Bulletin of the Seismological Society of America, Vol. 103, No. 1, pp. 588–594, February 2013, doi: 10.1785/0120110063

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Short Note

Assessing the Location and Magnitude of the 20 October 1870 Charlevoix, Quebec, Earthquake

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Abstract The Charlevoix, Quebec, earthquake of 20 October 1870 caused damage to several towns in Quebec and was felt throughout much of southeastern Canada and along the U.S. Atlantic seaboard from Maine to Maryland. Site-specific damage and felt reports from Canadian and U.S. cities and towns were used in analyses of the location and magnitude of the earthquake. The macroseismic center of the earthquake was very close to Baie-St-Paul, where the greatest damage was reported, and the intensity magnitude $\mathbf{M}_\mathbf{I}$ was found to be 5.8, with a 95% probability range of 5.5–6.0. After corrections for epicentral-distance differences are applied, the modified Mercalli intensity (MMI) data for the 1870 earthquake and for the moment magnitude **M** 6.2 Charlevoix earthquake of 1925 at common sites show that on average, the MMI readings are about 0.8 intensity units smaller for the 1870 earthquake than for the 1925 earthquake, suggesting that the 1870 earthquake was $\mathbf{M}_\mathbf{I}$ 5.7. A similar comparison of the MMI data for the 1870 earthquake with the corresponding data for the **M** 5.9 1988 Saguenay event suggests that the 1870 earthquake was $\mathbf{M}_\mathbf{I}$ 6.0. These analyses all suggest that the magnitude of the 1870 Charlevoix earthquake is between $\mathbf{M}_\mathbf{I}$ 5.5 and $\mathbf{M}_\mathbf{I}$ 6.0, with a best estimate of $\mathbf{M}_\mathbf{I}$ 5.8.

Online Material: Earthquake catalogs with distance to assignment epicenter and modified Mercalli intensity estimates.

Introduction

The Charlevoix Seismic Zone (CSZ), located along the St. Lawrence River in Quebec, Canada (Fig. 1), is the most seismically active zone in northeastern North America. This zone was likely the epicentral region of a strong earthquake that took place in February 1663 (Gouin, 2001; Ebel, 2011), which is estimated to have been **M** 7.5 ± 0.45 (Ebel, 2011). Since 1663, several other strong earthquakes have been centered in the CSZ, most notably events in 1791, 1860, 1870, and 1925. This study reassesses the epicenter and magnitude of the 1870 earthquake using intensity reports from Canada and the U.S.

Modified Mercalli Intensity Analyses

The Charlevoix earthquake of 20 October 1870 was strongly felt in the area of the CSZ in Canada, and widely felt throughout eastern Canada and in the northeastern U.S. (Fig. 2). It caused some damage in the epicentral region along with two deaths (Gouin, 2001; Lamontagne, 2008). This earthquake is rated at **M** 6.5 by the Canadian Geological Survey (Lamontagne, 2008; Lamontagne *et al.*, 2008), and it is listed by Lamontagne (2008) as the strongest earthquake that has been centered in the CSZ since 1663.

For this study, a dataset of intensity reports for the 1870 earthquake was accumulated from several sources. A list of 125 site-specific intensities for Canada and the U.S. was obtained from Gouin (2001). This was augmented with 10 additional site-specific intensity values for sites in Massachusetts and New York that were gleaned from reports that were published on the days following the earthquake in the *Boston Evening Transcript* and the *New York Times*. Both of these newspapers contained many felt reports from other communities throughout the northeastern U.S. and southeastern Canada, and those reports were incorporated into the intensity dataset if enough details were given such that an intensity assignment could be made and the site had not already been given in Gouin (2001). A total of 135 intensity reports comprised the full intensity dataset for the 1870 earthquake at epicentral distances out to almost 1700 km.

For the city of Boston, Massachusetts, Gouin (2001) assigned modified Mercalli intensity (MMI) II–III at ground level and IV–V at upper levels. He also stated, "The structural

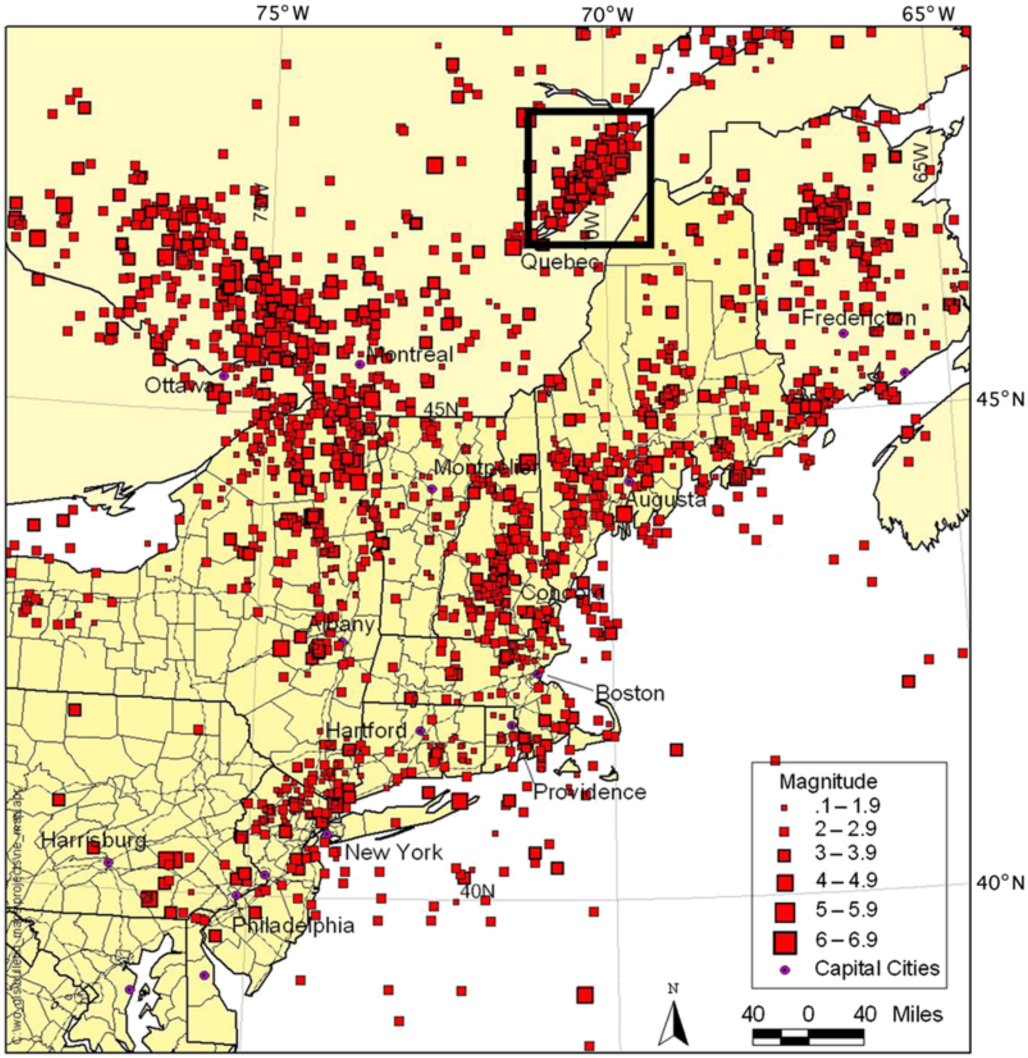

Figure 1. Seismicity map for the time period of 1975–2009. The box shows the location of the Charlevoix Seismic Zone. The color version of this figure is available only in the electronic edition.

damage described is probably inflated." Gouin (2001) includes some newspaper transcriptions that give reports of damage in Boston due to the 1870 earthquake, such as serious cracking of the Sears building, toppled chimneys on Young's Hotel, cracked walls on the city library, fallen slate from roofs, and broken windows. However, all of these reports in Gouin (2001) come from the *Northampton Free Press*, a newspaper from a town 170 km west of Boston. Articles in the *Boston Evening Transcript* on 20–21 October 1870 show that the damage reports for Boston in the *Northampton Free Press* were indeed exaggerated. The Boston newspaper explicitly states that the report of cracked marble of the façade on the Sears building was false, and there are no reports of either chimney damage, fallen slate roofing materials, or cracked walls in the city library in the Boston newspaper accounts. Some broken windows in Boston buildings are reported by the *Boston Evening Transcript*, and that newspaper states that some iron ornaments at the top of the Sears building were bent by the earthquake shaking. Most of the shaking effects in Boston were loose items that fell from shelves. While the earthquake was widely felt in Boston, persons in many buildings apparently barely noticed the tremor. The *Boston Evening Transcript* accounts suggest that the 1870 earthquake did not damage chimneys or crack brick walls in Boston as no such reports are mentioned anywhere in this newspaper.

The full dataset of 135 intensities were used to estimate the location and magnitude of the 1870 earthquake using the intensity-attenuation formula of Bakun and Hopper (2004) and the search method of Bakun and Wentworth (1997). This method searches for a location and magnitude that most closely predicts the intensity observations for the earthquake. The best estimated location of this event (Fig. 3) is at the southwestern end of the CSZ near the town of Baie-St-Paul, where the greatest amount of damage was reported. From the analysis, the intensity magnitude $\mathbf{M_I}$ for this earthquake (calibrated to equal moment magnitude on average) is in the range (95% probability) of 5.5–6.0, with a best estimate of $\mathbf{M_I}$ 5.8. The

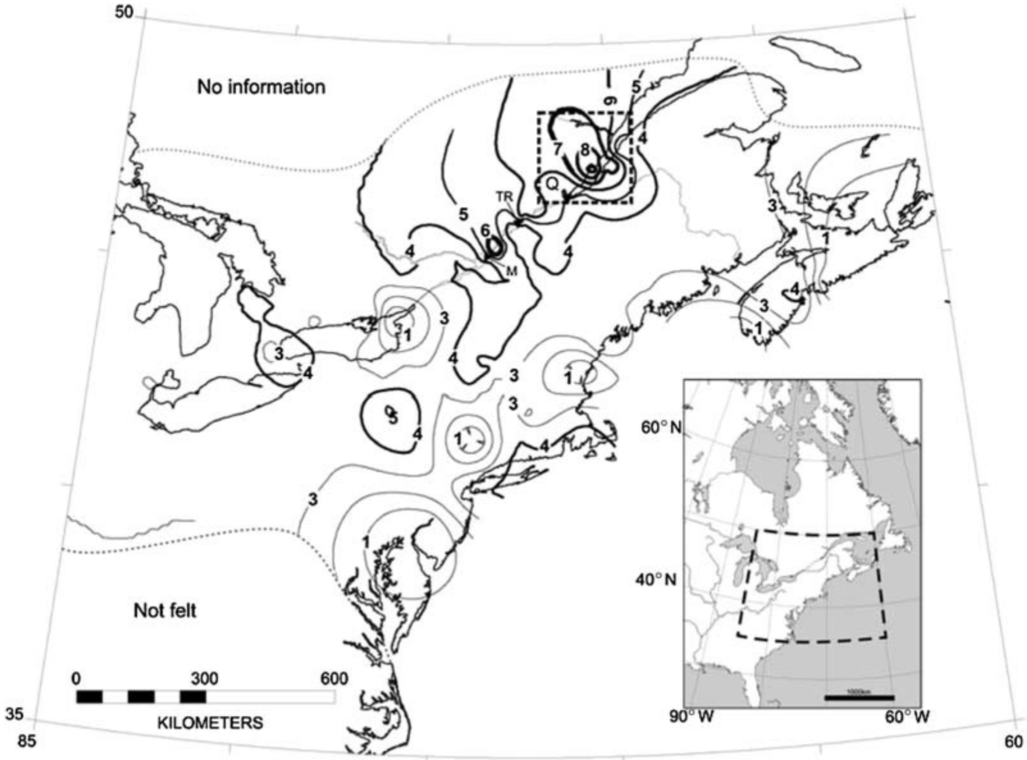

Figure 2. Isoseismal (modified Mercalli intensities) map of the Charlevoix earthquake of 20 October 1870 from Lamontagne (2008). The dashed box indicates the region where the highest earthquake intensities were reported.

location found in this study is close to the epicenter favored by Lamontagne (2008), whose epicenter was based on the localities where the greatest amount of damage was reported. However, the magnitude found in this study is significantly smaller than the *M* 6.5 value of Lamontagne (2008).

Another way to estimate the size of the 1870 earthquake is to compare the MMI values at common sites for the 1870 and 1925 Charlevoix-area earthquakes (i.e., MMI 1870–MMI 1925 for each site with MMI values for both earthquakes) and at common sites for the 1870 earthquake and the 1988 earthquake in the nearby Saguenay area of Quebec (i.e., MMI 1870–MMI 1988 for each site with MMI values for both earthquakes). For both the 1925 and 1988 earthquakes, instrumental-moment magnitudes have been determined, and so the intensity comparisons can be used to estimate the moment magnitude of the 1870 event. The 1925 earthquake had **M** 6.2 (Bent, 1992), and the 1988 earthquake had **M** 5.9 (North *et al.*, 1989). The use of common sites is important as it should serve to cancel out the dependence of the MMI values on site conditions, because for a given locality the site conditions can be assumed to be the same when the 1870 earthquake, and when either the 1925 or 1988 earthquakes, were experienced. Although intensity is a subjective measure of ground shaking, it can be assumed that, on average, stronger ground shaking will yield a higher intensity assignment at a locality. After evaluating the intensities and therefore indirectly the strength of the ground shaking, at many localities, one can combine these data with an attenuation relation to make an estimate of the seismic moment or moment magnitude of the earthquake source. This assumption is the basis of all estimates of the magnitudes of historical earthquakes for which only intensity data are available (such as Johnston, 1996a,b; Hough *et al.*, 2000; Bakun *et al.*, 2003; Hough and Page, 2011).

For this study, the intensity data come from different sources. As described above, most of the MMI values used in this study for the 1870 earthquake are from Gouin (2001). From reading the original reports reproduced in Gouin (2001), we agree with all of his MMI assignments. For the 1870 earthquake in Boston, we used MMI V based on the information gathered from the *Boston Evening Transcript* as discussed above. The intensities for the 1925 Charlevoix earthquake were evaluated by Cajka (1999) and came from the Earthquakes Canada website (see Data and Resources). The intensities for the 1988 Saguenay earthquake are those compiled by Cajka and Drysdale (1996) and were provided by G. Atkinson (personal comm., 2010). Different investigators made the intensity assignments for each of the earthquakes included in this analysis. While each of these investigators may have used somewhat different judgments to make their intensity assignments, it is assumed in this study that there is no bias toward either high or low intensities by any of the investigators. Hough and Page (2011) had four different scientists make independent MMI assignments for the same set of earthquakes from the New Madrid seismic zone and then evaluated these assignments for biases among

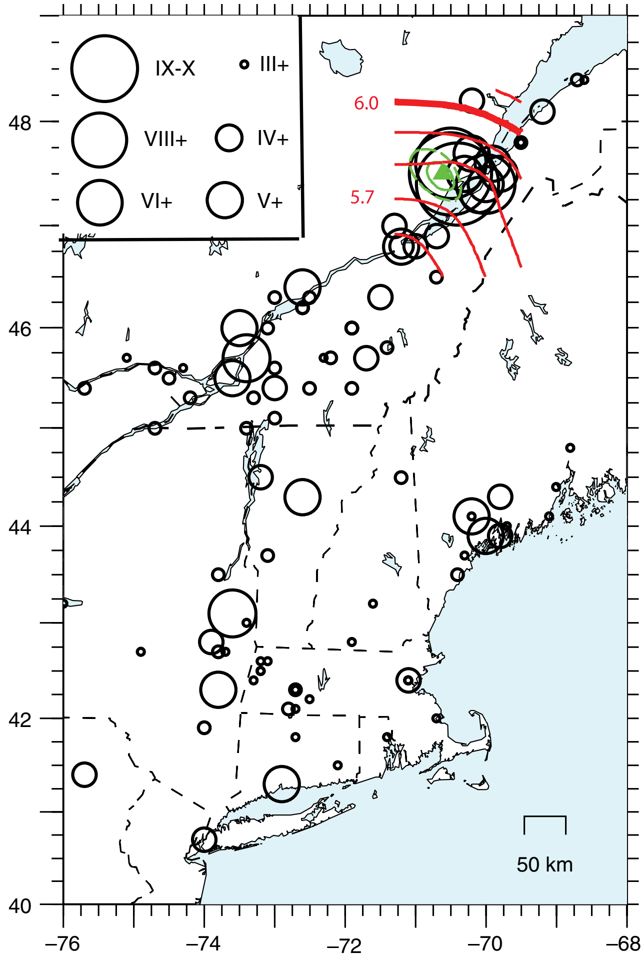

Figure 3. Map of the analysis of the epicenter and magnitude of the 20 October 1870 earthquake at Charlevoix, Quebec, using the method of Bakun and Wentworth (1997). The circles show the locations of the intensity readings, where the symbol labeled III+ is for MMI assignments of III and III.5, IV+ is for MMI assignments of IV and IV.5, etc. The circle labeled IX–X is for MMI of IX, IX.5 and X. There are no MMI values of VII or VII.5 in the dataset. Localities of equal $\mathbf{M_I}$ are shown as open contours, with the southwestern contour representing $\mathbf{M_I}$ 5.6 and the northeastern contour presenting $\mathbf{M_I}$ 6.1. The thick contour is $\mathbf{M_I}$ 6.0. The triangle shows the best location estimate, with the inner and outer closed contours around the triangle indicating the 67% (inner contour) and 95% (outer contour) confidence intervals on the location estimate. The color version of this figure is available only in the electronic edition.

the different scientists and among the different events. Hough and Page (2011) concluded that even though the individual-intensity assignments for a given locality did show variation up to one intensity unit and sometimes more among the different evaluators, there were no systematic biases among the intensity assignments for a given earthquake by the individual scientists. Furthermore, none of the scientists gave consistently high- or low-intensity assignments for all of the different earthquakes that they analyzed. Thus, based on the results of Hough and Page (2011), it is assumed here that there are no systematic biases among the intensity assignments made for the 1870, 1925, and 1988 earthquakes that were used in this study.

The epicenters of the 1870, 1925, and 1988 are at quite different locations, thus comparisons of the MMI readings for the different earthquakes at a common site must take the different source-receiver distances into account. As noted above, the location of the 1870 earthquake was near the southwestern end of the CSZ. The location of the 1925 earthquake was at the northeastern end of the CSZ (Stevens, 1980), about 65 km northeast of the 1870 location. The 1988 epicenter was about 60 km northwest of the 1870 location.

In order to compare the intensities at common sites for each pair of earthquakes, it was assumed that the intensity assignments could be treated as quantitative data and that an intensity-correction factor based on the difference in epicentral distance could be applied to those data. For sites where the shaking or damage description could be consistent with either of two different intensity values (such as either 4 or 5), a value halfway between those two (i.e., 4.5) was assigned to that locality, which is equivalent to using both intensity values but giving each a weight of 0.5 in the analysis. The MMI attenuation relation of Bakun and Hopper (2004) is

$$\mathrm{MMI} = 1.36\mathbf{M} - 0.00277\Delta - 2.10\log(\Delta), \quad (1)$$

where $\mathbf{M}$ is the magnitude of the event and Δ is the hypocentral distance from the earthquake to a site assuming the earthquake had a focal depth of 10 km. This formula was used to compute the MMI correction due to the distance difference between the locations of the 1870 and 1925 or 1988 earthquakes and those sites where MMI values were assigned for both earthquakes. From equation (1) the correction factor for an MMI reading, ΔMMI, is

$$\Delta\mathrm{MMI} = -0.00266(\Delta_2 - \Delta_1) - 2.10\log(\Delta_2/\Delta_1), \quad (2)$$

where Δ_1 is the hypocentral distance of the uncorrected reading and Δ_2 is the hypocentral distance of the corrected reading. Thus, the correction factor of equation (2) reduces the MMI value if $\Delta_2 > \Delta_1$ and it increases it if $\Delta_2 < \Delta_1$. In this study, the 1870 MMI values were corrected to the epicentral distances of the 1925 and 1988 earthquakes.

The datasets analyzed in this study had 60 common sites with MMI values for the 1870 and 1925 earthquakes and 41 common sites with MMI values for the 1870 and 1988 earthquakes. Figure 4 shows the differences in intensity values at common sites for the 1925 earthquake relative to the 1870 earthquake and for the 1988 earthquake relative to the 1870 earthquake after the intensity correction for hypocentral distance has been applied to the data. For the 1925–1870 MMI differences, at most localities the MMI determinations for the 1925 event are greater than those for 1870, indicating that the former earthquake has a larger magnitude than the latter. The mean difference after the distance correction has been applied is +0.8 MMI units, which corresponds to a magnitude difference of +0.5 units. Thus, if the 1925 earthquake is $\mathbf{M}$ 6.2, then the 1870 event is $\mathbf{M_I}$ 5.7. For the comparison

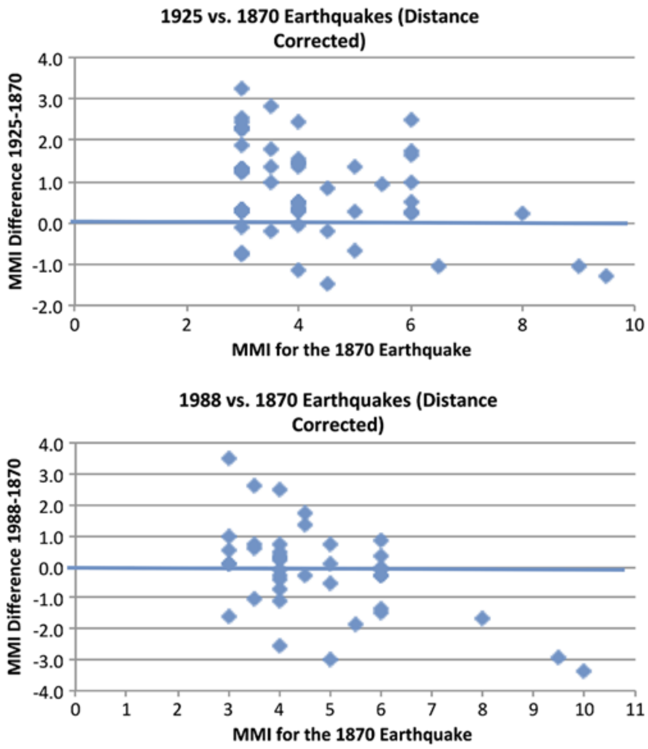

Figure 4. (top) Plot of the differences in MMI values at common sites for the 1925 Charlevoix earthquake relative to the 1870 Charlevoix earthquake after a correction for the difference in hypocentral distance has been applied. The mean difference is +0.8 MMI units. (bottom) Plot of the differences in MMI values at common sites for the 1988 Saguenay earthquake relative to the 1870 Charlevoix earthquake after a correction for the difference in hypocentral distance has been applied. The mean difference is −0.1 MMI units. The color version of this figure is available only in the electronic edition.

between the 1988 and 1870 earthquakes, the mean difference at common sites is −0.1 MMI units, which corresponds to a magnitude difference of −0.06 units. Thus, if the 1988 event is **M** 5.9, then the 1870 shock is about $\mathbf{M}_\mathbf{I}$ 6.0. These comparisons indicate that the 1870 earthquake is $\mathbf{M}_\mathbf{I}$ 5.7 to $\mathbf{M}_\mathbf{I}$ 6.0, similar to the 95% probability range of the magnitude estimate from the analysis using the Bakun and Wentworth (1997) method. Because of the estimates of the magnitude of the 1870 event in these analyses, which are based on intensity data, we refer to the magnitude as $\mathbf{M}_\mathbf{I}$, and we follow the Bakun and Wentworth (1997) assertion that on average $\mathbf{M}_\mathbf{I} = \mathbf{M}$. Putting the results from the Bakun and Wentworth (1997) analysis and the comparisons of the 1870 earthquake intensities with those for the 1925 and 1988 events, the range of the estimated magnitude for the 1870 earthquake is $\mathbf{M}_\mathbf{I}$ 5.5 to 6.0. The best estimate of the magnitude for this event is $\mathbf{M}_\mathbf{I}$ 5.8.

As a check on this procedure for estimating the relative magnitudes of two earthquakes using MMI determinations at common sites, the relative magnitudes of the 1925 and 1988 earthquakes were found. After correcting the 1988 MMI determinations to the epicentral distances of the 1925 earthquake for 22 common sites in our datasets where both earthquakes have MMI values, it was found that the average MMI determination for the 1925 earthquake was about 1.0 MMI unit larger than that of the 1988 earthquake. This corresponds to the 1925 earthquake being $\mathbf{M}_\mathbf{I}$ 6.5 if the 1988 earthquake is **M** 5.9, or alternatively the 1988 earthquake being $\mathbf{M}_\mathbf{I}$ 5.6 if the 1925 earthquake is **M** 6.3. Thus, within the uncertainties of the magnitude determinations (0.2–0.3 magnitude units), the corrected MMI data agree with the instrumental-magnitude determination of the 1925 earthquake relative to that of the 1988 earthquake.

Examining the damage reports at cities in Quebec can provide some additional information about the relative sizes of the 1870, 1925, and 1988 earthquakes. For Quebec City, the MMI values in the datasets utilized in this study give MMI VI, VII, and IV–V for the 1870, 1925, and 1988 earthquakes, respectively. Lamontagne (2009) presented a detailed analysis of the impacts of each of these earthquakes on Quebec City. He noted that most of the damage in Quebec City due to these earthquakes occurred in the lower town where there are deep unconsolidated sediments. He found that the most widespread damage was experienced in the 1870 earthquake compared to the 1925 and 1988 earthquakes. The epicentral distances to Quebec City from the 1870, 1925, and 1988 earthquakes were about 85 km, 153 km, and 147 km, respectively. Had the 1870 and 1925 earthquakes been at the 1870 epicenter, the MMI value at Quebec City for each of these events would have been about 0.8 intensity units greater. Thus, even though Lamontagne (2009) shows that the ground shaking at Quebec City in 1870 was the strongest of these three earthquakes, the differences in epicentral distance make it difficult to use this observation to argue that the 1870 earthquake had the largest magnitude of these three events.

At Montreal, the same situation as that at Quebec City applies to the MMI data. For the 1870 earthquake, Gouin (2001) assigned MMI VI–VII in the Old Town section of the city based on some masonry and chimney damage and 0–VI in the suburbs of Montreal. For the 1925 earthquake, the intensity dataset used in this study has MMI V, and there are no reports of damage in Montreal. In the 1988 earthquake, Cajka and Drysdale (1996) assigned MMI V to Montreal North and Montreal East. The Montreal East City Hall sustained some masonry damage in the 1988 earthquake, but that building had a problem with excessive settlement into the clay beneath its foundation prior to the earthquake (Mitchell *et al.*, 1989). Thus, this one report of damage in Montreal in 1988 may have been due to an unusually fragile building. The epicentral distances of the 1870, 1925, and 1988 earthquakes from Montreal were 318 km, 387 km, and 345 km, respectively, and putting the 1925 and 1988 epicenters at the location of the 1870 earthquake would have increased the expected MMI values at Quebec City by 0.4 and 0.2 MMI units, respectively. Had all of these earthquakes been centered at the 1870 epicenter, an MMI value of about V–VI at Montreal is estimated for the 1925 and 1988 events.

Thus, as at Quebec City the site specific reports of ground shaking at Montreal are not useful for helping constrain the relative sizes of the 1870, 1925, and 1988 earthquakes.

Another indication of the magnitude of an earthquake is the areal extent of soil-liquefaction features induced by strong earthquake shaking (Tuttle, 2001). In the 1870 earthquake, ground fissuring and sand venting was reported in the epicentral region near Baie-St-Paul (Smith, 1962). There was a report that spouts of water reached eight feet or more into the air following this earthquake (Dawson, 1870). In the 1925 earthquake, many ground cracks were reported (Hodgson, 1950), and at one locality between St-Urbain and Baie-St-Paul, water and sand oozed from some cracks that opened in the valley floor (Smith, 1962). Both Hodgson (1950) and Lamontagne (2009) note that the ground was deeply frozen at the time of the 1925 earthquake (28 February, local time), and this may have impeded the formation of liquefaction features and landslides. The 1988 Saguenay earthquake caused liquefaction at 30 km from the epicenter, and rockfalls and landslides were reported from as far as 200 km away from the epicenter (Lamontagne, 2002). For all of these earthquakes, the reported liquefaction features indicate strong levels of ground shaking, but the known liquefaction data are not sufficient to discriminate the relative sizes of the different earthquakes. Tuttle and Atkinson (2010) argue that the liquefaction features that formed within the past 10,000 years in the CSZ show that there have been at least three earthquakes with $\mathbf{M} \geq 6.2$ in the CSZ during that time period.

Conclusions

The analyses carried out in this study indicate that the 1870 earthquake was centered at the southwestern end of the CSZ and had a likely moment magnitude based on intensity observations between $\mathbf{M_I}$ 5.5 and $\mathbf{M_I}$ 6.0, with a best estimate of $\mathbf{M_I}$ 5.8. The 1870 earthquake was approximately comparable in size to or perhaps slightly larger than the 1988 Saguenay, Quebec, earthquake. The 1870 event appears to have been smaller than the 1925 earthquake, which was centered at the northeastern end of the CSZ. When combined with the compilation of Lamontagne *et al.* (2008), this study suggests that the 1925 earthquake was the largest event in the CSZ since 1663.

Data and Resources

The MMI data for the 1870 earthquake were taken from Gouin (2001) and augmented with felt and damage reports from the *Boston Evening Transcript* newspaper (the 20 October 1870 and 21 October 1870 editions) and the *New York Times* newspaper (the 21 October 1870 and 22 October 1870 editions). The MMI data for the 1925 earthquake were acquired from the Earthquakes Canada web site http://earthquakescanada.nrcan.gc.ca/histor/20th-eme/1925/intensitew-eng.php (last accessed July 2010). The MMI data for the 1988 Saguenay, Quebec, earthquake was provided by Gail Atkinson at the University of Western Ontario based on Cajka and Drysdale (1996). The seismicity shown in Figure 1 is from the Weston Observatory earthquake catalog for northeastern North America. All of the uncorrected and corrected MMI readings are given in Ⓔ Tables S1 and S2 in the electronic supplement to this paper.

Acknowledgments

We thank Boston College for an Academic Technology Innovation Grant that provided support to Megan Dupuy for the accumulation of the intensity data for this study. We appreciate the generosity of Gail Atkinson, who provided the MMI data for the 1988 earthquake in a convenient digital form. We thank three anonymous reviewers and Associate Editor Zhigang Peng for their reviews of this note.

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Manuscript received 28 February 2011