Collaborative Research

PALEOSEISMOLOGY INVESTIGATIONS IN THE GREATER BOSTON, MASSACHUSETTS, AREA

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Investigations Undertaken

The Greater Boston region has experienced two large historic earthquakes in 1727 (M~5) and 1755 (M~6). Both events were widely felt and caused damage to houses and other buildings in eastern Massachusetts (MA) and southern New Hampshire (NH). The 1727 earthquake caused ground failure in Newburyport, MA, and Hampton Falls, NH, indicative of liquefaction (Tuttle and Seeber, 1991). The 1755 earthquake caused similar ground failure in Scituate, MA (Boston Edison Company, 1976). Small to moderate earthquakes are common in the Greater Boston region. Although numerous bedrock faults are known, few are thought to be active at this time (e.g., Shride, 1976). Other significant earthquakes in the region include the 1940 (M_L 5.3 and 5.4) Ossipee earthquakes in central New Hampshire (Brown and Ebel, 1985). During this study, a collaborative effort between M. Tuttle, J. Sims, and D. Roy, we conducted reconnaissance for liquefaction and other earthquake related features in order to better understand the earthquake potential of the Greater Boston region.

Historic Liquefaction: In 1998, we visited the old Bailey property in Scituate, MA, where the 1755 earthquake apparently induced liquefaction, to assess the feasibility of trenching the site (Fig. 1) . Because liquefaction often recurs where susceptible sediments are present (e.g., Tuttle and Seeber, 1991), this site of historic liquefaction may contain evidence of prior events. Dr. David Roy and students from Boston College conducted a ground penetrating radar (GPR) survey of the site in an attempt to identify specific targets for trenching. In 1999, we returned to the site and excavated an area where subsurface deformation was identified with GPR.

River Surveys for Liquefaction Structures: We conducted reconnaissance for liquefaction and other earthquake-induced features along the North River southeast of Scituate, MA, the Concord and Sudbury Rivers south of Lowell, MA, the Parker River south of Newburyport, MA, the Merrimack River west of Newburyport, MA, and in the vicinity of Concord, NH, the Contoocook River northwest of Concord, NH, and the Baker and Pemigewasset Rivers near Plymouth, NH (Fig. 1).

Lake Surveys in New Hampshire: We conducted a survey of six lakes in central Hew Hampshire to assess the feasibility of coring them to search for liquefaction structures in their sediments. All the lakes are natural and have depths within the reach of Mackereth type corer that has been used in a variety of lakes in the western US (Sims, 1976).

Liquefaction Survey in the Vicinity of Gaza, NH: We also conducted a reconnaissance survey of surficial deposits in the vicinity of Gaza, NH to test the possibility that appropriate deposits are present to record historic earthquakes that have occurred in central New Hampshire.

Results of Investigations

Historic Liquefaction

Site evaluation: According to historic accounts, the 1755 earthquake damaged the home and induced liquefaction on the property of Deacon Joseph Bailey. Today, the old Bailey property is located on Country Way in Scituate Center, MA(Fig. 1) . The November 24, 1755 Boston Evening Post reported (Boston Edison Co., 1976) that the chimney of the house on the Bailey property was "demolished;" the ceiling in the house was "fractured into small parts" and "was in many places separated from the sides of the rooms," "about seventy square feet of firm cellar wall burst from its former position" and a "considerable part thrown to the ground." Seven "eruptions" of water and sand were found within a "circumference of twenty rods from the house." Another fissure of "considerable magnitude was made on the south side of the "great swamp." Any of the marshes in the area, including Sweat Swamp located south of the Bailey house and Great Swamp located west of Cohasset, may have been the swamp referred to in the account (Fig. 1) . The Bailey house still stands today on a stone foundation that shows evidence of numerous repairs, which have not been dated. There are two small dug basement rooms within the foundation perimeter. These small rooms are accessed by outside bulkhead doors. Small additions have been added to the house on the southwest and northwest sides of the house and a porch was added on the southeast side (Fig. 2a) or (Fig. 2b).The Bailey house site and Sweet Swamp to the south are underlain by 12 to 18 m of saturated stratified sand, silt, and gravel (Williams and Tasker, 1974). Williams and Tasker describe the sediment as dominantly fine to coarse sand with some thin beds and lenses of fine gravel and silt.

The sediments are chiefly fine-grained outwash deposits forming topset and foreset beds of Pleistocene deltas. These sediments are similar to those found by Ellis and de Alba (1999) in their penetration test borings described below.

Ellis and de Alba (1999) conducted *in situ* geotechnical testing, including standard penetration tests, at locations 1 and 2 near the present garden south of the old Bailey house (Fig 2a.)or (Fig 2b). According to their borings,the stratigraphy consists of brown topsoil, rock fragments (0-1.2 m); tan, fine-to-medium sand, some fine gravel and coarse sand, trace silt (1.2-4.3 m); tan fine sand, occasional thin silt layers, increasing thickness with depth (4.3-8.8 m); and tan silt, little fine sand, trace medium sand (8.8-12.2 m). The water table in the section was at 4.3 m at the time of testing. The $(N_1)_{60}$ blows/ft decreases linearly from 80 blows/ft at 0.9 m to 10 blows/ft at 4.9 m.; the blow count remains at about 10 blows/ft to a depth of 11 m. Proportions of fines (<74 microns) in the sediments of the section were measured from 3.4-9.4 m. Ellis and de Alba found low amounts of fines between the depths of 4 m and 7 m and consider the sediments in this interval to be the most susceptible to liquefaction. Because 245 years have past since the earthquake, Ellis and de Alba tried to take into account possible changes in the sediment since that time. They estimated the probable groundwater level in November 1755, densification due to compaction, and changes in grain and layer structures of the sediment after the earthquake. They conclude that liquefaction may have initiated at a depth of about 4.9 m. Due to the difficulty in liquefying sediment at the borehole locations, they suggest that the magnitude of the earthquake was larger (M 6) or located closer to the Bailey site than currently estimated.

Earthquake-induced liquefaction and related ground failure often occur in alluvial deposits adjacent to streams (Youd, 1978). At the Bailey site, there is at least 3 m of relief between the house and a stream that bounds the northeast side of the property. South of the house, the property is fairly flat lying. It appears that topography at the Bailey site has been modified by the stream, suggesting incision of the Pleistocene outwash deposits. We suspect that Holocene sediment, including silt and clay, may have been deposited above the outwash deposits along the stream. If so, conditions could be more conducive to liquefaction and ground failure between the house and stream than south of the house. Although Ellis and de Alba (1999) found sediment at 4.9 m to be susceptible to liquefaction, we doubt that elevated pore pressures could be sustained in the overlying coarse to very coarse material to produce the reported venting of sand and water. We think it is more likely that liquefaction induced by the 1755 earthquake occurred between the house and the stream bounding the northeast side of the property than south of the house where geotechnical testing was performed. Interestingly, the house occurs along the break in slope from fairly flat ground south of the house to sloping ground north of the house. Since ground failure is often influenced by topography, the position of the house may have contributed to the damage to the foundation in 1755.

Ground Penetrating Radar Profiles: Ground penetrating radar (GPR) is a non-invasive geophysical method of imaging near-surface stratigraphy. GPR operates by transmitting into the ground short pulses of electromagnetic energy in the range of 10 to 1000 MHz (Jol and Smith, 1991). The electromagnetic energy can be refracted and reflected at interfaces of contrast in the electrical properties of the subsurface. Changes in subsurface electrical properties are caused by changes in the physical characteristics of the subsurface material such as water content, grain size, grain shape, orientation of grains and other physical characteristics. A change in the physical characteristics of the subsurface can result in a change of the electromagnetic wave velocity of the material. Where velocity changes occur, GPR reflections are propagated to the surface (Gawthorpe et al, 1993). Reflected electromagnetic energy is detected at the surface by a receiver and is recorded in a format analogous to seismic profiles.

At the Bailey site, we used a Pulse-Ekko IV GPR system to image the subsurface stratigraphy and disturbances that could be associated with the 1755 event. The property is now largely wooded with a relatively young growth of trees and underbrush (Fig 2a.)or Fig.2b. The only available cleared areas are around the house and in a small field to the rear of the house. We were unable to run a GPR line from the house through the location of the drill sites because of a tenant's objection. A 100 MHz antenna was used and produced reflection images to a depth of approximately ten meters. All data were processed using Pulse-Ekko 42 (v2.0) software which corrected for topography and migration. Migration was performed using an electromagnetic ground velocity of 0.10 m per nanosecond and a 400 nanosecond window allowing GPR profile data to be displayed to a depth of approximately five meters. All GPR profile lines were located using a Topcon theodolite.

GPR Interpretations: Figures 3 and Figure 4 show GPR profiles in the vicinity of the Bailey House. Profile A-A" in Figure 3 shows the two styles of deformation that are common in the profiles of the site. Ellipses are used to enclose domains in which a few continuous sub-horizontal reflectors are "disrupted" and then appear to continue beyond the zone of disruption. Most of the disrupted zones are within 2-3 meters of the surface and are likely to be of anthropogenic origin. Lines (blue) are used in these figures to trace reflectors that cut across otherwise sub-horizontal continuous reflections. The "offset lines" are typically below two meters but some come to within a meter of the surface in the profiles. The offset lines are interpreted to be displacement surfaces (e.g. lateral spreads) or tabular liquefied sand bodies. Profiles A-A', B-B', D-D', and K-K' (Figs. 3 and 4) show possible offset reflectors in the vicinity of the house. True strikes and dips of the offset surface(s) cannot be obtained with the available data. These inclined reflectors may reflect sand dikes and lateral spreading towards the stream that borders the northeastern side of the property (Fig 2).

The M-series of GPR profiles located in the back clearingig. 2) are interpreted in Figures 5 and Figures 6. A prominent reflector is seen in Profile M2-M4 (Fig. 6) within a meter of the surface. Below the reflector in Profile M2-M4 there is a disturbed zone of unknown character between 1.5 m and 2.5 m. In Profile M2-M3 and between stations M5 and M3, the reflectors are difficult to trace because they are disturb in the top 1-2 m. Profile M3-M9 suggests deformation near the surface and to a depth of 1-2 m.

Stratigraphy imaged in profile M5-M6 appears relatively undisturbed to a depth of about 2 m; a small disturbed zone and possible reflector offsets occur below 2 m depth.

Excavations: During our evaluation of the Bailey site, we identified the area between the historic house and the nearby stream as the most likely location of 1755 liquefaction features. As described above, GPR surveys identified possible subsurface deformation of sediments in this area. Unfortunately, we were not able to trench in the area due to the safety concerns of the property owner. The only area we were given permission to trench was in the small clearing south of the house (see Fig. 2). Reviewing GPR profiles of the area, we selected two possible zones of subsurface deformation for trenching.

The location of trench 1 corresponds to the 2 m mark on Profile M3-M9 and 22 m mark on the M2-M3 profile. The trench was dug to a depth of about 1 meter. The exposed stratigraphy is simply 80-85 cm of boulder cobble gravel with sand matrix overlain by a 15-20 cm of sandy soil characterized by a gradational lower boundary. The location of trench 2 corresponds with the 9 m to 12 m marks on Profile M2-M3. Trench 2 stratigraphy is also characterized by about 0.8 m of boulder cobble gravel with sand matrix and a thin sandy soil. As in trench 1, we observed no bedding or soft-sediment deformation structures within the exposed sediment. The near-surface disturbances seen in the GPR profiles is attributed to boulders and cobbles.

The sediment is interpreted as coarse-grained, glacial outwash deposits. They are well-drained and unlikely to liquefy. Furthermore, it would be extremely difficult to propagate a sand dike from depth through these deposits given their coarse and permeable nature. We abandoned further trenching in these very coarse deposits and hope that at some future date we will be given permission to trench in a more favorable location.

River Surveys for Liquefaction Features

During the summers of 1998 and 1999, we conducted reconnaissance for liquefaction and other earthquake-related features along several rivers, including the Concord, Merrimack, North, and Parker Rivers in eastern Massachusetts, and the Baker, Contoocook, Merrimack, and Pemigewasset Rivers in southern and central New Hampshire (Fig. 1) .

South of Scituate, MA, we surveyed cutbanks along 10 km of the North River. The survey was conducted at low low tide and exposure was good. Sediment exposed in cutbanks was composed mostly of a fining upward sequence of sand to silt with peat occurring at the top of the sequence. At several locations, we observed pebbles and cobbles at the base of the cutbank. At one location, we found more than 0.3 m of sand at the base of the exposure. From 1680-1840, several shipyards were located along the lower 6 kilometers of the river. Here, we observed historic corduroy roads and large pieces of wooden ships within the upper 1 m of the cutbanks. Peat beds exposed in the lower few kilometers of the river contained large wood fragments. We sampled these for radiocarbon dating (Fig. 7). A wood sample collected about 2 m below the top of the cutbank at site NR-1 yielded a calibrated date of A.D. 680-1035 (Table 1). Clearly, the sediments exposed along the North River are appropriate in age for recording late

Holocene earthquakes. However, we found no liquefaction features along the lower 10 km of the river. It was not apparent from cutbank exposure that liquefiable sediment is widely distributed along the North River.

South of Newburyport, MA, we conducted reconnaissance along the lower 9 km of the Parker River at low low tide. Cutbank exposure was fair to good. We first traveled east toward the ocean from our entry point. Banks were about 3 m high and contained large quantities of roots from modern vegetation. We then headed upstream where cutbanks were about 2 m high and composed of fine to medium grained sand overlain by layered silt containing many roots. Wood and soil samples were collected from measured sections along the cutbanks. A wood sample collected about 1.5 m below the surface at site PR-1 yielded a calibrated date of AD 1650-AD 1950 (Fig. 7; Table 1). Further upstream at site PR-2, we collected both a wood sample and peat sample 74 cm below the surface. We dated only the wood sample, which yielded a calibrated date of 50 BC-AD 320. The sediments exposed along the lower few kilometers of the Parker River many be too young to record even the 1727 and 1755 earthquakes. However, sediments exposed upstream are appropriate in age to record late Holocene earthquakes but are limited in area. We found no liquefaction features in the exposed cutbanks along the Parker River.

Table 1. Radiocarbon analyses of charcoal and wood samples collected at liquefaction sites in the New Madrid region. Analyses performed at Beta Analytic, Inc.

Site Sample No. Lab No.	**Measured 14C Age**	**13C/12C Ratio 0/00**	**Conventional 14C Age**	**Cal yr AD/BC (2-sigma)[(1)]**	**Sample Context**
Baker River 2-W1 Beta-133342	4590 ± 50	-27.7	4550 ± 50	BC 3490-3470 BC 3380-3100	outer few cm of log in pebbly sand just above rythmite
Baker River 4-W1 Beta-133343	780 ± 50	-23.7	800 ± 50	AD 1160-1290	outer few cm of log in sand below organic-rich silt and dewatering stuctures
Baker River 4-W2 Beta-133344	270 ± 40	-27.8	230 ± 40	AD 1530-1550 AD 1640-1680 AD 1740-1810 AD 1930-	twig from organic-rich silt above dewatering structures

				1950	
Baker River 5-W1 Beta-133345	1870 ± 40	-26.9	1840 ± 40	AD 80-260	outer few cm of log in organic-rich layer near base on cutbank
North River 1-W1 Beta-121430	1020 ± 90	-16.7	1150 ± 90	AD 680-1040	leaves and organic debris 2.06 m below top of cutbank
Parker River 1-W1 Beta-121431	180 ± 60	-26.1	160 ± 60	AD 1650-1950	outer few cm of log 1.55 m below top of cutbank within marsh deposits
Parker River 2-W1 Beta-121432	1910 ± 80	-24.7	1910 ± 80	BC 50-AD 270 AD 290-320	wood 74 cm below top of cutbank and at base of marsh deposits
Pem. River 1-W1 Beta-133346	160 ± 40	-25.3	150 ± 40	AD 1660-1955	Outer few cm of log 1 m below water level and in pebbly sand

We surveyed the Merrimack River from Lawrence to Newburyport, MA by car and on foot seeking road and bridge access where available. There are very few exposures along this stretch of the river. Even an exposure visited in 1986 by M. Tuttle is now vegetated. We found good exposure along the Merrimack River in the vicinity of Concord, NH, however, and surveyed cutbanks along 22 km of the river from Boscawen to Bow Junction (Fig. 1). Floodplain deposits include recent silty sand overlying interbedded fine sand and silty sand. Although fine sand and silty sand are likely to be susceptible to liquefaction, aquitards of silt or clay that would promote the occurrence of liquefaction and formation of liquefaction features are, in general, not present in the deposits. In several locations, the Merrimack River has cut into Pleistocene terraces exposing loess overlying cross-bedded pebbly sand underlain by rhythmites of fine sand and silt as well as silt and clay. Given the sedimentology and stratigraphy of deposits along this portion of the river, it is not surprisingly that we found no liquefaction features.

We described sections at seven sites along the Merrimack River in NH, and collected organic samples at three of the sites. None of these organic samples have been submitted for radiocarbon dating. At one site, MR-6, glaciofluvial (fining upward sequence of boulders, pebbles, and sand) and glaciolacustrine (coarsening upward sequence of silty and sandy rhythmites) deposits are highly deformed (Fig. 8). Small folds occur within several subunits of the lacustrine deposit and probably formed close to the time of deposition. A large monoclinal fold involves the top of the fluvial deposit and bottom of the lacustrine deposit. Small-displacement normal faults (some appear rotated) occur within the folded deposits. The upper part of the lacustrine deposit exhibits no deformation. The glaciofluvial and glaciolacustrine deposits are truncated by an erosional contact and overlain by a pebbly sand deposit. Our interpretation is that the large monoclinal fold and normal faults formed while the lacustrine sediments were being deposited. The style of deformation is consistent with collapse of the sediment due to melting of ground ice. There is no evidence that the deformation was related to neotectonics.

We surveyed the lower 17 km of the Baker River from Rumney to the Pemigewasset River (Fig. 1). Exposure of cutbanks is fairly good except for a section from 2.5 to 4.5 km downstream from Rumney and the lower 4 km of the river. In general, a sandy deposit unconformably overlies a rythmite. The rythmite is composed of alternating beds and laminations of silt and sand. The sandy deposit is composed of crossbedded pebbly sand containing tree trunks overlain by interbedded very fine silty sand and crossbedded fine sand, followed by very fine sandy silt. Near the mouths of several streams entering Baker River, the middle subunit tends to be finer grained, contains more organics, and exhibits small (1 to 2 cm wide by 5 cm high) dewatering structures and load casts. Wood (sample BR 2-W1; Table 1) collected from the base of the crossbedded pebbly sand yielded a calibrated dates of BC 3490-3470 and 3380-3100. Two other wood samples (BR 5-W1 and 4-W1) collected from the middle subunit of interbedded sand and silt yielded dates of AD 80-260 and AD 1160 and 1290. A twig (BR 4-W2) from a filled channel cut into the middle unit yielded a date of AD 1530-1550, 1640-1680, 1740-1810, 1930-1950.

The sandy sediments exposed along the Baker River are interpreted as Middle to Late Holocene fluvial deposits of Baker River and its tributaries. The underlying rythmite is interpreted as a Late Wisconsin glaciolacustrine deposit. Although an earthquake origin can not be ruled, the dewatering structures observed in the sandy deposits are more likely the result of rapid sedimentation as tributaries entering Baker River deposited their sediment load. The relatively young sandy deposits along Baker River are likely to be susceptible to liquefaction. However, they lack layers of fine-grained sediment (silt and clay) that promote the build-up of pore pressures during ground shaking. Therefore, the absence of earthquake-induced liquefaction features should not be construed as evidence that strong ground shaking has not occurred in the area during past 5,000 years.

From Baker River, we continued south along the Pemigewasset River for about 5 km < a href ="G0001.htg/fig1.jpg">(Fig. 1). Exposure of cutbanks was fairly good, except in Plymouth. The stratigraphy was very similar to that along Baker Creek with a silty and sandy rythmite unconformably overlain by a predominantly sandy deposit. The sandy deposit is composed of a pebbly, coarse to medium sand overlain by interbedded fine sand with some crossbedding, silty very fine sand, and very fine sandy silt. Unlike sediments along Baker River, thin paleosols and thick (up to 80 cm) silt layers occur within the sandy deposit. Wood collected from a log within pebbly sand about 1 m below the water level and 4.1 m below the top of the cutbank yielded a calibrated date of AD 1660-1955 (Table 1). Given the thickness of overlying sediments and the occurrence of a 10 cm thick paleosol as well as a modern soil above, the true age of the sample is towards the earlier end of the range and the entire section is young or the log was either not *in situ* as had been thought. We prefer the latter interpretation given that similar deposits along Baker River are Middle to Late Holocene in age.

Given the occasional presence of thick silt layers within the predominantly sandy deposit, conditions are more favorable for the formation of earthquake-induced liquefaction features along the Pemigewasset River than along Baker River. Even where the silty aquitards occur within the sandy deposit, however, we observed no liquefaction features. Given that only 5 km were surveyed, additional reconnaissance of Pemigewasset River is advisable before drawing conclusions about the history of ground shaking in the region. Furthermore, geotechnical testing would help to determine the earthquake magnitude needed to liquefy the Pemigewasset sediments.

We also surveyed the lower portions of the Contoocook, Concord, and Sudbury Rivers where the rivers are accessible from roads and bridges. Along the Contoocook River, there are many closely spaced dams and bedrock is shallow in many places. We found no exposures of liquefiable sediments. Cutbanks along the Concord and Sudbury Rivers are low and almost completely covered by vegetation.

Lake Surveys in New Hampshire

In addition to surveying riverbank exposures for paleoliquefaction features, we explored the possibility of examining lake sediments for paleoliquefaction features. The coincidence of a large number of lakes in central New Hampshire with an area of seismic activity made this line of inquiry attractive (Fig. 1). Lake sediments have been found to be very useful in determining paleoseismic histories in other regions (Sims, 1973, Rymer and Sims, 1976). Those in Washington and Alaska are in formerly glaciated areas similar to the lakes in New Hampshire. Thus, we decided to explore the possibility of obtaining paleoseismic data from lakes to compliment and extend the data from river reconnaissance. Cores from lake sediments are required to study paleoliquefaction structures in them. This survey of lakes in central New Hampshire was aimed at determining if the lakes are suitable for such a study.

We selected six lakes to evaluate in and around the area affected by earthquakes in central New Hampshire including the events of 1638, 1940, and 1982. The selected lakes are Webster, Newfound, Winnisquam, Winnipessaukee, Squam and Ossipee (Fig. 1). Limnological data from the New Hampshire Department of Environmental Services (NHDES) suggested that the lakes could be a possible source of information for paleoseismic studies. However, most of the information gathered by the NHDES is of a biological nature. A limited number of cores had been collected from some of the lakes but the cores are all <1 meter long and penetrate only gytya (J. Connor, oral commun. 1999). Gytya is a common bottom sediment of lakes in formerly glaciated areas and frequently began accumulating shortly after ice retreat and revegetation of glacial deposits occurred.

Gelinas and others (1994) conducted bathymetric profiling, sub-bottom profiling, and collected cores in a study of four lakes within a 40 km radius of the 1940 Ossipee earthquake. Bathymetric profiles show that the lakes have steep near-shore slopes and low slopes near the centers of the lakes. The sub-bottom profiles they collected suggested less than optimum sediment type and depositional environments for the formation and preservation of paleoliquefaction structures. These profiles revealed numerous bedrock or till pinnacles mantled by gytya. The mantling sediment thinned over the tops of the pinnacles and thickened in the lows between them. They also described 13 cores from lake sediments in lakes Winnepessaukee, Ossipee, and Silver (Gelinas and others, 1994, table 13.6). The locations of the cores ranged from the toes of slopes to mid-lake. Twelve cores contained undisturbed gytya and the last contained medium sand. The findings of Gelinas and others (1994) are consistent with the information received from the NHDES.

The lakes of interest to us were all formed by glacial scour. Site surveys of the lakes showed numerous rock outcrops along shores and on islands in the lakes (Table 2). That coupled with limited information from coring done by others on behalf of the NHDES and by Gelinas and others (1994) strongly suggests that little or no information about paleoseismicity can be obtained from the lake sediments. Gytya by its fine-grained texture, low accumulation rate, and high water content lacks the qualities to preserve liquefaction structures.

Table 2. Selected central New Hampshire lakes and their physical characteristics

Lake	Trophic State	Area (ha)	Max Depth (m)	Mean Depth (m)	Watershed Area (ha)	Flush Rate	Bottom Sediment	Remarks
Newfound	oligotrphic	1,662	55.5	22.5	29,267	0.4	Gytya, rock silt, sand	bedrock outcrops on shores and islands
Ossipee	oligotrphic	1,251	15.2	8.5	84,822	4.6	Gytya, rock silt, sand	bedrock outcrops on shores and islands
Squam	oligotrphic	165	22	9.9	9,324	2.8	Gytya, rock silt, sand	bedrock outcrops on shores and islands
Webster	oligotrphic	248	11.8	5.5	4,507	1.5	Gytya, rock silt, sand	bedrock outcrops on shores and islands
Winnipessaukee	oligotrphic	18,043	54.9	13.1	87,128	0.2	Gytya, rock silt, sand	bedrock outcrops on shores and islands

Winnisquam	oligotrphic	4,262	173.8	15.2	118,028	2.2	Gytya, rock silt, sand	bedrock outcrops on shores and islands

Liquefaction Survey in the Vicinity of Gaza, NH

A number of historic earthquakes have occurred in central Hew Hampshire. Some are thought to have been as large as M 6.5 (Table 3). Earthquakes of M 5.5 have a strong likelihood of inducing liquefaction in susceptible sediments (Sims, 1973). The M 4.7 January 19, 1982 "Gaza" earthquake (latitude 43.51°N, longitude 71.62°W) occurred in the vicinity of Lake Winnisquam (Sauber, 1988). Earthquakes of greater magnitude occurred nearby in 1638 (M 6.5) and in 1940 (M 5.5 and 5.6). We examined the sedimentary units in the vicinity of Gaza, NH, for any possible liquefiable deposits. The area had been covered by Wisconsin glaciers and the surficial deposits are predominantly glacial outwash and till. We found that there is also a considerable amount of crystalline bedrock exposed. In addition, the outwash is predominantly boulder-cobble gravel and interbedded coarse sand. These lithologic types are generally not susceptible to liquefaction. Thus we conclude that liquifaction outside of river valleys is unlikely.

Table 3. Significant U.S. earthquakes from the NEIC USHIS earthquake catalog between latitude 45°N and 42°N and longitude 70°N and 73°W

Catalog	**Year**	**Month**	**Day**	**Lat**	**Long**	**Depth**	**Mag**	**Place**
USHIS	1627			44.40	70.80			
WOBS	1638	6	11	42.60	71.8		6.5	Central NH
WOBS	1639	1	14	44.40	71.8			Central NH
WOBS	1668	12	10	42.5	71.5		3.5	Littleton, MA
USHIS	1727	11	19	42.80	70.80			Newbury, MA
USHIS	1744	06	24	42.60	70.90			Eastern MA
USHIS	1755	11	18	42.70	70.30			Cape Anne, MA
USHIS	1761	03	12	42.70	70.30			
USHIS	1810	11	10	43.00	70.80			Exeter, NH
USHIS	1817	10	05	42.50	71.20			Woburn, MA
USHIS	1857	12	23	44.10	70.20			
USHIS	1918	08	21	44.20	70.50		4.20	Southeast ME
USHIS	1925	10	09	43.70	71.10		4.00	Southeast NH
USHIS	1940	12	20	43.87	71.37	10	5.50	Lake Ossipee, NH
USHIS	1940	12	24	43.91	71.28	8	5.61	Lake Ossipee, NH

USHIS	1957	04	26	43.53	70.25	5	4.70	Coastal SE ME
USHIS	1963	10	16	42.40	70.42	14	3.90	Coastal MA
USHIS	1963	10	30	42.70	70.80		3.20	Tilton-Laconia, NH
USHIS	1964	06	26	43.40	71.68	1	3.20	Warner, NH
USHIS	1977	12						