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Use of Ground Failure Case Histories to Characterize a Design Earthquake for Coastal New England

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Project Description

Introduction

The November 18, 1755 'Cape Ann' earthquake is the largest event experienced in southern coastal New England since European settlement. The most widely accepted location for the epicenter is East of Cape Ann Mass. (Figure 1). This location and a conservative magnitude estimate of m_b =6.25 has been used in the Metropolitan Boston Area earthquake loss study (Fratto, 1986; Ebel et al. 1990) and other regional hazard studies. Arguably, it will continue to be the reference event for future earthquake hazard evaluations in coastal Massachusetts, New Hampshire and southern Maine.

From an engineering viewpoint, It is interesting to note in this regard that in terms of Earthquake Disaster Risk Index (EDRI, Davidson and Shah, 1997) Boston ranks with Mexico City and about 1.5 times higher than Tokyo in physical infrastructure vulnerability, basically due to the fact that a large proportion of Boston's building stock predates the 1975 implementation of earthquake requirements in the local building code, and still includes a large number of unreinforced brick masonry buildings.

The location and magnitude of the modeling event are obviously of critical importance for hazard studies. This writer (de Alba) felt, however, that there was still significant uncertainty as to the actual size and epicentral location of this earthquake. The basic tools for determining the earthquake characteristics have been historical studies of intensity distribution, largely based on the extensive work carried out by Weston Geophysical Research (WGR) Inc. (1976). Most recently, Ebel (2006) proposed a moment magnitude **M**=5.9 for an offshore Cape Ann location, based on intensity distribution for the 1755 event. Additional arguments for this location are the distribution of small recent events interpreted as an ongoing aftershock sequence of the 1755 event, and a report of a fish kill in the general vicinity of Cape Ann. A somewhat different locations based on intensity distribution has been proposed by Bakun et al. (2003). WGR (1976) reports other possible locations in the same general area.

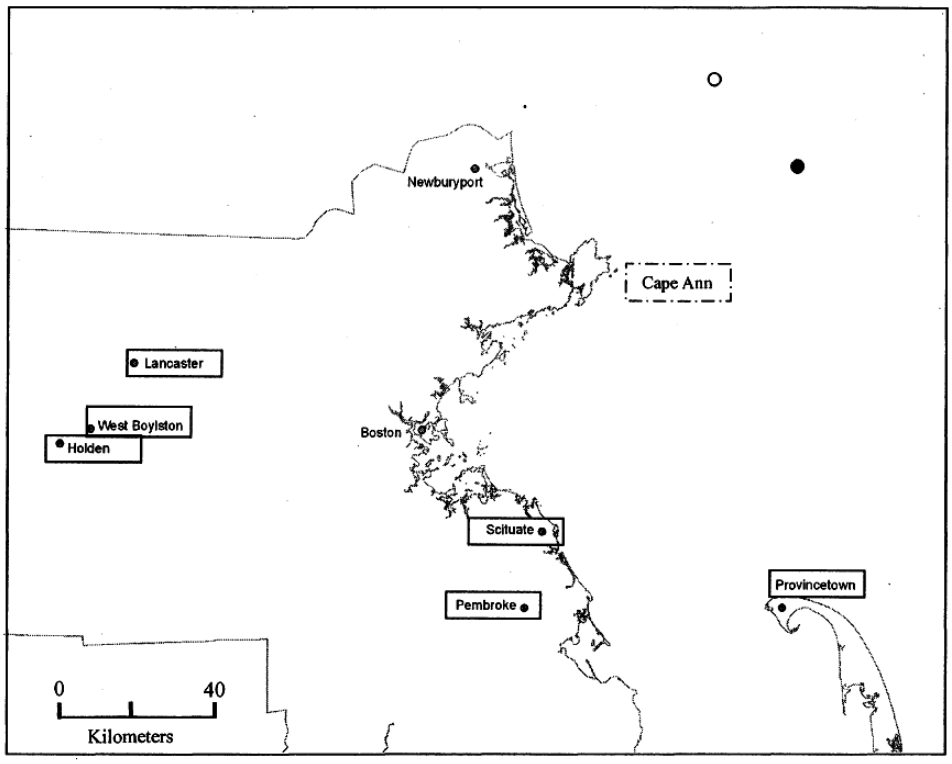

Figure 1. Epicentral locations for the November 18, 1775 earthquake proposed by Bakun et al., 2003 (open circle) and Ebel, 2006 (closed circle).

Earthquake intensity values are, of course, an extremely valuable tool (and in some cases the only source of information) for studying historic earthquakes. However, they depend on human reaction to a highly unusual event and, for historic earthquakes, on population density, level of literacy in different locations of the felt area, and on accidents of transmission.

In this regard, evidence of ground failure, and specifically liquefaction of saturated sands, can provide additional, quantifiable, evidence relative to the acceleration levels experienced at the liquefaction sites. Sand deposits below the ground water level subjected to earthquake accelerations may liquefy, i.e., exhibit a major loss of shearing resistance and behave, for a short period, as heavy fluids. Liquefaction is basically caused by the build-up of intergranular pore-water pressure as the deposit tries to densify under the cyclic loading produced by the earthquake; stresses are transferred from the soil grain structure to the pore water, with a resultant loss of shearing resistance. The high pore-water pressures result in ejection of the liquefied sand through sand boils and cracks. Liquefaction of sands has been a major source of damage to structures during earthquakes, as foundation soils lose their supporting capacity or spread laterally; natural slopes and embankments may exhibit flow sliding.
The liquefaction potential of a particular site basically depends on:

- earthquake magnitude, and thus number of cycles of strong motion
- cyclic shear stresses induced by the earthquake
- material density and fines content
- effective normal confining stress at the depth of interest.

These data are summarized in a plot such as that of Figure 2. Material density is measured through the Standard Penetration Test (SPT) blowcount (N, in blows per foot, bpf), adjusted to a hammer energy level of 60% of maximum theoretical energy and an effective confining stress of one atmosphere. Other

corrections are applied to take into account such variables as borehole diameter, sampler configuration, rod length and fines content.

The corrected $N_1)_{60}$ allows comparison of tests carried out with different types of equipment and at different depths. For a known value of $N_1)_{60}$ the <u>minimum</u> average cyclic shear stress required for liquefaction (τ_{ave}),normalized by the effective confining stress at the depth of interest (σ'_v) may be read from the chart (this is known as the "cyclic resistance ratio," CRR, shown as CSR_{eq} in Figure 2). To determine the liquefactions susceptibility of a particular site, this minimum failure value (corrected for the magnitude of the design earthquake) is compared to the normalized stress ratio induced by the earthquake, CSR, which is a function of the mean acceleration-induced cyclic shear stress induced by the earthquake in the liquefaction-susceptible layer:

$$\text{CSR} = \frac{\tau_{ave}}{\sigma'_v} = 0.65\,\frac{a_{\max}}{g}\left(\frac{\sigma_v}{\sigma'_v}\right) r_d \;\ldots\ldots\ldots\ldots(1)$$

Where a_{max} = surface PHA; σ_v = the total normal stress at the depth of interest and r_d is a factor that accounts for the reduction of shear stress with depth.

Consequently, if a site is known to have liquefied during a historic earthquake, this same information may be applied in reverse, i.e. it allows the back-calculation of the minimum surface PHA (a_{max}) at the ground surface required to liquefy the sand. It is fair to say that the data base of well-documented case histories is large enough to provide a reliable basis for such estimates, and is a key element of the proposed study.

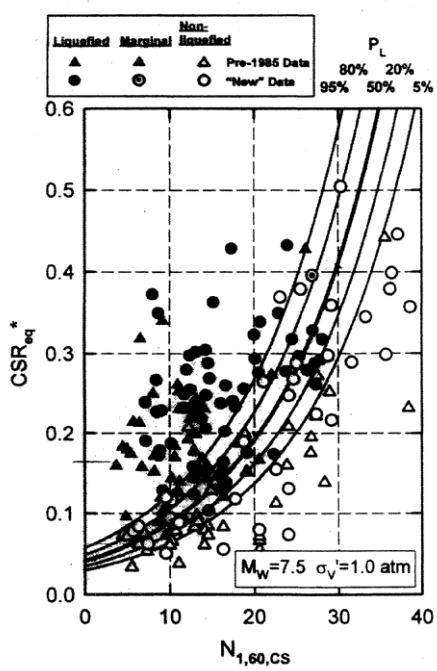

Figure 2. Normalized cyclic stress CSR_{eq} =CRR required for liquefaction, For M= 7.5 earthquake, versus equivalent normalized SPT blowcount in clean sand, $N_{1,60,cs}$. P_L = probability of liquefaction (Cetin et al. 2004)

Examples of Application to the 1755 earthquake.

In order to apply these techniques to the 1755 earthquake, a first archival study was carried out by the first author and collaborators in 1994-95 with support from the New Hampshire Office of Emergency Management, attempting to identify sites where liquefaction was produced. The literature of the 1755 earthquake was found to include a number of more-or-less detailed references to flow sliding and ejection of sand and water through boils and cracks. Several of these descriptions did not have sufficient information to pin down the exact sites referred to, but two cases seemed to be sufficiently documented for further study: Scituate and West Boylston, Massachusetts, Details of these studies are provided in Ellis (1996) and in Ellis and de Alba (1999).

This ground failure investigation showed that the PHA levels required to produce liquefaction at these two sites were higher than those that would be predicted from a earthquake with the magnitude and epicentral location described above. In his recent paper, Ebel (2006) recognized that the PHA level postulated for Scituate did not fit his proposed Cape Ann location, but suggested that the acceleration level had been overestimated. Consequently, the writer decided to re-analyze the Scituate failure using the approach more recently proposed by Cetin et al. (2004), which is based on 1200 well-documented case histories of liquefaction..

Scituate, Massachusetts:

The primary source describing the ground failure at Scituate was the Boston Evening Post of November 24, 1755 (in: WGR, 1976):

> "Scituate, November 20. Admidst the numerous bad consequences of the late amazing Convulsion of the earth ... as they are observable at & near the large Dwelling House of Mr. Joseph Bailey in this town. The chimney about the Roof of the House was entirely demolished, and most of the ceiling fractured into small parts, and in many Places separated from the Sides of the Rooms... About seventy square feet of firm Cellar Wall burst from its former Position, and another considerable part thrown to the Ground. This tremendous shock... was undoubtedly enhanced by those seven Eruptions contiguous to it which were immediately discerned.... one of them is within twenty yards of the House, and the whole seven within the circumference of a few Rods. The orifice of the largest measured twelve inches by three, and the rest are of smaller dimensions. From these we have found large Quantities of Water; and according to the lowest computations ten Cart loads of...Earth, as compressible as flour and of a white complexion."

Further details are provided by Samuel Deane (1831), in his history of Scituate:

> "Several water spouts bursted out in the Town; we can name particularly, one near the brook at Sweet Swamp, on the border of Dea. Joseph Bailey's garden. It threw out a considerable quantity of reddish sand of a singular appearance, and the spring thus opened continues to run at the present time. Another fissure of considerable magnitude was made on the south side of 'great swamp' so called."

The Deacon Joseph Bailey house is still standing, and was identified through the Scituate Historical Society. Two Standard Penetration Test borings were carried out in the assumed area of the garden, behind the Bailey house, and adjacent to Sweet Swamp. Figure 3 is a soil profile obtained from the boring data, showing the variation of $(N_1)_{60}$ with depth.

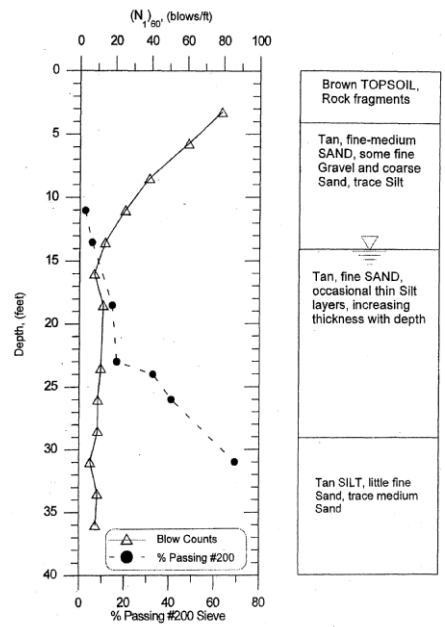

Figure 3. Soil profile with normalized standard penetration test blowcounts , $N_{1,60}$ and fines content distribution with depth, Bailey house, Scituate Mass.

While low $(N_1)_{60}$-values, averaging about 10 bpf, were recorded in the whole depth range from about 13 to 36 ft, the content of non-plastic silt passing the #200 screen increased significantly with depth below 23 ft as shown in Figure 3. For the same $(N_1)_{60}$, liquefaction resistance could be expected to increase with fines content, and thus the cleaner part of the layer would be the most vulnerable. Consequently, the sands between 13 and 23 ft were considered the most likely candidates for liquefaction, exhibiting both low blowcounts and the lowest fines content.

Before Figure 2 and Equation 1 could be used to back-calculate the minimum peak earthquake acceleration, it was necessary to account for differences in site conditions between 1755 and the present. In the first place, the groundwater level was moved upward a distance of two feet, to account for the higher groundwater to be expected in November; this value was chosen by inspection of the seasonal variation in groundwater level in the nearest USGS observation wells (Weymouth and Duxbury, Massachusetts). The higher groundwater level reduced the effective intergranular stress values, σ_o', by 4 to 6 percent, depending on the depth, resulting in lower predicted peak accelerations.

More importantly, it was also necessary to account for the densification experienced by the deposit during the earthquake, as sand was ejected and the natural grain structure was disrupted by shaking. These effects would result in a higher post-earthquake penetration resistance. The grain structure would also have gained penetration resistance through aging since the earthquake, as grain contacts reformed and the structure became stiffer. Therefore, the current $(N_1)_{60}$ values would be higher than those which would have been observed before the earthquake in 1755. Thus, accounting for time effects since the earthquake would bring the blowcounts back to those immediately <u>after</u> the earthquake; a further correction for density change would give the N-values that might have been observed <u>before</u> the event.

Densification effects can roughly be accounted for using the empirical procedure suggested by Seed et al. (1988), in which the change in blowcount in fine sands, $\Delta(N_1)_{60}$, is related to the original

relative density, D_r, (relative to its densest and loosest states) and to the assumed change in relative density, ΔD_r, as follows:

$$\Delta (N_1)_{60} = 110 \cdot D_r \cdot \Delta D_r \quad \text{.....} \quad (2)$$

It may reasonably be assumed that the pre-earthquake relative density was on the order of 40% to 50 %; based on experience with other sand deposits, the change in density would be no more than 4% or 5%. To account for time effects, Skempton (1986) observed that blowcounts in natural deposits more than 100 years old may be about 40% higher than those in freshly- compacted fills; thus, assuming that these effects can be superposed, equation (2) becomes:

$$\Delta (N_1)_{60} = 154 \cdot D_r \cdot \Delta D_r \quad \text{.....} \quad (3)$$

and the correction $\Delta (N_1)_{60}$ to current blowcounts may be calculated to be 3 bpf to 4 bpf. It should be emphasized that this is a very conservative assumption, reducing the current blowcounts by up to 40%, and thus significantly decreasing the deposit's resistance to liquefaction and the corresponding minimum PHA.

Figure 2 requires as an input value the equivalent blowcount in clean sand (<5% fines), so a correction for fines content was applied. Decreasing the current blowcounts by 4 bpf, correcting for fines content and applying the results to the appropriate curve of Figure 3, CRR values required to liquefy the sand in a **M**=7.5 event could be calculated.

As previously noted, the most widely accepted magnitude estimate for the 1755 earthquake is about **M** = 6.0. This smaller-magnitude event could be expected to produce fewer cycles of strong motion, and consequently would need to impose higher stresses per load cycle, and thus higher accelerations, than an **M** = 7.5 event. Cetin et al. (2004) suggest that, all other things being equal, an **M** = 6.0 event must impose accelerations about 60% higher than a 7.5 event to produce liquefaction. This increase is quite conservative for purposes of back-calculating PHA, being somewhat lower than the most widely accepted average increase of about 100% (NCEER, 1997).

As may be seen in Figure 2, Cetin et al. propose CRR values for different levels of probability. For the lowest blowcount, at 16 ft., the minimum peak horizontal ground surface acceleration calculated from the equivalent CRR values was between 0.14g (20% probability of liquefaction) and 0.17g (50% probability of liquefaction). These are obviously lower-bound values, since liquefaction demonstrably did take place. It should be noted that they are consistent with the PHA range previously suggested by Ellis and de Alba (1999).

Using the relationship proposed by Ebel and Wald (2003) peak accelerations on the order of 0.14g to 0.17g correspond to MM intensity of about VI-VII, which is consistent with intensity values assumed on the basis of observed damage for the 1755 event. These acceleration values are also consistent with those given by Whitman (2002) based on a model of chimney damage for eighteenth-century masonry; this model would suggest a mean PHA of 0.125g or more for the chimney damage observed at the Bailey house.

West Boylston, Massachusetts:

This second case history illustrates the use of another aspect of ground failure to roughly estimate intensity of shaking. After the 1755 earthquake, what was apparently a liquefaction flow slide was observed on the north bank of the Quinapoxet river, in what was then part of the town of Holden, and is

now West Boylston, Massachusetts. A description of this slide is given by the Reverend John Mellen (1756) in "An Account of some Effects of the Great Earthquake, in the Year 1755..":

> "At the north-east corner of the town of Holden .... there are several acres of land quite surrounded by a visible fracture in the earth... The breach upon the hilly sides is upon the declivity of the hill, and is a perpendicular sinking of the ground, in some places more than the height of a man... The trees on each side of the breach, by this means being thrown in various directions, and sometimes crossing one another, over head, at right angles, sometimes thrown out by the roots... Upon the river side, it is easy to see where the rupture was, but at present there is no opening, *only a sand that seems to have been thrown out* (emphasis added) and a great dislocation of stones, of vast bigness, in the channel....Some trees that stood upon the margin of the river, tumbled into it; and notwithstanding the large quantity of earth hanging to their roots, the place from which it was taken was not left void, but the earth behind has come forward and closed up the breach... *I observed upon a little hillock, not far from the center of the circumference, a small quantity of fine sand, spread upon the leaves, which seemed to be spewed out of the earth; and a little spring... oozing through it and falling down its sides.* (emphasis added). Had only such a rupture as this happened in a place inhabited and set with houses, the terrible effects of it are not hard to conceive... "

Local memory of this slide persists to this day; a local newspaper, the Clinton Courant mentions it in 1872; the History of Worcester County (Houghton, 1889) describes the effects of the earthquake and gives the location:

> " Soon afterwards it was discovered that a large piece of land of some acres in extent, situated in the northwest part of the town (then Holden) had sunk several feet; an acre or more seems to have sunk from forty to seventy-five feet... A visit to the spot at the present day will give the visitor a good idea of what happened... The location is on the banks of the Quinapoxet River, about 40 rods above the mills of S. R. Warfield, and near to Holden line. At this point there is a high bluff of from fifty to eighty feet high rising from the river's bank."

This description agrees well with the slide location pointed out to the writer by current residents.

Inspection of the slide area showed a bowl-shaped slump in the hillside approximately 250 feet wide at the top, narrowing to about 100 feet near the toe, where the slide was crossed by the embankment of an abandoned narrow-gauge railway. A section following the centerline of the slide area is shown in Figure 4 where the slope angle is seen to be about 37 degrees, compared to slope angles ranging from 23 to 30 degrees outside the slide. A much smaller, recent, slide, reported to be less than ten years old, was visible downstream of the study area. This slide was said to have occurred after a period of heavy rain, and seems to have been caused by a combination of rising water level in the slope and undermining of the toe by the river.

General soil conditions in the slope were available from borings carried out during the construction of the Route I-190 bridge, about 1400 feet upstream. These borings showed an upper layer, about eight feet thick, of fine to medium sand with field N-values less than 27 bpf, over a much denser sand and gravel layer (field N greater than 50 bpf) about twelve feet thick, over bedrock. Because of difficulties in operating on the steep slope, drilling on the slide itself was limited to one SPT boring carried out with portable equipment at a location about twelve feet upslope from the railroad bed (Figure 4), in the looser material which flowed.

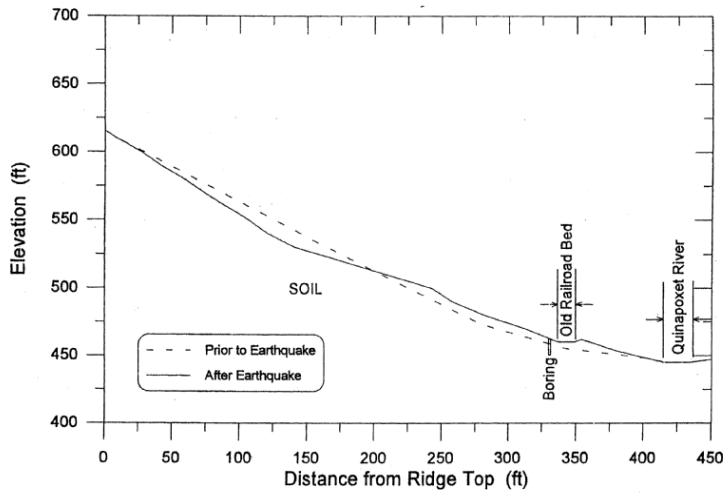

Figure 4. Slope profiles at West Boylston Mass. Slide site

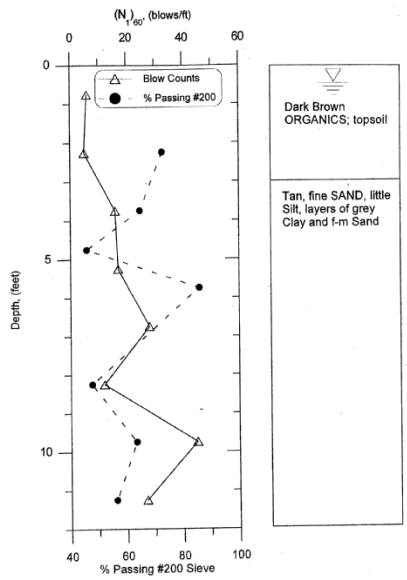

Figure 5. Soil profile with normalized standard penetration test blowcounts , $N_{1,60}$ and fines content distribution with depth, West Boylston, Mass.

The results are shown in Figure 5. The profile indicates looser sands to about 9 feet, underlain by denser material. All sands were found to have a high content of low-plasticity silt.

In this case, a different approach was taken to estimate pre-earthquake conditions; Mellen's observations clearly indicate that the material underlying a large part of the slope liquefied and flowed, and thus the strength of the material along the sliding surface was temporarily reduced to a small residual value. On the basis of 17 case histories of earthquake- and construction-induced flow slides, Seed and Harder (1990) proposed a relationship between pre-earthquake $(N_1)_{60}$ and residual strength, as shown in Figure 6. Although there is a great deal of scatter, a trend can clearly be seen. Consequently, if the residual strength of the flow slide material can be calculated, an approximate value of its pre-earthquake density may be inferred.

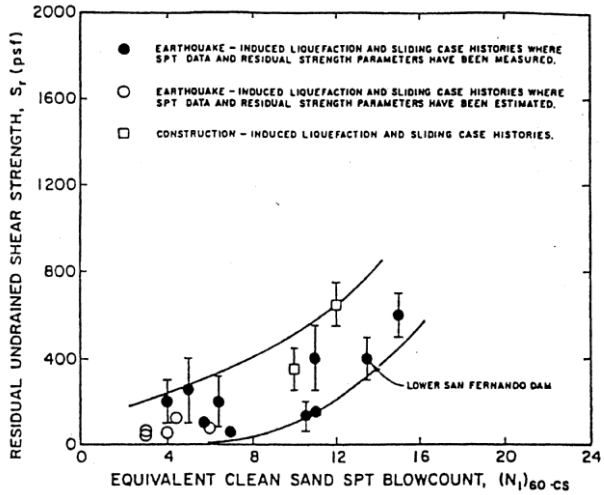

Figure 6. Residual undrained shearing strength of sand versus normalized clean sand blowcount, Seed and Harder, 1990

A rough estimate of the strength along the sliding surface at the moment of failure can be made by performing a slope stability analysis on the reconstructed pre-earthquake slope, assuming a uniform resistance along the failure surface (the residual strength) and back-calculating the resistance value for a safety factor of unity. The reconstructed pre-earthquake sliding mass is shown in Figure 4; its surface slope is consistent with the hill slopes outside the slide area, and a "mass balance" has been performed so that volumes currently above the assumed pre-earthquake ground surface are restored to the slope.

A general limiting equilibrium analysis by Spencer's method was performed assuming the slope to be divided into sliding blocks. The ground water level in the slope was assumed to be at the surface. It was assumed that the slide took place after the end of strong shaking, and thus that there were no earthquake-induced inertia forces acting, and only gravity forces were involved. The uniform strength along the sliding surface required for the mass to be at the point of failure was calculated to be about 400 psf.

For a residual strength of 400 psf, the corresponding range of $(N_1)_{60}$ values in Figure 6 is seen to be 8-14 bpf. Since these are values in clean sand, and liquefaction resistance of silty sands is higher, an equivalent silty sand blowcount, for a silt content on the order of 50%, might be about 4 bpf lower (Seed and Harder, 1990); therefore, the range of $(N_1)_{60}$ values becomes 4-10 bpf. We should emphasize that these values are very conservative; they are lower than a minimum pre-earthquake value of 10-12 bpf inferred from a static stability analysis of the reconstructed slope, and are consistent with the higher current value of 14 bpf measured at the toe of the slide, since densification and time effects have operated on the sand.

For the blowcount range of 4-10 bpf, Figure 2 can then be used, as at Scituate, to estimate a range CRR values for level-ground conditions and an **M**= 6.0 event. However, these are not level ground conditions, and the material underlying the slope was required to develop high levels of shear stress just to keep the slope from sliding under static conditions, and was thus closer to failure than it would have been under level ground. Consequently, lower additional earthquake shear stresses would have been necessary to produce liquefaction and flow than under level ground.

For the stress conditions which would have existed in the reconstructed pre-earthquake slope, it is possible that the acceleration required to trigger the liquefaction slide may have been 60% lower than that

required for level ground. Therefore, correcting the CRR values for this effect, the most likely peak acceleration values at West Boylston for the 1755 event are on the order of 0.05g to 0.09g, corresponding to an intensity of about I_{MM}= V (Ebel and Wald, 2003). It is interesting to note that Houghton (1889) reports that in near-by Holden, the effects of the 1755 event were:

> " Dwelling-houses were shaken so severely as to cause kettles and other things to rattle and make much noise, plates and other articles were thrown from shelves, and people who had retired found their beds rocking like cradles."

Again, an intensity of I_{MM}= V might plausibly be assigned on the basis of this description.

Archival Research

With USGS support, and building on the extensive study carried out in 1976 by Weston Geophysical Research Inc. mentioned above, 95 Massachusetts towns were selected for archival investigation. A complete list of these towns is included in D. Parmelee's report, Appendix 1. As can be seen from the list, all of the towns are in what can be considered the eastern third of the state. Appendix I also includes a complete description of the archival investigation methodology and a summary of the results obtained.

In summary, town historical societies and/or public libraries were contacted at each location; if the town did not itself have a history collection, other repositories were used to find secondary histories of the towns. For example, the Massachusetts Historical Society provided a substantial list of town histories that was quite valuable. Secondary town histories were also consulted for towns that were not separate polities in 1755; for example, Ashland was not yet a town by 1755, but part of Framingham. Therefore, particular attention was paid when investigating Framingham to those areas of the town that later separated into independent polities. This seemed appropriate because the town of Ashland (or another equivalent "new" town) does not have records as far back as 1755, so there would be no other way to access that geographical area for 1755.

In addition to the above methods of locating extant contemporary document sources, a wide variety of electronic and digital databases and catalogs were examined. Some of these, such as the Evans Digital Collections, provide digitized primary sources. Others, including the National Union Catalog of Manuscript Collections, provide digital catalogs of collections that would otherwise be inaccessible. Both types of electronic resources were used for this project.

Personal accounts of the earthquake, accompanied by descriptions of structural damage to houses which can still be identified, were obtained for four locations, in Chelmsford (1), Danvers (2) and Quincy (1). Unfortunately, no additional specific locations which liquefied were found; descriptions of extensive liquefaction in the area of Provincetown on Cape Cod were located, but exact locations were not available.

However, these results emphasized the contrasting effects of the 1727 and 1755 earthquakes, both of which affected the Cape Ann area: On November 9 of 1727, Newburyport (then part of Newbury) Massachusetts, and Hampton, N.H., were struck by an earthquake which produced a number of damage reports in letters, diaries and appendices to sermons preached in the local churches. Detailed descriptions exist of extensive liquefaction having taken place in at least two areas of Newburyport (Dudley, 1727; Plant, 1727; and Jacques , 1727) and one location in Hampton (Gookin, 1727).

As pointed out in the Parmelee report, one very significant observation resulting from this study is that residents of the town of Newburyport produced many more extant documents about the 1727

earthquake than the 1755 event, despite the fact that many authors of those documents were still alive in 1755. By the writings they produced in 1727 we know there was an educated population in Newburyport who were interested in what they called "natural science." "*The fact that this same population did not produce a larger quantity of material in 1755 seems to indicate that the 1755 earthquake was not as severe in Newburyport as the 1727 event.*[1]"

Newburyport, Massachusetts

In light of these conclusions, two sites which liquefied in 1727 but did not fail in 1755 are also relevant to this problem. Studies in Newburyport by Tuttle et al. (1987), Tuttle and Seeber (1991), and Hasash et al. (1988) indicate deposits of fine, liquefaction-susceptible sands. Tuttle and co-workers report evidence for at least two liquefaction events, the younger of which they identify as 1727 liquefaction. They also report artesian conditions in the liquefaction-susceptible strata, which, if they had existed in 1755, would make the deposit even more liquefaction-prone, as the artesian pore water pressures would reduce the effective stresses (σ_o') and thus reduce the cyclic shear stress (τ_{av}) required to liquefy the material.

However, liquefaction was reported at neither Newburyport nor Hampton in the 1755 event. While it is possible that this is due to accidents of transmission, this is rather unlikely (see above), especially in the case of Newburyport, where seven different descriptions of the 1727 liquefaction were collected by WGI . The question is then, why wasn't liquefaction observed in 1755? Field evidence from recent earthquakes has shown that liquefied deposits compact slowly, from the bottom up, and will remain susceptible to liquefaction at the same levels of acceleration, in subsequent events (Youd, 1984; Yasuda and Tono, 1988). The earthquakes took place at approximately the same time of year, and it is unlikely that groundwater conditions could have been greatly different, and more unfavorable, in 1727 than 1755. This strongly suggests that acceleration levels in 1755 must have been lower in Newburyport and Hampton than in 1727.

In 1988, one of the reported 1727 liquefaction sites was drilled by a team from MIT (Hashash et al, 1988), and SPT blowcounts were obtained from the sand layer presumed to have liquefied. Using the same approach described above, a surface PHA of 0.13g was estimated (50% probability of liquefaction). Conservatively assuming an amplification factor of two for the 9-m deep soil profile, and using Atkinson and Boore's (1995) attenuation relationship for an **M**6 event, an epicentral distance of about 72 km is obtained. The offshore Cape Ann epicenters shown in Figure 1 are within this range, yet liquefaction was not observed in 1755; on the other hand, for comparable bedrock acceleration levels and site conditions, liquefaction was observed at Scituate in 1755, about 85 to 98 km from the epicenters proposed by Ebel and Bakun et al. respectively.

Discussion

It is fair to say that the spatial distribution of currently-identified liquefaction ground failures produced by the 1755 event does not support an epicentral location off Cape Ann. Figure 7 shows the locations currently known to have liquefied in the 1775 event. None of these sites are significantly to the north of Boston. Newburyport and Hampton, where liquefaction was observed in 1727, did not report ground failure in 1755.

[1] Personal conversation, D. Parmelee with Jay Williamson, Curator, Historical Society of Old Newbury, August 10, 2009.

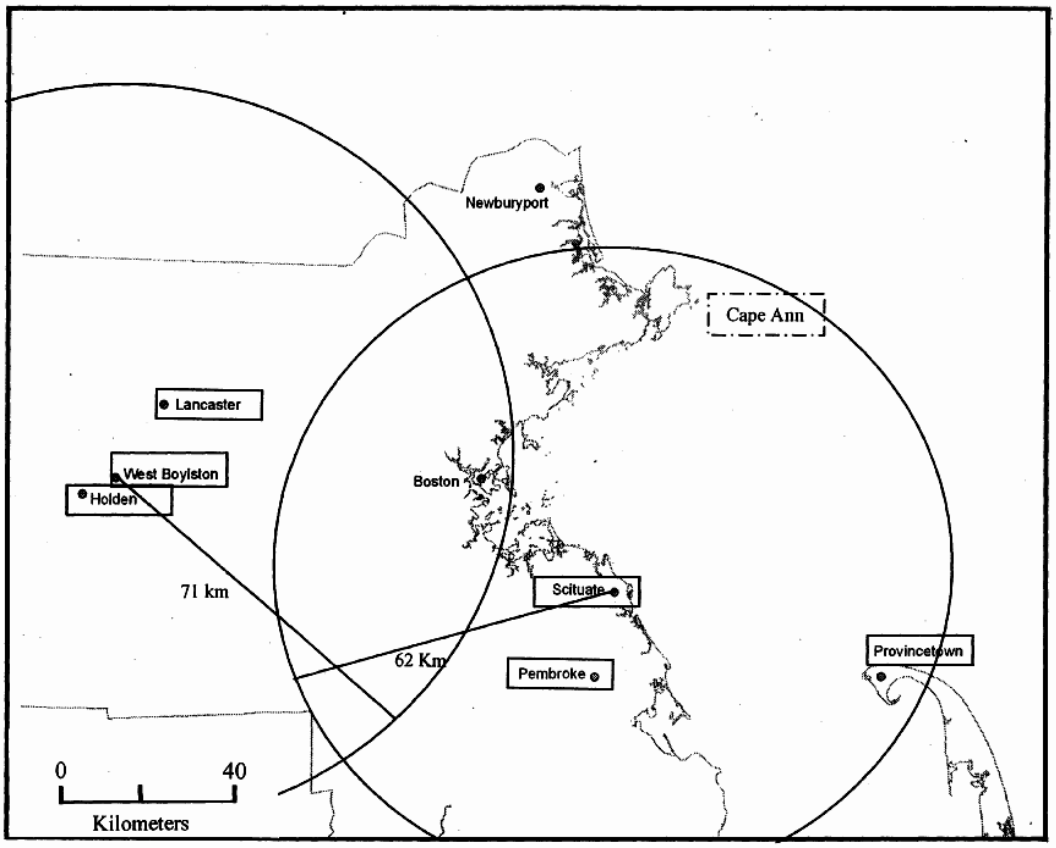

Figure 7. Loci of possible epicenters required to produce upper limit PHA calculated for West Boylston and Scituate. Sites where liquefaction was reported in 1755 event are boxed.

Further, and based on the acceleration levels calculated from ground failure at Scituate and West Boylston, loci of epicentral distances may be drawn as shown in Figure 7. These circles represent the furthest-out loci of epicenters for the PGA values on rock calculated at these two sites using the relationship proposed by Atkinson and Boore (1995). At West Boylston, the calculated acceleration was taken directly as the rock value, given the shallow depth to rock at that site. At Scituate, the surface value was reduced to account for amplification due to the soft soil profile using the relationship proposed by Idriss (1990); a rock value of about 0.08 g was estimated. These results suggest an epicentral location inland from Boston.

Alternately, it is possible to argue that the interpretation of the West Boylston case has a higher level of uncertainty than Scituate (although ground failure demonstrably did occur), and other evidence should be considered. Parmelee (Appendix I, p.9) presents a description of the event by Col. Anthony Thomas of Marshfield, Mass. which states: "… but the sea was roaring at the shore with such a noise as hardly ever was known…" and Fansler (Appendix II, p.4) reports that: "in Gloucester, Mass, a major harbor on Cape Ann, the earthquake seemed to have started fires, toppled chimneys and cracked the wheels of carriages. In all respects, this represented one of the more violent accounts of the earthquake."

Further, he also includes contemporary observations from sailing vessels (Appendix II, p.2):

"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 [about 245 miles], at ½ past 4, but concluded 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 Surprize, 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 the Harbour." And also (Appendix II, p.3)
"…And some Vessels in the Bay under Sail, tho' 'twas very calm, were so agitated, that the Men could not keep on their Legs; and 'twas the same with the Vessels in our Harbour.—A fishing Vessel being at Sea, about 17 Leagues [almost 60 miles] from Land, during, or immediately after the Shock, observed the Fish to come up to the Surface of the Water in vast numbers."

Figure 8 shows recorded liquefaction sites and the locations of Gloucester and Marshfield. On the basis of the Scituate ground failure, which is the best documented and simplest to interpret, the lack of liquefaction observations in Newburyport, and these last observations, it is possible to postulate an offshore epicenter for the 1755 earthquake, but further South, quite possibly in Massachusetts Bay. Overall, either model strongly suggests that the epicenter of the 1755 event was further South than the currently accepted location, and closer to Boston. This probability merits being taken into consideration in future earthquake studies of the Boston metropolitan area.

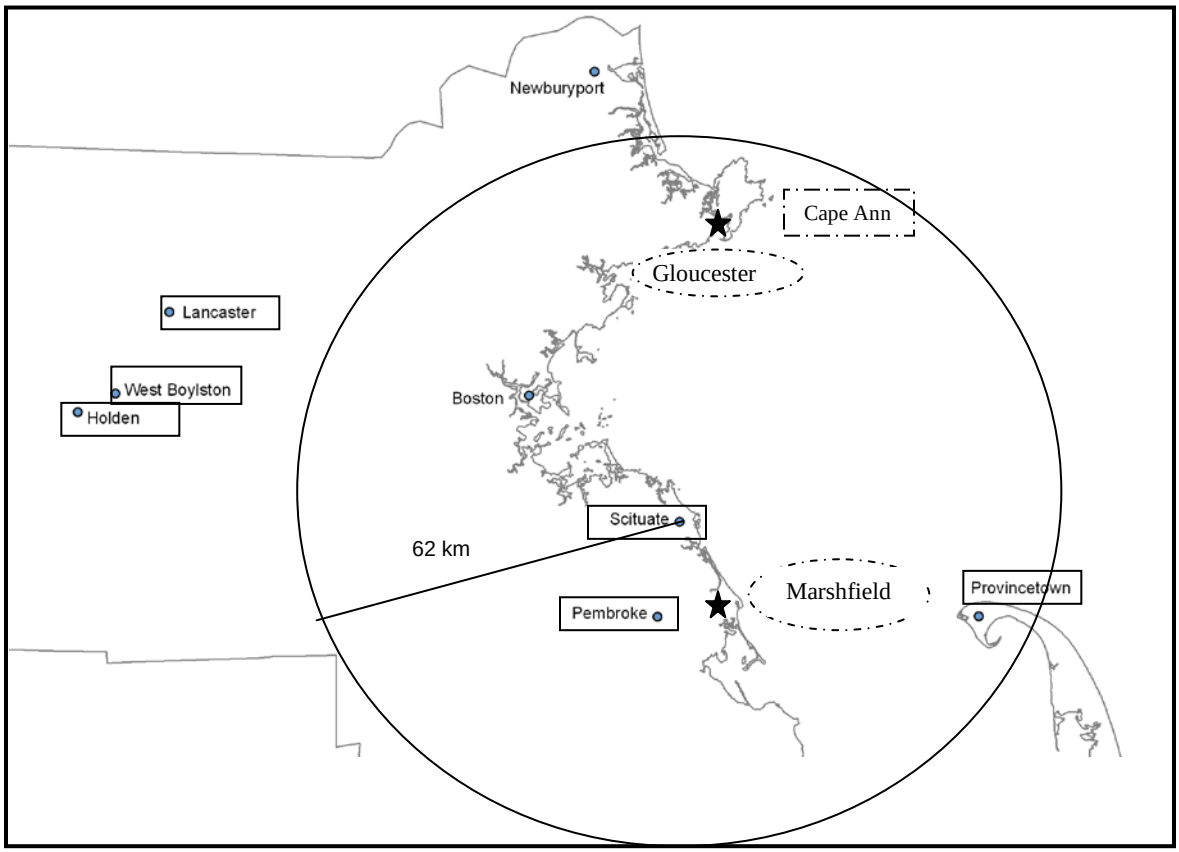

Figure 8. Location of Gloucester and Marshfield and Sites where liquefaction was reported (boxed) Circle shows limits of possible epicentral locations for Scituate.

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Appendix I

Archival Research Report, Deena Parmelee, Summer 2009

1. Methodology Statement

By using the grant proposal and the 1978 WRG report, I identified one hundred Massachusetts towns to be investigated. Rather than "re-invent the wheel," I intentionally removed six towns that were fully represented by WRG's research. A complete list of these towns is included in this report. As can be seen from the list, all of the towns are in what can be considered the eastern third of the state. The remaining ninety-five towns were investigated in the following ways:

First I determined whether the towns had historical societies. I contacted the historical societies that indicated on their websites that they had archive collections or research libraries. The e-mail letter I sent out is included in this report.

If a town did not have a viable historical society, or if I received no response to my attempt to contact the historical society, I next investigated the towns' public libraries[2]. Many public libraries have collections of material about town history or are the repositories for town records and/or historical society document collections. Due to the fact that many towns' historical societies are very tiny and staffed by volunteers, the libraries often proved more valuable than historical societies.

When a town had no viable historical society and the library did not possess a local history collection, I used other repositories to find secondary histories of the towns. For example, the Massachusetts Historical Society provided a substantial list of town histories that was quite valuable. These secondary town histories are of varying value to this project (see individual report work sheets and the project summary). Secondary town histories were also consulted for towns that were not separate polities in 1755; for example, Ashland was not yet a town by 1755, but part of Framingham. Therefore, I paid particular attention when investigating Framingham to those areas of the town that later separated into independent polities. This seemed appropriate because the town of Ashland (or another equivalent "new" town) does not have records as far back as 1755, so there would be no other way to access that geographical area for 1755.

I found no sources at all for a tiny percentage of the original hundred towns. In mid-August I made conscious decisions regarding the remaining towns that I had not yet fully investigated. In some cases, I made additional efforts; in others, I determined that the likelihood of finding anything substantive was so small that my efforts and time were better spent pursuing materials from other towns that seemed to offer better prospects. I made these individual decisions based on secondary research about the towns, and geographic considerations.

In addition to the above methods of locating extant contemporary document sources, I examined a wide variety of electronic and digital databases and catalogs. Some of these, such as the Evans Digital Collections, provide digitized primary sources. Others, including the National Union Catalog of Manuscript Collections, provide digital catalogs of collections that would

[2] The term "viable historical society" indicates that the historical society of any particular town exists in some form but either does not have a document archive or collection, or that collection is not available to researchers. The latter situation can occur if there has been no cataloging of the collection the historical society does possess. This is a very rare occurrence, but did happen.

otherwise be inaccessible. Both types of electronic resources were used for this project (see list provided elsewhere in this report).

In most cases I refrained from repeating WRG's work, but in a handful of examples I examined sources they had previously identified, and included them on the map and in the worksheets. I did this when it seemed to me that additional information was gained by a deeper examination of those sources. I read the contemporary newspaper articles, for example, but did not mention them in this report. WRG's 1976 report covers those sources adequately. However, other primary sources such as Reverend Parkman and Reverend Bridge's journals are re-examined here because the WRG report does not fully explore the information available in those sources.

The combination of these methods and the organizational planning I put into this project have, I believe, insured that the research was conducted well and thoroughly.

2. Towns investigated

Acton	Andover	Arlington
Ashland	Ayer	Bedford
Berlin	Beverly	Billerica
Bolton	Boxboro	Braintree
Brookline	Burlington	Cambridge
Canton	Carlisle	Chelmsford
Chelsea	Clinton	Concord
Danvers	Dartmouth	Dedham
Dover	Dracut	Dunstable
Duxbury	Everett	Falmouth
Foxboro	Framingham	Franklin
Georgetown	Haverhill	Hingham
Holliston	Hopkinton	Hudson
Hull	Lancaster	Lawrence
Lincoln	Littleton	Lynn
Lynnfield	Malden	Marblehead
Marlborough	Maynard	Medford
Melrose	Methuen	Millis
Milton	Natick	Needham
Newburyport	Newton	North Reading
Northborough	Norwood	Peabody
Quincy	Randolph	Reading
Revere	Salem	Saugus
Sharon	Sherborn	Somerville
Southborough	Stoneham	Stow
Sudbury	Swampscott	Taunton
Tewksbury	Tyngsboro	Walpole
Waltham	Watertown	Wayland
Wellesley	Westborough	Westford
Weston	Westwood	Weymouth
Wilmington	Winthrop	

3. Summary of Findings

While I make no pretense to qualification for assessing the scientific value of the results of this project, a summary of the findings is still in order.

Perhaps the most significant finding is that the 1755 earthquake does not seem to have generated more notice in extant records. For example, one might reasonably expect to find notations in municipal or colonial records regarding repairs of roads or bridges. Municipal records from the mid-eighteenth century survive in reasonable quantities, and colonial records from the period are abundant. However, none of these contain any mention of such repairs in connection with the earthquake. For instance, Watertown's municipal records (from the town council and treasury) frequently mention repairs to a bridge over the Charles River, but maintaining the bridge was an on-going project for the town and none of the repair listings mention structural damage caused by the earthquake. It is possible, of course, that such information was merely left out of the records. However, given the duration and cost of the project it seems more likely that such details would have been included if the earthquake had in fact caused any damage.

Further, despite the hyperbole found in many sources, the earthquake does not seem to have done a great deal of damage in Massachusetts. Secondary sources such as *The History of Lynn*, and the *Chronicles of Danvers* refer to it as the "greatest earthquake ever known in New England," and use adjectives like "tremendous."[3] Primary sources feature phrases such as "most terrible."[4] These descriptions may speak to the fear caused by the earthquake, but the physical damage seems to have been comparatively minimal. If there had been more damage, or more severe damage, the sources we have would mention it, and we might have more sources. The fact that this earthquake apparently did not cause any deaths in the region may also contribute to the comparatively small number of sources still in existence. *For example, residents of the town of Newburyport produced many more extant documents about the 1727 earthquake than the 1755 event, despite the fact that many authors of those documents were still alive in 1755. By the writings they produced in 1727 we know there was an educated population in Newburyport who were interested in what they called "natural science." The fact that this same population did not produce a larger quantity of material in 1755 seems to indicate that the 1755 earthquake was not as severe in Newburyport as the 1727 event.*[5]

Additional evidence to support the idea that this particular earthquake failed to really alarm a majority of the population is that it is not even mentioned in many secondary town histories of towns where we know the earthquake was felt! Herman Packard De Forest's 1891 *The History of Westborough, Massachusetts* makes no mention on the November, 1755 earthquake, but Reverend Ebenezer Parkman's journal is one of the best known primary sources of the event. Of course, nearly all of the secondary histories of individual towns were written more than a hundred years after the event, which certainly helps determine what material was or

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[3] Alonzo Lewis and James R. Newhall. *History of Lynn, Essex County, Massachusetts, including Lynnfield, Saugus, Swampscott, and Nahant*. (1865): p 330; Harriet Silvester Tapley. *Chronicles of Danvers (Old Salem Village) Massachusetts 1632 – 1923.* (1923)

[4] Reverend Ebenezer Bridge cited in Waters, Wilson. *History of Chelmsford, Massachusetts*. (Lowell, MA: 1917) p. 640

[5] Personal conversation with Jay Williamson, Curator, Historical Society of Old Newbury, August 10, 2009.

was not included. However, those nineteenth- century authors often had access to primary sources no longer available to us; if stories of the earthquake were in those sources, the stories would have been included in the later histories.[6]

Geographically speaking, the discovery of sources identifying Harwich and Dartmouth as places where the earthquake was definitely felt seem to bear out the idea that the earthquake was not centered off Cape Ann. Conversely, reports and descriptions of a tsunami-like event in the Caribbean later in the day on the 18th may indicate an oceanic center. However, I am certainly not qualified to make even the most general assessment of these findings with regard to science or engineering.

Unfortunately, extant church records from the region did not yield the additional sources hoped for. The published sermons previously known do indeed seem to be the complete extant collection of such sources. Despite searches of church records in several likely towns, other sermon material relating to the earthquake was not located. Several ministers wrote privately of their earthquake experience; presumably, they included the event in their sermons as an example of the work of God. However, copies of these were either never made at all, or have not survived (it is quite unlikely that no single copy would have survived if they had been printed).

A few words about the reliability of nineteenth-century secondary sources are in order. Nineteenth-century antiquarians had nothing like modern historical methodologies. However, an overwhelming majority of them did follow methodologies of their own when compiling projects such as town histories. These men (and very rarely women as well) were often long-time residents of the towns in question, and usually comparatively well educated. Frequently they were clergy or retired career military men. Their familiarity with their towns, combined with their education, made them fairly well qualified to write town histories, and quite often they wrote several books about their towns. Consequently, the fact that these books are secondary sources compiled over a hundred years after the 1755 earthquake should not disqualify them as reliable sources on the subject. Reading the accounts of the earthquake found in these books, it is easy to see which ones used which specific contemporary sources, whether the author included attributions or not (usually it's *not*). It is very obvious which authors used articles from the *Boston Evening Post* or the *Boston Gazette*, for example. This demonstrates that even without modern attribution systems, the authors did indeed do research for their histories, and that such research did not consist only of local hearsay.[7]

At the same time, it is important to recognize that such histories may not be accurate. A lack of attributions must always make the historian wary; sources that merely mimic contemporary documents are also a cause for some concern. Without the inclusion of local information, we cannot tell if the antiquarian merely included general information about the

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[6] Paine's *A History of Harwich, Barnstable County, Massachusetts: 1620-1800*. is a case in point. Paine refers to a diary kept by a Miss Mary Fleet, but that journal apparently no longer exists. It is not listed in Harriette M. Forbes' exhaustive *New England Diaries, 1602 – 1800: a descriptive catalogue of diaries, orderly books and sea journals*., so presumably no longer existed by 1923.

[7] The subject of the validity of oral testimony is still deeply contested among historians. However, most historians (including me) have come to realize that the passage of time does not necessarily dilute the accuracy of such testimony. In an extreme case cited in David Hurst Thomas' *Skull Wars*, Klamath Indians may have preserved an accurate story for over seven thousand years. Since the time between the 1755 earthquake and the writing of most of the town histories examined for this project would have been four generations or fewer, it is certainly possible that any oral testimony used (but perhaps unattributed) is reasonably accurate.

earthquake because they *assumed* it was felt in their town. However, the number of town histories that neither mention local information nor quote directly from primary sources, but do contain a report of the 1755 earthquake, is quite small. Much more common are the secondary histories that make no mention of the event at all.

As discussed in the Methodology Statement, it is likely that there are still some secondary "holes" in this research. This final report is specifically designed to provide a starting point if further research should be required in the future. However, I believe that the primary research was conducted as thoroughly as possible, taking into account that which was previously conducted by WRG. Valuable new information and insights can be gleaned from this new research.

4. New locations identified

Danvers, MA
Dartmouth, MA
Framingham, MA
Harwich, MA
Newburyport, MA
Wayland, MA

specific location information

Chelmsford, MA: The house Reverend Bridges lived in is no longer standing but it was across Westford Street from the Forefather's Burying Ground in Chelmsford (see Chelmsford worksheet).

Danvers, MA:
1. Folly Hill, site of the original Browne Hall, is still there, although a great deal of construction has taken place there since 1755 (see Danvers, Tapley worksheet).
2. Colonel Hutchinson's home still stands at 181 Centre Street in Danvers. It would be advisable to determine whether the home was ever relocated (see Danvers, HisSoc worksheet).

Marshfield, MA: Colonel Thomas' home still stands at 497 Parsonage Street, Marshfield (see Marshfield worksheet).

Quincy, MA: John Adams lived at his father's house in 1755. This home is the focal point of the Adams National Historical Park, although its status as a National Park could have an impact on its viability for soil testing (Adams' journal is quoted in the WRG report).

5. New Location Worksheets: see following pages.

Location: Chelmsford, MA

Creator: Reverend Ebenezer Bridge

Synopsis: Demonstrates event was felt in Chelmsford, MA; some detail that could provide a specific location for research.

Reverend Bridge lived across the street from Forefather's Burying Ground in Chelmsford. The Forefather's Burying Ground is on Westford Street. The house Bridge lived in is no longer standing.

Listed but not quoted on p. 167 of WRG report

Quotations: "1755 Nov. 18 About 4 o clock this morning we were suddenly awaked out of sleep by a most terrible & shocking Earthquake. I was awaked whether by ye noise or ye shaking I know not, but I immediately thot what it was. Called to my wife & she & I leaped immediately out of bed - & were casting about in our minds wt Course to take for safety. She ran to ye chamber where 4 of our children & our Servt. lay. I run after her & then took back to dress me. She then ran to ye chamber where my Sons Ebr. & Jno lay – My dear lambs were all in a dreadful surprise – I believe this shock was as great as yt in ye year 1727 wch I well remember. We all got up & dressed ourselves & I could not enough praise & bless the Lord who had preserved us and ours. I observed presently a little repetition of ye Shock & about an hour & a half another Considerable one. I discoursed with my family upon this loud call in ye providence of ye lord & gave em ye best counsel I could. My son Ebenr. & Daughter Sarah were effected. While my wife & I were in our greatest Confusion & she running to ye Kitchen Chamber. I perceived ye shock to abate, but then it Came again with a greater force, & I called to her to stand still & see ye Salvation of the Lord. About this time a hand bell in our garret was set a ringing by the shake. Two bricks fell from the top of our chimneys, but the Lord preserved us and ours from all damage. Blessed and forever blessed be his great and holy name. I soon went out and walked about. Ye night had been remarkably serene & clear but a considerable Cloud had lain in ye East, as it had done for a night or two before. Oh, it is a night much to be observed by me & by all people in ye land. I pray I may never forget it."

Source: Waters, Wilson. *History of Chelmsford, Massachusetts*. (Lowell, MA: 1917) p. 640

Source Location: Massachusetts Historical Society

Location: Danvers, MA

Creator: Harriet Silvester Tapley

Synopsis: Demonstrates event was felt in Danvers. While Tapley quotes the earlier work by Hanson (without attribution!), she adds the interesting story of Browne's Hall, a private residence built on Folly Hill in the late 1740s. It would not be difficult to locate Folly Hill in Danvers for further testing; however, there are indications that a great deal of construction has been undertaken there in recent years, so it may not be a viable test site.

Despite the lack of attribution for the Browne's Hall story, it seems likely that this story is fairly reliable. The movement of an entire residence, especially one that was comparatively grand, would not have been undertaken lightly in the mid-eighteenth century.

Quotations:
"In 1755 a tremendous earthquake occurred in this vicinity. Glass was broken, chimneys destroyed, and great consternation created. It has been stated that Browne's Hall was so shaken, 'that the owner dared no longer reside in it, and practically acknowledging that its ambitious site rendered it indeed a folly, he proceeded to locate it on humbler ground.'"

Source: Harriet Silvester Tapley. *Chronicles of Danvers (Old Salem Village) Massachusetts 1632 – 1923.* (1923)

Source Location: Danvers Archival center, Peabody Institute Library, Danvers, MA

Location: Danvers, MA

Creator: Danvers Historical Society

Synopsis: The chimney of birthplace of Col. Israel Hutchinson was "badly cracked," allegedly by the 1755 earthquake. This house is still standing, at 181 Centre St. in Danvers. (It would be worthwhile to investigate whether this is the original location of the house. The source specifies that Hutchinson's birthplace was on Newbury Street.)

Quotations:

Source: *Historical Collections, V. 13,* Danvers Historical Society

Source Location: Danvers Archival Center, Peabody Institute Library, Danvers, MA

Location: Marshfield, MA

Creator: Colonel Anthony Thomas

Synopsis: Demonstrates event was felt in Marshfield, MA.

This entry was made in the Thomas family bible. The Thomas home still stands in Marshfield, at 497 Parsonage Street.

Quotations: "Tuesday morning, Nov. 18 1755. An earthquake about 18 minutes after four o'clock in ye morning. The air clear and calm, the Heavens bright, the moon shining and about two hours high, as pleasant a morning as ever was seen, - but the sea was roaring at the shore with such a noise as hardly ever was known, & ye continuance of the shock, by all the calculations I can make about one minute and a half, & then we seemed to think it was going off, but ye repeated shock was more terrible, and shook down many tops of chimleys, both in Boston and country & ye whole shocks as near as I can think, two minutes & a half, - after that we had dull, heavy calm weather, and one shock more, but small comparatively yet felt considerably, & ye twenty second of ye same month, Saturday at 40 minutes after eight in the evening we were alarmed with another still, though not to be compared with the first these were all I heard til December the 19 about 10 o'clock at night, some noyse but little or no shock."

Source: ***New England Historical and Genealogical Register for the Year 1862, Volume 16*** **(Albany: J. Munsell, 1862): p. 171**

Source Location: Watertown Public Library

Location: n/a

Creator: Sidney Perley, *Historic Storms of New England*

Synopsis: Although Perley offers no attributions, the nature of this book makes it clear that Perley had made a study of "storms," including earthquakes. His language demonstrates that he was familiar with every available contemporary source. So while the lack of source information diminishes the reliability of this work, it certainly isn't worthless.

Perley offers several interesting observations about the intensity of the quake as well as its physical manifestations.

Quotations:
"It came suddenly like gigantic pulsations of the earth and tossed everything about. This was followed for about a minute's duration with a peculiar tremulous motion of the earth, which some people thought was the resultant motion of the first shock and the gradual lessening of its force. But it was followed instantly by a quick vibration and several jerks, much more terrible than the first had been." (p. 60)

"In the valley of the Merrimac river, this earthquake was not quite as severe as that of 1727; its noise was not as loud, and it did less damage. The towns along the sea-shore felt it most, and it gradually lessened in force as it progressed inland." (p. 62)

Source: Perley, Sidney. *Historic Storms of New England*. (1891)

Source Location: n/a

Appendix II

Archival Research Report, Jordan Fansler, Summer 2010

Introduction and Methods

This study, which is a continuation of one conducted in the Summer of 2009, has as its object, the location and analysis of historical records relating to the New England earthquake of 1755. The purpose is to use these sources as a way for determining the relative strength of the earthquake across the countryside and, thus, to have a better understanding of the epicenter and strength of the earthquake.

As this is a continuation of a previous study, the focus was on areas perceived as requiring further investigation. Specifically, emphasis was placed on the possibility of a tsunami created by the earthquake, the farthest reaches of the earthquake's effect, and its effect on Gloucester, MA, Portsmouth, NH and their surrounding areas. Attempts to find the effects of the earthquake proved elusive for the inland counties, such as Worcester and Middlesex, owing to sparse populations and publications from that area.

The study had focused mostly on printed materials, especially newspapers and pamphlets, while manuscript sources such as diaries had also been incorporated where extant and relevant. There are two primary reasons for this emphasis. The printed sources have survived in much greater numbers, and they are more likely to carry relevant information for the study. Newspapers of the day focused on reporting events and occurrences from a range of places and included letters and notes from private persons, with less emphasis on editorializing or opinion in the modern sense. In that way, the newspapers were ideally suited for carrying information regarding the earthquake including personal testimonials from various places and providing the type of accounts useful in this study. The study thus started with a survey of the newspaper sources with closer inspection of areas that revealed potential information based on that survey and on those that had been previously identified as needing further investigation.

Thanks to the resources of the University of New Hampshire's library system, much of the research could be done through its holdings and networks. This work was, as described above, primary source work in all but a very few cases. It was necessary at various points, however, to travel to certain archives that showed potential for information, as when they housed manuscripts or other rare materials. The Massachusetts Historical Society, located in Boston, Massachusetts and the Portsmouth Athenaeum, located in Portsmouth, New Hampshire, were the other major archives visited during the project.

Account of Relevant Sources Found With Brief Analysis

In this manner and using these resources, some interesting sources were found and explored which illuminate the nature of the earthquake of 1755. In the case of a tsunami, however, just the opposite was the case. There is only one source that indicates a tsunami happening on the shores in the Americas on 18 November, the day of the earthquake. On 29 December, the Boston Evening Post ran a story from the West Indies, reporting a strange happening with the sea.

‘About 2 o’Clock in the Afternoon, the Sea withdrew from the Harbour of St. Martins for several Leagues, so as to leave Oyster-Bay and the Vessels dry and abundance of Fish on the Banks where there used to be 3 or 4 Fathom of Water [18 or 24 feet], and continued out a considerable Time, which gave the People an Opportunity to retire to the Mountains, fearing the Consequences of its Return; and when it came in, it arose 6 Feet higher than usual, and carried off some Sheep, &c, but no Person’s Life was lost.’ There was no Shock of an Earthquake felt at that Time.

It is clear from the final comment and other similar reports that such wave actions were understood to be associated with earthquake activity in the eighteenth century. However, this report and a copy of it that also appeared in the Boston Gazette of the same day were the only mentions of such wave action that occurred on 18 November. Given that there were multiple reports of anomalous tides associated with the great Lisbon earthquake of 1 November 1755, some appearing side by side with the St. Martin report, its clear that a major earthquake and its even distant consequences would have been recognized.

It is also worth noting that Oyster-Bay is located on the southern side of the island. St. Martin is a small island, a former Dutch colony, located east of Puerto Rico. It seems unlikely, too, that this small island, in the midst of a large chain of inhabited islands, should be the only one to report such an event from about 2,000 miles away on the face of the island that stands opposite from New England.

Though the St. Martin event was the only instance of a tidal disturbance that can be found in conjunction with 18 November, some other, closer incidents were reported describing the earthquake as felt by ships in the water. The Boston Gazette of 24 November reported:

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 [about 245 miles], at ½ past 4, but concluded 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 Surprize, 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 the Harbour.

A similar report, found in a town history of Portsmouth, the Annals of Portsmouth from 1825, indicated that “the sand and river were in great agitations, and the shock was so severely felt on board vessels in the harbor, that these persons who were on board, thought they had struck the rocks.” Because this second report was written in the early nineteenth century, almost seventy years after the event, its veracity should be suspect, but its similarity to the Cape-Ann report and the fact that it could conceivably still have been in living memory as the author compiled his information lends some credibility to the account.

New Hampshire’s seacoast region also produced reports of damage on land as well. Hampton, Newington and Greenland all have reports associated with them, which claim damage to property and fissures opening. The Boston Evening Post of 1 December described a “letter from

New-Hampshire, dated a week ago" that told of shocks "more than in these Parts of the Country." Though there is also a report of a fissure that opened in Newington due to the earthquake in this issue, modern investigations have determined that such an event was unlikely given the condition of the soil. In Greenland, a town south of Portsmouth along the Great Bay, there is a building known as the Weeks House, which has cracks in the walls and timbers reputed to have been suffered during the earthquake. Physical inspection is likely necessary to confirm this assertion and may prove useful in determining the strength of the earthquake in southeastern New Hampshire. A History of the Town of Hampton, New Hampshire reports standard damage such as cracked and toppled chimneys and recorded a day of feasting and fasting called for two weeks later to reflect upon the earthquake. Like the Annals of Portsmouth, this account was part of a town history written after the fact, making the veracity questionable, but the account is typical and in keeping with the accounts that were closer to the event.

At the time of the earthquake, Boston was the largest urban area in New England and thus, unsurprisingly, the majority of reports on the earthquake are found in Boston newspapers and regard the event as it happened in Boston. The reports from Boston are typically the most destructive reports received, though this is likely a function of the higher incidence of reports and structures in the area increasing the reported damage.

The Boston Gazette printed, on 24 November, a memorandum created by a private citizen of Boston, "having taken a View of several Parts of the Town, the Morning after the late terrible Earthquake." The rather lengthy memo described the author's personal experience of being woken and moving about his house in search of a safe place during the earthquake, which he estimated "could be but little more, and certainly not much less, than 2 Minutes." The remainder of the memo described the state of the city the following morning, noting especially the large numbers of chimneys "not much less than an 100," that had fallen down and the many more which were damaged without completely falling down. He described entire streets "almost covered with the Bricks that have fallen. Some Chimnies, tho' not thrown down, are dislocated, or broken, several Feet from the Top and partly turned round, as upon a Swivel." He also describes other, similar damage to buildings and the destruction of a "strongly put together" cistern. A similar account given in the Boston Evening Post from the same day reported "the Ends and Sides of several Brick Buildings were thrown down, and, in a Word, the Instances of Damage done to our Houses and Chimnies area so many, that it would be endless to recount them."

The Evening Post report also contained information from the surrounding countryside, most interestingly regarding the ships in the harbor.

In the Country also, we hear many Chimnies and Stone Fences were thrown down, and much other Damage done' And some Vessels in the Bay under Sail, tho' 'twas very calm, were so agitated, that the Men could not keep on their Legs; and 'twas the same with the Vessels in our Harbour.—A fishing Vessel being at Sea, about 17 Leagues [almost 60 miles] from Land, during, or immediately after the Shock, observed the Fish to come up to the Surface of the Water in vast numbers.

This account, which was reprinted in the Pennsylvania Gazette 4 December, echoed the previously mentioned reports of disturbances to fish and vessels on the water, lending still further credence to the account given in The Annals of Portsmouth.

The Boston Gazette, on 24 November, the same day as the memo was printed, included the following measurements for the extent of the earthquake: "70 Miles E[ast], 80 W[est], & 42 S[outh]." It is unknown exactly how they reached this number, but the very existence is telling. Boston, the assumed relative location for these estimates, appears to be almost in the center as east and west are concerned, but the claim that the earthquake only extended forty miles south is somewhat discredited by subsequent claims from Philadelphia and New York. The absence of a distance to the north remains a mystery, especially since it was clear that the earthquake was felt in New Hampshire and Cape Ann. By the diary of Samuel Chandler, a minister in Gloucester, MA, a major harbor on Cape Ann, the earthquake seemed to have started fires, toppled chimneys and cracked the wheels of carriages. In all respects, this represented one of the more violent accounts of the earthquake. Perhaps the compilers of the above estimate felt they did not have adequate information to estimate the extent to which it was felt in the north other than to say that it was felt at least a small distance away.

The Boston Evening Post of one week later, 1 December, also reported damage from the countryside. In this report, the chimneys and stone fences are mentioned again, but also springs drying up, changing their course, and appearing where none had flowed before is mentioned. This is said to have occurred throughout the region, as well as eruptions of water and sand. Unfortunately, the report is no more specific than to say that it occurs throughout the region, and thus the exact location of such potentially informative eruptions seems lost. Joseph Andrews, a farmer from Hingham, MA, southeast of Boston confirmed in his journal that the earthquake was indeed felt but made little of it except to note its occurrence. Further down the coast, Josiah Cotton of Plymouth, MA did not even see fit to mention the earthquake in his diary, which points to diminishing power of the earthquake to the southeast of Boston.

A second report in the same issue of the Boston Evening Post indicated, "By Southern and Western Papers," that the earthquake was felt in "all the neighboring Provinces and Colonies" but no major damage was reported from outside the New England Coastal areas. This is corroborated by reports from New York and Philadelphia. In the New York Mercury of 24 November, the earthquake is reported as "a Smart Shock of an earthquake" but explicitly mentioned it "has done no Damage that we can hear of." It also mentioned that it was particularly felt in Oysterbay, Newton, Jamaica and Flushing, all on the northwestern coast of Long Island, though there is no word of any affect on the waters or shipping around that area.

Connecticut, as would be expected, also seems to have experienced the earthquake with some force, as the Boston Gazette of 1 December reported "houses shook and crack'd" and "many Tops of Chimnies were thrown down" but this was designated as "no considerable damage." Likewise, Minister Ebenezer Gay, of Suffield, MA (now in northern Connecticut), briefly mentioned "Earthquake in ye Night" in his journal devoted mostly to weather observation.

On 20 November 1755, the Pennsylvania Gazette of Philadelphia reported the main shock occurring "between three and four a clock…which lasted about two minutes" but no report

of damage was made. Though this appears to have been earlier than the Boston area felt the tremor, it should be remembered that time keeping was a localized endeavor in this period and could vary widely between towns and regions. If the tremor was indeed much weaker in Philadelphia, as it seems to have been, it may not have elicited such excited and careful observation regarding its exact timing as occurred in Boston. The time discrepancy, therefore, is likely the result of these factors, rather than indicative of the properties of the earthquake.

Though reports from the southwest were numerous in the Boston papers, reports from the northeast were less common. In the immediate aftermath of the earthquake, no reports from Canada or northern Maine mention the earthquake. In one particular instance, the Boston Gazette of 8 December, reported the contents of a letter from Halifax, Nova Scotia and added a publisher's note upon its conclusion, "there was no mention made in the above Letter, of the late terrible Earthquake." Clearly the publisher who inserted the note expected there to be news of the earthquake's effect in that region and just as clearly it must not have been very strong. No other reports were found of the earthquake affecting Halifax.

Several years later, in the 31 August 1786 issue of the Cumberland Gazette printed in Portland, Maine, a retrospective report on recent earthquakes was made. This indicated that the earthquake was weakly felt in Halifax, as well as southeast to the eastern shore of the Chesapeake Bay, and west to Lake George in New York. Though no corroborating evidence was found regarding the Halifax report, the report from the Chesapeake Bay appears credible given the Philadelphia and New York accounts. To the west, a journal of Robert Treat Paine, on a military expedition to Crown Point near Lake George reported "abt 4 o'clock this morning a shock of an earthquake was felt" and also recorded an aftershock felt on 22 November. Paine gave no other details or the earthquake but its inclusion in his sparse journal indicates some of its strength, even to northern New York. It should be noted in assessing the reports from Canada and northern Maine, that this was a period of warfare between France and Britain and news from their frontiers and contested areas such as northern New England was dominated by martial rather than natural events. Disappointingly, though several other military journals from the period exist, giving the possibility of accounts of the earthquake from far-flung and under-populated areas such as Paine's, no other report of the earthquake was found among them.

The Cumberland Gazette report was one created by "Professor Williams, F.A.A." It is apparent from the report that Williams was not a witness to the earthquake, but that he relied on the accounts of certain witnesses and his description of the extent of the earthquake and the quantity of damage done echoes the accounts found in the newspapers immediately following the event. Including the activity in Halifax, Williams included a number of other evaluations that do not have corresponding accounts in the other evidence examined. The lack of corroboration lessens the credibility of Williams's assessments because the accounts cannot be fully confirmed, but it by no means destroys the credibility. It is important, then, to at least consider some of Williams's more relevant points, especially how he carefully described the mechanics of the earthquake's motion.

The surface of the earth seemed to be suddenly raised up; and, in subsiding, was thrown into a universal trembling or a very quick, jarring, vibratory motion, which acted in an horizontal direction. This motion continued for about a quarter of a minute, and then abated for three or four seconds. Then, all at once, came on a violent, prodigious shock, as suddenly, to appearance,

as a thunder-clap breaking upon a house, and attended with a great noise. This sudden and great shock began with the same *kind* of motion; and was immediately succeeded by quick and violent concussions, jerks and wrenches, attended 'with an undulatory, waving motion of the whole surface of the ground, not unlike the shaking and quaking of a very large bogg.'

The report continued and asserted the motion of the waves was perceptibly "nearly from north-west to south-east." Williams qualifies this as coming from "the accounts of those who were in the commons and open places, when the earthquake began." Again, the veracity of Williams' report, as secondhand, comes into question as no other accounts of this nature were found to verify this assertion. This evidence remains a compelling clue to the epicenter of the earthquake, but based on the secondhand nature and the questionable nature of such observation during a traumatic event, this report must be relegated to secondary evidence and weighed against the more immediate, if less explicit, evidence that can be found.

The Boston Gazette of 8 December contains the most specific references to the effect on Cape-Cod. Where other papers had merely mentioned the surrounding area's eruptions of pine colored sand and slight structural damage, this issue reported "Eruptions," "Chasms," and "about the [town] Centre a few Rods of the Earth had sunk near six Feet," all occurring in Province Town. The report made no mention of damage to structures, but upheaval on the level indicated can still be instructive when considering the strength of an earthquake.

It is worth noting that the London Magazine or Gentleman's Monthly Intelligencer, a publication noted for its dedication to world affairs and events of note in the sciences or arts, gave no mention to the New England event. Coming in the wake of the much more destructive Lisbon earthquake of 1 November 1755, the magazine gave great attention to the causes, mechanics, and power of the Lisbon quake, but did not even acknowledge the North American disturbance until a passing reference in its January 1756 issue, referring to earthquakes in New York and Philadelphia and their possible relation to the great Lisbon earthquake. Though a major colonial city, Boston was not large by continental standards and was not known as a center of scientific enquiry, which could explain the association of the earthquake with the relatively larger and more cosmopolitan cities.

By the same token, a lack of international notice should not reflect upon the estimated strength of the earthquake. The 1755 earthquake was consistently referred to as the greatest to that point since English settlement. The previous major earthquake had occurred in 1727 and was still a memory for many of the older residents, but still the 1755 earthquake was often deemed stronger. Jeremiah Wheelwright, born 1717, listed earthquakes in 1727, 1744, 1755 including an aftershock of the main earthquake, 1757, 1759, two in 1761, and one in 1769. Of all those listed, only the earthquakes of 1727 and 1755 were listed as "very great EARTHQUAKE." This is not concrete evidence of the strength of the earthquake, but it is a clear indicator of its relative strength and of the frequency of earthquakes in the area at the time. From 1755 on, Wheelwright's diary became noticeably more detailed and it can be inferred from this that there were earthquakes previous to 1755 that had gone unmentioned just as there were several in the immediate aftermath. It, therefore, should be assumed that the appellation "very great" is not given out of surprise but rather of familiarity with the phenomena. It also can lend

more credence to the eyewitness accounts, as those more familiar with a situation are more likely to be able to observe it accurately.

Conclusions

From this varied information and sources it is possible to make some conjectures. It is clear from the evidence that the earthquake affected both land and sea around the coasts of New Hampshire and Massachusetts. However, there does not seem to be support for a tsunami occurring. The scarcity of accounts and the anomalies relating to the existing accounts indicate that such an event is unlikely to have happened. Given the constraints of the study, the archives of Bermuda, likely to be affected by a tsunami from New England, have not been examined, but if a tsunami or other strange tidal action had occurred, it is likely that reports of it would exist in colonial newspapers, hungry as they were for news of the earthquake or anything affecting trade and maritime activities.

On land, the earthquake appears to have been felt far and wide across New England and into the Mid-Atlantic colonies. Along the coast southeast of Boston, however, there seems to be a significant drop in the strength of the earthquake. Southwest of Boston, towards Connecticut and beyond, as well as into the New England interior the earthquake continued to be felt at much greater distances. To the north, into New Hampshire, the earthquake was reported to damage buildings and walls.

Even if some of these reports were exaggerated, the number of reports of damage in contrast to the lack of specific reports from the south shore, exaggerated or otherwise, would seem to confirm that the area north of Boston was more affected than that of the south. This coupled with the violent account from Gloucester as well as Boston indicates that the earthquake may have been centered somewhere at the base of Cape Ann. Such a location could also account for the varying strength of the earthquake. To reach the south shore, the earthquake would travel from land, across Massachusetts Bay and back onto land, losing energy in the process. Halifax, at much greater distance, would require a similar changing of mediums as the earthquake traveled.

By contrast, to reach Boston, Connecticut, and New York from this location, the earthquake would travel entirely through the land. Admittedly, these are preliminary conclusions of a non-specialist in the science of earthquakes, but it fits the historical data. There remains more room for study of the issue, primarily in travel to specific areas such as the south shore, Bermuda, and Halifax to see if on-site archives or specific geographic features are able to shed more light upon the earthquake as experienced, or not, in those locations. The question of epicenter and exact strength may never fully be resolved, but this study had as its end refinement of estimates for the New England earthquake of 1755 and new evidence seems likely to have achieved just that.