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

Final Technical Report

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Abstract

A review of the geological literature and field review of outcrops found several northwest-trending fractures with slickensides and fault gouge in the Newburyport area. These structures occur along strike of a northwest-oriented fault mapped near Ipswich rather than a proposed northwest-trending seismogenic fault in Newburyport. In addition, we found no additional liquefaction features in the Newburyport area during reconnaissance of the Little River or a subsurface investigation near a previously studied liquefaction site. During reconnaissance near Hampton Falls, New Hampshire, however, we found earthquake-induced liquefaction features and a distinctive sand layer that may be a tsunami deposit. The liquefaction features include a 3-cm-wide sand dike. Radiocarbon dating of organic samples collected adjacent to the sand dike indicates that it formed less than 2,750 years ago. The distinctive sand layer occurs at several locations from 1.5 to 4 km inland from the present-day shoreline. The deposit is 2 to 4 cm thick, composed of massive silty, fine to very fine sand with few angular rock fragments, and occurs below marsh deposits and immediately above a paleosol with large *in situ* tree roots. Radiocarbon dating of one of these tree roots suggests that the overlying sand layer was deposited less than 3,000 years ago. The sedimentary characteristics and geomorphic position of the sand layer is similar to a tsunami deposit in southern Newfoundland resulting from the 1929 Grand Banks earthquake and submarine slides. If the Hampton sand layer is a tsunami deposit and if it formed at the same time as the liquefaction features, a earthquake source capable of large earthquakes may exist off the coast of southern New Hampshire. If so, this finding would have implications for seismic hazard assessment for northern New England. Additional study is needed to delineate the area affected by earthquake-induced liquefaction, to further evaluate the origin of the distinctive sand layer, and to constrain the ages of earthquake-related features.

Introduction

Studies of seismicity worldwide found that the largest earthquakes occur in rifted crust, especially if 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 **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 during Mesozoic 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, placing Boston, Concord, Hartford, and Providence, the capitals of Massachusetts, New Hampshire, Connecticut, and Rhode Island, respectively, at risk (Figure 1).

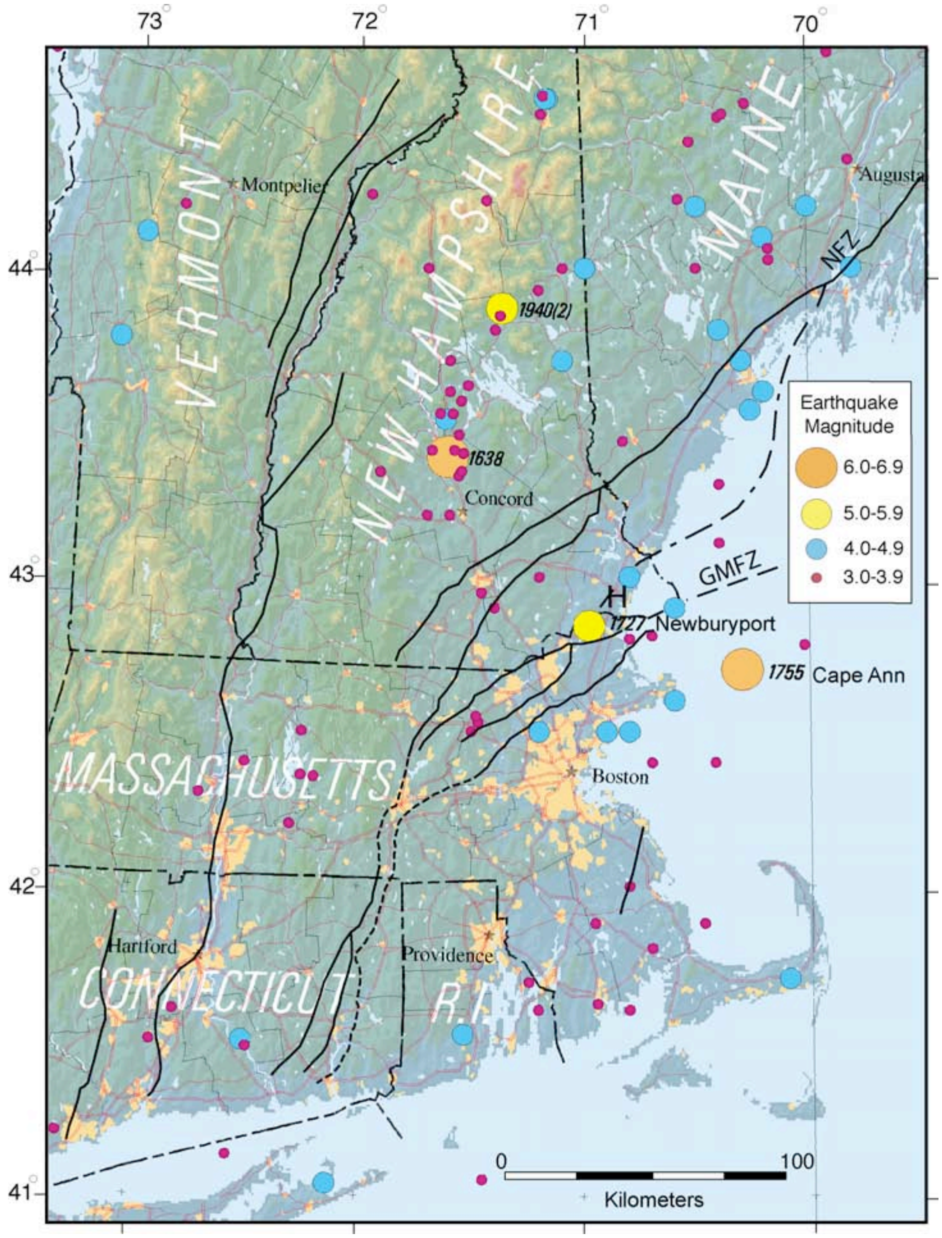


Figure 1. Map of New England showing epicenters of modern and historic earthquakes, including 1727 Newburyport and 1755 Cape Ann events, (from Wheeler et al., 2001) and major faults indicated by heavy black lines (from Bothner and Hussey, 1999; Ebel and Spotilla, 1999); GMFZ – Gulf of Maine fault zone; NFZ – Norumbega fault zone; H - Hampton, NH.

Northeastern Massachusetts (MA) and southeastern New Hampshire (NH) have experienced many small and several moderate to large earthquakes during the past 400 years (Figure 1). The two most notable earthquakes, the 1727, felt-area magnitude, **M**fa ~5.5, Newburyport and 1755, **M**fa ~6, Cape Ann events, induced liquefaction and damaged buildings (Tuttle and Seeber, 1991;

Ebel, 2000 and 2001). There is no doubt that a repeat of these events would cause more damage today in this heavily developed and densely populated region. Important questions remain to be addressed in this seismically vulnerable part of the country, such as: What are the earthquake sources in the region, what is the earthquake potential of those sources, and what hazards do they pose to metropolitan areas such as Boston, Massachusetts?

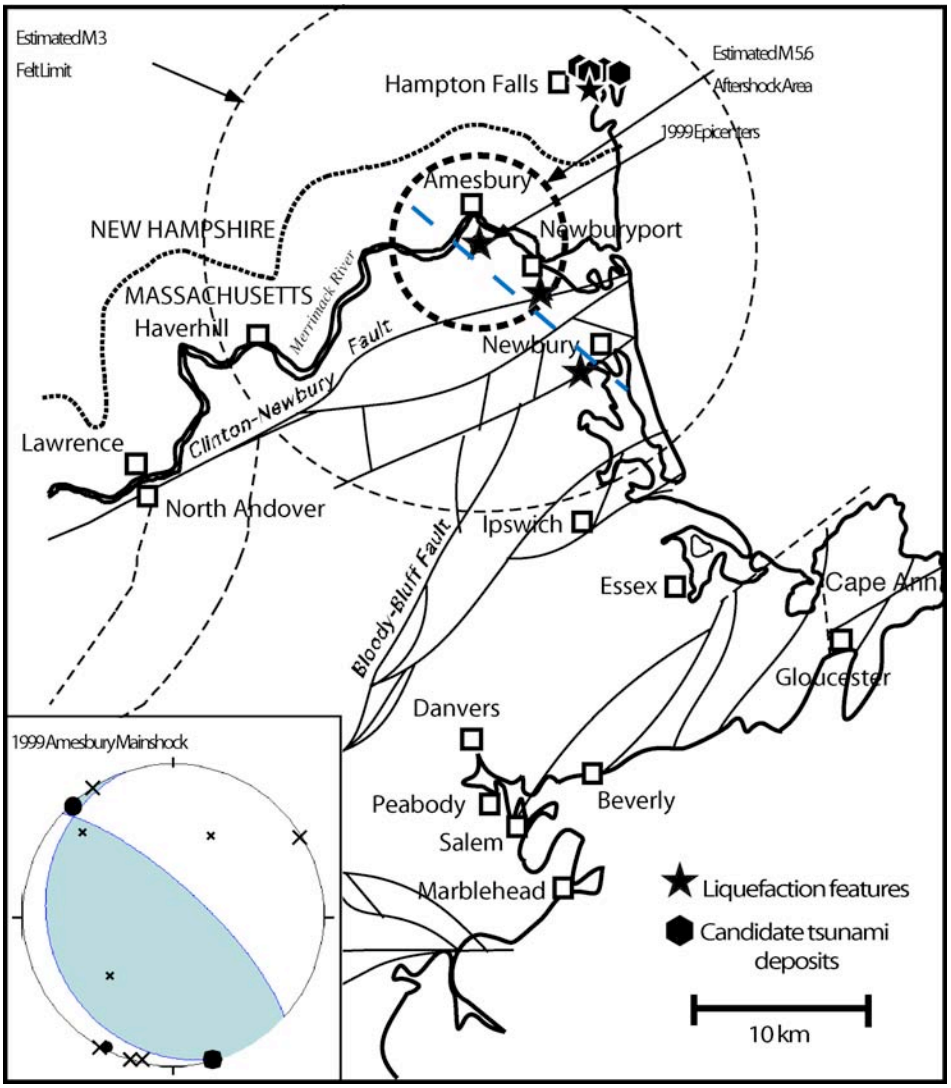


Figure 2. Map of the northeastern Massachusetts and southeastern New Hampshire (modified from Ebel, 2000) showing epicenter and aftershocks of 1999 Amesbury earthquake as well as its proposed source, a northwest-trending fault (blue dashed line), other mapped faults (light solid and dashed lines) from state bedrock map of Massachusetts (Zen et al., 1983), and locations of liquefaction features and candidate tsunami deposits (Tuttle and Seeber, 1991; and this report).

A paleoseismic study conducted about 15 years ago began to address questions about the earthquake potential of the seismically active area of northeastern Massachusetts and southeastern New Hampshire. The study found historic and prehistoric liquefaction features in the Newburyport area, the inferred epicenter of the 1727 earthquake (Tuttle and Seeber, 1991;

Figure 2). The historic features are attributed to the 1727 earthquake, while the prehistoric features formed prior to 1727 but since 4,000 yr B.P. The comparable sizes of the liquefaction features suggest that ground shaking was of similar intensity during the prehistoric event(s) as during the 1727 earthquake. The ages of the prehistoric liquefaction features are poorly constrained, however, so the number and timing of earthquake(s) that caused them are not known. In addition, the area over which the prehistoric earthquake(s) induced liquefaction was not determined, limiting interpretations of earthquake source area and magnitude.

A recent seismological study of the Newburyport area suggests that an unmapped northwest-trending fault may be the source of local earthquakes, including the 1727 Newburyport and the 1999 Amesbury events (Ebel, 2000; Figure 2). Accounts of the 1727 aftershocks indicate that the earthquake source is located in the Merrimack River valley just northwest of Newburyport (Ebel, 2000). The location and felt area of the 1999 Amesbury earthquakes are reminiscent of the 1727 aftershock sequence. The 1999 mainshock is located near a bend in the Merrimack River about 2 km south of Amesbury and 5 km northwest of Newburyport and had a thrust focal mechanism with northwest-oriented nodal planes (Figure 2). The three Amesbury aftershocks are assumed to have originated from the same hypocenter. Ebel (2000) observes that the Merrimack River turns southeast near the epicenter of the 1999 Amesbury earthquakes, following a course subparallel to the 1999 nodal planes. He hypothesizes that the lower Merrimack River may be controlled by a northwest-oriented seismogenic fault. In addition, Ebel (2000) suggests that the Amesbury earthquakes are aftershocks of the 1727 mainshock. If so, the 1727 mainshock also may have been a thrust event on a northwest-oriented fault. This fault orientation is perpendicular to the northeast trend of major faults in the region.

The goals of this study are to test the hypothesis that there is northwest-oriented seismogenic fault in the vicinity of the lower Merrimack River and to uncover more paleoseismological data that would help constrain the timing, source, and magnitude of prehistoric earthquake(s) that induced liquefaction in Newburyport. Towards this end, we (1) reviewed bedrock geology data and conducted reconnaissance for evidence of recent faulting in Newburyport and nearby areas, (2) conducted geophysical surveys and trenching near a site of historic liquefaction in Newburyport, and (3) searched for liquefaction and other earthquake-related features along several coastal rivers in northeastern MA and southeastern NH. Participants in this research include the Principal Investigtor, Martitia Tuttle, collaborator John Ebel of Boston College, and Boston College graduate students, Ed Myskowski, Jennifer Krauser and David Wertz. Under the supervision Ebel and Tuttle, Myskowski wrote much of the section on the review of mapped faults and Krauser and Wertz prepared the section on the geophysical surveys of the Hale Street site.

Investigations

Review of Mapped Faults

Newburyport, Massachusetts (MA), is located near two major fault systems, the Gulf of Maine and the Norumbega (Figure 1; Bothner and Hussey, 1999). There are several faults that may link the Gulf of Maine and Norumbega systems. The Clinton-Newbury and Bloody-Bluff faults, members of the Gulf of Maine fault system, actually traverse the Newburyport area (Shride, 1976a; Figures 1 and 2). Although there is a spatial relationship between the 1727 Newburyport earthquakes and the Gulf of Maine fault system, a genetic relationship has not been established between them. Furthermore, no unequivocal geologic evidence of Holocene slip has been found for any of the faults in the Gulf of Maine and Norumbega systems.

The initial objective of this task was to review the literature for descriptions of features that may be related to northwest-trending faulting to help test the hypothesis of Ebel (2000) that there is a northwest-oriented seismogenic fault in the Newburyport area (see Figure 2). The specific evidence sought includes internal fractures, slickensides and gouge, as well as offsets of glacial pavements or Quaternary deposits. We quickly recognized that the area of mapped northwest trending fault segments was more extensive than originally understood, extending from near the coast in Ipswich, MA, through Newburyport, and northwesterly to Mount Pawtuckaway, NH. On the basis of this finding, we decided to conduct reconnaissance from Pawtuckaway to Ipswich for fault-related features and to identify areas or features of promise for more detailed investigation.

Review of Geologic Data

Four quadrangles in the Newburyport study area were mapped in the 1970s. One of the quadrangles was ultimately published (Dennen, 1990), while the other three are available in open-file format (Shride, 1976a; Bell and others, 1976). These resources are useful for locating outcrops and identifying the accepted formation names and descriptions. The major rock groups of the four geologic quadrangles are the intrusive Newburyport units, and questionably associated diorites and fine-grained granite, separated from the Newbury Formation to the south by north- and northeast-trending faults. In western Newburyport, and in southeastern New Hampshire, the metasedimentary formations of the Merrimack Group are separated from the Newburyport units to the south by northeast-trending faults. In the quadrangle reports, the northeast-trending structures that separate mappable rock units receive the most attention. However, Dennen (1990) and Shride (1976a) have mapped northwest-trending fault segments of potential importance. Barosh (1984a, b) mentions in passing the possibility of northwest-trending faults, but without specific localities. Hydrologic reports for the region (Gay and Delaney, 1980; Sammel, 1967) are useful for identifying Quaternary deposits and outcrop localities.

Shride (1976b) described the northern segment of the Newbury Formation wedge as bounded by northeast-trending faults, with strata striking northeast, and dislocated by lesser cross faults that strike northwest. His map shows two such cross faults as dashed lines. There is no direct evidence for these two faults. They are inferred from the stratigraphic dips of. bedrock outcrops. These faults are shown truncated at the northerly contact of the Newbury Formation. Again, there is no direct evidence for truncation of the faults. It is just that there is no stratigraphic reason to extend the faults further. By the time they were transferred to the Massachusetts State geologic map (Zen and others, 1983), only one of the inferred faults was shown, and that as a solid (observed) rather than dashed (inferred) line. The net result appears to be that a fault block inferred to explain stratigraphy has been translated and summarized as an observed fault, implying that there are also data to support its very limited extent. This however does not appear to be the case.

Morency (1986) used geophysical methods to advance Shride's observations of the Newbury Formation, but primarily to define the nature of the north- and northeast-trending boundary faults. He did not specifically detect Shride's northwest-trending faults. However, Morency (1986) does cite other sources for northwest-trending faults at Seabrook, NH, (within the Merrimack Group) which he attributes possibly to Cretaceous White Mountain magma series activity; he also provides the most complete summary of the rock units and tectonic history of the region.

Hussey and Bothner (1995) and Bothner and Hussey (1999) have studied and published extensively on the Merrimack Group, but primarily with the intent of understanding the northeast-trending faults with regional tectonic significance. They do not mention structures with northwest trends. Ferguson and others (1997) interpret remote sensing data to infer a multitude of bedrock features with various trends, including many with northwest trends. Freedman (1950) documents northwest-trending offsets of the intrusive rocks of the Mount Pawtuckaway quadrangle. The offsets are spectacularly visible in the aerial photograph used as the front piece to his report. Northwest-trending features are nearly continuous through the map area of Ferguson and others (1997).

Reconnaissance

We conducted reconnaissance along roadways between Newburyport and Mount Pawtuckaway, New Hampshire, traversing as much as possible the northwest-trending features of Ferguson and others (1997). Similarly, we conducted reconnaissance throughout the Newburyport area and southeast of Newburyport to Ipswich, crossing northwest-trending features of Schride (1976a), Bell et al. (1977), and Dennen (1991). We made observations and took measurements and photographs of northwest-trending features on selected outcrops of the intrusive rocks of Mt. Pawtuckaway and of the volcanic rocks of the Newbury Formation in the Newburyport area, and of one outcrop in Ipswich.

The low-lying topography between Amesbury and Mt. Pawtuckaway is consistent with the hypothesis that inferred northwest-trending bedrock fractures (Ferguson and others, 1997) represent a fault system. Unfortunately, we encountered no exposures of Quaternary deposits or bedrock outcrops during our reconnaissance of this low and swampy area. This is not surprising, since the underlying bedrock is mainly the relatively erodable metasedimentary units of the Merrimack Group, perhaps further weakened (if the hypothesis is correct) by Quaternary faulting. Testing of the fault hypothesis of Ferguson et al. (1997) is a daunting task in this low-lying area. In the future, geophysical investigations may help to further this cause.

In the vicinity Mount Pawtuckaway, we inspected numerous outcrops. Most of them had measurable northwest-trending features consistent with the regional-scale offsets mapped by Freedman (1950). However, it did not seem productive to put a great deal of effort into making detailed structural measurements on Mount Pawtuckaway until a more definite connection were established between Newburyport and Pawtuckaway.

Reconnaissance in the area of the Artichoke Reservoirs in western Newburyport confirmed low-lying topography consistent with a northwest-trending fault in the area as proposed by Ebel (2000). We searched the area with the hope of finding recent construction exposures of the contact between Merrimack Group (metasedimentary) and Newburyport (crystalline) rocks, which Shride (1976a) mapped as approximately north trending, but found no new outcrops. In fact, areas of the Newburyport quadrangle mapped as abundant outcrops are in reality quite sparse. The contact between the Merrimack Group and Newburyport rock was not observed but outcrops of both groups were examined. One outcrop of the Merrimack Group had measurable northwest-trending structure.

We inspected several roadside outcrops in the Newbury Formation, three with northwest-trending structure. The outcrop with the most impressive structure appeared to have been partly exposed by recent road construction. A northwest-striking, northeast dipping (50°) fracture, with slickensides and fault gouge, was traced 7 m down section. Two other outcrops in the vicinity have similar measurable but less extensive northwest-trending structure. The structures of the three outcrops are approximately on strike with the mapped fault of Dennen (1991), described below, rather than the proposed fault of Ebel (2000). However, most of the Newbury Formation in the vicinity of the proposed fault is poorly exposed and difficult to access in the salt marsh.

In Ipswich, we inspected an outcrop mapped as cataclastic granodiorite and in close association with a northwest-oriented fault (Dennen, 1991) but not along strike with the proposed fault of Ebel (2000). The outcrop exposure is small, about 10 sq m, and without specific northwest structure. The cataclastic description is suitable, as brittle fractures with no dominant orientation are pervasive in the rock. There is topographic expression nearby consistent with the mapped fault. The extent of the fault is greater on the published map (Dennen, 1991), extending to the northern quadrangle boundary, than it was on the open-file version of the map. The fault is not indicated on the adjacent Georgetown quadrangle open-file map (Bell and others, 1977). Bill Dennen was reached by telephone to try to recover the original data for the mapped fault, but he has unfortunately lost (by flood) his original copies of the open-file material.

Hale Street Subsurface Investigation

During a previous paleoseismology study in the Newburyport area, historic and prehistoric liquefaction features were found northwest of the Hale Street in Newburyport (Tuttle and Seeber, 1991). Unfortunately, the soil profile at the site had been disturbed by construction practices, limiting age constraints of the liquefaction features. During the current study, we sought and gained permission to work in a flat grassy field on a nearby property southeast of Hale Street (Figure 3). We hoped to find additional liquefaction features and to better constrain their ages. The owners agreed to allow us to excavate the site if we conducted geophysical surveys to identify targets and to limit site disturbance. We first conducted electromagnetic (EM) and ground-penetrating radar (GPR) surveys to identify areas of disturbed stratigraphy; and then on the basis of the results, selected a site for trenching.

Geophysical Surveys

We used electromagnetics (EM) and ground-penetrating radar (GPR) to map the soil electrical conductivity and the subsurface stratigraphy of the Hale Street site. In the EM method, a transmitter coil produces a low frequency (1-20 KHz) time-varying electromagnetic field, which induces a secondary electromagnetic field in the earth measured by a receiver coil. The larger the ratio of the secondary to primary electromagnetic fields, the greater the electrical conductivity of the soils. In the GPR method, a transmitter fires a high frequency (50-1500 MHz) electromagnetic pulse into the ground, which reflects off of stratigraphic layers and structures with dielectric constants significantly different than the surrounding soils. A receiver antenna records the travel times of reflected energy from the transmitter antenna. By moving the transmitter and receiver at a constant offset along a transect, a cross-sectional image can be constructed. Highly detailed stratigraphic maps of the top 3 m of the ground can be produced from high-frequency GPR data, while the EM method gives an effective electrical conductivity value for the top 1-5 m of the ground over the study area.

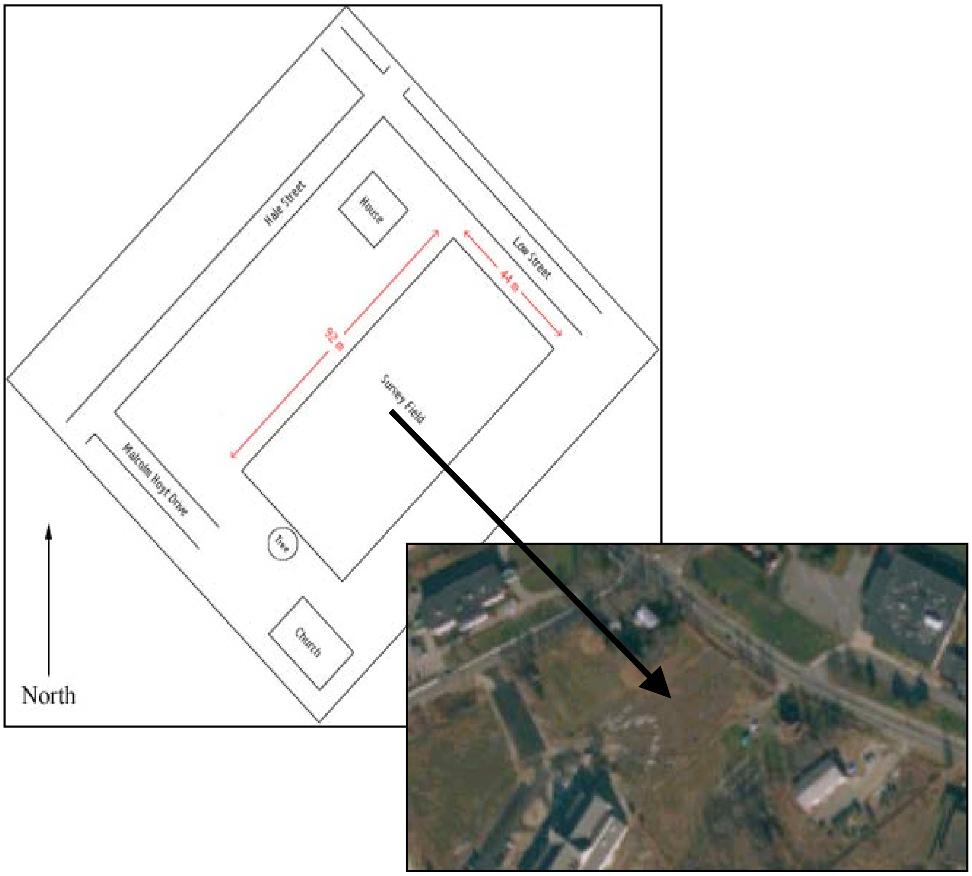


Figure 3. Map and aerial photograph of the Hale Street study site.

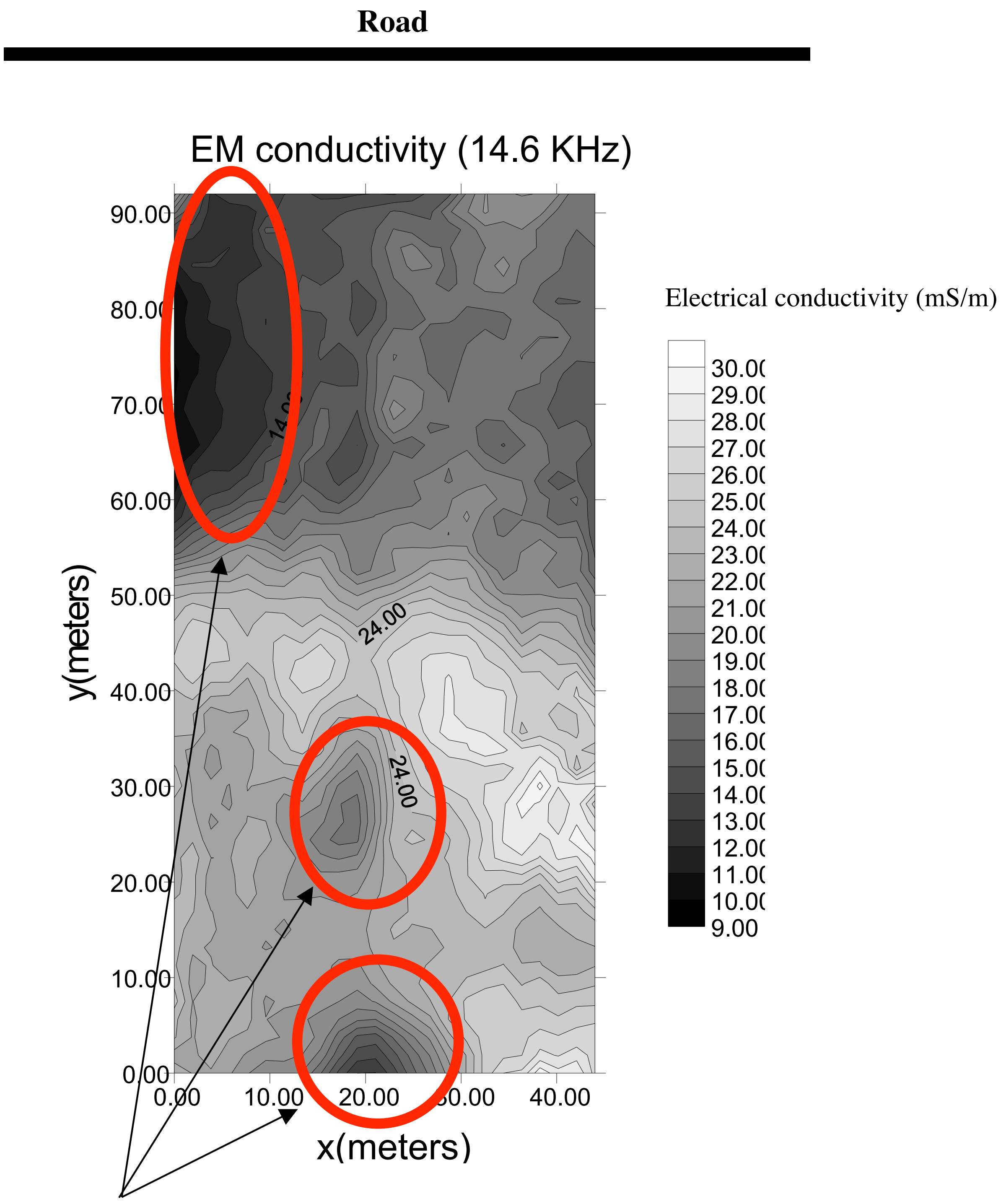
In temperate environments like Newbururyport, the EM conductivity response is often controlled by the sand and clay content of the soil, where a high EM conductivity response is indicative of high clay content and a low EM conductivity response is indicative of high sand content.

Because the sand dikes would be intruded into marine clays, there should be a significant decrease in the EM conductivity response over areas containing liquefaction features. By locating areas of low electrical conductivity and then performing GPR surveys to map local stratigraphy in detail, we attempted to identify areas of earthquake-induced liquefaction features at the Hale Street site.

The EM instrument that we used is called GEM and is manufactured by GSSI. The EM survey covered a 92 m x 44 m area. The data collection procedure consisted of walking the field with the GEM at hip-level and taking an EM measurement every 2 m along 92 m lines spaced 2 m apart (2 m x 2 m measurement spacing). The electrical conductivity values were then downloaded from the GEM polycorder to a computer via an RS 232 cable. After analysis of the EM conductivity data, we picked areas of locally low conductivity for further investigation using a Pulse Ekko IV GPR unit, manufactured by Sensors and Software. A series of parallel GPR transects were recorded over low conductivity areas. During the survey the transmitter and receiver were maintained at 0.5 m separation distance and moved 0.1 m after recording each measurement. A 1.0 second delay was set between each measurement, providing time to re-position the GPR unit. The GPR data was recorded directly on a laptop computer during the data acquisition process.

A map of electrical conductivity of the field site is shown in Figure 4. This map was produced using a linear variogram in Surfer. The areas of low electrical conductivity are named areas A, B and C and marked on Figure 5. The GPR profiles across areas A, B and C are displayed in Figures 6-10. Figure 6 shows the GPR results for a 92 m transect along the length of the field; except for a concave channel structure visible at coordinate (0, 70), no major disturbances were detected. In area A, shown in Figures 7 and 8, we find one diffraction pattern located at coordinate (2, 62) and a second diffraction pattern that starts at coordinate (2, 79) and continues to coordinate (4, 79). The first diffraction pattern may be caused by a sand dike but is of limited extent. The second structure, because it appears in two adjacent profiles and therefore may extend at least 2 m, may be a larger sand dike. In areas B and C, shown in Figures 9 and 10, we do not see any convincing interruptions or diffraction patterns in the stratigraphy. In area C between coordinates (20, 1) and (24, 1), there appears to be a second signal superimposed on the primary signal. We think that this signal is artificial and is due to its close proximity to a building on the site.

In conclusion, we have identified locations of possible liquefaction features to be investigated by trenching. The features that we have identified are at coordinate (2,62), possibly a small sand dike, and at coordinates (2,79) to (4,79), possibly a larger sand dike of greater lateral extent. This integrated, non-invasive geophysical approach is especially useful where minimal use of destructive methods (i.e. trenching) is desirable. Only through trenching, however, can the interpretations of geophysical anomalies be verified.



Low conductivity areas (possibly indicative of sand intrusions)

Figure 4. EM conductivity map of Hale Street site produced from GEM data. Low conductivity areas, circled in red, were further investigated using GPR.

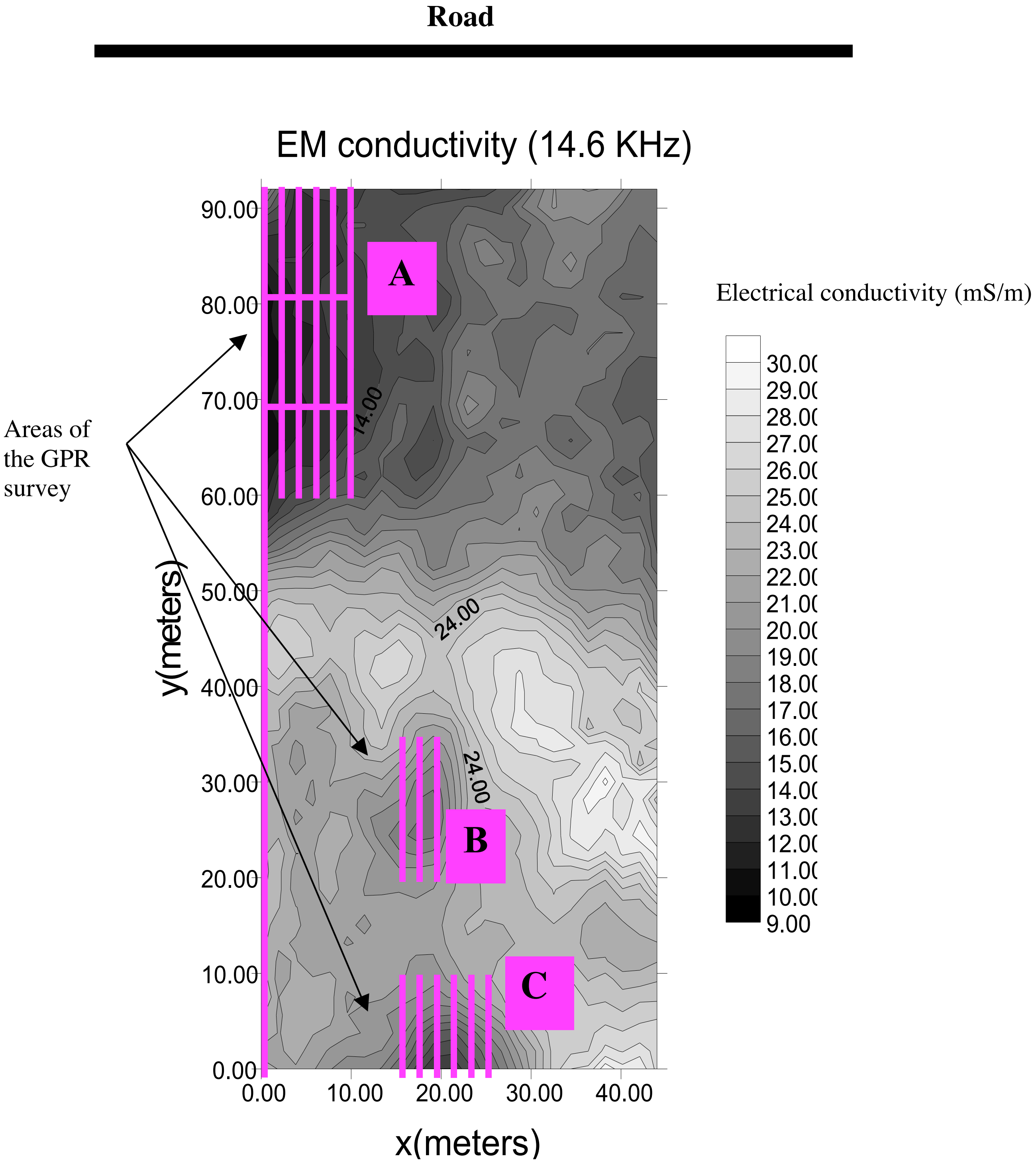


Figure 5. Pink line segments show where GPR surveys were performed. The GPR survey of area A revealed possible liquefaction features. The GPR surveys over areas B & C showed no sign of soil disturbance.

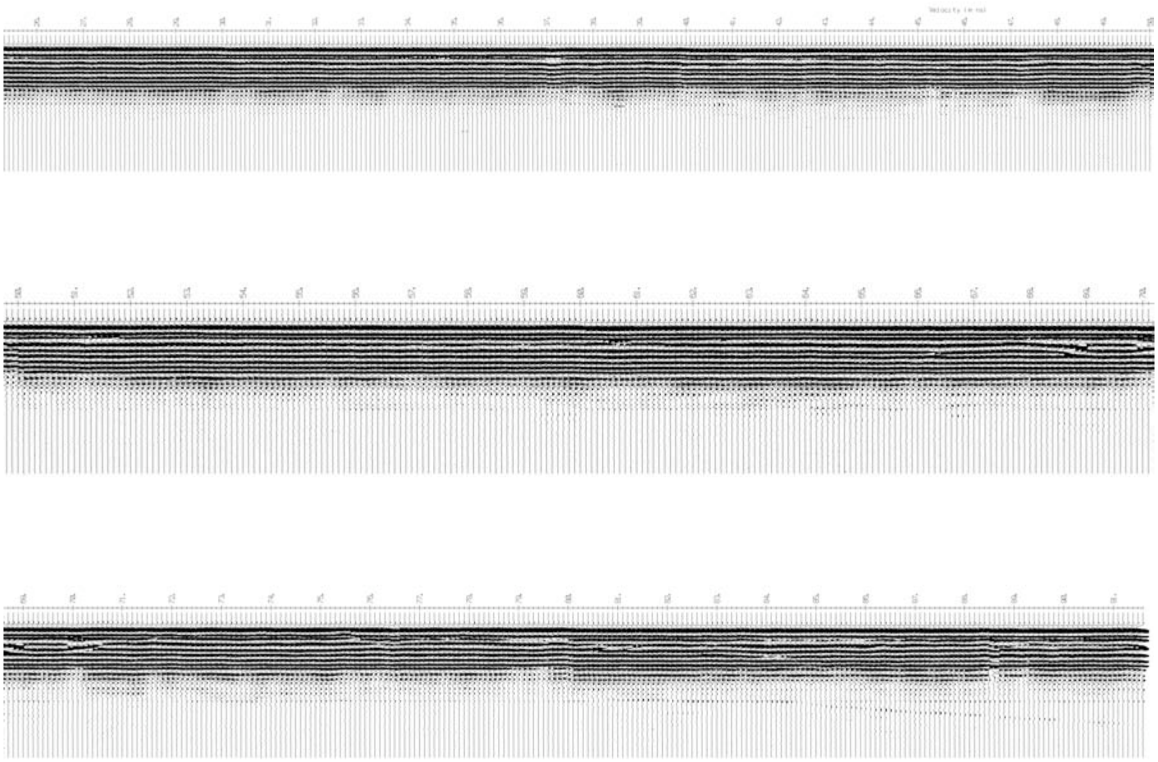


Figure 6. Cross-field profile using GPR from (0,0) to (0,92). GPR did not reflect any major disturbance of stratigraphy.

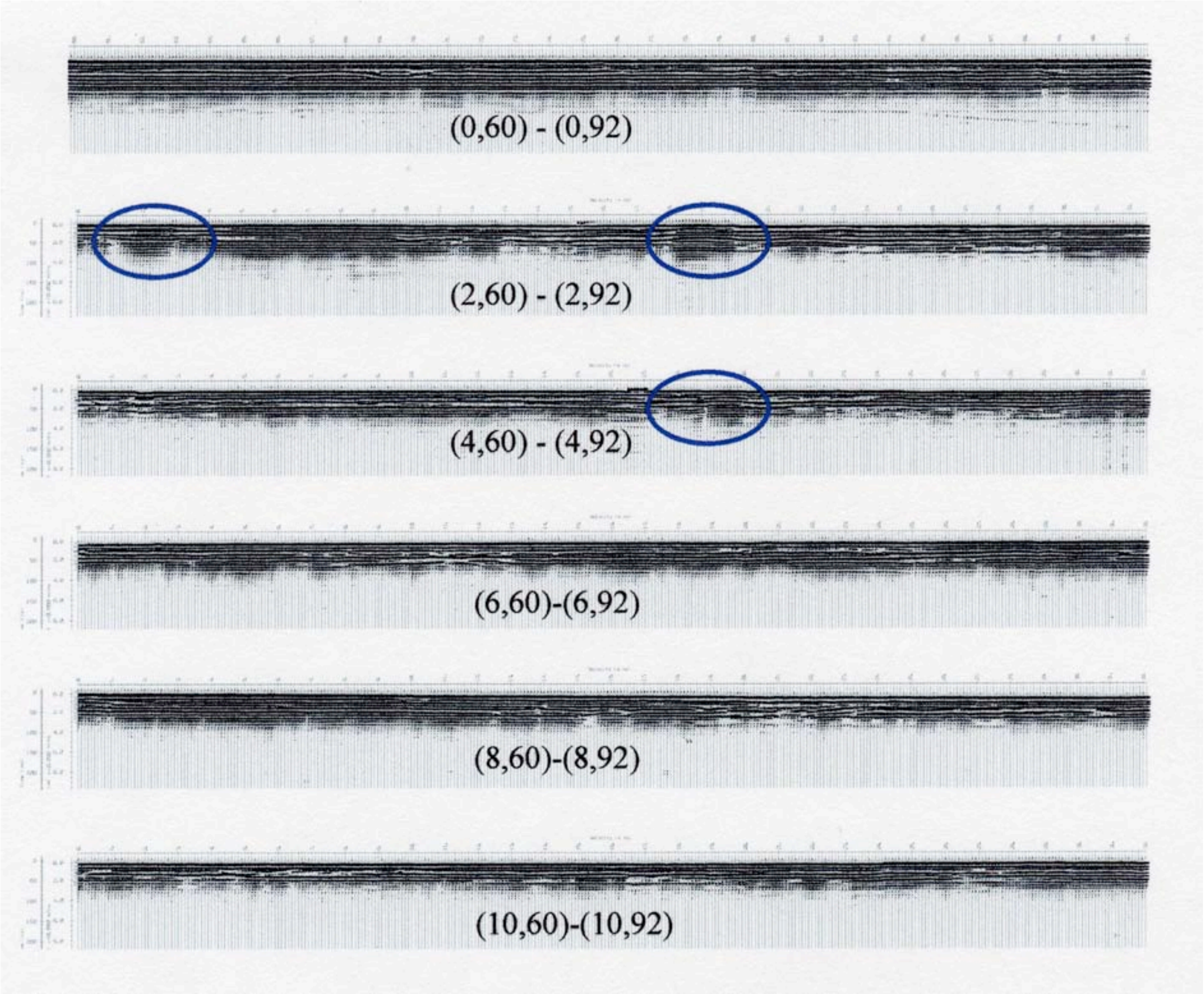


Figure 7. GPR profiles of area A. Possible liquefaction features are circled in blue.

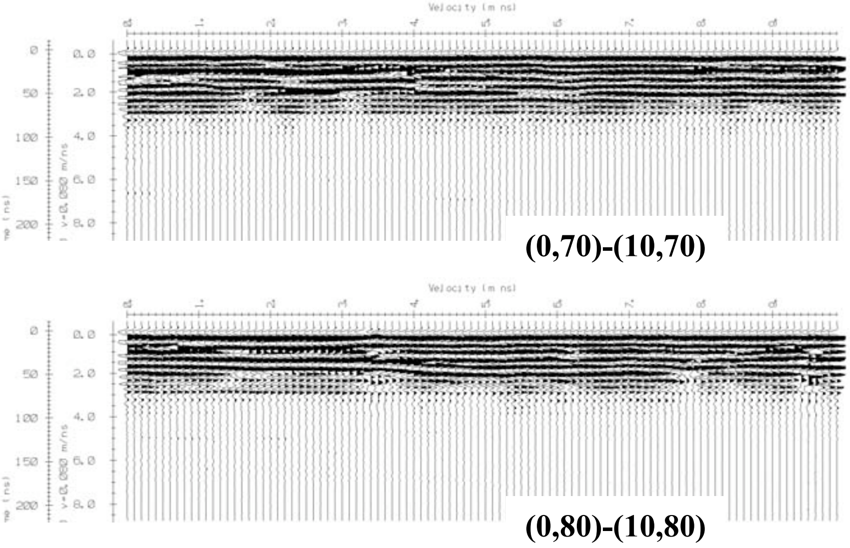


Figure 8. GPR of lines of area A

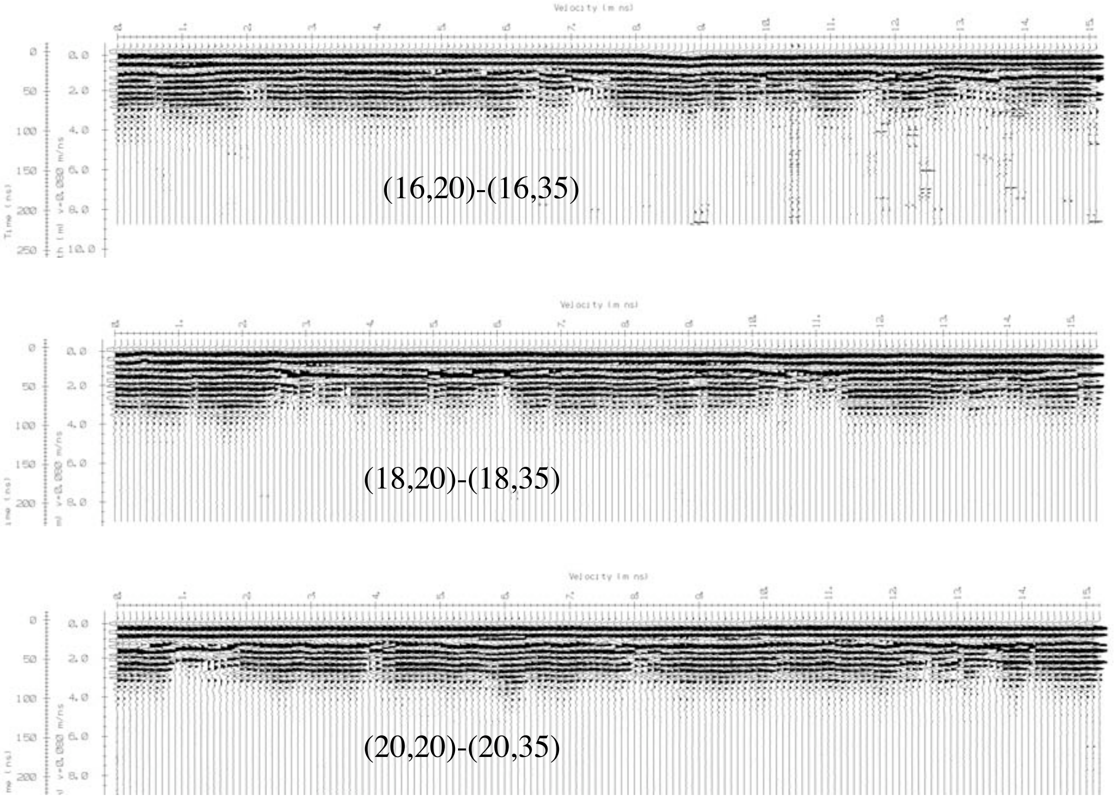


Figure 9. GPR profiles of area B. The profiles reveal no evidence of soil disturbance.

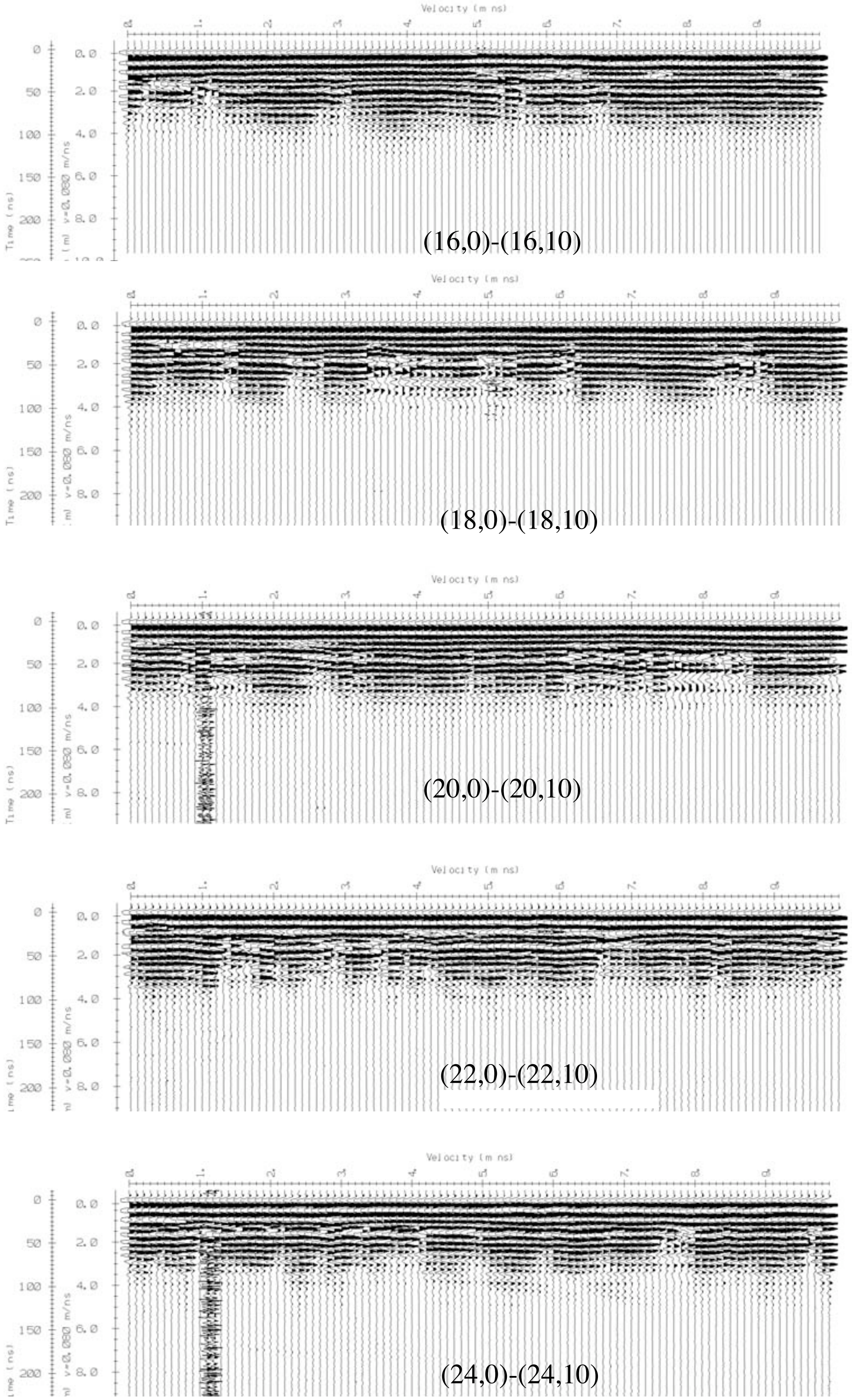


Figure 10. GPR profiles of area C. The profiles reveal no evidence of soil disturbance.

Trenching

The most promising target identified by the geophysical surveys was at coordinates (2,79) to (4,79) of the geophysical grid. On the GPR profiles, disturbance of the sediments appeared to extend to within 1 m of the ground surface. Therefore, we excavated a 4- m-long trench to a depth of 1.8 m along a bearing of N15°W to cross the geophysical anomaly. In the trench, we found 0.5 m of fill over a buried silty loam soil developed in mottled clayey silt (Figure 11). The basal contact of the clayey silt was clear and sharp and underlain by interbedded and laminated sand and silt typical of rhymites. The sedimentary section was interpreted as a glacial marine deposit overlying a glacial lacustrine deposit.

Figure 11. Photograph of trench at Hale Street site, showing an undisturbed section of silty clay overlying interbedded and laminated sand and silt. Except in upper 50 cm of fill, red flags mark a vertical section at 25 cm intervals down to 175 cm below the surface.

We did not find earthquake-induced liquefaction features within the sediments. Given that the sand layers were fairly thin and separated by laminations of silt, conditions were not ideal for the formation of earthquake-induced liquefaction features at this location. However, sediments were wetter at the location of the geophysical anomaly, leading us to wonder if there might be a structure with a higher hydraulic conductivity, such as a sand dike, at depth. Unfortunately, a high water table at the base of the trench and the sandy nature of the sediments led to caving of the base of the trench walls and prevented us from excavating deeper. Any future investigations at this or nearby sites should plan for shoring and pumping of trenches so that deeper sections can be examined.

River Reconnaissance

In our search for additional liquefaction features, we surveyed about 5 km of the Little River south of Newburyport from Boston Street to the confluence of the Parker River (Figure 12). Although exposure was very good, we found no liquefaction features or other earthquake-related deformation structures within the Holocene marsh deposits. A previous search along the Parker River also had found no liquefaction features (Tuttle et al., 2000). We think that the lack of liquefaction features along the Little and Parker Rivers may be due in part to limited distribution of sandy, glaciomarine deposits in this area.

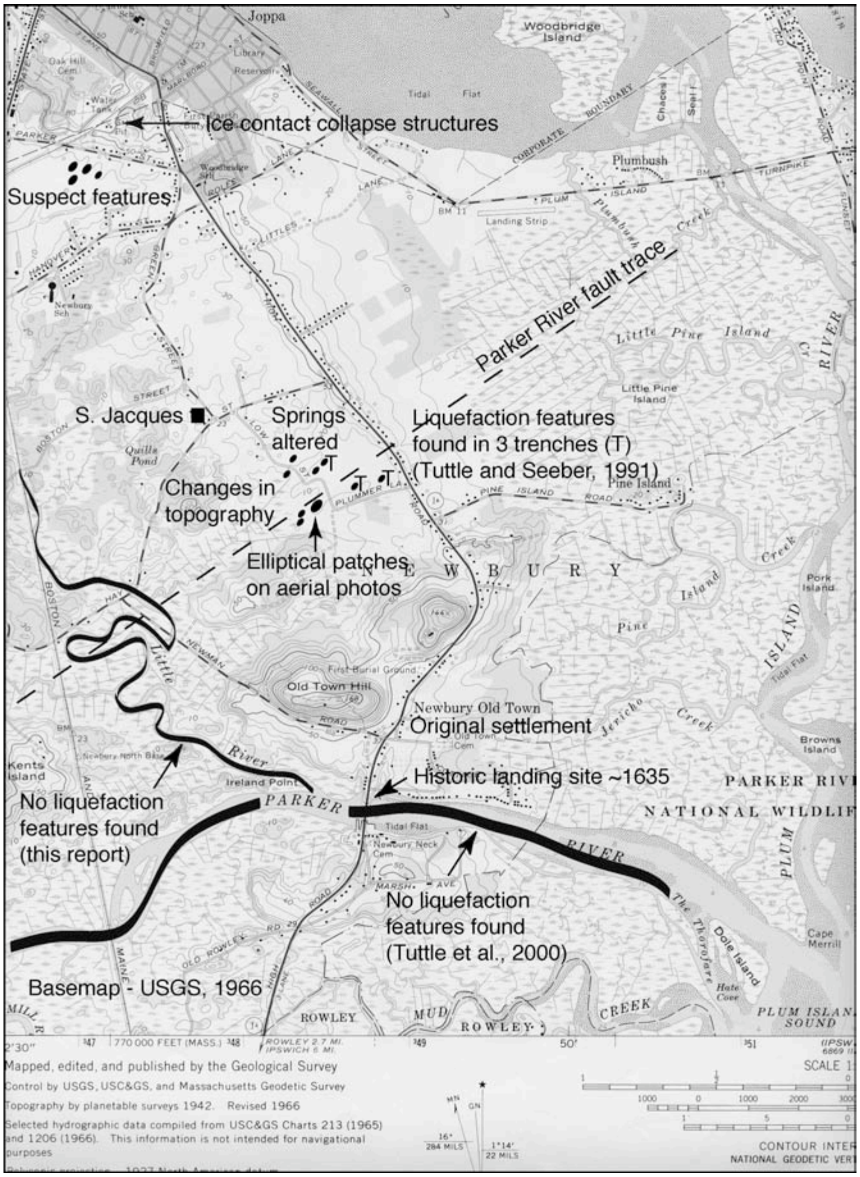


Figure 12. Annotated portion of USGS Newburyport East quadrangle showing sections of Little River and Parker River surveyed for liquefaction features. Also noted are locations of liquefaction-related phenomena during the 1727 earthquakes and liquefaction features found during previous paleoseismic study (Tuttle and Seeber, 1991).

We also surveyed Tide Mill Creek and Hampton, Hampton Falls, and Taylor Rivers in southeastern NH (Figure 13). We had selected these rivers for reconnaissance because accounts of vented sand and water in nearby Hampton and Hampton Falls, located ~25 km north of Newburyport, during the 1727 earthquake (Brown, 1900) are indicative of earthquake-induced liquefaction. We have learned through previous experience that sites of historic liquefaction, where liquefiable sediments occur, provide good targets for paleoliquefaction studies.

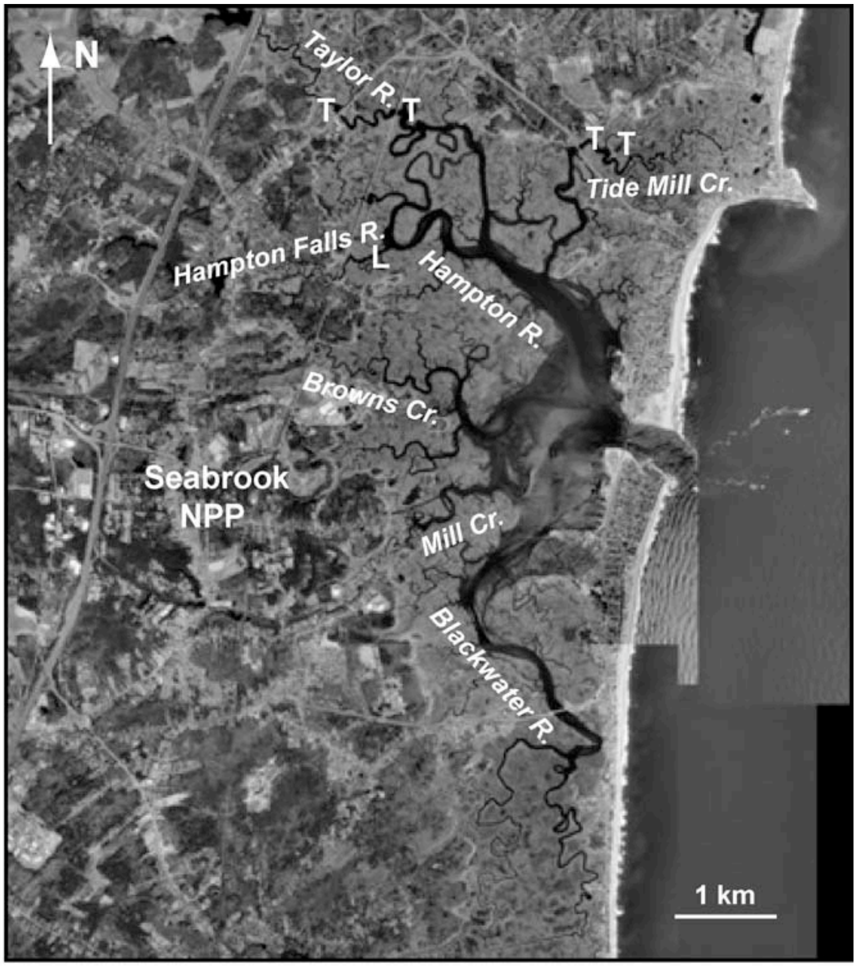


Figure 13. Orthophotoquad (modified from US Geological Survey terraserver image) of Hampton Marsh showing locations of liquefaction feature (L) and possible tsunami deposit (T).

Liquefaction Features

During reconnaissance of the Hampton Falls River, we found a 3-cm-wide sand dike in marsh deposits about 3 km from Seabrook nuclear power plant (Figure 13). The dike is composed of silty, very fine sand and extends at least 60 cm above the base of a 213-cm-high cutbank when exposed at low tide. The sand dike may have extended higher in the section but the marsh deposits had eroded more than a meter back into the cutbank along the strike of the dike. At 68 cm above the base of the cutbank, or 145 cm below the surface, a 3-cm thick layer of silty, very fine sand extends away from and pinches out within 50 cm of the sand dike. Its similarity in grain-size and position above the dike suggest that the sand layer is either a related sand blow or sill. This interpretation is uncertain due to erosion of the structural relationship. Radiocarbon dating of organic samples collected adjacent to the sand dike and 7 cm (2750-2680, 2660-2480 B.P.) and 18 cm (3070-2860 B.P.) below the possible sand blow or sill indicates that they formed less than 2,750 years ago.

During low tide, we traced the sand dike down section into very fine sand below the marsh deposits. Unfortunately, it was not possible to trace the sand dike further because water immediately filled our hand-dug excavation. A lower portion of the sand layer may have been the source of the sand dike but this was not confirmed. In several other locations, we observed very fine sand below marsh deposits and grading downward into a silty clay. This coarsening upward deposit is probably the sandy facies of the Late Wisconsin Presumpscot Formation resulting from shoaling during regression of the sea (Thompson, 1987; Koteff, 1991).

Possible Tsunami Deposit

During reconnaissance of Taylor River and Tide Mill Creek, we found a 2 to 4-cm thick layer of massive silty, fine to very fine sand including angular lithic fragments below marsh deposits and immediately above a paleosol in which large *in situ* tree roots and other woody material occur (Figures 13 and 14). The distinctive sand layer occurs at several locations from 1.5 to 4 km inland from the shoreline and near the landward margin of Hampton Marsh. The underlying paleosol is developed in silty, very fine sand and contains a few, small subrounded pebbles and granules, but no angular rock fragments. Radiocarbon dating of a sample collected from one of the tree roots yielded a radiocarbon age of 3140 ± 70 years B.P. This result suggests that the overlying distinctive sand layer was deposited less than 3,000 years ago.

From Portsmouth, NH to the head of the Bay of Fundy, tree stumps have been noted below marsh deposits (e.g., Lyon and Goldthwait, 1934). Burial of the forests has been attributed to Holocene sea-level rise and downward crustal movement. Perhaps the killed trees at Hampton Marsh and the overlying sedimentary sequence are related to sea-level rise. However, in reviewing the literature of coastal Holocene stratigraphy for this part of New England, the occurrence of sand between buried soil below and marsh deposits above apparently is not very common. In Wells Marsh located in southeastern Maine (ME) and about 36 km north of Hampton Marsh, a stratigraphic section near the landward margin of the marsh shows a sand layer above a basal peat deposit in which tree stumps are rooted (Hussey, 1970). These tree stumps are similar in age (2810 ± 200 yr B.P. and 2980 ± 180 yr B.P.; Hussey, 1959, 1970) to the one we dated at Hampton Marsh. In other stratigraphic sections of marshes northeast of Portland, ME, there are no similar sand layer described at the base of the Holocene section. The sand layers at Hampton and Wells Marshes appear to have been deposited about the same time and in similar geomorphic positions.

The Hampton Marsh sand layer resembles a tsunami deposit related to the 1929 Grand Banks earthquake that was documented at 8 sites along 40 km of the southern coast of Newfoundland (Tuttle et al., 1995; 2004). At Taylor's Bay, the tsunami deposit ranges from a massive sand containing many lithic fragments to a fining upward, very coarse to fine-grained sand. At this site, the tsunami sand was deposited on a peat bog behind a tidal pond at an elevation 3 m above the top of the barrier beach. At other sites in along the Newfoundland coast, the tsunami deposit overlies a paleosol containing tree stumps. So in the Newfoundland, where coseismic subsidence was not involved, trees were killed by short-term, salt-water inundation.

The question arises, could the distinctive sand layers at Hampton and Wells be tsunami deposits resulting from an offshore earthquake and/or subacqueous slide? A northwest-oriented trend of seismicity has been noted about 40 km off the coast of southeastern New Hampshire and Maine, and the 1755 Cape Ann earthquake probably occurred near the southern end of the trend (Ebel, 2001). If the sand layers at Hampton and Wells Marshes are tsunami deposits, offshore seismicity may delineate an active fault capable of large earthquakes.

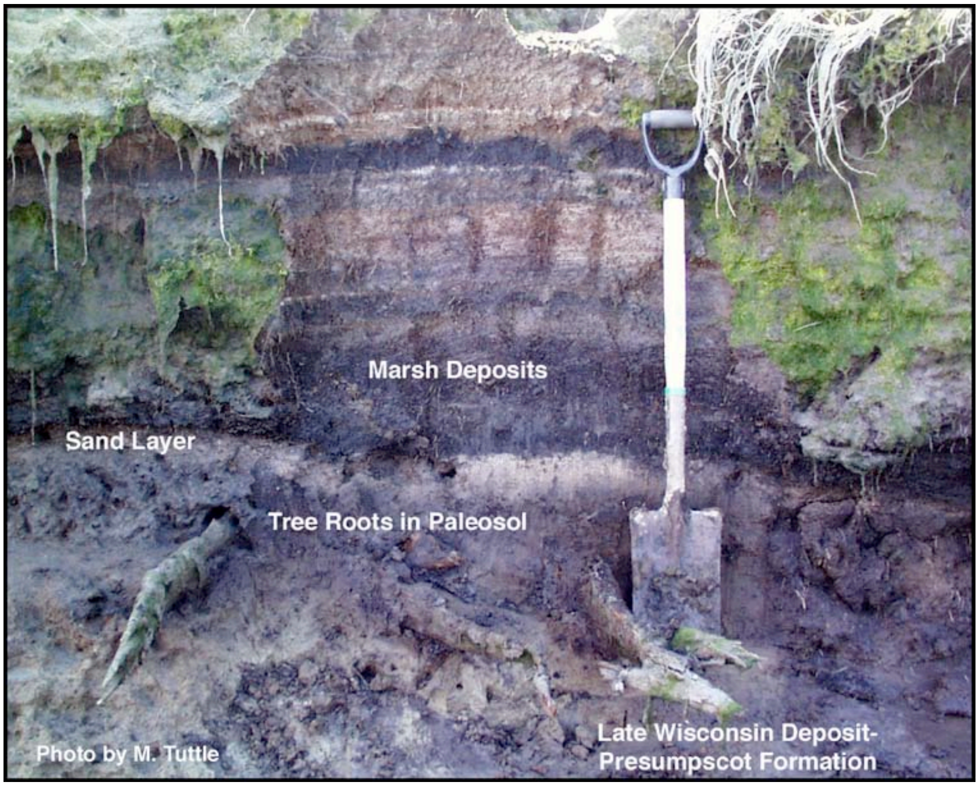


Figure 14. Photograph of distinctive sand layer at Taylor River site about 3.5 km from the current shoreline. The sand layer buries paleosol with tree roots and is overlain by marsh deposits.

Conclusions

Low-lying and swampy ground in the greater Newburyport area might reflect a zone of weakness due to faulting but certainly confounds efforts to look for geologic evidence of faulting. Despite the conditions, a few outcrops of the Newbury Formation occur in the vicinity of the proposed northwest-trending seismogenic fault thought to be the source of the 1999 Amesbury and 1727 Newburyport earthquakes (Ebel, 2000). The outcrops exhibit northwest-trending fractures with slickensides and fault gouge suggestive of faulting. However, the structures occur along strike of a northwest-oriented fault mapped by Dennen (1991) in Ipswich rather than the proposed fault in Newburyport.

We found no additional earthquake-induced liquefaction features during a subsurface investigation at the Hale Street site in Newburyport or during river reconnaissance of the Little River south of town. However, the sedimentary conditions at the Hale Street site were not ideal for the formation of earthquake-induced liquefaction features and the occurrence of sandy sediment along the Little River is very limited.

During river reconnaissance near Hampton Falls, NH, however, we found a 3-cm wide sand dike that formed less than 2,750 years B.P. In addition, we found a distinctive sand layer containing large rock fragments overlying a buried soil with *in situ* killed trees. Radiocarbon dating at one of the sites indicates that the sand layer was deposited less than 3,000 years ago. The sand dike and sand layer could, but are not required, to have formed about the same time. Although the sand layer may be the result of coastal processes during sea-level rise, the unusual sand layer might be a tsunami deposit and warrants further study.

Uncertainties remain regarding the origin of the distinctive sand layer near Hampton Falls, New Hampshire, the timing of its formation, and its relationship, if any, to the nearby liquefaction features. If the sand layer is a tsunami deposit and the nearby liquefaction feature formed at the same time, these features could point to an earthquake source offshore of southeastern New Hampshire capable of large events.

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