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Determining Relative Sea-level Change from Salt-marsh Foraminifera and Plant Zones on the Coast of Maine, U.S.A.

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ABSTRACT

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The modern relation of foraminifera and plants to tidal levels is determined in Maine salt marshes for application in Holocene sea-level studies. The distribution of salt-marsh foraminifera in Maine is similar to that of adjacent maritime Canada. The most useful sea-level indicators are an almost monospecific assemblage of *Trochammina macrescens* forma *macrescens* (faunal zone 1A), found in a ~20 cm vertical range near the upper limit of tidal influence of modern marshes, and peak abundances of *Tiphotrocha comprimata*, found today between mean high water and mean higher high water. Faunal zone boundaries and peak abundances of *Tiphotrocha comprimata* indicate tide levels with an estimated precision of ±15 cm or better. Faunal assemblages, faunal zone boundaries, and peak abundances of agglutinated salt-marsh foraminifera are more precise sea-level indicators than communities of salt-marsh plants. The modern distribution of salt-marsh foraminifera is applied to a study of Holocene sea level in eastern Maine. Fossil foraminiferal assemblages and accelerator mass spectrometry (AMS) ^{14}C ages on plant fragments tightly constrain a relative sea-level chronology for Machiasport. Sea level rose ~1.0 mm/yr between 5,500 and 2,500 cal yr BP, ~0.5 mm/yr in the past 2,500 years, and perhaps accelerated in the past 1,000 years. Long-term rates of relative sea-level rise for the eastern Maine coast are similar to those from 'stable' coasts and to those previously determined along the central and southern Maine coast.

ADDITIONAL INDEX WORDS: *Accelerator mass spectrometry ^{14}C dating, neotectonics, sea-level rise, sea-level indicator, intertidal zonation.*

INTRODUCTION

Tide-gauge records indicate historic rates of sea-level rise along the Maine coast that are the highest of the past 4,000 years. Between 1930 and 1990, sea level has been rising at average rates of 2.1 mm/yr in Portland and 2.5 mm/yr in Eastport (Lyles *et al.*, 1988), compared to long-term middle and late Holocene rates of ~1.0–1.4 mm/yr (Belknap *et al.*, 1989; Gehrels *et al.*, 1993; Gehrels and Belknap, 1993). These high contemporary rates and predicted accelerations of sea-level rise under global warming conditions (Wigley and Raper, 1992) raise questions about the future stability of Maine salt marshes. Salt marshes have undergone dramatic vegetation changes during the past 50 years in southern New England (Warren and Niering, 1993). Net marsh loss has not occurred as it has along Chesapeake Bay (Kearney and Stevenson, 1991) and in the Mississippi deltaic plain (Gagliano *et al.*, 1981). Predicting the future response of Maine salt marshes to sea-level rise requires study of the evolution of salt marshes under past sea-level regimes.

Warped late-glacial shorelines in eastern Maine indicate that as much as 12 m of crustal subsidence may have occurred some time during the past 12,000 years (Thompson *et al.*, 1989). Moreover, it has been argued, from contemporary seismicity (Chiburis, 1981) and leveling studies (Tyler and Ladd, 1981; Tyler, 1989), that eastern Maine is subsiding in modern times (Anderson *et al.*, 1984, 1989). In addition to changing global climate and eustatic sea-level change, regional isostasy and local tectonics may play important roles in coastal evolution. From the Holocene relative sea-level record, partially preserved in the sediments of salt marshes, it may be possible to isolate the role of crustal movements as a contributor to relative sea-level rise (Newman *et al.*, 1987).

In a previous investigation of Holocene relative sea-level changes, Belknap *et al.* (1989) constructed local sea-level curves for four locations along the central and southern Maine coast. The

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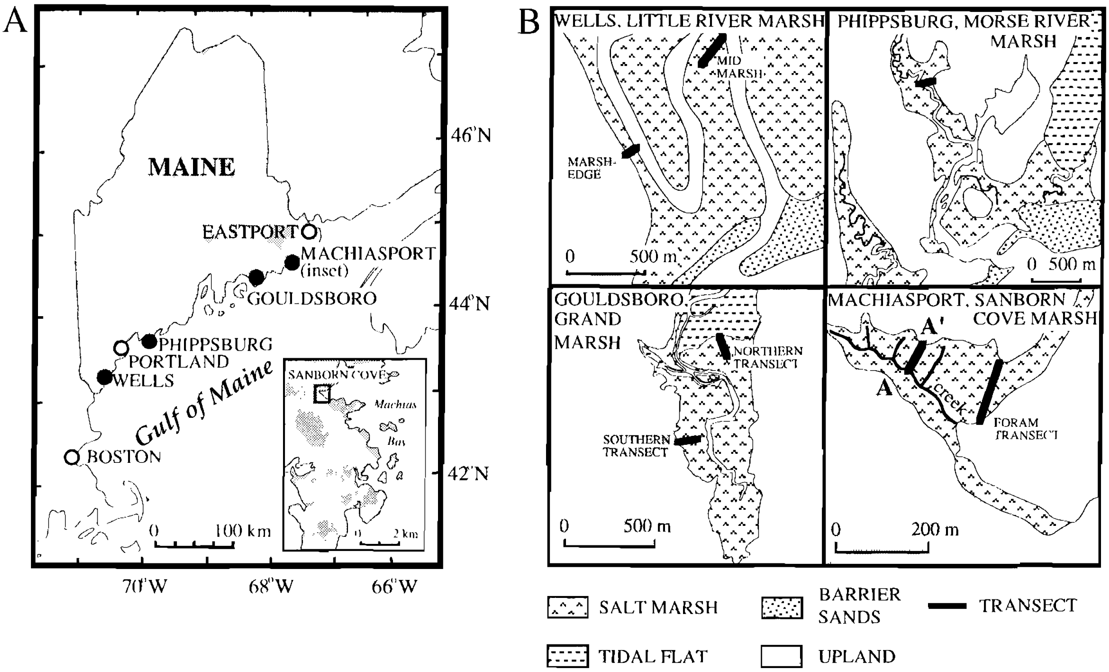

Figure 1. A. Location map. Solid circles are locations where the surficial distribution of salt-marsh foraminifera was investigated. Tide gauges are located in Eastport and Portland. B. Transects mark sample sites for surface foraminifera. Stratigraphic cross section A-A' from Sanborn Cove is shown in Figure 9.

sea-level curves were relatively imprecise, primarily due to uncertainties involved with conventional dating of large peat samples (Belknap and Kraft, 1977). Another source of uncertainty was introduced from using salt-marsh plants as primary sea-level indicators. The vertical range of salt-marsh plants on the modern marsh surface is relatively large, as demonstrated below.

Accurate sea-level histories are based on precise ages and sea-level indicators. Accelerator mass spectrometry (AMS) radiocarbon ages on plant fragments embedded in basal high salt-marsh peats provide precise ages for sea-level points (Gehrels and Belknap, 1992). In Nova Scotia, Scott and Medioli (1978) considered fossilized agglutinated foraminifera in the peats the most reliable sea-level indicators, due to the narrow and tightly constrained vertical zonation of modern assemblages.

In this paper, it is hypothesized that using fossilized assemblages of salt-marsh foraminifera as sea-level indicators improves the precision of local sea-level chronologies. To test this hypothesis, the altitudinal relationship among modern foraminiferal assemblages, modern plant communities, and tidal levels is investigated in four locations on the Maine coast (Figure 1). As an example of the application of foraminifera as sea-level indicators, the modern distribution of salt-marsh foraminifera is used to determine Holocene relative sea-level changes on the eastern Maine coast. For Sanborn Cove marsh, Machiasport (Figure 1), located within the region of proposed subsidence, a late Holocene sea-level history is constructed from detailed analyses of fossil foraminiferal assemblages and AMS ^{14}C ages on basal plant fragments. Comparison with sea-level histories from the central and southern Maine coast (Belknap *et al.*, 1989) yields information about relative crustal motion along the Maine coast (Gehrels and Belknap, 1993).

PHYSICAL SETTING

Though the 'classic' Maine coast is often perceived as a rocky shoreline, salt marshes are an important coastal environment along Maine's highly convoluted 5,970 km coastline. In fact almost 79 km^2 of salt marsh are found in Maine, more than any other New England state, New York, or the Bay of Fundy (JACOBSON *et al.*, 1987). Salt marshes, beaches, tidal flats, and shallow estuaries are generally frozen during the winter months. Sediment transport by ice is an important sedimentary process in Maine salt marshes (WOOD *et al.*, 1989). Maine's humid, northern temperate climate has mean annual coastal temperatures of 6 °C–7 °C and a mean annual precipitation of 115 cm. Average annual snowfall in coastal Maine is 175 cm (FEFER and SCHETTIG, 1980).

Westerly winds are most frequent in Maine. In the summer, winds from the southwest prevail, and in the winter prevailing winds are from the northwest (U.S. NAVAL WEATHER SERVICE COMMAND, 1975; BELKNAP *et al.*, 1988). Storm winds, particularly southeasters and northeasters, are more important in shaping the barrier systems along the Maine coastline. However, storms do not contribute significantly to marsh sedimentation (DUFFY *et al.*, 1989).

The Maine coast is meso- to macrotidal. Tidal range increases systematically along the coast from 2.6 m in southwestern Maine to 6.0 m in easternmost Maine (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA)/NATIONAL OCEAN SERVICE (NOS), 1991). Tides are semidiurnal in character. In the head of embayments, tidal range may be amplified due to funneling effects. At the head of deep and geometrically regular bays, amplification of the tidal wave is minimal and tides are similar to predicted tides on the open coast (SHIPP *et al.*, 1985).

The surficial distribution of salt-marsh foraminifera was studied along six transects in four salt marshes, evenly distributed along the Maine coast. These marshes are: Little River marsh in Wells (43°21′N, 70°33′W, two transects); Morse River marsh in Phippsburg (43°45′N, 69°49′W); Grand Marsh in Gouldsboro (44°26′N, 68°01′W, two transects); and Sanborn Cove marsh in Machiasport (44°41′N, 67°24′W). Plant zonations were investigated in these marshes and also in the Webhannet marsh in Wells (43°18′N, 70°34′W).

KELLEY *et al.* (1988) classified Maine salt marshes as back-barrier, transitional, fluvial, and bluff-toe marshes on the basis of their origin and geomorphic setting. Webhannet River, Little River, and Morse River marshes are back-barrier marshes, fronted by sandy barrier beaches. Grand Marsh and Sanborn Cove can be classified as bluff-toe marshes, as their sediment is derived from nearby eroding bluffs. The marshes are not directly located at the 'toe' of the bluff but farther landward in the head of the embayments.

METHODS

Extensive reconnaissance coring in Sanborn Cove marsh with an Eijkelkamp hand corer (a semi-closed tube corer of 1 m length and 3 cm diameter) located thick sections of high salt-marsh peat, consisting primarily of the remains of *Spartina patens* and *Solidago sempervirens*. Peats were sampled with a 7.6 cm diameter, gasoline-powered, vibracorer. Corrections for compaction that occurred during vibracoring (usually ~10%) were applied by stratigraphic comparison with an uncompacted Eijkelkamp core from the same site. The cores were opened in the laboratory, logged, photographed, and portions were sampled for radiocarbon dating.

Detrital plant fragments, horizontally embedded in *basal* peats were dated by the AMS ^{14}C method to provide chronological control for the Machiasport sea-level history. Basal peats overlie an incompactible substrate and are not vertically displaced by autocompaction (KAYE and BARGHOORN, 1964). These peats are often contaminated with humic acids and younger roots (BELKNAP *et al.*, 1989). To circumvent this problem, I selected individual plant fragments for AMS ^{14}C dating (GEHRELS and BELKNAP, 1992, 1993). The ages obtained are considered to represent the age of the marsh surface at the time of deposition. The plant fragments are probably too fragile to have been significantly reworked. Ages on vertical, *in situ*, roots or rhizomes would introduce a larger vertical uncertainty, because the penetration depth cannot be exactly determined.

Elevations of cores, plants, and sample sites of surface foraminifera were measured with an infrared Total Survey Station relative to a nearby U.S. Coast and Geodetic Survey benchmark. The National Ocean Service provided relations between open-coast tidal levels and the National Geodetic Vertical Datum (NGVD) of 1929 (Table 1). However, core sites in this study are located at a considerable distance from the open coast. High water in the marsh occurs at a lower level due to frictional effects (JOHNSON, 1913). Long-term measurements, preferably over a 29-day period (SCHUREMAN, 1958), are necessary in order to satisfactorily establish the true *local* mean high water (MHW) datum in the backbarrier. Tide-gauge measurements are not possible without the

Table 1. *Relationships between geodetic and tidal datums (1960–1978; National Ocean Service, written communication, 1992), tidal range, and local MHW elevations for study sites. MHHW (mean higher high water), MHW (mean high water) and mean tidal range values are from NOAA/NOS (1991). MSL-NGVD is inferred from sea-level rise since 1929 determined at the closest tide-gauge station (Eastport or Portland). Mean sea level (MSL) is not always equal to mean tide level (MTL) due to the asymmetry of the tidal wave (Jardine, 1975). Local MHW datum is a botanical datum inferred from the Spartina patens/Spartina alterniflora boundary (see text).*

Salt Marsh	Tidal Station	MHW-NGVD (m)	MHHW-MHW (m)	MSL-NGVD (m)	MSL-MTL (m)	Mean Tidal Range (m)	Estimated Local MHW Datum (m above NGVD) at Transects
Wells: Webhannet River, Little River	Cape Porpoise	1.43	0.40	0.11	0.01	2.62	1.43 ± 5
Phippsburg: Morse River	Hunniwell Point	1.36	0.40	0.09	0.01	2.56	1.34 ± 6
Gouldsboro: Grand Marsh	Gouldsboro Bay	1.67	0.49	0.06	0.01	3.29	1.55 ± 6 (southern transect) 1.67 ± 1 (northern transect)
Machiasport: Sanborn Cove	Machiasport	2.03	0.55	0.06	0	3.84	1.92 ± 7 (coring transect) 2.03 ± 7 (foram transect)

presence of a large tidal creek near the coring transect. Therefore, local MHW is estimated from a botanical datum. The elevation of the *Spartina patens/Spartina alterniflora* boundary on the seaward side of Maine salt marshes is close to the open coast MHW (14 observations in four marshes, mean = 0.065 m below MHW, standard deviation = 0.036 m; independent of tidal range; Gehrels, 1994). These data are in general agreement with other localities in New England (Gordon, 1980; Bertness and Ellison, 1987; Lefor *et al.*, 1987). From observations on this plant boundary, the local MHW datums at the foraminifera transects and the coring transect in Sanborn Cove marsh are estimated (Table 1).

Methods for foraminifera sampling and sample preparation are similar to those described by Scott and Medioli (1980a). Surface foraminifera samples, approximately 3 × 3 × 1 cm (length × width × depth) in size, were collected using a knife and a plastic bottle from which the bottom was removed. In the field, the samples were put into a solution of 10% formaldehyde containing baking soda to buffer the solution and Rose Bengal to stain living foraminifera. From the ^{14}C peat samples retrieved from the cores, a 10 cc fraction was analyzed for fossilized foraminifera. Surface and core foraminifera samples were sieved between 63 μm and 500 μm and put in a 15 cm high beaker. The beaker was filled with turbulent water, and the suspended organic material was carefully decanted after allowing one minute for the foraminifera to settle. The decanted portion was checked for foraminifera to assure that small individuals were not lost. Decantation was repeated five or six times.

Samples were split with a wet splitter, similar to that described by Scott and Hermelin (1993). The specimens in a split portion of the sample were identified and counted under a binocular microscope in water. Specimens of each species and unidentifiable individuals were picked and mounted on slides for future reference. Abundances reported in this paper are percentages of the total (living and dead) population. The purpose of identifying living specimens is to determine which foraminifera are absolutely indicative of the conditions at the marsh surface during sampling. However, the living population varies greatly from season to season; whereas, the total population of the upper centimeter (representing the integrated population of several years) remains relatively constant (Scott and Medioli, 1980b). Fossilized deposits contain the former total population, making the relative abundances of total foraminiferal populations on today's marsh surface more suitable for application in stratigraphic studies.

Radiocarbon ages are reported as radiocarbon years before present (BP), where present is 1950 AD. By international convention, the Libby half-life of ^{14}C is taken as 5,568 years and 95% of the activity of the National Bureau of Standards Oxalic Acid modern standard. Radiocarbon ages that were used to compute rates of sea-level rise were calibrated into calendar years with the calibration program CALIB 3.0.3 (Stuiver and Reimer, 1986, 1993) and are reported as cal yr BP.

Table 2. *Statistics on surveyed plant elevations (meters above NGVD) in five salt marshes.*

	Statistic	*Spartina patens*	*Juncus* sp.	*Solidago* sp.	*Scirpus* sp.	*Distichlis spicata*	*Phragmites*/ *Typha* sp.
Wells: Webhannet River marsh	N (measurements)	34					5
	range	1.09–1.87					1.72–2.19
	mean	1.53					1.92
	standard deviation	0.18					0.20
Wells: Little River marsh	N	21			3	5	
	range	1.34–1.85			1.77–1.98	1.42–1.45	
	mean	1.58			1.88	1.44	
	standard deviation	0.18			011	0.01	
Phippsburg: Morse River marsh	N	8	5	2	2	4	
	range	1.53–1.71	1.71–1.91	1.82–1.91	1.70–1.76	1.53–1.68	
	mean	1.61	1.79	1.79	1.73	1.60	
	standard deviation	0.08	0.08	0.06	0.04	0.07	
Gouldsboro: Grand Marsh	N	17	6	10			
	range	1.59–2.09	1.93–2.08	2.13–2.49			
	mean	1.78	1.99	2.31			
	standard deviation	0.14	0.05	0.12			
Machiasport: Sanborn Cove marsh	N	6	11	9			
	range	1.81–2.18	2.17–2.99	2.41–2.99			
	mean	2.02	2.53	2.60			
	standard deviation	0.15	0.21	0.16			

SALT-MARSH PLANT ZONATION

Salt marshes in temperate coastal regions commonly exhibit a distinct plant zonation that is controlled by tolerance of plants to tidal inundation and inter-specific competition (*e.g.*, NIXON, 1982; BERTNESS and ELLISON, 1987; JACOBSON and JACOBSON, 1989). Salt marshes are divided into a low marsh and high marsh. In New England, the low marsh occupies a zone between mean tide level and about MHW, and the high marsh occupies the intertidal zone from MHW upwards (FREY and BASAN, 1985). The high marsh can often be subdivided into a lower *Spartina patens* zone, a middle *Juncus gerardii* zone, and an upper zone bordering the upland inhabited by brackish plants and upland grasses (MILLER and EGLER, 1950).

Because of its apparent correlation with elevation (*i.e.*, tide levels), the zonation pattern has been of great use for sea-level investigators. In New England, for example, sea-level curves have been based on radiocarbon-dated remains of high salt-marsh plants (*e.g.*, REDFIELD and RUBIN, 1962; BELKNAP *et al.*, 1989). The low marsh plant *Spartina alterniflora* is considered less desirable as a sea-level indicator, because its vertical range is wide and poorly correlated with tide levels (MCKEE and PATRICK, 1988).

In Maine, important salt-marsh plants in the upper part of the intertidal zone include *Spartina patens*, *Juncus* sp. (*gerardii* and *balticus*), *Solidago* sp. (*sempervirens* and *rugosa*), *Scirpus* sp. (*maritimus* and *americanus*), *Distichlis spicata*, *Triglochin maritimum*, *Festuca rubra*, *Spartina pectinata*, *Limonium carolinianum*, and the freshwater plants *Phragmites australis* and *Typha angustifolia* (JACOBSON and JACOBSON, 1989; GEHRELS, 1994). Remains of the high marsh plants *Spartina patens*, *Juncus* sp. and *Solidago* sp. are most commonly identified in cores. Vertical ranges of these plant species are given in Table 2. These ranges are minimum values, because the addition of new data will undoubtedly lead to an increase of the ranges. Elevation control was best established for *Spartina patens*. The vertical range of this species varies from ~30 cm in Sanborn Cove marsh to ~80 cm in Webhannet River marsh. In the Morse River marsh, the range is only 18 cm. This marsh is geologically mature (*i.e.*, low marsh is not present) and relief is small. Though Sanborn Cove has the largest tidal range (3.84 m; NOAA/NOS, 1991), the vertical range of *Spartina patens* is smaller than at Wells (2.62 m tidal range; NOAA/NOS, 1991) and Gouldsboro (3.29 m tidal range; NOAA/NOS, 1991). In Sanborn Cove marsh, *Spartina patens* grows lower relative to MHW than in the other marshes. SCOTT and MEDIOLI (1980a) suggested that most of the increase in tidal range in Bay of Fundy marshes is absorbed by the *Spartina alterniflora* zone.

Elevations of the upper high marsh plants, *Juncus* sp. and *Solidago* sp., were measured in Morse River marsh, Grand Marsh, and Sanborn Cove marsh. In Morse River marsh, ranges are narrow. The *Juncus* zone is 15 cm wide in Grand Marsh, but ~80 cm wide in Sanborn Cove marsh. The *Solidago* zone is 36 and 58 cm wide, in Grand Marsh and Sanborn Cove marsh respectively. There are too few observations on other plants (Table 2) to be meaningful.

SURFICIAL DISTRIBUTION OF SALT-MARSH FORAMINIFERA

Like plants, assemblages of agglutinated foraminifera are known to exist in distinct biofacies in many salt marshes of North America. In marshes along the Pacific coast, the distinction between assemblages allows the separation of the marsh into a high marsh and a low marsh zone (JENNINGS and NELSON, 1992), and in some cases the low marsh can be subidivided into two subzones (SCOTT, 1976; PATTERSON, 1990). In Texas, three plant zones correlate with distinct faunal assemblages (PHLEGER, 1965). High and low marsh faunal zones are present in the saline marshes of the lower Mississippi Delta (SCOTT *et al.*, 1991). In medium-salinity marshes along Chesapeake Bay (ELLISON and NICHOLS, 1976) and in Delaware tidal marshes (FLETCHER *et al.*, 1993b), two high marsh subzones and one low marsh zone are recognized. SCOTT and MARTINI (1982) found a high and a low marsh faunal zone in subarctic marshes around Hudson and James bays despite a low number of foraminifera. On Plum Island, northeastern Massachusetts, JONES and CAMERON (1987) could only distinguish between high and low marsh zones. In southern Massachusetts, SCOTT and LECKIE (1990) distinguished a high marsh, a transitional high marsh and a low marsh faunal zone. However, salt marshes in the northeastern United States and the Canadian Maritime provinces often display four distinct faunal zones (SCOTT and MEDIOLI, 1978, 1980a; SCOTT *et al.*, 1981; SMITH *et al.*, 1984; THOMAS and VAREKAMP, 1991), two high marsh faunal zones (zone 1A and 1B) and two low marsh faunal zones (zone 2A and 2B). Marsh foraminiferal faunal zones in Maine closely resemble those of marshes in the Canadian Maritimes.

Thirteen species, nine agglutinated and four calcareous, were encountered on the modern surface of salt marshes in Maine. The calcareous species are usually not preserved in marsh peats. Taxonomy follows SCOTT and MEDIOLI (1980a), except for *Haplophragmoides manilaensis* (SCOTT and LECKIE, 1990; SCOTT *et al.*, 1990), *Pseudothurammina limnetis* (SCOTT *et al.*, 1981), and *Elphidium williamsoni* (HAYNES, 1973; MILLER *et al.*, 1982), which are equivalent to SCOTT AND MEDIOLI'S (1980a) *Haplophragmoides bonplandi*, *Thurammina*(?) *limnetis* and *Cribrononion umbilicatulum*, respectively. Calcareous species, not found in Nova Scotia by SCOTT and MEDIOLI (1980a), are *Astrononion* sp. (CUSHMAN and EDWARDS, 1937), *Cibicides* sp. (DE MONTFORT, 1808), and *Elphidium subarcticum* (CUSHMAN, 1944). Zone 1A contains an almost pure *Trochammina macrescens* forma *macrescens* assemblage. The upper boundary of this zone is approximately the highest astronomical tide (HAT) mark, above which foraminifera are rare. Zone 1B includes other high marsh species, such as *Trochammina inflata*, *Tiphotrocha comprimata*, and *Haplophragmoides manilaensis*. In zone 2A, *Tiphotrocha comprimata* and *Haplophragmoides manilaensis* are replaced by *Miliammina fusca*. Finally, zone 2B is heavily dominated by *Miliammina fusca*, with occurrences of *Ammotium salsum* and calcareous species.

Machiasport

Eighteen surface samples were taken along an 88 m transect in Sanborn Cove marsh at regular vertical intervals between the lowest occurrence of *Spartina alterniflora* and the upland/marsh transition. Foraminifera are rare higher than 68 cm above MHW (Figure 2, Table 3). Zone 1A, between 50 and 68 cm above MHW, is characterized by an almost pure assemblage of *Trochammina macrescens* forma *macrescens*. *Tiphotrocha comprimata* occurs with *Trochammina macrescens* forma *macrescens*, *Trochammina inflata*, and low abundances of *Miliammina fusca* in zone 1B (8–50 cm above MHW). High abundances of *Miliammina fusca*, together with occurrences of *Trochammina macrescens* forma *macrescens* and *Trochammina inflata*, characterize zone 2A (28 cm below to 8 cm above MHW). Zone 2B, with the abundant occurrence of *Miliammina fusca* (> 85%), lies lower than 28 cm below MHW. Around 137 cm below MHW, at the lowest occurrence of *Spartina alterniflora*, the mudflat species *Ammotium salsum* increases in abundance.

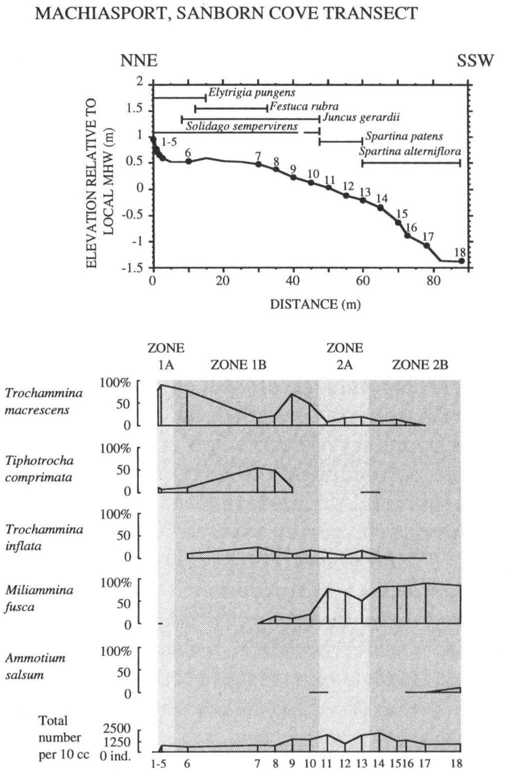

Figure 2. Surficial vertical zonation of foraminifera in Sanborn Cove marsh, Machiasport, with ranges of dominant plants.

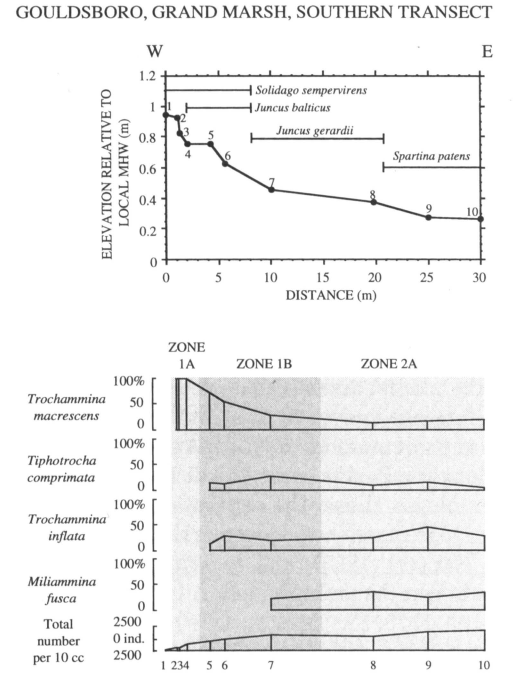

Figure 3. Surficial vertical zonation of foraminifera along southern transect, Grand Marsh, Gouldsboro, with ranges of dominant plants.

Gouldsboro

Two transects in Grand Marsh were sampled, one in the northern part, covering the low marsh and the lower high marsh, and one in the southern part, covering the higher high marsh. The southern transect contains Zone 1A between 0.75 and 0.93 m above MHW (Figure 3, Table 4). Two samples were taken at 0.75 m above MHW, one of which was 100% *Trochammina macrescens* forma *macrescens* assemblage. The other contained a Zone 1B assemblage, marking a transition at this level. The lower portion of the transect consists of Zone 1B foraminifera, with a peak of *Tiphotrocha comprimata* at 0.45 m above MHW. The lower portion of the transect is a transition to Zone 2A.

The lower part of the northern transect is characterized by Zone 2B foraminifera (Figure 4, Table 5). Between 0.13 m below MHW and 0.17 m above MHW, the foraminifera make up a Zone 2A assemblage. Sample 5, at the *Spartina alterniflora*/*Spartina patens* boundary, is somewhat anomalous, with relatively high percentages of *Ammotium salsum.* The presence of *Tiphotrocha comprimata,* a Zone 1B species, marks the upper part of the transect.

Phippsburg

Eight samples were taken in the Morse River marsh. Low marsh on this part of the Maine coast is rare. Plant communities along the transect are dominated by *Spartina patens* and *Juncus* species. Along the landward edge of the marsh, an almost monospecific assemblage of *Trochammina macrescens* forma *macrescens* was found in Sample 1 at 0.55 m above MHW (Figure 5, Table 6). The lower boundary of Zone 1A is somewhere between 0.55 and 0.45 m above MHW. Samples were not collected near the upper boundary of Zone 1A, estimated at 0.70 m above MHW. Between ~0.50 and 0.20 m above MHW, the population is characteristic of Zone 1B. A relatively high abundance of *Haplophragmoides manilaen-*

Table 3. *Percentages of foraminifera on the modern surface of Sanborn Cove marsh, Machiasport. Liv. = living individuals; Tot. = living and dead individuals. x = less than 1%.*

		Sample Site																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
MHW elevation (m):		0.96	0.77	0.71	0.65	0.59	0.53	0.48	0.38	0.23	0.13	0.03	−0.12	−0.21	−0.35	−0.63	−0.88	−1.07	−1.37
Distance Along Transect (m):		0	0.75	1.0	1.75	2.5	10	30	35	40	45	50	55	60	65	70	72.5	78	88
Individuals per 10 cc:		16	40	48	180	752	496	904	888	1,512	1,384	1,824	984	1,880	2,200	1,312	1,432	848	728
Ammotium salsum	Liv.											2			x				1
	Tot.											2	1		x		1	1	9
Elphidium williamsoni	Liv.													2			4		1
	Tot.													2			4		2
Haplophragmoides	Liv.														x	1			
manilaensis	Tot.					2									x	1			
Miliammina fusca	Liv.										2	25	26	17	36	36	15	18	3
	Tot.				3	1	1		14	10	17	78	70	53	85	85	87	94	88
Pseudothurammina	Liv.									1	1		2						
limnetis	Tot.						2			1	1		6	4	1				
Tiphotrocha comprimata	Liv.						2	10	11	1	9			x					
	Tot.			17	6	4	10	57	52	7	13			1	x				1
Trochammina inflata	Liv.							4	5	1	6	3	3	2	2	1	1	1	
	Tot						7	27	12	7	16	13	5	17	3	1	3	2	
Trochammina macrescens	Liv.					3	24	1	1	14	12	2	11	5	5	1	2	1	
forma *macrescens*	Tot.	100	100	83	90	93	82	16	22	76	54	7	18	20	9	14	4	2	

Table 4. *Percentages of foraminifera on the modern surface of Grand Marsh, Gouldsboro, southern, more landward, transect. Liv. = living individuals; Tot. = living and dead individuals.*

		Sample Site									
		1	2	3	4	5	6	7	8	9	10
MHW Elevation (m):		0.94	0.92	0.82	0.75	0.75	0.62	0.45	0.37	0.27	0.26
Distance Along Transect (m):		0	1.10	1.30	2	4.20	5.60	10	19.8	25	30
Individuals per 10 cc:		136	416	656	1,216	2,923	2,155	3,264	2,987	3,755	4,203
Miliammina fusca	Liv.							1	6	1	10
	Tot.	24					1	21	38	22	38
Pseudothurammina	Liv.										
limnetis	Tot.						1		1		2
Tiphotrocha comprimata	Liv.					1	5	3	5	6	1
	Tot.					13	13	28	13	15	7
Trochammina inflata	Liv.					2	7	9	23	19	15
	Tot.					12	30	20	36	47	29
Trochammina macrescens	Liv.	12	2	66	79	5	18	13	2	5	11
forma *macrescens*	Tot.	76	100	100	100	75	55	31	13	17	24

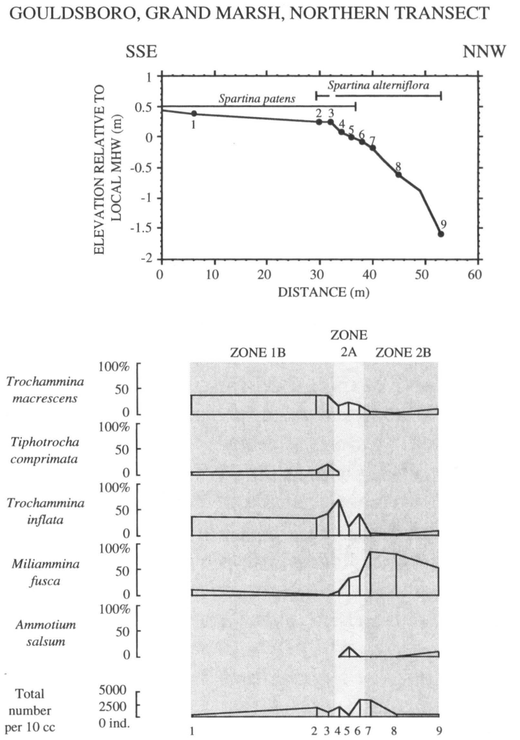

Figure 4. Surficial vertical zonation of foraminifera along northern transect, Grand Marsh, Gouldsboro, with ranges of dominant plants.

sis in Samples 2 and 3 indicates low salinities (Scott, 1977; Scott and Medioli, 1980a). *Tiphotrocha comprimata* peaks in Samples 4 and 5. Sample 8 has higher abundances of *Miliammina fusca* and marks a transition to Zone 2A.

Wells

Samples in the Little River marsh were taken along two transects. A mid-marsh transect crossed a broad meander of the Little River to include some of the sparse low marsh. The upper marsh-edge transect includes the upper high marsh.

Nine agglutinated and four calcareous species were identified along the mid-marsh transect in eight samples between the lowest occurrence of the marsh grass *Spartina alterniflora* and the highest portion of the interfluvial area, dominated by *Spartina patens* (Figure 6, Table 7). Calcareous species were found in the low marsh, near the creek bank. Below 0.06 m above mean high water (MHW), a Zone 2B assemblage occurs, with abundant *Miliammina fusca*. In the upper 12 centimeters of the transect, *Miliammina fusca* decreases in abundance while *Trochammina inflata* increases, a species characteristic of Zone 2A.

Along the marsh-edge transect, between 0.40 and 0.60 m above MHW, *Trochammina macrescens* forma *macrescens* is found in high abundances (Figure 7, Table 8). The presence of *Pseudothurammina limnetis* here is unusual. The marsh surface is very hummocky and wet. In a core, *Pseudothurammina limnetis* was found only in the upper 5 cm. The peat in the core was soupy and rotten. All these factors point to recent dis-

Table 5. *Percentages of foraminifera on the modern surface of Grand Marsh, Gouldsboro, northern, more bayward, transect. Liv. = living individuals; Tot. = living and dead individuals. x = less than 1%.*

		Sample Site								
		1	2	3	4	5	6	7	8	9
MHW Elevation (m):		0.38	0.25	0.25	0.08	0	−0.08	−0.18	−0.62	−1.59
Distance Along Transect (m):		6	32	30	34	36	38	40	45	53
Individuals per 10 cc:		1,920	2,202	1,818	1,958	92	2,816	2,920	191	81
Ammotium salsum	Liv.								2	
	Tot.		1				20	x	11	6
Arenoparella mexicana	Liv.			1						
	Tot.			1						
Elphidium williamsoni	Liv.					2				
	Tot.					2				
Miliammina fusca	Liv.	9			4	11	11	36	18	9
	Tot.	21	5		8	36	37	89	83	57
Pseudothurammina	Liv.						1			
limnetis	Tot.	1	1		1		1		3	5
Tiphotrocha comprimata	Liv.	1	5	10	2		1			
	Tot.	6	10	20	3		1			
Trochammina inflata	Liv.	10	25	25	44	8	20	3	1	
	Tot.	36	44	43	70	14	42	6	1	11
Trochammina macrescens	Liv.	4	10	16	6	8	11	2		
forma *macrescens*	Tot.	37	39	37	18	24	19	5	2	
Trochammina macrescens	Liv.									
forma *polystoma*	Tot.								1	10
Calcareous, unidentified	Liv.				4					11
	Tot.				4					11

turbance of this part of the marsh. Zone 1B, with the marked peak of *Tiphotrocha comprimata* in Sample 5, extends down to 0.06 m above MHW. Sample 8, with increased abundance of *Miliammina fusca,* indicates a transition to Zone 2A. Note the occurrence of *Arenoparrella mexicana* in Sample 4, a species common in southern New England (Jones and Cameron, 1987; Scott and Leckie, 1990).

DISCUSSION

Vertical ranges of salt-marsh plant species and foraminiferal faunal zones are summarized in Figure 8. Salt-marsh plants have larger and more variable vertical ranges than foraminifera, making them less attractive as sea-level indicators. A possible exception is the *Spartina patens/Spartina alterniflora* boundary which is found between 1 cm above and 14 cm below MHW on the modern marsh surface when bordering tidal flats. Along creeks the elevation of this boundary is much more variable. Generally, *Spartina patens* grows approximately from slightly below MHW to MHHW. *Juncus* sp. and *Solidago* sp. are found around and above MHHW. Identification of plant remains, especially in highly macerated peats, can be problematical. An advantage of using plant remains is that they can be identified with the naked eye.

The correlation between foraminiferal zones and elevation above a chosen tide level allows the use of fossilized foraminiferal assemblages as accurate altitudinal indicators in marsh sediments (Scott and Medioli, 1978, 1986). Foraminifera are excellent sea-level indicators in Maine, due to low species diversity and narrow modern vertical ranges. Foraminiferal analyses are time-consuming but large numbers of preserved agglutinated foraminifera in peats make possible statistical analyses (Scott and Medioli, 1978). The foraminiferal assemblage of Zone 1A (an almost monospecific *Trochammina macrescens* assemblage) is a useful sea-level indicator for two reasons. First, this faunal zone has a vertical range of only ~20 cm. In Maine, Zone 1A occurs somewhere between 40 and 93 cm above MHW. In the Little River marsh, Wells and Sanborn Cove marsh, Machiasport (tidal ranges 2.62 and 3.84 m, respectively), Zone 1A was found at approximately the same elevation above MHW (Figure

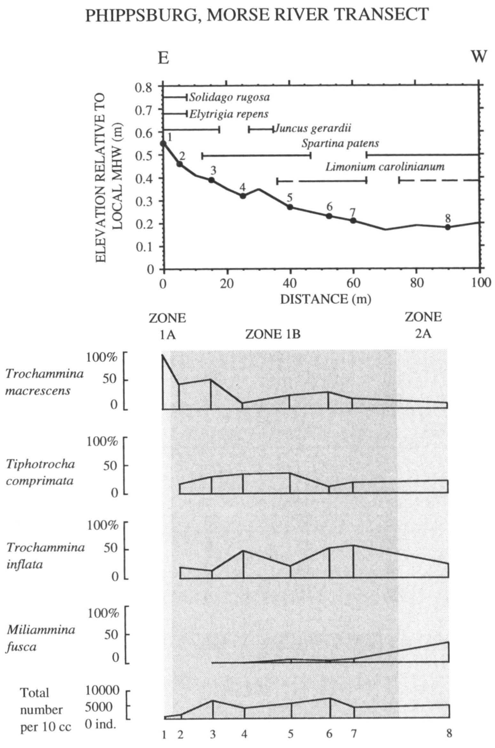

Figure 5. Surficial vertical zonation of foraminifera in Morse River marsh, Phippsburg, with ranges of dominant plants.

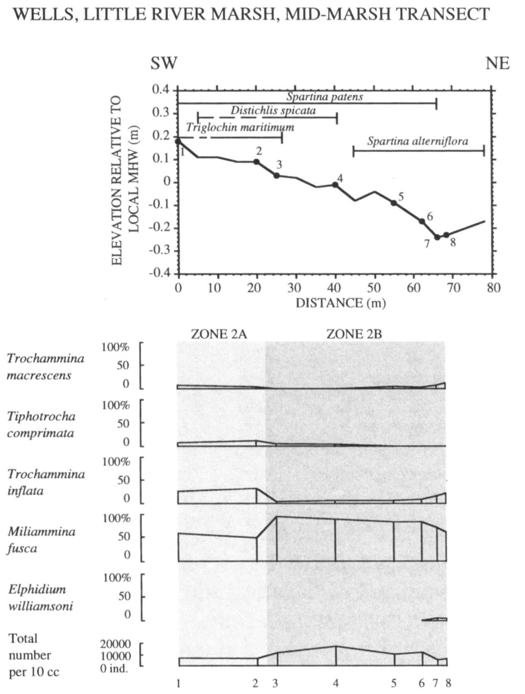

Figure 6. Surficial vertical zonation of foraminifera along mid-marsh transect, Little River marsh, Wells, with ranges of dominant plants.

8). By comparison, SCOTT and MEDIOLI (1978) found Zone 1A restricted to a 6 cm vertical range along the upper marsh edge in Nova Scotia, and the absolute elevation of zone 1A above MHW appears to be independent of the tidal range. Second, Zone 1A is found along the landward edge of the marsh. The fossilized assemblage of Zone 1A found in salt-marsh peats represents the initial marine incursion and often directly overlies an incompactible (often Pleistocene) substrate. Plant fragments obtained from this basal peat are the ideal material for dating because the peat would not be vertically displaced by autocompaction (KAYE and BARGHOORN, 1964).

An alternative to using the entire vertical range of assemblage zones as sea-level indicators is using their boundaries instead. SCOTT and MEDIOLI (1978, 1980a) claim that the upper boundary of Zone 1A is indicative of HAT with a precision of ±5 cm. However, because this boundary is seldom found directly overlying an incompactible substrate, a compaction error is usually introduced. In Maine, the upper boundary of Zone 1A is only present in cores when the basal peat is a freshwater peat. When the basal peat is a salt-marsh peat, which is often the case, the entire vertical range of Zone 1A, rather than its upper boundary, must be used for paleo-tide level estimation.

Other faunal boundaries may be more easily found in cores. On the modern marsh surface, the Zone 1A/1B boundary can be estimated within precisions of ±6 cm along the upper marsh transect in the Little River marsh, ±4 cm along the Morse River marsh transect, ±1 cm along the southern transect in Grand Marsh, and ±3 cm along the Sanborn Cove marsh transect. The precision of the Zone 1B/2A boundary is ±3 cm along the Little River marsh-edge transect, ±2 cm along the Morse River marsh transect, ±4 cm along the Grand Marsh southern transect, ±9 cm along the Grand Marsh northern transect, and ±7 cm along the Sanborn Cove transect. The upper limit of *Miliammina fusca* can be located along the transects within 10 cm. However, these precisions are based on measurements along single transects. In

Table 6. *Percentages of foraminifera on the modern surface of Morse River marsh, Phippsburg. Liv. = living individuals; Tot. = living and dead individuals. x = less than 1%.*

		Sample Site							
		1	2	3	4	5	6	7	8
MHW Elevation (m):		0.55	0.46	0.39	0.32	0.27	0.23	0.21	0.18
Distance Along Transect (m):		0	5	15	25	40	52.5	60	90
Individuals per 10 cc:		142	1,370	5,856	3,232	4,608	7,104	3,616	4,224
Haplophragmoides	Liv.		2	3					
manilaensis	Tot.		19	7	1		x		
Miliammina fusca	Liv.					1	x		7
	Tot.			1	3	5	2	4	34
Pseudothurammina	Liv.		1	1	1	2			3
limnetis	Tot.		1	1	2	17	1		10
Tiphotrocha comprimata	Liv.		4	9	6	17	2	7	8
	Tot.	1	18	29	35	35	11	19	23
Trochammina inflata	Liv.		1	4	7	7	9	22	5
	Tot.	1	20	11	48	20	54	61	23
Trochammina macrescens	Liv.	28	17	12		12	6	6	2
forma *macrescens*	Tot.	97	43	52	11	23	31	16	9

Table 7. *Percentages of foraminifera on the modern surface of Little River marsh, Wells, mid-marsh transect. Liv. = living individuals; Tot. = living and dead individuals. x = less than 1%.*

		Sample Site							
		1	2	3	4	5	6	7	8
MHW Elevation (m):		0.18	0.09	0.03	−0.01	−0.09	−0.17	−0.24	−0.23
Distance Along Transect (m):		0	20	25	40	55	62.1	66	68.4
Individuals per 10 cc:		6,464	5,728	11,680	17,408	8,640	11,232	5,312	4,176
Ammotium salsum	Liv.								
	Tot.						x		
Arenoparella mexicana	Liv.								
	Tot.						x		
Astrononion sp.	Liv.								x
	Tot.								x
Cibicides sp.	Liv.								
	Tot.							1	x
Eggerella advena	Liv.								
	Tot.								1
Elphidium subarcticum	Liv.								
	Tot.							1	x
Elphidium williamsoni	Liv.							1	x
	Tot.						x	2	2
Haplophragmoides	Liv.								
manilaensis	Tot.	x							
Miliammina fusca	Liv.	18	1	20	3		9	9	10
	Tot.	60	51	95	89	85	84	61	72
Pseudothurammina	Liv.		1						
limnetis	Tot.		1		x		x		
Tiphotrocha comprimata	Liv.	2	6	1			x	1	
	Tot.	7	13	3	4	1	1	2	1
Trochammina inflata	Liv.	5	8	1	1	1	6	12	3
	Tot.	26	31	1	5	7	10	22	15
Trochammina macrescens	Liv.	1	1	x	x		1	5	3
forma *macrescens*	Tot.	7	4	1	2	6	4	10	9
Calcareous, unidentified	Liv.								
	Tot.								x

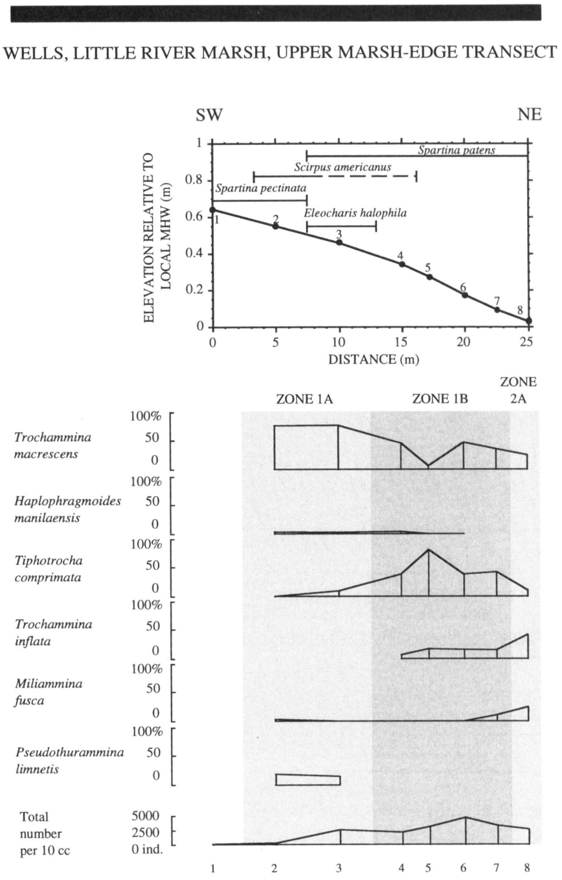

Figure 7. Surficial vertical zonation of foraminifera along marsh-edge transect, Little River marsh, Wells, with ranges of dominant plants.

fact, elevations of faunal boundaries show variability within marshes. For example, in Grand Marsh the Zone 1B/2A boundary occurs at 41 ± 4 cm above MHW along the southern, more landward, transect and at 16 ± 9 cm above MHW along the northern transect close to the tidal flat (Figures 3, 4, 8). The accuracy of using a zone boundary as a sea-level indicator at any location within a marsh is estimated at ±15 cm, provided that the site where the modern foraminifera distribution is investigated provides a reasonable analog for the paleo-setting. When cores are collected close to where the zonal boundary is established on the modern surface the accuracy may be even better.

A third way of using salt-marsh foraminifera as sea-level indicators is looking at peak abundances. *Tiphotrocha comprimata* is characteristic of faunal Zone 1B, which has a vertical range of ~40 cm. However, the middle of Zone 1B is often characterized by peak abundances of *Tiphotrocha comprimata*, ranging from 28% of the total population in Grand Marsh to 80% in Little River marsh. This peak indicates a tide-level position with an average precision of ±6.5 cm between MHW and MHHW along the modern transects (± 4 cm in Little River and Grand marshes; ± 8 cm in Morse River marsh; ± 10 in Sanborn Cove marsh). Within-marsh variability reduces the precision to an estimated ±15 cm.

APPLICATION: A LATE HOLOCENE RELATIVE SEA-LEVEL HISTORY FOR EASTERN MAINE

The peats from which plant fragments are AMS-dated contain fossil foraminifera in assemblages that are similar to those found on the present marsh surface. The correlation between modern populations of foraminifera and tidal elevations determines the paleotide-level relationships of fossil marsh peats, or their *indicative meaning* (VAN DE PLASSCHE, 1986), defined as "the relationship of the environment in which [the peat] accumulated to a reference tide level" (SHENNAN, 1986).

Four vibracores were collected in Sanborn Cove marsh. The stratigraphy shows a thick high marsh peat section that has been spared from erosion by a meandering tidal creek (Figure 9). The base of the peat is almost 5,000 years old in one core, suggesting that high marsh has been in existence for a considerable time.

A sea-level chronology for eastern Maine is based on four basal and two in-core accelerator mass spectrometry ^{14}C ages on small detrital plant fragments (Table 9). The peats in which the basal plant fragments were embedded contain foraminiferal assemblages characteristic of Zone 1A (97%–99% *Trochammina macrescens* forma *macrescens*; Table 10; index points 1–4). The modern faunal Zone 1A lies 50–68 cm above MHW (Figure 2, Table 3). Neglecting tidal range changes, this places paleo-MHW at 50–68 cm below the basal peats whose depths are measured relative to the modern MHW (Figure 10).

To constrain the sea-level history after 2,500 BP, basal peat dates are not available. Using in-core peat samples introduces a small compaction error. KELLEY *et al.* (in press) suggest that the low organic component of the 'peats' (< 10% by dry weight) reduces its compactability and that

Table 8. *Percentages of foraminifera on the modern surface of Little River marsh, Wells, marsh-edge transect. Liv. = living individuals; Tot. = living and dead individuals. x = less than 1%.*

		Sample Site							
		1	2	3	4	5	6	7	8
MHW Elevation (m):		0.64	0.55	0.46	0.34	0.27	0.17	0.09	0.03
Distance Along Transect (m):		0	5	10	15	17.2	20	22.5	25
Individuals per 10 cc:		4	165	2,464	2,160	3,072	4,928	3,296	2,560
Arenoparella mexicana	Liv.				1				
	Tot.				4				
Haplophragmoides	Liv.			x					
manilaensis	Tot.		2	1	3	1	1		
Miliammina fusca	Liv.								4
	Tot.		3		2	x	1	9	24
Pseudothurammina	Liv.		2	2					
limnetis	Tot.		18	14					
Tiphotrocha comprimata	Liv.				1	x	7	12	8
	Tot.		1	7	40	80	38	43	11
Trochammina inflata	Liv.				1	1	3	8	18
	Tot.	75	1		5	16	17	14	41
Trochammina macrescens	Liv.		9	9	5	x	11	17	12
forma *macrescens*	Tot.	25	74	77	46	4	44	35	24

ice-loading in the winter season 'pre-compacts' the peats. By comparison, McCaffrey and Thomson (1980) concluded that even in the more organic marshes in Connecticut compaction is insignificant in the upper meter. In this study, shallow in-core peats are estimated to have been compacted by 0–10% of the original peat thickness. Two foraminifera samples associated with in-core ^{14}C-sample BETA-57808/CAMS-4610 (index point 5) contain a Zone 1B assemblage and a 1A assemblage, respectively. The Zone 1A/1B faunal boundary is indicative of an elevation of 48–53 cm above MHW. Sample BETA-57809/CAMS-4622 (index point 6) has a Zone 1B assemblage in two associated foraminifera samples with high percentages of *Tiphotrocha comprimata* (30–50 cm above MHW).

Sea-level points in Figure 10 are represented as

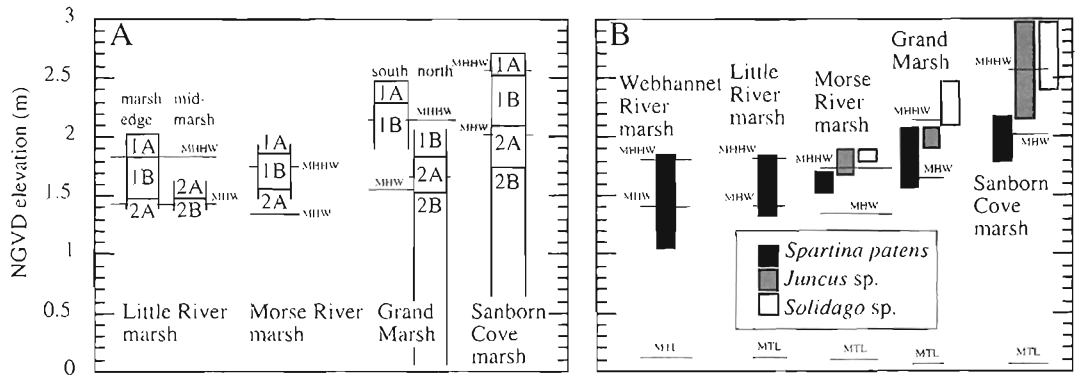

Figure 8. A. Elevations of foraminiferal faunal zones (subdivision after Scott and Medioli, 1978) in four Maine salt marshes relative to the National Geodetic Vertical Datum of 1929 (NGVD-29). MHW (mean high water) is local botanical datum. MHHW (mean higher high water) is open-coast value (NOAA/NOS, 1991). B. Elevations of high marsh plants in five Maine salt marshes relative to NGVD-29. MTL (mean tide level), MHW, and MHHW are open-coast values (NOAA/NOS, 1991; NOS, written comm. 1992). Data from Table 2. See Figure 1 for locations: Little and Webhannet River marshes are in Wells; Morse River marsh in Phippsburg; Grand Marsh in Gouldsboro; and Sanborn Cove marsh in Machiasport.

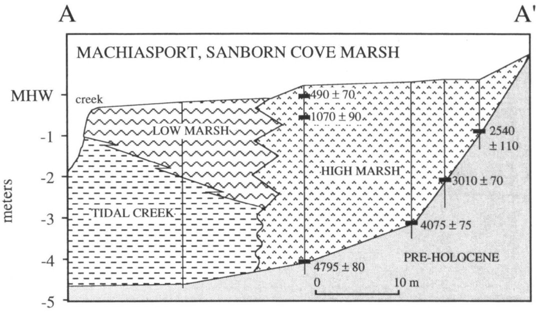

Figure 9. Stratigraphic cross section and AMS-radiocarbon ages (^{14}C yr BP) from Sanborn Cove marsh, eastern Maine. Vertical lines are vibracores. Though much of the record has been destroyed by channel meandering, this section shows evidence that high marsh was established shortly after 5,000 BP. After GEHRELS and BELKNAP (1993, Figure 2A).

error boxes. The age in ^{14}C years $\pm 2\sigma$ controls the size of the box in the x direction. In the y direction, the indicative range as deduced from foraminifera analyses (Table 10) and the precision estimate of the local MHW datum (Table 1) determine the size of the box. The true sea-level curve should lie within the envelope enclosing the error boxes. This analysis ignores additional errors that may arise from uncertainties related to elevation measurements. These may include measurement of depth in a borehole, potential angle of a borehole, measurement of compaction with uncompacted hand core, surveying to benchmark, accuracy of benchmark elevation relative to NGVD, and measurement of water-level relationship of modern sea-level indicators (see also: SHENNAN, 1982). The total uncertainty resulting from these factors is probably on the order of ±20 cm (GEHRELS, 1994). The envelope also does not take into account changes in paleo-tidal range (SCOTT and GREENBERG, 1983; GEHRELS *et al.*, 1993).

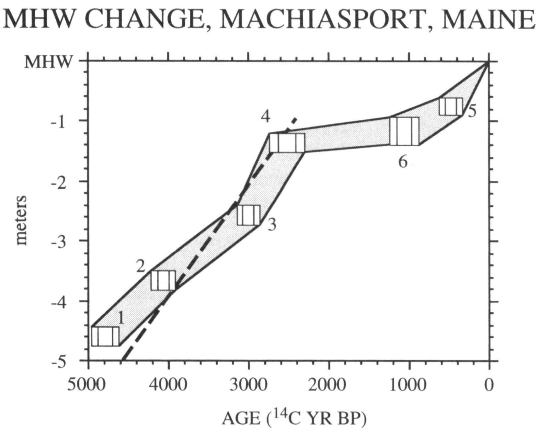

Figure 10. Mean high water (MHW) envelope for Sanborn Cove marsh, Machiasport. The error boxes represent two standard deviations of the age (x direction) and the paleo-MHW estimate with associated uncertainties (y direction). Index numbers correspond with Tables 9 and 10. Dashed line is average MHW curve for coastal Maine (1.44 mm/^{14}C yr), proposed by BELKNAP *et al.* (1989).

Radiocarbon ages were calibrated into calendar years using the computer program of STUIVER and REIMER (1986, 1993). Two linear regressions, on the upper three (index points 4, 5, 6, plus the origin) and the lower four samples (index points 1, 2, 3, and 4) respectively, yield average rates of

Table 9. *Accelerator mass spectrometry ages on salt marsh peats from Sanborn Cove marsh, Machiasport, and Grand Marsh, Gouldsboro. Index point numbers correspond with Figure 10. comp. = compaction; MHW = local mean high water (botanical datum); B = basal; plant fr. = unidentified plant fragment; detr. = detrital; S.a. = Spartina alterniflora; S.p. = spartina patens; Sc. = Scirpus sp.*

Laboratory Number	Index Point Number	Core	MHW Depth (m)	^{14}C age BP ± 1σ	Max. Comp. (m)	Calibrated Age (cal yr BP) ± 1σ Range (calculated age)	δ^{13}C	Material Analyzed
AA-8210	1	SN-VC-1	3.98–4.00	4,795 ± 80	0	5,335–5,642 (5,491, 5,513, 5,577)	−28.0	B. plant fr.
AA-8211	2	SN-VC-2	3.06	4,075 ± 75	0	4,447–4,817 (4,559, 4,598, 4,600)	No data	B. detr. *S.a.*
AA-8941	3	SN-VC-3	1.97	3,010 ± 70	0	3,073–3,330 (3,179, 3,209)	−15.7	B. detr. *S.a.*
AA-8942	4	SN-VC-4	0.77	2,540 ± 110	0	2,369–2,756 (2,719)	−28.7	B. plant fr.
BETA-57808 CAMS-4610	5	SN-VC-1	0.27–0.28	490 ± 70	0.06	496–545 (517)	−19.4	detr. *S.a.*
BETA-57809 CAMS-4622	6	SN-VC-1	0.80–0.83	1,070 ± 90	0.11	922–1,062 (961)	−16.8	detr. *S.p.* + *Sc.*

Table 10. *Indicative meaning of AMS radiocarbon-dated plant fragments from Sanborn Cove peat samples. Paleo-MHW estimates are based on modern relations between foraminifera assemblages and tide levels. See Table 9 for laboratory numbers, ages, and cores from which the samples were collected.*

Index Point Number	Sample MHW Elev. (m)	Number of Foraminifera	*Trochammina macrescens* forma *macrescens*	*Tiphotrocha comprimata*	*Trochammina inflata*	*Miliammina fusca*	Others	Faunal Zone	Paleo-MHW Elevation (m)
1	−3.98	6,784	97	1	1	0	1	1A	0.50–0.68
2	−3.06	1,056	97	3	0	0	0	1A	0.50–0.68
3	−1.97	2,432	99	0	1	0	0	1A	0.50–0.68
4	−0.77	1,304	99	1	0	0	0	1A	0.50–0.68
5	−0.285	5,280	52	19	26	0	2	1B	0.48–0.53
	−0.26	7,840	87	9	3	0	1	1A	
6	−0.835	4,672	32	42	32	0	0	1B	0.30–0.50
	−0.81	5,184	71	25	4	0	0	1B	

MHW-rise in eastern Maine of ~1.0 mm/year between 5,500 and 2,500 cal yr BP and 0.5 mm/yr during the past 2,500 calendar years. The envelope indicates an acceleration of sea-level rise in the past 1,000 years. A regression on index points 5 and 6, including the origin, gives a rate of rise of 1.2 mm/yr for the late Holocene. More dates are needed to firmly establish the past 2,000 years of sea-level history at Machiasport.

The sea-level envelope for eastern Maine has implications for neotectonic investigations in the area, described in more detail in a separate paper (GEHRELS and BELKNAP, 1993). BELKNAP *et al.* (1989) determined an average rate of relative sea-level rise of 1.44 mm/^{14}C yr between 5,000 and 1,500 BP for the Maine coast. Holocene sea-level rise determined at Machiasport does not exceed this rate (Figure 10). In contrast to suggestions by previous workers (ANDERSON *et al.*, 1984, 1989), this work implies that vertical crustal motion has not contributed significantly to relative sea-level change in eastern Maine during the past 5,000 years (GEHRELS and BELKNAP, 1993).

CONCLUSIONS

Foraminifera are extremely useful as sea-level indicators in Maine. The surficial zonation is similar to those reported from southern New England and the Canadian Maritimes. In most cases, faunal assemblage boundaries and peak abundances of *Tiphotrocha comprimata* indicate tide levels in cores with a precision of ±15 cm (or better) in Maine. Faunal assemblage 1A occupies a vertical range of ~20 cm in the extreme upper part of the intertidal zone at an elevation between 40 and 93 cm above MHW (independent of tidal range). Precisions compare favorably with other studies in New England and the Canadian Maritimes, except for the ±5 cm precision claimed by SCOTT and MEDIOLI (1978, 1980a) for the upper boundary of Zone 1A in Nova Scotia. Though SCOTT and LECKIE (1990) could not distinguish between a Zone 1A and 1B, they estimated that the Zone 1 assemblage is indicative of a tide-level position between 0 and 22 cm below HAT. It is important to note, however, that precisions in the literature usually refer to precisions along single transects. Variability within a marsh may decrease the precisions claimed by various workers. Optimal precision is achieved when modern distributions are related to tidal elevations as close as possible to where they are used as sea-level indicators.

Foraminiferal studies are a useful tool in producing precise Holocene sea-level chronologies. When samples from basal peats are dated, the indicative range of the foraminiferal assemblage that is present in the basal peat determines the relation of a sea-level point to a reference tide level. Within a core, a faunal boundary may be located yielding a higher precision for the paleo-sea level estimate than faunal assemblages. In-core peats are compacted, though compaction is probably negligible in the upper meter of salt-marsh peat in Maine.

In this study, foraminiferal analyses are used to construct a sea-level chronology which yields the middle and late Holocene long-term (10^2–10^3 yr) average trend of sea-level change for eastern Maine. Long-term rates of relative sea-level rise were slow: 1.0 mm/yr between 5,500 and 2,500 cal yr BP, and 0.5 mm/yr during the past 2,500 calendar years. These rates are close to those of isostatically and tectonically 'stable' coastlines, such as south Florida (SCHOLL *et al.*, 1969). It appears that crustal subsidence has not played an important role in the relative sea-level history of eastern Maine during the past 5,000 years.

Marshes have been able to keep up with slow long-term rates of sea-level rise in eastern Maine throughout the past 5,000 years. Detailed foraminiferal stratigraphy will be a useful tool in deciphering whether short-term accelerations, comparable to present rates of sea-level rise, have occurred at any time in the Holocene history of the marshes. In Connecticut, for example, VAREKAMP *et al.* (1992) identified from foraminiferal analyses two periods before modern global warming during which sea-level rise accelerated and plant communities were drastically altered (THOMAS and VAREKAMP, 1991; VAN DE PLASSCHE, 1991). Marshes in Delaware were affected by a rapid increase in sea-level rise around 1,800 BP, as freshwater marsh environments changed into high salt marsh, and high salt marsh changed into low marsh or tidal flat (FLETCHER *et al.*, 1993a). At some time during the past 1,000 years, sea-level may have accelerated in eastern Maine. This acceleration would reconcile the apparent discrepancy between long-term late Holocene rates, determined from the salt-marsh record, and short-term rates, indicated by tide gauges. Increased flooding, correlated with climatic warming at the end of the Little Ice Age, has been found in several marshes in southern New England and England (THOMAS *et al.*, 1993) and in Chesapeake Bay (KEARNEY and STEVENSON, 1991). If short-term sea-level accelerations occurred in eastern Maine, they apparently did not affect the plant communities. A one-year sedimentation study in Maine (WOOD *et al.*, 1989) implies that many marshes may, at least temporarily, not be keeping up with accelerated rates of sea-level rise (LYLES *et al.*, 1988). However, the stratigraphic record indicates that marshes in Maine may be able to recover quickly, provided humans do not interfere with natural sedimentation patterns.

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