



## Associated terrestrial and marine fossils in the late-glacial Presumpscot Formation, southern Maine, USA, and the marine reservoir effect on radiocarbon ages

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### ARTICLE INFO

#### Article history:

Received 24 February 2010

Available online 31 March 2011

#### Keywords:

Presumpscot Formation

Maine

Late Pleistocene

AMS and  $\beta$ -decay radiocarbon ages

Radiocarbon age calibrations

Marine reservoir effect

Dendrochronology

Marine bivalves and barnacles

Fossil mosses and insects

Plant macrofossils

Pollen

Landslides

### ABSTRACT

Excavations in the late-glacial Presumpscot Formation at Portland, Maine, uncovered tree remains and other terrestrial organics associated with marine invertebrate shells in a landslide deposit. Buds of *Populus balsamifera* (balsam poplar) occurred with twigs of *Picea glauca* (white spruce) in the Presumpscot clay. Tree rings in *Picea* logs indicate that the trees all died during winter dormancy in the same year. Ring widths show patterns of variation indicating responses to environmental changes. Fossil mosses and insects represent a variety of species and wet to dry microsites. The late-glacial environment at the site was similar to that of today's Maine coast. Radiocarbon ages of 14 tree samples are  $11,907 \pm 31$  to  $11,650 \pm 50$   $^{14}\text{C}$  yr BP. Wiggle matching of dated tree-ring segments to radiocarbon calibration data sets dates the landslide occurrence at ca.  $13,520 + 95/-20$  cal yr BP. Ages of shells juxtaposed with the logs are  $12,850 \pm 65$   $^{14}\text{C}$  yr BP (*Mytilus edulis*) and  $12,800 \pm 55$   $^{14}\text{C}$  yr BP (*Balanus* sp.), indicating a marine reservoir age of about 1000 yr. Using this value to correct previously published radiocarbon ages reduces the discrepancy between the Maine deglaciation chronology and the varve-based chronology elsewhere in New England.

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### Introduction

Excavations in 2007 near the Fore River in Portland, Maine, for the new Mercy Hospital, revealed *Picea* logs, other plant fossils, insect remains, and shells of marine invertebrates in late-glacial marine clay of the Presumpscot Formation. The Presumpscot sediments occur widely across southern Maine, but the site described here is only the second known locality where they have been found to contain well-preserved tree remains. The first such occurrence was found in 1976 at a gravel pit just 150 m northeast of the 2007 hospital site (Fig. 1). A vertical pit face at the 1976 site exposed 3–5 m of marine clay with tree fragments and other terrestrial fossils near the base of the clay (Fig. 2; Hyland et al., 1978). Anderson et al. (1990) concluded that the tree remains and

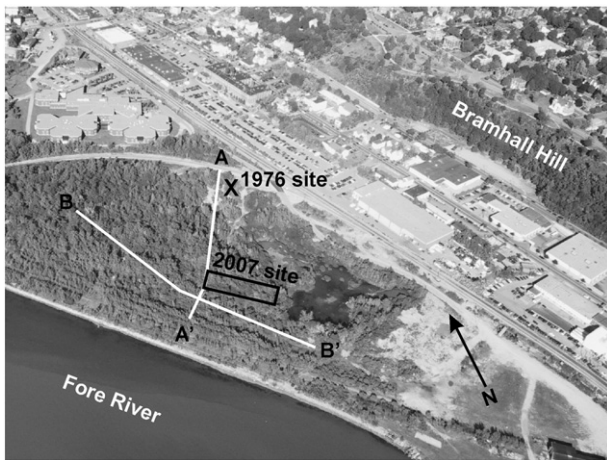
diverse biota at the 1976 site were eroded from a forest floor and were transported only a short distance in the ocean before being rapidly buried. Here we offer a more comprehensive paleoenvironmental interpretation of these two fossil localities, based on the stratigraphy of the hospital site and its surroundings along with detailed analysis of associated organic remains.

We collected plant and shell samples from trench and pit exposures immediately southeast of the hospital buildings that were under construction in 2007. Marine shells were found adjacent to tree remains, enabling us to compare terrestrial and marine radiocarbon ages from coeval organics. Marine shell ages underpin much of the deglaciation chronology for southern Maine (Borns et al., 2004), but their utility has been limited by reservoir effect uncertainty.

Our objectives are to (a) describe and interpret the origin of stratigraphic units and associated organic materials at the new site in reference to the 1976 exposure; (b) evaluate the terrestrial fossil assemblage relative to the late-glacial and Holocene environmental and climatic history of Maine and northeastern North America; (c) use the radiocarbon ages of decadal tree-ring segments to obtain wiggle-matched calibrated ages; and (d)

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**Figure 1.** Pre-construction view of the Mercy Hospital property (forested area in foreground) and vicinity, showing locations of the 1976 and 2007 fossil sample sites, geological cross-sections (Fig. 3), and west side of Bramhall Hill.

compare radiocarbon and calibrated ages of coeval marine and terrestrial organics to determine the local marine reservoir effect and assess its impact on previously published deglaciation chronologies for southwestern Maine. Different parts of this paper represent contributions by Thompson, Weddle, Miller, and Griggs (field study), stratigraphy (Thompson and Weddle), paleobotany and paleoecology (Miller and Griggs), dendrochronology (Griggs), paleontology (Thompson and Weddle), and paleoentomology and palynology (Nelson and Kilian).

## Methods

Shallow excavations (typically 2–3 m deep) at the Mercy Hospital construction site were examined during the spring of 2007. We recorded the stratigraphy of these exposures and collected samples of tree remains and associated organic materials. Data from the new site were compared with Thompson's unpublished 1976–1984 field notes for the nearby locality where tree remains were discovered in 1976.

We supplemented our observations at the hospital site with photos and other information from Shaw Brothers Construction Inc. and Haley & Aldrich Inc. Their records were used to interpret the stratigraphy in excavations that had been backfilled prior to our visits. We also examined numerous test-boring logs from the study area compiled by Haley & Aldrich, Inc. (2005, 2006).



**Figure 2.** Desiccated spruce log protruding from marine clay in pit face at the 1976 site. This is specimen no. 3 of Hyland et al. (1978). Exposed part of log was 18–23 cm in diameter and 102 cm long. Shovel blade marks sloping clay/gravel contact.

## Paleobotany

Seven samples of organic detritus from the area of exposure (~150 m<sup>2</sup>), Thompson locality numbers 07-6 and 07-13, were cleaned in the field and wrapped for transportation to the laboratory where surface area was determined by planimetric measurement of sample outlines traced on graph paper and volume was measured by displacement in water. Samples were disaggregated by hand in deionized water heated overnight. Slurries were washed through a 125- $\mu$ m sieve aided by a weak jet of tap water, with flow controlled by squeezing the end of the rubber delivery hose. The wet volume of each residue was measured in a graduated funnel-flask. Fossils in the residues were picked, sorted, and identified, using dissecting microscopes. Botanical reference collections at the Biological Survey, New York State Museum were employed in the identification process. Fossil mosses, dissected and mounted in Hoyer's solution on microscope slides, were studied at low and high magnification, using reference samples to aid identification. Samples for plant macrofossil analysis were sieved within a week of collection, and the residues were refrigerated for up to four months during picking. Names of mosses follow Anderson et al. (1990), and those of vascular plants follow Gleason and Cronquist (1991). The plant fossils have been deposited in the Quaternary Paleobotanical Collection of the New York State Museum.

Small (5–10 cm<sup>3</sup>) subsamples for pollen analysis were taken in the lab from two macrofossil samples collected by Weddle from different localities. Processing proceeded using standard techniques in a hot water bath (10% KOH for 5 min, washing over a 0.25-mm screen, 48% HF for 1 h, acetolysis for 5 min, followed by fine-washing over a 10- $\mu$ m sieve to remove fine detritus, and dewatering using ethanol and tertiary-butyl alcohol washes). Residues were mounted on standard microscope slides in silicone oil using 22 $\times$ 40-mm cover slips, and counted at 200 $\times$  magnification in non-overlapping transects; difficult grains were identified at 400 $\times$  magnification. Percentages were calculated on the basis of the total number of identifiable pollen grains encountered in a count of at least 300 total grains.

## Wood and dendrochronology

Griggs and Miller collected samples from tree trunks and branch segments representing at least five different trees at the hospital site, and Griggs studied notes describing one log collected by Thompson at the 1976 site (Log # 7 in Thompson field notes, 28 March 1978). Branch samples of unusual context were also collected. The excavated wood segments were cleaned in the field with a trowel and, for most segments, one or more samples were cut from the ends, choosing the end with the largest diameter. In the laboratory the samples were cleaned with tap water and further cut at the widest point with a band saw. The samples were further cleaned with tap water in the laboratory, microtomed, and the thin sections identified (Panshin and de Zeeuw, 1970); all are spruce (*Picea* sp.). Transverse surfaces of samples with over 50 rings were cut with steel blades for ring-width measurements. Ring-widths were measured on a computer-linked moving table beneath a stereomicroscope with crosshairs. Each series of ring-widths was compared with all others, and a chronology was built from the ring-width series of all tree trunk samples, with patterns matched visually and statistically, using CORINA software (available at <http://dendro.cornell.edu/>) and the COFECHA 6.06 program (Holmes, 1983). Seven segments of 10–24 yr were selected from across the site chronology for wiggle-matched radiocarbon dating and the corresponding rings were cut from two samples (see “Radiocarbon dating” below). In addition, the average ring width of the first 100 yr of growth in all sampled trees was compared with the average ring width of the first century in the lives of *Picea glauca* trees from other periods across northeastern North America.

## Paleoentomology

Samples picked by Miller for plant macrofossil analysis were transmitted to Nelson for fossil insect extraction. Additional sediment samples were obtained from Thompson and Weddle. Insect remains were picked from sieved fractions of dried material beneath a dissecting microscope. Identifiable remains were mounted on standard microfossil slides using gum tragacanth on a 1×1-mm gridded white background. Remains were identified by comparison with literature descriptions and modern specimens.

## Radiocarbon dating

Accelerator Mass Spectrometric (AMS) radiocarbon ages were obtained at two facilities, the NOSAMS facility at the Woods Hole Oceanographic Institution and the MICADAS AMS system at the ETH Zurich laboratory, for four samples of wood, three other plant samples, and five samples of marine invertebrate shells. Sample pretreatment was performed according to each lab's procedures. Terminal or lateral buds of *P. glauca* and *Populus balsamifera* were cleaned of adhering sediment in the laboratory and dried promptly in an oven. Storage of plant fossils selected for dating did not exceed two weeks prior to oven drying. In addition, seven decadal wood samples were sent for long-count  $\beta$ -decay radiocarbon dating to the Heidelberg Radiocarbon Laboratory at the Akademie der Wissenschaften, Heidelberg, Germany. Their procedure lowers error values as a result of the equipment used and the number of days samples are measured (Kromer and Münnich, 1992). Further details are in the supplementary material associated with this paper.

Radiocarbon ages of marine samples were calibrated using Marine04 (Hughen et al., 2004). All terrestrial sample ages were initially calibrated using the IntCal09 calibration curve (Reimer et al., 2009). In addition, the radiocarbon ages of the seven decadal wood segments and two of the buds were fit to the calibration curve by "wiggle matching" to form a fixed sequence of ages, using the method described by Bronk Ramsey et al. (2001) and Galimberti et al. (2004). This sequence was also calibrated by fitting it to the "wiggles" of radiocarbon ages of tree-ring segments in the samples used to build a late-glacial floating pine chronology for Germany and Switzerland (Kromer et al., 2004; Hua et al., 2009) and to the Cariaco calibration data (Hughen et al., 2006).

## Results and discussion

### Site stratigraphy

Clay-rich marine sediments of the Presumpscot Formation underlie low terrain in the Portland area. Test borings have penetrated as much as 43 m of clay, silt, and sand beneath the Fore River (Thompson, 1999, 2008). These sediments were deposited on Maine's isostatically depressed coastal lowland during the late-glacial to early postglacial marine transgression. A relative sea-level curve (Retelle and Weddle, 2001) indicates that the shoreline had withdrawn to its present position by ~13,000 cal yr BP.

Test borings (Fig. 3; Haley & Aldrich, Inc., 2005, 2006) and surface exposures at the hospital site showed stratigraphic units identical to those recognized at the 1976 site. Massive Presumpscot marine clay overlay poorly sorted, massive to moderately well-stratified gravel and gravelly sand. The moist clay ranged from gray or dark-gray (N6/–N4/) to bluish-gray (5B 6/1). The clay/gravel contact was abrupt and sloped gently west to southwest where observed. Dip directions of bedding in exposed portions of the gravel varied from north–northwest through west to south. Clasts in the gravel ranged from pebbles to small boulders, most of which were angular or subangular. The thickness of this unit varied from

2 m to at least 12 m, with the greatest thickness in an area where gravel pits formerly existed in the northeast part of the hospital complex.

Surface excavations and borings did not reveal any buried tree remains between the 1976 and 2007 sites. However, five borings elsewhere near the hospital encountered buried plant material. One of them (HA 05-121; Fig. 3) was immediately northwest of the surface exposures of the Presumpscot Formation that we sampled. The others (HA 05-6, 7, 124, and 125) spanned a distance of 150 m along the Fore River near the I-295 Connector highway. The boring logs variously described the organic zone as containing wood, peat, organics, organic soil, and marine grass. This zone was up to 1.2 m thick and occurred immediately above the gravel at elevations very close to present sea level (–0.2 to +2.4 m; Fig. 3).

Borings also revealed up to 15 m of clay and silty sand beneath the gravel. Shells were encountered in the uppermost part of this buried unit in boring HA 05-6 (Fig. 3). Borings just west and southwest of the hospital showed one thick continuous sequence of marine clay and silty sand with scattered shells but no interstratified gravel. We interpret all of these fine-grained sediments as parts of the Presumpscot Formation.

The composite stratigraphy associated with the tree remains at the hospital site comprised the following units (from oldest to youngest):

- Unit 1** 4–14 cm of oxidized gravelly sand. This unit occurred locally just below the fossiliferous units. It probably was reworked from the underlying gravel and gravelly sand deposit.
- Unit 2** 2–4 cm of silty very fine sand containing laminae and disseminated fragments of small twigs and other plant material. We interpret this sand as having the same origin as Unit 1.
- Unit 3** Thin layer of peaty organic detritus (typically ~1–2 cm, but thicker in a few places and absent in others) containing *P. glauca* (white spruce) needles, wood fragments, and various other plant remains and insects. Some of the *P. glauca* needles were green when collected (Fig. 4). This organic layer is generally near the base of the Presumpscot Formation, though locally it has been disturbed and stringers of it were sheared up into the overlying clay.
- Unit 4** Organics-bearing zone up to ~1 m thick in the Presumpscot Formation, consisting of gray marine clay with abundant parts of *P. glauca* including cones, needles, branches, trunk sections, and root fragments. A few leaves and numerous marine shells and shell impressions were found in the clay with the logs and other *Picea* remains. Well-rounded stones ranging in size from pebbles to small boulders (30 cm) were scattered throughout Unit 4, and lenses of coarse sand (some with shell fragments) occurred locally. The mixing of the marine clay with tree fragments, deformed peaty clasts from Unit 3, and coarse sedimentary debris indicates that Unit 4 is allocthonous.
- Unit 5** Gray to bluish-gray Presumpscot marine clay with shells of various mollusks, but no apparent plant material and few or no stones.

The tree remains and associated plant and animal fossils described here were collected from Units 2, 3, and 4. These three units likewise overlay the gravel at the 1976 site and occurred in the same sequence (W.B. Thompson field notes).

### Site interpretation

Understanding the process by which the terrestrial plant material was transported and buried in the Presumpscot Formation is important to our interpretation of the stratigraphy and chronology of the hospital site. We determined the position of sea level when the tree remains were deposited by comparing the marine

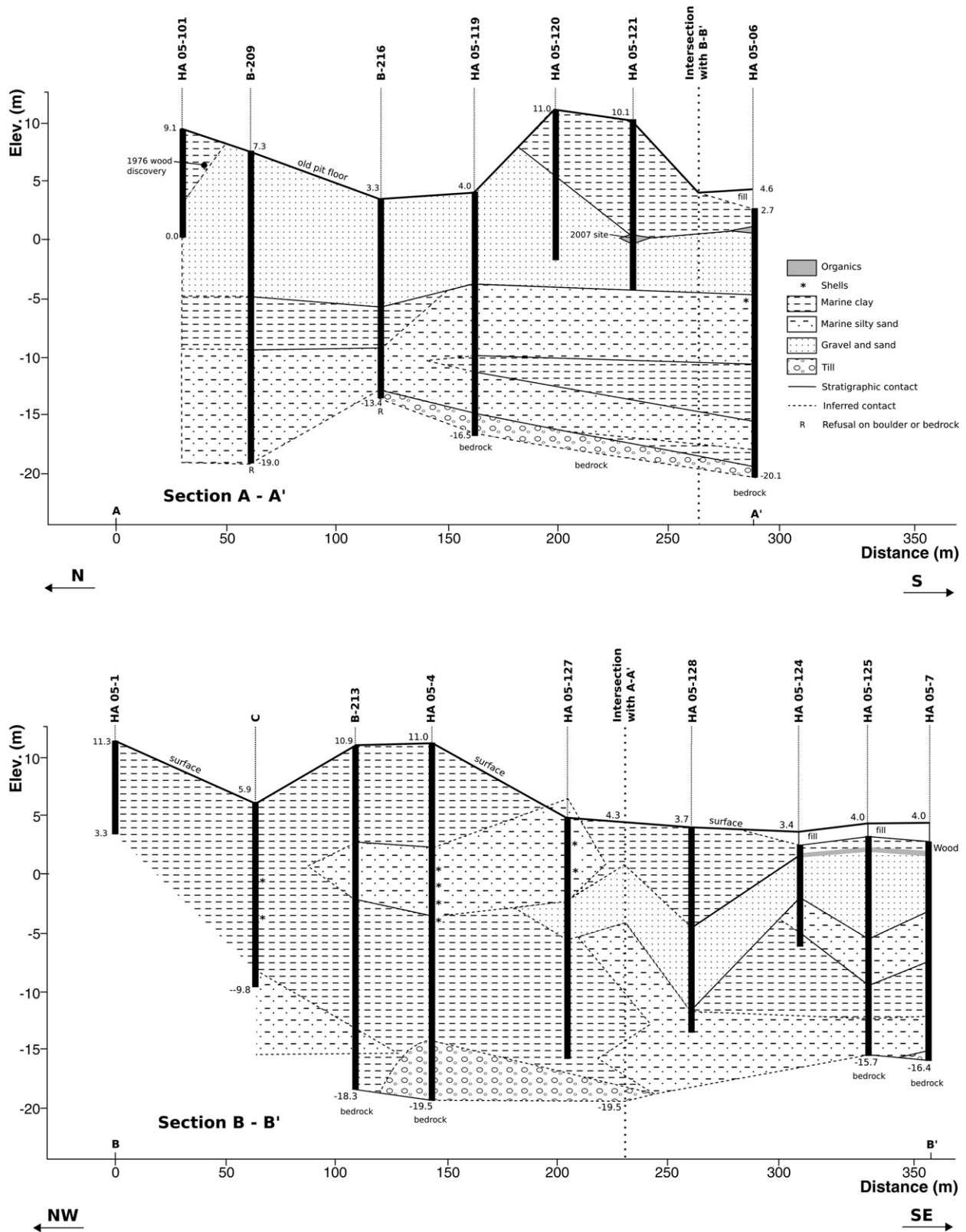


Figure 3. Stratigraphic interpretation along lines A-A' and B-B' in Fig. 1, based on test-boring data from Haley & Aldrich, Inc. (2005, 2006).

shell ages with the relative sea-level curve of Retelle and Weddle (2001) derived from radiocarbon ages of marine shells in the lower Androscoggin River valley and greater Portland region. Adjusting for crustal tilt yields a shoreline elevation in Portland ~37 m higher than today and a water depth of 30–37 m where the tree remains

were deposited. Nearby Bramhall Hill was a roughly circular island ~1 km across and reaching ~20 m above sea level. Most of the Portland area was submerged, but other contemporary islands and peninsulas existed within 2–10 km of our study site (Thompson, 2008).



Figure 4. Fossil white spruce (*Picea glauca*) twigs with needles. From Unit 3.

The following explanations were considered to account for the organic deposit:

- (1) *In situ* forest developed during a brief regression of relative sea level and then drowned and was buried by marine clay when sea level rose.
- (2) Trees and associated forest litter were eroded from a nearby shoreline and floated in the sea for an uncertain time and distance prior to deposition and burial.
- (3) Trees and associated forest litter were swept into the sea by a landslide from Bramhall Hill (Fig. 1) and were quickly buried by marine clay disturbed by the slide.

We found no evidence to support the *in situ* forest hypothesis. No paleosol was evident, and none of the tree trunks was preserved in growth position or connected to a root system. Even the largest trunks were broken during what was probably a violent event. Moreover, the forest hypothesis requires that the site emerged from the sea for at least 200 yr and then drowned by renewed marine transgression. There is no record of such a fluctuation in relative sea level for the time period when the trees were living (Retelle and Weddle, 2001).

The marine transport hypothesis is likewise problematic. Numerous landslides have occurred in the Presumpscot Formation near Portland (Morse, 1869; Devin and Sandford, 1990), and a slide on Bramhall Hill or other nearby shoreline could have broken the tree trunks and swept them into the sea. However, the organic material at the study site could not have drifted long or far in the sea because needles were still attached to many *Picea* twigs. The abundant stones in the fossiliferous clay (Unit 4) further argue against marine transport.

Morse (1869) described a prehistoric landslide that originated on the west flank of Bramhall Hill. Ridges in the toe of the slide were removed by urban development, but they are evident on the 1866 U.S. Coast Survey map of Portland Harbor. However, if the plant materials at the hospital site had been carried by a subaerial slide from the hill, they probably would have been mixed farther up into the overlying clay.

Our preferred interpretation involves a submarine landslide. We infer a sequence of events starting when the top of Bramhall Hill was about to emerge from the sea during late-glacial uplift. Gravelly sediments resulting from marine erosion of the hill top prograded over clay that lapped against the hillside. This regressive marine

stratigraphy occurs elsewhere on Bramhall Hill (Packard, 1867; Thompson, 1999) and throughout coastal Maine. The upper part of the hill then emerged, and an open boreal-type forest grew there for at least 200 yr. During this time, nearshore gravel continued to accumulate on clay deposits that were still underwater, and the sediment pile became unstable. Slope failure occurred, carrying large, more-or-less intact masses of gravel into the sea. Trees and associated biota from the shoreline were swept downward with sufficient force to break the trees apart. Some of the forest and wetland organics – including the peaty material comprising Unit 3 – clung to the top of the slide mass and were quickly buried by marine clay (Unit 4) disturbed by the slump. The remobilized clay contained marine invertebrates mixed with rounded beach gravel that cascaded into deeper water during the slide.

#### Marine fossils

We collected *Balanus* sp. and *Mytilus edulis* shells from clay and silty sand as close as 15 cm from *Picea* wood (Fig. 5) in trench exposures. *Mytilus* shells occurred in clusters of disarticulated, but commonly intact, valves. At the base of Unit 4, adjacent to one of the logs, a complete impression of a *Mya arenaria* valve was found next to *Picea* twigs with green needles. Valve impressions of *Hiatella arctica* and *Macoma* sp. occurred next to tree remains in the equivalent of Unit 4 at the 1976 site (W.B. Thompson field notes).

The dated *Balanus* plate fragments (Table 1) have not been identified to species. They were in sandy sediment that probably was transported by mass movement on the sea floor. Undated barnacle plates in the clay were identified as *Balanus balanus*, and the calcified plate base of a barnacle attached to a well-rounded pebble in the clay was probably the same species.

Some of the trenches yielded shells of other invertebrates stratigraphically higher in the clay, in Unit 5, as much as 1–2 m above the wood-bearing zone. These include *Macoma balthica*, *Serripes groenlandicus*, and *Cerastoderma pinnulatum*. With the occasional exception of *Macoma*, all species found in Units 4 and 5 are filter (suspension) feeders. They are widespread in the late-glacial marine clays of Maine and still occur along this part of the Atlantic coast.

The shells from Unit 4 are intertidal to shallow-water species, while those from Unit 5 are found in deeper water. *M. balthica* generally lives in waters ranging from intertidal to 20 m deep, while *C. pinnulatum* and *S. groenlandicus* typically inhabit waters that are 6–180 m and 9–60 m deep, respectively (Abbott, 1996). The presence of nearshore species in Unit 4, in contrast to the deeper-water fauna

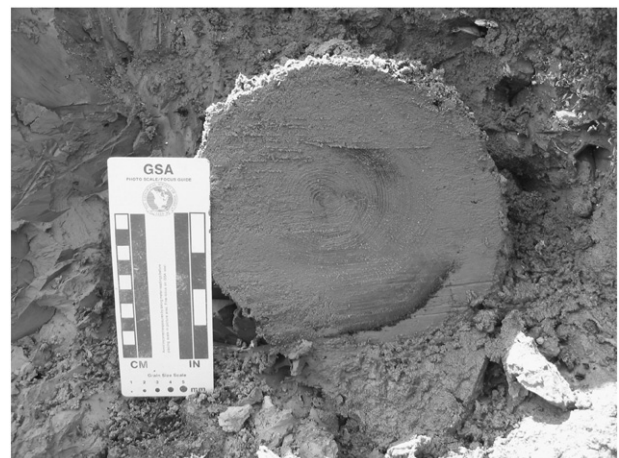
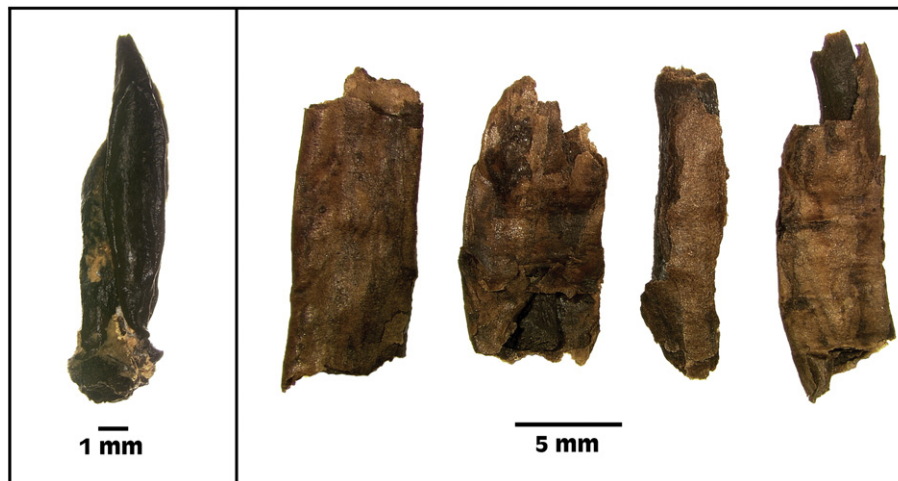


Figure 5. Spruce log in clay at Mercy Hospital site. *Mytilus edulis* shells (upper right) yielded a radiocarbon age of  $12,850 \pm 65$   $^{14}\text{C}$  yr BP (OS-61188).

**Table 1**  
Radiocarbon and calibrated ages of terrestrial and marine samples from the Mercy Hospital site, Portland, Maine. "Cal yr BP" refers to AD 1950. Calibrated ages based on "Kromer/Hua" were obtained by wiggle-matching wood and bud ages indicated below to the radiocarbon data constructed by Kromer et al. (2004) and placed in absolute time by Hua et al. (2009).

Stratigraphic unit	Age, <sup>14</sup> C yr BP	Method	δ <sup>13</sup> C	Sample type	Laboratory and number	Calibrated cal yr BP (2σ)	Calibration based on
<i>Terrestrial samples</i>							
Peat (3)	11,650 ± 50	AMS	-28.15	Single bud of <i>Populus balsamifera</i>	OS-64546	(13,510 ± 166) 13,520 + 95/-20	(IntCal09) or Kromer/Hua
Peat (3)	11,650 ± 65	AMS	-26.47	Bud and woody branch tip of <i>Picea glauca</i> with needles attached	OS-64547	(13,514 ± 184) 13,520 + 95/-20	(IntCal09) or Kromer/Hua
Peat (3)	11,800 ± 50	AMS	-25.25	Bud and woody branch tip of <i>Picea glauca</i> without attached needles	OS-64548	13,626 ± 169	IntCal09
Sand (2)	11,700 ± 50	AMS	-26.52	Twig or root of woody plant	OS-70191	13,559 ± 163	IntCal09
Interface of Sand (2) and Peat (3)	11,849 ± 29	AMS	-29.5 ± 0.1	Wood of <i>Picea</i> sp.	ETH-35171	13,706 ± 128, 13,514 ± 25	IntCal09 – 91.4%, 4.0% probability
Marine clay (4)	11,900 ± 55	AMS	-25.25	Wood	OS-60259	13,753 ± 170, 13,516 ± 15	IntCal09 – 94.0%, 1.4% probability
Marine clay (4)	11,750 ± 55	AMS	-26.85	Wood	OS-60933	13,594 ± 167	IntCal09
<i>Ring segments of two logs used for radiocarbon wiggle-matching</i>							
Marine clay (4)	11,779 ± 48	β-decay	-24.0	PRF1-2, 10 rings, 1087–1096 RY	Hd-26255	13,629 + 95/-20	Wiggle-match fit
Marine clay (4)	11,803 ± 31	β-decay	-23.6	PRF1-2, 10 rings, 1097–1106 RY	Hd-26283	13,619 + 95/-20	Kromer/Hua
Marine clay (4)	11,834 ± 35	β-decay	-25.8	PRF2-3, 22 rings, 1111–1132 RY	Hd-26254	13,599 + 95/-20	Kromer/Hua
Marine clay (4)	11,778 ± 43	β-decay	-22.4	PRF1-2, 10 rings, 1132–1141 RY	Hd-26335	13,584 + 95/-20	Kromer/Hua
Marine clay (4)	11,907 ± 31	β-decay	-25.7	PRF1-2, 15 rings, 1147–1161 RY	Hd-26285	13,567 + 95/-20	Kromer/Hua
Marine clay (4)	11,721 ± 40	β-decay	-26.1	PRF1-2, 15 rings, 1162–1176 RY	Hd-26273	13,552 + 95/-20	Kromer/Hua
Marine clay (4)	11,812 ± 31	β-decay	-26.4	PRF1-2, 24 rings, 1177–1200B RY	Hd-26272	13,532 + 95/-20	Kromer/Hua
<i>Marine samples associated with tree remains</i>							
Marine clay (4)	12,850 ± 65	AMS	-0.2	<i>Mytilus edulis</i> valve	OS-61188	14,532 ± 362	Marine04
Marine clay (4)	12,800 ± 55	AMS	0.21	Barnacle fragments	OS-60406	14,511 ± 389	Marine04
<i>Marine samples above wood-bearing zone</i>							
Marine clay (5)	12,650 ± 55	AMS	-0.05	<i>Macoma balthica</i> valve	OS-60388	14,143 ± 208	Marine04
Marine clay (5)	12,500 ± 55	AMS	-0.11	<i>Serripes groenlandicus</i> valve	OS-60390	13,944 ± 137	Marine04
Marine clay (5)	12,350 ± 90	AMS	1.65	unidentified valve fragment	OS-60389	13,816 ± 199	Marine04

PRF1 and PRF2 are trench numbers. RY = relative years. B indicates outer ring just below bark.



**Figure 6.** Fossils of balsam poplar (*Populus balsamifera*). At left, lateral bud used for AMS age determination; at right, four twig segments with bark. From Unit 3.

of the overlying clay, is consistent with our interpretation that Unit 4 was transported by a landslide from a shallow marine environment.

#### Terrestrial plant fossils

All excavated wood samples from both the hospital and 1976 sites are of *Picea*. *Picea* wood is not identifiable to a species, but since only the hairless branches of *P. glauca* (Fig. 4) were present in the sediments at the hospital site, we are confident that the logs are the same species. Wood of *Populus* (poplar) was not present, although branch fragments identified as those of *P. balsamifera* (balsam poplar) were found (Fig. 6). The *Picea* logs occurred as broken segments up to at least 1.2 m long and 20–25 cm in diameter, and usually with bark attached. They lay parallel to the surface on which they were deposited. The trunk segments were scattered, not stacked on each other, and were randomly oriented. One of the largest logs was curved, reflecting how the tree grew. This log and all but one of the other trunk segments contained compression cells, indicating the trees grew on slopes. Similarity of ring structure and ring-width patterns in the samples indicated that some had come from the same tree, but at least five trees were represented. Branches were abundant, and many had needles still attached. Roots and root masses were also found but none was attached to a trunk segment. Despite the breakage and clay overburden, details of growth rings and cell structure in the tree samples were very well preserved. This good preservation was also noted by Hyland et al. (1978) for logs in the 1976 site.

Paleobotanical studies of large-volume (100–700 ml) samples of organic detritus from an area of ~150 m<sup>2</sup> at the study site established the presence of fossils of *P. glauca* (twigs with needles attached and gone, and seed and pollen cone scales, all taxonomically diagnostic) and of *P. balsamifera* (diagnostic lateral buds; Fig. 6). In addition, the deposit contained fossils of wetland sedges (fruits of *Carex* and *Cladium*), raspberry or blackberry (*Rubus*) nutlets, a seed of the dry-land herb *Arenaria/Minuartia* (Caryophyllaceae), and leafy plants of 20 different mosses (Tables 2 and 3).

The two pollen spectra recovered are essentially identical (Table 4). Both samples were overwhelmingly dominated by pollen of *Picea* (87 and 88%), with minor *Pinus* (pine), *Betula* (birch), and Poaceae (grass) pollen percentages (each ≤2% of the pollen sum). Sedge (Cyperaceae) pollen was 5 or 6% of the totals. Other taxa were represented by one or two grains each. Spores of ferns, *Sphagnum*, and native *Lycopodium* (clubmoss) were rare but present. One sample had an abundance of spores of *Tilletia*, a fungus with more than 100

species, of which one (*T. sphagni*) is a known spore capsule parasite of *Sphagnum* moss (Davis, 1903).

#### Paleoecology

#### Paleobotany

Botanical results from the Mercy Hospital site add new information to the late-glacial vegetation history of northeastern North America. The open forest consisted of *P. glauca* and *P. balsamifera*, both of which invade raw, often calcareous soil in the contemporary

**Table 2**

Plant macrofossil abundance in samples of Presumpscot Formation organic layer (Unit 3) from exposures 07-6 (#s 1–4) and 07-13 (#s 5–7), Mercy Hospital site, Portland, Maine.

Fossil type/sample #	1	2	3	4	5	6	7
<i>Picea glauca</i>							
Branches with needles	++	+	–	+	–	–	–
Branches without needles	++	++	+	+	–	+	+
<i>Picea</i> sp., probably <i>P. glauca</i>							
Bark plates	+++	++	+	–	++	+++	++
Brown needles	++	+++	++	++	–	++	++
Green needles	+++	+++	+	+++	–	+	+
Needle/sterigma cushions	–	+++	++	++	+	+++	+++
Sterigmata	+	++	–	+	–	+	–
Buds/bud scales	++	+++	–	++	–	+	+
Seed cones	+	+	–	+	–	–	–
Seed cone scales	–	+	–	+	–	+	–
Seeds	–	+	+	+	+	++	+
Seed wings	+	+	–	–	–	+	+
Pollen cones	+	+	–	–	–	+	+
Microsporangia	+	+	–	–	–	–	–
<i>Populus balsamifera</i>							
Buds/bud scales	+	+	–	+	–	+	–
Twig fragments	+	–	+	+	+	++	+
<i>Carex</i> perigynia	–	–	–	–	+	–	–
<i>Carex</i> achenes trigonous	–	–	–	–	+	–	–
<i>Cladium mariscoides</i> nutlets	–	+	–	–	–	–	–
Caryophyllaceae ( <i>Arenaria/Minuartia</i> )	–	–	–	–	–	+	–
<i>Rubus</i> nutlets	–	–	–	+	–	–	+
Unknown seed	–	–	–	–	–	–	+
<i>Nostoc</i> thalli	–	+	–	+	–	–	–
<i>Cenococcum</i> sclerotia	–	–	++	–	–	+++	–
Sample area (cm <sup>2</sup> )	125	95	80	80	150	180	150
Sample volume (ml)	700	500	125	100	300	190	200
Wet residue volume (ml)	340	280	180	150	80	190	160

Key: +++ (abundant), ++ (sparse), + (one to few), and – (absent).

**Table 3**

Moss frequency and abundance in samples of Presumpscot Formation organic layer (Unit 3) from exposures 07-6 (#s 1–4) and 07-13 (#s 5–7), Mercy Hospital Site, Portland, Maine.

Moss name/sample #	1	2	3	4	5	6	7
<i>Abietinella abietina</i>	–	–	–	+	–	–	–
<i>Aulacomnium palustre</i>	++	–	–	–	–	–	–
<i>Bryum pseudotriquetrum</i>	–	+	–	–	–	–	–
<i>Bryum</i> sp.	++	+	–	+	–	–	–
<i>Calliergon giganteum</i>	+	+	–	–	–	–	+
<i>Ceratodon purpureus</i>	–	+++	–	++++	–	–	–
<i>Cynodontium</i> cf. <i>tenellum</i>	–	–	–	+	–	–	–
<i>Dicranella heteromalla</i>	–	–	–	+	–	–	–
<i>Dicranum fuscescens</i>	–	+	–	+++	–	–	–
<i>D. scoparium</i>	–	–	–	+	–	–	–
<i>Didymodon asperifolius</i>	–	+	–	–	–	–	–
<i>Drepanocladus aduncus</i>	+	+	–	–	–	–	–
<i>D. sordidus</i> <sup>a</sup>	+	–	–	–	–	–	–
<i>Eurhynchium pulchellum</i>	–	+++	–	++	–	++	–
<i>Limprichtia cossonii</i>	++	–	–	–	–	–	–
<i>Orthotrichum</i> sp.	+	–	–	+	–	+	–
<i>Palustriella falcata</i>	+++	–	–	–	–	–	–
<i>Philonotis fontana</i>	++++	+	–	–	–	–	–
<i>Pohlia</i> sp.	–	–	–	+	–	–	–
<i>Polytrichum juniperinum</i>	–	+++	–	–	–	–	–
<i>Pseudocalliergon turgescens</i>	–	+	–	–	–	–	–
<i>Sanionia uncinata</i>	+	+++++	+++	+	–	+	+
<i>Tomenthypnum nitens</i>	+	–	–	–	–	–	–
Number species per sample	11	12	1	11	0	3	2

Key: + (few, 1 or 2 fossils), ++ (several, 3–5), +++ (many, 6–25), ++++ (numerous, 26–50), +++++ (very numerous, >50), – not present.

<sup>a</sup> *Drepanocladus sordidus* (*D. sendtneri*, as applied by various North American authors).

vegetation of northern regions. While pollen and plant macrofossils establish that “poplars” were generally the first arriving trees in this region after deglaciation (Davis and Jacobson, 1985), few reports specify which of three or four potential species (*P. balsamifera*, *P. deltoides*, *P. grandidentata*, and *P. tremuloides*). Our record of *P. balsamifera*, a dated bud (Fig. 6), establishes that this species grew in southwestern Maine at ~11,600 <sup>14</sup>C yr BP, ca. 1500 <sup>14</sup>C yr after the

**Table 4**

Pollen counts of two samples from Presumpscot Formation organic layer (Unit 3), Mercy Hospital site, Portland, Maine.

Taxon	Sample Weddle #1			Sample Weddle #2		
	Grains counted	%	Grains/cm <sup>3</sup>	Grains counted	%	Grains/cm <sup>3</sup>
<i>Pinus</i>	7	2.1	2703	5	1.5	3949
<i>Picea</i>	289	87.3	111,586	292	88.2	230,614
<i>Betula</i>	5	1.5	1931	7	2.1	5528
<i>Salix</i>	1	0.3	386	1	0.3	790
<i>Populus</i>	1	0.3	386	2	0.6	1580
<i>Corylus</i>	1	0.3	386	1	0.3	790
Poaceae	6	1.8	2317	6	1.8	4739
Cyperaceae	20	6.0	7722	16	4.8	12,636
<i>Artemisia</i>	1	0.3	386	1	0.3	790
Grains Counted	331	100.0	127,803	331	100.0	261,415
Unidentifiable	18	5.4	6950	4	1.2	3159
Monolete fern spores	3	0.9	1158	2	0.6	1580
Trilete fern spores	1	0.3	386	1	0.3	790
<i>Sphagnum</i> spores	2	0.6	772	1	0.3	790
<i>Lycopodium</i>	3	0.9	1158	3	0.9	2369
annotinum-type spores						
<i>Tilletia</i> spores	439	132.6	169,503	11	3.3	8688
<i>Lycopodium</i> tracers	36	10.9	13,900	16	4.8	12,636
Initial sample volume (ml)	1.0			1.1		

first arrival of poplars according to the Davis and Jacobson (1985) interpretation of the pollen record. This new information may mean that the arrival history of *P. balsamifera* needs revision, or just as likely that the regional migration history of *Populus* is constrained by too few, species-specific, non-pollen data points.

Fossils of only *P. glauca* were recovered from the organics and clays at the hospital site, even though pollen analysis at other coastal sites 60 and 160 km away (Schauffler and Jacobson, 2002; Lindbladh et al., 2003) demonstrated late Pleistocene presence of both *Picea mariana* (black spruce) and *P. glauca*. This probably indicates the lack of suitable edaphic conditions for *P. mariana* in the Fore River area at that time, including soil instability. *P. glauca* is absent from forests in contemporary southern coastal Maine, but it is common in the mid-coast region and northeastward. There, and especially on offshore islands in Penobscot Bay and farther east along the coast, *Picea* and *Abies balsamea* (balsam fir) can comprise two-thirds or more of the forest (Davis, 1966). From pollen data, Schauffler and Jacobson (2002) traced this dominance to cooler and moister conditions along the eastern Maine coast beginning between 6000 and 5000 yr ago, which they related to independent evidence of cold water influx into the Gulf of Maine at this time.

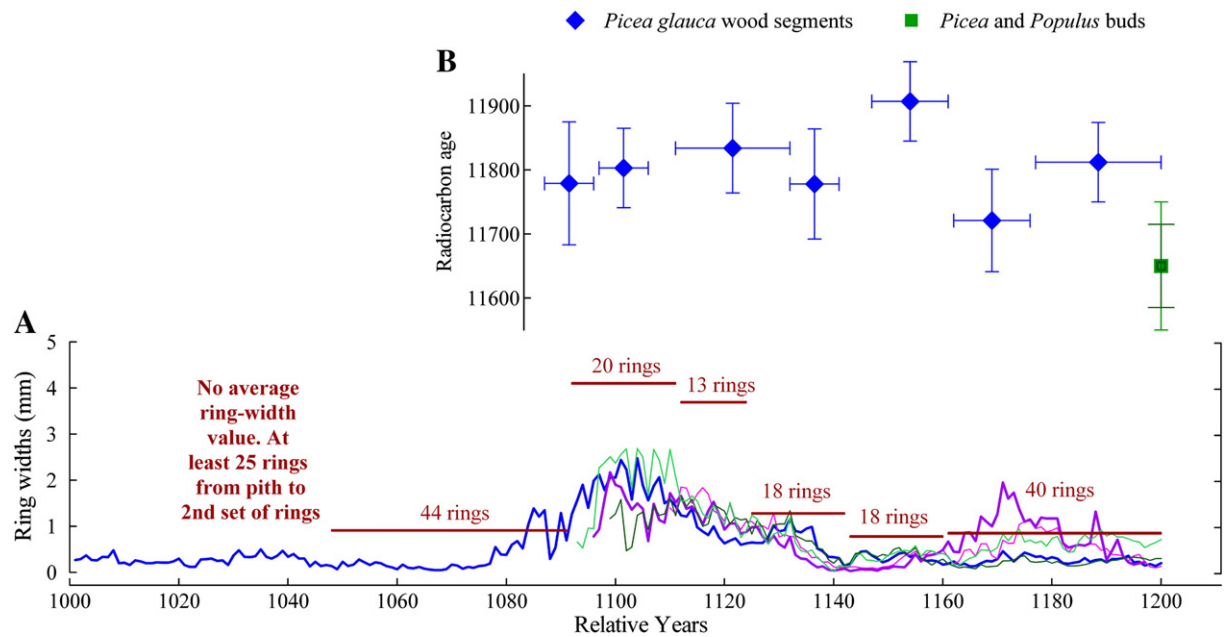
While tree cover at the study site consisted of two species, a diverse series of ground-layer plant communities containing many different mosses and herbaceous vascular plants establishes that the vegetation was heterogeneous and complex, particularly at a scale measured in meters to tens of meters. Most of the organic samples contained moss assemblages characteristic of a single plant community, but a few had mixtures representing more than one community. This suggests that the organic layer (Unit 3) was mostly deposited as clasts, ripped up from the original place of growth and transported more or less intact, with little mixing during transport and deposition. Moss assemblages in organics from the hospital site do not differ greatly from the contemporary bryophyte flora of this region, indicating a late-glacial climate in southern Maine similar to that presently characteristic of central and eastern coastal Maine.

Fossils of *P. glauca* and *P. balsamifera* provide indirect evidence of soil acidity in the region near the Fore River, where local units of calcareous bedrock (Hussey, 2003) perhaps contributed to the glacial and postglacial sediments on which the soils developed. The fossil mosses and vascular plants indicate the presence of varied wetland (pH generally circumneutral) and dryland plant communities associated with *P. glauca*–*P. balsamifera* forest, including (1) calcareous fens with standing water and/or calcareous spring seeps (*Calliergon giganteum*, *Limprichtia cossonii*, *Pseudocalliergon turgescens*, and *Tomenthypnum nitens*), (2) dry, well-drained soil, somewhat calcareous to acidic, beneath sparse tree cover (*Abietinella abietina*, *Aulacomnium palustre*, and *Polytrichum juniperinum*), and (3) open mixed, acidic to weakly calcareous forest floor of *P. glauca*–*P. balsamifera* (*Dicranum fuscescens*, *Eurhynchium pulchellum*, and *Sanionia uncinata*). Five of 23 identified mosses (*Didymodon asperifolius*, *Drepanocladus sordidus*, *Limprichtia cossonii*, *Palustriella commutata*, and *Pseudocalliergon turgescens*) are evidently not part of the contemporary Maine moss flora (Allen, 1999, 2005), although localities for all five are known from other parts of New England and adjacent Canada (Crum and Anderson, 1981).

*Dendrochronology*

A tree-ring chronology of 200 yr was built from the ring-width measurements of five trees (Fig. 7A; Table 5). This chronology shows that all the trees, including one found at the 1976 site, grew during the same time. Identical relative years of the complete outer rings of these samples with bark or a waney edge (just bark removed) established that they died in the same year during winter dormancy. Twigs found at the 1976 site died during their growing season (Hyland et al., 1978). Those twigs could have been part of the forest floor litter prior to landslide transport, or they may have been deposited slightly later





**Figure 7.** (A) Matched tree-ring sequences of six wood sections from five trees found at the Mercy Hospital site, and average ring widths, represented by the horizontal lines above the 2007 sequences, of segments in a log collected by W. Thompson at the 1976 site. The blue line represents overlapping segments from the 200-yr-old tree. (B)  $^{14}\text{C}$  ages of seven ring segments from logs PFR1-2 and PFR2-3 (the two thicker lines in part A) showing the relative placement of the segments in the 200 yr of the tree-ring chronology. This relative placement is key to wiggle-matching the radiocarbon ages to reduce error in the calibrated ages.

by continued slope failure on Bramhall Hill. A log from the 1976 site has the same ring-width patterns as those found in 2007 (Fig. 7A), so it is likely that deposition of organic materials at the 1976 locality occurred at the same time or soon after deposition at the hospital site.

Our dendrochronological record established a minimum life span of 200 calendar years for the forest, and thus the associated organic detritus presumably represents plant litter that accumulated over at least two centuries. The ring-width patterns of the trees showed responses to changes in microenvironments. Very small ring widths in centers of the two oldest tree segments indicate growth in a relatively flat but stressed microenvironment (typical of soil development on dense marine clay), and possibly a high water table, for the first 90 yr. Some abrupt event such as a slump or the initiation of strong unidirectional winds caused the trees to tilt at age 90, when compression cell growth began. This response is an outcome of an inclined tree trying to return to, or stay in, a vertical position. Compression growth continued for about 20 yr, after which there was a slight reduction in ring width over the next 30 yr. During these 50 yr, the trees produced wider rings than during the first 90 yr, indicating conditions conducive to growth such as better drainage or

warmer temperature. At 140 yr there was a return to small, less-dense ring widths with no compression cells, indicating the trees had attained an upright position, or possibly the water table had risen or wind direction and speed had changed. This growth phase lasted about 20 yr. Finally, the trees grew under slightly better conditions for their last 40 yr, all with denser cell growth but varied amounts of compression cells depending on the individual tree. The absence of root systems attached to the logs plus their broken ends suggest that the trees were snapped off and further broken in transport, which is consistent with our landslide interpretation.

Our tree-ring record from the hospital site reflects environmental changes on scales of 10s to 100s of meters. Unfortunately, the relationship between local (10–1000 m) and regional (>1000 m) tree growth is not known, because there are no other *P. glauca* tree-ring chronologies covering the same period in northeastern North America. Ring-width data are available for late-glacial *Picea* sp. chronologies built from trees that grew in New York about 200 yr before our chronology (Griggs and Kromer, 2008) and also from within the Younger Dryas chronozone (Miller and Griggs, unpublished data). In the Holocene record, ring-width data sets are available for modern *P. glauca* chronologies only from northern Newfoundland and Quebec in the International Tree Ring Data Base (ITRDB, <http://www.ncdc.noaa.gov/paleo/treering.html>).

Comparing average ring width of the first 100 rings (starting at the pith) in the trees of each series, the three late-glacial groups from New York and our study site in Maine show a linear increase in average ring width from the earliest group to the end of that period (Table 6). *P. glauca* grows wider annual rings in response to higher summer temperatures (Briffa et al., 1995), so the ring-width data from our site are consistent with the trend of increase in summer temperature through the late-glacial period.

Comparing modern *P. glauca* ring growth, data sets from nine northern Newfoundland and Quebec forests were broken into two classes by their proximity to the ocean (Table 6). The interior trees, on average, grew substantially larger rings in their first 100 yr's growth than all except those at the Cohoes, New York site (an interior Younger Dryas site). The modern trees in coastal Newfoundland,

**Table 5**

Crossdating details of the five spruce trees from seven samples that are included in the Mercy Hospital tree-ring chronology. Statistical tests between trees give an average Student's *t*-score of 4.39, average correlation coefficient of 0.411, and average trend coefficient of 66.3%; all are significant at 95%. The "correlation with chronology" values are correlations between each sample and a chronology composed of all other samples; these values are likewise significant at 95%. Notations in the series columns are: RY – relative years; p – pith present; W – Waney edge, only bark missing; and B – bark present. See Supplemental Table 5 for additional information.

Wood sample	Series begins (RY)	Series ends (RY)	Number of rings	Correlation with chronology
PFR1-1&2&3	1001p	1200W	200	0.44
PFR2-2	1111p	1200B	90	0.51
PFR2-3	1096p	1200W	105	0.56
PFR2-5	1099p	1200W	102	0.57
PFR2-8	1093p	1200B	108	0.53

**Table 6**

Average ring-widths (ARW) of the first 100 yr of growth in spruce trees from the indicated sites in northeastern North America. Note the consistent increase in the ARW over time for the late-glacial sites, ending with the Cohoes site ARW which is comparable to the modern northern interior sites. The Mercy Hospital site ARW is in between the two modern values, but closer to the coastal average. Each average is taken from the raw ring-width data of 5 to 64 tree-ring series. See Supplemental Table 6 for modern site locations and sources.

Site	Average ring width in mm	Period represented
Moffet mastodon site, North Java, New York	0.65	12.2–11.9 <sup>14</sup> C ka BP
Mercy Hospital site, Portland, Maine	0.67	11.9–11.7 <sup>14</sup> C ka BP
Harmony Mills Pump House site, Cohoes, New York	0.80	10.5–10.2 <sup>14</sup> C ka BP
5 interior sites, northern Newfoundland to northern Quebec	0.79	AD 1660–1988
4 coastal sites, northern Newfoundland	0.60	AD 1634–2001

north of latitude 55° N, grew smaller rings than any others, indicating that coastal *P. glauca* trees are generally more stressed in that environment than in a continental ecosystem. Since the average ring width of the coastal modern trees is also substantially less than in trees at our coastal site in Portland (0.60 vs. 0.67 mm, respectively), the trees at our site probably were growing in warmer conditions than are seen today on coastlines above 55° N.

#### Paleoentomology

At least 26 different Coleoptera were represented in samples from the hospital site, among which 15 in six families could be identified to species (Table 7). These results show two distinct local environments, one with moist to wet organic-rich substrates, the other underlain by dry sandy ground, and including both forested and non-forested local conditions. *Agonum melanarium*, *Bembidion versicolor*, *Elaphrus clairvillei*, and *Bradycellus badipennis* are ground beetles that live on

damp to marshy ground, often at the margins of still waters (Lindroth, 1961–1969). The rove beetles *Acidota subcarinata* and most species of *Stenus* are almost invariably found in the same habitats. The Dytiscidae are predaceous diving beetles that require some surface water, though perhaps no more than a small pool <1 m across. *Cercyon* and *Aegialia terminalis* are detritus feeders of damp to wet substrates. *A. terminalis* is often found on gravelly or rocky substrates at the margins of streams or ponds (Gordon and Cartwright, 1988).

*Plateumaris* is a genus of leaf beetles known to feed almost exclusively on emergent sedges (Askevold, 1991), which is consistent with the sedge pollen content and achenes of *Carex* in the samples. *Orsodacne atra* is found transcontinentally and feeds on leaves of a variety of broadleaved angiosperms (Downie and Arnett, 1996). The pill beetle *Cytilus alternatus* is known to feed on the mosses *Ceratodon purpureus*, *Philonotis fontana*, and *Bryum* (P. J. Johnson, pers. comm., 27 Dec. 2007), all of which are represented in the moss flora from the deposit.

*Agonum placidum*, *Bembidion nitidum*, and *Aegialia blanchardi*, by contrast, are taxa of dry, sandy substrates (Lindroth, 1961–1969; Gordon and Cartwright, 1988). In the modern Maine fauna, *B. nitidum* is found almost exclusively on sandy roadsides and in commercial sand pits, while *A. placidum* is commonly encountered on dry, sandy stream bars; neither is a pronounced halophyte or coastal species. *A. blanchardi*, however, is almost exclusively a coastal dune species, occurring from Quebec south to Georgia (Gordon and Cartwright, 1988).

Bark beetles (family Scolytidae) are also consistent with the plant macrofossil record. *Phloeotribus piceae* is found from the northeastern United States into Canada and west to Manitoba, while *Scolytus piceae* is transcontinental in distribution. Both attack *Picea*, most commonly dead and dying limbs (Ashworth and Brophy, 1972; Bright, 1976). *Hylastes porculus* is found in Canada and the United States east of the Rocky Mountains and attacks species of pine, whereas *Polygraphus rufipennis* is known to attack all conifers in its range, which is transcontinental in Canada and south to North Carolina and Tennessee in the eastern United States. *Xylechinus americanus* “adults

**Table 7**

Coleoptera from Presumpscot Formation organic layer (Unit 3), Mercy Hospital site, Portland, Maine.

Family	Genus and species	Weddle Sample	Thompson Peat “A”	Miller #1	Miller #2	Miller #3	Miller #4
Byrrhidae	<i>Cytilus alternatus</i> (Say)	–	–	1	–	–	–
Carabidae	<i>Agonum melanarium</i> Dej.	–	1	–	–	–	–
	<i>Agonum placidum</i> Say	–	–	–	–	–	1
	<i>Bembidion nitidum</i> Kirby	–	–	1	–	–	–
	<i>Bembidion versicolor</i> LeC.	–	1	–	–	–	–
	<i>Bradycellus badipennis</i> (Hald.)	–	–	1	–	–	–
	<i>Cicindela</i> sp.	–	1	–	–	–	–
	<i>Elaphrus clairvillei</i> LeC.	–	–	1	–	–	–
Chrysomelidae	<i>Orsodacne atra</i> Ehr.	–	–	–	–	–	1
	<i>Plateumaris</i> sp.	–	1	1	–	–	–
Curculionidae	gen. et sp. indet.	–	1	–	–	–	–
Dytiscidae	<i>Agabus</i> sp.	–	–	1	–	1	–
	<i>Hydroporus</i> sp.	–	–	1	–	–	–
Elateridae	gen. et sp. indet.	–	1	–	–	1	–
Hydrophilidae	<i>Cercyon</i> sp.	–	–	1	–	–	–
Leiodidae	<i>Agathidium</i> sp.	–	–	1	–	–	2
Scarabaeidae	<i>Aegialia blanchardi</i> Horn	5	1	–	8	6	1
	<i>Aegialia terminalis</i> Brown	2	3	–	5	9	–
Scolytidae	<i>Hylastes porculus</i> Er.	–	–	–	–	1	–
	<i>Phloeotribus piceae</i> Swain	1	–	–	–	1	–
	<i>Polygraphus rufipennis</i> Kirby	–	–	–	2	2	2
	<i>Scolytus piceae</i> (Swain)	–	–	–	–	2	–
	<i>Xylechinus americanus</i> Blackm.	–	–	–	1	–	–
Staphylinidae	<i>Acidota subcarinata</i> Er.	–	1	–	–	–	–
	Omalinae, gen. et sp. indet.	–	1	–	1	–	1
	<i>Quedius</i> sp.	–	1	–	–	–	–
	<i>Stenus</i> spp.	–	5	1	1	1	1
	Staphylininae, gen. et sp. indet.	–	7	–	–	–	–

attack small, weakened, dying, usually suppressed spruce trees” (Bright, 1976, p. 65). Thus, the Scolytid fauna is consistent with the stressed *Picea* growth indicated by the tree-rings, with possible rare outliers of *Pinus* within a few tens of kilometers.

The terrestrial plant and insect fossils at the hospital site collectively indicate the establishment of an open *Picea* forest on a variety of raw, low-relief, calcareous soils dominated by mosses. The climate at this site during the represented time period was not substantially different from modern conditions along the coast in Maine and maritime Canada, south of latitude 52° N.

#### Radiocarbon ages

Table 1 lists the radiocarbon ages of the terrestrial and marine samples submitted for dating, as well as their calibrated ages. The radiocarbon ages in this paper are in  $^{14}\text{C}$  yr BP relative to AD 1950. Calibrations of  $^{14}\text{C}$  ages, especially terrestrial sample ages, prior to 11,000  $^{14}\text{C}$  yr BP give different ages and ranges depending on the sources and programs used, but these differences generally are much less than 100 cal yr.

The dated terrestrial samples were collected from a small area (Fig. 1) and were found near the bottom of the exposed marine clay (Units 2, 3, and 4). Their radiocarbon ages range from 11,907 to 11,650  $^{14}\text{C}$  yr BP. Marine shells found adjacent to the tree remains in Unit 4 yielded ages of 12,850–12,800  $^{14}\text{C}$  yr BP, while shells from slightly higher in the section (lower part of Unit 5) dated to 12,650–12,350  $^{14}\text{C}$  yr BP.

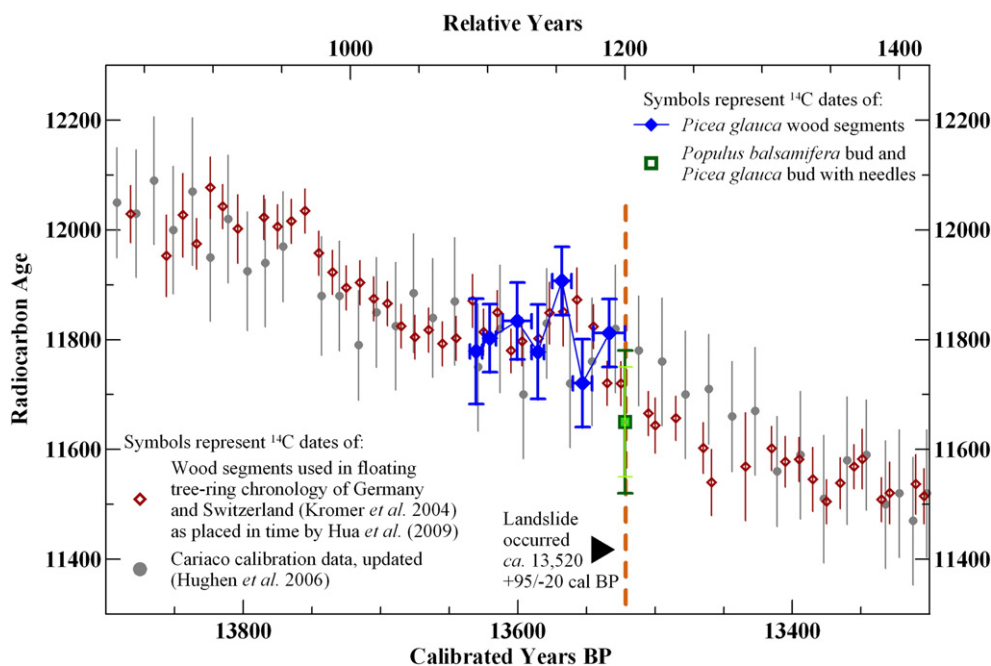
Two *P. glauca* bud/branch apices and a *P. balsamifera* bud found in the detrital organic layer (Unit 3) were dated. One *Picea* branch sample had attached needles, representing growth during the year prior to tree death; the other was without needles. The radiocarbon ages of these samples are  $11,650 \pm 65$  and  $11,800 \pm 50$   $^{14}\text{C}$  yr BP respectively (Table 1). While the ages obtained for these two fossils do not differ statistically at  $2\sigma$ , the branch without needles probably represents older tree growth and was incorporated into the detrital unit prior to the landslide. The age of the associated *P. balsamifera* bud was the same as the *P. glauca* bud/branch apex with needles. Both

buds were closed as is normal during winter dormancy, and their two ages were used to represent the same year as the last year of ring growth before the landslide occurred at the hospital site (see below).

From two of the logs, seven ring segments containing 10–24 rings were dated (Table 1; Fig. 7B). The radiocarbon ages of these samples and the two bud ages were wiggle-matched (Fig. 8) to calibrate them to calendar years. Accurate calibration of any late-glacial terrestrial radiocarbon age from before the middle of the Younger Dryas chronozone (prior to 10,650  $^{14}\text{C}$  yr BP) is difficult, because tree-ring and other terrestrial or atmospheric high-frequency radiocarbon data are scarce. The IntCal09 curve before 10,650  $^{14}\text{C}$  yr BP is based on marine data adjusted with the Holocene marine reservoir value of approximately 410 yr (see Table 1 in Reimer et al., 2009), including the Cariaco Basin data (Hughen et al., 2004, 2006). However, wiggle-matching the variability in our tree-ring  $^{14}\text{C}$  sequence to IntCal09 yielded anomalous results; instead we compared our sequence to those in two single-source radiocarbon calibration data sets from the late-glacial period (Fig. 8).

The relationship of the radiocarbon ages of the wood segments across the lifetime of the trees, plus the two bud ages (Fig. 8), indicate that there were substantial changes in atmospheric radiocarbon content during that period. Rather than showing the normal pattern of relatively decreasing  $^{14}\text{C}$  ages from inner to outer tree rings, the ages in this sequence are fairly constant over time with a marked increase in the 5th segment corresponding to a period of very small ring growth, followed by a marked  $^{14}\text{C}$  decrease, then a return to about the same level in the wood, and ending with a substantial decrease in the bud ages (Fig. 7B). These changes in  $^{14}\text{C}$  ages are potential indicators of rapid climate change, reflecting the higher variability in both atmospheric and marine radiocarbon content commonly found during the late-glacial period (Kromer et al., 2004; Bondevik et al., 2006). This variability in  $^{14}\text{C}$  content is also evident in the Cariaco Basin marine radiocarbon record (Hughen et al., 2000, 2006) and has been noted in speleothems for the late-glacial period (Beck et al., 2001; Hoffmann et al., 2010).

The  $^{14}\text{C}$  sequence in our tree rings is supported by a similar pattern in the radiocarbon content of the tree rings used to build a floating



**Figure 8.** The radiocarbon ages of the wood and buds were wiggle-matched to the  $^{14}\text{C}$  ages of wood segments in a floating chronology of central European pines placed in time by the Huon pine  $^{14}\text{C}$  data (Kromer et al., 2004; Hua et al., 2009), plus the revised Cariaco calibration curve (Hughen et al., 2006). A potential date for the landslide event is noted with the appropriate error calculated from the possible fits of the data to these two curves. Horizontal bars indicate the range of the rings that are included in the sample; vertical bars indicate the  $2\sigma$  error.

tree-ring chronology of central European pines over that particular period (Fig. 8; Friedrich et al., 1999; Kromer et al., 2004). This floating chronology was placed more securely in time by a comparison with  $^{14}\text{C}$  data from Huon pine (Hua et al., 2009). Variability in the two tree-ring-based  $^{14}\text{C}$  sequences plus the Cariaco curve over this period may indicate a time of significant change in the meridional overturning circulation in the Atlantic Ocean, but the two tree-ring sequences are not totally synchronous, suggesting additional regional influences.

Wiggle-matching the nine radiocarbon ages to these curves places the date of the Portland landslide at  $13,520 \pm 95/-20$  cal yr BP (Fig. 8). 13,520 cal yr BP is to the right of center in the  $2\sigma$  range of ages, but is indicated both by the variation of ages in the tree-ring segments and the considerably younger radiocarbon ages of the buds.

#### Marine reservoir effect

Deglaciation chronologies for southern Maine (e.g., Borns et al., 2004) have relied on radiocarbon ages of marine shells in ice-proximal sediments to constrain the timing of ice retreat, and these ages likewise anchor late-glacial relative sea-level curves (Barnhardt et al., 1995; Retelle and Weddle, 2001). However, there has been little information concerning the carbon reservoir effect on marine shell ages from Maine. Dorion et al. (2001) suggested a reservoir age of 700 yr for eastern Maine, and Borns et al. (2004) inferred a reservoir age of 600 yr. Neither of these estimates was based on radiocarbon ages of juxtaposed marine and terrestrial organics from the same stratigraphic unit.

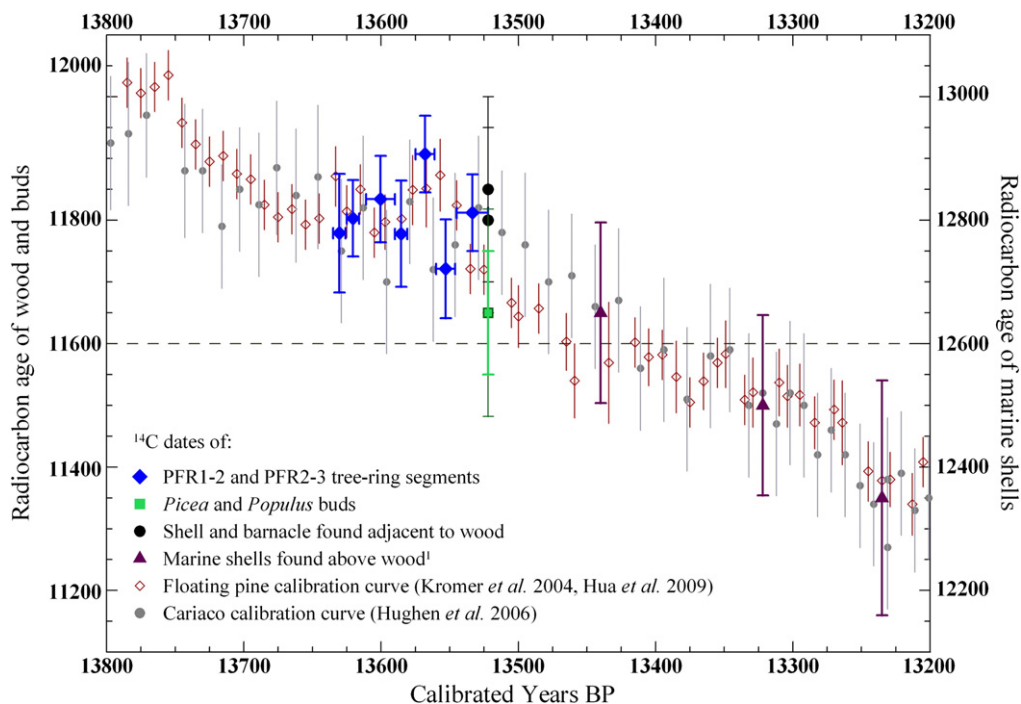
We compared the ages of associated marine and terrestrial fossils from the Mercy Hospital site to evaluate the late-glacial marine reservoir effect in southwestern Maine. The validity of our reservoir determination depends on these fossils being coeval. Although the clay in which they occurred (Unit 4) is allocthonous, the *M. edulis* shells found next to a *Picea* log in this unit do not appear to have been transported far. Many of the fragile valves were still intact, and their intimate association with the terrestrial biota suggests they were not deeply buried prior to being juxtaposed with the tree remains. The radiocarbon ages of both the *Mytilus* and *Balanus* shells (likewise

found next to wood) are statistically identical (Table 1), so these shells were not introduced from sources of disparate age. They are typical of intertidal to shallow marine environments and probably were transported into deeper water from the nearby flank of Bramhall Hill.

We conclude from these observations that the terrestrial biota and associated marine organisms in Units 2, 3, and 4 lived at essentially the same time. The difference in radiocarbon ages between wood and shells from Unit 4 (Table 1) indicates a local marine reservoir age of approximately 1000 yr, with a possible range of 950 to 1200 yr (Fig. 9). Comparison of the calibrated wood and shell ages in Table 1 yields a reservoir value of the same magnitude. This discrepancy between marine and terrestrial ages is at least 300 yr greater than previous estimates for Maine.

The only other published late-glacial marine reservoir ages from the vicinity of New England were obtained from Champlain Sea deposits. Cronin et al. (2008) reported radiocarbon ages for eight paired samples of marine shells (*Portlandia arctica* and *M. balthica*) and terrestrial plant material from sediment cores taken from beneath Lake Champlain on the Vermont–New York border. Their results indicated reservoir ages averaging 1481 yr for *Portlandia* and 1717  $^{14}\text{C}$  yr for *Macoma*. In a related study, Rayburn et al. (2006) found that *H. arctica* shells had smaller reservoir values of 500–800 yr. Tremblay and Lamothe (2007) reported a reservoir age of  $600 \pm 150$  yr for marine shells associated with terrestrial vegetation at the Lac-des-Pins site in St-Antoine-Abbé, Québec (near the New York border); and Richard and Occhietti (2005) obtained a value of 1780 yr from comparison of *Macoma* sp. and terrestrial plant ages in Champlain Sea sediments beneath Lac Hertel (near Montréal, Québec). Several factors such as feeding habits and carbonate-rich bedrock influenced reservoir ages of marine shells in the Champlain Sea basin (Richard and Occhietti, 2005).

Studies of radiocarbon ages from shoreline or nearshore environments in other regions indicate that solar fluctuations and deviations in oceanic–atmospheric circulation, plus the influence of terrestrial freshwater drainage and brackish waters, contribute to differences in reservoir ages of fossils of coastal marine organisms (Ingram and Southon, 1996; Kennett et al., 1997; Kovanen and Easterbrook, 2002;



**Figure 9.** The placement of marine shell and wood radiocarbon ages from the Mercy Hospital site on the same calibration data sets as in Fig. 8. Terrestrial  $^{14}\text{C}$  ages are indicated on the left y-axis, and marine  $^{14}\text{C}$  ages are shown on the right y-axis. The horizontal dashed line illustrates the reservoir correction of approximately 1000 yr for southwestern Maine marine radiocarbon ages during this period. <sup>1</sup>For each dated shell found above the wood, the reservoir correction may be different, but none could have less than a 550-yr correction.

Hutchinson et al., 2004; Rick et al., 2005; Bondevik et al., 2006). These reservoir variations were noted especially for the late-glacial period but may be typical of coastal environments in general (Stuiver et al., 1986). Hutchinson et al. (2004) discussed differences in  $^{14}\text{C}$  ages from marine organisms in open coastal locations and sheltered coves, resulting from the dead-carbon content of sediments and feeding habits of marine organisms used for radiocarbon age determinations. The latter authors reported late-glacial reservoir ages of ~950–1200 yr along the north Pacific coast, with larger values in sheltered locations. Bondevik et al. (2006) discussed variation between terrestrial and marine ages along the Norwegian Sea, which reached a maximum of 600 yr. The above studies indicate that reservoir ages have a local signature that may vary by hundreds of years from region to region, so our value of ~1000 yr for coastal Maine is not unusual.

#### Deglaciation chronology

The timing of deglaciation across most of New England is based on a high-precision varve chronology obtained from glacial-lake sediments. The varve record originally developed by Antevs (1922) has been refined and calibrated by Ridge (2004; <http://geology.tufts.edu/varves/default.asp>). However, it is difficult to extend this chronology into Maine because of the scarcity of suitable varve sequences. The deglaciation history of Maine is largely based on minimum-limiting radiocarbon ages from pond sediments above the marine limit and ages of marine shells from the Presumpscot Formation in the coastal lowland. In southwestern Maine the deglaciation chronology proposed by Borns et al. (2004) was older by 1000–1500  $^{14}\text{C}$  yr than Ridge's (2004) chronology in adjacent New Hampshire. We attribute part of this difference to problematic terrestrial ages obtained from bulk sediment samples or from pond biota that may not have been in equilibrium with the atmosphere. Subtracting our marine reservoir value of 1000 yr from the shell ages of Borns et al. (2004) suggests deglaciation of the Portland area at ~12,700–12,600  $^{14}\text{C}$  yr BP (15,100–15,000 cal yr BP), which is consistent with Ridge's varve chronology.

#### Conclusions

The Mercy Hospital site in Portland, Maine, and the adjacent fossil locality found in 1976, have an unusual late-glacial stratigraphy not previously recorded elsewhere in New England. Tree-trunk segments occur with other plant and insect remains and marine shells in an allocthonous marine clay unit belonging to the Presumpscot Formation. Juxtaposition of the marine and terrestrial organics is best explained by a submarine landslide that transported clay and nearshore gravel from the adjacent side of paleo Bramhall Hill. Part of the shoreline, with associated biota, was swept into the sea during this event.

The terrestrial organisms at the hospital site indicate that a varied plant and insect community developed as the Portland area emerged from the sea. Local environmental conditions at the time of the inferred landslide (~13,520 cal yr BP) were remarkably similar to those of today's southern Maine coast. During the 200 yr immediately prior to the landslide, the trees and other terrestrial organics indicate a dynamic open forest environment that experienced mass wasting with variations in water table height, plus possible climate fluctuations in temperature and wind.

Radiocarbon ages of the coeval terrestrial and marine organics indicate that a reservoir correction of approximately 1000 yr can be applied to local marine shells during the period 11,900–11,650  $^{14}\text{C}$  yr BP. Our calibrated ages support a difference of the same magnitude. This correction, extrapolated to other late-glacial marine shell ages in southwestern Maine, improves the correlation of the region's deglaciation chronology to the varve-based chronology for other parts of New England.

#### Acknowledgments

The authors thank Andrew Blaisdell and Bryan Steinert (Haley & Aldrich Inc., Portland, ME) for photos and test-boring data from the Mercy Hospital site. We are grateful to Steve Walton (Shaw Brothers Construction Inc., Gorham, ME) for prompt notification of newly excavated exposures that were critical to our study. Radiocarbon dating of our samples was funded in part by the U.S. Geological Survey STATEMAP program, and in part by the Cornell Tree-Ring Laboratory; we thank Bernd Kromer for his expertise. The Cornell Laboratory, funded by The Malcolm Hewitt Wiener Foundation, provided facilities for tree-ring analysis. Nelson's work was supported by a grant from the Natural Sciences Research Fund of Colby College. The Maine Forest Service Entomology Laboratory and Charlene Donahue graciously granted access to their extensive collections for insect fragment identifications, and Paul J. Johnson (South Dakota State University) shared his extensive knowledge of Byrrhidae. Peter Brewer (Cornell Tree-Ring Laboratory) digitized the geologic cross-sections, and John Gutwin of Pepperchrome (Portland, ME) supplied the aerial photograph of the Mercy Hospital area. Thomas Sandford (Civil Engineering Department, University of Maine) provided helpful suggestions regarding causes of landslides in the Presumpscot Formation. We thank the editors of Quaternary Research and the two anonymous reviewers, whose comments and suggestions greatly improved this paper.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.yqres.2011.02.002.

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