The Cape Ann, Massachusetts Earthquake of 1755: A 250th Anniversary Perspective

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ABSTRACT

The earthquake of November 18, 1755, was experienced over a wide area along the East Coast of North America. It caused considerable damage to masonry chimneys and walls in eastern Massachusetts, eastern New Hampshire, and southern Maine. A reexamination of the felt reports, immediate aftershocks and modern seismicity indicate that the most likely epicenter was about 40 km ENE of Cape Ann, Massachusetts, within a cluster of recent earthquake epicenters. Based on the attenuation of MMI with epicentral distance, the Lg-wave magnitude of the earthquake was about M_{Lg} 6.2, corresponding to a moment magnitude of **M** 5.9. From analyses using modern ground-motion attenuation relations, conversions from MMI, and estimations from the number and severity of damaged chimneys, it is estimated that in Boston this earthquake caused peak ground accelerations of about 0.08 g–0.12 g on soil sites, while the 5%-damped response spectral value at a period of 0.3 sec in Boston may have been as small as 0.09 g or as large as 0.21 g. The Boston ground-motion estimates in this study correspond approximately to the 5% in 50 yr ground motions on the 1996 and 2002 USGS National Seismic Hazard Maps.

INTRODUCTION

The most damaging earthquake in historical times in the northeastern United States occurred about 4:30 a.m. (local time) on November 18, 1755. This shock affected a wide area along the East Coast of North America (Figure 1); contemporary reports indicate that ground shaking from this earthquake was felt at great distances from Cape Ann (Winthrop, 1758). To the northeast it was reported at Halifax, Nova Scotia, while to the northwest and southwest it was experienced along what is today Lake Champlain in New York State and in Winyah, South Carolina, respectively. Considerable damage, primarily to masonry chimneys and walls, was reported in eastern Massachusetts, coastal New Hampshire, and south coastal Maine. Minor damage was reported over a wider area. Coming just 17 days after the major earthquake and tsunami that devastated Lisbon, Portugal, on November 1, 1755, and less than 30 years after a damaging earthquake had rocked northeastern Massachusetts in 1727 (Ebel, 2000), the 1755 Cape Ann event helped sensitize eighteenth-century New Englanders to the great hazard that earthquakes can pose to the northeastern part of North America. Also, this is the first earthquake in North America upon which a scientific report was published (Winthrop, 1758).

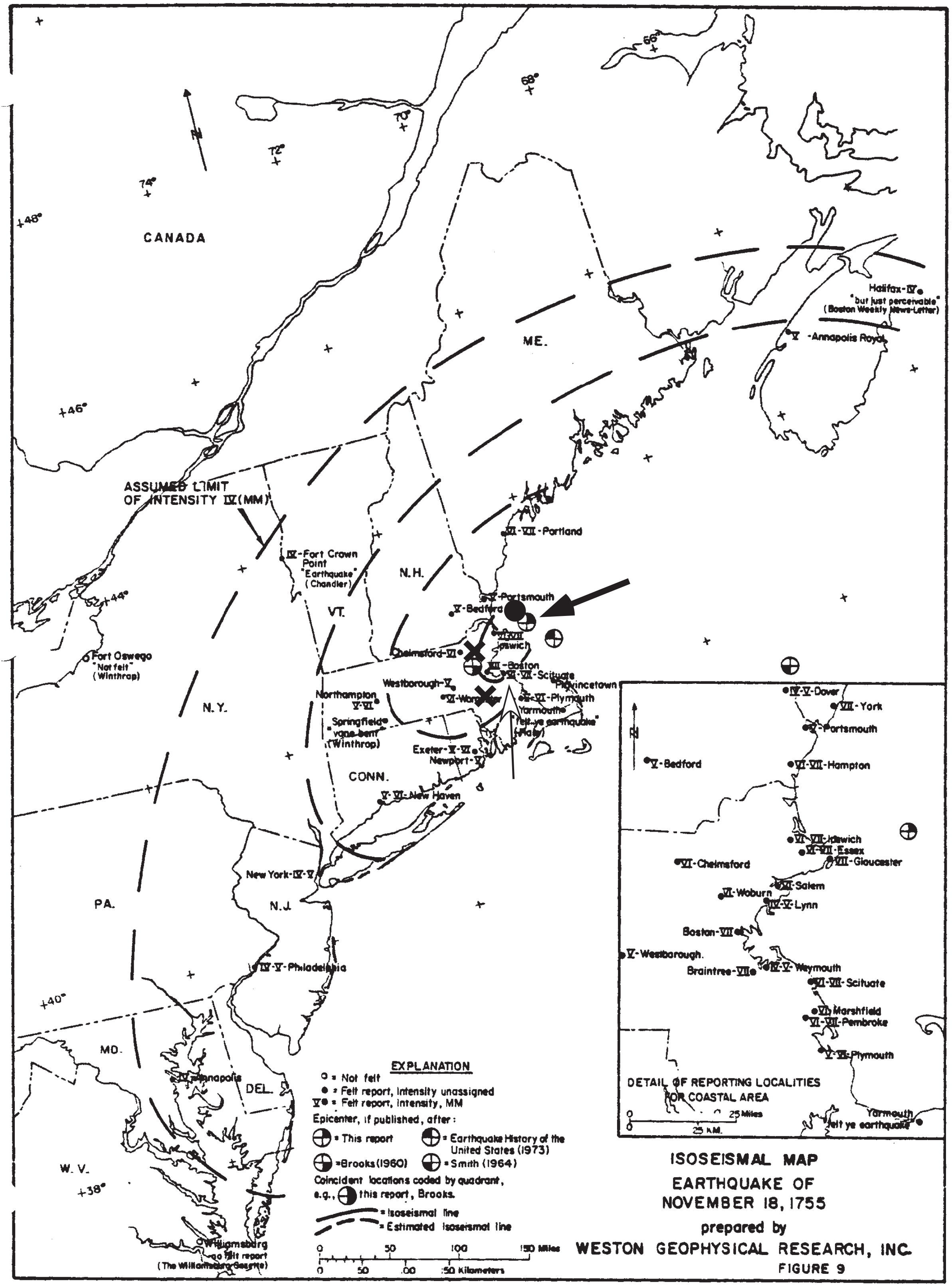
There are a large number of extant contemporary historical records that describe this earthquake and its effects at localities throughout the East Coast of North America. Most of these texts have been transcribed in a large volume on historical earthquakes in New England by Weston Geophysical Research, Inc. (WGRI, 1976). WGRI (1976) contains 66 separate written accounts of the 1755 mainshock, along with 21 accounts of an aftershock on November 22, 1755. Several of the accounts of both the mainshock and the aftershock come from newspapers of the time (15 reports), and many of these summarize information that was received from other sources. In many of the newspaper reports, the information and wording are very similar, suggesting that they were merely reprinting information that probably came from one or just a few common sources. Thus, most of the newspaper accounts must be viewed as secondary sources of information, and collectively their information content is much less than the total number of accounts available.

There are also a number of diary and other firsthand accounts of the 1755 earthquake and aftershock in WGRI (1976) as well as some that WGRI (1976) did not discover. Some of these contain detailed descriptions of local effects of the earthquake, while others only make note of the occurrence of the event. Some also contain secondary information from other sources.

This paper is a reevaluation of the source parameters of the 1755 earthquake as inferred from firsthand historical documents that describe the earthquake and its effects. It reexamines the historical accounts in light of the modern understanding of earthquake source processes and seismic wave propagation. It also builds on recent research that provides new ways to estimate earthquake source parameters from historical accounts. Finally, it uses the past 30 years of modern instrumental earthquake monitoring of seismicity in the northeastern United States to provide support for the new interpretations of the 1755 earthquake source parameters developed in this study.

THE EPICENTER, MAGNITUDE, AND FOCAL MECHANISM OF THE 1755 CAPE ANN EARTHQUAKE

As for all historical events, the location and size of the 1755 Cape Ann earthquake cannot be computed directly but rather



▲ **Figure 1.** Isoseismal map of the November 18, 1755 earthquake from WGRI (1976). The solid arrow points to the epicenter favored by WGRI (1976), while the solid circle shows the epicenter favored by Bakun *et al.* (2003). The onshore crosses show possible epicentral locations argued for by Ellis and de Alba (1999) based on reported liquefaction at Scituate, Massachusetts, which is indicated by the open arrow. The Smith (1964) epicenter is actually in Smith (1962). Earthquake History of the United States (1973) is Coffman and Von Hake (1973).

must be inferred based on historical descriptions. The apparent coastal location for this event makes this a more difficult problem than for events within the center of the continent, since there is an unavoidable lack of felt information in the offshore areas. Nevertheless, there are several lines of reasoning that give strong constraints on the area where the earthquake epicenter must have been located.

1755 Earthquake Epicenter

Early earthquake catalogs identified the Cape Ann area as the place where this earthquake originated (Brigham, 1871; Mather and Godfrey, 1927). The Cape Ann area had experienced an M_{Lg} 5.6 earthquake in 1727 (see Ebel, 2000) and a weaker but still jarring earthquake in 1744. Thus, it probably seemed logical to these early compilers that the 1755 earthquake must have originated from the same area as these earlier shocks. WGRI (1976) created an isoseismal map for this event and used that to estimate its epicenter (Figure 1). It also put the earlier reported epicenters on its map. The offshore location for the earthquake was influenced in part by a report that the earthquake was felt by a ship at sea about 70 leagues (210 nautical miles or 350 km) east of Cape Ann. The felt report from the ship from *The Boston Gazette, or Country Journal* newspaper of 24 November 1755 (transcribed in WGRI, 1976) reads:

> By a Person which came in Capt. Burnam, who arrived at Marblehead from Cadiz last Week, we learn that they felt the above Shock 70 leagues E of Cape Ann, at ½ past 4, but concluded that they ran foul of a Wreck, or got upon a Bar, but on throwing over the Lead, found they could not sound in 50 Fathom of Water, and continued ignorant of what it was till morning, when to their great Surprise, they saw a vast Number of Fish, large as well as small, floating on the Water dead, when they concluded it could be nothing but an Earthquake, and were informed it was so, as they were going into Harbour.

More recent work has used other methods to estimate the epicenter of this earthquake. Ellis and de Alba (1999) argued for an onshore epicenter either about 20 km NNW of Boston or 35 km SSW of Boston based on the localities where liquefaction effects were observed (Figure 1). An unambiguous report of a sand blow at Scituate, Massachusetts, was printed in the 24 November 1755 issue of the *Boston Evening Post* (WGRI, 1976). Using this report along with a report of a liquefaction landslide or lateral spread at West Boylston, Massachusetts, Ellis and de Alba (1999) argued that one of these onshore locations is most consistent with these sites of soil failure. On the other hand, Bakun *et al.* (2003) used the intensity reports and the grid-search method of Bakun and Wentworth (1997) and determined that the best location for the earthquake is offshore, probably northeast of Cape Ann (Figure 1). Ebel (2002) also argued for an epicenter east of Cape Ann. Thus, except for the Ellis and de Alba (1999) analysis, all of the researchers who have looked at this earthquake have favored an offshore epicenter east of Cape Ann.

Ebel (2002) used several different lines of reasoning to assign an epicenter to the 1755 earthquake at 42.33°N, 71.10°W. First, the pattern of intensity reports (Figure 1), with the greatest damage from Boston northwest to Portland, Maine, appears most consistent with an epicenter either at Cape Ann or somewhere to its east. Second, the observation of dead fish by the vessel that sailed into Marblehead harbor shortly after the earthquake is evidence for an offshore epicenter since offshore earthquakes have been known to kill fish (Richter, 1958).

The reports of the aftershocks from the 1755 mainshock also point to an epicenter somewhere near northeastern Massachusetts. Ebel (2000) argued that the small aftershocks from the 1727 earthquake put strong constraints on the location of the mainshock. Since small aftershocks are not felt far from their epicenters, they can help strongly delimit the location of the mainshock rupture. Unfortunately, no lists of individual aftershocks of the 1755 earthquake have been found, unlike the situation for the 1727 earthquake at Newbury, Massachusetts (Ebel, 2000). Even so, the contemporary reports suggest that it was the coastal area north of Boston where most aftershocks were noticed. There were three aftershocks that appear to have been widely felt throughout eastern Massachusetts. One occurred about 1¼ hours after the mainshock, while another took place on 22 November at 8:27 PM local time. The third, stronger aftershock was reported on 19 December at 10:00 PM local time. These apparently were the only aftershocks that were unquestionably felt in Boston. Chauncy (1755) from Boston wrote in a period citation that

> on the 22d of this same month, at 40 minutes after 8, in the evening, we were alarmed with another still, which, tho' not to be compared with the first, was very affecting to most people. These are all the shocks we have had in this town, tho' elsewhere they have been more numerous. In some places they have felt 5 or 6; in others 10 or 11; & in others still, at least 20.

The places reported by Chauncy that felt greater numbers of aftershocks than Boston may well have been the communities to the northeast, according to the reports compiled by WGRI (1976). Dow (1893) from Hampton, New Hampshire, reported in an 1898 history that shocks were frequently felt during the fortnight following the mainshock. Similarly, Holyoke (1890) in a history of Salem, Massachusetts, reported "less shocks afterwards," and Fuess (1935) in a history of Essex County stated that slight shocks occurred daily during the four days following the mainshock. Banks (1931) gives a very similar description in a 1931 history of York, Maine, stating "and for the next four days slight rumblings ensued." Unfortunately, the original source or sources used by the authors of these later histories are not given, so it is difficult to evaluate exactly what was felt and where. WGRI (1976) gives a report from a contemporary diary by Kelly (1913) of Amesbury, Massachusetts, in which he stated, "I have heard it every day since to ye 22nd day of said month." However, WGRI (1976) follows this citation with a note that the actual location of the diarist is uncertain. While somewhat circumstantial, taken together these pieces of evidence suggest that the highest rate of aftershock activity was experienced from about Salem, Massachusetts, to York, Maine.

Another contemporary report reprinted in WGRI (1976) contains an intriguing description of the mainshock shaking. Hyde (1755) of Boston recounted his experiences during the earthquake shaking:

> I was awaked by the shaking of my bed, and of the house; the cause whereof I immediately concluded could be nothing but an earthquake, having experienced one before. The trembling … increasing I soon got out of bed and went towards the window on the other side of the chamber… By the time I had got about half way across the room, which might be six or seven seconds from my first awaking, the shaking was a little abated; … instantaneously the shock came on with redoubled violence, and loud noise … the whole house rocking and cracking to such a degree, that I concluded it must soon fall, or be racked to pieces …. According to the best computation I am able to make … I think it could be but little more, and certainly not much less, than two minutes.

According to Hyde, he was awakened by the earthquake shaking, but the ground motions redoubled in strength about 6 or 7 seconds after he first became aware of it. His description of the strongest shaking is consistent with *S*- and *Lg*-wave motions. If Hyde was awakened by the *P* wave and the later, stronger shaking began with the arrival of the *S* wave, then Hyde's description suggests that the *S-P* time is around 6–7 sec. Of course, this is a rough estimate of the *S-P* time because it was not measured by any timing device and because it cannot be established that Hyde became awake immediately upon the arrival of the initial *P* wave. Even so, from Hyde's report of his movements once he was awakened, one might guess that an *S-P* time between 5 and 10 seconds probably brackets the *S-P* time that was experienced by Hyde. *S-P* times of 5 and 10 sec correspond to hypocentral distances of about 40 km and 86 km from Boston, respectively.

Finally, the modern earthquake activity recorded instrumentally by regional seismic network monitoring in New England provides another clue about the possible location of the 1755 epicenter. Ebel *et al.* (2000) argued that clusters of small, recent intraplate earthquakes detected by regional earthquake monitoring could represent very late aftershocks of strong earthquakes that took place decades to centuries previously. There is a cluster of small earthquakes about 40 km ENE of Cape Ann recorded since 1975 (Figure 2), and this cluster could represent very late aftershocks of the 1755 earthquake. An MLg 3.6 earthquake took place within this spatial cluster of local earthquakes on July 22, 2003 (Figure 2), and the Community Internet Intensity Map (http://pasadena.wr.usgs.gov/shake/ne/STORE/Xwnat_03/ciim_display.html) for this event shows that it was felt throughout northeastern Massachusetts but not in Boston (Figure 3). The felt area of this small 2003 earthquake is reminiscent of the areas where most of the aftershocks of the 1755 earthquake apparently were felt.

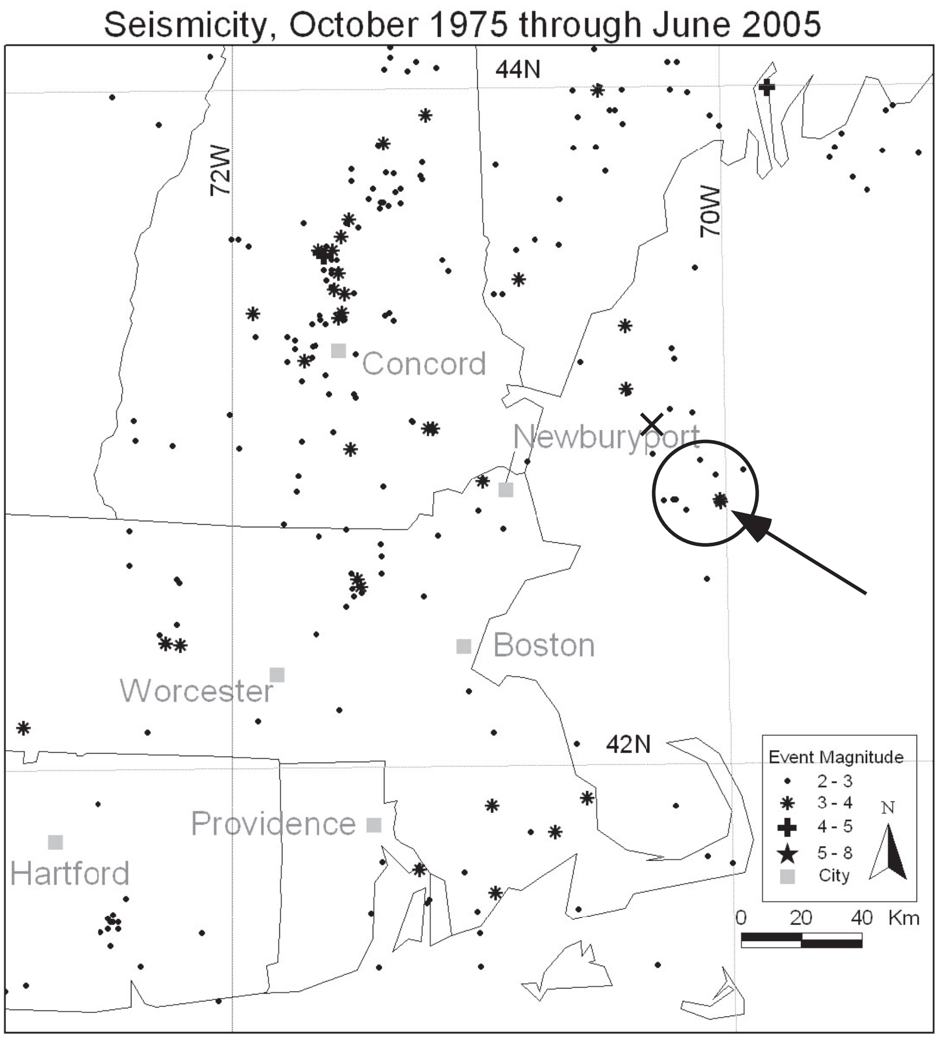
It is interesting to note that if the 1755 earthquake epicenter was about 40 km ENE of Cape Ann within the modern earthquake cluster, then the epicentral distance to Boston would have been about 85–90 km. This epicenter would be associated with an *S-P* time of about 10 sec at Boston, approximately consistent with the possible *S-P* time inferred from the description of the shaking by Hyde.

All of these arguments taken together converge on an area about 40 km ENE of Cape Ann as the most likely epicenter of the 1755 earthquake. The most likely epicentral area for the 1755 earthquake probably lies somewhere within the circle in Figure 2. An offshore location within the circle in Figure 2 is consistent with the damage and felt reports from the earthquake, with Hyde's description of the felt shaking, with the aftershocks reports, with the reported fish deaths, and with the modern earthquake activity. It is also in the same general area as the epicenters estimated in earlier studies (Figure 1), except for those of Ellis and de Alba (1999).

1755 Earthquake Magnitude

The magnitude of the 1755 earthquake has been estimated in several different studies. Street and Lacroix (1979) used the isoseismal map of Figure 1 to estimate an Lg-wave magnitude of 6.02 ± 0.15 for this earthquake based on their analysis of the felt area and the area of the modified Mercalli intensity (MMI) IV shaking for the event. Bakun *et al.* (2003) computed a best estimate of intensity magnitude M_I 6.1 (corresponding to a moment-magnitude **M** 6.0) for this earthquake using their analysis method based on individual MMI reports in southeastern New England. They report that the 95% confidence interval for **M** is between 5.6 and 6.6.

Ebel (2000) estimated the *Lg*-wave magnitude of the 1727 earthquake by matching the attenuation of the MMI reports with epicentral distance with the MMI attenuation relation of Klimkiewicz (1980). The same kind of analysis was carried out in this study for the 1755 earthquake based on the epicenter determined in this paper (the center of the circle in Figure 2). Using a set of 32 MMI values at epicentral distances of 45 km to 691 km, this analysis found the best fit to the MMI values is for an earthquake with M_{Lg} 6.2 (Figure 4). This value is close to the M_I 6.1 value found by Bakun *et al.* (2003) and the M_{Lg} 6.0 value determined by Street and Lacroix (1979). Taken together, these analyses agree that the best estimate of the *Lg* magnitude of the 1755 earthquake apparently lies between 6.0 and 6.2, with M_{Lg} 6.2 being the value that is favored in this study. Using the conversion from M_{Lg} (or M_N) to moment magnitude suggested by Atkinson and Boore (1995), M_{Lg} values of 6.0 and 6.2 correspond to moment magnitude (**M**) estimates of 5.6 and 5.9, respectively. The estimate of moment magnitude for the 1755 earthquake that is favored in this study is **M** 5.9, very close to the **M** 6.0 value estimated by Bakun *et al.* (2003).



▲ **Figure 2**. Map of the instrumental epicenters in southeastern New England from October 1975 through June 2005. The arrow points to the epicenter of the M_{Lg} 3.6 earthquake on July 22, 2003. The cross marks the epicenter of the 1755 earthquake favored by Bakun *et al.* (2003), while the circle delimits the epicentral area for the 1755 earthquake favored in this study.

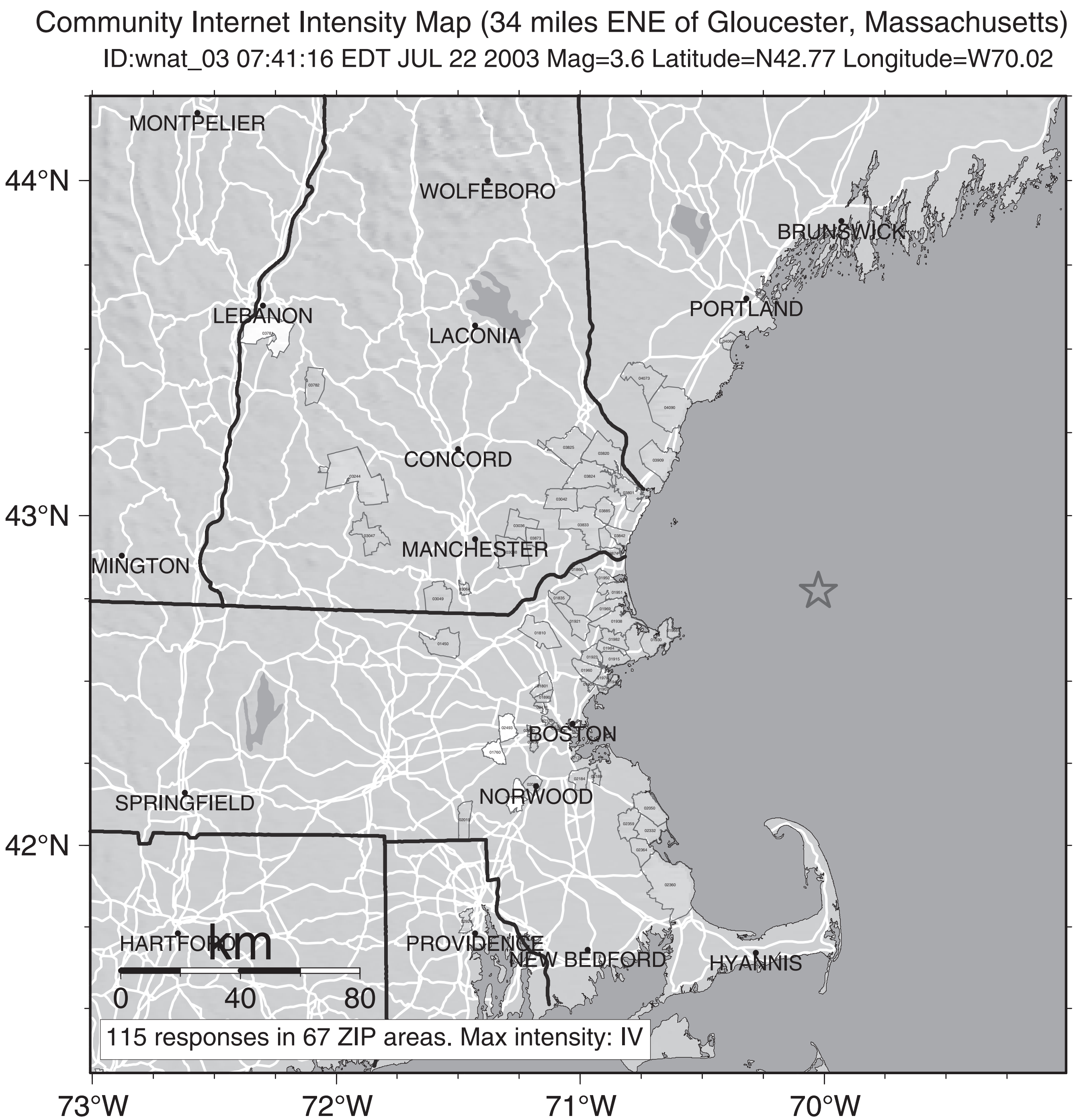
1755 Earthquake Focal Mechanism

Ebel (2000) argued that modern earthquake focal mechanisms in the epicentral zone of an historic earthquake can be used to infer the focal mechanism of that historic event. Unfortunately, the modern earthquakes that have been located offshore east of Cape Ann have not been recorded well enough to allow for any focal mechanism determinations. Thus, the focal mechanism of the 1755 earthquake cannot be estimated using present data, although recordings of future earthquakes from the 1755 epicentral area suggested in Figure 2 for which focal mechanisms can be determined could give an indication of the focal mechanism of the 1755 event.

GROUND MOTIONS GENERATED BY THE 1755 CAPE ANN EARTHQUAKE

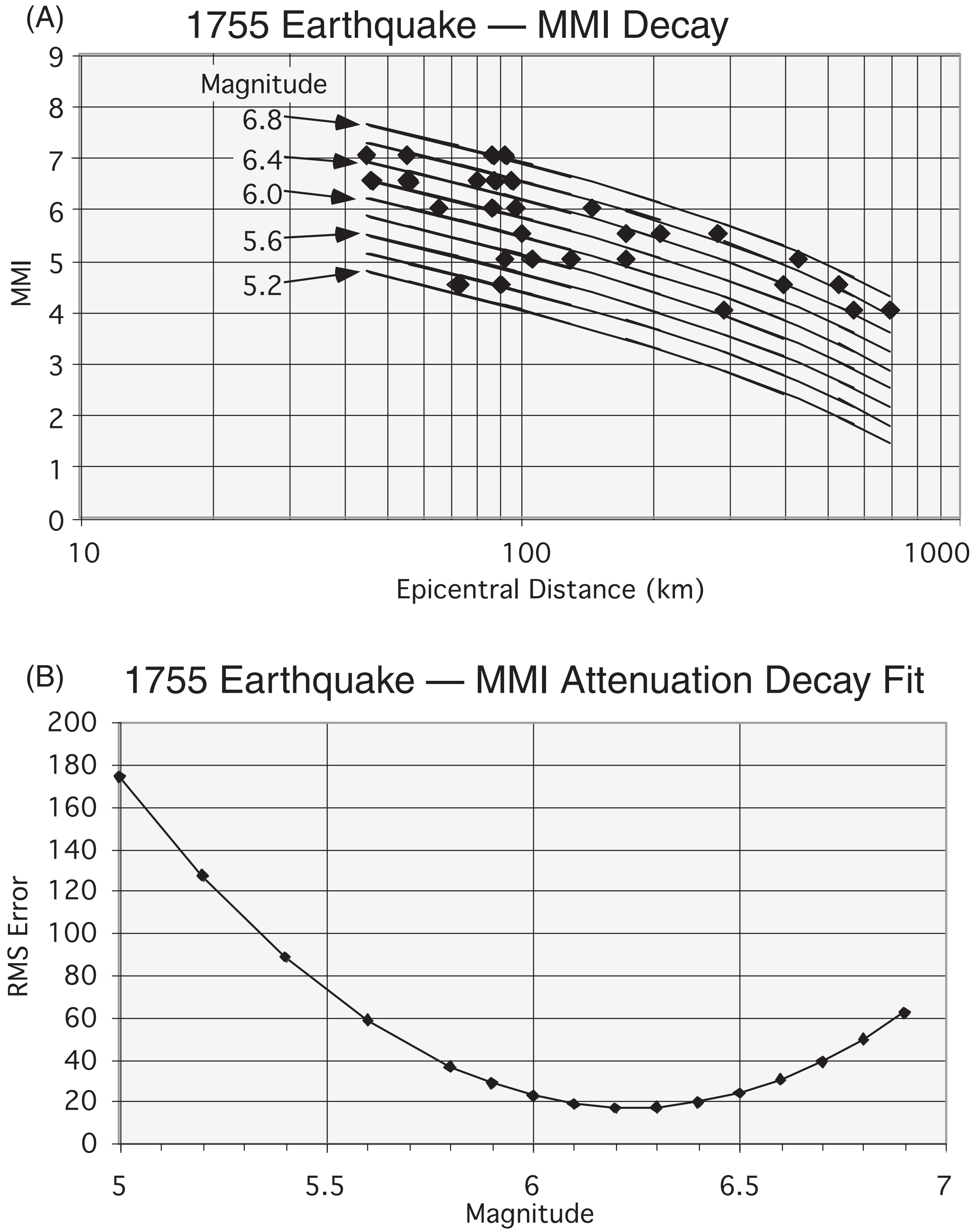
While there are no direct instrumental measurements of the ground shaking generated by the 1755 earthquake, there are several different ways in which to estimate the ground motion values that were probably experienced at sites in New England. Once the location and magnitude of the earthquake have been found, the ground motions experienced at different localities from this earthquake can be estimated from modern strong-motion attenuation relations. Also, the large number of damage descriptions and associated intensity assignments can be used to infer what levels of ground motions were probably experienced at different localities in the earthquake. Taken together, these various methods for estimating the ground motions can bracket the likely range of ground accelerations generated by the 1755 earthquake.

Several different strong-motion attenuation relations have been developed for application in the eastern United States and Canada. The attenuation relations for central and eastern North America that were applied in this study are those of Atkinson and Boore (1995), Campbell (2003), Frankel *et al.* (1996), and Toro *et al.* (1997). Table 1 lists the peak ground accelerations (pga) and the pseudospectral accelerations for a 5%-damped harmonic oscillator with a period of 0.3 sec (SA0.3) that are pre-



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy

▲ **Figure 3.** Community Internet Intensity Map (CIIM) for the July 22, 2003 earthquake that was centered east of Cape Ann, Massachusetts (http://pasadena.wr.usgs.gov/shake/ne/STORE/Xwnat_03/ciim_display.html). Most of the felt reports came from northeastern Massachusetts and southeastern New Hampshire, while there were virtually no felt reports at all from the city of Boston.



▲ **Figure 4.** (A) The diamonds show the distribution with epicentral distance (from the center of the circle in Figure 2) of MMI reports for the 1755 earthquake. Also plotted are intensity-attenuation curves from Klimkiewicz (1980) showing the attenuation of mean MMI with epicentral distance as a function of Lg-wave magnitude. (B) Plot showing the RMS error of the fit of the data point to the attenuation curve for each magnitude in part (A). The minimum RMS suggests an M_{Lg} of about 6.2–6.3 for the 1755 earthquake.

TABLE 1
Estimated Ground Motions for the 1755 Cape Ann Earthquake from Ground-motion Attenuation Relations

Town	Epicentral Distance (km)	MMI	Atkinson and Boore (1995)	Campbell (2003)	Frankel *et al.* (1996)	Toro *et al.* (1997)
			pga (rock)	pga (rock)	pga (rock)	pga (rock)
York, ME	55	7	0.0475 g	0.0489 g	0.0519 g	0.0413 g
Boston, MA	87	7	0.0269 g	0.0265 g	0.0299 g	0.0229 g
Braintree, MA	93	7	0.0257 g	0.0247 g	0.0283 g	0.0210 g
Northampton, MA	208	5.5	0.0087 g	0.0123 g	0.0106 g	0.0065 g
New Haven, CT	281	5.5	0.0046 g	0.0096 g	0.0062 g	0.0039 g
			pga (soil E)	pga (soil E)	pga (soil E)	pga (soil E)
York, ME	55	7	0.1045 g	0.1045 g	0.1142 g	0.0908 g
Boston, MA	87	7	0.0592 g	0.0592 g	0.0658 g	0.0504 g
Braintree, MA	93	7	0.0565 g	0.0565 g	0.0622 g	0.0461 g
Northampton, MA	208	5.5	0.0192 g	0.0272 g	0.0232 g	0.0143 g
New Haven, CT	281	5.5	0.0101 g	0.0101 g	0.0136 g	0.0087 g
			SA0.3 (rock)	SA0.3 (rock)	SA0.3 (rock)	SA0.3 (rock)
York, ME	55	7	0.0382 g	0.0530 g	0.0657 g	0.0545 g
Boston, MA	87	7	0.0248 g	0.0296 g	0.0431 g	0.0393 g
Braintree, MA	93	7	0.0249 g	0.0274 g	0.0420 g	0.0374 g
Northampton, MA	208	5.5	0.0142 g	0.0122 g	0.0211 g	0.0189 g
New Haven, CT	281	5.5	0.0090 g	0.0089 g	0.0136 g	0.0139 g
			SA0.3 (soil E)	SA0.3 (soil E)	SA0.3 (soil E)	SA0.3 (soil E)
York, ME	55	7	0.0840 g	0.1167 g	0.1446 g	0.1198 g
Boston, MA	87	7	0.0546 g	0.0650 g	0.0948 g	0.0864 g
Braintree, MA	93	7	0.0548 g	0.0602 g	0.0923 g	0.0822 g
Northampton, MA	208	5.5	0.0313 g	0.0268 g	0.0465 g	0.0416 g
New Haven, CT	281	5.5	0.0198 g	0.0195 g	0.0298 g	0.0306 g

dicted by the four ground-motion attenuation relations examined here. Ground motion values are given in Table 1 for two different site conditions, rock and U.S. National Earthquake Hazards Reduction Program (NEHRP) (Frankel *et al.,* 1996) soil class E (very soft soils). The values in Table 1 show the range of predicted ground motions at five towns that reported at least minor damage from the earthquake shaking in 1755.

A second way to make determinations of the probable ground motions in historic earthquakes is to convert macroseismic intensity to a ground motion value. At one time ground motion values such as peak ground acceleration (pga) were estimated using relations in which pga was regressed against modified Mercalli intensity (MMI), such as in the relation of Trifunac and Brady (1975). Such simple relations do not take into account neither the magnitude of the earthquake nor the epicentral distance to the site of the MMI value. Murphy and O'Brien (1977) proposed conversions from MMI to pga that explicitly include the even magnitude and the epicentral distance. More recently, Atkinson and Sonley (2000) published an analysis of conversions from MMI to pga and pseudospectral acceleration (SA) at different periods for a data set from eastern North America. Their relations included the event magnitude and the epicentral distance in the calculation of the estimated ground motions. Ebel and Wald (2003) suggested a Bayesian probability method to estimate ground-motion parameters from MMI readings. In their method, a strong ground-motion attenuation relation is included explicitly in the Bayesian probability calculation.

Table 2 shows the pga and SA0.3 ground motions calculated at the same five towns as in Table 1 using the MMI-ground-motion relations from Trifunac and Brady (1975), Murphy and O'Brien (1977), Atkinson and Sonley (2000), and Ebel and Wald (2003). Of these, only the method of Ebel and Wald (2003) requires information on the site soil conditions where the MMI observation was taken. For this reason, two different conversions from MMI to ground motion for the Ebel and Wald (2003) method are given in Table 2, one for rock site conditions and one for soil E site conditions, to show how much site condition affects the outcome of this conversion method. In Table 2, the ground-motion attenuation relations used to compute the Ebel and Wald (2003) values were those of Atkinson and Boore (1995).

There is a rather wide variation in the pga values among the different methods for each site in Table 2. The discrepancy

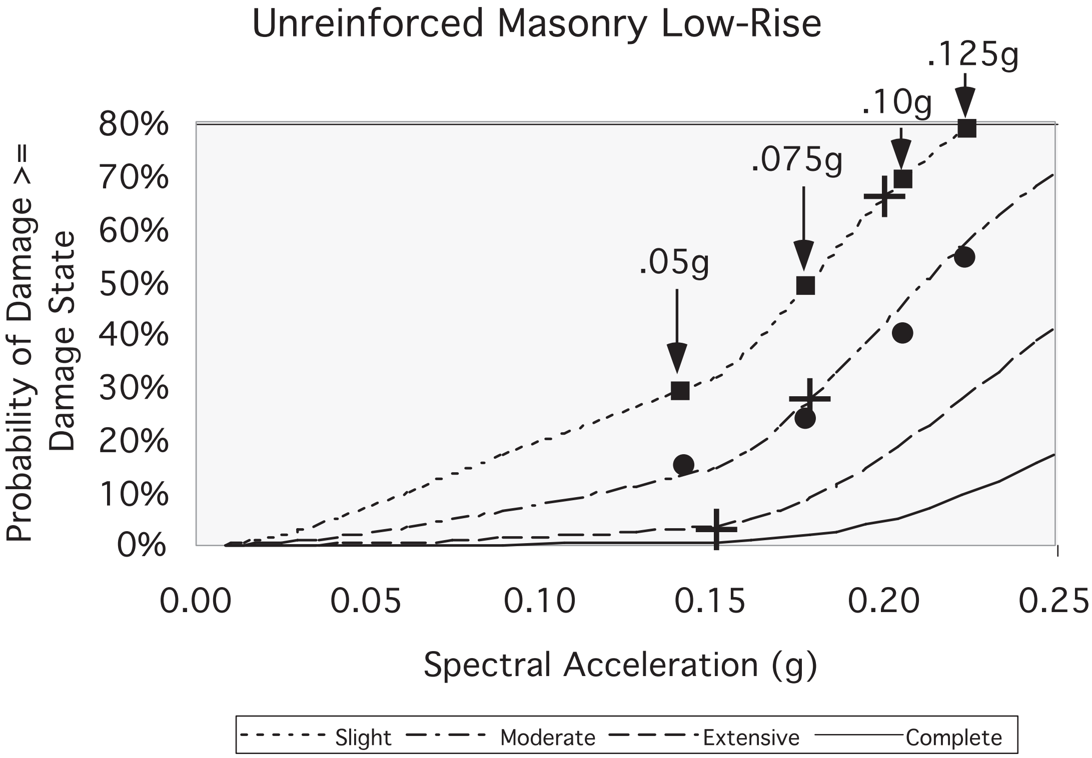
TABLE 2. Estimated Ground Motions for the 1755 Cape Ann Earthquake from MMI to Ground-motion Conversions							
Town	**Epicentral Distance (km)**	**MMI**	**Trifunac & Brady (1975)**	**Murphy & O'Brien (1977)**	**Atkinson & Sonley (2000)**	**Ebel & Wald (2003)**	**Ebel & Wald (2003)**
			pga	pga	pga	pga (rock)	pga (soil E)
York, ME	55	7	0.1325 g	0.0779 g	0.1088 g	0.1025 g	0.1514 g
Boston, MA	87	7	0.1325 g	0.0579 g	0.0881 g	0.0752 g	0.1122 g
Braintree, MA	93	7	0.1325 g	0.0554 g	0.0854 g	0.0752 g	0.1122 g
Northampton, MA	208	5.5	0.0470 g	0.0194 g	0.0355 g	0.0124 g	0.0250 g
New Haven, CT	281	5.5	0.0470 g	0.0161 g	0.0309 g	0.0078 g	0.0147 g
					SA0.3	SA0.3 (rock)	SA0.3 (soil E)
York, ME	55	7			0.2284 g	0.0677 g	0.1118 g
Boston, MA	87	7			0.1867 g	0.0555 g	0.0917 g
Braintree, MA	93	7			0.1813 g	0.0555 g	0.0917 g
Northampton, MA	208	5.5			0.0740 g	0.0183 g	0.0369 g
New Haven, CT	281	5.5			0.0652 g	0.0144 g	0.0257 g

grows worse for the more distant sites, likely reflecting differences in how each method handles the distance dependence in the MMI-pga conversions. Also, the pga values in Table 2 at New Haven from the Trifunac and Brady (1975) and Atkinson and Sonley (2000) methods are significantly greater than all of the soil E ground motion estimates in Table 1. For SA0.3, there are only estimates from the Atkinson and Sonley (2000) and Ebel and Wald (2003) methods. The Atkinson and Sonley (2000) SA0.3 values are significantly greater than those from the Ebel and Wald (2003) method, even for class E soil sites, and they are also much greater than all of the SA0.3 values in Table 1.

A third method to estimate the ground motions of the 1755 earthquake can be derived from suggestions by Ebel (2003) and Whitman (2002). Ebel (2003) argued that quantification of the amount of chimney damage from an earthquake can be used to make an estimate of the strength of the local earthquake ground shaking necessary to cause that amount of damage. Whitman (2002) presented a similar argument, and he analyzed the amount of ground shaking that probably caused the observed chimney damage in Boston in 1755. In this paper, the methods of Ebel (2003) and Whitman (2002) are cast in a more general form and then applied to the five towns examined in Tables 1 and 2. Kochkin and Crandell (2004) performed a similar study based on damage experienced by structures in the midwestern United States due to the 1811–1812 New Madrid earthquake sequence.

Estimating the ground motion associated with an observed amount of chimney damage is possible by modifying the procedure of Kircher *et al.* (1997), used in the earthquake loss program HAZUS (NIBS, 1999) and its later multihazard version HAZUS-MH (http://www.fema.gov/hazus) from the Federal Emergency Management Agency (FEMA), to compute the percentage of different levels of damage due to a given level of earthquake shaking. In the procedure of Kircher *et al.* (1997), buildings and other manmade structures are divided into a number of classes, with each class determined from the structural support system and the materials used to construct a building. The size of the building as well as whether or not it was built to earthquake-resistant standards also control which class a building falls into. Each class of structure has a set of fragility curves, each of which quantifies the probability that the structure will experience that level of damage as a function of the strength of the ground shaking. Kircher *et al.* (1997) and the HAZUS programs define probability (*i.e.*, fragility) curves for five categories of damage: no damage, minor damage, moderate damage, extensive damage, and complete failure (*i.e.*, collapse). Of course, once a set of fragility curves has been defined, one can reverse the process by using the percentage of damage to estimate what level of ground shaking was experienced. It is this approach that is taken here.

For the 1755 Cape Ann earthquake, one needs to know the fragility curves for an eighteenth-century masonry chimney that was part of a wood-frame or unreinforced brick building of the period. Kircher *et al.* (1997) and the HAZUS programs can be used to find fragility curves for unreinforced masonry (*i.e.*, brick) buildings from the twentieth century, but the sources do not have fragility curves specifically for eighteenth-century chimneys. Whitman (2002) discussed an unpublished analysis of the behavior of eighteenth-century chimneys to earthquake shaking, and he presented a matrix containing some damage probabilities as a function of four different levels of pga for chimneys that experienced no damage, minor cracking, and shattering. Whitman (2002) noted that for chimneys that are part of wooden and masonry buildings the HAZUS programs define: slight damage—small cracks in chimneys; moderate damage—large cracks in chimneys; and extensive damage—toppling of most chimneys. In his paper, Whitman (2002) does not explain explicitly how to relate "minor cracking" or "shattering" to the HAZUS damage states. In this study, it is assumed that chimneys that were badly cracked or lost parts of their tops experienced moderate damage, while chimneys that were bro-



▲ **Figure 5.** Fragility curves for low-rise (1 or 2 story) unreinforced masonry buildings as used in the HAZUS software (Kircher *et al.*, 1997). The squares and circles show the estimated levels of slight and moderate damage for four different pga values (above the arrows) from the analysis of the fragility of eighteenth-century brick chimneys from Whitman (2002). The plus symbols show the estimated amount of slight, moderate, and extensive damage in the city of Boston in 1755 by Whitman (2002).

ken off at the roof line experienced extensive damage. It is also assumed that the natural period of a standard one- or two-story masonry chimney is 0.3 sec, so the fragility curves for such chimneys should be determined relative to the SA0.3 ground motions. Figure 5 shows the fragility curves from Kircher *et al.* (1997) and the HAZUS computer programs for low-rise (1 or 2 story) unreinforced masonry structures (URML) as a function of spectral acceleration SA0.3.

Whitman (2002) contains a table of the probabilities of no damage, minor cracking, and shattering of eighteenth-century chimneys for pga values of 0.05 g, 0.075 g, 0.10 g, and 0.125 g. The percentages of slight damage chimney damage (assumed to be minor cracking) and moderate chimney damage (assumed to be chimney shattering) for the four pga values analyzed by Whitman (2002) for eighteenth-century chimneys are plotted at their corresponding positions on the URML curves of Kircher *et al.* (1997) in Figure 5. The Kircher *et al.* (1997) URML curves can be used to extrapolate the Whitman (2002) eighteenth-century chimney fragilities to other damage states through ratios of the pga to SA0.3 values. Thus, if the percentages of structures in an eighteenth-century community with minor, moderate, and extensive chimney damage are known, then Figure 5 can be used to estimate the pga and SA0.3 ground-motion values that were experienced at that location. Figure 5 also suggests that eighteenth-century chimneys started losing some bricks (*i.e.*, experienced moderate damage) at pga and SA0.3 values of about 0.01 g and 0.03 g, respectively.

Also, it should be noted that Kochkin and Crandell (2004) fit a fragility curve to the four Whitman fragility values for shattered chimneys. The Kochkin and Crandell (2004) fragility curve agrees well with the fragility curve for moderate damage in Figure 5.

A number of historic accounts of the 1755 earthquake from different communities contain references or descriptions of the damage to chimneys. The most detailed and quantitative description is for Boston from Hyde (1755) (WGRI, 1976), which reads:

> The visible effects of the earthquake are very considerable in the town ... Many chimnies, I conjecture (from observation) not much less than an hundred, are levelled with the roofs of the houses: many more, I imagine not fewer than 12 or 1500 are shattered, and thrown down in part; so that in some places, especially on the low loose ground, made encroachments on the harbour, the streets are almost covered with the bricks that have fallen. Some chimnies, though not thrown down, are dislocated, or broken several feet from the top, and partly turn'd around, as upon a swivel; some are shoved on one side horizontally, jutting over, and just nodding to their fall; the gable ends of several brick buildings, perhaps of twelve or fifteen, are thrown down, and the roofs of some houses are quite broken in by the fall of the chimnies.

TABLE 3
Estimated Ground Motions for the 1755 Cape Ann Earthquake from Chimney and Unreinforced Masonry Damage

Town	Epicentral Distance (km)	MMI	Moderate Damage	Extensive Damage	pga	SA0.3
York, ME	55	7		50%? 20%?	0.23 g? 0.10 g?	0.27 g? 0.20 g?
Boston, MA	87	7	27-30%	2-3%	0.08-0.11 g	0.18-0.21 g
Braintree, MA	93	7		>1%	>0.03 g	0.08 g
Northampton, MA	208	5.5	>1%		>0.01 g	>0.03 g
New Haven, CT	281	5.5	>1%?		>0.01 g?	>0.03 g?
New York, NY	396	5.5	0%		<0.01 g	<0.03 g

Based on the descriptions of damage in Boston by Hyde and others, and using an estimate of about 5,000 chimneys in Boston in 1755, Whitman (2002) proposed the following percentages of damaged chimneys in Boston: 33%—no damage; 38%—minor cracking (slight damage); 27%—shattered, etc. (moderate to extensive damage), and 2%—thrown down at roof line (extensive damage). It is not clear whether chimneys that are described as "shattered" in the historical accounts were merely heavily cracked, were heavily cracked with some brick knocked loose, or lost a large number of bricks due to the earthquake shaking. Hence, the "shattered" chimneys might either fall into the moderate damage or the extensive damage category. Chimneys that were broken at the roof line would be classed as having extensive damage. Whitman's (2002) damage percentages for Boston in 1755 are plotted on Figure 5. Whitman (2002) argued that the pga in downtown Boston in 1755 was about 0.075 g to 0.10 g based on his percentages of chimney damage. That range is quite comparable to the ground-motion values for Boston bracketed in this study in Figure 5 for slight and moderate damage in Boston in 1755.

WGRI (1976) contains accounts from several other towns from which some estimate of chimney damage can be made. York, Maine, was only 55 km from the epicenter proposed here, and it clearly was strongly shaken in the earthquake. According to a period account published in a later history (Banks, 1931), in York, "chimneys bore the greatest injuries being generally broken at the roof hue and otherwise twisted out of position. The Ingraham brick house was badly shaken up, bricks being loosened and cracks in the walls started." While the percentage of chimneys that were broken at the roof line is not mentioned, this report implies that a great many chimneys received extensive damage due to the earthquake. For the sake of argument, it is assumed here that 50% of the chimneys at York experienced extensive damage. Braintree, Massachusetts, just southeast of Boston, was also heavily shaken. John Adams was at his father's house in Braintree when the earthquake struck. He reported that 7 chimneys were shattered within one mile of his father's house. If there was a house every 1/8 mile, then perhaps 10% of the houses experienced extensive chimney damage. At Northampton, Massachusetts, "many chimneys injured" according to a period journal entry by a Mr. Lyman in the Judd manuscript at the Northampton Forbes Library (WGRI, 1976) and crockery was thrown from shelves, suggesting that Northampton experienced at least moderate chimney damage. A period description from *The Boston Gazette, or Country Journal* of 1 December 1755 includes a mention of the effects at New Haven, presumably the town in Connecticut. The description states that "the tops of many chimneys were thrown down." This statement occurs just after mention of New Haven, suggesting that New Haven suffered the loss of many chimney tops due to the earthquake shaking. However, earlier in the paragraph is a discussion of the damage apparently in Boston, Massachusetts, and the mention of the damaged chimney tops might refer to the earlier discussion of Boston rather than to New Haven. For New York City, WGRI (1976) cites Smith (1892) who stated that no bricks fell from the chimneys in New York City, although the earthquake was felt with "jarring vibrations."

The mention of chimney damage at these other towns in New England provides some information on the possible ground motions that were experienced at these towns. Table 3 summarizes the ground-motion values that were found using Figure 5 and the damage estimates discussed in the previous paragraphs. The damage reports indicate that pga might have been as strong as 0.23 g at York, Maine, and probably exceeded 0.01 g at New Haven, Connecticut, if indeed there were chimneys damaged there. Also included in Table 3 is an entry for New York City, for which no chimney damage was reported. This fact indicates that the ground motions at New York City were below the threshold for chimney damage. With the exception of York, Maine, the ground-motion values in Table 3 are somewhat higher than the corresponding soil E ground motions in Table 1, suggesting perhaps that the damage reported in 1755 is consistent with an earthquake somewhat larger than **M**5.9 situated at the epicenter favored in this paper. The York, Maine pga and SA0.3 ground motions overestimate by about a factor of 2 the soil E ground motions in Table 1. If only 20% of the chimneys at York were extensively damaged, the pga and SA0.3 values reduce to about 0.10 g and 0.20 g, bringing them more in line with the ground motions predicted in Table 1. The ground motions in Table 3 are also approximately consistent with the ground-motion values in Table 2 except for the SA0.3 values of Atkinson and Sonley (2000), which are significantly higher than the values in Table 1 as well as in Table 3.

The information in Tables 1, 2, and 3 together delimit fairly well the ground motions that were experienced throughout southern New England in the 1755 earthquake. At Boston, pga may have been as small as 0.05 g (from the Toro *et al.*, 1997, number in Table 1), but it was more likely between 0.08 g and 0.12 g on soft soils based on the reported damage (*i.e.*, Tables 2 and 3). The rock pga at Boston was probably significantly smaller. Several of the contemporary historical reports in WGRI (1976) state that the greatest damage occurred on the lowland, include landfill, near the waterfront, and these are places where ground shaking amplification was likely to have been experienced. The SA0.3 values in Boston estimated from the chimney damage are about a factor of 2 higher than the SA0.3 predictions for soil E from the ground-motion attenuation relations. Thus, SA0.3 may have been as large as 0.21 g (based on the chimney damage analysis) or as small as 0.05 g (from the Atkinson and Boore, 1995, attenuation relation). A value of 0.09 g for SA0.3 is favored in this study for soil E sites, since this value is approximately that found from the Frankel *et al.* (1996) and Toro *et al.* (1997) ground-motion attenuation relations (Table 1) and the Ebel and Wald (2003) estimate from MMI VII for a soil E site (Table 2). From the 1996 US National Seismic Hazard Maps, the pga and SA0.3 values with a 975-year mean repeat time (5% in 50 years) are 0.082 g and 0.130 g, respectively. Thus, in Boston the 1755 earthquake generated roughly the once-in-a-thousand-years ground motions (*i.e.*, 5% probability of exceedance in 50 years).

The Braintree ground-motion estimates in Tables 1 and 2 are smaller than those for Boston due to Braintree's slightly greater epicentral distance. Scituate, Massachusetts, located east of Braintree and at about the same distance from the epicenter favored in this study, was the site of a notable liquefaction feature that is described in detail in the *Boston Evening Post* on 24 November 1755 (WGRI, 1976). The Ellis and de Alba (1999) study focused primarily on the Scituate liquefaction site. To explain the occurrence of a sand blow at the Bailey house at Scituate, geotechnical analyses led Ellis and de Alba (1999) to conclude that the peak horizontal ground surface acceleration (pga) was probably between 0.14 g and 0.17 g. This range of values is greater than the pga estimates for Braintree in Tables 1 and 2. Assuming the 1755 earthquake epicenter favored in this study, either Ellis and de Alba (1999) overestimated the pga value needed to induce liquefaction at Scituate or the 1755 earthquake had a larger magnitude than assumed in Tables 1 and 2. A moment magnitude for the 1755 earthquake of **M**6.7 is required to give a soil E pga at Scituate of 0.14 g using the Frankel *et al.* (1996) attenuation relation, and the other ground-motion attenuation relations require an even higher magnitude value to reach 0.14 g. Thus, at present the liquefaction report at Scituate is rather difficult to explain with the earthquake source parameters favored in this study for the 1755 earthquake.

CONCLUSIONS

Several lines of evidence in this paper localize with good confidence the probable epicentral location of the 1755 earthquake. That epicenter is about 40 km east of Cape Ann. The magnitude for this earthquake that is most consistent with the macroseismic intensity pattern and the felt area is about M_{Lg} 6.2 (**M** 5.9), although the extent of chimney damage and the observation of a sand blow in Scituate, Massachusetts suggest that the magnitude of this earthquake may have been as large as **M** 6.7. Modern ground-motion attenuation relations and an analysis of the number of damaged chimneys indicate that pga in Boston may have been as small as 0.05 g, but was much more likely to have been between 0.08 g and 0.12 g on soil sites. The 5%-damped spectral acceleration at a period of 0.3 sec was probably about 0.09 g on soil sites in Boston based on modern ground-motion attenuation relations, but the chimney damage analysis suggests that this ground motion might have been as large as 0.18 g to 0.21 g.

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