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Holocene Evolution of Boston Inner Harbor, Massachusetts

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ABSTRACT

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Recent building excavations in the previously landfilled Back Bay section of Boston, Massachusetts, permitted direct observation of the Holocene estuarine stratigraphic sequence. The environmental changes that occurred during this period were a concomitant decreasing submergence rate and an increasing energy level. While the diminishing submergence rate is well-documented in the regional stratigraphy, it is believed that this sequence reflects the growth of tidal resonance in the Gulf of Maine system, resulting in a change from microtidal to mesotidal conditions. Three major estuarine depositional units define the changing conditions at this site. The Lower Unit reflects rapid deepening and low energy depositional conditions; the Middle Unit marks sufficient tidal prism to lead to the formation of tidal channels; while the Upper Unit, with coarser material and tidalities, reflects higher energy during deposition.

The 5 m thick estuarine sequence unconformably overlies a weathered surface of the Boston Blue Clay, a glacio-marine meltwater deposit (approximately 14,000 yr BP). The Lower Unit (5,630 to 3,570 yr BP) defines the beginning of the Holocene submergence of Boston Inner Harbor with a sequence grading from intertidal saltmarsh to subtidal laminated muds. Average accumulation rates of 1 mm/yr roughly correspond to the thickness of laminations, suggesting an undisturbed annual deposit. The Middle Unit (3,570 to 3,090 yr BP) is interpreted as channel deposits based on numerous channel-bottom shell-lag layers. Initial average accumulation rates of 11.7 mm/yr diminish to 1.3 mm/yr at the top of the unit. The Upper Unit is a well-mixed sandy silt with occasional interfingered tidalities. Initial accumulation was 3 mm/yr, and diminished to 0.5 mm/yr at the top of the sequence. This is interpreted as a tidal flat environment, corresponding to historical records showing tidal flats and salt marsh in the area.

The stratigraphy concurs with archaeological observations at the Boylston Street Fishweir, a 4,400 yr old series of structures built and used over a several-hundred year period. The exposure of the weir is located in the Lower Unit of this sequence. Despite the collection of over 65,000 wooden stakes (parts of the weir) since it was discovered in 1913, no other artifacts have been found associated with it. Since modern fishweirs in New England, which have similar construction, are maintained by foot at low tide, this appeared inconsistent. However, as this was a microtidal setting at that time, the fishweir was probably a subtidal device maintained by canoe rather than on foot, as in the Chesapeake Bay during historic times.

ADDITIONAL INDEX WORDS: *Estuarine sedimentation, Boylston Street Fishweir, laminated muds, stratigraphy.*

INTRODUCTION

The purpose of this investigation was to develop an interpretation for the geologic evolution of Inner Boston Harbor. The drowning of the lower portion of the Boston Basin during post-glacial sea-level rise formed the Boston Harbor estuary. The Back Bay, an embayment in innermost Boston Harbor, is located at the former mouth of the Charles River, the major drainage into the harbor. The Back Bay was land-filled in the mid-1800's, preserving the estuarine stratigraphy that recorded this submergence (Figure 1).

The Boylston Street Fishweir, the oldest preserved fishweir in New England (estimated to be 4,400 years old), was discovered during excavation for a subway line in 1913. Reports from the fishweir site during building excavations in 1939 and 1946 (JOHNSON, 1942, 1949) provided thorough descriptions of the general trends of the feature.

The recent building excavation at 500 Boylston Street uncovered additional fishweir remains which led to the present opportunity to record the estuarine stratigraphy. The excavation at the construction site allowed direct observation of a large area so that subsurface cores could be collected from known stratigraphic locations.

Using the data from 11 sediment cores, as well as supporting data collected from the site, a detailed stratigraphy has been developed and the evolution of Boston Inner Harbor could be interpreted. This includes the roles of changing sea-level and tide range, which affect sedimentation

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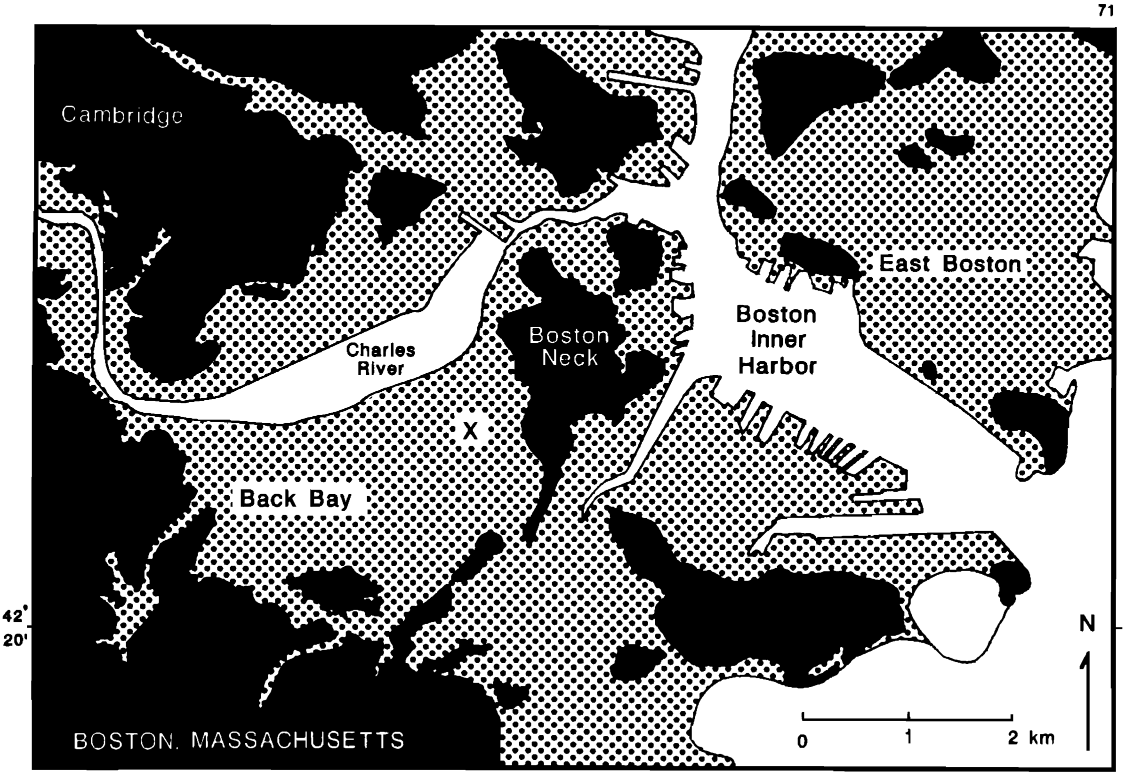

Figure 1. Map showing historic landfill areas of Boston, Massachusetts (dot pattern) and the probable 1630 shoreline (black). The project location (X) is within the former Back Bay at the mouth of the Charles River (adapted from KAYE, 1976).

patterns and accumulation rates. Based on the stratigraphy, an assessment of the lateral variability of the deposits across a small area is possible. The geologic interpretation of this site plays a pivotal role in the archaeological characterization of the Boylston Street Fishweir.

SETTING

Regional Geologic Setting

The City of Boston and its surrounding area, including Boston Harbor, are situated within a topographic and structural lowland known as the Boston Basin (LAFORGE, 1932). This wedge-shaped, down-faulted body of sedimentary, granitic and volcanic rock has been interpreted to have formed in the very Late Precambrian to Middle or Late Cambrian (KAYE, 1982). The Basin is bounded by thrust faults to the northwest and south (BILLINGS, 1976).

During Pleistocene time, glaciers scoured the bedrock in the area and subsequently covered most of the area with drift. Glacial drift includes deposits of two different ages. The older deposit is probably Illinoisan in age (NEWMAN *et al.*, 1990). It is the primary component of drumlins that dominate the topography of Boston Harbor. The younger drift was deposited in late Wisconsinan time, after which ice retreat and marine submergence occurred simultaneously, and local relative sealevel rose to about +18 m approximately 14,000 yr ago (KAYE and BARGHOORN, 1964; OLDALE, 1985; NEWMAN *et al.*, 1990). The upper Wisconsinan sequence includes thin discontinuous drift composed of gravel, sand, and till as well as relatively thick (up to 25 m) and areally extensive glaciomarine muds (MENCHER *et al.*, 1968; RENDIGS and OLDALE, 1990).

These muds, known as the Boston Blue Clay, were laid down in coastal marine waters between 14,000 and 12,600 yr BP (KAYE, 1982). SCHNITKER and Borns (1987) described the evolution of the Presumpscot Formation in Maine, which correlates with the Blue Clay to the south. In Maine, at approximately 11,600 yr BP, climatic warming resulted in relatively warm sea water intruding beneath the melting ice sheet and over the isostatically depressed land, causing glacial sediments to be deposited into a marine environment. As the glaciers retreated further and marine waters advanced, the mud was deposited inland of the present shoreline. The clay extends into the offshore zones of Massachusetts and Cape Cod Bays as well as Boston Harbor. The well-bedded clay, silt, and interbedded fine sand deposits reach a maximum thickness of 75 m beneath Boston Harbor (Kaye, 1982).

During the immediate post-glacial period, isostatic rebound caused the harbor area to emerge, and local relative sea-level fell to −22 m about 10,000 yr ago (Kaye and Barghoorn, 1964). The Back Bay region emerged as a poorly drained grassland with a few shallow ponds formed in closed depressions (Kaye, 1982). Soon after, the emerged land became tree covered (Johnson, 1949) as the sea level maintained a stable position for nearly 2,000 yr.

The area was then resubmerged in response to a eustatic rise of sea level and slowing of isostatic rebound. The shoreline reached −3 m or less about 3,000 yr ago, when there was a sharp reduction in the rate of sealevel rise (Kaye and Barghoorn, 1964; Oldale, 1985). During the transgression, waves reworked the surface of older sediments, and localized deposits of marine clayey silts and sandy muds accumulated above the transgressive unconformity (Rendigs and Oldale, 1990; Knebel *et al.*, 1991).

The Back Bay Site

Geology

Geotechnical investigations (Haley and Aldrich, 1985) in the study area identified bedrock at −36 m (MLW) as Cambridge Argillite, which underlies most of the Boston Peninsula. This is overlain by a 4 m thickness of till and 28.5 m thickness of Boston Blue Clay. The clay at the site is characterized by a 1.5 to 4.5 m thick yellow-brown crust resulting from oxidation, which is typical of the Blue Clay in the Boston area. A discontinuous layer of outwash sand up to 0.3 m thick occurs in the vicinity of the study area overlain by 5 m of organic silt.

These organic silts form the Back Bay estuarine deposits which are the focus of this study. The area was landfilled between 1851 and 1861 (Aldrich, 1970). The fill material, derived both from excavation of nearby drumlins and material from surrounding towns, averages 6 m thickness of heterogeneous sediments. Back Bay is one of a continuum of landfill projects in Boston that began in the 1630's and continued to the 20th century, doubling the land area of the City (Figure 1).

The Boylston Street Fishweir

In 1913, during the excavation for the subway system beneath Boylston Street, a number of wooden stakes were discovered which were termed fishweirs. The weirs were made of vertical stakes driven into the substrate, with smaller twigs or brush ("wattling") woven horizontally between the larger stakes. The stakes found in 1913 were 1 to 2 m in length; however, many were broken by power shovels during construction and may have been considerably longer (Johnson, 1942). Many of the stakes were driven 0.5 m into the Blue Clay, while the upper wattling lay approximately 0.5 m above the Blue Clay surface. In 1939, during the foundation excavation for an adjacent building (New England Life Building) on Boylston Street, some 65,000 fishweir stakes were found over the entire 6,000 m^2 of the site and appeared to extend beyond the construction site boundaries. The stakes had been driven into the substrate in crudely linear rows running north–south across the site. In 1946, more fishweir remains were uncovered with the excavation for another nearby building (John Hancock Building) (Johnson, 1949). With the recent excavation and construction at 500 Boylston Street, more fishweir remains were found, resulting in further archaeological investigation and the present stratigraphic study (Figure 2).

The stakes at the Boylston Street site were driven through estuarine mud, sometimes extending down into the Blue Clay. An intertidal setting for the weir system was proposed by Carlson (1986) based on the similarity in design with modern weirs still operating in Maine and the Bay of Fundy. Preliminary dating indicates that the weir system is about 4,400 yr old (Maybury, 1989).

At both the John Hancock and New England Life Building sites, the archaeological investigations recovered no artifacts linking the fishweirs to a particular cultural group (Dincauze, 1985). The present study, while uncovering additional

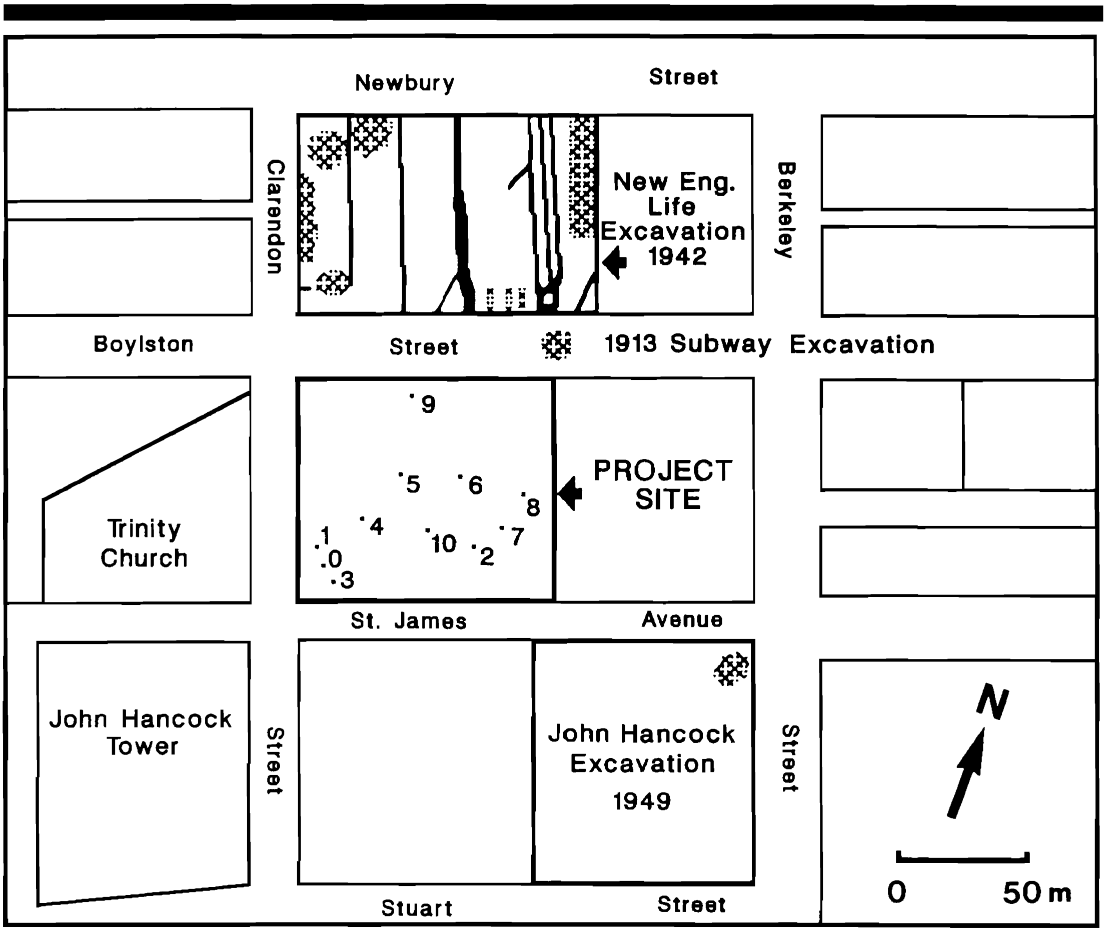

Figure 2. Map showing the project site at 500 Boylston Street, Boston and location of cores within the site. Earlier exposures of the Boylston Street Fishweir are shown, including the 1913 Boylston Street subway excavation, the 1942 New England Life Building excavation, and the 1949 John Hancock Building excavation. Pattern shows locations of clumps of wooden stakes and irregular black lines show distinct rows of stakes.

stakes and wattling, also failed to recover any other artifacts. The structure itself remains the only evidence of man's earliest presence in the Boston lowlands. The lack of tangible evidence at the sites has been a hindrance in the determination of the antiquity and duration of the fishweir structures (JOHNSON, 1942).

Previous Estuarine Stratigraphic Investigations

JOHNSON (1949) compiled a generalized stratigraphy for the estuarine sequence overlying the Blue Clay (Figure 3):

The basal unit in contact with the upper, "weathered" surface of the Blue Clay was termed the Lower Peat unit. The peat ranges in thickness from 20 cm to trace amounts of plant material. The lower contact is sharp where it overlies Blue Clay but gradational where it rests on sand. Freshwater material is found at the base/of the peat, but is overlain by thicker salt-water peat. Where the peat is well developed, a distinct lower horizon of black, amorphous peat grades up into the thicker, brown laminated peat. Sand lenses are sometimes found within the peat. The upper contact of the peat may be sharp or gradational, grading into the overlying silt deposit. Tree stumps were found buried in the peat.

A marine silt lies above the Lower Peat and its upper surface is approximately 0.0 m (MLW). The silt is usually between 3 and 7.6 m thick and is

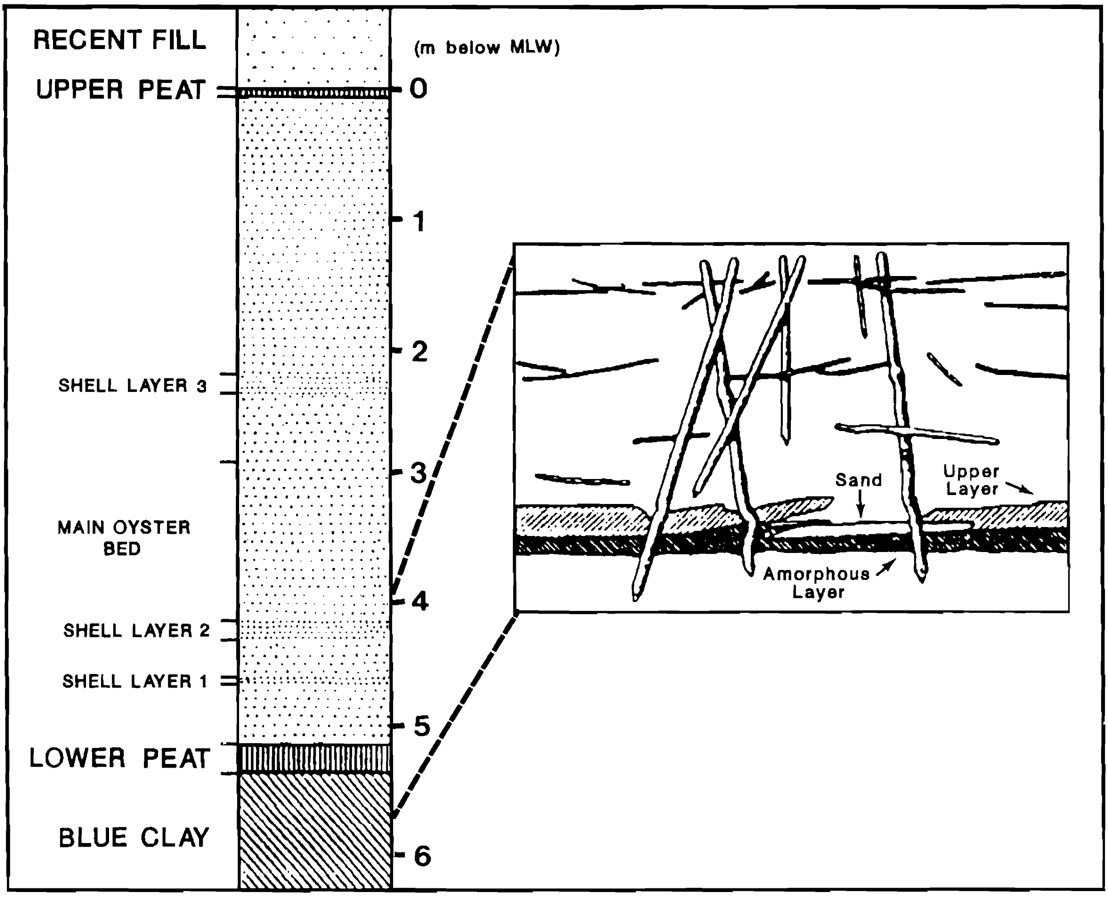

Figure 3. Stratigraphic description of the New England Life Building excavation site. Enlarged detail shows relation of fishweir stakes and wattling to sedimentary deposits (after JOHNSON, 1942).

light, greenish-grey when fresh. Bedding can be observed under certain moisture conditions. It is a fine-grained deposit that becomes slightly coarser at higher elevations, reflecting a change in depositional conditions. Shell material was found throughout the silt.

A principal oyster bed lies between 2.7 and 4.0 m below MLW at both the New England Life and John Hancock sites. The oysters are elongate and grew vertically in thick masses that are irregular in occurrence. Thick silt deposits interrupted the upward growth of the beds. A few oysters were also found near the lower contact of the silt. At the John Hancock site, two additional oyster layers and a layer of mollusk shells lie above the oyster bed.

At the New England Life site, three distinct shell layers were found. One layer was −4.3 m (MLW) associated with the lower wattle of the fishweir. This layer is approximately 7.6 cm thick and composed of small mollusk shells, single valves, and shell fragments mixed with silt and fine sand. About 1 m above this layer is a less distinctive layer associated with the upper wattle. The few shells present are usually found in living position. This layer has a thickness of about 15 cm. A third shell layer occurs approximately 1.5 m below the upper surface of the silt. The layer slopes to the southwest and ranges from 2.5 to 18 cm thick. It is composed of shell fragments, single valves, and silt with coarse sand and small pebbles. Whole mollusks in living position are found beneath the layer.

Covering the silt over most areas is a saltwater

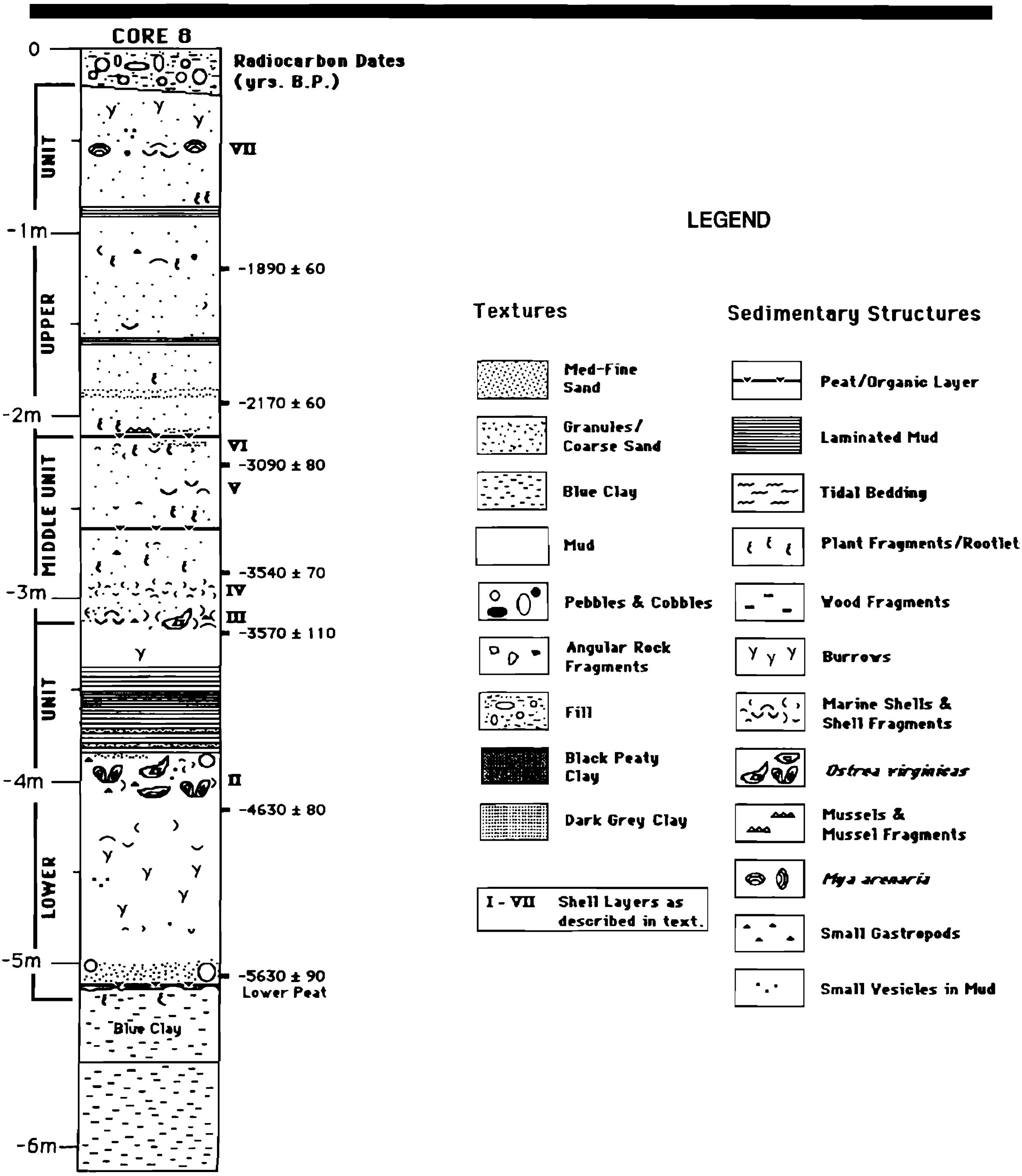

Figure 4. Stratigraphic description of the deposit at Core 8, which encompasses the complete estuarine sequence. Elevations are referenced to Mean Low Water (MLW).

Table 1. *Radiocarbon dates and calculated sedimentation rates from the 500 Boylston Street estuarine stratigraphic sequence.*

Date Number	Description	Depth (cm MLW)	Date (yr BP)	Time Interval (yr)	Sedimentation Rate (mm/yr)
1	Recent Fill	0	130*	1,790	0.5
2	Upper Unit	121–117	1,890 ± 60	280	2.8
3	Upper Unit	196–193	2,170 ± 60	920	0.3
4	Middle Unit	228–225	3,090 ± 80	450	1.3
5	Middle Unit	287–284	3,540 ± 70	30	11.7
6	Lower Unit	321–318	3,570 ± 110	1,060	0.9
7	Lower Unit	420–418	4,630 ± 80	1,000	0.9
8	Lower Unit	510–504	5,630 ± 90		

* Date based on historical records

peat deposit known as the Upper Peat. It averages about 5 cm thick and is brown to black with occasional occurrences of large amounts of silt and sand. The top of the peat, which is nearly horizontal, represents Back Bay sedimentation during colonial time.

METHODS

The field work for this study consisted of sampling the entire stratigraphic sequence from the top of the Boston Blue Clay up to the bottom of the historic landfill. The field sampling was carried out concurrently with construction activities on the site, so sampling was done on an opportunistic basis. Due to the nature of the sampling, sediment samples or cores were only taken when an accessible, undisturbed, near-vertical face of the estuarine deposit was exposed.

Rectangular sampling boxes (10 × 10 × 50 cm) constructed of stainless steel allowed undisturbed 0.5 m box-cores to be taken from vertical exposures. The face of the sediment generally was scraped by hand to expose unaltered sediments. The boxes were aligned in a stepped vertical arrangement with a 2 to 5 cm overlap between successive boxes. Each box was pounded into the sediment with a sledge hammer. A trowel was used to excavate around, cut, and remove each box.

Photographs were taken of the exposure when light and groundwater conditions permitted. Bulk samples of shell horizons were sampled adjacent to box cores. The location and elevation of each core sequence was surveyed following sampling. All elevations are based on Boston City Base, which is approximately Mean Low Water (MLW).

Due to sampling constraints, most cores are partial sequences. There were a total of 11 sampling sites with 36 individual box cores successfully recovered. Core 8 represents the only exposure where recovery of the entire stratigraphic sequence was possible (Figure 4).

In the laboratory, each box core was cut along its length using a wire in a coping saw frame to expose a smooth surface for description, sampling, and photography. The 5.5 m length of Core 8 was sampled at 10 cm increments for analyses. All samples were analyzed for grain-size distributions. Seven samples were radiocarbon dated (Table 1). The dated samples were selected at elevations that bracketed major depositional changes in the sediment, which included grain size, organic content, and shell content. Seven shell deposits that were bulk-sampled in the field adjacent to cores were sieved to collect macrofossils. Some shell samples were identified by CARLSON (1988). Organic content was determined on all samples by loss-on-ignition (NEWBY and WEBB, 1988). Pollen analysis was performed on all samples to provide a regional and local record of vegetation changes (NEWBY and WEBB, 1988). Fifteen subsamples from Core 8 were also examined for diatom content (RICE, 1988).

RESULTS

Estuarine Stratigraphy

Based on the core descriptions (Figure 5), the estuarine deposit is divided into three distinct units, the Lower, Middle, and Upper Units.

Lower Unit

The Lower Unit was sampled at four locations on the site. Core 8 (−5.27 to −3.15 m MLW) represents the only continuous record of this unit (Figures 4 and 5). The sediment is also characterized by a low organic content, averaging less than 7% of dry weight (Figure 6). A fresh- to saltwater marsh transition at the base of the unit marks a change from an intertidal to shallow subtidal environment that initiates the transgressive

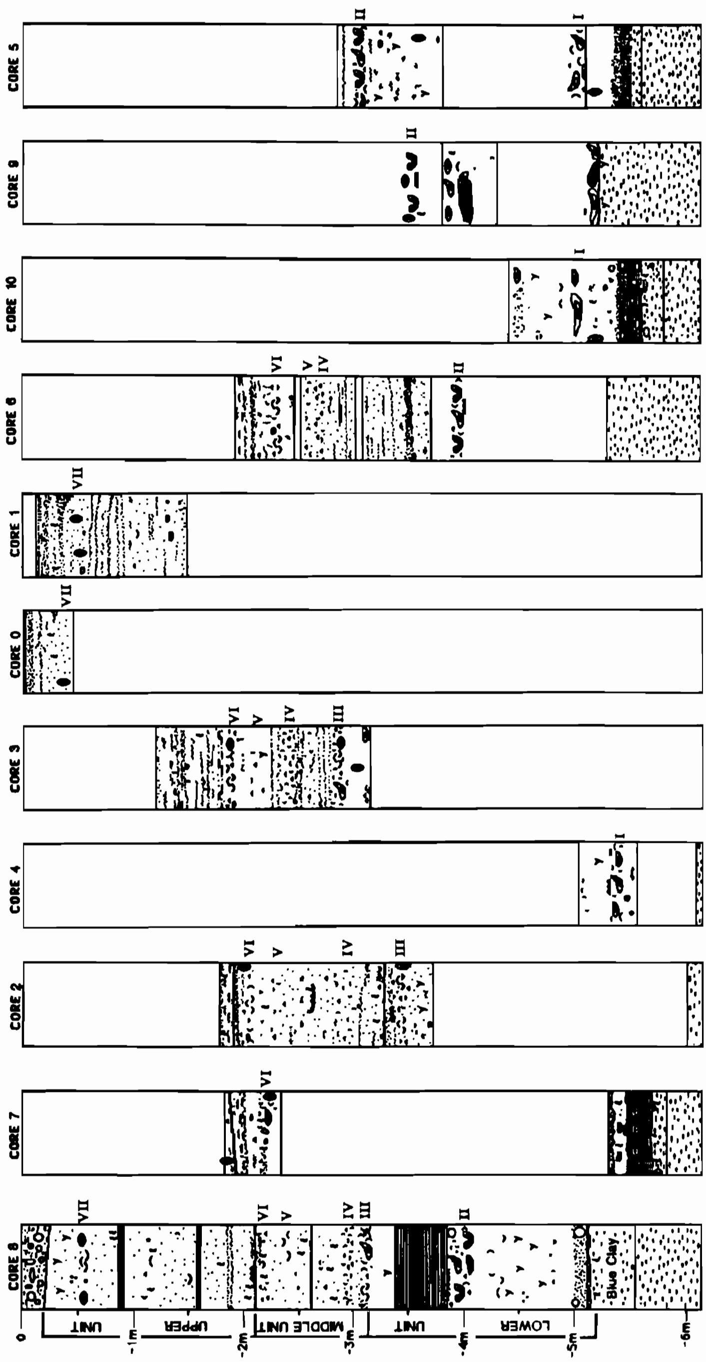

Figure 5. Stratigraphic descriptions of the 11 cores recovered at the 500 Boylston Street site showing elevations of the sequences, shell layers observed, and small-scale variations. The cores are grouped by geographic proximity on the site: 8, 7, 2, east; 4, 3, 0, 1, west; 6, 10, 9, 5, central/north. The location of each core within the site is shown in Figure 2. The legend for the symbols is in Figure 4.

sequence. The upper limit of the Lower Unit is defined by an abrupt increase in sand content and the presence of a shell hash layer (Shell Layer III, *q.v.*).

The lowest part of the Lower Unit overlies the Boston Blue Clay. While the top 1 to 3 m of the clay is typically marked by a yellowish color (CROSBY, 1903; KAYE, 1982; JOHNSON, 1942; HALEY and ALDRICH, 1985), only about 20 cm of this alteration was observed on this site. The upper 12 cm of the Blue Clay is a massive silty clay (70–80% clay) with some fine sand, gravel and pebbles present. The Blue Clay sampled at −5.10 m (MLW) from Core 8 is dominated by fresh-brackish water diatoms (RICE, 1988). Rice interprets the environment at this depth to have been deposited above high tide level based on the low concentration of diatoms as well as the species found. The uppermost clay is penetrated by abundant *Spartina alterniflora* rhizomes from overlying peat. Some burrow or root-like features extend down into the clay to a maximum of 15 cm and are infilled with the grey silt from above. The pebbles are angular, with long axes (1 to 3.5 cm) parallel to bedding. The upper boundary of the Blue Clay is transitional, grading grey-blue then brown to black as it becomes more organic-rich over about 10 cm. As this contact represents a depositional hiatus, the transitional zone is likely due to reworking. Pollen and vegetation analysis at the base of the Lower Unit indicates sedge seeds and roots from herbaceous plants which suggests the initiation of a sedge peat on the site from fresh water encroachment into the area. Additional evidence from pollen suggests the presence of a swampy lowland forest in the area at the time (NEWBY and WEBB, 1988).

The upper, gradational contact of the Blue Clay has occasional disarticulated shells of *Crassostrea virginica*, pebbles and cobbles, or, most commonly, a distinct salt marsh layer directly above the clay. This Lower Peat is a black, clay-rich (80%) deposit which reaches a maximum thickness of 30 cm. Quartz sand layers (approximately 0.5 cm thick) occur within the peat. No shells were found within the peat. Radiocarbon dating of sediment from this depth (−5.10 to −5.04 m MLW) puts the earliest transgression at 5,630 ± 90 yr BP (Table 1).

A layer of sand up to 6 cm thick occurs intermittently overlying the peat. The sand is poorly sorted and contains a few pebbles. Black/brown organic debris is mixed with the sand.

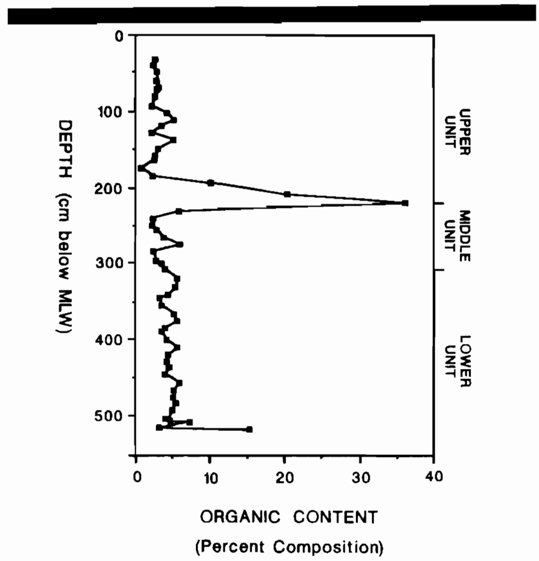

Figure 6. Diagram showing variations in organic content through the estuarine sequence (Core 8).

Overlying this sand is a grey, clayey silt that forms most of the Lower Unit. The lower section of the clayey silt is characterized by intermittent traces of plant remains and shell fragments, and small gastropods, including *Mulinea lateralis, Nassarius obsoleta,* and *Aequipecten irradians,* all common to brackish estuarine conditions. Dark, sub-vertical, burrow-like features are common at this depth. One example, which extends into the Blue Clay, is 35 cm long with a 5 cm diameter. Isolated small patches of gravel and sand occur. Core 8 sediment shows an increase in abundance of more saline planktonic diatoms in the lower silt from −5.05 to −4.93 m MLW. In the interval of −4.93 to −4.76 m MLW, a decrease in salinity in the depositional environment is indicated by the presence of more brackish-water diatoms (RICE, 1988). Pollen data from this depth suggest that a freshwater marsh grew nearby, and that brackish conditions may have existed at this location (NEWBY and WEBB, 1988).

Based on observations from nearby archaeological sampling sites, a shell layer (designated Shell Layer I) is associated with the top of the weir zone and upper wattling and is between 30 and 50 cm above the lower sand layer. JOHNSON (1942) reported two shell layers (designated 1 and 2; Figure 3) associated with the weir zone. Johnson's shell layer (1) is predominantly composed of barnacle fragments and small mollusks (*Mu-*

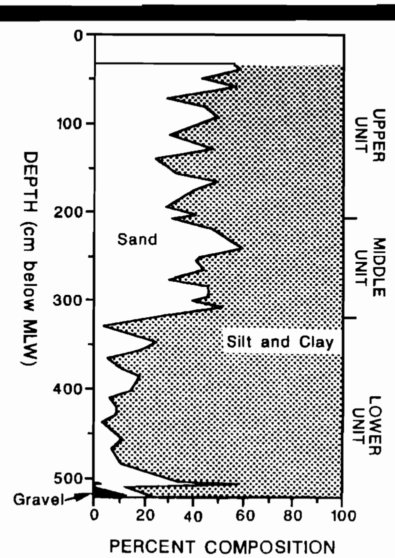

Figure 7. Diagram showing variations in grain-size through the estuarine sequence (Core 8).

linia lateralis, Nassarius obsoleta, and *Crepidula fornicata*). Johnson's shell layer 2 is associated with the upper wattle and equivalent to Shell Layer I (this study). This layer is dominated by larger mollusks including disarticulated shells of *Crassostrea virginica, Mya arenaria,* and *Macoma balthica.* The layer is between 6 and 10 cm thick and thin sand lenses are present within the layer. The shells are not in living position. Shell Layer I is observed at most archaeological sites, Cores 10, 4 and adjacent to Core 5, but was absent from Core 8.

Above Shell Layer I, the silt is featureless with occasional shell fragments. The second shell layer (II), which varies from 30 to 90 cm above Shell Layer I, is an oyster bed (*Crassostrea virginica*), which corresponds to Johnson's main oyster bed (Figure 3). The oysters are elongate (up to 13 cm long) and found in living position cemented into a mass forming an oyster bank about 30 cm thick. The layer is discontinuous within the site. Other shells associated with this layer are *Modiolus demissus, Nassarius obsoleta, Mulinia lateralis, Gemma gemma, Crepidula fornicata, Hydrobia* sp., thick shelled *Mercenaria mercenaria* (some with barnacles attached), and *Mya arenaria* (7 to 10 cm long) (CARLSON, 1988).

The zone above the oyster bank is a uniform deposit of grey, clayey silt which is predominantly shell-free, except for occasional occurrences of *Nassarius obsoleta.* Sand laminae, 1 to 2 mm thick, are found in the silt just above the oyster bank. This zone is about 70 cm thick, and is dominated by rhythmic bedding. There are two degrees of spacing in the laminated mud. Between −3.71 and −3.64 m MLW in Core 8, there are four couplets with dark layers 0.2–0.5 cm thick and light layers 1.5–2.0 cm thick. Between −3.64 and −3.55 m MLW, the dark/light couplets become thinner, with laminae about 2–2.5 mm thick. Occasional sand laminae, 1 to 5 mm thick, composed of clean quartz grains, occurs from −3.89 to −3.72 m and −3.61 to −3.57 m MLW.

The upper sediment of the Lower Unit (−3.30 to −4.30 m MLW) is characterized by a fluctuation in pollen concentration suggesting changing depositional processes. Fewer fresh-water plants are present at the depth of the laminated muds, perhaps because of deepening water (NEWBY and WEBB, 1988). Freshwater diatoms are less abundant above Shell Layer II, indicating an increase in marine dominance (RICE, 1988).

Middle Unit

The Middle Unit is represented by samples from five locations across the site. The major characteristics that differentiate it from the Lower and Upper Units are the abundance of shells and overall sandier composition (Figure 7) compared to underlying sediments. Organic content remains the same as the Lower Unit, less than 7% average by dry weight (Figure 6). The Middle Unit ranges from 1.0 to 1.5 m thick across the site.

Four shell layers were identified within this unit. These layers are not continuous across the site. These have been designated Shell Layers III through VI, of which III and VI are the most distinctive.

Shell Layer III, which is 15 cm thick, defines the lower boundary of the Middle Unit. It is a distinctive shell hash from which 11 species were identified. *Gemma gemma, Mulinia lateralis,* and *Nassarius obsoleta* account for 50, 30, and 10 percent of the total population, respectively. Other species found include *Crassostrea virginica* (up to 10 cm long), *Mya arenaria* (up to 5 cm long), *Modiolus demissus, Retusa caniculata, Hydrobia* sp., *Odostomia* sp., *Mitrella lunata,* and *Mercenaria mercenaria* (CARLSON, 1988). Sand laminae, 1 to 2 mm thick and composed of clean, quartzose sand, occur at the base and at the top of this layer. The sharp boundary below this layer indicates changing energy conditions.

Shell Layer IV lies 5 to 30 cm above Shell Layer III. It is a shell-rich zone composed predominantly of *Gemma gemma,* with lesser amounts of *Mulinia lateralis* (whole shells) and fragments of *Modiolus demissus.* In Core 8 this layer is found from −2.90 to −3.00 m MLW.

Shell Layer V is not well-defined, occurs 25 to 40 cm above Shell Layer IV, and is composed of shell debris and *Mulinea lateralis.* In Core 8 this layer is found from −2.60 to −2.40 m MLW.

Shell Layer VI, consisting of shell hash (as in III) that has a maximum thickness of 15 cm, forms the upper boundary of the Middle Unit. Species that have been identified include *Gemma gemma* (58%), *Nassarius obsoleta* (14%), *Mulinea lateralis* (7%), *Odostomia* sp. (6%), *Modiolus demissus, Mya arenaria, Mitrella lunata, Retusa caniculata,* and *Crepidula fornicata.* Larger shell fragments, small angular pebbles, and organic material are also present. Shell Layer VI is equivalent to JOHNSON's (1942) shell layer 3, which was compared to shell occurrences found below present-day mud flats. In Core 8, this layer is found from −2.20 to −2.10 m MLW.

Upper Unit

The Upper Unit was sampled at four locations. It is 2.0 m thick and is bounded on the top by saltmarsh peat. Shells are much less common and there are thicker sand layers with abundant sand/mud bedding as compared to the lower units.

The lower limit of the unit is defined by a 2 cm thick sand layer overlying Shell Layer VI. The sand is overlain by a 1 to 4 cm thick organic layer with organic content of 27%, probably representing a period when an intertidal saltmarsh occurred at the site (NEWBY and WEBB, 1988).

Above this organic layer, the sediment is composed of sections of sand/silt laminae separated by homogeneous sandy silt. At about −1.30 m and −1.00 m MLW there are concentrations (5 cm thick) of shell debris and pebbles. At −0.30 m MLW is a zone of abundant *Mya arenaria,* 2 to 10 cm long, in living position (Shell Layer VII) found throughout the site. Above the *Mya* zone, the sediment becomes very sandy with several distinct layers up to 5 cm thick. The layers have sharp and often wavy contacts with the dark sandy silts separating them.

At the top of the Upper Unit, representing the end of the estuarine sequence, is the Upper Peat, as defined by JOHNSON (1942). The peat is a black organic layer 6 to 15 cm thick with *Spartina alterniflora* roots extending into the underlying sediment. At some sites, the position of the peat is marked only by organic-stained muds.

The overlying artificial fill was emplaced between 1851 and 1861 (HALEY and ALDRICH, 1985) for land reclamation and is poorly sorted sand with varying amounts of clay, pebbles, and assorted debris.

DISCUSSION

Changing Holocene Tidal Range

At present, Boston Harbor is a mesotidal estuary with a mean tide range of 2.7 m (FITZGERALD, 1980). It is part of the Bay of Fundy–Gulf of Maine tidal system in which the range is amplified by resonance due to the natural period of oscillation of the basin closely coinciding with the period of the tide wave (SCOTT and GREENBURG, 1983). Estimates of when the amplification of tide range began vary from 5,000 yr BP (AMOS and ZAITLIN, 1985) to 7,000 yr BP (SCOTT and GREENBURG, 1983). Since that time, the relative sea level increase in New England has been the controlling factor in the increase in tidal amplitudes in this system (SCOTT and GREENBURG, 1983). A major implication of an increasing tide range is an increase in tidal prism and current velocities. A change in energy conditions is reflected in the nature of sediments deposited.

During the time interval of the Lower Unit (5,630 to 3,370 yr BP), tides within the Bay of Fundy (and hence, Boston) were at a minimum (AMOS and ZAITLIN, 1985), estimated to be no greater than 25% of today's tides (Amos, *personal communication,* 1986). Amos and Zaitlin estimated a rapid increase in range from 4,000 to 3,000 yr BP, when tide range approached modern values. SCOTT and GREENBERG's (1983) estimates suggest that tidal amplification had begun by the time of the first submergence of Back Bay, and that the tides had reached 75% of the present range by 4,000 yr BP.

Although the estimate of the time of rapid increase in tide range by Amos and Zaitlin does not coincide with the estimate of Scott and Greenberg, both show that by 3,570 yr BP, the base of the Middle Unit, tidal energy would have increased significantly in Back Bay. This unit records the presence of tidal channels in the estuary, and its sandier texture reflects higher energy conditions. The sandy Upper Unit also reflects higher energy conditions.

Holocene Depositional Model

The Back Bay was a well-protected, lagoonal environment during its entire 5,600 yr depositional history. The Lower Unit (5,630 to 3,570 yr BP) ranges from an uplands setting, a possible beach deposit in the intermittent lower sand layers, and an intertidal saltmarsh through deepening waters to a shallow subtidal setting. The rapid submergence (KAYE and BARGHOORN, 1964) may account for minimal evidence of shoreline deposits. Using the radiocarbon dates and thicknesses from Core 8, an average sedimentation rate of 0.9 mm/yr is calculated, which is significantly lower than submergence rates (KAYE and BARGHOORN, 1964), so rapid deepening took place compared to sedimentation rates. The estuarine muds that dominate the sequence are similar to other Holocene lagoonal deposits (*i.e.*, FINKELSTEIN and FERLAND, 1987; KRAFT and JOHN, 1979). Laminated muds within this unit are comparable to seasonal rhythmites described by REINECK and SINGH (1986) consisting of couplets of very fine grained material where each layer is of a different color or material. ANDERSON (1970) showed that variation in concentration of suspended particulate matter in an estuary is seasonally controlled. Rhythmites such as this are common in low energy estuarine deposits (NICHOLS and BIGGS, 1985). In the study area, the annual sedimentation is comparable to the rhythmite thickness, further indicating that these are annual deposits. The rhythmites are also indicative of a relatively tranquil environment.

The abrupt transition between the mud of the Lower Unit and the sandy silt of the Middle Unit occurred about 3,500 yr BP. Two radiocarbon dates bracketing this contact indicate that the interval between the samples is 30 to 240 years. This suggests a conformable contact with no major break in sedimentation. The coarser, shell-rich, Middle Unit was deposited over a time period of only about 500 yr. The lower portion had an average deposition rate of 11.7 mm/yr, a high rate comparable to the dynamic nature of tidal channel processes. Similar environments containing shell material are described by YEO and RISK (1981), FREY and HOWARD (1986), and BELKNAP *et al.* (1986) as channel-lag deposits. The Middle Unit represents the formation or migration of a tidal channel into this site. It signifies a period of increasing tidal and saltwater influence, also bringing more faunal diversity.

The Upper Unit was deposited over the last 3,000 yr at an average deposition rate of 0.7 mm/yr. This time period may include a period of about 1,000 yr of nondeposition or erosion at the base of the unit. The Upper Unit is distinguished by numerous sand laminae and a minimal shell content. In part due to the diminished rate of sealevel rise over this period, the rate of sedimentation was greater than submergence, resulting in the emergence of this tidal flat environment. Energy fluctuations in a tidal flat environment result in tidal bedding. WUNDERLICH (1970) and REINECK and WUNDERLICH (1968) describe tidal bedding in a similar environment where sand layers are deposited during both ebb and flood, and mud is laid down during slack water periods. REINECK and SINGH (1972) describe sand-mud rhythmites in deeper water that may be due to storm activity. Clearly, the Upper Unit represents a period of increasing tidal activity and increasing energy. BELKNAP *et al.* (1986) found that *Mya arenaria* in the sediment represent an intertidal flat environment. Finally, as sedimentation continued, a saltmarsh environment grew out of the mudflats, leading to the formation of the Upper Peat. This saltmarsh peat has been described in the Back Bay prior to landfill activities.

Lateral Variability

Comparison of deposits within a few tens of meters separation shows distinct differences. Many estuarine studies are based on sample intervals of hundreds of meters to several kilometers to characterize depositional environments. For example, BELKNAP *et al.* (1986) vibracored a protected upper estuarine environment at an average spacing of 300 m. AMOS (1978), FREY and HOWARD (1986), KRAFT (1971), KRAFT and JOHN (1979), and FINKELSTEIN and FERLAND (1987) sample areas on the order of tens of km at average sample spacings of 15 km, 1 km, 1.5 km, 250 m, and 1.5 km, respectively. Documentation of lateral changes in estuarine sediments is based on these sample intervals (for example, FREY and HOWARD, 1986).

In the present study, a larger scale examination of estuarine stratigraphy was possible due to the dewatering of an excavated construction site. The high level of variability of preserved estuarine environments over a relatively small area in this study provides perspective to the generalizations of stratigraphic change in areas with limited data over larger areas.

CONCLUSIONS

The stratigraphy of the Back Bay site reveals an estuarine depositional sequence underlying 19th-Century landfill material and unconformably overlying Boston Blue Clay. The estuarine sequence represents continuous deposition beginning 5,600 yr BP and ending in historic times, recording the submergence of the Back Bay and Inner Boston Harbor. The Back Bay was a well-protected, lagoonal environment throughout its 5,600 yr depositional history.

Three major depositional units are identified in this sequence. The Lower Unit marks the transition from an upland setting to an intertidal saltmarsh, representing the leading edge of the transgression. A period of rapid submergence is evidenced by a transition from saltmarsh to a shallow subtidal setting. Oyster beds grew in the sheltered bay and laminated muds reflect periods of undisturbed, annual deposition.

The abrupt transition between the mud of the Lower Unit and the sandy silt of the Middle Unit occurred about 3,500 yr BP. This coarser Middle Unit was deposited over a time period of only about 500 yr. It is a shell-rich unit containing several channel-lag deposits. This Middle Unit represents the establishment or migration of a tidal channel into this site. It signifies a period of increasing tidal and saltwater influence, bringing more faunal diversity.

The Upper Unit was deposited over the last 3,000 yr and is distinguished by numerous sand laminae and a minimal shell content. The rates of sedimentation were apparently greater than submergence, in part due to diminished rates of sea-level rise. This resulted in the establishment of a tidal flat environment. Energy fluctuations in the tidal flat environment resulted in typical tidal bedding. As sedimentation continued, a saltmarsh became established, leading to the formation of the Upper Peat. This saltmarsh existed in the Back Bay prior to landfill activities between 1851 and 1861.

During deposition of these units, sea level was rising at changing rates. A sharp reduction occurred between 3,000 and 4,000 yr BP, when the rate was reduced to one-half to one-tenth the former value. Accumulation rates also fluctuated through time. The Lower Unit accumulated at about 1 mm/yr while submergence proceeded at 3 mm/yr, leading to deepening waters and an increase in marine influence. As submergence diminished, sedimentation rates doubled in the Middle and parts of the Upper Unit, leading to shallowing and emergence of the sequence.

The abrupt change in sediment characteristics from low energy muds to higher energy silty sands corresponds to a significant rise in tide range occurring at that time. The change in tide range also affects the type of depositional environments. The initial lower tide range corresponds to a lack of tidal flat deposits during submergence. The subsequent higher tide range corresponds to extensive tidal flat deposits in the top of the sequence representing emergence.

There is a significant amount of lateral variability in depositional environments over a small area, such that no single core would thoroughly represent the site stratigraphy.

The fishweir assemblages are located in the lower portions of the Lower Unit. This study indicates that the weir was most probably active in a microtidal environment. This setting does not correspond to any modern analogs in the Gulf of Maine region. Despite collection of over 65,000 relicts of wooden weir stakes or wattling, there is a lack of non-weir artifacts. While detailed archaeological investigations revealed no pounding instruments, thousands of stones to pound stakes would have been needed. Rigorous, physically-demanding working conditions would have existed for weir-builders working in soft estuarine muds, where simply standing without sinking knee-deep would have been a challenge. There is also an abundant local supply of massive cobbles and boulder-sized implements from nearby glacial deposits. As large implements would be necessary to penetrate the stiff Blue Clay substrate, it is difficult to imagine that workers would carry such implements back to a shoreline at least 200 m away at the end of a workday. These archaeological constraints are consistent with the geologic evidence to indicate a microtidal setting, such as the modern Chesapeake Bay, corresponding to weir times. In the Chesapeake Bay microtidal environment, both pre-colonial and modern fishweirs were subtidal and could be accessed by boats or canoes. This would account for the lack of artifacts found associated with the wooden stakes at the Boylston Street site.

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