distances.

In the present study, the data set has been extended to other regions to verify whether the conversion relations from Bent and Vadnais (2016) are applicable elsewhere in southeastern Canada. All amplitudes, periods and event magnitudes used in the present study come from the CNED (2017, Data and Resources). The CNED sometimes includes both M_N and M_L data for a single station and sometimes only one. In the latter case I calculated whichever magnitude type had not been previously calculated. Note that a visual inspection of the database shows that M_N and M_L when available for a given station and earthquake are calculated from the same phase (i.e period, amplitude, time). Thus, calculating the magnitude for one of them using the amplitude-period data in the pick file for the other is consistent with current practice and should not contaminate the data set. For the purposes of subsequent discussion, “close” distances are defined as being less than 50 km and “very close” distances as less than 5 km.

Extending the Charlevoix data set to cover a longer time period (2012 to present) and adding in the aftershocks of the 2010 Val-des-Bois earthquake, the conclusions were very similar to those obtained by Bent and Vadnais (2016). These results suggest that the previously derived magnitude conversion relations should be valid outside the Charlevoix Seismic Zone. To avoid confusion I use the term $M_{N(event)}$ to represent the M_N magnitude of the event as stated in the CNED (2017; see Data and Resources) and $M_{N(close)}$ to represent M_N values obtained from single stations at distances of less than 50 km. All M_L values discussed in this paper are for distances of less than 50 km and therefore do not need such a designation. The combined dataset to this point of the study consisted of 3283 station magnitudes from 1206 events. Uncertainties are expressed as one standard deviation unless indicated otherwise.

$M_{N(event)} = M_L + 1.18 \pm 0.41$
$M_{N(event)} = M_{N(close)} + 0.12 \pm 0.38$

However, an evaluation of the data set for the 2012 McAdam, New Brunswick swarm (Bent et al., 2017) led to very different results. In this case, M_L overestimates M_N by 1.1 magnitude units on average. There are several possibilities that could explain the difference. The McAdam events occurred in Appalachian crust and both the Charlevoix and Val-des-Bois events occurred in the Canadian Shield. Differences in attenuation could affect the M_N values from regional data. Local differences in shallow crustal structure or attenuation not accounted for in regional velocity models could possibly affect the local M_L values. Another possibility would be the range of distances covered by each data set and the potential effects of epicentral vs hypocentral distance for the closest events. Earthquakes in the Charlevoix and Val-des-Bois regions typically occur at depths of 10-20 km and are recorded by stations at distances of a few to a few tens of km. The McAdam events were extremely shallow (< 1.5 km) and recorded by stations 1-2 km from the epicenters.

To test the hypothesis that regional attenuation is a factor the analysis comparing magnitudes at distances of less than 50 km to M_N values calculated at distances of 50 km or more was repeated for all other New Brunswick earthquakes since 2006. The data set includes a few earthquakes occurring in the state of Maine and is therefore referred to as the Appalachian data set. The results were comparable to those from the two Quebec data sets, suggesting that differences in regional attenuation is not a dominant factor in the M_N-M_L differences despite there being some evidence for regional attenuation differences (Bent, 2010, 2011b)

The data set was then further extended to focus on magnitude readings from very close, less than 5 km, distances to determine whether McAdam is unique or whether the same difference in magnitude scales is seen in other regions. This data set consists of (mostly) mining related events in Northern Ontario predominantly from the Sudbury region, which like the McAdam events are shallow, as well as any other events in eastern Canada with magnitude readings at very close distances. The latter group is a combination of earthquakes and blasts from Quebec and Ontario. For these two data sets, events since 2006 were selected where there was a least one magnitude calculated from a station at a distance of 5 km or less. Additional station magnitudes at 5-50 km were included in the data set only if they were present in the extracted events. The resultant Charlevoix, Val-des-Bois and Appalachian data should adequately cover the 0-50 km range across a broad region of eastern Canada. Figures 4a and 4b compare $M_{N(close)}$ and M_L to $M_{N(event)}$. The complete dataset consists of 3728 station magnitudes and leads to the following magnitude conversions with uncertainty expressed as one standard deviation:

$M_{N(event)} = M_L + 1.14 \pm 0.46$
$M_{N(event)} = M_{N(close)} + 0.13 \pm 0.39$

Values for specific regions are summarized in Table 1. Note that the data sets for some regions were preferentially selected to focus on distances of less than 5 km and those are the ones for which the mean differences are the most different from the values derived from the overall data set. It should be noted that the scatter for each group is quite large and the uncertainties are 1.5-2 times what would be considered a typical standard deviation (0.1-0.3) for a specific magnitude type calculated for an individual earthquake.

Table 1
Mean Difference between Event Magnitudes and Magnitudes from Stations at 0-50 km Assuming a Constant Conversion Relation

Region	# points	M_N(event)-M_L(station)	M_N(event)-M_N(close stations)
All	3728	1.14 ± 0.46	0.13 ± 0.39
Charlevoix	2585	1.16 ± 0.40	0.13 ± 0.38
Val-des-Bois	704	1.24 ± 0.43	0.14 ± 0.37
Appalachian	211	1.13 ± 0.51	0.14 ± 0.49
McAdam	14	-1.06 ± 0.47	-0.51 ± 0.37
Northern Ontario	114	0.45 ± 0.40	0.23 ± 0.41
other Quebec-Ontario	106	1.04 ± 0.48	0.39 ± 0.38

A linear relation was also considered and the results are summarized in Table 2 where Δ is distance in km and uncertainty is expressed as standard error. Region specific linear conversions were determined only for those regions where the dataset covers a broad range of distances.

Table 2
Mean Difference between Event Magnitudes and Magnitudes from Stations at 0-50 km Assuming a Linear Conversion Relation

Region	# points	M_N(event)-M_L(station)	M_N(event)-M_N(close stations)
All	3728	$1.10 + 0.0019\Delta \pm 0.46$	$0.20 - 0.0031\Delta \pm 0.39$
Charlevoix	2585	$1.21 - 0.0019\Delta \pm 0.43$	$0.21 - 0.0038\Delta \pm 0.38$
Val-des-Bois	704	$1.19 + 0.0021\Delta \pm 0.43$	$0.10 + 0.0017\Delta \pm 0.37$
Appalachian	211	$1.37 - 0.0077\Delta \pm 0.50$	$0.29 - 0.0048\Delta \pm 0.49$

Table 1 confirms that the conversion relations appear to be different for those data sets dominated by magnitude measurements made at very close distances (McAdam, Northern Ontario). Figure 5a shows what appears to be a fall-off in the $M_{N(event)}$-M_L curve at approximately 10 km. A similar but somewhat less pronounced change is also seen when $M_{N(close)}$ is compared to $M_{N(event)}$. Binning the data in 5 km windows and calculating the mean difference (Figure 5c) also suggests that the relation changes somewhere in the 5-10 km distance range. Bearing that in mind, the analysis described above was repeated using only magnitudes from stations at 10-50 km. The results are summarized in Tables 3 (constant) and 4 (linear). Further discussion will focus on the 10-50 km range. Distances of 0-10 km will be treated as a separate case and the definition of very close is revised to <10 km to reflect this.

Table 3
Mean Difference between Event Magnitudes and Magnitudes from Stations at 10-50 km Assuming a Constant Conversion Relation

Region	# points	M_N(event)-M_L(station)	M_N(event)-M_N(close stations)
All	3147	1.20 ± 0.41	0.11 ± 0.36
Charlevoix	2290	1.18 ± 0.40	0.08 ± 0.36
Val-des-Bois	582	1.33 ± 0.36	0.19 ± 0.33
New Brunswick	204	1.13 ± 0.50	0.13 ± 0.49

Table 4
Mean Difference between Event Magnitudes and Magnitudes from Stations at 10-50 km Assuming a Linear Conversion Relation

Region	# points	M_N(event)-M_L(station)	M_N(event)-M_N(close stations)
All	3147	$1.44 - 0.0087\Delta \pm 0.40$	$0.16 – 0.0015\Delta \pm 0.36$
Charlevoix	2290	$1.39 - 0.0079\Delta \pm 0.35$	$0.08 + 0.0004\Delta\pm 0.36$
Val-des-Bois	582	$1.57 - 0.0102\Delta \pm 0.31$	$0.33 - 0.0059\Delta \pm 0.32$
Appalachian	204	$1.45 – 0.0096\Delta \pm 0.50$	$0.28 – 0.0045\Delta \pm 0.49$

To determine the relative value of a constant conversion relation versus a linear one, whether a region-specific conversion has any value over a global (i.e. applicable to all regions studied) conversion and whether converting from one magnitude type (either M_L or $M_{N(close)}$) to $M_{N(event)}$ gives more consistent results, a series of tests were run. Station magnitudes from distances of 10-50 for the data sets noted in Tables 3 and 4 were converted to a regional M_N equivalent (i.e. $M_{N(event)}$) using the various conversion relations summarized in those tables. The residuals, defined as the difference between the M_N calculated from regional data (i.e. $M_{N(event)}$) and the converted M_N, were calculated and compared using the statistical F-test. Except in the case where regional differences are explored, the conversion relations used are those derived for the specific regions.

Although the residuals vary by orders of magnitude they are all considerably smaller than the precision to which magnitude is normally calculated- usually one and occasionally decimal place. Comparing the constant and linear relations for the combined data set, the p value from the statistical F-test is 0.592 for $M_{N(close)}$ and 0.713 for M_L. Neither of these values is statistically significant, which suggests there is no value in applying the more complex linear relation. Comparing the same complexity of conversion for M_L and $M_{N(close)}$ the p values are 0.845 for the constant conversion relation and 0.934 for the linear one. These values have even less statistical significance and imply that there is no value in using one magnitude type over another for the calculation of $M_{N(event)}$.

For routine magnitude calculations it would be preferable to employ a universally applicable conversion relation as it is much simpler to automate. However, it is also important that magnitude conversion relations be as accurate as possible. To properly compare regional vs. global conversion relations, the magnitudes for the regional data sets should be compared using the two conversion relations. Note that the word "global" is used to refer to the combined data set from all regions. The values derived from the regional conversion relations were previously tabulated in Tables 4 and 5 and those from the global conversion relations are summarized below in Table 6.

Table 5
Summary of Mean Residuals Using the Regional Conversion Relations from Tables 3 and 4

Data Set	M_L constant	M_N constant	M_L linear	M_N linear
All	0.0023 ±0.41	0.0042 ± 0.36	-0.0015 ± 0.40	-0.00067 ± 0.36
Charlevoix	-0.0019 ± 0.40	0.0085 ± 0.36	0.00010 ± 0.39	0.000012 ± 0.35
Val-des-Bois	-0.00079 ± 0.36	0.0038 ± 0.33	0.0017 ± 0.35	0.000020 ± 0.32
Appalachian	0.0063 ± 0.51	0.0024 ± 0.49	0.00009 ± 0.50	-0.0039 ± 0.48

Table 6
Mean Residuals using Global ("All") Conversion Relations from Tables 3 and 4

Data Set	M_L Constant	M_L Linear	$M_{N(close)}$Constant	$M_{N(close)}$ Linear
Charlevoix	-0.022 ± 0.40	-0.027 ± 0.39	-0.022 ± 0.36	-0.031 ± 0.36
Val-des-Bois	0.13 ± 0.36	0.096 ± 0.35	0.084 ± 0.33	0.069 ± 0.33
Appalachian	-0.064 ± 0.51	-0.023 ± 0.50	0.022 ± 0.49	0.021 ± 0.49

The statistical F-test comparing the differences in regional residuals for each of the above global conversion relations returns a p value of 0 implying that the regional differences are highly significant. Moreover, the same relation is found when the residuals for the complete data set (from Table 5 and in which case "all" is the regional relation) are considered. These results suggest that from a purely statistical perspective it would be better to apply regional corrections than global ones. However, it should be reiterated that for the most part, the mean residuals are smaller than the precision to which magnitude is usually calculated. A notable exception is the M_L constant conversion relation applied to the Val-des-Bois data set. It is also noted that in terms of absolute value, the $M_{N(close)}$ conversion relations generally lead to smaller residuals than do the M_L conversions. Another issue to consider is that regional corrections have not been determined for all regions of eastern Canada. Taking all of these factors as well as earlier discussion into consideration, the global $M_{N(close)}$ constant conversion relation would likely be the best compromise solution for routine analysis. That is, for distances of 10-50 km $M_{N(close)}$ should be calculated from the data and then 0.11 added to the calculated value. When there are stations at distances of more than 10 km, it is recommended that stations at distances of less than 10 km not be used to calculate event magnitudes.

The conversion constant is small and magnitudes from stations at 10-50 km will be mixed with magnitudes from stations at greater than 50 km when the event magnitude is calculated. To determine whether the effect is significant or negligible, the Charlevoix events were used as a test case. This region has, on average, a higher number of stations in the 10-50 km distance range than elsewhere and, thus, any effect should be largest here. Bent and Vadnais (2016) noted that for the time period they studied 45% of all M_N's for Charlevoix were based on a single station and only 32% were based on data from three or more stations. Conversely, there were no M_L magnitudes based on only one station and 93% were from three or more stations despite the fact that M_L is used for smaller earthquakes. Thus, including data recorded at less than 50 km can significantly increase the number of stations used, and should provide better azimuthal coverage, which, in turn, should lead to better corrections for factors such as radiation pattern and ultimately to a better average magnitude.

Using the same Charlevoix events that were used thus far in the present study, $M_{N(event)}$ was recalculated including stations at 10-50 km. In one case, the M_N magnitudes were corrected by adding 0.11 (the global constant conversion) and in the other case they were used "as is". In the first instance the difference between the catalog magnitude and the recalculated magnitude is -0.013 ± 0.17, and in the second instance, it is -0.056 ± 0.24. The statistical F-test returns a p value of 0.001 indicating that the difference is highly significant. Thus, there is value in applying the correction. When the same test is applied to the complete data set, the results are equivocal. Applying the conversion reduces the mean residual from 0.013 ± 0.20 to 0.0077 ± 0.15 but the p value of 0.435 indicates that the results are not statistically significant. Not surprisingly, these tests show that the significance of applying the correction increases when the percentage of stations at distances of less than 50 km used in the magnitude calculation increases.

Discussion

Hypocentral vs. Epicentral Distance

Magnitudes are traditionally calculated using epicentral distance. This practice stems partly from the fact that reliable depths cannot always be determined, especially in the initial analysis of an earthquake, and partly because, except for the very deepest events, the difference between hypocentral and epicentral distance is generally insignificant over the distance range at which most magnitudes are calculated. The m_b scale, which was historically used for very deep earthquakes, does include a depth correction.

At close and especially at very close distances the difference between epicentral and hypocentral distance becomes more significant, more so as the depth increases. Bent and Vadnais (2016) showed the effect as a function of depth and distance and provided some examples from the Charlevoix region. When the M_N magnitude scale is used at the appropriate distances (> 50 km) the difference is relatively insignificant for typical earthquake depths in eastern Canada. Eastern Canadian earthquakes occur within the crust and generally in the upper to mid-crust (for example, Lamontagne, 1999; Bent and Perry, 2002; Ma and Atkinson, 2006) and thus the epicentral distances is generally greater than the depth by a factor of two. For M_L magnitudes used for close distances, the impact can range from negligible to highly significant (see the aforementioned examples in Bent and Vadnais, 2016). Recent studies focused on magnitudes at close distances have suggested that hypocentral distance should be used (for example, Butcher et al, 2017; Yenier et al., 2017; Atkinson et al, 2015). A comparison of Figures 6a and 6b shows the difference in the number of events in the "very close" distance range depending on whether the distance is defined as epicentral or hypocentral.

The magnitudes used in the current study from epicentral distances of 5 km or less were recalculated using hypocentral distance (Figure 6b). The recalculated distances and, by extension, magnitudes based on fixed depths will be less reliable than those with free depths but they are retained as they at least separate the shallow from the mid-crustal earthquakes, which may move a reading from the "very close" to the "close" distance range. Outside of the Charlevoix Seismic Zone free depths are rarely calculated as part of the initial location process. In eastern Canada depths are most often fixed at 18 km (mid-point of the crust) but other values may be used. For example, if a strong Rg phase is noted a shallower depth will be used. In cases where there is a priori information about typical depths in a particular region a value other than 18 km may be used. Regardless of whether epicentral or hypocentral distance is used the average difference between the event magnitudes and the magnitudes calculated at very close distances (< 5-10 km) are noticeably different from those calculated for close (5-10 to 50 km) distances. Thus, very close distances need to be treated as a special case.

Very Close Distances

A fully satisfactory method for dealing with very close distances is beyond the scope of the present study. There are insufficient data to fully resolve some of the issues raised in the previous sections and in the discussion that follows.

First, it is noted that (see also Figures 4-6) that the magnitude conversion relations for very close distances seem to vary from one region to another, suggesting that regional corrections may be more important at these distances than for 10-50 km. Second, at these distances the difference between hypocentral and epicentral distance may be significant but outside of the Charlevoix Seismic Zone free depths are rarely determined for small earthquakes. The McAdam swarm is an exception due to the deployment of several local stations. A search of the database (CNED, 2017, Data and Resources) shows that free depths have been determined for only 10% of events with depths listed as 5 km or shallower, mostly from the two previously mentioned regions. In Charlevoix, because of the station distances, there are very few events with hypocentral distances less than 5 km and few where the hypocentral distance is less than 10 km. Thus, it is only for the McAdam swarm where there is a data set of hypocentral distances less than 5 km based on free depths. Given that the magnitude relations for McAdam appear to be anomalous, that the complete very close data set shows more regional variations than the close data set, and that the data set for McAdam is relatively small, it would not be advisable to make generic recommendations from the McAdam data alone.

As was noted in the "Magnitudes in Eastern Canada" section, the M_L scale as used in eastern Canada does not have distance corrections for distances of less than 5 km, but an assumed extrapolation from the 5-15 km corrections suggests that this has only a minor effect on the magnitudes. The IASPEI recommendations for M_L (IASPEI, 2013) are based on an equation that can, in theory, be used for shorter distances but it is noted that this equation assumes that M_L will be measured from horizontal components and that a conversion to a Wood-Anderson instrument will be made, neither of which is a valid assumption based on current practice in eastern Canada as was discussed in a previous section. In western Canada, where M_L is widely used, the IASPEI recommendations are followed (T. Mulder, personal communication). A comparison of the IASPEI equation and the GSC extrapolation for M_L at distances of less than 15 km is shown in Figure 7. The absolute magnitudes should not be compared as they are based on different criteria. However, the fall off in magnitude with decreasing distance is much more extreme and closer to what is seen in the observed data (Figures 5a, 6a, 6b). This suggests, but does not prove, that if M_L were calculated following the IASPEI recommendations the disconnect at about 10 km distance might be resolved.

As an aside, it may be difficult to implement the IASPEI recommendations using the software in current use in eastern Canada (Dan- see Data and Resources section) but it would be relatively simple should other programs (for example, Antelope, SeisComP3, see Data and Resources Section) be adopted. It is not possible to back calculate M_L for eastern Canada following these recommendations using the earthquake catalog as amplitude data from the horizontal components are rarely read or archived. There are published studies (for example, Boore and Atkinson, 1987; Atkinson, 1993; Atkinson and Boore, 1997; Siddiqqi and Atkinson, 2002; Bent and Delahaye, 2007) that provide horizontal to vertical or H/V ground motion relations for eastern Canada that could be applied to convert the amplitudes in the database to approximate horizontal equivalents. Alternatively, it would be possible to start reading these amplitudes in the future and then evaluate the difference. As the horizontal component is almost always larger than the vertical, using the horizontal should decrease the difference between M_L and M_N.

It is also noted, that while the $M_{N(close)}$-$M_{N(event)}$ relation for very close distances is not the same as for close distances (Figure 5b), the difference is considerably less than for the M_L-$M_{N(event)}$ relation (Figure 5a) but the issue of regional differences remains. Using the M_N scale for very close distances would be preferable to using the M_L scale in terms of categorizing the size of the earthquake but it is not ideal. There have been several recent publications proposing region-specific M_L scales (for example, Butcher et al., 2017; Di Bona, 2016 and references therein). There are currently insufficient data to develop an M_L or other magnitude specifically for use at very close distances in eastern Canada. The published regional scales were developed for regions where the velocity structure and attenuation are not necessarily comparable to eastern Canada but further evaluation of these magnitude scales might reveal whether one of them would be preferable to those scales in current use.

For the short term it is recommended that when data from stations at distances of 10 km or greater are available for an earthquake that magnitudes not be determined from closer stations. In the rare instances that data only from distances of less than 10 km are available, the procedure for 10-50 km should be followed but it should be explicitly noted (for example, in the comment line of a pick file) that the magnitudes may not be equivalent to those calculated at greater distances. In terms of procedure, this means that M_N should be calculated and a correction of 0.11 magnitude units applied. While hypocentral distance would be preferable, the lack of well constrained depths make it impractical for routine application and, at least for the short term, epicentral distance can be used. If hypocentral distance is used, it needs to be explicitly stated in the pickfile, whether it was used for all stations or only those at a specific distance range and whether it was based on a fixed or a free depth.

While this procedure is not ideal and might not result in magnitudes that are truly equivalent to those calculated at greater distances, it should be an improvement over current practice where the difference between the magnitudes used for local (M_L) and regional (M_N) stations differ by more than an order of magnitude. In cases, such as the McAdam swarm, where there are a large number of earthquakes recorded by local stations, the relative magnitudes should be internally consistent and it may be possible to develop a local conversion relation using earthquakes that were recorded both locally and regionally.

It is also recommended that the issue of magnitudes at very close distances be given further study and if possible, a solution developed that is applicable over the complete range of distances typically used to determine magnitudes. Most of the topics in need of further study have been previously raised in this document. One further avenue for consideration is the calculation of magnitudes from spectral data.

A Short Note on M_W

M_W (Hanks and Kanamori, 1979) or moment magnitude, which can be related to the physical properties of the fault rupture and which does not saturate at high magnitude, is currently generally considered the preferred magnitude scale for characterizing the size and for use in seismic hazard assessments. It is, however, difficult to calculate for small earthquakes and was not until recently calculated routinely for Canadian earthquakes of any magnitude. Bent (2011a) developed an M_N-M_W conversion relation. The conversion relation is reliable for moderate sized earthquakes but should be used with extreme caution for smaller ones. First, the Bent (2011a) study did not include any earthquakes of magnitude (type) less than 2.5. Second, recent research (Deichmann, 2017) has shown that the conversion relations between M_W and other magnitude types break down for very small magnitudes as the scaling relation is different.

Conclusions

A variety of issues surrounding magnitudes at close distance in eastern Canada were explored. The principal conclusions, recommendations for routine magnitude calculations over the short term and recommendations for future research to improve magnitude calculations over the long term summarized below.

1. For routine M_N calculations at distances >50 km, use Nuttli's (1973) distant equation for all distances as recommended by Wetmiller and Drysdale (1982). Research is needed to improve the attenuation relation. Continue to explore alternate magnitudes, such as $M_{Lg(f)}$, also taking attenuation into consideration.

2. For distances of 10-50 km, calculate M_N as above but add a 0.11 magnitude unit correction and then calculate event magnitude in the usual manner. Note that there are some regional differences in the ideal correction and, for region-specific studies, there might be some value in recalculating the magnitudes using the region-specific corrections.

3. Magnitudes should not be calculated from stations at distances of less than 10 km unless there are no recorded waveforms from stations at greater distances. In this case the procedure outlined in conclusion 2 should be followed but somewhere it should be noted that the resulting magnitude may

not be the equivalent of an M_N calculated at the appropriate distances. Although this was not explicitly discussed in the text, one option would be to use a slightly different magnitude designation, such as $M_{N'}$. If the data set is large enough, determine and apply a regionally appropriate correction and make note of it.

4. While hypocentral distances would be preferable especially for very close distances, practical considerations make this difficult to apply universally and it is therefore recommended to continue to use epicentral distance. If hypocentral distance is used in particular cases, it should be clearly noted as well as whether it was used for all stations or only those within a particular distance range.

5. Explore alternative methods and magnitude scales to determine whether there is one option that would provide consistent results across the range of distances for which small and moderate earthquakes are typically recorded in eastern Canada. One choice to consider is the use of spectral methods.

6. Any changes to current practice must be documented and available to users of the earthquake database.

Acknowledgements

I thank Michal Kolaj for his constructive review and comments and Nicholas Ackerley, John Adams and David McCormack for discussion on the topic.

Data and Resources

Most figures were plotted using GMT software:

Wessel, P., W. H. F. Smith, R. Scharroo, J. F. Luis, and F. Wobbe (2013). Generic Mapping Tools: Improved version released, ***EOS Trans. AGU***, **94**, 409-410.

Amplitude and period data used in the magnitude calculations were obtained from:
CNED (2017). Canadian National Earthquake (Digital) Database, http://www.earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php, last accessed January 2017.
Note that the event magnitudes may be obtained directly by accessing this link. Phase data are available on request by contacting Earthquake_Info@NRCan.gc.ca .

The statistical F-tests were performed using the online ANOVA calculator:

http://www.danielsoper.com/statcalc/calculator.aspx?id=43

Earthquake location software packages briefly mentioned in the text include:

DAN – currently used for routine locations and magnitudes in eastern Canada, originally proprietary software from Nanometrics (http://www.nanometrics.ca/, last accessed 14 July 2017) with in-house modifications

Antelope is proprietary software by Boulder Real Time Technologies (http://www.brtt.com/software.html, last accessed 14 July 2017).

SeisComP3 is a seismological software for data acquisition, processing, distribution and interactive analysis that has been developed by the GEOFON Program at Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences and gempa GmbH. (last accessed 14 July 2017)

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Figures

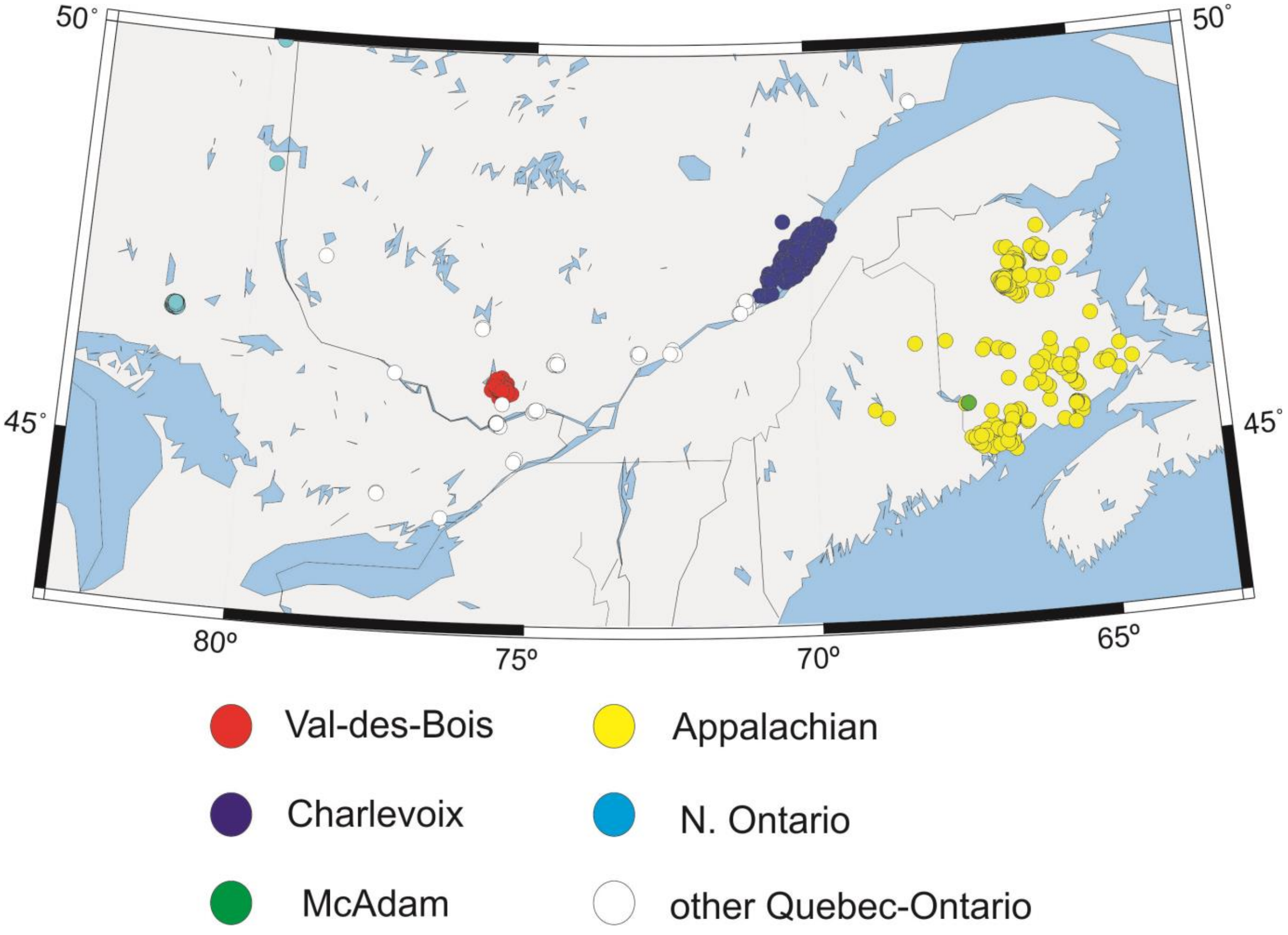

Figure 1: Map showing events used in the analysis of magnitudes at distances of less than 50 km. Note that the same color scheme is retained in subsequent plots.

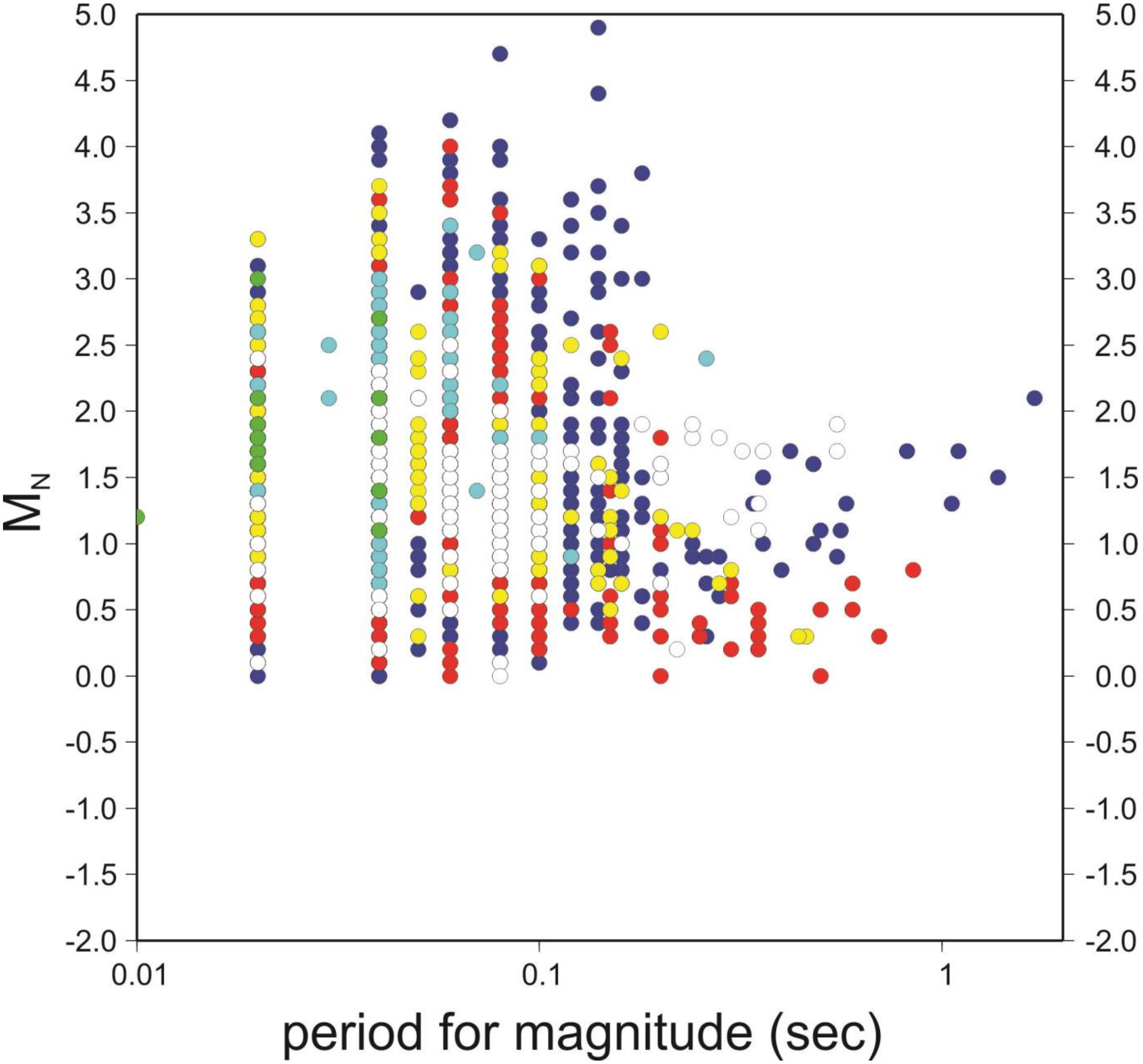

Figure 2a. M_N magnitudes used in this study plotted against the period at which the amplitude measurement was made. Note that the x-axis is plotted on a logarithmic scale.

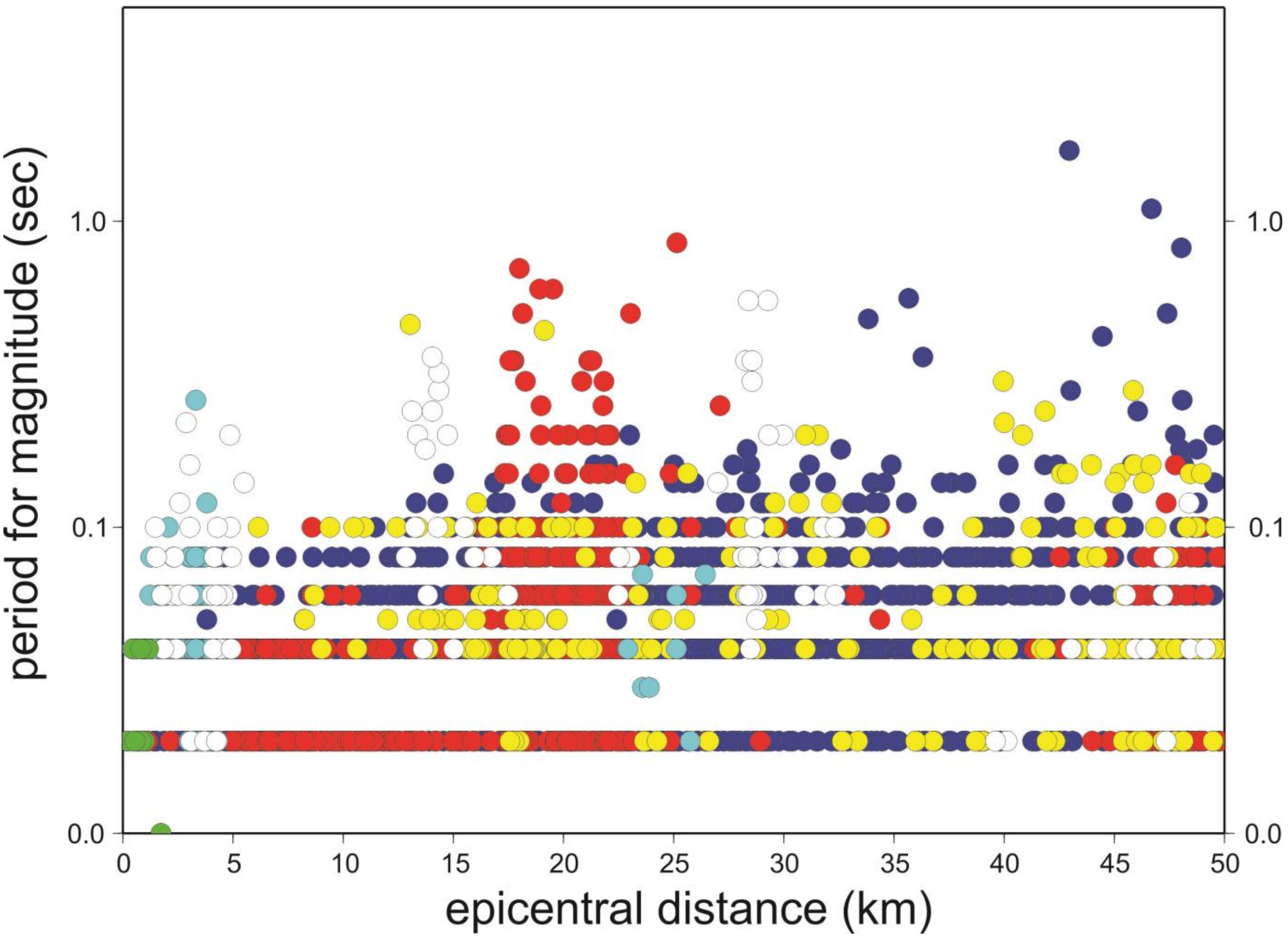

Figure 2b. Period at which magnitudes were calculated plotted as a function epicentral distance. Note that the y-axis is plotted on a logarithmic scale.

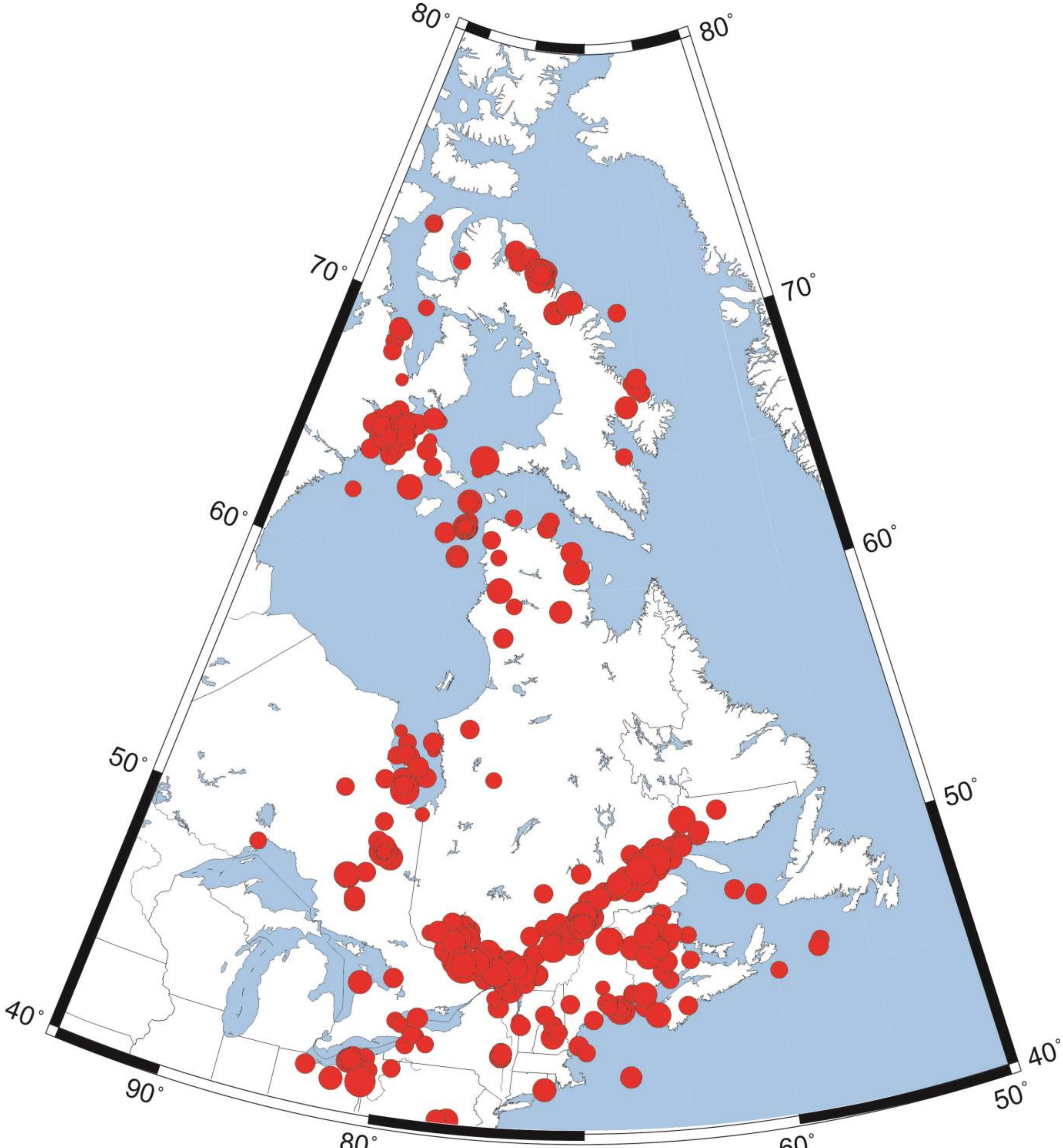

Figure 3: Events used in the evaluation of M_N equations. Symbol size is scaled to M_N.

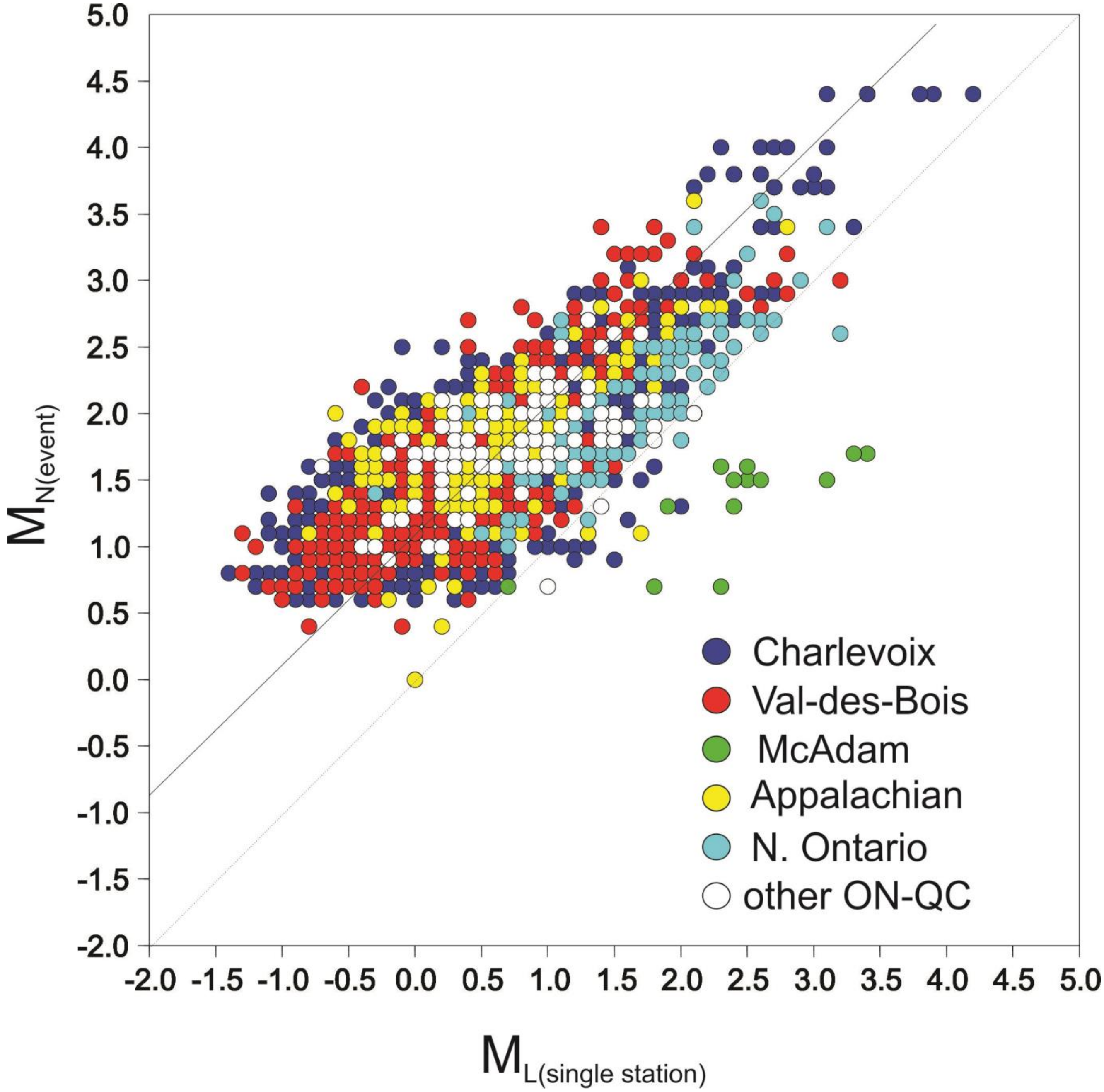

Figure 4a. Comparison of M_L magnitudes calculated at stations within 50 km of the epicenter and the event-averaged M_N based on amplitudes at distances beyond 50 km. Note that many data points plot at the same coordinates. The largest datasets (Charlevoix and Val-des-Bois) are plotted as the back layers. The apparent lower magnitude cut-off of M_N at approximately 0.5 is not intentional but reflects that smaller earthquakes are rarely recorded at distances appropriate for the M_N scale to be used. The dashed diagonal line shows a 1:1 correspondence between M_L and M_N and the solid line shows the best fit to the data.

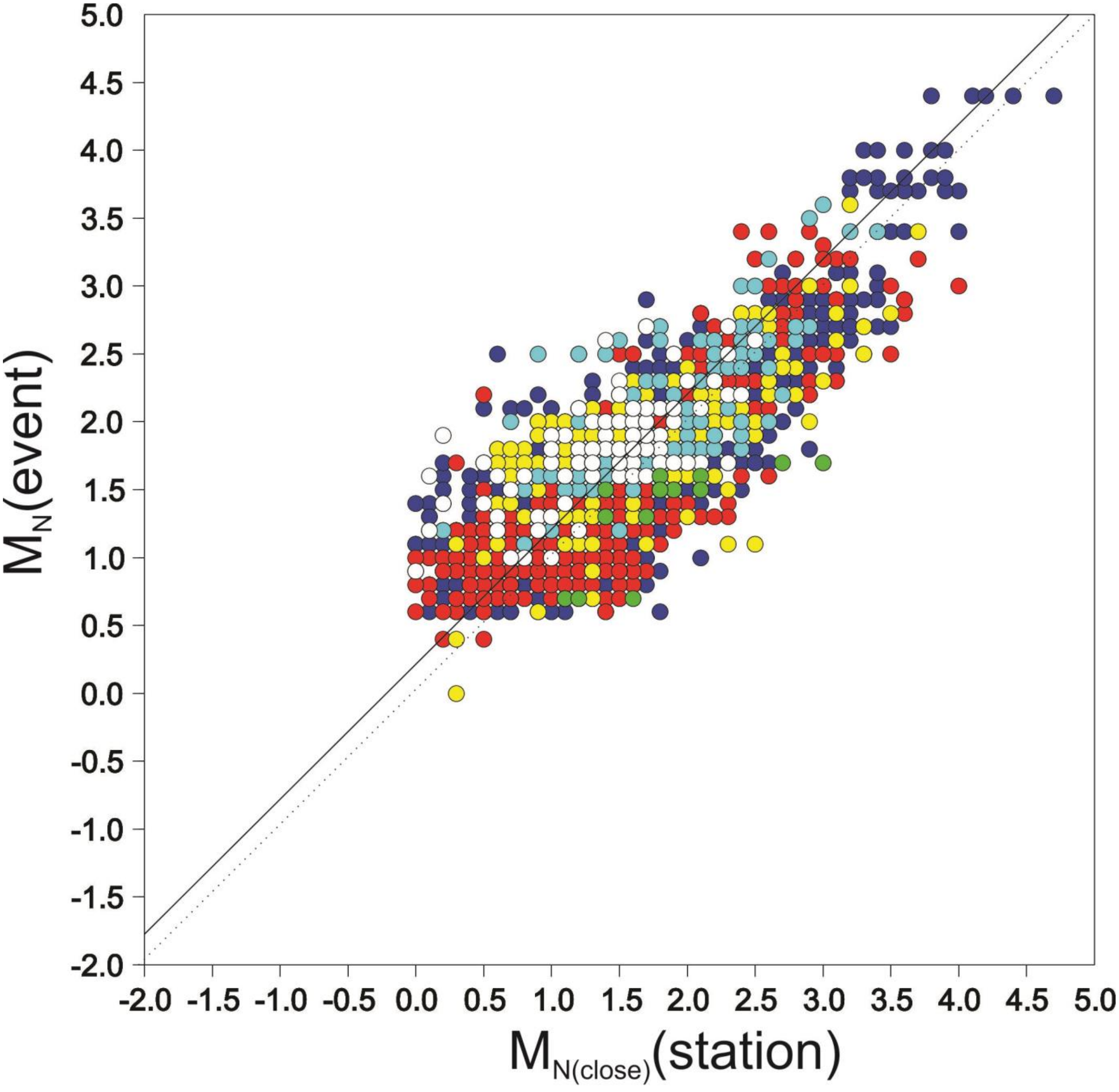

Figure 4b: Comparison of $M_{N(close)}$ magnitudes calculated at stations within 50 km of the epicenter and the event-averaged M_N based on amplitudes at distances beyond 50 km. See caption for Figure 4a for more details on plotting and data set. The dashed diagonal line shows a 1:1 correspondence between $M_{N(close)}$ and M_N and the solid line shows the best fit to the data.

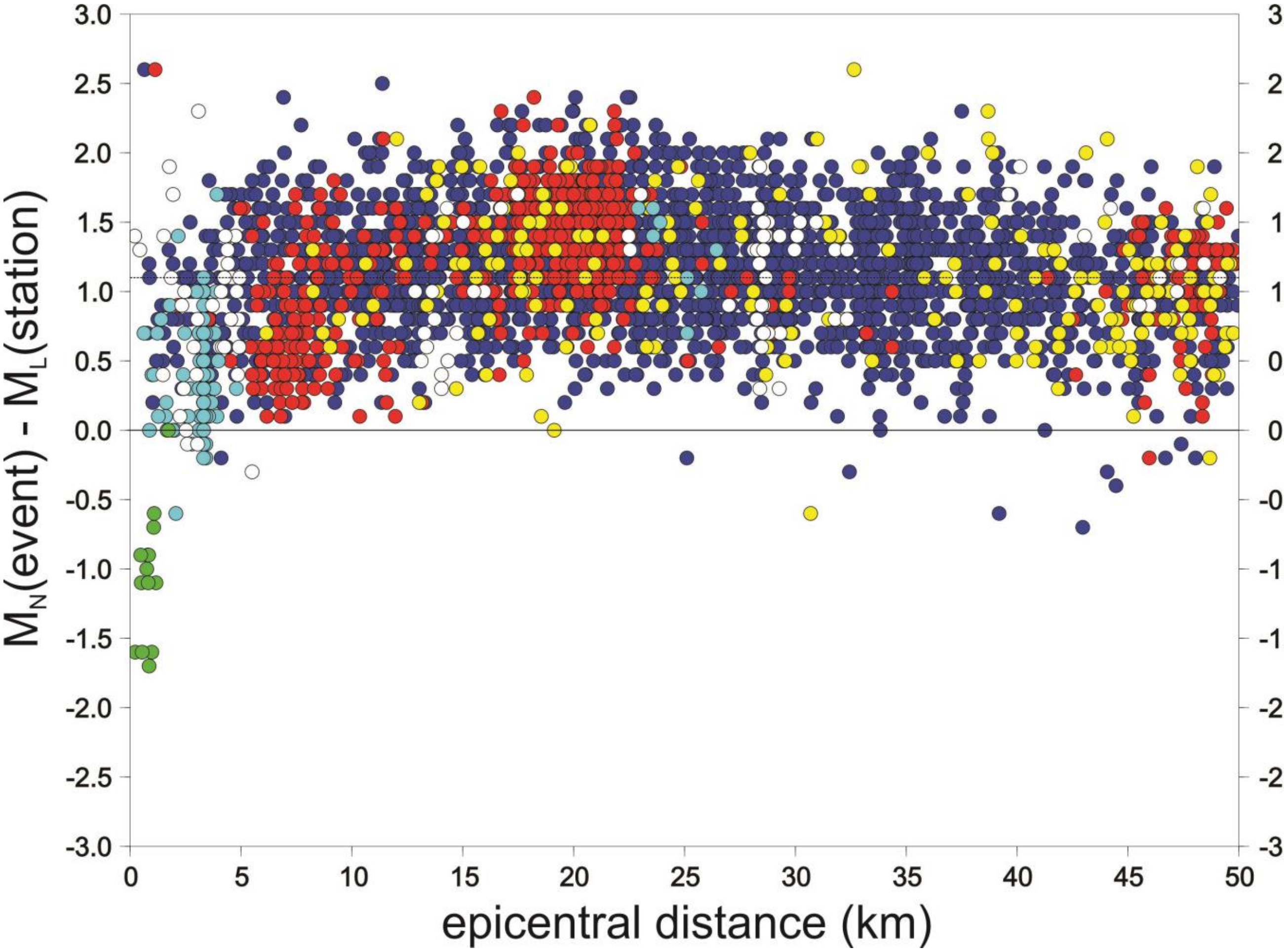

Figure 5a. The difference between the event M_N and single station M_L values plotted as a function of epicentral distance. The solid horizontal line shows a 0 difference and the dashed line shows the mean difference.

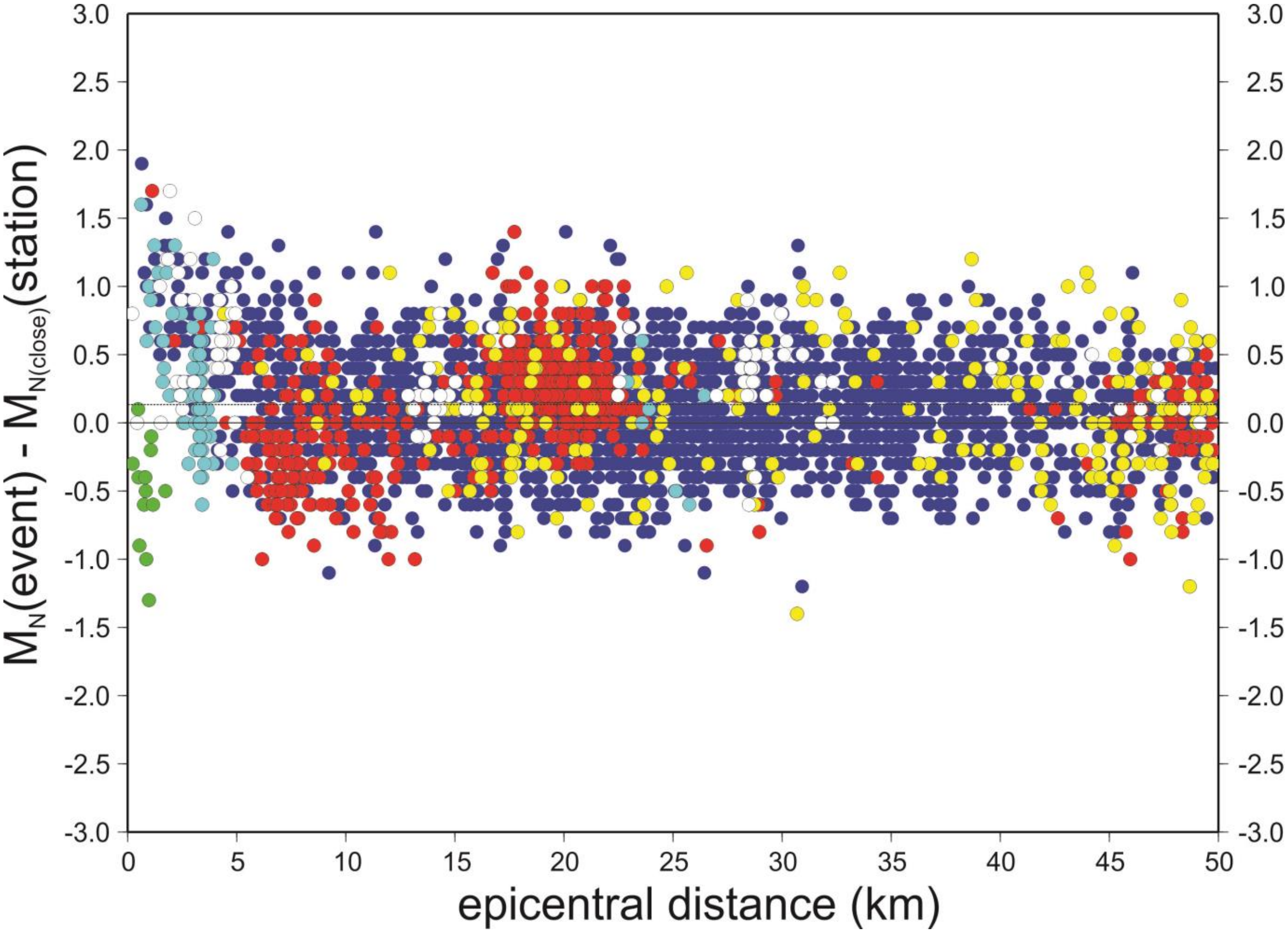

Figure 5b. The difference between the event M_N and individual station $M_{N(close)}$ values plotted as a function of epicentral distance. The solid horizontal line shows a 0 difference and the dashed line shows the mean difference.

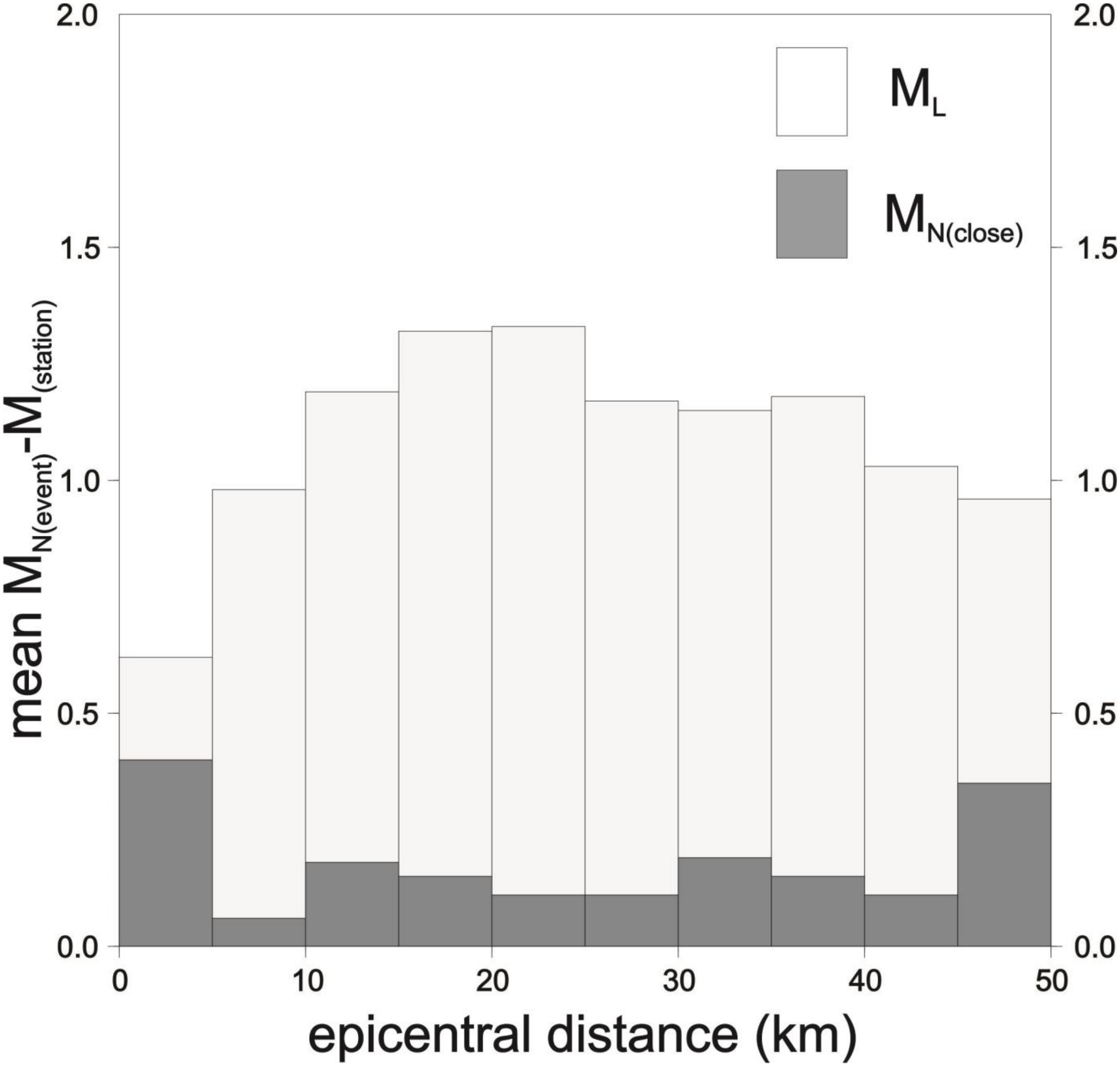

Figure 5c. The mean difference between $M_{N(event)}$ and M_L (light gray) and $M_{N(close)}$ (dark gray) binned in 5 km epicentral distance windows.

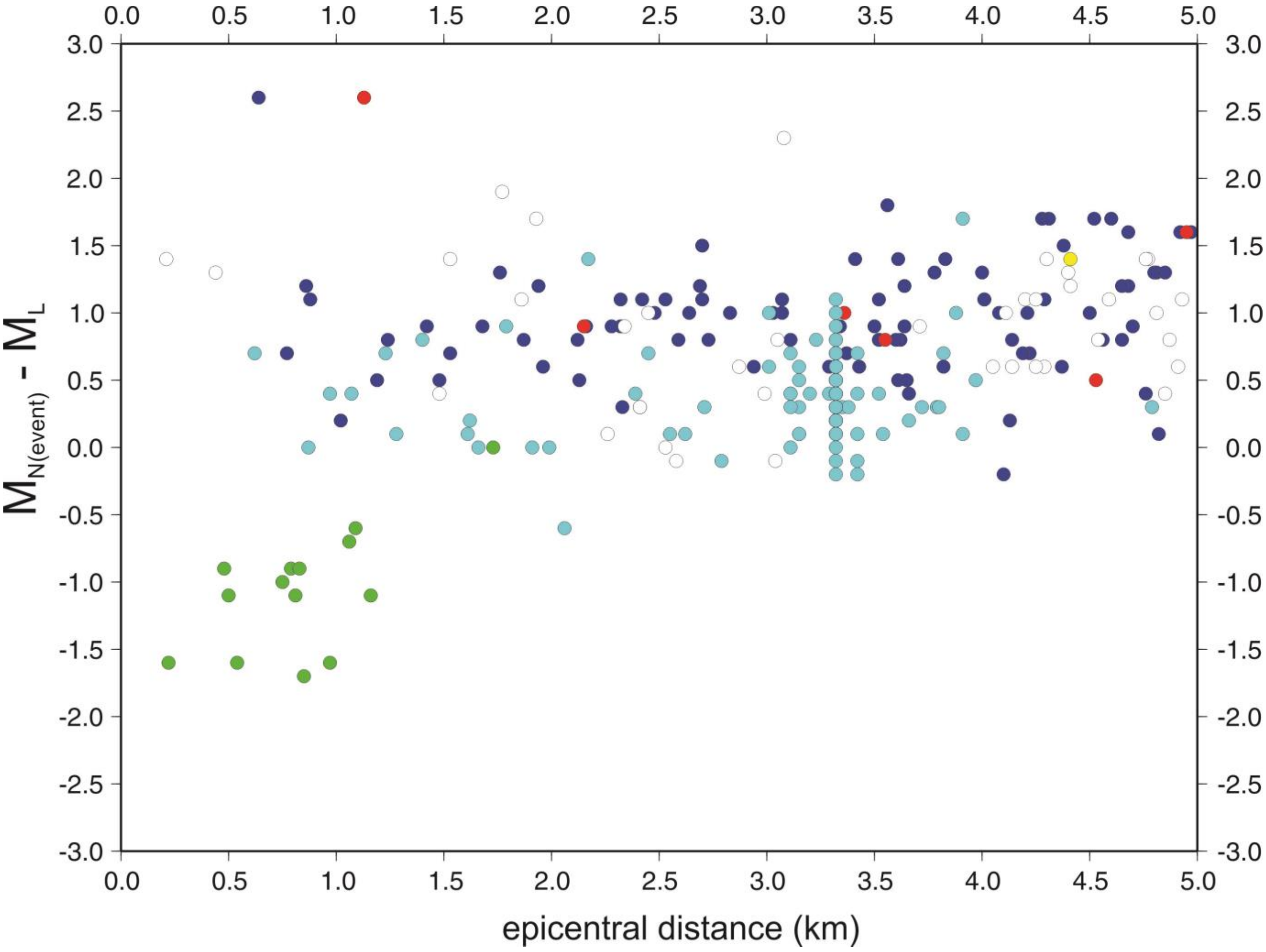

Figure 6a. Same as Figure 5a but highlighting the data from epicentral distances of 5 km or less. The vertical line of light blue (N. Ontario) points at 3.36 km represent events whose locations were pegged to a particular mine.

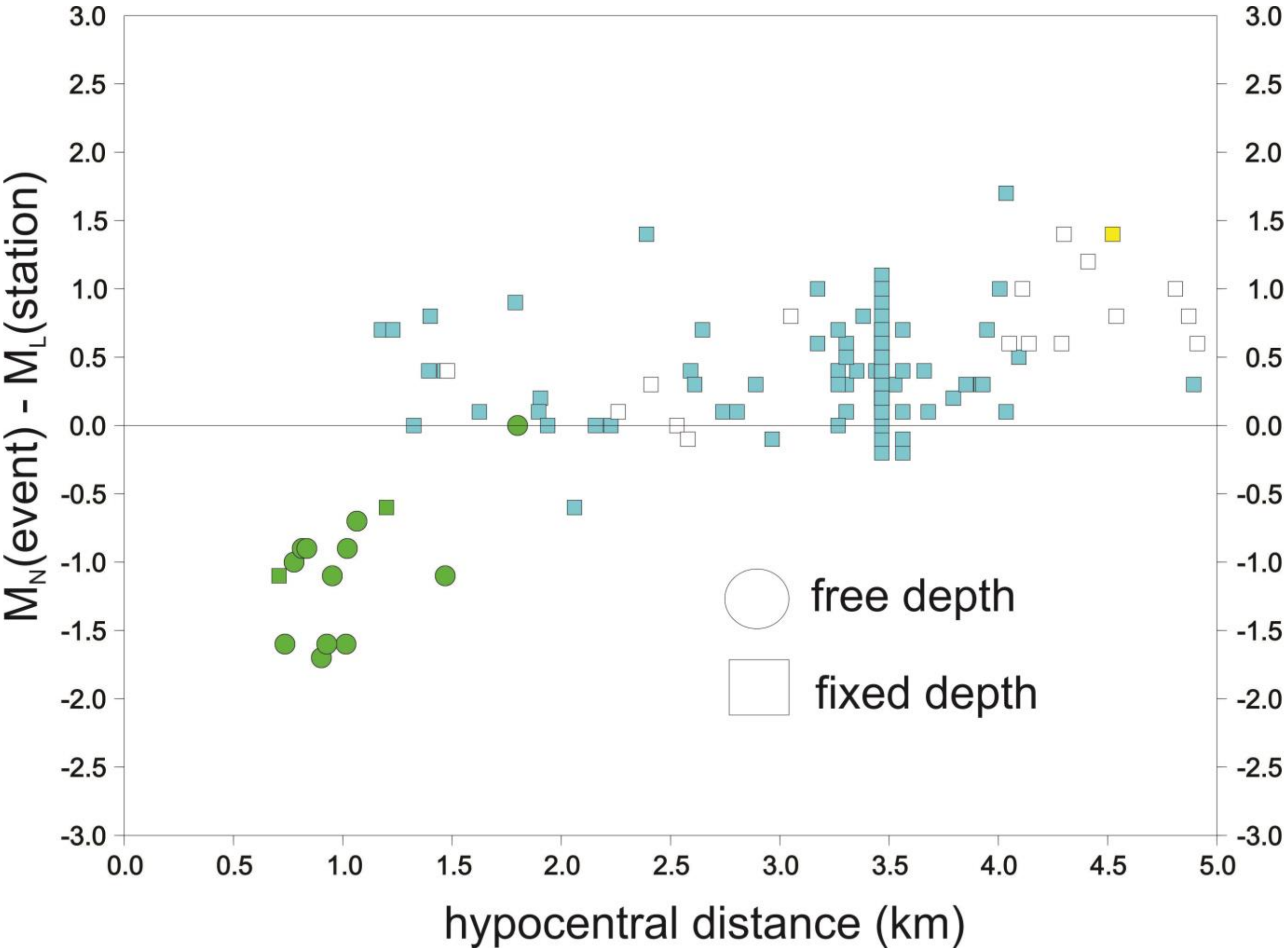

Figure 6b: Same as Figure 6a except that epicentral distance has been replaced by hypocentral distance. Circles represent events with free depths; squares represent events with fixed depths, which are less well constrained. The horizontal line at 0 magnitude difference is shown only for reference purposes.

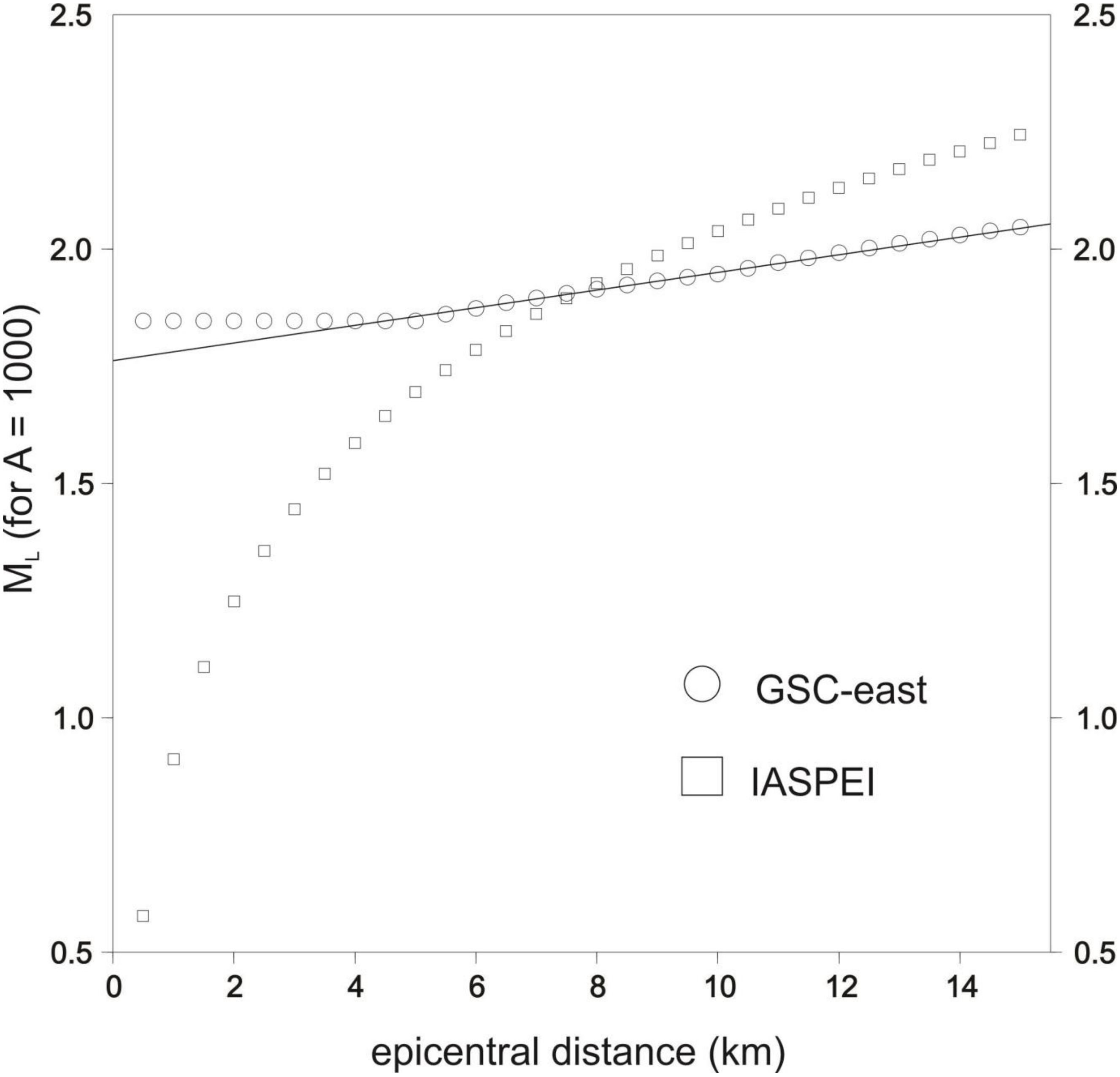

Figure 7: A comparison of IASPEI M_L magnitudes (squares) to the M_L magnitudes as calculated by the GSC for eastern Canada (circles) at distances of less than 15 km assuming an amplitude of 1000 nm. Because of differences in how the magnitudes are calculated (see text) only the trend and not the absolute amplitudes should be compared. The solid line shows the GSC magnitude trend for 5-15 km extrapolated for 0-5 km.