RE-EVALUATION OF EARTHQUAKE POTENTIAL AND SOURCE IN THE VICINITY OF NEWBURYPORT, MASSACHUSETTS

Final Technical Report

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Abstract

In the early 1990s, a search for and study of liquefaction features induced by the 1727 Newburyport earthquake also found paleoliquefaction features that formed sometime in the past 4,000 years. Because the ages of the paleoliquefaction features were poorly constrained, the number and timing of the paleoearthquakes responsible for the features were not estimated. In addition, the area over which the earthquake(s) induced liquefaction was not determined, limiting interpretations of earthquake location and magnitude. Picking up where the 1990s study left off, a more recent effort attempted to relocate other liquefaction sites reported during the 1727 earthquake in the hopes of finding additional paleoliquefaction features. During that search, paleoliquefaction features, a sand dike and possible sill, were found in Hampton Falls, NH in close proximity to a 1727 liquefaction site. In addition, an unusual sand layer was found in Hampton marsh that resembles the tsunami deposit in southern Newfoundland resulting from the 1929 **M** 7.2 Grand Banks earthquake and submarine slides. This study involved a broader search for liquefaction features and possible tsunami deposits. No additional liquefaction features were found but sand layers similar to that in Hampton marsh were found in marshes in Essex and Ipswich, MA and in Kennebunk, ME, a distance spanning ~80 km of coastline. Typically, the sand layers are composed of one bed of structureless to normally graded coarse to silty very fine sand, containing angular lithic fragments. They are 6-10 cm thick and thin as they rise in elevation towards marsh margins. The sand layers occur 1.5 to 5 km inland from present-day barrier beaches and near the landward margins of marshes. Radiocarbon dating in Essex and Ipswich marshes as well as Hampton marsh indicates that the sand layers formed about 2 ka (thousands of years ago). Diatom identification and analysis were performed on samples collected from a startigraphic section in Ipswich marsh. The analysis found that diatoms within the sand layer indicate entrainment and landward transport of sediment across several ecological zones and that the assemblage of diatom in the section indicates an abrupt and long-lasting change in the ecosystem coincident with the deposition of the sand layer. Although the age constraint is poor, earthquake-induced liquefaction features in Newburyport, MA, and Hampton Falls, NH, could have formed at the same time as the unusual sand deposit. If so, they both may have formed as the result of a large local earthquake. However, the origin of the unusual sand layers is still in question. An alternative interpretation is that the unusual sand layers represent bayhead or pocket deposits that formed during the early stage of marsh development. Additional study is needed to resolve the origin of the 2 kyr old sand layers, to better constrain the age(s) and spatial distribution of paleoliquefaction features in the same region, and thereby, to improve understanding of the Late Holocene earthquake record along the central New England coast.

Introduction

Northeastern Massachusetts, and southeastern New Hampshire, is a seismically active area (Figure 1). It has experienced many small and several moderate to large earthquakes during the past 400 years. The two largest earthquakes in the area are the 1727, felt-area magnitude, **M**fa, ~5.5 Newburyport and 1755, **M**fa ~6 Cape Ann events (Figure 2; Ebel, 2000 and 2002).

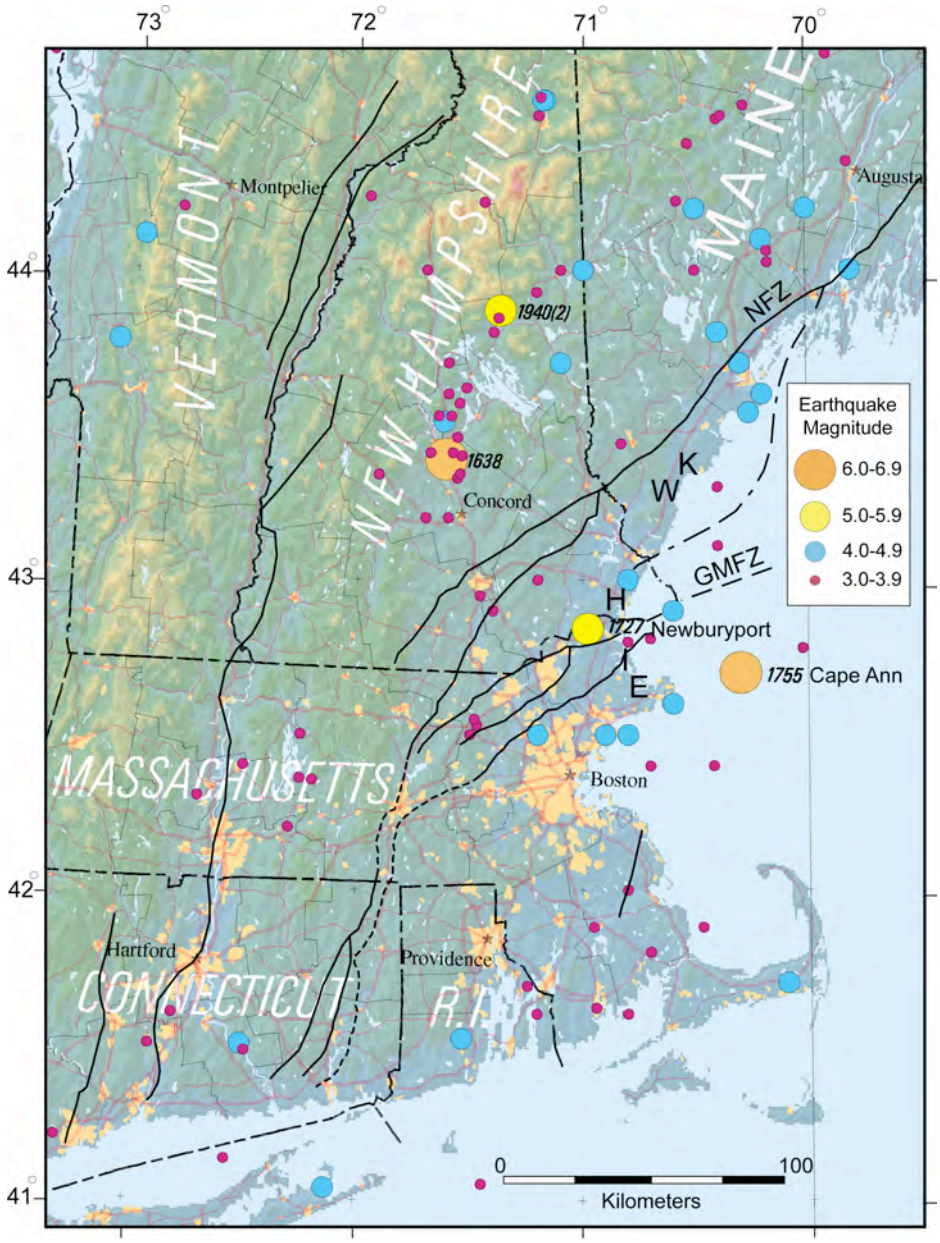

Figure 1. Map of New England showing epicenters of modern and historic earthquakes (from Wheeler et al., 2000) and major faults including Gulf of Maine fault zone (GMFZ) and Norumbega fault zone (NFZ) indicated by heavy black lines (from Ebel and Spotilla, 1999). Locations of marshes mentioned in text as follows: E = Essex, H = Hampton, I = Ipswich, K = Kennebunk, and W = Wells.

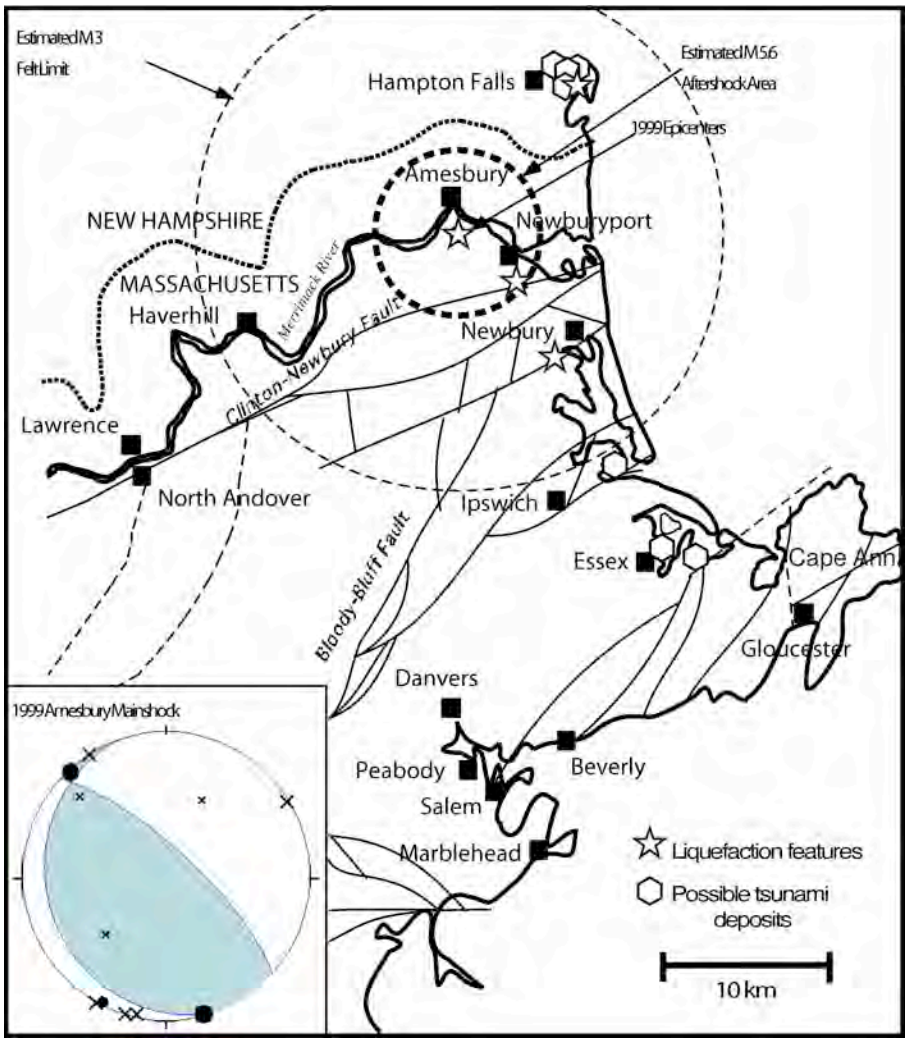

Figure 2. Map of northeastern Massacusetts and southeastern New Hampshire, showing epicenter and felt area of 1999 Amesbury earthquakes (from Ebel, 2000). Faults (thin solid and dashed lines) from state bedrock map of Massachusetts (Zen et al., 1983). Also shown are locations of earthquake-induced liquefaction features and unusual sand layers postulated to be tsunami deposit.

Both of these earthquakes induced liquefaction and caused damage to buildings. Two major fault systems, the Gulf of Maine and Norumbega systems, traverse this region and may be linked to one another (Bothner and Hussey, 1999). However, no unequivocal geologic evidence of Holocene slip has been found along either fault system.

Studies of seismicity worldwide found that the largest earthquakes occur in rifted crust, especially crust rifted during the Mesozoic or later (e.g., Adams and Basham, 1991; Johnston et al., 1994; Johnston, 1995). Three very large historic earthquakes, the 1933 moment magnitude, **M,** 7.3 Baffin Bay, 1929 **M** 7.2 Grand Banks, and 1886 **M** 7.3 Charleston, South Carolina events, occurred along the Atlantic margin, which was rifted in the Mesozoic during opening of

the Atlantic (Johnston, 1995). The New England coast has a similar tectonic history to the rest of the Atlantic margin, and therefore may be subject to very large earthquakes.

Although the region is seismically active, the earthquake potential of northeastern Massachusetts, and southeastern New Hampshire, is poorly understood. Twenty years ago, an effort was made to improve understanding of the earthquake potential by looking for paleoliquefaction features at sites of liquefaction during the 1727 earthquake. During that study, several historical sites of liquefaction in the Newburyport area were relocated and excavated. Two generations of liquefaction features were found in many of the trenches (Tuttle and Seeber, 1991). The younger features were attributed to the 1727 earthquake and the older features were attributed to an earlier earthquake sometime during the past 4,000 years based on radiocarbon dating of sediments. Because the ages of the prehistoric liquefaction features were poorly constrained, the number and timing of paleoearthquakes were not estimated. In addition, the area over which the prehistoric earthquake(s) induced liquefaction was not determined, limiting interpretations of earthquake source and magnitude.

Tsunami Geology

The 2004 **M** 9.3 Sumatran-Andaman and 2011 **M** 9.0 Tohoku earthquakes revealed that countries around the world are poorly prepared for great earthquakes and their resulting tsunamis. Forewarnings of these events, paleotsunami deposits, were hiding in plain sight below the coastal plains of the Indian Ocean and northeast Honshu Japan. Only after the 2004 Sumatran-Andaman event, did scientists look for and find field evidence of earlier events beneath the coastal plains of Sumatra and western Thailand (e.g., Monecke et al., 2006; Jankaew et al., 2008). During the ten years preceding the 2011 Tohoku event, Japanese scientists had studied three paleotsunami deposits below the Sendai and Fukushima coastal plains (e.g., Minouri et al., 2001; Namegaya et al., 2010). They concluded that there had been larger (**M** > 8.3) than normal events produced by the northern Japan subduction zone during the previous three thousand years and that the region was due for another similar event. The results of the paleotsunami studies were being incorporated into seismic hazard assessment when the 2011 earthquake and tsunami struck.

Eleven tsunamis have struck the Atlantic Seaboard since 1600 (Lockridge et al., 2002; Ruffman, pers. comm., 2005). Most notable among these is the trans-Atlantic tsunami associated with the 1755 **M** 8.0 Lisbon, Portugal, earthquake generated by collision of the African and Eurasian plates (Buforn et al., 1988). The tsunami devastated the coasts of Portugal and Morocco, where it killed more than 60,000 people, and extended as far away as the West Indies and Cape Bonavista, Newfoundland (Lockridge et al., 2002). Another significant tsunami was produced by the 1929 **M** 7.2 Grand Banks earthquake and submarine slides about 350 km south of Newfoundland (Doxsee, 1948; Piper et al., 1988; Bent 1995). The 3- to 7-m-high tsunami swept into bays along northeastern Nova Scotia and southern Newfoundland, wrecking wharves and killing 28 people (Ruffman, 2001). The resulting onshore tsunami deposit in southern Newfoundland indicates that the inundation distance and run-up elevation exceeded 480 m and 8.5 m, respectively (Figure 3; Tuttle et al., 2004). The 1886 **M** 7.7 Charleston, South Carolina, earthquake may have produced a small local tsunami in Jacksonville, Florida (Lockridge et al., 2002). And as recorded in the Holocene record, a tsunami struck the shores of Norway and the

United Kingdom about 7.9 ka as the result of the Second Storegga submarine slide in the North Sea (e.g., Dawson et al., 1988; Bondevik et al., 1997; Smith et al., 2005). Tsunami runup from that event is thought to have exceeded 25 m on the Shetland Islands, 11 m along the western coast of Norway, and 5 m along the eastern coast of Scotland.

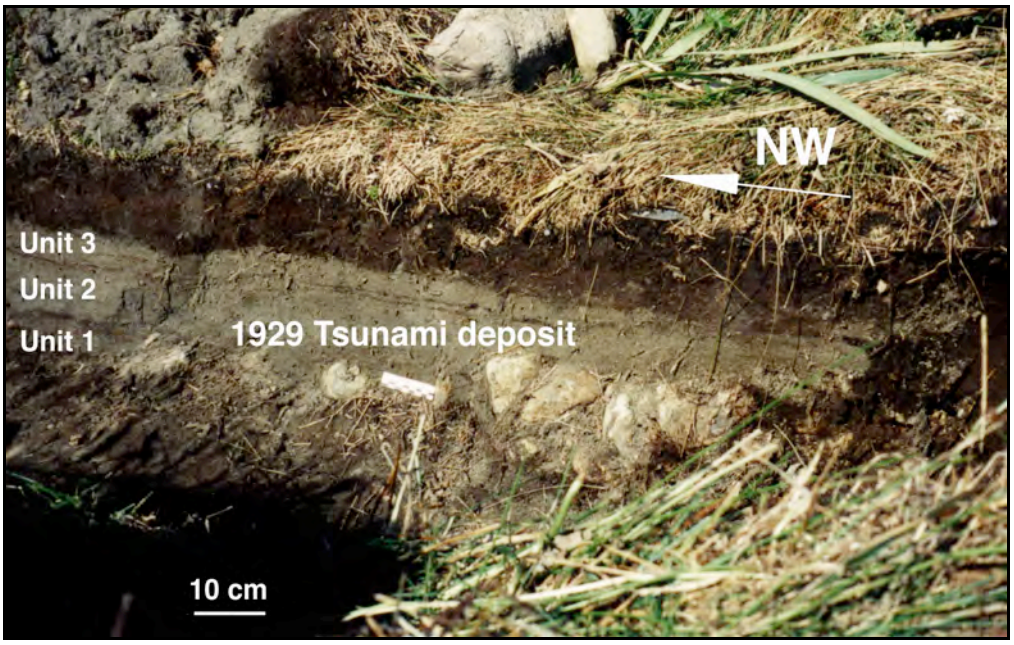

Figure 3. Three layers of sand separated by laminations of organic material deposited by three onshore pulses of the 1929 tsunami adjacent to Taylor's Bay Pond in southern Newfoundland (from Tuttle et al., 2004). In general, the layers fine upward from very coarse sand to fine sand. At this location, pebbles and cobbles occurred at the bottom of the lowest most unit sand layer.

Earthquake-generated tsunamis have occurred in the Atlantic Ocean and undoubtedly will occur again. Regional tsunamis, like the 1929 Grand Banks event, triggered by large earthquakes and submarine slides, probably occur more often than trans-Atlantic tsunamis, like the 1755 Lisbon event and the postulated mega-tsunamis resulting from collapse of the flank of the Cumbre Vieja volcano in the Canary Islands (Ward and Day, 2001). Numerous landslide scars have been mapping along the continental slope and some of them are known to be Holocene in age (J. Adams, pers. comm., 2005; ten Brink, 2009). Since the 1998 **M** 7.1 Papua New Guinea earthquake and tsunami that killed more than 2,000 people, there is widespread recognition that very damaging regional tsunamis can result from submarine slumps triggered by large earthquakes (Tappin, 1999).

As demonstrated in northeastern Honshu, Japan, and also in the Pacific Northwest, USA, paleotsunami deposits can provide critical information about offshore earthquake sources and improve earthquake hazard assessments (e.g., Minouri et al., 2001; Atwater and Hemphill-Haley, 1997; Nelson et al., 1996 and 2006; Namegaya et al., 2010). Therefore, it is prudent to be alert to paleotsunami deposits while conducting paleoseismology studies in coastal areas.

Previous Paleoseismology Studies in the Newburyport, MA Region

About twenty years ago, a search for and study of liquefaction features induced by the 1727 Newburyport earthquakes also found paleoliquefaction features that formed sometime in the past 4,000 years. Because the ages of the paleoliquefaction features were poorly constrained, the number and timing of the paleoearthquakes responsible for the features were not estimated. In addition, the area over which the earthquake(s) induced liquefaction was not determined, limiting interpretations of earthquake location and magnitude. A more recent effort attempted to relocate other liquefaction sites reported during the 1727 earthquake in the hopes of finding additional paleoliquefaction features. During that search, a liquefaction site was found in Hampton Falls, NH, in close proximity to a 1727 liquefaction site (Tuttle, 2002). In addition, an unusual sand layer was found in Hampton marsh that resembles the tsunami deposit in southern Newfoundland resulting from the 1929 **M** 7.2 Grand Banks earthquake and submarine slides. The sand layer was unusual in that it was thicker and coarser than other clastic layers within the marsh stratigraphy.

During a subsequent study, reconnaissance for earthquake-induced liquefaction features and tsunami deposits was conducted along several rivers in southeastern New Hampshire as well as additional dating of the sand dike and further investigation of the possible tsunami deposit previously found in Hampton marsh (Tuttle, 2004). No new liquefaction sites were found despite surveying about 27 km of river length along the Blackwater River, Browns River, Hunts Island Creek, and Mill Creek in Hampton marsh as well as the Exeter River and Squamscott Rivers northwest of Hampton marsh. This may be due in part to inability to access the landward margin of the Hampton marsh due to the security perimeter around Seabrook nuclear power plant, scarcity of liquefiable sediments for portions of Hampton marsh, and relatively poor exposure along the Exeter and Squamscott Rivers. Radiocarbon dating of samples collected in Hampton marsh indicated that the sand dike formed after 2750-2680, 2660-2480 B.P. (before 1950), whereas, the possible tsunami deposit was laid down between 2370-1990 B.P. (Figure 4). It is possible, but not required, that the liquefaction features and unusual sand layers formed about the same time, ~2 ka. Analyses of stratigraphy and diatom assemblages at several sites where the possible tsunami deposit had been found suggested that the unusual sand layers mark an abrupt change from a freshwater, grass-covered environment to a brackish-water, tidal-flat habitat consistent with rapid submergence and tsunami inundation (Tuttle, 2004). A recommendation of the study was that a broader search be conducted for liquefaction features and tsunami deposits along the central New England coast to help to gather additional information that might help to estimate the timing, source areas, and magnitudes of prehistoric earthquake(s) in the region (Figure 1).

As reported below, this study involved additional reconnaissance for earthquake-related features along rivers near Essex and Ipswich, MA, and Kennebunk, ME. Stratigraphic sections were described for representative sites along the rivers, monoliths were collected for diatom analysis at sites of particular interest, and organic samples were collected for radiocarbon dating. Jeremy Efros and Caroline Moseley assisted with field work, Andrzej Witkowski and Genowefa Daniszewska-Kowalczyk of University of Szczecin in Poland performed performed diatom taxonomic identification and analysis of stratigraphic sections, and Beta Analytic Radiocarbon

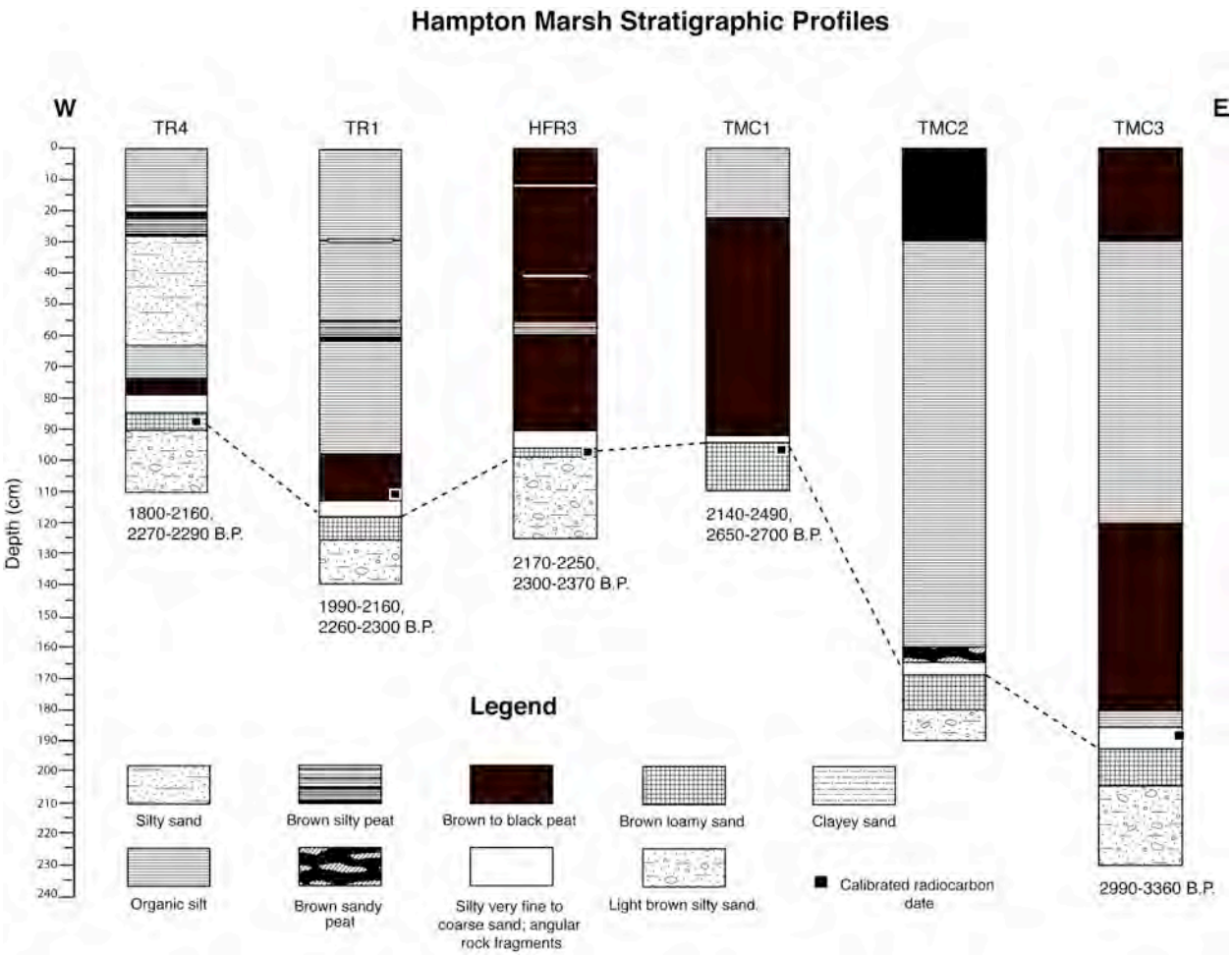

Figure 4. Stratigraphic sections and 2 sigma calibrated dates for sites in Hampton marsh. Dating suggests that unusual sand layers (silty very fine sand to coarse sand containing angular rock fragments) were deposited between 1990 and 2290 years B.P. (before 1950) or about 2,140 ± 150 years B.P.

Laboratory conducting radiocarbon dating. Brian Atwater and John Ebel visited several field sites and discussed observation and interpretations.

Results of Investigation

We searched other marshes along the central New England coast for liquefaction features and sand layers similar to those in Hampton marsh that have been postulated to be a tsunami deposit. We found no additional liquefaction features, but we did find more unusual sandy layers in marshes near Ipswich and Essex, Massachusetts, 20-30 km to the south, and near Kennebunk, Maine, 50 km to the north (Figures 1 and 2). It is worth noting that a similar sandy layer was described in Wells marsh not far from Kennebunk (Hussey, 1970). At sites in the Essex, Ipswich, and Kennebunk marshes, we described stratigraphic sections and collected additional samples for radiocarbon dating and diatom analysis. In these three marshes, like Hampton marsh, the unusual sand layers occur low (> 70 cm) in the marsh sections. Other discontinuous

sandy layers that occur higher in the sections are thinner (<1 cm) and finer-grained (silty, very fine sand to silt) than the possible tsunami deposit and are probably related to severe storms. So far, similar unusual sand layers have not been found in marshes landward of Plum Island, a barrier island near Newburyport, and Newbury, Massachusetts, that is 6 to 9 m high, 0.4 to 1.3 km wide, and extends 12 km from the Merrimack River to Ipswich Bay (Figure 2). It appears that Plum Island may have protected this part of the coast from inundation responsible for the formation of the sand layers.

In the Essex, Ipswich, and Kennebunk marshes, the unusual sand layers are 1-10 cm thick, structureless to fining-upward, coarse sand to silty, very fine sand, containing angular rock fragments up to 16 cm by 8 cm in size (Figure 5). In these three marshes, the sand layers are underlain by peat, rather than paleosols, and occur 1 to 5 km inland from the barrier beach and near the landward margin of the marshes. In Ipswich marsh, there was evidence of erosion of peat prior to deposition of the sand layer. In Essex and Hampton marshes, the sand layer thins and rises in elevation towards the landward edge of the marsh. In Kennebunk marsh, however, the deposit was found only 0.5 km from the barrier beach and may be related to storm washover or inlet switching. Radiocarbon dating of peat immediately below the deposits in Ipswich and

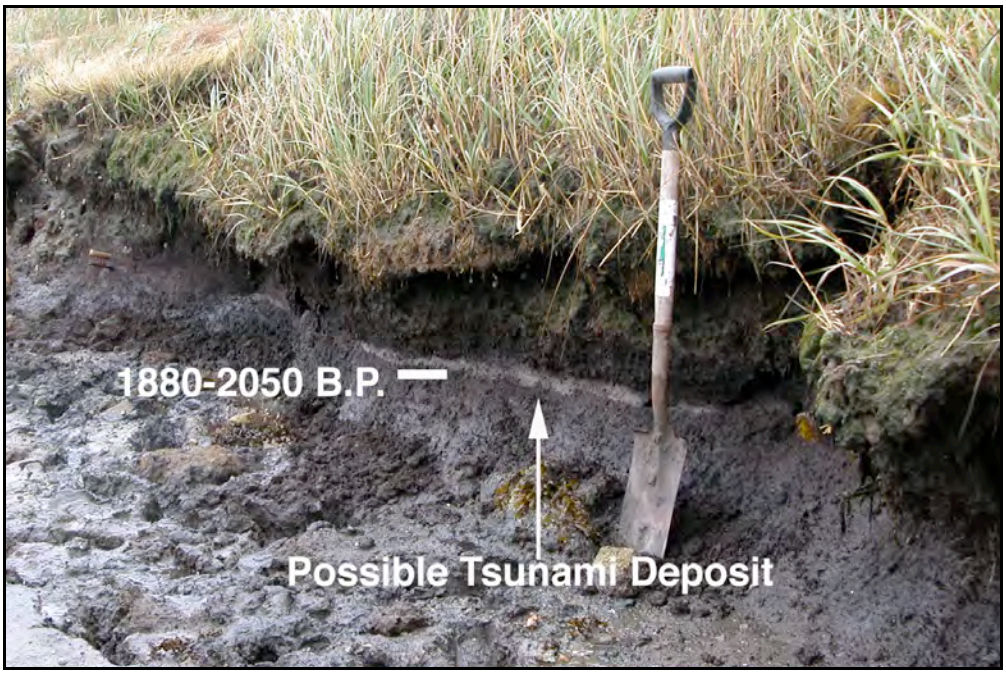

Figure 5. Distinctive 2-cm thick sand layer occurs at 75 cm below the surface within peaty marsh deposits (WC1) exposed in Essex, MA. Radiocarbon dating of peat immediately below the sand layer provides close maximum date and indicates that the sand layer was deposited soon after 2050 B.P.

Essex marshes yielded close maximum calibrated dates of 1870-2030 B.P. and 1880-2050 B.P., respectively (Figure 6). The Ipswich and Essex dates are almost identical to and overlap the dates of the deposit in Hampton. Given that the unusual sand layers in the Essex, Ipswich,

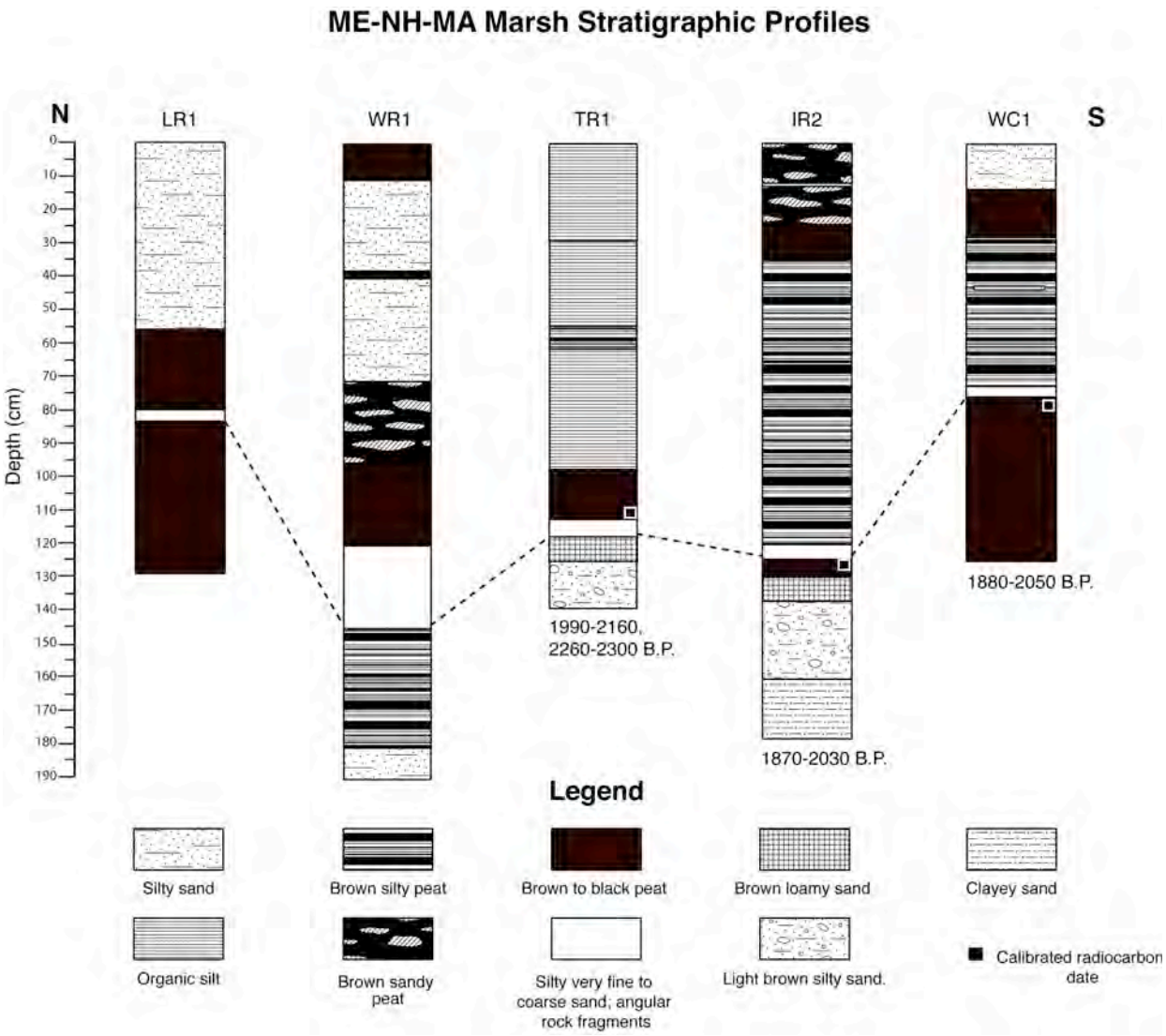

Figure 6. Stratigraphic sections and 2 sigma calibrated dates for sites at marshes in Maine (LR1 and WR1), New Hampshire (TR1), and Massachusetts (IR2 and WC1). Radiocarbon dating suggests that unusual sand layers (silty very fine sand to coarse sand containing angular rock fragments) were deposited between 1990 and 2030 years B.P. or about 2,010 ± 20 years B.P.

Kennebunk, and Hampton marshes are similar in sedimentary characteristics, stratigraphic position, and age, they probably formed as a result of the same event.

To further test the hypothesis that the unusual sand layer is a tsunami deposit, diatom taxonomic identification and analysis were performed on samples collected from vertical sections of site IR2 in Ipswich marsh (Patrick and Reimer, 1966; Witkowski et al., 2000). The samples were 1 cm-thick and 10 cm-square and cut at 10 cm intervals from a vertical profile. Sediment samples of 1.0-1.5 g were treated with 10% HCl to remove calcium carbonate, washed several times with distilled water, boiled in concentrated H_2O_2 to oxidize all organic matter, and washed several more times with distilled water. From the sample residue, a defined aliquot was taken from the homogenized suspension, placed on cover glasses and left to dry. Permanent diatom

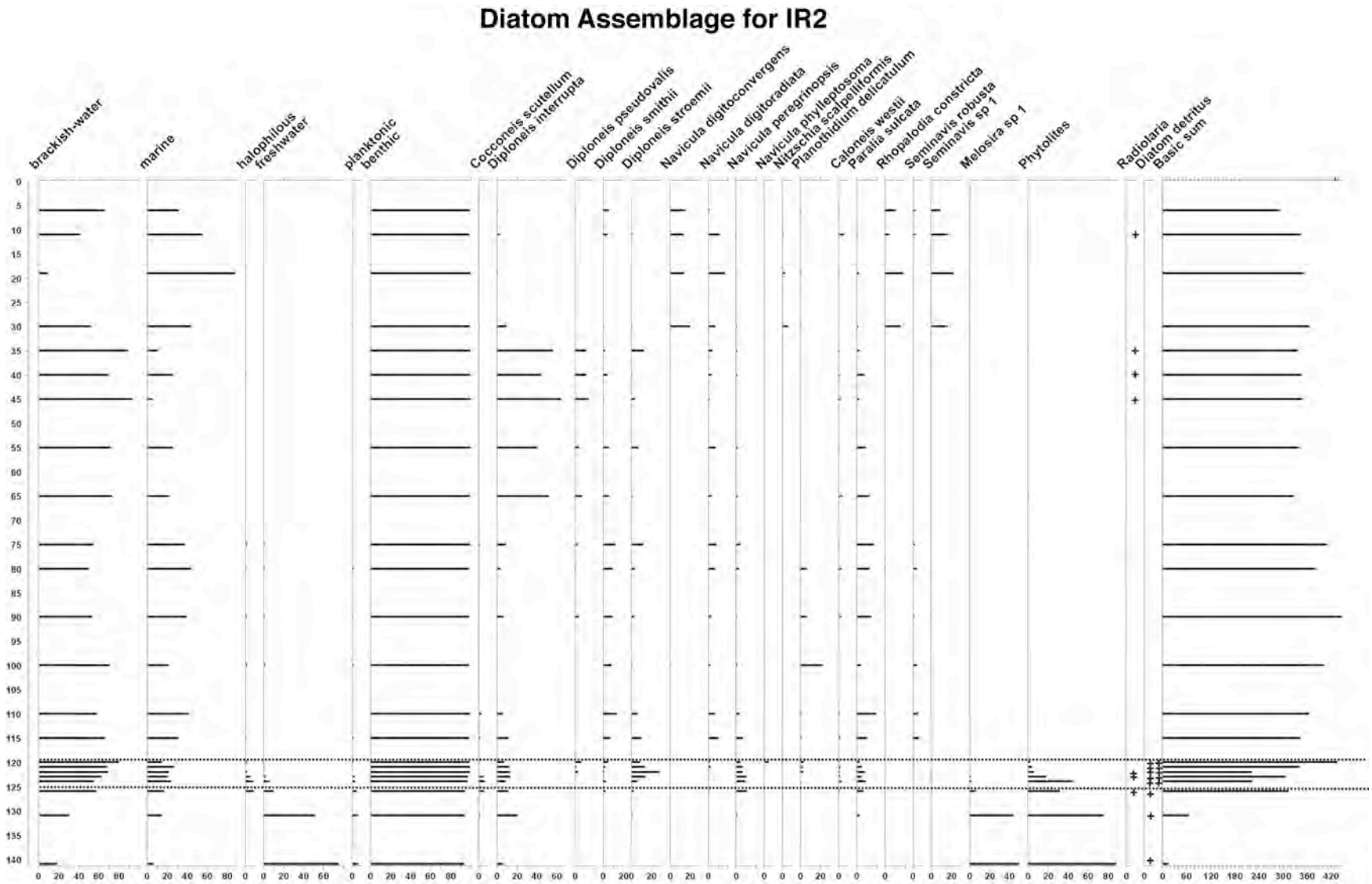

Figure 7. Diagram showing results of diatom analysis of samples collected at Ipswich Marsh site IR2. Depth (cm) below surface shown on vertical axis; diatom type shown on upper horizontal axis and valve count shown on lower horizontal axis. Position of sand layer in question bounded by dashed lines.

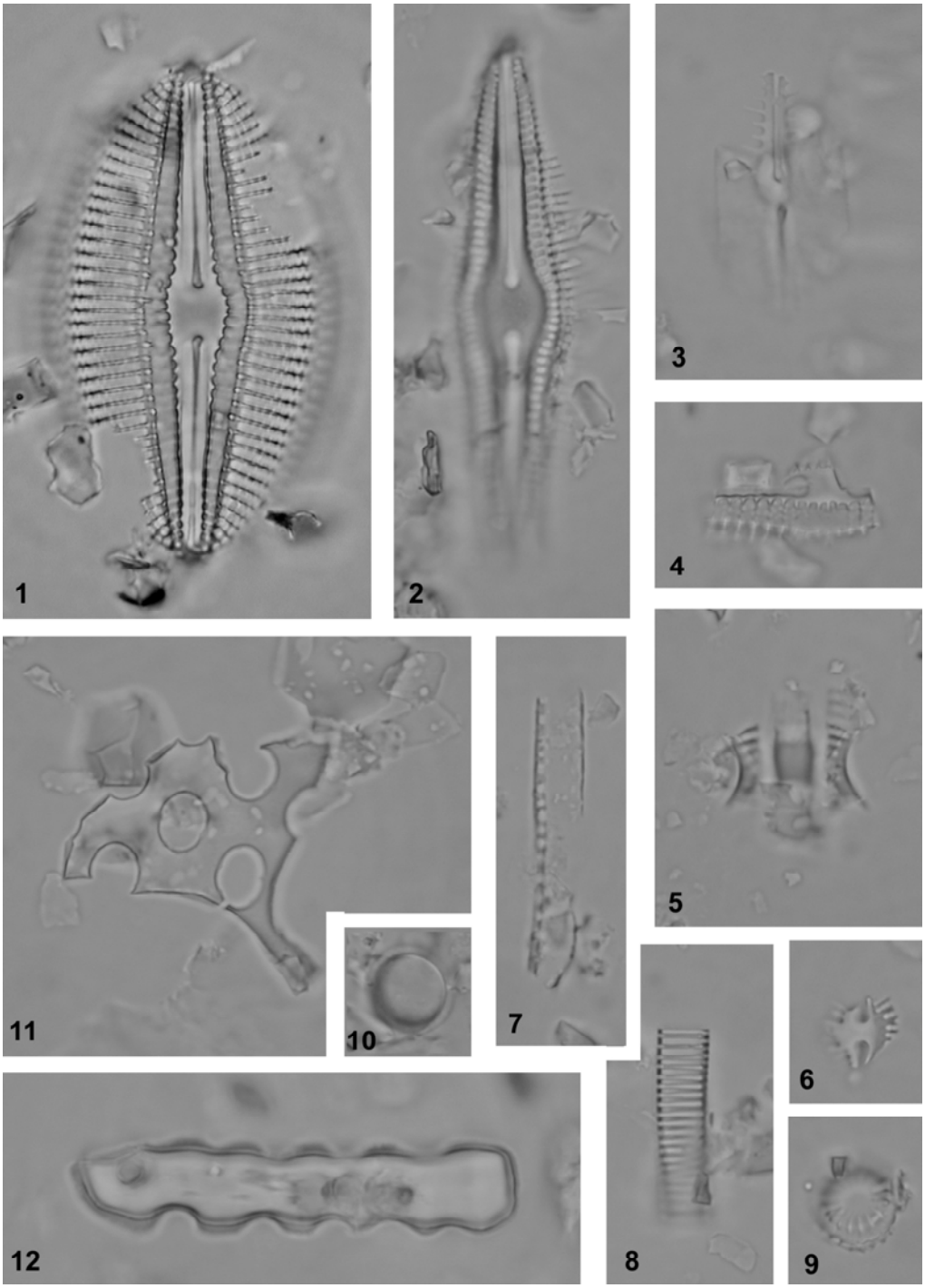

Figure 8. Microscopic plates showing fragmented diatom and phytoliths from sand layer at 86-87 cm depth at site HR3; Plates 1-3, 5-7 - brackish-water forms; Plates 4, 9, 11 - marine forms; Plates 8 and 10 - freshwater forms; Plate 10 - soil diatom. Plate 1. Diploneis smithii; Plate 2. Diploneis spec. 1; Plate 3. Pinnularia lundii var. baltica; Plate 4. Diploneis spec.; Plate 5. Diploneis interrrupta; Plate 6. Cosmioneis pusilla; Plate 7. Nitzschia clausii; Plate 8. Eunotia spec.; Plate 9. Paralia sulcata; Plate 10. Melosira spec. 1. (Martitia Tuttleae); Plate 11. Isthmia spec.; Plate 12. Phytolith.

preparations were mounted in Naphrax. Diatom identification was performed using a Leica DM LB microscope with x100 Planapo optics (bright field) and oil immersion.

The possible tsunami deposit at IR2 in Ipswich marsh contains a mixture of a high number of taxa of marine, brackish-water, and fresh-water diatoms, radiolaria, and phytoliths with many diatom valves broken (Figures 7 and 8). Several of the diatoms, including *Paralia sulcata, Diploneis smithii, and Cocconeis scutellum*, also occurred in the 1929 Grand Banks tsunami deposit in Newfoundland and the Storegga tsunami deposits in Caithness, Scotland (Dawson et al., 1996). The diatom assemblages at IR2 is similar to that of TR1 and HR3 in Hampton marsh reported previously (Tuttle, 2004) and reflects an abrupt change in the ecosystem from freshwater grass-covered environment to brackish water, tidal flat habitat coincident with deposition of the sand layers about 2,000 years ago (Figures 4 and 6). The abrupt change in the depositional environment is consistent with rapid submergence, possibly due to tsunami inundation, and appears to have occurred along at least 30-km of coastline.

Origin of the Unusual Sandy Layer

Identifying tsunami deposits in the geologic record of coastal regions is a challenging endeavor. Coastal processes can result in sandy layers that may resemble tsunami deposits. Overwash deposits resulting from severe storms and hurricanes are of chief concern. Several studies have attempted to address the issue of distinguishing tsunami deposits from storm and hurricane deposits. One study reviewed literature regarding storm and tsunami deposits in temperate as well as tropical localities and compared characteristics of tsunami deposits in southern Newfoundland resulting from the 1929 **M** 7.2 Grand Banks earthquake with storm deposits in southeastern Massachusetts, resulting from the 1991 Halloween storm, also known as the "Perfect Storm" (Tuttle et al., 2004). The study concluded that sedimentary characteristics (e.g., bedding, grading, presence of broken valves and tests of marine microfossils) and geomorphic position (e.g., inland and coastwise extent, elevation above barrier beaches) can be used to distinguish these types of deposits. The following criteria were proposed for distinguishing paleotsunami from paleostorm deposits in the geologic record (Tuttle et al., 2004):

1. Tsunami deposits exhibit sedimentary characteristics consistent with landward transport and deposition of sediment by only a few, energetic surges over a period of minutes to hours; whereas characteristics of storm washover deposits are consistent with landward transport and deposition of sediment by many more, less energetic surges during a period of hours to days.
2. Both tsunami and washover deposits contain mixtures of diatoms indicative of an offshore or bayward source; but tsunami deposits are more likely to contain broken valves and benthic marine diatoms.
3. Biostratigraphic assemblages of sections in which tsunami deposits occur are likely to indicate abrupt and long-lasting changes to the ecosystem coincident with tsunami inundation.
4. Tsunami deposits occur in landscape positions, including landward of tidal ponds, that are not expected for storm deposits.

Other studies in New Zealand (Goff et al., 2004) and Portugal (Kortekaas, 2002) also found clear differences between storm and tsunami sediments. A more recent study, reached similar conclusions, recommended study at multiple sites, and suggested that the most reliable means to

differentiate tsunami and storm deposits may be the context within which the deposit is found, such as association with liquefaction features and co-seismically buried soils (Morton et al., 2007).

The unusual sand layers found in several marshes of the central New England coast seems to meet criteria proposed for recognizing tsunami deposits. The sand layers are composed of one bed of structureless to normally graded coarse to silty very fine sand and thins and rises in elevation towards the landward edge of the marsh consistent with landward transport and deposition of sediment by a few energetic waves. The sand layers contain a mixture of diatoms, including benthic and planktonic marine forms, with many valves broken, indicating entrainment and landward transport of sediment across several ecological zones. Also, the diatom assemblages indicate an abrupt and long-lasting change in the ecosystem coincident with the deposition of the sand layers. For, the three sites in Massachusetts and New Hampshire, the sand layers occur landward of fairly large bays which would serve as sediment traps for storm washover deposits. If paleoliquefaction features in the region formed during the same time ~2 ka, this might also support a co-seismic and tsunami origin for the sand layer.

There are characteristics of the unusual sand layer, however, that leave some doubt about its origin. For example, nowhere does the sand layer appear to extend as a continuous sheet for more than 0.6 km. Tsunami deposits are often thought to exhibit extensive lateral continuity, especially in regions subjected to co-seismic subsidence (Atwater et al., 1995). In other regions, lateral continuity of tsunami deposits may be very patchy (Morton et al., 2007). For example, along the western coast of Thailand, distribution of onshore deposits resulting from the 2004 **M** 9.3 Sumatran-Andaman earthquake and tsunami was highly dependent on nearshore bathymetry and onshore vegetation type (Tuttle et al., 2007; Jankaew et al., 2008). On aerial photographs of one western Thailand estuary, the tsunami knock-down pattern of mangroves (and probably the tsunami deposit as documented at other locations) resembled feathers. In the same region of Thailand, paleotsunami deposits from predecessor events may have been difficult to find due to patchy distribution and disturbance of coastal plain sediments by tin mining. Therefore, it may be possible that the patchy distribution of the sand layer in the central New England marshes may be due to an initial irregular pattern of deposition, destruction of marsh stratigraphy by meandering channels, erosion landward of the bay mouth, and inlet switching, and to historical ditching of the marshes.

Most of the observed occurrences of the unusual sand layers are near the landward edge of marshes or near rock outcrops or “islands” within the marshes. Although this distribution is consistent with tsunami deposits, it is also suggestive of bayhead or pocket beaches that are often limited in extent and form around the edges of large embayments or between headlands in coves of rocky shorelines (e.g., Bascom, 1980). These type of beaches form when rock and/or sediment is eroded from the headlands by wave action, transported by waves and currents, and deposited within coves or bays. Given their position low in the marsh stratigraphy, perhaps the sand layers represent bayhead or pocket beaches that formed during the early stages of marsh development along the New England coast. Further comparison with bayhead and pocket beach deposits is needed to fully evaluate the possibility that unusual sand layers formed during these relatively ordinary coastal processes.

Conclusions

During this study, a broader search for earthquake induced liquefaction features and possible tsunami deposits was conducted along the central New England coast. In particular, surveys of river exposures were conducted in marshes in Essex and Ipswich, MA, and in Kennebunk, ME, a distance spanning ~80 km of coastline. No liquefaction features were found, but unusual sand layers, similar to those in the marsh in Hampton Falls, NH, postulated to be a tsunami deposit, were found in all three marshes. The sand layers are unusual in that they are the thickest and coarsest clastic layer in the startigraphic sections studied in the four marshes. Radiocarbon dating indicates that the sand layers formed about 2 ka in Essex and Ipswich marshes, similar to those previously studied in Hampton marsh. Given that they are unique (thickest and coarsest clastic layer) and similar in age in all of the stratigraphic sections, the sand layers seems to record a significant event (rapid change in sea-level, severe storm, or tsunami) that affected perhaps ~80 km of coastline about 2 ka.

Typically, the unusual sand layers are composed of one bed of structureless to normally graded coarse to silty very fine sand, containing angular lithic fragments. They are 6-10 cm thick and thin as they rise in elevation towards marsh margins. They occur 1.5 to 5 km inland from present-day barrier beaches and near the landward margins of marshes. Diatom analysis found that the sand layers contain a mixture of diatoms, including benthic and planktonic marine forms, with many valves broken, indicating entrainment and landward transport of sediment across several ecological zones. In addition, the diatom assemblages in the stratigraphic sections indicate an abrupt and long-lasting change in the ecosystem coincident with the deposition of the sand layers. Uncertainty in the age estimates of paleoliquefaction features in Newburyport, MA, and Hampton Falls, NH, allow for the possibility that they formed at the same time as the unusual sand deposit. If so, they both may have formed as the result of a large local earthquake.

Many of the characteristics of the unusual sand layers are consistent with a tsunami inundation. However, the origin of the unusual sand layers remains in question. An alternative interpretation that may explain the limited local lateral continuity of the sand layers is that they are bayhead or pocket deposits that formed about 2 ka at multiple locations along the New England coast. Additional study is needed to compare the sand layers in question with bayhead or pocket deposits and resolve its origin, to better constrain the age(s) and spatial distribution of paleoliquefaction features in the region, and thereby to improve understanding of the Late Holocene earthquake record along the central New England coast.

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