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2016

Canada

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2016

doi:10.4095/297964

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Recommended citation
Bent, A.L. and Vadnais, F., 2016. Magnitude Conversion Relations for Very Short Distances: The Charlevoix, Quebec, Seismic Zone; Geological Survey of Canada, Open File 7945, 17 p., doi:10.4095/297964

Publications in this series have not been edited; they are released as submitted by the author.

Abstract

The Nuttli (M_N) scale is the most commonly 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 only when the Lg phase is non-existent or highly attenuated, generally for earthquakes recorded at distances of less than 50 km or earthquakes occurring in oceanic crust. In the Charlevoix, Quebec, Seismic Zone the station density is such that it is possible to routinely locate earthquakes of magnitude 1.0 or smaller. Magnitudes for these smallest earthquakes are usually M_L. For many slightly larger earthquakes, the M_N values are based on readings at a single station, most often DAQ, as the earthquakes are usually not well-recorded at greater distances. Establishing a magnitude relation between M_N calculated at appropriate distances and M_N or M_L calculated at close distances would enable more magnitude readings to be used for the small earthquakes and a magnitude recurrence relation to be established over a wider magnitude range. Using data from earthquakes occurring within the Charlevoix Seismic Zone for which M_N was reported as the preferred magnitude we calculated M_L and M_N from stations at less than 50 km from the epicenter and compared them to the published or event magnitudes. M_L underestimates the magnitude by about 1 magnitude unit whereas the M_N (close) values were only about 0.2 units smaller than the presumed magnitude. These results suggest that M_N would be a better measure of the earthquake size even when calculated out of range and not from an Lg wave. We also evaluated the effect of using hypocentral distance instead of epicentral distance for earthquakes at less than 50 km but found that the difference was not significant in most cases. An evaluation of DAQ single station versus multi-station magnitudes suggests that DAQ station M_N magnitudes may overestimate the size of the earthquake by about 0.2 magnitude units.

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.

In eastern Canada, the Nuttli (1973) M_N scale is the primary magnitude scale for day-to-day use. 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, is calculated more frequently than it was in the past but is difficult to calculate for the smallest earthquakes (less than M_N 4.0) and generally takes longer to determine than M_N meaning that it is not 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.

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 earthquake at local and regional distances. Using data from the Charlevoix region we develop magnitude conversion relations between magnitudes recorded at distances of less than 50 km and the standard M_N magnitude based on the Lg phase. We expect that the resulting relations will be applicable elsewhere in southeastern Canada and adjacent regions of the United States.

Magnitudes in Eastern Canada

As previously stated, the Nuttli (1973) M_N magnitude scale is the most commonly calculated magnitude for earthquakes occurring in eastern Canada. However, only the equation for distances greater than 4° is used regardless of the distance. The details of the use of M_N in eastern Canada are discussed further in Bent (2011) and Bent and Greene (2014). While these studies raise some issues questioning whether it is the most appropriate choice, it is, nevertheless, the one 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 specifically excluded or x'd out. We also note that while M_N in eastern Canada is calculated at frequencies, generally higher, beyond the range near 1 Hz that Nuttli (1973) intended, which has resulted in some complications converting M_N to M_W (see Bent and Greene, 2014), we do not consider this practice to be a significant issue for the current study as the earthquakes evaluated cover a fairly narrow range of magnitudes where all amplitude measurements have been made at high frequencies. It could be a factor should the results of this study be applied to larger earthquakes.

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.

Comparison of Magnitudes at Close and Far Distances

We evaluated all earthquakes in the Charlevoix Seismic Zone occurring over a six month period (January-June 2012; Figure 1) for which M_N was noted as the official event magnitude type. The data set consisted of fifty-six earthquakes with 210 magnitude readings. We calculated both M_N and M_L for stations at distances of less than 50 km and compared them to M_N calculated from stations at the appropriate distance range (50-3000 km) for that scale. To avoid confusion, we refer to the M_N magnitudes as M_N(close) and M_N(far) where 50 km demarcates the close-far boundary. All M_L magnitudes discussed are for close distances.

The mean M_L value was 1.19 magnitude units smaller than M_N(far), suggesting that M_L significantly underestimates the size of the earthquake and that M_L and M_N(far) values should not be used together to estimate b values or similar parameters unless a correction is applied to one of them. M_N(close) does a better job of estimating the size of the earthquake but, on average, underestimates the value by 0.18 magnitude units. The conversion equations derived from the above are as follows:

$M_N(\text{far}) = M_L + 1.19$ (S.D. 0.40)
$M_N(\text{far}) = M_N(\text{close}) + 0.18$ (S.D. 0.41)

A direct comparison of the difference between M_N(close) and M_L is consistent with the above results. In this and subsequent discussion the terms over- and underestimation of earthquake size are based on the premise that M_N(far) is an appropriate measure of earthquake size. Whether it is or is not is well beyond the intended scope of this study.

To verify whether the conversion relations could be magnitude dependent we performed a least squares linear regression on the data set (Figures 2a and 2b). We did not explore more complex relations. Both magnitude types show evidence for magnitude dependence and, interestingly, the slope is very similar. We note that the uncertainty is slightly less for the linear conversion relation than for the constant conversion relation.

$M_N(\text{far}) = 0.66 + 0.67 M_N(\text{close})$ (S.E. 0.33)
$M_N(\text{far}) = 1.35 + 0.68 M_L$ (S.E. 0.33)

We also note that the results for M_L are fairly consistent with those of an earlier study by Lamontagne (1999) whose best fit relation was

$M_N(\text{far}) = 1.41 + 0.63 M_L$

To evaluate whether there is any advantage to using the linear relation over the simpler constant we converted the station magnitudes to the equivalent M_N(far) magnitudes and compared the residuals between the converted magnitude values and the event M_N(far) magnitudes. The residuals for the linear relations were about an order of magnitude less than those for the constant relation. Both, however, were several orders of magnitude smaller than the precision to which magnitudes are usually measured. For example, for the M_L conversions, the mean residual is 0.0005 magnitude units for the constant conversion and -0.00007 for the linear conversion relation. The application of the statistical F-test shows that the statistical significance between the two conversion relations for each magnitude type is 0%. Thus, there is no real advantage to using the more complex relation although we exercise caution if the constant conversion is applied far outside the magnitude range of the current dataset.

We redid the analysis averaging the station magnitudes into event magnitudes at close distances and compared the resulting relations to the M_N(far) values. There was very little difference between these and the relations discussed above and we do not discuss them further.

Discussion

Hypocentral Distance

At very close distances the difference between epicentral and hypocentral distances is more significant than at larger distances. We undertook a series of tests to determine the effect of the choice on the magnitude value. Magnitudes in eastern Canada and elsewhere are routinely calculated using epicentral distance.

First we developed a set of corrections for the difference in M_L magnitudes calculated from epicentral ($M_{L(epi)}$) and hypocentral ($M_{L(hypo)}$) for distances of 0 to 50 km and depths of 1 to 30 km (Figure 3). The depth distribution of Charlevoix earthquakes (Figure 4) suggests that in most cases the difference will be insignificant but for deeper (greater than 15-20 km) events at distances of less than 10 km the effect can be quite pronounced- up to 0.8 magnitude units. It should, however, be noted that M_L magnitudes in Charlevoix are rarely based on only one or two amplitude readings (Table 1) and the total effect would be less when multiple station magnitudes are averaged.

We then took the station distribution for two Charlevoix earthquakes and calculated the mean magnitude from the combined seven stations at 1 km intervals for depths from 0 to 30 km (Figure 5). One event (24 May 2004, M_N 3.0) had what would be considered a typical station distribution and the other (24 September 1996, M_N 3.1), referred to as the worst case, had a higher than usual number of stations at very close distances. For depths of less than 20 km, the difference between $M_{L(epi)}$ and $M_{L(hypo)}$ is less than the typical magnitude standard deviation of about 0.2 magnitude units for both station distributions. For greater depths the effect is more pronounced in both cases and there is a noticeable difference between the typical and worst case distributions. It should be emphasized that while the difference between $M_{L(epi)}$ and $M_{L(hypo)}$ for shallow depths may be within the uncertainty range of the event magnitude the difference is always of the same sign (i.e. biased) unlike the usual scatter in station magnitudes. That is, $M_{L(hypo)}$ will always be greater than $M_{L(epi)}$. For consistency, if the hypocentral correction is applied it should be applied for all depths and distances.

Recalculating the magnitudes at close stations for the earthquakes that formed the basis of the conversion relations discussed in this paper using hypocentral distance and then comparing them to the event magnitudes we find that the conversion constant is reduced by approximately 0.1 magnitude units regardless of the magnitude scale used for close distances. For M_L the difference between close and far magnitudes is still significant, 1.08 magnitude units. For M_N the results become murky. There is still a difference but it is less than 0.1 magnitude units. Given that the uncertainty associated with the conversion relations themselves is greater than 0.1 magnitude units, it is not clear whether there is any advantage to using epicentral distance and applying the conversion relation or using hypocentral distance and accepting the magnitude as is. We recognize, however, that both of these solutions are more pragmatic than sound science as the M_N magnitude would not be calculated from an Lg phase.

Single Station Magnitudes

For many of the smaller earthquakes that are large enough to be recorded at distances of 50 km or more, the event M_N magnitude is often based on a single station, almost always DAQ. For Charlevoix earthquakes occurring in 2012-13 45% of the M_N magnitudes were derived from one station and only 32% were based on readings at three or more stations. By contrast, all of the M_L magnitudes (about 10% of all Charlevoix magnitudes) were based on two or more stations and 93% used data from three or more stations (Table 1) despite the fact that M_L is, in general, used for smaller earthquakes. Thus, incorporating data from close distances could significantly increase the number of stations used to calculate magnitudes and provide data from a wider range of azimuths, which should give a more accurate estimate of the earthquake's magnitude. The wider azimuthal range would help ensure that the magnitudes are not unduly influenced by the radiation pattern.

In most cases, the single station magnitudes are derived from data recorded by station DAQ (Figure 6). In a study of station magnitude corrections (Bent, 2010) the station DAQ was shown to have a negligible correction. The mean residual was 0.04 magnitude units higher than the published event magnitude. However, that number was based on earthquakes occurring throughout eastern Canada. In theory, the station correction is a site correction. If, however, a single station is used for earthquakes occurring in a small region, there could be consistent path or source effects that would affect the magnitudes.

To determine whether the DAQ station correction was valid for the Charlevoix region, we started by using the Bent (2010) data set and considering only those magnitudes calculated at distances of 50-150 km. the majority of which would be for Charlevoix earthquakes. The mean residual of 0.22 magnitude units larger than the event magnitude was considerably larger than expected based on the station correction. To verify that this residual was truly representative of the Charlevoix region and not unduly influenced by the small number of non-Charlevoix earthquakes in that distance range, we extracted all Charlevoix earthquakes occurring from 2003 through 2013 for which M_N was the published magnitude type and where a minimum of five stations were used to calculate the magnitude. Again, the mean residual was 0.22.

These results suggest that the magnitudes of many Charlevoix earthquakes are being slightly overestimated. This overestimation could impact the magnitude recurrence rates of small earthquakes used in seismic hazard analyses. Subtracting 0.2 from DAQ single station magnitudes would be one way to correct for the bias. Although converted magnitudes may not always give the best estimate of the size of a particular earthquake, they are appropriate when dealing with large data sets.

Given that M_N magnitudes calculated at close distances underestimate the magnitude by 0.18 and that nearly half of the magnitudes are based on DAQ alone, one could argue that the mean from the close stations is at least as good as the single-station DAQ magnitude despite the fact that M_N is not appropriate for very close distances. Dropping the automatic exclusion by the GSC's location-magnitude software of M_N readings from distances of less than 50 km would enable these data to be used. We redid the conversion analysis separating the single station M_N(far) values from the multi-station values but found very little difference between the two data sets. When rounded to one decimal place, the mean residuals were identical.

Conclusions

While the distance correction used in the M_L magnitude equation is known to be inappropriate for eastern North America, M_L magnitudes are, nevertheless, calculated in some circumstances when other magnitude scales cannot be used. Earthquakes reasonably well recorded at local distances but too small to be recorded at regional and teleseismic stations are once such instance. However, to be useful for hazard assessments or for comparison purposes we must be able to relate the M_L's for these earthquakes to other magnitudes in common use. Because M_N is the most commonly used magnitude scale in eastern Canada we have focussed on developing conversion relations between M_L at close distances and M_N. We used data from the Charlevoix region for this purpose as there is a relatively large data set to work with and both M_L and M_N data are available. We found that, on average, M_L is more than a magnitude unit smaller than M_N calculated at appropriate distances. Although the M_N scale is not intended for use at distances of less than 50 km because the Lg wave on which it based is not fully developed, we can take amplitude and period data and plug them into the M_N magnitude equation. We found that while these M_N's from close distance underestimate the size of the earthquake, assuming that M_N is an appropriate measure, the average difference is approximately 0.2 magnitude units. Using hypocentral distance instead of epicentral distance for M_L calculations has only a small effect on the resulting magnitude. We note that using converted magnitudes is not ideal, but in Charlevoix where a very large percentage of the M_N values are based on a single station (shown in this study to have a bias), the inclusion of converted magnitudes from close stations, would perhaps provide additional data points over a wider range of azimuths for determining the magnitude.

Acknowledgements

The work at UQAM was supervised by Fiona Darbyshire. All figures were plotted using the GMT software package of Wessel et al. (2013). We thank John Adams for his constructive review.

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Table 1
Charlevoix Magnitude Statistics

M_N Statistics*

# stations	% events	Magnitude range
1	45	0.6-2.5
2	22	0.6-2.1
3-5	19	1.1-2.4
6+	13	1.5-4.4

M_L Statistics*

# stations	% events	Magnitude range
1	0	N/A
2	7	-0.1 (all events)
3-5	73	-0.6 - +0.6
6+	20	-0.6 - +0.3

* 324 events total for time period 2012-2013; M_L is listed as the preferred magnitude for 30 earthquakes and M_N for all others; # stations refers to the number of stations used to calculate the event magnitude listed in the CNED (2015).

Figures

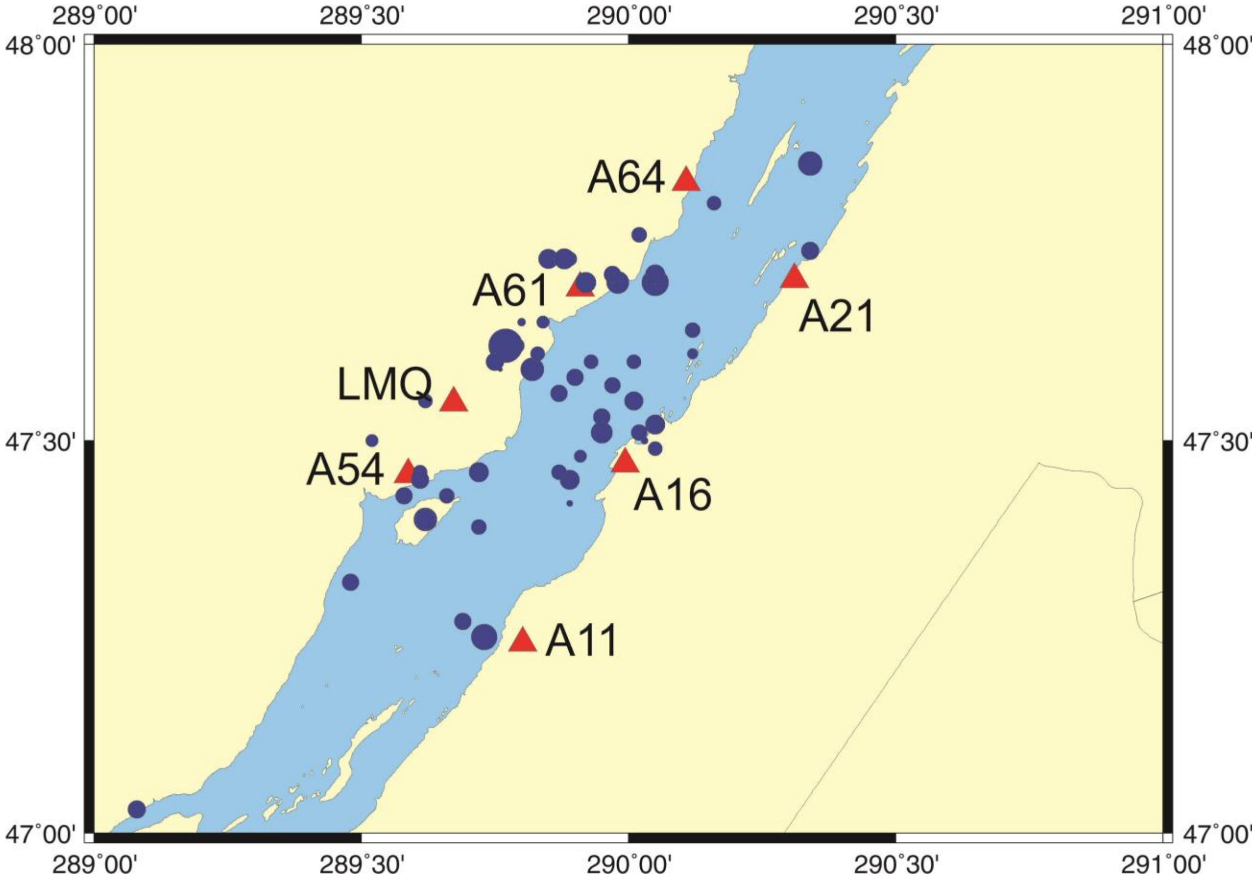

Figure 1. Map showing earthquakes (blue circles) used to develop the magnitude relations. Symbols size is scaled to magnitude (range -0.6 to 4.1). The red triangles show the locations of seismograph stations in the Charlevoix Seismic Zone.

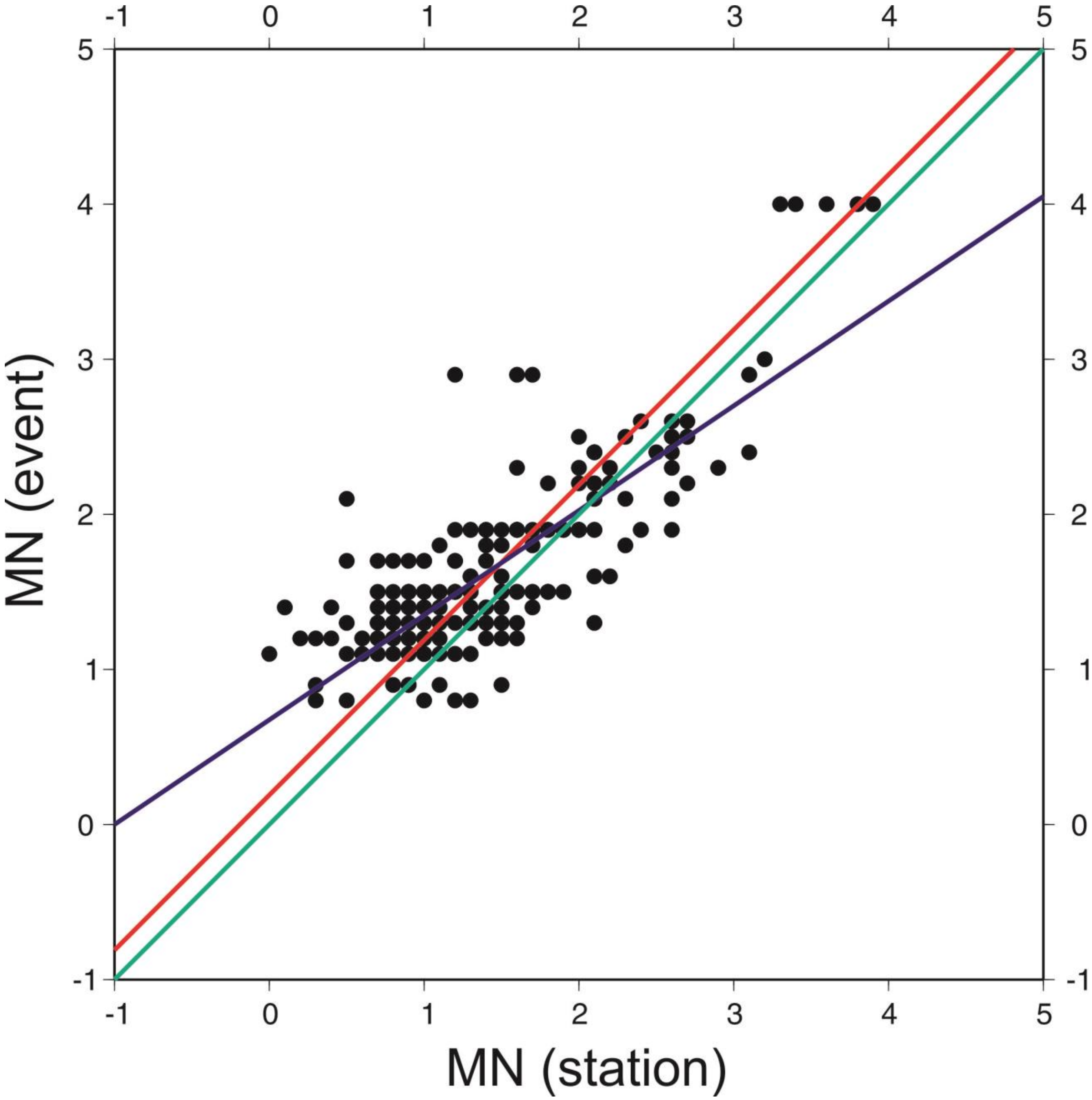

Figure 2a

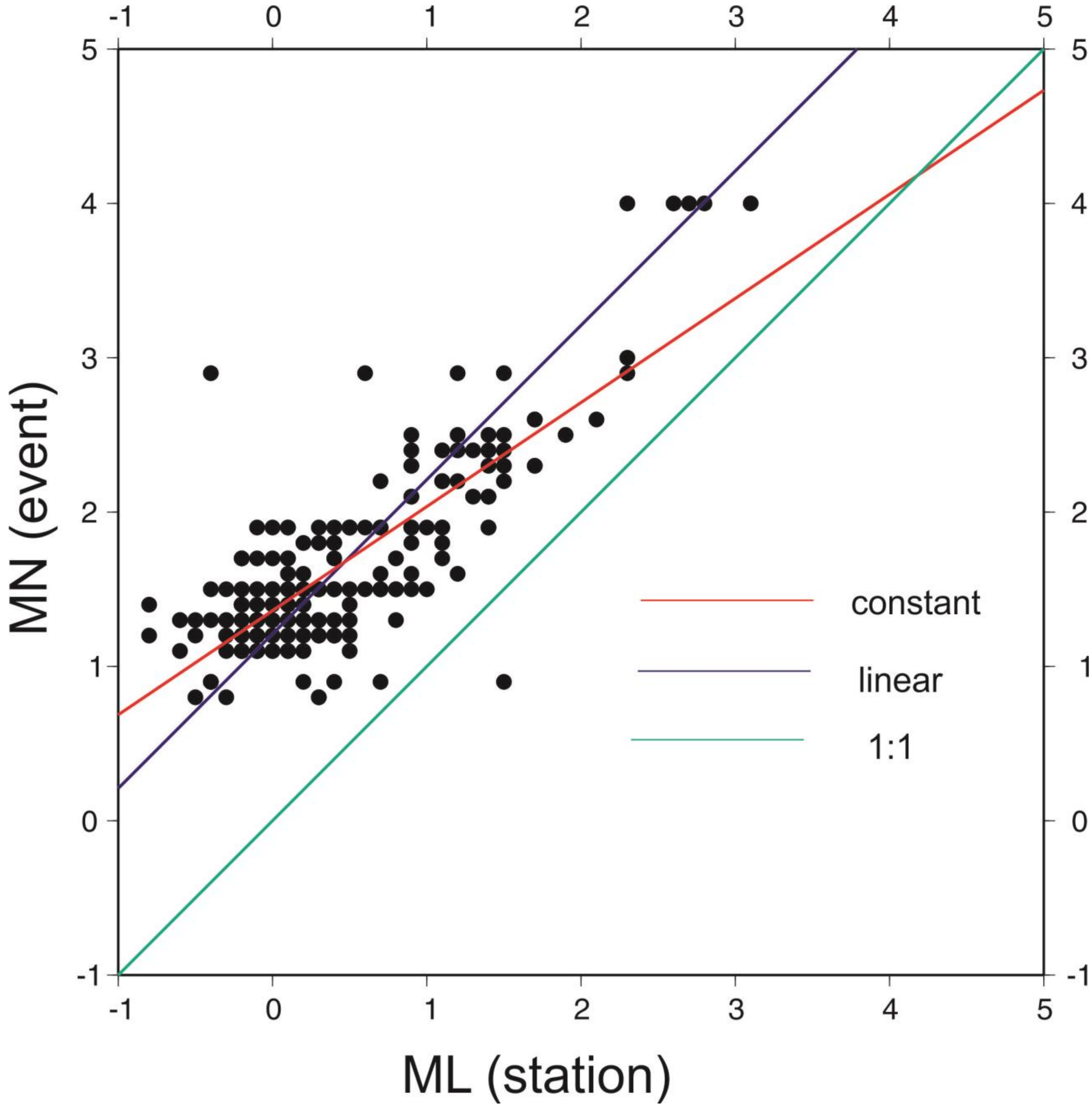

Figure 2b

Figure 2. Comparison of magnitudes calculated at stations within 50 km of the epicenter and the event M_N, based on amplitudes at distances beyond 50 km. The green line shows a 1:1 correspondence; the red line shows the best fit if a constant conversion relation is assumed; the blue line indicates the best least squares linear conversion relation. Note that some data points plot at the same coordinates. a) $M_{N\,(close)}$ b) M_L

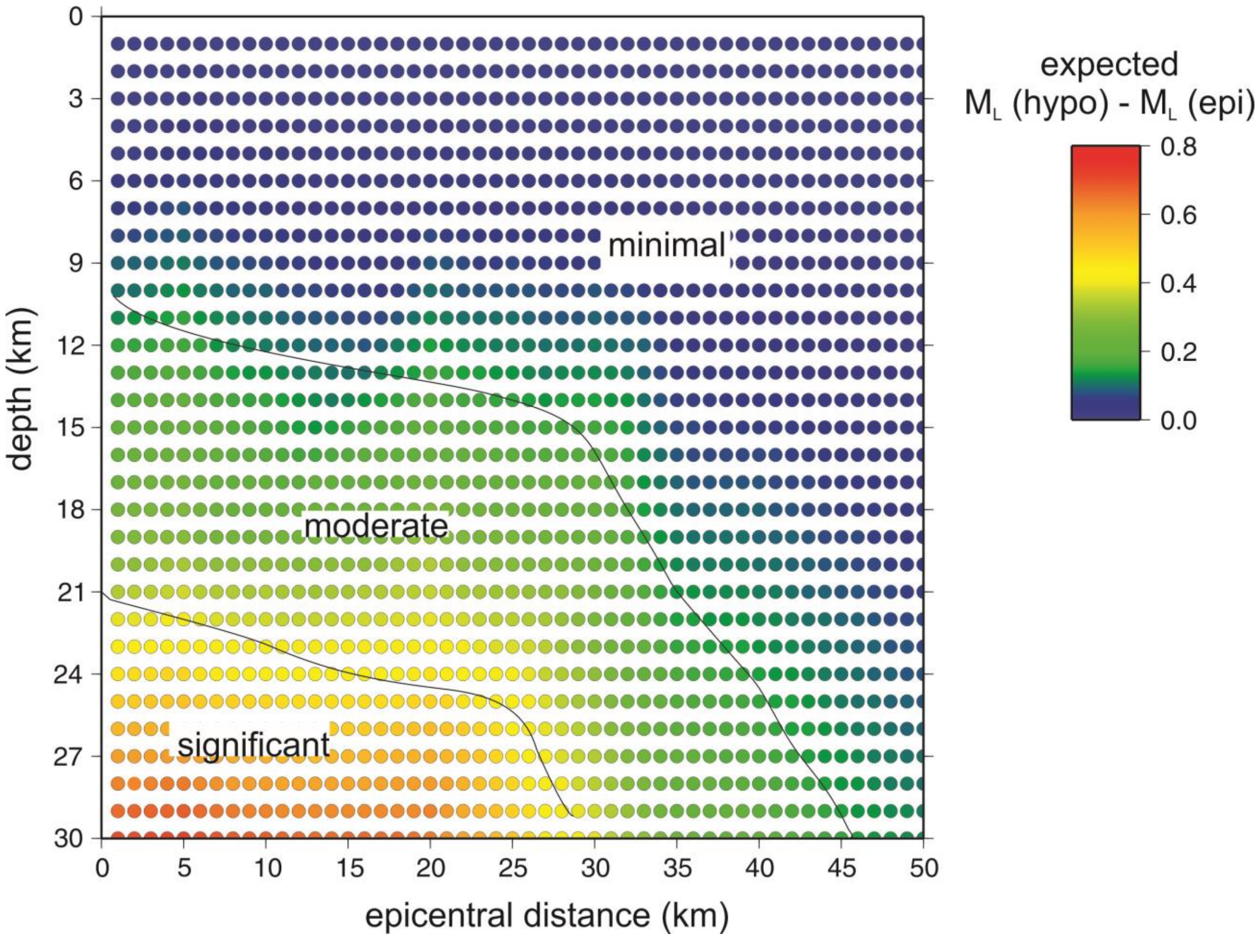

Figure 3. The difference in M_L magnitudes calculated for hypocentral and epicentral distances for a range of depths and distances. The labels showing ranges significant, moderate and minimal difference are qualitative only.

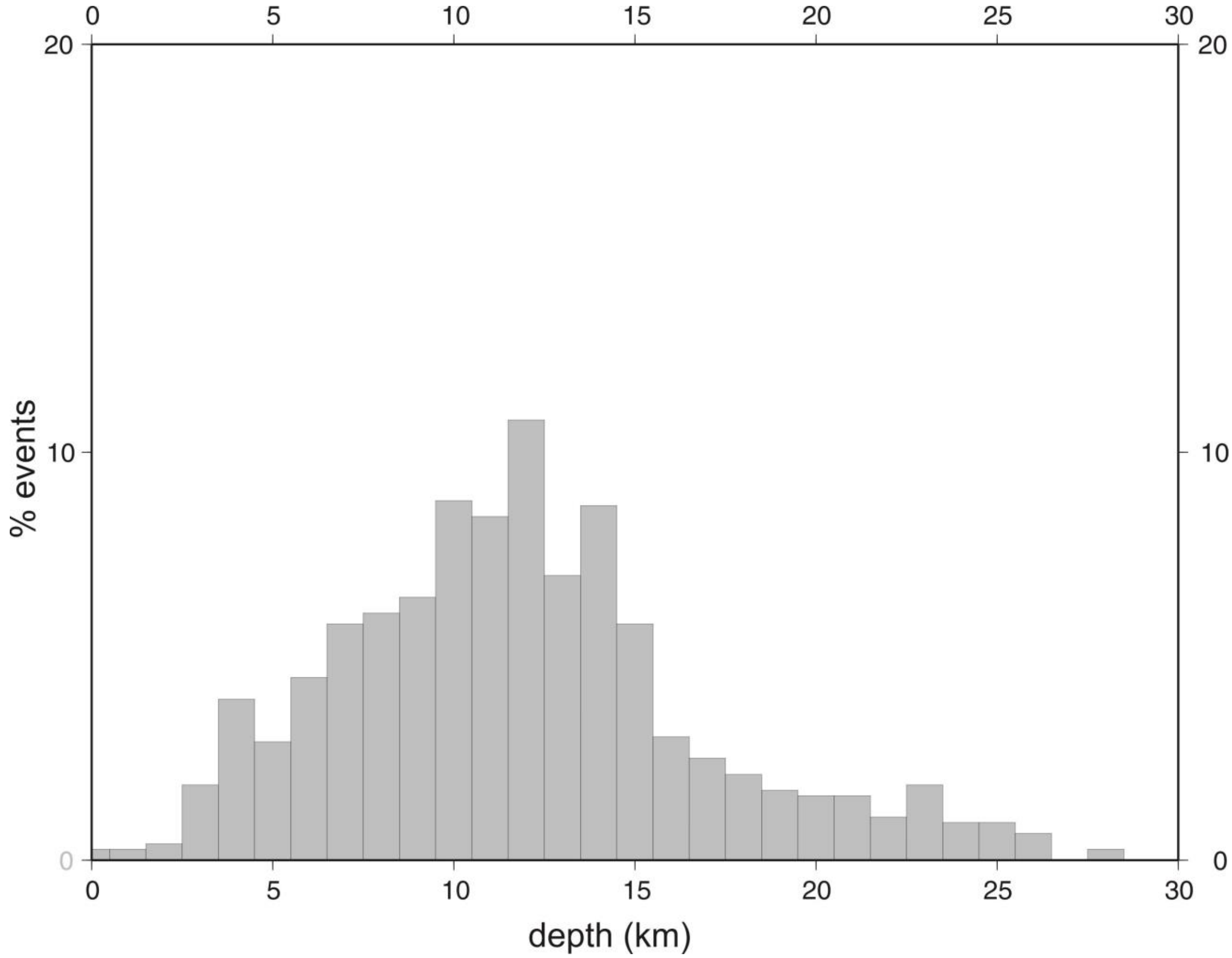

Figure 4. Histogram showing the depth distribution of Charlevoix earthquakes for the period 2012-2013 for events for which free depths were calculated (306 out of 325 events).

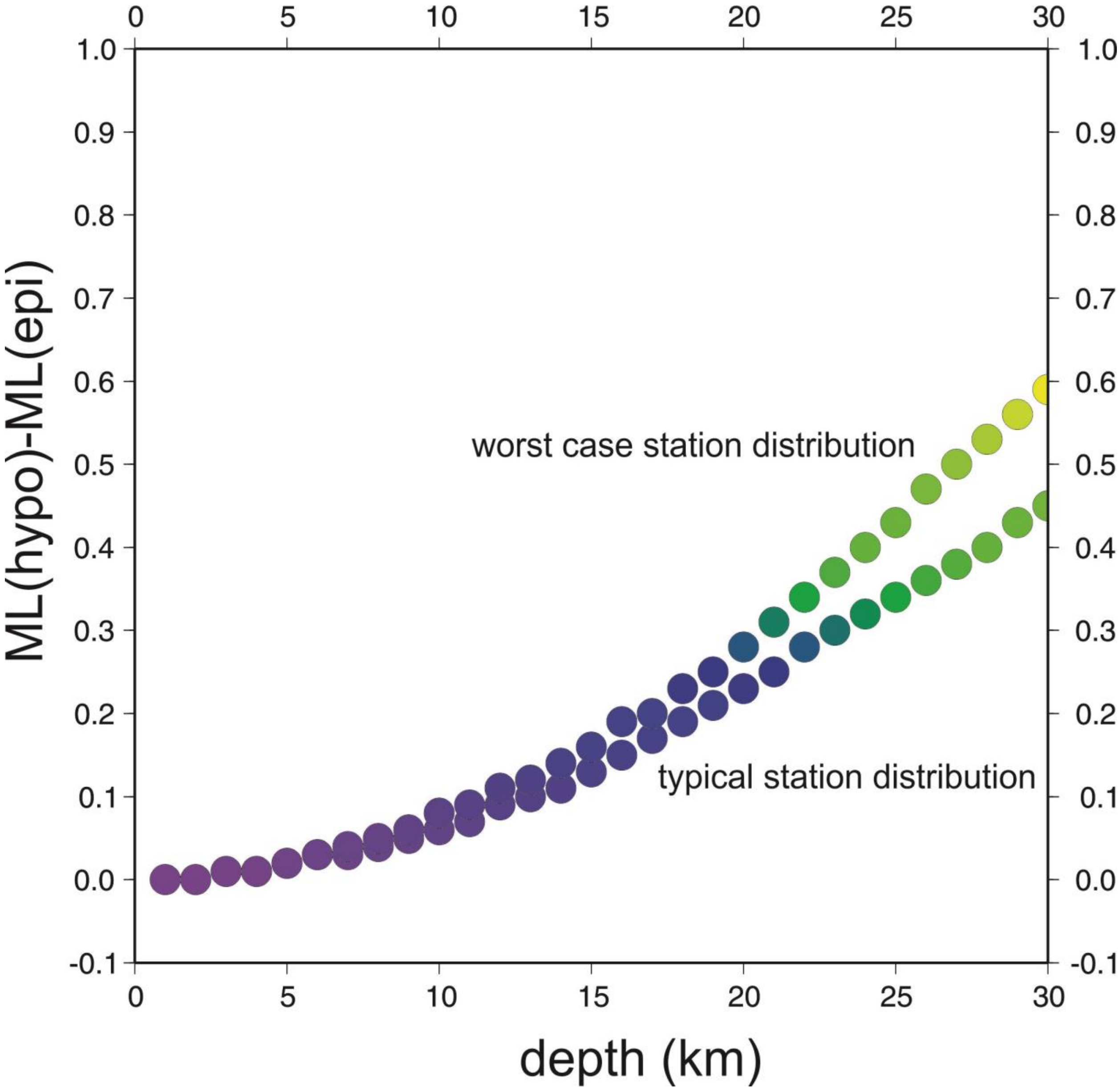

Figure 5. The effect of using hypocentral depth instead of epicentral depth. The station distributions are based on real earthquakes recorded by all seven Charlevoix stations (see Figure 1). The magnitudes are calculated at 1 km depth intervals and plotted as an average of the seven stations. Examples are shown for an earthquake with a typical station distribution and one where a higher than usual number of stations have epicentral distances of less than 25 km, indicated on the plot as the worst case distribution. The color scheme is the same as for Figure 3.

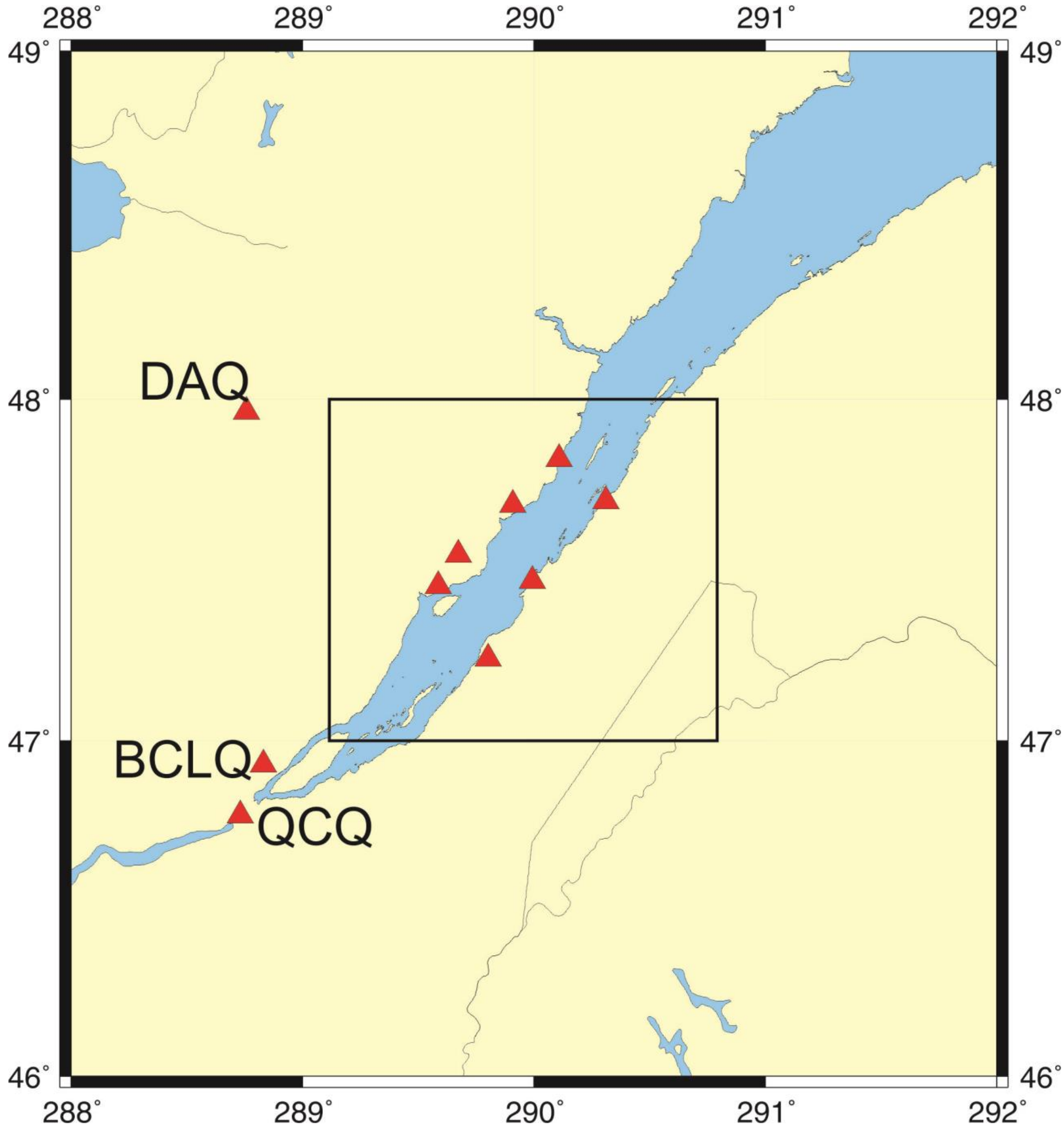

Figure 6. Seismograph stations within and near the Charlevoix Seismic Zone. The box indicates the region shown in Figure 1, where the stations within it are labeled.