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The Duxbury Sunken Forest—Constraints for Local, Late Holocene Environmental Changes Resulting from Marine Transgression, Duxbury Bay, Eastern Massachusetts, U.S.A.

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ABSTRACT

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The present marine transgression has forced geological and ecological zones vertically higher and landward since the late Pleistocene. A recent investigation in Duxbury Bay, Massachusetts, identified 18 *Juniperus virginiana* tree stumps emergent on an intertidal flat immediately seaward of a small marsh and pond situated between two eroding drumlins. The position of each stump was mapped with global positioning system (GPS), and its elevation with respect to mean lower low water was surveyed. Samples were selected from four stumps with elevations ranging from 2.03 and 0.75 m above mean lower low water for radiocarbon dating. The samples returned calibrated ages between 2219 ± 94 and 2867 ± 79 cal YBP, with the topographically highest sample returning the youngest date. Stump positions suggest a landscape gradient of 1.4 mm/yr between 2000 and 3000 cal YBP. The results are comparable with high-resolution studies of sea level in eastern Massachusetts for the same time period. Comparison of the youngest paleostumps with modern living trees suggests a dramatic change in the landscape gradient, an increase to 1.8 mm/yr. While this is contrary to sea-level studies nearby, it may represent an increase in the energetics of Duxbury Bay and resultant coastal erosion as the bay floods. The site can be used to put the impacts of changing sea-level rates into a landscape evolution framework.

ADDITIONAL INDEX WORDS: *Coastal evolution, radiocarbon dating, Cape Cod Bay, sea level, tree stumps, paleoforest.*

INTRODUCTION

Sea level has been rising globally since the end of the Wisconsin glaciation, approximately 22,000 cal YBP (Fairbanks, 1989), and studies have shown that nearly all of the coastal systems in the United States are experiencing erosion in response (Pilkey and Thieler, 1992). In glaciated areas, the location of the coastal system with respect to moraines and other sediment-rich glacial landforms from the glacial maximum and the resultant sediment supply exert a strong control over the ability of the coastal system to respond to changes in sea level resulting from eustatic sea-level rise (Fairbridge, 1992).

Coastal Massachusetts and Cape Cod Bay have experienced a slightly different sea-level history than the majority of the continental United States. The region was covered with thick continental ice until 16,500 cal YBP, when the ice retreat created the moraine that forms the southern and western margins of Cape Cod Bay (Balco *et al.*, 2002). The weight of the thick ice sheet resulted in isostatic depression of the land surface, causing an immediate deglacial flooding event in coastal northern Massachusetts, followed by regression and subsequent transgression to present-day sea levels and coastlines (Nydick *et al.*, 1995; Oldale, Colman, and Jones, 1993; Uchupi and Bolmer, 2008). In southeastern Massachusetts, the Cape Cod moraine complex impounded large proglacial lakes during the initial phases of ice retreat, followed by regression to a lowstand approximately 45 m below present sea level at approximately 12,000 cal YBP and a subsequent transgression (Nydick *et al.*, 1995; Oldale, Colman, and Jones, 1993; Uchupi and Bolmer, 2008).

Sea-level curves have relied on various sources of material for chronological control. Radiocarbon accelerator mass spectrometry (^{14}C AMS) dating of organic material from species that live within narrowly defined ecozones serves as the best indicator of sea level. In New England, preferred samples for dating include the first occurrence of high marsh peat over uplands sediments (Gehrels, 1999) and the intertidal soft shell clam, *Mya arenaria* (Barnhardt, Belknap, and Kelley, 1997). Other species can serve as an upper boundary limit, such as the eastern red cedar, *Juniper virginiana*, but cannot establish sea level with confidence. However, such species can provide valuable information about the paleolandscape, paleoclimate, and processes, as well as the timing and style of landscape change and evolution (Gehrels, Belknap, and Kelley, 1996).

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Understanding how coastal landscapes respond to varying sea-level rise rates is critical when attempting to assess the preservation potential and location of submerged terrestrial environments (Belknap, Gontz, and Kelley, 2005; Maio *et al.*, 2012b; Momber, 2000; Shaw, Fader, and Taylor, 2009) and threats to coastal sites of cultural heritage (Kirschen *et al.*, 2008; Gontz *et al.*, 2011; Maio *et al.*, 2012a, b), and in evaluating processes related to sea-level rise (Buynevich, 2007; Hein *et al.*, 2012). Of recent interest is the potential for the preservation of underwater archaeological sites (Bailey and Flemming, 2008; Kelley, Belknap, and Claesson, 2010; Spiess and Lewis, 2001; Straight, 1990) and the ways in which we, as a society, conserve, preserve, and manage these resources. Additionally, if sea level continues to rise as predicted by Solomon (2007) and others, present-day subaerially exposed landscapes will begin the process of conversion to tidally influenced lands. Such conversions may have great impacts along the world's developed coastlines, and an understanding of the way in which a landscape transitions from upland forest to beach to tidal flat can provide information to assist in developing mitigation plans for the future.

This study reports on a series of tree stumps recently exposed on an intertidal sand flat in Duxbury, Massachusetts, USA, and relates their occurrence to the elevation of present sea level, providing insight into the rate of landscape migration in response to sea-level rise. While tree stumps are notoriously poor indicators of sea level, certain species can provide an upper limit on sea-level positions and provide important information on the rates of transgression.

GEOLOGICAL SETTING

The Kingston–Duxbury–Plymouth Bay system is a coastal re-entrant along the south shore of Massachusetts (Figure 1). The combined bays have an area of 46 km^2 and are protected from wave attack by two shore-oblique spits, Duxbury Beach to the north and Plymouth Long Beach to the south. Duxbury Beach and the northern portions of the complex bay have been the subject of detailed study (FitzGerald, Buynevich, and Rosen, 2001; Hill and FitzGerald, 1992). This body of previous work has examined the transgressive nature of the Duxbury Beach system (FitzGerald, Buynevich, and Rosen, 2001) and the stratigraphic relationships of the late Holocene development of the system (Hill and FitzGerald, 1992). Earlier work has not been focused on the details of the evolution of the land-water interface and its relationship to the transgression along the mainland coast.

Standish Point and Duxbury Bay are located on the western shore of Cape Cod Bay in southern Massachusetts (Figure 1). The area experienced glaciation during the late Pleistocene (Knebel *et al.*, 1996; Uchupi and Mulligan, 2006). The resulting present-day terrestrial landscape consists of drumlins, fluted topography, and ice-contact deposits, including recessional and medial moraines (Hill and FitzGerald, 1992). The marine landscape of Cape Cod Bay hosted a large proglacial lake, Glacial Lake Cape Cod, during the immediate deglacial phases that transitioned into a marine environment during ice retreat and subsequent transgression (Knebel *et al.*, 1996). The deepest portion of Cape Cod Bay exceeds 58 m and exhibits evidence of scour, suggesting rapid drainage of the lacustrine system through the Race Point Channel, adjacent to the northern tip of Cape Cod. Present-day depths in Duxbury Bay rarely exceed 4 m, and 10 m in deeper subtidal channels (Hill and FitzGerald, 1992; National Ocean Service, 2010).

Coastal processes occurring during the past 6000 years resulted in the development of a series of sandy barriers and spits, which have evolved to link the eroding drumlins and protect the bay from wave attack (FitzGerald, Buynevich, and Rosen, 2001; Hill and FitzGerald, 1992). All of the spits and barriers of the complex bay show strong evidence of transgression and varying phases of barrier stability (Hill and FitzGerald, 1992).

The stratigraphy of the area immediately adjacent to the present high tide line consists of granitic bedrock overlain by various thicknesses of till and a sequence of glacial lacustrine clays, capped by modern sandy marine and marginal marine salt marsh deposits. During the regression, terrestrial facies, including paleosols and freshwater marshes, were deposited over the clays. As sea level began to rise, the older units were eroded and reworked, and a transgressive sand sheet was deposited (Hill and FitzGerald, 1992).

METHODS

After a series of two large coastal storms impacted the area in March 2010, 18 tree stumps were discovered in the intertidal zone immediately seaward of the Miles Standish Homestead, Duxbury, Massachusetts. The preserved bark of the stumps was identified as eastern red cedar, *Juniperus virginiana*, using botanical keys (Bertness, 1999; Petrides, 1998).

Topographic and Geo-Locating

The position of all stumps was located in three-dimensional space using a combination of high-resolution global positioning system (GPS) equipment and traditional land surveying methodologies. The stumps were located using a Trimble GeoXH handheld GPS system. Each stump was occupied for 2 minutes, and the positions were averaged using the Trimble Pathfinder software package. The horizontal error reported by the Pathfinder software for each location was less than 0.5 m. The vertical errors were in excess of 2 m, and, thus, traditional survey methods were used to locate each stump with respect to mean lower low water (MLLW).

A Sokia Autolevel and metric Philadelphia Rod were used to relate the elevation of each stump, the high tide wrack line, and other shoreline features to a locally established benchmark. The elevations were then referenced to MLLW using the National Oceanic and Atmospheric Administration (NOAA) Duxbury, Massachusetts, tidal station (NOAA, 2010a). The elevation for each stump was recorded at the junction of the highest root with the trunk. Based on observations of living eastern red cedar trees in coastal areas, this is approximately 0.1 m below the ground surface. The survey method is accurate to 0.005 m, and elevations are reported to 0.01 m.

Radiocarbon Dating

Four samples from tree stumps were selected for submission to the National Ocean Science Marine Accelerator Mass

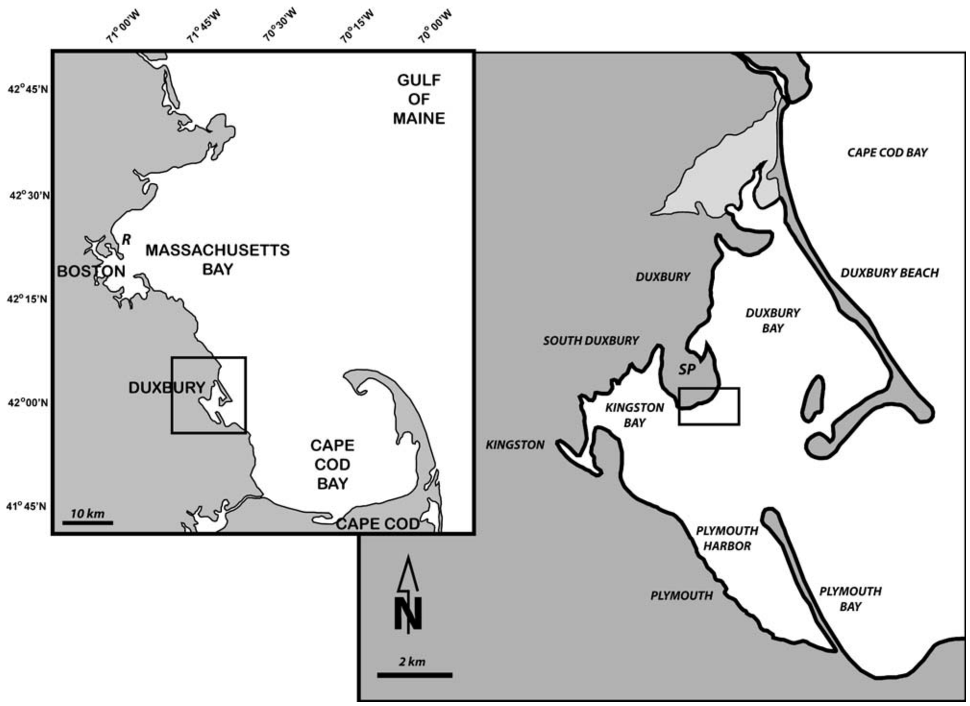

Figure 1. The location of Standish Point, Duxbury Bay, Massachusetts. The inset map provides a context for the state of Massachusetts and location of Standish Point within the Duxbury Bay system. SP = Standish Point; R = Romney Marsh. The black box indicates the study area.

Spectrometry (NOSAMS) facility at Woods Hole Oceanographic Institute, Woods Hole, Massachusetts. Samples were selected from the highest root and closest to the trunk. A section of the root was removed using a saw close to the trunk and from the root that showed the least amount of alteration and with intact bark. The remaining portion of trunk of the stump was not used, as it was the most degraded. The root material showed a higher degree of preservation and less impact by shipworm borings, algal holdfasts, and abrasion than samples collected from the trunk. Samples were also examined from wood beneath preserved bark, but those samples also showed indications of a high possibility for contamination. Samples were isolated from undisturbed wood as close to the wood-bark interface as possible. Samples were washed in deionized water to remove sediment, dried at 50 °C for 24 hours, and subsampled before shipping to NOSAMS for analysis. All dates were calibrated using Calib 6.0.1 with the IntCal09 calibration data set (Stuiver and Reimer, 1993).

A single *Mya arenaria* shell was collected from the sediment surface. The shell was articulated and in growth position, with approximately 66% of the shell imbedded in the blue clay layer that underlies the sandy intertidal sediments. The sample was washed with deionized water and sent to NOSAMS for AMS ^{14}C dating.

Coring

In total, 28 of shallow sediment cores were acquired with a 5 cm × 1 m gouge auger. All cores sites were located using the method described above for locating tree stumps. The cores were arranged throughout the site based on a rough grid (Figure 2). Several cores were located in close proximity to tree stumps to capture the stratigraphic sequence and depositional environments adjacent to the trees. Cores were measured and described in the field visually for stratigraphy and sedimentology and characterized using a Munsell color chart. Cores were photographed, and reference samples from each stratigraphic unit were extracted and archived at 4°C.

Relationships to Other Data Sources

The rates and elevations measured in this study were compared the sea-level curve of Donnelly (2006) and to tide gauge data to establish a landscape gradient. To accomplish the comparisons, conversion and representation of the data were required.

Elevations of stumps were surveyed with respect to MLLW and converted to mean high water (MHW) using the Boston tide gauge data set (NOAA, 2010b). Surveying the high tide line on two different days and comparing the observed elevations to the elevations predicted by tide models verified the conversion. This allowed for determination of the MLLW to MHW offset of 3.05 m.

Donnelly (2006) presents a high-resolution sea-level curve for southeastern Massachusetts that spans the last 3000 years. To compare these sea-level points to the stumps surveyed in this study, data points from Donnelly (2006) that were within the temporal range of the dated stumps were extracted and plotted to determine a linear regression sea-level rate based on

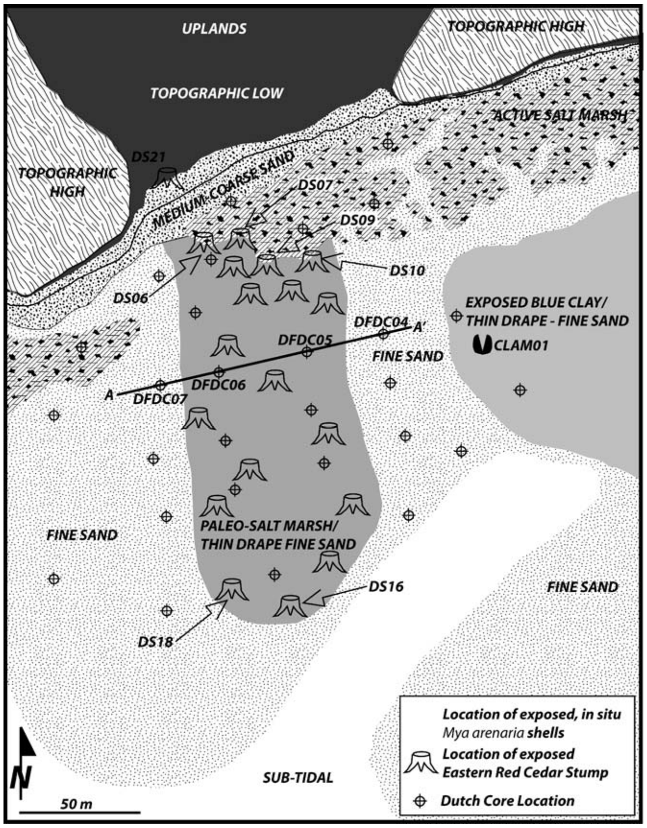

Figure 2. Location of *Juniperus virginiana* (eastern red cedar) stumps and surficial geologic environments of the intertidal zone of Standish Point, Duxbury Bay. Line A-A′ shows the location of Figure 3.

similar timescales. While Donnelly (2006) presents a rate of 0.80 ± 0.25 mm/yr, when the data for the time period of interest are extracted, the rate increases slightly to 1.00 ±0.10 mm/yr.

RESULTS

The series of tree stumps studied here was located in the intertidal zone at Standish Point, Duxbury Bay (Figure 2). The stumps were located in three-dimensional space using survey methods (Table 1). The elevation of the stumps ranges between 0.75 and 2.03 m above MLLW. All observed stumps were rooted in either eroding peat deposits or an iron-stained gravelly sand layer just beneath a well-sorted medium sand layer. The root systems of the stumps penetrated into the iron-stained layer. Stumps located where peat was absent had roots elevated above the iron-stained layer, suggesting that the layer was removed. The stumps closer to the modern shoreline were rooted in peat layers, while those more seaward were in the exposed iron-stained layer.

Table 1. *Locations and elevations of the Duxbury stumps.*

UMass Number	Latitude (°N)	Longitude (°W)	Elevation (m) MLLW	Elevation (m) MHW
DS01	42°00.327	70°40.511	0.86	−2.19
DS02	42°00.336	70°40.515	0.82	−2.23
DS03	42°00.334	70°40.536	0.78	−2.27
DS04	42°00.363	70°40.525	1.47	−1.58
DS05	42°00.365	70°40.536	1.73	−1.27
DS06[a]	42°00.365	70°40.538	1.63	−1.42
DS07[a]	42°00.365	70°40.542	1.47	−1.58
DS08	42°00.360	70°40.542	1.54	−1.51
DS09	42°00.361	70°40.537	1.52	−1.53
DS10	42°00.367	70°40.537	1.64	−1.41
DS11	42°00.369	70°40.551	1.89	−1.16
DS12	42°00.364	70°40.556	1.64	−1.41
DS13	42°00.367	70°40.562	1.83	−1.22
DS14	42°00.367	70°40.563	2.03	−1.02
DS15	42°00.366	70°40.477	1.96	−1.09
DS16[a]	42°00.315	70°40.556	0.81	−2.24
DS17	42°00.321	70°40.5	0.75	−2.30
DS18[a]	42°00.324	70°40.549	0.84	−2.21

[a] Stumps subsampled for ^{14}C AMS dating (see Table 2).

Coring of the area hosting the stumps and immediately surrounding the stumps revealed that the iron-stained gravelly sand layer was present beneath the peat in all areas associated with tree stumps (Figure 3). Thickness of peat ranged from absent to 0.95 m over the iron-stained layer, and the overlying sand layer was less than 0.20 m thick. The iron-stained gravelly sand layer ranged in thickness between absent and 0.35 m. Thickest accumulations were observed in the landward-most and central portions of the area hosting stumps. On the eastern and western margins of the area hosting the stumps, the iron-stained, gravelly sand layer was absent, and the surface was characterized by either the well-sorted medium sand sheet or blue clay that relates to lacustrine phases of Cape Cod Bay (Hill and FitzGerald, 1992; Uchupi and Mulligan, 2006). In these areas, the iron-stained layer was absent (Figure 4).

Samples were collected from all tree stumps located within the intertidal zone. Four stumps were selected for AMS ^{14}C dating. The two most landward and two most seaward tree stumps were selected in an attempt to capture the landscape gradient across the field of tree stumps. The age of the stumps formed two clusters, with the seaward stumps clustering together and the landward stumps clustering together (Table 2). The age of the stumps ranged between 2219 ± 94 and 2867 ± 79 cal YBP.

In addition to intertidal tree stumps, the location and elevation of modern beach and shoreface features were also measured and compared to the paleofeatures (Table 3). The modern features included living and dead eastern red cedar trees, elevations of the frontal dune ridge, and the most recent high tide line. These modern environmental indicators serve as a reference point for comparison to similar indicators observed in the geologic record and will assist in reconstructing the timing and style of the transgression.

DISCUSSION

While the tree stumps discovered at Standish Point are not applicable to assist in the development of high-resolution sea-level curves, they can provide some constraint to sea level and information about the evolution of the landscape at the land-water interface and the preflooding terrestrial environment

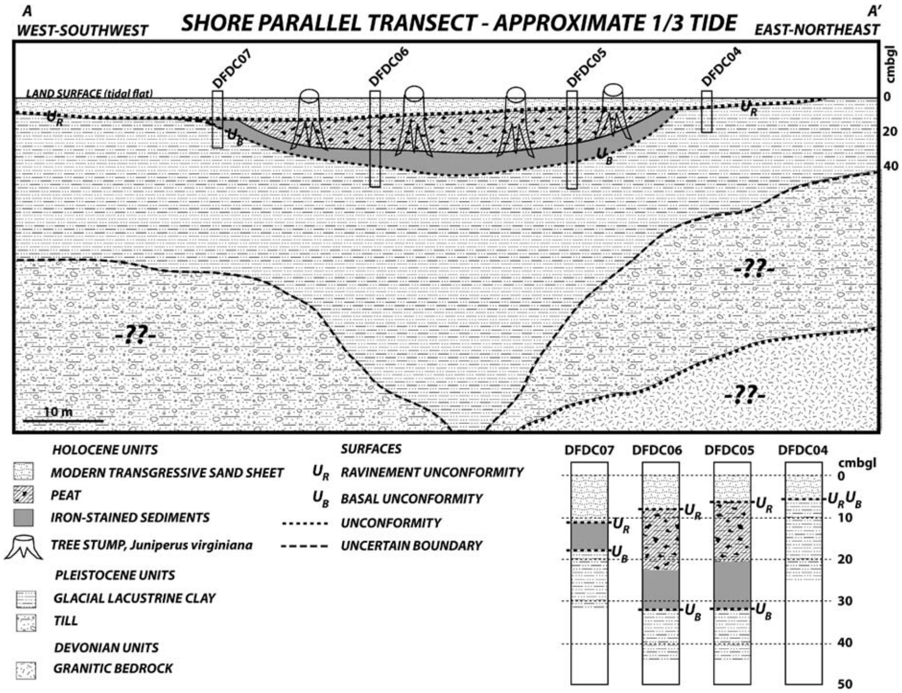

Figure 3. Stratigraphy of the Duxbury forest site. A simplified cross section A-A′ (Figure 2) illustrates the stratigraphic relationship of the major stratigraphic units. Dashed lines indicate uncertain boundaries, and dotted lines indicate unconformities. Stratigraphic information was extracted from shallow coring and previous studies (*cf*. Hill and FitzGerald, 1992).

(Barrie and Conway, 2002; Lacourse, Mathewes, and Fedje, 2003).

The ages of the stumps span nearly 650 years during a time when sea-level rise rates were significantly lower than present. Current measurements for the City of Boston suggest 2.68 mm/yr over the past 100 years, and Donnelly (2006) reported 1.0 mm/yr for the period between 2000 and 3000 years ago from salt marsh studies. The rate compares well to the 1 mm/yr rate reported for the period around 2500 cal YBP in Cape Cod Bay (Oldale and O'Hara, 1980; Redfield and Rubin, 1962). The rate suggested by the tree stumps is 1.4 mm/yr, with an R^2 of 0.97 (Figure 5). None of the stump positions plots below the Donnelly (2006) sea-level curve, and most plot 0.75 to 1.25 m above the Donnelly (2006) sea-level curve.

Eastern red cedars have been observed growing in close proximity to salt marshes and on coastal barrier systems. Data from Waquoit Bay National Estuarine Reserve (C. Maio, 2011, unpublished data; C. Wiedman, 2011, unpublished data) suggest that these trees are capable of living within 0.5 m vertically of mean high water when on exposed barrier systems and lower when in close proximity to sheltered salt marsh and back barrier environments.

Three modern cedars were surveyed as well. One was dead, but upright. The other two appeared healthy with no signs of dead growth (Table 3). Tree DS21 was located on the upper portion of the frontal dune ridge. The elevation of the sand against the trunk was 4.73 m with respect to MLLW. The sand was removed to determine the elevation of the intersection of the highest root with the trunk. The elevation of the intersection was 4.33 m with respect to MLLW. A total of 0.40 m of sand had accumulated at the base of the trunk since this tree germinated. Examination of eastern red cedars in areas without high mobile sediments suggests that the intersection of the highest root with the trunk occurs at approximately 0.10 m below ground level. When compared with the intertidal tree stumps, this elevation results in a slightly higher rate of 1.4 mm/yr. If this rate is compared to the Donnelly (2006) sea-level curve, it shows a clear change, deceleration, in the rate of sea-level rise at 1000 cal YBP. The slowing of sea-level rise and increasing landscape gradient suggest that the sea-level curve does not represent the actual rate of landscape migration. A series of elevations would be required between 2200 cal YBP and the present to better constrain the landscape migration rate and the relationship to the sea-level rise rate.

The distance between tree DS21 and stump DS18 is 179 m. If an assumption is made that the surface on which DS21 is presently growing is a time-transgressive surface and is directly correlative to the surface on which DS18 was growing when alive, then a gradient can be calculated that represents the slope of the landscape during the transgression. The vertical distance between DS21 and DS18 is 3.49 m. The landscape gradient was calculated as 0.020. However, the preserved stumps of the sunken forest occur in a linear zone that is 141 m in length, measured perpendicularly from the

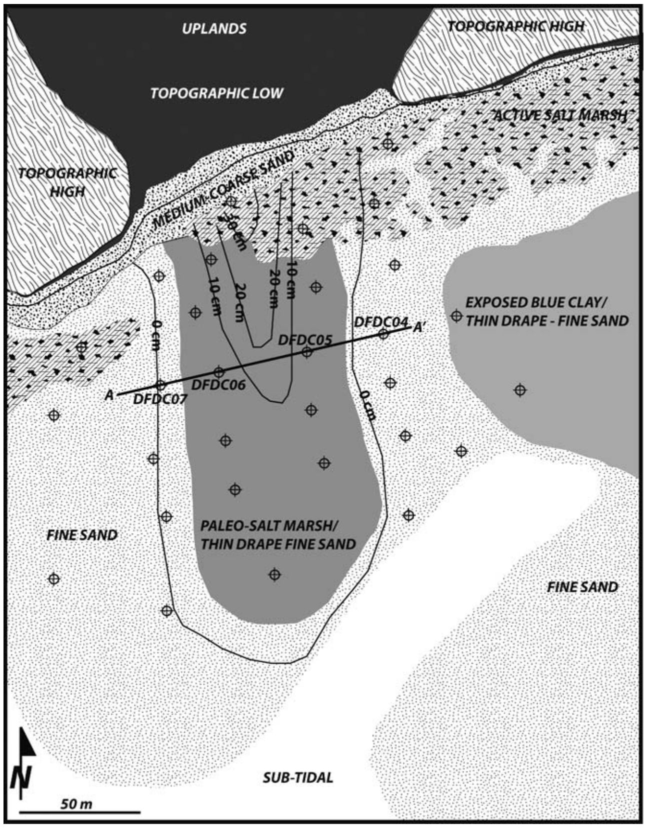

Figure 4. Thickness of the iron-stained, gravelly sand layer. Coring and observation of erosive cuts in the salt marsh deposits allowed for the measurement of the thickness of the iron-stained layer. Thickness ranged from absent over most of the study area to >0.30 m in the central-most portion of the area with stumps. Stumps were not observed in any locations that were not underlain by the iron-stained layer.

present high tide line. The distance from DS21 to the shore-parallel position of the most landward stump, DS06, is 38 m. There are no data points between DS21 and DS06. The landscape gradient for the sunken forest is 0.006 m, while the landscape gradient between the modern trees and the landward-most stump is 0.077 m (Figure 6). The change in gradient suggests either a change in the rate of sea-level rise, which is also seen in sea-level curves for the area and the northeastern United States coastal system (Barnhardt, Belknap, and Kelley, 1997; Church and White, 2006; Donnelly, 2006; Gehrels, 1999; Gehrels, Belknap, and Kelley, 1996; Gehrels *et al*., 2005; Oldale and O'Hara, 1980; Redfield and Rubin, 1962) or influence of the preexisting topography. Elevation surveys with DS21 and the low-lying Allen Pond, as well as the drumlin-trough-drumlin morphology, do not support a strong preexisting topography.

The lack of the iron-stained layer and preserved peat below the modern estuarine/beach sands east and west of the area with tree stumps suggests the transgression removed the original terrestrial landscape. In these locations, the ravinement unconformity is either just below or at the present surface. The paleo-environmental conditions were reconstructed by interpreting the surficial geology (Figure 2), the core stratigraphy (Figure 3), and the iron-stained layer thickness (Figure 4). The reconstruction suggests that the eroding drumlins extended further seaward from their present location, and the low area between drumlins was low enough to develop a paleosol, the iron-stained layer, and peat deposits, which survived transgressive reworking. Large areas of the paleolandscape were removed from the geologic record by erosion and reworking of sediment during the transgression. The locations of these areas are highlighted by the lack of the iron-stained layer and/or peat, the presence of blue clay at the surface, and/or a thin drape of modern sands over blue clay or till.

CONCLUSIONS

The stumps discovered at Standish Point, Duxbury, record a component of the evolution of the Duxbury Bay system. The presence of the 18 stumps and the associated preserved landscape features strongly suggest that the existing topography extended seaward much further than today. The eroding drumlins to the east and west created a small topographic depression that allowed for the development of a lowland coastal forest that was preserved during the transgression by creation of a salt marsh in the low areas as sea level rose. The morphology of the paleosystem and relationship of features and depositional environments are strongly represented by the present system as a retreating sandy beach links to two drumlins and is migrating landward into a low area that hosts eastern red cedar trees, freshwater marsh areas, and a small pond.

Table 2. *Age and elevation of the Duxbury samples.*

NOSAMS Laboratory Number	Elevation (m) MLLW	Elevation (m) MHW	^{14}C AMS Age (YBP)	^{14}C Error (±y)	^{14}C Age Calib (YBP)	2σ Range (±y)	UMass Number
81437	1.35	−1.70	0	25	N/A	N/A	CLAM01[a]
81438	1.63	−1.42	2210	25	2234	83	DS06
81439	1.47	−1.58	2190	30	2219	94	DS07
81440[b]	0.81	−2.24	2730	30	2819; 2915	58; 1	DS16
81441	0.84	−2.21	2770	30	2867	79	DS18

[a] CLAM01 was an in-growth position *Mya arenaria* exposed on the intertidal flat east of the tree stumps (see Figure 2 for location). The sample was fully articulated and partially in the blue glacial lacustrine or marine clays. The age of 0 ± 25 cal YBP was unable to be calibrated by Calib 6.0.1.

[b] DS16 returned two ages when calibrated: 2819 ± 58 cal YBP with 99.8% and 2915 ± 1 cal YBP with 0.1%.

Table 3. *Elevations of modern coastal features, Standish Point, Duxbury, Massachusetts*.

UMass Number	Elevation (m) MLLW	Elevation (m) MHW	Description
HT	3.26	0.21	High tide line[a]
FDR	4.85	1.80	Crest, frontal dune ridge
DS19	4.60	1.55	Dead cedar tree, upper frontal dune ridge
DS20	4.64	1.59	Living cedar tree, upper frontal dune ridge
DS21a	4.33	1.28	First root, living cedar
DS21b	4.73	1.68	Sand level, living cedar

[a] High tide line was the highest wrack line observed during the field survey day. The monthly astronomically high tide occurred three (3) days after the survey.

The presence of the stumps allows for the development of a rate of landscape transgression. While similar to a sea-level rise curve, the landscape transgression curve relates the conversion of one depositional environment to another. In this case, eastern red cedar–dominated coastal forest to exposed beach face and/or salt marsh. The vertical rate of landscape transgression is estimated as 1.4 mm/yr, *i.e*. slightly higher than the 1.0 mm/yr local sea-level rise extracted from Donnelly (2006) for the same time period. The preservation of the iron-stained layer and tree stumps further suggests a low-energy environment with a passive style of flooding, unlike the exposed areas of Duxbury Beach, as reported by FitzGerald, Buynevich, and Rosen (2001). Further, it suggests that a barrier system may have been in place by ~2900 cal YBP, as suggested by Hill and FitzGerald (1992).

The Duxbury sunken forest represents a window into the evolution of the region's coastline. The preserved paleogeographic and paleo-environmental information highlights the style of flooding during the transgression, as well as the change in landscape gradients in response to flooding of Duxbury Bay and higher-energy wave attack due to deeper water throughout the bay. The information contained within sites such as the Duxbury sunken forest can provide detailed contexts for the precolonial coastal system and constrain models of evolution and impacts of natural processes for both hindcasting and forecasting. The insight from the site has the potential to elucidate the precolonial Native American uses of the landscape through reconstruction of the geography and locating preserved submerged cultural heritage sites.

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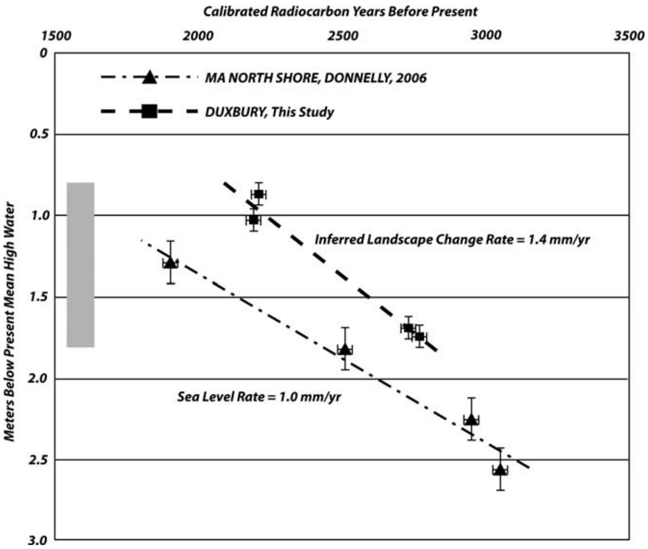

Figure 5. Elevation and age of the Duxbury forest stumps and potential relationship to local sea level. Elevation and age of the Duxbury stumps (squares) and the sea-level points used by Donnelly (2006) (triangles) are plotted to illustrate the relationship of sea level, eastern red cedar stumps, and the correlation of sea-level rise trends. Error bars are shown where they exceed the size of the point. Vertical dashed error bars on the Duxbury stump points indicate 0.5 m. The gray bar on the right side of the figure indicates the elevations at which stumps were observed on the Standish Point intertidal flats, inclusive of vertical errors.

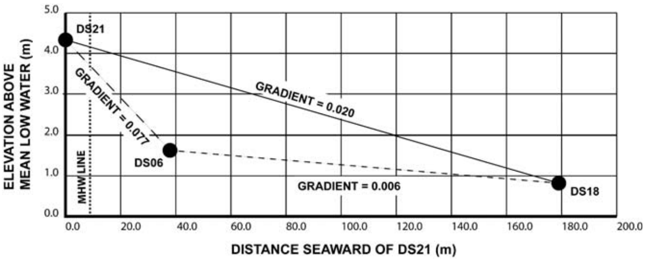

Figure 6. Potential landscape gradients. Elevations and horizontal distance of the stumps suggest gradients for paleolandscapes. The short horizontal distance and large vertical distance between the most landward stump and modern trees suggest a dramatic change in the processes that have driven the landscape change between today and about 2000 cal YBP.

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