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A New Analysis of the Magnitude of the February 1663 Earthquake at Charlevoix, Quebec

by John E. Ebel

Abstract This paper presents a new and comprehensive analysis of the magnitude of the 1663 Charlevoix, Quebec, earthquake. Based on a modified Mercalli intensity scale (MMI) of about VI from reports of damage to chimneys and a masonry wall in Roxbury and Boston, Massachusetts, the best estimate of the moment magnitude of this earthquake is $M_{7.3}$ to $7.9$ from MMI attenuation relations. Using ground-motion attenuation relations and the threshold for chimney and masonry damage from fragility curves for seventeenth- and eighteenth-century dwellings in Boston, the magnitude of the 1663 earthquake is at least $M_{6.9}$ if the damage occurred on very soft soil conditions and is $M_{7.3}$ to $M_{7.7}$ if the damage took place on firm soil or bedrock. Both the best estimate of a length of 73 km for the most active section of the Charlevoix Seismic Zone and an estimated fault area of $73 \times 25$ km for the 1663 earthquake are consistent with an earthquake of $M_{7.3}$ to $7.6$ based on scaling relationships. Also, in the 1811–1812 New Madrid earthquake sequence only the 7 February 1812 shock, the largest of the sequence, caused chimney damage beyond about 600 km. The 7 February New Madrid event is thought to have taken place on the Reelfoot fault, for which the length of the recent earthquake activity and of the suspected 1812 rupture is less than that of the active seismicity zone at Charlevoix. These observations suggest that the 1663 Charlevoix earthquake was approximately comparable in magnitude to or even larger than the largest of the 1811–1812 New Madrid earthquakes and therefore was at least $M_{6.8}$. When put together, the several lines of analysis in this study indicate that the best estimate of the size of the 1663 earthquake is $M_{7.5} \pm 0.45$.

Introduction

The accurate assessment of the seismic hazard of a region requires a detailed understanding of the past seismicity of that region. One important element of seismic hazard assessment is a determination of the maximum earthquake that is possible in each seismic source zone without a consideration of when such an earthquake might occur. In most parts of central and eastern North America, the estimation of the maximum earthquake is difficult because there is no certainty that the largest possible earthquake has been observed in the different seismic source zones of the region during the past four centuries for which there is historical information on the earthquake activity. Furthermore, with a few exceptions no paleoseismological evidence of earlier strong earthquakes has been found so far. At the present time, for each seismic source zone one only can put a lower bound on the maximum possible earthquake by determining the largest earthquake that has taken place in the historic record.

It is well known that there was a series of very strong earthquakes that took place in the midwestern United States in 1811–1812 (Fuller, 1912) in what is known as the New Madrid seismic zone (NMSZ). Johnston (1996) argued that the largest earthquake of this sequence, with moment magnitude $M_{8.1}$, was the strongest known historically in the intraplate region of North America and perhaps the strongest known historically from all stable cratonic regions. Later, Hough et al. (2000) estimated that the largest of the 1811–1812 earthquakes was $M_{7.4}$–7.5, whereas Bakun and Hopper (2004) reported that the 1811–1812 earthquakes ranged up to $M_{7.8}$. Recently, Hough and Page (2010) argued that a maximum magnitude of about $M_{6.8}$–7.0 in the NMSZ can reconcile the repeating seismicity of that zone with a strain rate due to postglacial rebound, and is also at the low end of the magnitude range inferred from a recent analysis of consensus intensities from the largest events in the 1811–1812 earthquake sequence. While clearly large earthquakes, the magnitude of the largest of the 1811–1812 seismic sequence still has an uncertainty of at least several tenths of a magnitude unit.

Also known, but much less well studied, is a strong earthquake that took place in eastern Canada in February 1663,
which was probably centered somewhere in the Charlevoix seismic zone (CSZ) along the St. Lawrence River in Quebec. According to the Canadian earthquake catalog (see the Data and Resources section), this earthquake was about magnitude 7.0, although the source of this magnitude assignment is unclear. Gouin (2001) included this earthquake in his study of historic earthquakes of eastern Canada, and he argues that this earthquake is $m_L$ 6.5 $\pm$ 0.5 based on the area where it was felt. Clearly there is some uncertainty concerning the magnitude of this historic earthquake, due in large measure to the paucity of data for this event because it took place during the early days of European settlement of North America.

This paper presents a new and comprehensive analysis of the magnitude of the 1663 Charlevoix earthquake. The magnitude of this earthquake is estimated based on analyses of damaged structures reported in the Boston, Massachusetts, area as well as on the modern seismicity that is routinely reported from the CSZ. Comparisons are also made between the 1663 earthquake and the largest events from the 1811–1812 New Madrid earthquake sequence. The major conclusion that is reached in this paper is that the 1663 earthquake probably was about $M$ 7.5 and was similar in magnitude to or larger than the largest of the 1811–1812 earthquakes in the NMSZ.

Summary of the Historic Accounts of the 5 February 1663 Earthquake

It has long been known from the lore of eastern North America that a very strong earthquake was experienced along the St. Lawrence River in Canada in 1663 (Brigham, 1871). The mainshock took place about 5 p.m. local time on 5 February on the Gregorian calendar, which was in use in New France at that time. Figure 1 shows a map from Gouin (2001) that summarizes from historic reports the locations where the earthquake is known to have caused damage or been felt.

In Canada, the most detailed and notable accounts of the strongest effects due to the earthquake were sent by Catholic missionaries such as the Jesuit Fr. Jerome Lalemant, S.J. back to their superiors in Europe (Jesuit Relations, 1663). Ebel (1996) and Gouin (2001) present comprehensive summaries and transcriptions of the reports of this earthquake. Hodgson (1928) summarizes the reports of landslides along

![Figure 1](image-url)  
*Figure 1.* Map of the area affected by the earthquake of 5 February 1663 (Gregorian calendar), modified from Gouin (2001). The proposed epicentral region near La Malbaie is indicated, as are localities where landslides were reported due to the earthquake. Localities for which Gouin (2001) has felt reports are indicated by closed circles (where an intensity assignment was made by Gouin, 2001) and plus signs (where no intensity assignment was made by Gouin, 2001). Open circles were added to show additional localities where the earthquake was reported felt.
The crack in the front wall, said to have been caused by an earthquake in 1663, “which made all New England tremble.”

The crack in the brick wall must have come early in the history of the building, because Boston itself had only been founded in 1636. Furthermore, the crack from 1663 must have been quite notable because its cause was remembered for more than two centuries. This structure would also have experienced potentially damaging shaking in the later 1755 Cape Ann earthquake, which was known to have caused much masonry damage throughout Boston. Even so, the nineteenth-century author (Porter) did not attribute the crack in the Ship Tavern wall to the better-known 1755 earthquake, but rather he ascribed it to the earlier 1663 event.

Other felt reports for the 1663 earthquake come from the New Netherland colony of North America, comprising what is today southern New York state. The most direct evidence of this earthquake is a line in a letter dated 7 August 1663 from Jeremias van Rensselaer of Rensselaerswyck in New Netherland to his brother Jan Baptist in Amsterdam in the Netherlands. The letter contains a line that can be translated from the original Dutch as (J. Jacobs, personal communication, 2009)

There is not much news to tell except that last winter we had an earthquake which was very strong further inland and did a lot of damage to the houses of the French.

Not only does this report show that an earthquake was felt in New Netherland in the winter of 1662–1663, but it indicates that this was the same earthquake that caused damage in New France. Thus, the evidence in this report supports the idea that the 5 February 1663 earthquake was felt throughout the New Netherland colony.

Other New Netherland sources also attest to an earthquake in 1663, although they give less information than does van Rensselaer. Peter Stuyvesant, the last Dutch governor of New Amsterdam, wrote in his annals that (Abbott, 1873)

The year 1663 was a year of many disasters. Early in the year an earthquake shook severely the whole of New Netherland and the adjacent regions.

Joannes Nevius reported that during the year 1663 there was an earthquake (Honeyman, 1900). O’Callaghan (1865) reports in his annals for 1663 an earthquake in New Netherland. A later report by Fiske (1899) states,

An earthquake shook the valley of the Hudson, all the way from Beverwyck down to Fort Amsterdam, and sent reverberations far into Canada and Acadia.

Beverwyck is now Albany, New York, and Fort Amsterdam stood in what is currently the financial district of New York City (Fig. 1). None of these reports indicate any damage in New Netherland due to the 1663 earthquake, but they state that the earthquake was felt throughout the entire Dutch colony.

New Netherland is the farthest south that the 1663 earthquake from Canada is known to have been felt. So far, Internet searches by the author have failed to turn up any felt reports from Maryland, Virginia, or the Carolinas or from farther south or west. The 1925 M 6.2 Charlevoix earthquake (Bent, 1992) was felt in Virginia and North Carolina (earthquakescanada.nrcan.gc.ca/histor/20th-eme/1925/intensitew-eng.php); the 1663 earthquake should also have been felt in these areas if it was at least as large as the 1925 earthquake.

To the east, the earthquake was reported felt in Acadia, which is now Nova Scotia (Gouin, 2001; Fig. 1) and at Percé at the eastern tip of the Gaspé peninsula. Gouin (2001) cites the description of the 1663 earthquake written by Nicolas Denys in Acadia that was published in Ganong (1908). According to Denys, the earthquake was a “small” affair that nevertheless was made up of three distinct shocks that rattled cooking...
utensils and tableware. Gouin (2001) states that Denys was probably at what is now St. Peters, which is located on Cape Breton Island in eastern Nova Scotia, but curiously Gouin (2001) does not show that location on his map of felt locations of the 1663 earthquake (Fig. 1). A. Ruffman (personal commun., 2009) also believes that St. Peters was the likely location of Denys in February 1663, so this evidence suggests that the 1663 earthquake rattled dishes in eastern Nova Scotia.

Some other sources that give less believable reports of the felt area of the 1663 earthquake have been found. Kingsford (1887) states,

The movement extended from Labrador to the Ottawa, passing thence to New York and New England.

The statement that the earthquake was felt in Labrador has not been confirmed by any primary accounts or independent sources. No colonial settlements in what today is Labrador are known from 1663, and at that time all of the area that drained into Ungava Bay was considered Labrador (M. Staveley, personal commun., 2009). Thus, this statement from Kingsford (1887) cannot be used to confirm how far to the northeast this earthquake was felt.

In addition to the strong earthquake in Quebec on 5 February 1663, there was also a strong earthquake probably centered along the west coast of Mexico on this same day. Some sources apparently link these two seismic events into a single earthquake. For example, Perley (1891), in describing the 1663 earthquake, states,

Although New England was more or less shaken, the country on either side of it suffered more. It extended as far north as Canada, and south to Mexico, probably being felt farther in both directions.

The historic earthquake catalog of Garcia and Suarez (1996) gives a brief description of an earthquake on 5 February 1663 in Mexico. As part of their description, they cite M. Iluet, who states in his Manual de Geografia

“...estos sacudimientos se extendieron desde las costas del Ecuador hasta el Canada” [trans., ...the shaking extended from the coasts of Ecuador to Canada].

Apparently, Iluet learned of reports of the strong earthquake in Canada and perhaps of an earthquake in Ecuador on this same day, and he used these reports to argue that the 5 February 1663 earthquake was felt from the coast of Ecuador all the way to Canada. Clearly, no single crustal earthquake could have been felt over such a large area.

Estimation of the Magnitude of the 1663 Earthquake from the MMI at Roxbury and Boston, Massachusetts

The reports from Roxbury and Boston in Massachusetts for the 1663 earthquake are consistent with a modified Mercalli intensity (MMI) of about VI based on the chimney damage and cracked masonry wall. One can argue that the early colonials in Massachusetts could only produce very weak mortar for their chimneys, and so perhaps the true main-shock intensity was somewhat less than VI, such as V.5 or perhaps even V. On the other hand, if the very sparse existing accounts do not report the full extent of earthquake damage that was experienced throughout the Massachusetts colony due to the 1663 ground shaking, then perhaps the MMI there might have been somewhat larger than VI, such as VI.5.

An estimate of the magnitude of the 1663 earthquake can be made from the MMI value at Boston using published intensity-attenuation relations if the epicentral distance is known. Two intensity-attenuation relations that are applicable to earthquakes in northeastern North America, those of Klimkiewicz and Pulli (1983) and Bakun et al. (2003), are used in this analysis. Figure 2 shows the location of Boston compared with that of the zone of high earthquake activity that is called the Charlevoix seismic zone. At its closest, the CSZ is about 560 km from Boston, and its farthest point is about 640 km from Boston. Thus, the mean distance of the CSZ is about 600 km from Boston.

Table 1 summarizes magnitude estimates for the 1663 earthquake using the Klimkiewicz and Pulli (1983) and Bakun et al. (2003) intensity-attenuation relations. The Klimkiewicz and Pulli (1983) intensity-attenuation relation is based on $m_b$, whereas the Bakun et al. (2003) intensity-attenuation relation is based on $M$. To allow a direct comparison of the magnitude values in the table, the $m_b$ values were
assumed to be equivalent to \( m_n \) values, and the conversion formula from \( M_n \) to \( M \) of Atkinson and Boore (1995) was used in Table 1. Because the epicenter of the 1663 earthquake is not known, magnitude estimates were computed based on the closest distance, the average distance, and the greatest distance of Boston from the CSZ. The best estimate of the MMI at Roxbury and Boston is VI, which yields magnitude estimates based on possible variations in the MMI values that were experienced at Roxbury and Boston. Estimation of the Magnitude of the 1663 Earthquake from Chimney and Masonry Damage at Roxbury and Boston, Massachusetts

Another way to estimate the magnitude of the 1663 earthquake is to directly use the observation of chimney damage at Roxbury and a cracked masonry wall in Boston. While the analysis in this section effectively is based on the same data as in the previous section, the analysis methods between the two sections are quite different. In the previous section the analysis was based on relationships involving predictions of MMI values as a function of event magnitude and epicentral distance that were derived directly from intensity data, whereas the analysis in this section makes use of modern ground-motion attenuation relations that have been determined using instrumental recordings and simulations of instrumental ground-motion data with no input of earthquake intensities at all.

According to Jenison (1976) during the first half of the seventeenth century in New England, there was no known source of limestone for making cement; most chimneys were laid with clay or mud mortar on their interiors with just an exterior application of lime-based mortar to make the structure watertight. Only small amounts of mortar could be made during this time by burning shells that were collected from coastal areas. Economic limestone deposits were only discovered near Providence, Rhode Island, in the late 1660s and near Newburyport, Massachusetts, in the late 1690s. For this reason, large brick or stone structures that used lime-based mortars were rare until the 1720s in Massachusetts, although the historical account cited previously indicates that the Ship Tavern in Boston was constructed of a lime mortar made from shells. Jenison (1976) notes that mortars made from shells and mortars made from limestone undergo exactly the same chemical reactions, and so they presumably have the same strength.

Ho (1979) carried out an analysis of the ground motions that would lead to chimney damage in a typical early eighteenth-century house in eastern Massachusetts. The structure he studied was a two-story heavy timber-frame dwelling with a brick chimney made from clay and shell mortar that had been built about 1638. He considered a wide range of chimney strengths because there were no standard construction practices during the seventeenth and early eighteenth centuries. Ho (1979) determined that the natural period of the entire structure was about 12 Hz and that damage to the weakest chimneys would occur in ground motions between 0.015 and 0.04 g. In another study Whitman (2002) determined fragility values for typical eighteenth-century masonry construction in Boston. Ebel (2006) used the Whitman (2002) fragility values and the Kircher et al. (1997) fragility curves for unreinforced masonry structures to estimate the fragility curves for the chimneys of eighteenth-century New England houses. Ebel (2006) argued that the threshold for chimney damage in eighteenth-century structures is 0.01 g for peak ground acceleration (PGA) and 0.03 g for pseudospectral acceleration (SA 0.3 s period) and that the natural period of the structures is about 0.3 s. The Ho (1979), Whitman (2002), and Ebel (2006) studies together can be used to bracket the expected range of minimum ground motions that were required to cause damage to seventeenth-century chimneys and masonry walls in eastern Massachusetts.

In this analysis of the 1663 earthquake it is assumed that the ground motions at Roxbury and Boston in 1663 were at least equal to the threshold damage values to explain the reported chimney damage and masonry damage. Modern

| Estimation of the Magnitude of the 1663 Earthquake from Chimney and Masonry Damage at Roxbury and Boston, Massachusetts |

Table 1

<table>
<thead>
<tr>
<th>Intensity-Accumulation Relation</th>
<th>MMI V at Boston</th>
<th>MMI V.5 at Boston</th>
<th>MMI VI at Boston</th>
<th>MMI VI.5 at Boston</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assuming an Epicentral Distance of 560 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klimkiewicz and Pulli (1983)</td>
<td>7.0 ((m_b) (6.9 M))</td>
<td>7.2 ((m_b) (7.4 M))</td>
<td>7.5 ((m_b) (7.8 M))</td>
<td>7.8 ((m_b) (8.3 M))</td>
</tr>
<tr>
<td>Bakun et al. (2003)</td>
<td>6.7 ((M))</td>
<td>7.0 ((M))</td>
<td>7.3 ((M))</td>
<td>7.6 ((M))</td>
</tr>
<tr>
<td>Assuming an Epicentral Distance of 600 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klimkiewicz and Pulli (1983)</td>
<td>7.0 ((m_b) (7.1 M))</td>
<td>7.3 ((m_b) (7.5 M))</td>
<td>7.6 ((m_b) (7.9 M))</td>
<td>7.9 ((m_b) (8.4 M))</td>
</tr>
<tr>
<td>Bakun et al. (2003)</td>
<td>6.8 ((M))</td>
<td>7.1 ((M))</td>
<td>7.3 ((M))</td>
<td>7.7 ((M))</td>
</tr>
<tr>
<td>Assuming an Epicentral Distance of 640 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klimkiewicz and Pulli (1983)</td>
<td>7.1 ((m_b) (7.2 M))</td>
<td>7.4 ((m_b) (7.6 M))</td>
<td>7.7 ((m_b) (8.1 M))</td>
<td>7.9 ((m_b) (8.5 M))</td>
</tr>
<tr>
<td>Bakun et al. (2003)</td>
<td>6.9 ((M))</td>
<td>7.2 ((M))</td>
<td>7.5 ((M))</td>
<td>7.8 ((M))</td>
</tr>
</tbody>
</table>

\(^*\)The Klimkiewicz and Pulli (1983) magnitudes were converted to moment magnitudes using the relation between \( M \) and \( M_n \) of Atkinson and Boore (1995) under the assumption that \( m_b = M_n \).
ground-motion attenuation relations can be used to estimate the magnitude of the earthquake in the CSZ necessary to cause a damaging level of ground motion in Roxbury and Boston. In this study, four attenuation relations are applied, namely those of Somerville et al. (2001; the intraplate rift relation), Campbell (2003), Tavakoli and Pezeshk (2005), and Atkinson and Boore (2006).

Table 2 summarizes the magnitude estimates for the 1663 earthquake using these four attenuation relations and the threshold ground-motion values in Roxbury and Boston. All of the ground-motion attenuation relations in Table 2 are based on moment magnitude \( M \) and use the closest distance to the fault as the distance parameter. As noted previously, the distance from Roxbury and Boston to the closest part of the current active seismicity zone at Charlevoix is approximately 560 km, so that is assumed in this analysis to be the closest distance to the 1663 rupture, a value that is needed for the attenuation-relation computations. The site conditions in Roxbury where the damage occurred are unknown because the locations of the structures with the chimney damage are not given in the existing reports about the earthquake. In 1663 most buildings in what was then called Roxbury probably were located on glacial till, glacial outwash deposits, or bedrock (Woodhouse et al., 1991; Brankman and Baise, 2008), although a few structures may have been built on unconsolidated alluvium along the local rivers and drainages. Bedrock is probably no deeper than a few tens of feet below the surface beneath much of the original seventeenth-century Roxbury settlement (Woodhouse et al., 1991). Buildings on bedrock would probably have experienced hard-rock ground motions, while buildings on glacial till or outwash likely experienced soft rock or hard-soil ground motions. Buildings in seventeenth-century Roxbury on unconsolidated alluvium may have experienced National Earthquake Hazard Reduction Program (NEHRP) class C or possibly D soil conditions. The Ship Tavern in Boston was located on one of the glacial drumlins that comprise much of Boston’s original Shawmut peninsula (Woodhouse et al., 1991; Brankman and Baise, 2008), and this most likely corresponds to soft rock or hard-soil site conditions.

In Table 2 ground-motion values for each of the four attenuation relations were computed for \( M \) 7.0, 7.3, and 7.6 for soil site conditions (NEHRP class D soil conditions) for PGA, SA 0.1, and SA 0.3 at a distance of 560 km from the 1663 rupture. Also shown in Table 2 for each ground-motion parameter is the estimated minimum ground motion that was needed to cause damage to chimneys or masonry in seventeenth-century Roxbury and Boston based on the work of Ho (1979), Whitman (2002), and Ebel (2006). The last column in Table 2 shows for each attenuation relation the \( M \) value where the predicted ground motion for hard-rock site conditions is to equal that of the threshold for chimney or masonry damage. The values in Table 2 can help bracket the magnitude of the 1663 mainshock.

From the analysis of Ho (1979), it appears that the SA 0.1 ground motions are the most important for determining the possibility of chimney damage at Roxbury in 1663. If the 1663 damage occurred to weak chimneys (with a damage threshold of 0.015\( g \)) that were located on thick soft soils, then, depending on the attenuation relation, an earthquake as small as \( M \) 6.9 to 7.2 would have been sufficient to damage the Roxbury chimneys. On the other hand, if the

<table>
<thead>
<tr>
<th>Table 2</th>
<th>1663 Magnitude Estimates Based on the Chimney Damage at Roxbury, Massachusetts</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Magnitude ( M_w )</td>
</tr>
<tr>
<td></td>
<td>7.0</td>
</tr>
<tr>
<td>PGA ((g)) Soil Site (D) Conditions**&lt;sup&gt;1&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Atkinson and Boore (2006)</td>
<td>0.008</td>
</tr>
<tr>
<td>Campbell (2003)</td>
<td>0.008</td>
</tr>
<tr>
<td>Somerville et al. (2001) Rift</td>
<td>0.006</td>
</tr>
<tr>
<td>Tavakoli &amp; Pezeshk (2005)</td>
<td><strong>0.010</strong></td>
</tr>
<tr>
<td>SA at 0.1 s ((g)) Soil Site (D) Conditions&lt;sup&gt;1&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Atkinson and Boore (2006)</td>
<td><strong>0.016</strong></td>
</tr>
<tr>
<td>Campbell (2003)</td>
<td>0.015</td>
</tr>
<tr>
<td>Somerville et al. (2001) Rift</td>
<td>0.012</td>
</tr>
<tr>
<td>Tavakoli &amp; Pezeshk (2005)</td>
<td>0.013</td>
</tr>
<tr>
<td>SA at 0.3 s ((g)) Soil Site (D) Conditions&lt;sup&gt;3&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Atkinson and Boore (2006)</td>
<td>0.020</td>
</tr>
<tr>
<td>Campbell (2003)</td>
<td>0.008</td>
</tr>
<tr>
<td>Somerville et al. (2001) Rift</td>
<td>0.006</td>
</tr>
<tr>
<td>Tavakoli &amp; Pezeshk (2005)</td>
<td>0.019</td>
</tr>
</tbody>
</table>

*Threshold for chimney/masonry damage = 0.015\( g \)
1Threshold for chimney damage = 0.015\( g \) to 0.04\( g \)
3Threshold for chimney/masonry damage = 0.03\( g \)
3Attenuation relation does not allow a rock ground-motion value as large as 0.03\( g \).
chimney damage occurred to structures that were located on bedrock, then the magnitude of the 1663 event must have been \( M \) 7.3 to 7.7. If the damaged chimneys were part of structures situated on glacial till or outwash deposits, then the 1663 mainshock magnitude was probably \( M \) 7.3 to 7.5. It is unlikely that any structures at that time were built on alluvium deposits, because those structures would have been prone to flooding during strong coastal storms. For this reason, it is considered most probable that the Roxbury structures that sustained chimney damage in the 1663 earthquake were located on glacial outwash, till, or bedrock.

The SA 0.3 and PGA values can also be used to estimate the magnitude of the 1663 mainshock based on the ground motions that may have been experienced in Roxbury and at the Ship Tavern in Boston. If the chimney and masonry damage occurred to structures on soil site conditions, the SA 0.3 ground-motion estimates from Atkinson and Boore (2006) and Tavakoli and Pezheshk (2005) are consistent with \( M \) about 7.4–7.5, while the other two ground-motion relations suggest a magnitude above \( M \) 7.6. Rock or hard-soil site conditions for the chimney masonry damage would suggest a moment magnitude close to or above \( M \) 8.0. In the case of the Atkinson and Boore (2006) attenuation relation for SA 0.3, the predicted ground-motion value does not reach 0.03\( g \) for any magnitude value, presumably due to nonlinear effects at large ground motions. The estimated magnitude values from the PGA threshold for soil site conditions at Roxbury and Boston are somewhat lower than for SA 0.3 for almost all of the attenuation relations: about \( M \) 7.0 using Tavakoli and Pezheshk (2005), \( M \) 7.3 from Atkinson and Boore (2006) and Campbell (2003), and \( M \) 7.4 from Somerville et al. (2001). For PGA, rock, or hard-soil site conditions for the Roxbury chimney damage and for the damage and the masonry wall at the Ship Tavern in Boston mean that the magnitude of the earthquake is between about \( M \) 7.3 and \( M \) 7.7.

Taken together, the ground-motion values in Table 2 suggest an estimated magnitude value of at least \( M \) 6.9 to \( M \) 7.0 for the 1663 earthquake if all of the damaged structures were on very soft soils and if the damaged chimneys in Roxbury were of weak construction. It is more likely that the damaged structures in Roxbury and Boston were constructed on glacial till or wash deposits, which correspond to firm soil or soft-rock site conditions. For this case, the estimated magnitude of the 1663 earthquake falls in the range of about \( M \) 7.3 to \( M \) 7.7, even for weakly constructed chimneys.

Estimation of the Magnitude of the 1663 Earthquake from the Spatial Extent of the Modern Seismicity in the Charlevoix Seismic Zone

Another way to estimate the magnitude of the 1663 earthquake is to assume that the spatial extent of the modern seismicity shows the configuration of the aftershock zone of the 1663 earthquake. This idea builds on the suggestion of Ebel et al. (2000) that aftershock zones in intraplate regions can be observed as long as a couple thousand years after a mainshock. Support for this idea comes from the NMSZ, where the active lineations in the modern seismicity are interpreted to show the locations of the major earthquake ruptures in the 1811–1812 sequence (e.g., Johnston and Schweig, 1996; Hough et al., 2003).

Figure 3 shows the spatial extent along the St. Lawrence River of the CSZ. The length along the river of the highest seismicity zone is about 73 km, although arrows on the figure show alternate interpretations that are about 54 km and 100 km. Outside of this zone of highest seismicity there are elongated belts of much lower seismicity that stretch southwest to Quebec City and northeast past the confluence of the Saguenay River with the St. Lawrence. Following the reasoning of Ebel et al. (2000), the central zone of highest seismicity is taken as an estimate of the fault segment that ruptured in the 1663 earthquake.

Focal mechanisms of the largest earthquakes in the CSZ since 1924 generally show thrust faulting on northeast-southwest striking nodal planes (Bent et al., 2003), suggesting that this may have been the focal mechanism of the 1663 earthquake. The modern microseismicity at Charlevoix dips southeast from near the surface to a depth of about 25–30 km (Lamontagne and Ranalli, 1997), which indicates a southeast-dipping fault plane for the 1663 earthquake. The dimensions of the modern seismicity at Charlevoix (73 km long and 25 km wide) can be used to estimate the magnitude of the 1663 earthquake under the assumption that the zone of modern high seismic activity delineates the 1663 rupture. Using the Wells and Coppersmith (1994) scaling relations for thrust earthquakes, one finds that both a surface rupture length and a subsurface rupture length of 73 km are consistent with an earthquake of \( M \) 7.3. In addition, if one takes fault dimensions of 73 km \( \times \) 25 km to estimate the fault area of the 1663 rupture, one also computes \( M \) 7.3 from the Wells and Coppersmith (1994) magnitude versus fault area relationship. On the other hand, if the fault area versus moment magnitude relation of Somerville et al. (2001) is used, then a fault with dimensions 73 km \( \times \) 25 km yields \( M \) 7.6.

Uncertainty in the estimated fault length can be explored by testing different rupture length scenarios for the 1663 earthquake, such as those in Figure 3. For example, if the 1663 fault rupture was only 54 km, the estimated magnitude using Wells and Coppersmith (1994) is \( M \) 7.1, and a fault area of 54 km by 25 km also yields \( M \) 7.1. If the 1663 rupture extended farther to the southwest than the edge of the most active earthquake belt (such as for a total fault length of about 100 km as indicated in Fig. 3), then the estimated magnitudes based on a fault area of 100 km \( \times \) 25 km are both \( M \) 7.4 using Wells and Coppersmith (1994) and \( M \) 7.7 using Somerville et al. (2001). Thus, if the modern microseismicity delineates the 1663 fault rupture, then this seismicity suggests that the 1663 earthquake may have been as small as \( M \) 7.1 but more likely had \( M \) 7.3 to 7.6.
It is interesting to compare the modern seismicity in the CSZ with that in the NMSZ (Fig. 3). The Reelfoot fault segment of the NMSZ is a northwest-southeast striking thrust fault that connects two active northeast-southwest striking strike-slip faults (Johnston and Schweig, 1996). Unlike the rather steep dip of the CSZ down to 25 km or more in depth (Lamontagne and Ranalli, 1997), the modern seismicity on the Reelfoot fault ranges in depth between about 5 km and 15 km, with dips between 30° and 45° on the deeper parts of the fault and ranging up to 80° on the shallower parts of the fault (Mueller and Pujol, 2001). The Reelfoot fault zone is thought to have failed in the 7 February 1812 earthquake (Johnston and Schweig, 1996; Hough et al., 2003). As can be seen in Figure 3, the total length of the seismicity along Reelfoot fault thrust segment of the NMSZ is about 61 km (Mueller and Pujol, 2001), somewhat shorter than the length of the active seismicity of the CSZ. Kinematic considerations of the interaction of the strike-slip and thrust segments of the NMSZ may have limited the length of the 7 February 1812 thrust segment to only about 40 km (Mueller et al., 2004). The magnitude estimates of the 7 February 1812 earthquake by Johnston (1996), Hough et al. (2000), Mueller and Pujol (2001), and Bakun and Hopper (2004) are M 8.0, M 7.4–7.5, M 7.2–7.4, and M 7.8, respectively. The modern active seismicity zone at Charlevoix is somewhat larger in spatial extent than that along the Reelfoot fault segment of the NMSZ, suggesting that the 1663 earthquake was approximately comparable in magnitude to or perhaps even larger than the largest of the 1811–1812 New Madrid earthquakes. Using the smallest estimate of the magnitude of the largest of the 1811–1812 earthquakes proposed by Hough and Page (2010), the spatial extent of the CSZ when compared with that of the Reelfoot fault indicates that the 1663 earthquake was at least M 6.8.

Comparisons of Chimney Damage between the 1663 Charlevoix Earthquake and the 1811–1812 New Madrid Earthquakes

Another way to estimate the magnitude of the 1663 earthquake is indirectly by comparing its intensity pattern to that of each of the three largest of the 1811–1812 New Madrid earthquakes. Specifically, the occurrence of chimney damage at Roxbury, Massachusetts, in the 1663 earthquake at a distance of 560–640 km from the causative fault gives a basis of comparison with the New Madrid earthquakes. According to Kochkin and Crandell (2004), chimneys in the area of the midwestern United States at the time of the 1811–1812 earthquakes were generally made of brick or stone and were constructed using locally sourced lime and sand mortar. In this analysis it is assumed that the midwestern chimneys and masonry structures in 1811–1812

Figure 3. (a) Seismicity map for the time period 1985 to 2010 in the vicinity of the Charlevoix seismic zone from the Earthquakes Canada database. The spatial extent of this modern active seismicity is about 73 km and is indicated by the bold arrows. Short narrow arrows show a possible minimum extent of the CSZ of about 54 km; long narrow arrows show a zone that extends from the northeastern end of the most active zone to the southwestern end of the most concentrated small earthquake activity, a distance of 100 km. (b) Seismicity map for the time period 1985 to 2010 of the NMSZ from the CERI database at the University of Memphis. The total spatial extent of this modern active seismicity of the Reelfoot thrust segment of this zone (bold arrows) is about 61 km from Mueller and Pujol (2001), although kinematic considerations may have limited the 12 February 1812 rupture to about 40 km (Mueller et al., 2004; narrow arrows). The color version of this figure is available only in the electronic edition.
were of comparable strength to those in Massachusetts in 1663.

Figures 4a,b,c show intensity maps for the three largest of the 1811–1812 New Madrid earthquakes from Hough et al. (2000), who used the areas within the MMI IV, V, VI, VII, and VIII contours to estimate the magnitudes for each of these events. Each of these maps has been modified to show those locations where chimney damage was reported, and each map also contains a circle of 600 km radius centered on the center of the fault that is thought to have ruptured in that event. For the 7 February 1812 shock (M 7.4–7.5 according to Hough et al., 2000), chimney damage was reported at an epicentral distance exceeding 600 km, while for the 16 December 1811 event (M 7.2–7.3 according to Hough et al., 2000), there was chimney damage as far away as Cincinnati, close to 600 km from the causative fault. For the 23 January 1812 event (M 7.0 according to Hough et al., 2000), the greatest distance at which chimney damage is reported is about 400 km. It must be mentioned that Hough and Page (2010) have made arguments that the largest of the New Madrid earthquakes was no more than M 6.8 to 7.0 to reconcile the observed repeat times of the large New Madrid earthquakes with the current regional strain release data. The magnitudes in this paragraph from Hough et al. (2000) are higher than the magnitudes favored by Hough and Page (2010).

Hough et al. (2000) note that the chimney damage that was reported at Cincinnati occurred on soft ground and that the ground shaking was considerably reduced on the upland areas away from the Ohio River. In Roxbury the site conditions in 1663 for most structures were probably glacial till or bedrock; so the 1663 earthquake ground shaking at Roxbury was probably comparable to the ground shaking in the upland areas away from the rivers of the Midwest in the 1811–1812 earthquake sequence. From these comparisons, it appears that the chimney damage report at Roxbury in 1663 at an epicentral distance of about 560 km to 640 km means that 1663 earthquake was comparable in size to or perhaps even larger than the largest of the New Madrid earthquakes on 7 February 1812. This qualitative comparison supports the conclusion in the previous section of this paper that the 1663 earthquake in Quebec and the 7 February 1812 earthquake in the New Madrid seismic zone had approximately comparable magnitudes.

Best Estimate of the Magnitude of the 1663 Charlevoix Earthquake

The previous sections of this paper present estimates of the magnitude of the 1663 earthquake based on several different analyses. From the MMI analyses, the best estimate of the magnitude of the 1663 earthquake is M 7.3 from the Bakun et al. (2003) relation and M 7.9 from the Klimkiewicz and Pulli (1983) relation. From the chimney damage analyses, the best estimate of the 1663 earthquake magnitude appears to be in the range between M 6.9 and M 7.2 for very soft soil conditions, M 7.3 and M 7.5 for very firm soil/soft rock site conditions, and between M 7.5 and 7.7 for hard-rock conditions (ignoring the larger hard-rock values in Table 2). From the analysis of the dimensions of the modern seismicity, the best estimate of the 1663 magnitude is M 7.3 to 7.6. Taking all of these analyses together, the estimates all overlap in the range between M 7.4 and M 7.6. The center of this overlap region, M 7.5, is taken in this study as the best estimate for the magnitude of the 1663 earthquake.

The uncertainty in the best estimate of M for the 1663 earthquake can be found from the total range R of estimated M values found in all of the analyses in this paper, using the rule of thumb that the standard deviation is approximately R/4 (Mendhall et al., 2009). There is a wide range of magnitude estimates presented in the previous sections of this paper, with the extremes being as low as M 6.7 to as large as M 8.5 from the MMI analyses (again ignoring the M 9.0 values in Table 2). This range of magnitude estimates suggests that the standard deviation of M for the 1663 earthquake is about 0.45 magnitude units. Thus, the estimated magnitude of the 1663 earthquake is M 7.5 ± 0.45, and there is a 95% probability that the magnitude of the event is between M 6.6 and M 8.4.

Discussion

The 1663 event is one of several strong earthquakes that have been centered in the CSZ since the European settlement of northeastern North America. From the evidence presented in this study, it confirms that the 1663 earthquake was larger than all of the subsequent Charlevoix events. Instrumental records of the earthquake of 1 March 1925 were studied by Ebel et al. (1986) and Bent (1992) to estimate the source parameters for the event. Bent (1992) found that the 1925 event had M 6.2, Ms 6.2 ± 0.3, and M0 6.5 ± 0.4. She reported a seismic moment of 3.1 ± 2.5 × 10^18 N-m, which gives a range of M from 5.8 to 6.5. Ebel and Hart (2001) reported on observations of the shaking effects of the 1925 earthquake in Boston and vicinity from newspaper accounts. While the earthquake was felt strongly enough that many people ran out of buildings that were heavily shaken, no damage was reported in Boston. Thus, the masonry damage reports in Roxbury and Boston for the 1663 earthquake suggest that the 1663 event was larger than the 1925 event, and hence larger than M 6.2. According to Ebel et al. (2011), the 1870 earthquake at Charlevoix was about M 5.8, although it is rated at M 6.5 by the Canadian Geological Survey (Lamontagne, 2008). An examination by Ebel et al. (2011) of accounts in The Boston Evening Transcript newspaper of the 1870 earthquake reveals that this event did not damage chimneys or crack brick walls in Boston (which included the Roxbury section of the city), and thus the extant evidence suggests that the 1663 earthquake generated stronger ground shaking in Boston than did the 1870 earthquake. Thus, at Boston the ground shaking in the 1663 earthquake appears
Figure 4. (a) Isoseismal map of the $M_{7.4-7.5}$ New Madrid earthquake of 7 February 1812, showing the locations where chimney damage was reported. (b) Isoseismal map of the $M_{7.2-7.3}$ New Madrid earthquake of 16 December 1811, showing the locations where chimney damage was reported. (c) Isoseismal map of the $M_{7.0}$ New Madrid earthquake of 23 January 1812, showing the locations where chimney damage was reported. On all three maps, a star shows the center of the fault on which the earthquake is thought to have taken place, and a dashed circular arc is drawn at an epicentral distance of 600 km. Intensity reports where chimney damage was reported are circled. An inset on the upper left corner of each figure shows the observed MMI values plotted as a function of epicentral distance in degrees. The arrows on these inset graphs indicate an epicentral distance of 600 km. All three maps are modified from those in Hough et al. (2000), and the magnitudes given in this figure caption are those of Hough et al. (2000). The color version of this figure is available only in the electronic edition.

(Continued)
to have been greater than that in either the 1925 or the 1870 earthquakes.

One assumption that has been made in this study is that the 1663 rupture today is represented by the modern earthquakes in the CSZ, which experiences the highest rate of small earthquake activity in northeastern North America. Ebel (2009) argued that in the rupture zones of past major earthquakes the modern earthquake activity of $M \geq 4$ tends to cluster near the ends of those past ruptures. At Charlevoix, this appears to be the case. Figure 5 show the $M \geq 4$ seismicity in the CSZ and its immediate vicinity from 1985 to 2010. It is clear that most of the $M \geq 4$ events during this time period took place at the northeast end of the active seismicity zone along with two $M \geq 4$ events at the southwest end of the zone. Stevens (1980) noted that the earthquake of $M \geq 4\frac{1}{2}$ from 1924 to 1978 also took place at the southwest and northeast ends of this seismicity zone. Thus, if these larger events since 1924 are indicative of the ends of the 1663 rupture, they support the idea that the 1663 earthquake had a rupture length of about 70 km.

For many large earthquakes, another way to constrain their magnitude is by the size and distribution of liquefaction features, particularly sandblows, that were induced by the earthquake (Obermeier, 1996). In the Charlevoix area, Tuttle and Atkinson (2010) report young liquefaction features (less than 540 yr old), although they do not know whether to attribute these to the 1663 earthquake or to one of the later strong earthquakes that took place in the Charlevoix area, such as those in 1870 and 1925. Thus, while the Charlevoix area does contain liquefaction features that might have been caused by the 1663 earthquake, these features do not directly help constrain the magnitude of that earthquake. In addition,

Figure 4. Continued.

Figure 5. Map for the time period 1985 to 2010 in the vicinity of the Charlevoix seismic zone showing earthquakes of magnitude 4 and greater. The bold arrows show the same spatial extent of the most active seismicity as is indicated by the bold arrows in Figure 3. The color version of this figure is available only in the electronic edition.
A New Analysis of the Magnitude of the February 1663 Earthquake at Charlevoix, Quebec

Tuttle and Atkinson (2010) found evidence for two earlier seismic events that were strong enough to cause the formation of liquefaction features. One event dates to about 5000 yr B.P., while the other took place approximately 9770 yr B.P. Thus, the 1663 earthquake appears to have been one of a series of strong earthquakes centered in the CSZ during the past 10,000 yr, although the magnitudes of those earlier events are unknown.

If the recent seismicity in the CSZ is aftershock activity from the 1663 earthquake, then focal mechanisms of the seismicity can be used to infer the focal mechanism of the 1663 earthquake. Lamontagne (1987), Bent (1992), Lamontagne and Ranalli (1997), and Bent et al. (2003) all report focal mechanisms for earthquakes in the CSZ. The largest earthquake analyzed, the 1925 M 6.2 earthquake, was a thrust event with northeast-southeast nodal planes (Bent, 1992). Many of the other earthquakes in this seismic zone have similar focal mechanisms. The recent seismicity at Charlevoix defines a pair of parallel, tabular zones that dip steeply toward the southeast (Lamontagne and Ranalli, 1997), which may indicate that this was the fault plane in the 1663 earthquake. However, some of the earthquakes in the Charlevoix area have nodal planes that strike north–south or even northwest-southeast, similar to earthquakes in other parts of Quebec (Bent et al., 2003). Thus, there may have been a complicated pattern of faulting that took place during the 1663 earthquake.

Analyses of modern geodetic deformations in Quebec suggest that an earthquake of M 7.5 and even larger is possible in the Charlevoix area. Mazzotti et al. (2005) showed from GPS evidence that the St. Lawrence Valley of Quebec is shortening at an average rate of about 0.6 ± 0.2 mm yr−1, with the rate in the CSZ being about double that of the entire St. Lawrence valley. From their analysis of the GPS data, they argued that the maximum earthquake magnitude in the CSZ is about M 7.8 ± 0.6 and that the recurrence time of M ≥ 7 earthquakes is 400–1300 yr. Thus, the magnitude of the 1663 earthquake found in this study is consistent with the geodetic deformations that have been observed in the Charlevoix area. Mazzotti and Adams (2005) argued that the lack of significant deformation markers in the Charlevoix area suggests that the local high strain rate may be a short-term transient that only lasts hundreds to thousands of years.

If the 1663 earthquake had a magnitude of M 7.5, it could have been felt over a significant part of eastern North America. Figure 6 shows theoretical MMI III isoseismals computed with the two different intensity-attenuation relations that were used earlier in this paper. Figure 6 indicates that the 1663 earthquake should have been felt in Virginia and the Carolinas as well as in Newfoundland, and it might possibly have been felt in Florida. If felt reports of this earthquake can be found in these far-flung localities, they would provide further evidence for the magnitude of the 1663 earthquake that is argued for in this study. As noted previously, no felt reports of the 1663 earthquake from Virginia, Florida, or Newfoundland have yet been discovered from a search of the Internet.

Another indication of the size of the 1663 earthquake could come from finding the full distribution of sandblows and landslides that were caused by the event. Regarding liquefaction effects, Tuttle, Schweig, et al. (2002) reported that the major area of sandblows in the 1811–1812 sequence extended out as far as about 100 km from the earthquake faults, although smaller, more isolated sandblows exist as far as 240 km from the inferred epicenters (M. Tuttle, personal commun., 2010). For the M 7.7 Bhuj, India, earthquake of 26 January 2001, Tuttle, Hengesh, and Lettis (2002) report widespread liquefaction within about 140 km of the epicenter and smaller, individual sandblows out to 240 km. Thus, if the 1663 earthquake had M 7.5, then it may have caused liquefaction effects beyond 200 km from the fault zone. Finding such evidence may be quite difficult, because liquefiable areas are generally confined to river valleys in northeastern North America and because the frozen ground surface of midwinter when the earthquake took place may have suppressed some liquefaction features from forming. So far, all of the liquefaction features that can be attributed directly to the 1663 earthquake have been found within 30 km of Les Eboulements in the CSZ (M. Tuttle, personal commun., 2010).

Landslides and land slumps can also be generated by strong ground shaking at large distances from strong earthquakes. Keefer (1984, 2002) analyzed the maximum distance from the epicenter and from the fault rupture of landslides induced by earthquakes as a function of earthquake magnitude, and his analyses indicate that the greatest epicentral distance where a landslide would be expected for an earthquake of M 7.5 is about 200 km. Keefer (2002) noted that the 1988 Saguenay, Quebec, earthquake caused landslides at epicentral distances beyond what would have been expected from the Keefer (1984) analysis, and so landslides at an epicentral distance beyond 200 km might be possible for an M 7.5 earthquake. Locat (2008) reviewed the observations of landslides and underwater sediment slumps that have been attributed to the 1663 earthquake. Landslides have been found at several places in Quebec province, and submarine slumps have been found in the St. Lawrence estuary, the Saguenay Fjord, and several lakes on the Canadian Shield. Also, some underwater slumps in a lake in the Appalachians of Quebec may also have been caused by the 1663 earthquake. Based on the landslide data, Locat (2008) favored an epicentral region for the 1663 earthquake in the Saguenay region of Quebec and a magnitude M ≥ 7.6. The Locat (2008) epicentral region is at odds with the proposed 1663 fault rupture that is favored in this study, but his magnitude agrees well with the size of the 1663 earthquake that is inferred in the analyses presented in this paper. Further work to find landslides and underwater slumps that were caused by the 1663 earthquake could help refine the estimated magnitude and location of the 1663 earthquake.
Conclusions

Several lines of evidence indicate that the 1663 earthquake had $M_{7.5} \pm 0.45$. One line of evidence is the MMI at Roxbury and Boston, Massachusetts, which suggests the earthquake was $M_{7.3}$ to $7.9$. A second line of evidence is the masonry damage reported at Roxbury and Boston, Massachusetts, which requires that the magnitude of the earthquake at Charlevoix was probably $M_{7.3}$ to $M_{7.6}$ to have caused ground shaking that was damaging to chimneys and masonry in Massachusetts. A third argument is the 73-km extent of the recent seismicity at Charlevoix, which is consistent with an earthquake of about $M_{7.3}$ to $M_{7.6}$ from scaling relations of fault length or fault area as a function of magnitude. Finally, comparing the epicentral distance of the chimney damage at Roxbury with that for each of the major shocks in the 1811–1812 New Madrid earthquake sequence in the midwest United States suggests that the 1663 Charlevoix earthquake was roughly comparable in magnitude to, or perhaps even larger than, the 7 February 1812 New Madrid event, the largest event in that earthquake sequence. The 7 February New Madrid event is thought to have taken place on the 61-km long Reelfoot fault, for which the length of the recent earthquake activity is somewhat smaller than that of the modern active seismicity at Charlevoix. If the 7 February 1812 earthquake was $M_{7.4}$–$7.5$ (Hough et al., 2000) or $M_{7.8}$ (Bakun and Hopper, 2004), then the magnitude 1663 earthquake equaled or exceeded $M_{7.4}$. On the other hand, if the largest of the 1811–1812 earthquakes was only $M_{6.8}$–$7.0$ (Hough and Page, 2010), then this comparison indicates that the 1663 earthquake was larger than $M_{6.8}$–$7.0$. Based on the results of all of the analyses of this study, the maximum magnitude for the CSZ, and perhaps for other sections of the St. Lawrence rift valley as well, is at least $M_{7.5}$, the best estimate in this study for the magnitude of the 1663 earthquake.

Data and Resources

All of the historical data used in this paper came from published sources (primarily Ebel, 1996 and Gouin, 2001), and all reports are given proper references in the text where
the historical reports are reproduced or described. In addition, research on the Dutch accounts from New Netherland was provided to the author by Jaap Jacobs in an unpublished report. That report is available from this author. All pertinent historic accounts from the report by Jacobs have been reproduced in this paper. The earthquake epicentral data come from the earthquake catalogs at Weston Observatory, the Canadian Geological Survey, the University of Memphis, and the Canadian earthquake catalog (http://earthquakescanada.nrcan.gc.ca/histor/top10-eng.php, last accessed December 2010).

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References


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