Reports

Freshwater Peat on the Continental Shelf

Abstract. *Freshwater peats from the continental shelf off northeastern United States contain the same general pollen sequence as peats from ponds that are above sea level and that are of comparable radiocarbon ages. These peats indicate that during glacial times of low sea level terrestrial vegetation covered the region that is now the continental shelf in an unbroken extension from the adjacent land areas to the north and west.*

Evidence of sea levels lower than the present level has long been provided by submerged intertidal or shallow-water topography, sediments, fauna, and flora. So many examples of these features are known throughout the world in the narrow depth range of the continental shelves that they must denote eustatic changes of sea level recent enough to have been associated with Pleistocene glaciation.

One of the most interesting sediments on the continental shelf and one that is related to the low sea levels is deeply submerged peat, especially that of freshwater bogs. These deep deposits are much older than the well-known peat and tree stumps that are common just beyond the shoreline. The longest-known examples are off Europe. One is Dogger Bank in the English Channel (*1*), where a sample from 39 m has been dated, by the radiocarbon method, as 9300 years old (*2*); another is in the Baltic Sea (*3*), where a deposit at 35 to 37 m dates from 7375 years (*4*). Cores of the sea floor in the Gulf of Mexico off Texas include a transgressive salt-marsh and freshwater peat whose seaward limit at about 25 m has been dated by radiocarbon at 10,200 years (*5*). Dates for many freshwater peats encountered in borings of the Mississippi Delta have been reported (*6*). Bridge borings off western Australia penetrated freshwater peat, at 21 m, having an age of 9850 years (*7*). Other bridge borings off British Guiana reached freshwater peat, which had an age of 8590 years, at 20 m (*8*). Freshwater peat cored in Malacca Strait, off Malaya, at a depth of 27 m has been dated at 10,000 years (*9*); similar peats containing the bivalve *Cyclina* have been dredged from 50 to 80 m in Naruto Strait, an entrance to the Inland Sea of Japan, and others containing large palm trees have been observed in Toyama Bay, Japan (*10*). Submerged soils rich in organic debris, and about 12,000 years old, have also been cored off Nigeria (*11*) and elsewhere. Hence, freshwater, as well as salt-marsh, peats are widely distributed on the continental shelves of the world.

In 1964 a large mass of peat was recovered by Captain Norman Lepire

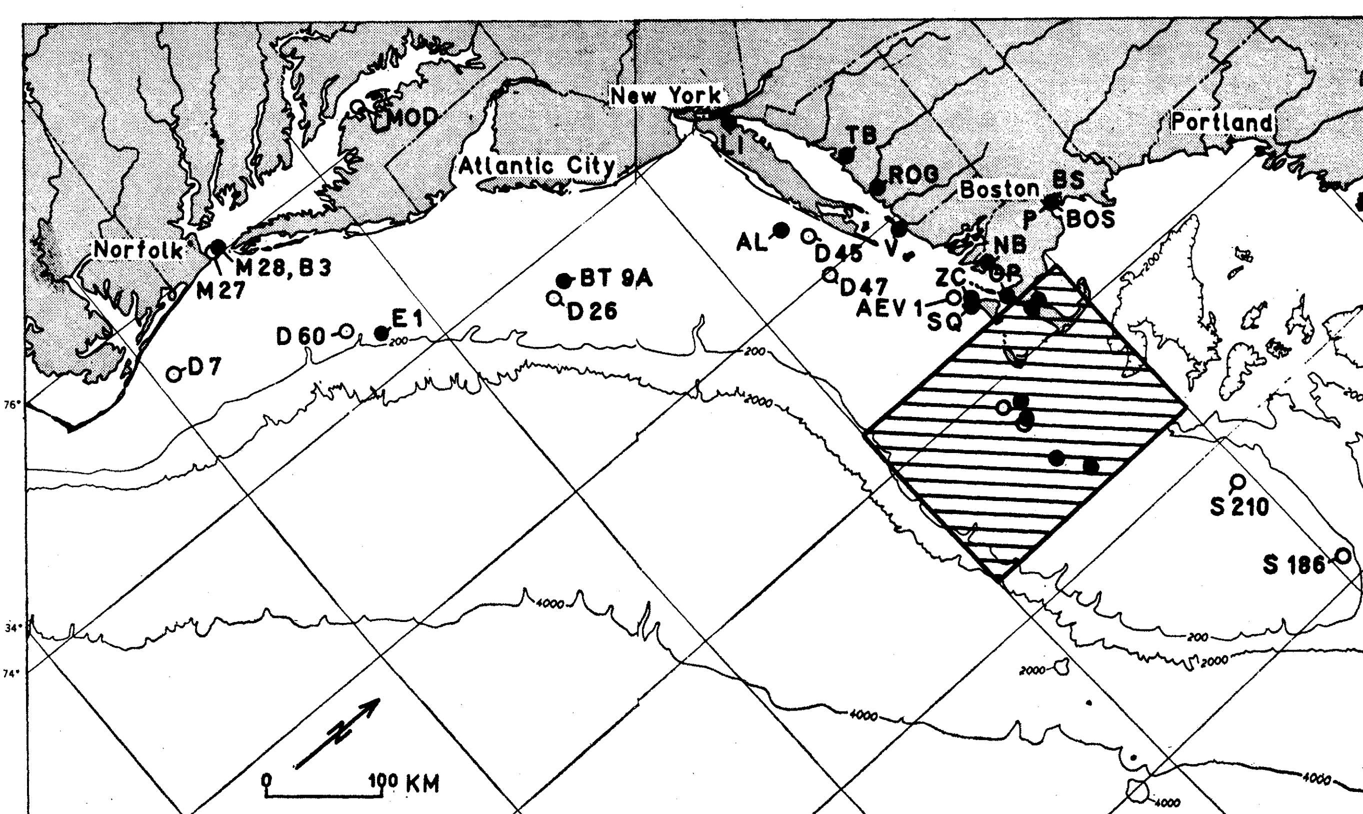


Fig. 1. Positions of peat samples (closed circles) and of near-intertidal oyster shells (open circles) on the continental shelf and in coastal areas from New England south to Cape Hatteras. Sources of data are listed in Table 1; contours are in meters. Cross-hatching denotes the area of the more detailed Fig. 2.

Table 1. Base data for peat and shells. MLW, mean low water; n.d., no data.

	Location	Material	North Lat.	West Long.	Depth (m) Below sea level (MLW)	Depth (m) Below sediment surface	Source	Weight (g)	Sampler	Age (yr)	Lab. No.	Ref.
					Peat							
G 2198	*Gosnold* 2198	Wood	40°59′	69°01′	−82	0	W.H.O.I.–U.S.G.S.	10	Rock dredge	1,320 ± 250	W-2001	
E 1	*Explorer* 1	Matrix	37°38′	74°30′	−64 to −68	0	Tim Furtado	300	Scallop dredge	13,500 ± 350	W-2014	
RL 1	*Ruth Lea* 1	Wood	41°09′	68°43′					Scallop dredge	n.d.		
		Matrix	41°09′	68°43′	−59	0	Capt. Norman Lepire	100,000		11,000 ± 350	W-1491	(*12*)
BT 9A	Bell Telephone 9A	Debris	39°00′	73°42′	−43	0.4	Robert Allen	10	Corer	n.d.		
RL 2	*Ruth Lea* 2	Wood	41°06′	69°42′					Scallop dredge	10,630 ± 300	W-1736	
		Matrix	41°06′	69°42′	−40	0	Capt. Norman Lepire	500		11,090 ± 300	W-1737	
LI	Long Island	Matrix	40°48′	73°50′	−34	?	Columbia University	?	Boring	11,950 ± 200	L-606A	(*27*)
V	A. E. Verrill 1874	Matrix	41°18′	71°52′	−33	0	Yale University	5	Biology dredge	n.d.		
AL	*Albatross IV* 63-7 (157)	Matrix	40°43′	72°40′	−28	0	Bur. Comm. Fisheries	10	Otter trawl	n.d.		
M 28	Chesapeake Bay	Matrix	36°59′	76°06′	−27	10.7	Bridge tests	?	Boring	15,280 ± 200	ML-91	(*28*)
B 3	Chesapeake Bay	Matrix	36°59′	76°06′	−26	6.1	Bridge tests	?	Boring	11,590 ± 150	ML-89	(*28*)
RL 3	*Ruth Lea* 3	Matrix	41°02′	69°30′	−20 to −27	0	Capt. Norman Lepire	1000	Scallop dredge	8,620 ± 300	W-1735	
OP 2	Oyster Pond 2	Debris	41°33′	70°38′	−18	13	E. S. Deevey	?	Boring	11,750 ± 300	Y-1459	(*29*)
ROG	Rogers Lake, Conn.	Debris	41°21′	72°18′	−10	15	J. P. Schafer	?	Boring	14,240 ± 240	Y-950/1	(*30*)
NB	New Bedford, Mass.	Matrix	41°38′	70°55′	−8	0	E. S. Barghoorn	?	Boring	4,150 ± 130	O-1127	(*15*)
BS	Boylston Street fish weir	Matrix	42°21′	71°05′	−8	4	E. S. Barghoorn	?	Excavation	4,450 ± 130	O-475	(*31*)
BARN	Barnstable core 23	Matrix	41°43′	70°22′	−8	8.3	P. Butler	?	Boring	5,480 ± 120	W-676	(*32*)
OP 1	Oyster Pond 1	Debris	41°33′	70°38′	−5	2.3	E. S. Deevey	?	Boring	3,420 ± 120	Y-1663	(*29*)
P	Boston (Prudential Bldg.)	Matrix	42°20′	71°06′	−5	2	C. A. Kaye	?	Excavation	3,850 ± 130	O-1124	(*33*)
CEN	Centerville, Mass.	Matrix	41°38′	70°21′	−4	4	A. C. Redfield	?	Boring	5,500 ± 300	W-586	(*15*)
BOS	Boston Commons garage	Wood	42°21′	71°04′	−2	8	C. A. Kaye	?	Excavation	12,170 ± 300	W-991	(*33*)
ZC	Zacks Cliff	Debris	41°20′	70°50′	+4	8	C. A. Kaye	?	Sea cliff	15,300 ± 800	W-1187	(*18*)
TB	Totoket Bog, Conn.	Debris	41°20′	72°49′	+6	8	E. S. Deevey	?	Boring	15,090 ± 160	Y-446A	(*34*)
SQ	Squibnocket Cliff	Matrix	41°18′	70°47′	+9	3	C. A. Kaye	10,000+	Sea cliff	12,700 ± 300	W-710	(*18*)
					Crassostrea virginica (Gmelin)							
D 60	*Delaware* 60-7		37°24′	74°39′	−64	0	Bur. Comm. Fisheries		Scallop dredge	9,600 ± 600	L-948	
D 26	*Delaware* 26		38°49′	73°39′	−55	0	Bur. Comm. Fisheries		Scallop dredge	9,780 ± 400	W-1403	(*22*)
S 186	S 186		42°05′	67°15′	−53	0	Canadian Fisheries Board		Scallop dredge	10,600 ± 130	S-186	(*23*)
D 47	*Delaware* 47		40°40′	71°59′	−51	0	Bur. Comm. Fisheries		Scallop dredge	10,850 ± 500	W-1401	(*22*)
AEV 1	*A. E. Verrill* 1		41°18′	71°00′	−34	0	Marine Biological Lab.		Biological dredge	9,300 ± 250	W-2013	
IN 1	*Invader* 1		40°59′	69°44′	−45	0	Capt. Norman Lepire		Otter trawl	7,310 ± 300	W-1981	
D 45	*Delaware* 45		40°43′	72°25′	−37	0	Bur. Comm. Fisheries		Scallop dredge	9,920 ± 400	W-1400	(*22*)
S210	S210		41°55′	67°35′	−46	0	Canadian Fisheries Board		Scallop dredge	10,300 ± 150	S-210	
D 7	*Delaware* 7-1		36°09′	75°20′	−33	0	Bur. Comm. Fisheries		Scallop dredge	8,130 ± 400	W-1402	(*22*)
M 27	Chesapeake Bay		36°59′	76°06′	−21	?	Bridge tests		Boring	8,135 ± 160	ML-196	(*28*)
MOD	Chesapeake Bay		38°33′	76°13′	−2	0	Harvard University		Hand	Modern	W-1399	(*22*)
					Crepidula fornicata (L)							
TT 3	Texas Tower 3		41°01′	69°30′	−47	29	J. M. Zeigler		Boring	11,465 ± 400	I-852	(*13*)(*35*)

aboard his scalloper *Ruth Lea* from 59 m on Georges Bank. The material contained both a salt-marsh component (*Spartina*) and a freshwater one (twigs and pollen of spruce, fir, and pine; and frustules of freshwater diatoms) (*12*). Subsequently, additional samples of freshwater peat were obtained in trawlings by Captain Lepire, and others were found in samples of bottom sediments collected for biological and geological studies by ships of the U.S. Bureau of Commercial Fisheries and of the Woods Hole Oceanographic Institution–U.S. Geological Survey program. One peat was supplied by T. J. M. Schopf (Marine Biological Laboratory at Woods Hole, Mass.) from a dredging made by A. E. Verrill in 1874. Other samples were found within cores from the sea floor taken for engineering studies and for investigations of pollen succession. These peats from the sea floor are supplemented and compared with others obtained in borings made on land or in freshwater ponds during studies of postglacial history (Table 1). The many samples materially extend the information that was previously available on the distribution, nature, and age of freshwater peat.

The distribution pattern of the peats (Table 1; Figs. 1 and 2) shows a high degree of correlation with areas that were glaciated. This is reasonable in view of the ability of glaciers to form depressions by both erosion and deposition. Especially striking is the presence of four samples bordering Great South Channel (Fig. 2). The fabric and composition of till on nearby Cape Cod indicate that a tongue of the Wisconsin glacier moved through this channel (*13*). Some of the samples, however, are from unglaciated regions, and presumably they are representative of deposits on poorly drained topography bordering estuaries and lagoons.

Many of the samples of peat from the sea floor are small, but those collected aboard the *Ruth Lea* had estimated weights (on an air-dry basis) as great as 100 kg (Table 1). The samples were irregular in shape, but they broke easily into flat slabs because of their bedded structure. Usually one surface, considered the top one, is more or less riddled with the holes of boring organisms, chiefly the pelecypod *Zirfaea crispata* L. [Fig. 3 and (*12*, Fig. 2)]. The presence of borings on only one side of a slab, the fragile nature of the peat, the large size of some pieces (to 60 cm), and the fact that at least sample RL 1 is from a peat-covered area reported to be at least 1 km^2 in extent, indicate that many of the samples are from outcrops of the sea floor. Other samples are small (10 g or less), perhaps because of washing during the dredging operation. Although some small samples may not represent *in situ* deposits, they are generally from so near the sites of larger samples that only a short distance of transport is suggested. Sample BT 9A consists of only 2 cm of thinly interbedded organic debris and detrital sand; thus some transportation occurred prior to deposition at the coring site.

Most of the samples consist only of fine-grained fibrous organic material packed into thinly bedded masses containing few or no visible inorganic grains. For convenience here, this type of peat is given the general term matrix, whereas the obviously reworked organic fragments occurring in dominantly inorganic sediment are called debris. Samples RL 1 and RL 2 (Fig. 3B) contain pieces of wood as long as 30 cm, which are partly to completely surrounded by matrix; sample G 2198 is a piece of wood that at the time of recovery was thought to have come from a deeply submerged peat deposit.

Twenty-three freshwater peat samples are listed in Table 1. Analyses of pollen content, all in the form of pollen diagrams, are reported in the literature for eleven of these samples. Table 2 lists our readings of the more diagnostic pollens from these diagrams. In addition, we made new counts for seven samples and listed them in Table

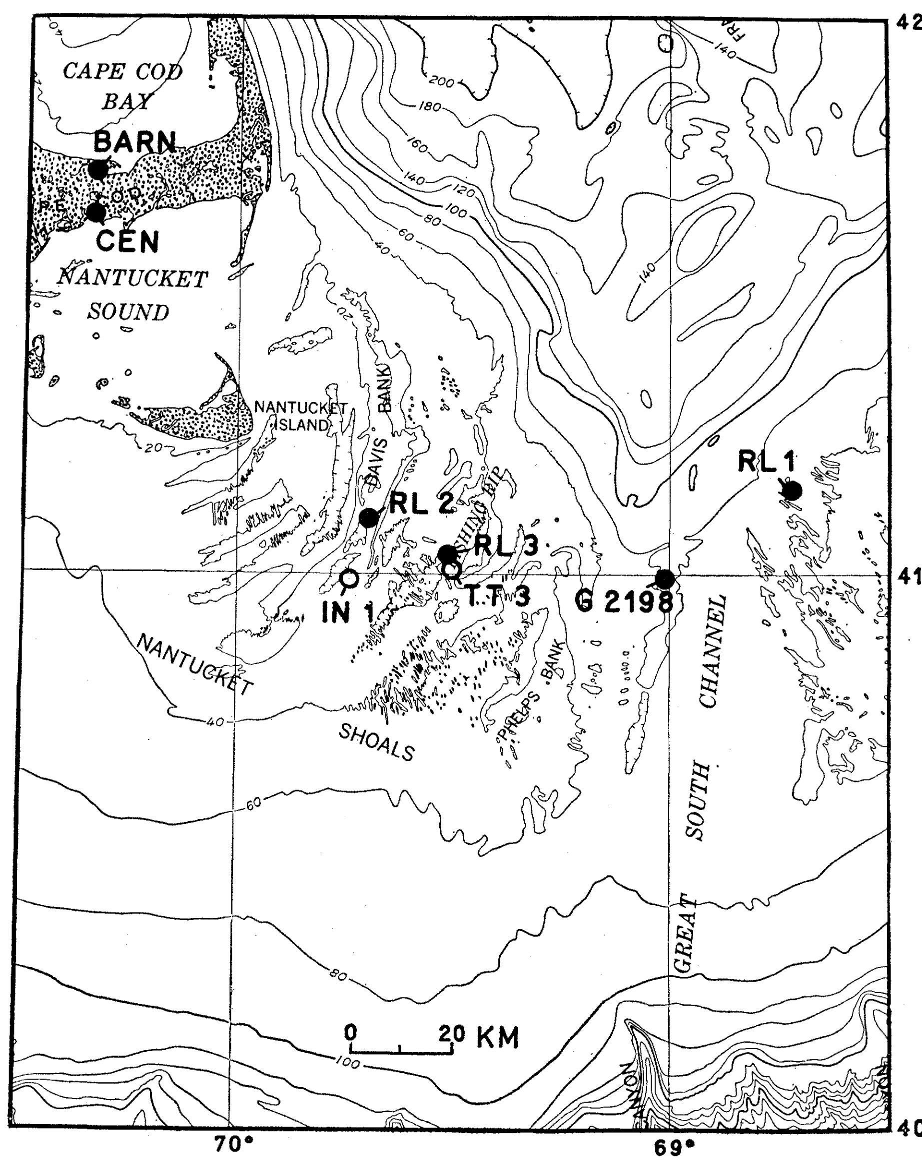
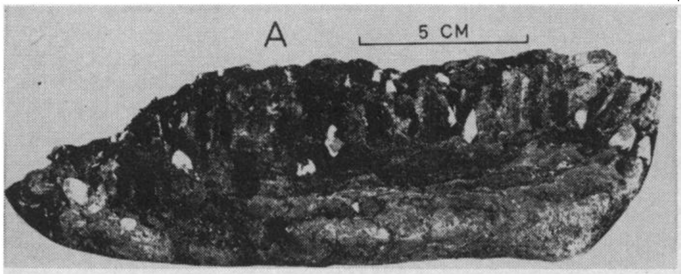


Fig. 2. Positions of peat samples (closed circles) and of oyster shells and Texas Tower No. 3 (open circles) superimposed upon the topography of the sea floor off Cape Cod (see crosshatched area of Fig. 1). Contour interval is 20 m to a depth of 200 m; contour interval at greater depths is 200 m [from Uchupi (*41*)].



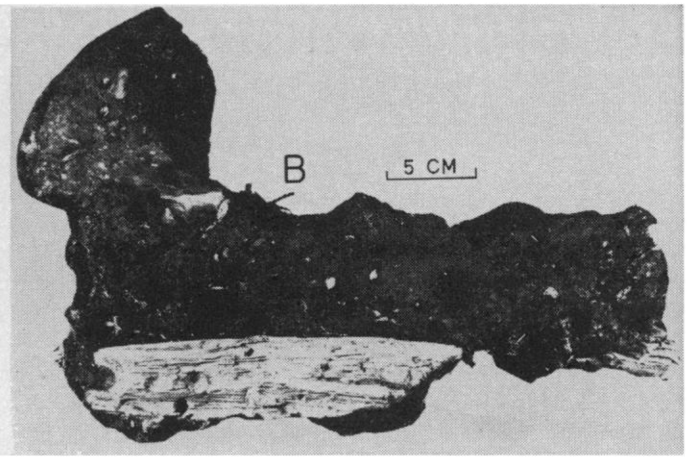


Fig. 3. Photographs of peat fragments from two large samples. (A) Fibrous peat from sample RL 3 that shows holes bored by pelecypods into the top surface, indicating that the peat was broken from a larger mass that had remained in an undisturbed position on the sea floor for a long period of time. (B) Peat from sample RL 2 showing abundant pieces of wood enclosed in a fibrous matrix.

2 along with notations of the kind of wood that was present. The pollen counts provided the basis for assignment of the samples to pollen zones A, B, and C, respectively. Several samples also contained pollen of *Nymphaea* (water lily), Cyperaceae (sedges), *Sagittaria* (arrowhead), or abundant fern spores, or all of these, which provides additional evidence of their freshwater origin.

Efforts to construct standard pollen sequences of general stratigraphic and chronologic application to late glacial and postglacial climatic and vegetational history of New England have resulted in the generalized scheme given in Fig. 4. The major palynological divisions, designated zone A (spruce dominance), zone B (pine dominance), and zone C (oak–mixed hardwood dominance), have repeatedly been verified from intensive study of both coastal and inland postglacial sediments from the northeastern United States. Although analyses of specific palynological sequences may differ in detail, climatic control of the basic vegetational succession can be demonstrated in the samples studied in this investigation (Table 2). It should be noted, however, that latitude influences the chronology of this sequence of forest transition. For example, the transition from zone A of spruce dominance to zone B of pine dominance clearly took place at an earlier date in the southern parts of the New England coastal plain than in the more northern and upland sites. The generalizations regarding the latitudinal variations of the major forest transitions are verified by the two pollen spectar B 3 and M 28 from near the mouth of Chesapeake Bay, and of E 1 (Table 2) that is far out on the shelf at about the same latitude. The age of the first two samples, in terms of New England forest history, would indicate occurrence in zone A; instead, they are in zone B, in which pine rather than spruce is dominant. The third sample has pollen ratios that differ from those of New England for the same date, but they still indicate zone A. Apart from these three samples, the pollen zones and the radiocarbon dates of peat samples from the more northeasterly areas agree closely (Fig. 5). Accordingly, two samples (*V* and *AL*) that were too small for radiocarbon dating can be approximately dated by their pollen content.

Support for the freshwater origin of several samples of matrix and wood is provided by measurements of stable carbon isotopes. As shown in Table 3, the δC^{13} measurements are between −23.5 and −27.8 per mil, in contrast to measurements of between −11.6 and −15.5 per mil for six samples of salt-marsh peat from Barnstable salt marsh at approximately the same position as *BARN* (Table 1 and Fig. 2). Each of the sets of measurements is well within the range that characterizes freshwater organic matter and marine organic materials, respectively (*14*). We were surprised that the value for salt-marsh peat was so clearly typical of marine plants, in view of the fact that the peat surface is exposed to the air a large part of the time. This point was further investigated by determining the δC^{13} for a composite sample of the

Table 2. Identified pollen and wood in peat samples. P, present; D, dominant; n.s., not significant.

Sample No.	Pollen percentages						Wood	Pollen zone	References
	Fir	Spruce	Pine	Oak	Water lily and/or sedge	Others			
OP 1	0	0	22	40	n.s.	38		C	(*36*), Fig. 7, 2.0–2.7 m
BS	0	<5	18–50	2–28	20–58	?		C	(*37*), Fig. 8, Lower Peat
BARN	0	0	30	47	0	23		C	(*32*), Fig. 1, 327 inches
RL 3	0	0	17	20	5	58		C	
B 3	2	15	60	7	6	10		B	(*28*)
M 28	1	26	60	2	6	10		B	(*28*)
AL	0	12	73	2	2	9		A-B	
V	0	36	13	3	10	38		A	
RL 1	P	83	9	0	0	8	Juniper Spruce	A	
BT 9A			P			D‡			See also (*38*), Fig. 1, 43–49 cm
RL 2	3	21	16	4	0	56§	Juniper	A	
OP 2	7	15	15	11	n.s.	52‖		A	(*36*), Fig. 7, 13.1–13.5 m
E 1	2	12	8	4	11	63¶		A	
BOS							Birch	A?	(*33*)
SQ	2	<5	4	1	50	>38¶		A	(*39*), Plate 1
TB								A	(*40*)
ROG	0	5	22	2	35	36		A	(*30*), Fig. 3A, 14.5 m
G 2198							Conifer		

* Not stated in publication. † Pure sphagnum peat, a freshwater indicator. ‡ Mostly worn and redeposited fern spores. § Abundant Ericacea. ‖ Mostly birch. ¶ Includes fern spores, sphagnum spores, *Lycopodium*, and arrowhead.

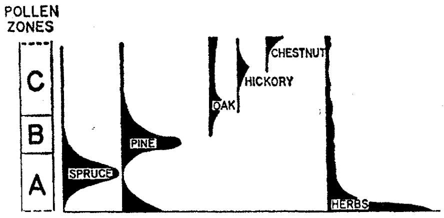


Fig. 4. A generalized standard pollen zonation for northeastern coastal United States for postglacial time [after Leopold (*40*)].

Table 3. The δC^{13} for peat samples. Analyses were made in duplicate by J. M. Hunt, Woods Hole Oceanographic Institution, relative to Chicago standard Cretaceous belemnite (PDB).

Sample No.	Depth (m)	Type of material	δC^{13} (‰)
G 2198	−82	Wood	−26.9
E 1	−64 to −66	Matrix	−27.6
RL 1	−59	Wood	−23.5
		Matrix	−26.2
BT 9A	−43	Debris	−25.8
RL 2	−40	Wood	−27.1
		Matrix	−26.8
V	−33	Matrix	−26.0
AL	−28	Matrix	−26.1
RL 3	−20 to −27	Matrix	−26.0
	Barnstable salt marsh		
Six samples	−1.5 to +1.5	Matrix	−11.6 to −15.5
	Spartina patens		
		Blades	−11.7
		Rhizomes	−12.7

blades of ten specimens of *Spartina patens* from Barnstable salt marsh and for another composite sample of their rhizomes (rootlike parts). *Spartina patens* is a high-marsh plant, submerged only at high tide. The values of δC^{13} for blades and rhizomes are similar and within the range obtained for the salt-marsh peat. Thus δC^{13} appears to be a useful tool for distinguishing between salt-marsh and freshwater peats.

During the past decade about 400 radiocarbon dates of calcareous and carbonaceous materials from known depths below sea level have permitted the construction of generalized curves of sea level versus time. Radiocarbon dates, based mostly upon borehole samples from salt marshes, show that sea level rose slowly to its present position from about −3 m approximately 4000 years ago (*15, 16*). Prior to that date the rise was much faster. Dates of shells, coral, and other materials extend this faster rate back to about 15,000 years ago (*17*). Earlier dates from the sea floor are rare, but they are supplemented by dates of the glacial maximum on land (*18, 19*), dates and isotopic temperatures of deep-sea sediments (*20*), and estimates of ice volumes (*21*). These sources suggest that sea level was as low as −123 m about 19,000 years ago; before this, the levels were higher.

Data on low sea levels of postglacial time are provided on the Atlantic continental shelf of the United States and Canada by radiocarbon dates on shells of the commercial oyster, *Crassostrea virginica* (Gmelin) that generally lives in a restricted zone between high tide and a depth of several meters in estuaries and lagoons. The depth-date measurements for the oysters (*22, 23*) and for a salt-marsh component of the peat in sample RL 1 are somewhat erratic, perhaps because the oysters were not completely restricted to shallow water or because currents moved some shells seaward. A rather wide variation was also present in the data used by Shepard (*17*), whose best-fit curve is shallower than our oyster-shell and peat data. We believe that our data indicate a postglacial subsidence of the continental shelf off northeastern United States relative to most other shelves of the world. In Fig. 6 the points plotted for the freshwater peats are shallower than the sea level of the same general age, as one would expect.

In order to avoid the complexities of Fig. 6, a simplified version (Fig. 7) is useful; this version is based upon the past sea levels shown in Fig. 6 for the shelf off northeastern United States. The zone a few meters below or above this line (illustrated by vertical marks on the sea-level line of Fig. 7) serves to limit the age and present depth of salt-marsh peats and of most remains of oyster shells. This zone defines the shore or lagoonal environment. The region below this zone and the one extending beyond the lower depth limit of the figure represents the ocean environment. The region above the zone and that extending beyond the upper limit of the figure is the subaerial or the freshwater pond environment. The area to the right on the diagram shows glacial ice occupying part of the shelf off New England; in other regions the pond environment extends to the right through this area of the graph until limited by high sea levels 25,000 to 30,000 years ago (*24*). In other words, Fig. 7 is a boundary diagram which shows that the dates and depths for future recoveries of marine shells should lie within the area marked *OCEAN* and

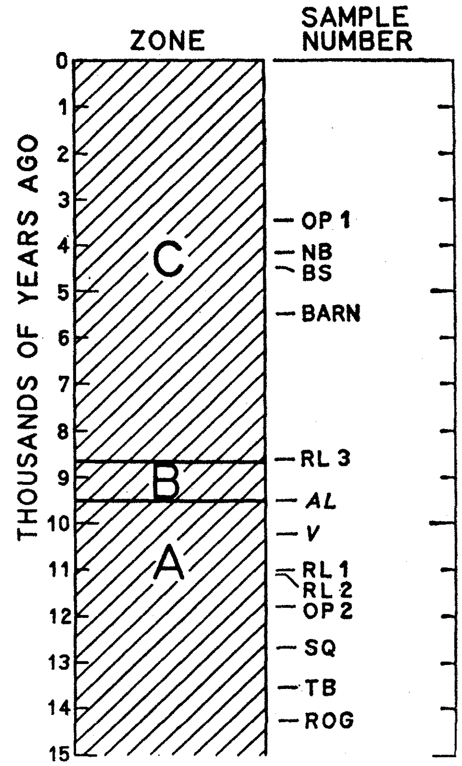


Fig. 5. Positions of the sea-floor and coastal peats of Table 1 with respect to the pollen zones of Fig. 4. Age limits for the pollen zones are those of Davis (*42*). Most peat samples are plotted according to both radiocarbon ages and pollen percentages, but *V* and *AL* are plotted only by their pollen percentages because both samples were too small for accurate radiocarbon measurements.

that the dates and depths for future recoveries of freshwater peats should lie within the area marked *PONDS*.

The presence of freshwater peats on the continental shelf reinforces the belief that during glacial stages of low sea levels the shelves became seaward extensions of the previous (and present) land areas. Coastal plains were enormously widened. The belt of new land soon became covered by vegetation similar to that of the adjacent old land, so that the former shore zones were almost obliterated. Land animals, including elephants, moose, musk ox (*25*), and probably man (*26*), soon followed. Their new habitation was temporary, however, for when the sea advanced several thousand years later, it flooded the land vegetation, leaving only some peat deposits as evidence of former forests and grasslands. Similarly, the advancing sea either drove ahead of it the animal inhabitants or submerged their remains, as, even now, it continues to displace them with its present advance of a few millimeters per year.

Detailed quantitation and integration of chronological and palynological data have not been available for assigning precise values to the latitudinal retreat of the boreal forest during the period of climatic amelioration that began about 11,000 years ago. Evidence needed for such a quantitative approach may be present in the freshwater autochthonous peats that are submerged off the southeastern coast of New England as the result of the postglacial worldwide rise in sea level. The exposed broad coastal plain of low relief provided abundant shallow sedimentary basins in which the gradual transition of forest types may have been recorded. Many of the offshore swamps and bogs should have been relatively free of the local edaphic and physiographic variables that complicate many upland sites of organic deposition, such as the pollen rain from the windward montane forests of the Appalachian Highlands. Accordingly, further work on the offshore peat deposits may be highly rewarding for studies of paleoclimatology.

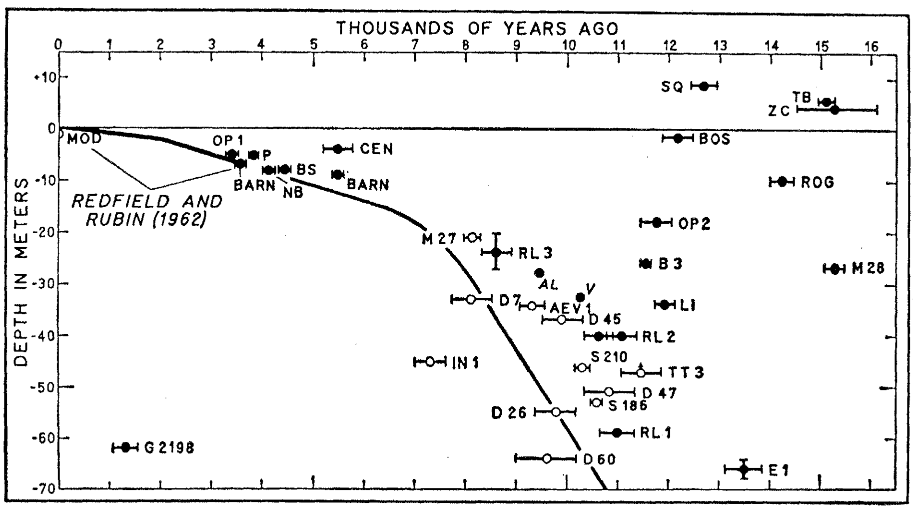


Fig. 6. Depths of radiocarbon-dated samples of peat (closed circles) and shells (open circles) whose positions are given by Table 1 and in Figs. 1 and 2. Dates for *V* and *AL* are based only upon their pollen contents. The curved line shows the position of sea level 4000 to 11,000 years ago according to the ages and present depths of oyster shells and of the salt-marsh peat within sample RL 1. At the left, the wide straight lines indicate the position of sea level during the past 3800 years according to radiocarbon dates of Barnstable salt marsh (*15*).

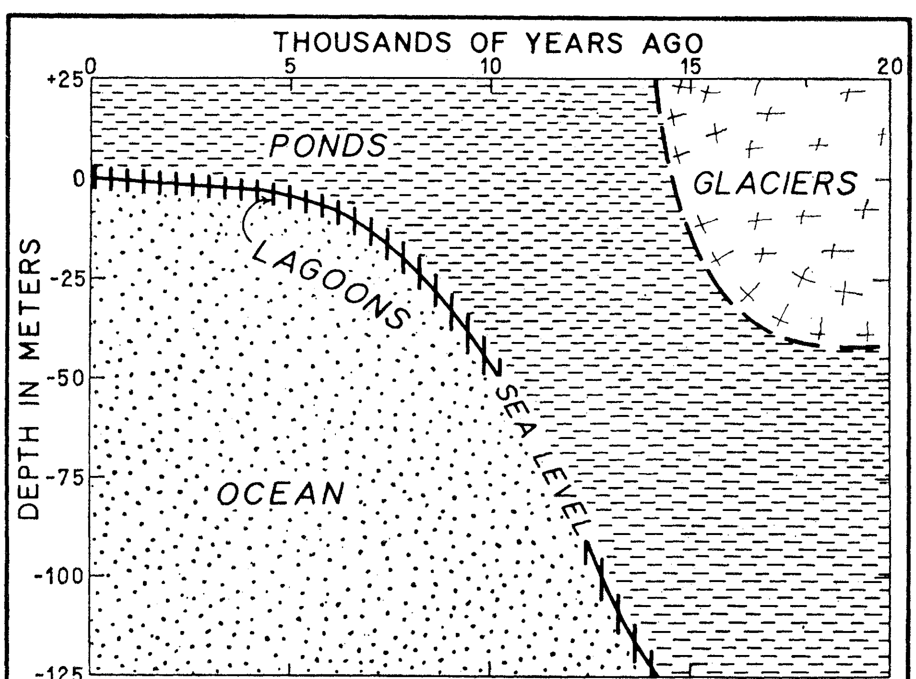


Fig. 7. Schematic diagram of the relation of freshwater ponds to other environments of New England. Areas marked *PONDS* are characterized by freshwater peats, *LAGOONS* by salt-marsh peats and oyster shells, *OCEAN* by marine sands and silts, and *GLACIERS* by till and outwash.

An interesting problem of plant physiology is raised by the finding that plants high on the salt-marsh have ratios of stable carbon isotopes similar to those of marine plants, in spite of the short length of time that they are submerged. The measurements that were made indicate that δC^{13} is a useful means of distinguishing between ancient salt-marsh and freshwater peats.

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Radium-226 and Radon-222: Concentration in Atlantic and Pacific Oceans

Abstract. *Measurements of radon-222 in seawater suggest the following. The radium-226 content of surface water in both the Atlantic and Pacific oceans is uniformly close to about 4 × 10^{-14} gram per liter. The deep Pacific has a concentration of radium-226 that is four times higher and the deep Atlantic a concentration twice as high as that of the surface. These distribution profiles can be explained by the same particle-settling rate for radium-226 from surface to depth for the two oceans and by a threefold longer residence time of water in the deep Pacific than in the deep Atlantic. The vertical distribution of the deficiency of radon-222 in the surface water of the northwest Pacific Ocean suggests a coefficient of vertical eddy diffusion as high as 120 square centimeters per second and a gas-exchange rate for carbon dioxide in surface water between 14 and 60 moles per square meter per year. Vertical profiles of the excess of radon-222 in near-bottom water of the South Atlantic give coefficients of vertical eddy diffusion ranging from 1.5 to more than 50 square centimeters per second.*

Shipboard analysis of the concentration of radon gas in samples of seawater offers three important types of information: (i) the distribution of Ra^{226} in the world ocean, (ii) the exchange rates of gases across the air-sea interface, and (iii) the rates of vertical mixing near the surface and near the bottom of the ocean. Briefly, Rn^{222} (half-life, 3.85 days) is produced in seawater by the decay of its parent Ra^{226} (half-life, 1600 years). Well away from the air-sea and sediment-sea interfaces, the rate of radioactive decay of radon is equal to that of its parent radium.

Thus, a measurement of the radon content of such a water sample is a measurement of its radium content. As the radon content of the atmosphere is negligible, compared to that in surface seawater, radon continually escapes from the sea. By analyzing the vertical distribution of radon deficiency in the surface ocean it is possible to determine the rates of both vertical mixing and gas exchange. Water in the pores of deep-sea sediments contains 10^4 to 10^5 times more radon than the overlying seawater. Hence, radon diffuses from the sediment into the sea. The vertical distribution of excess radon in near-bottom water provides an index of the rate of vertical mixing. This report extends an earlier study (*1*) by presenting positive results for each of these applications.

Radon was extracted from 20 to 40 liters of seawater by circulating He gas in a closed system at the rate of 2 liter/min for 90 minutes. The condensable gases (including radon) were continuously collected in traps cooled with liquid air. The radon was then separated from CO_2 and H_2O by circulating the condensed gas through ascarite. Next it was quantitatively transferred to a 30-cm^3 scintillation cell where the count of its α-particles was determined. Overall recovery yields averaged 90 percent; accuracy of the measurements is about ± 10 percent. Details of the procedure have already been published (*1*).

Although our results change neither the average content of radium content in the ocean nor the broad picture of its distribution from that given by previous workers (*2, 3*), they do show far less scatter and suggest that radium is uniformly mixed throughout a given water mass. The radium content of surface water in both the Atlantic and Pacific oceans is 4×10^{-14} g/liter (Table 1 and Fig. 1). In both oceans a smooth increase in radium takes place downward through the main thermocline; in the Pacific the increase is fourfold (to 16×10^{-14} g/liter) and in the North Atlantic, twofold (to 8×10^{-14} g/liter).

Two explanations have been offered for the deficiency of radium in surface relative to deep water. Koczy (*2*) suggested that it reflected radioactive decay during the period in which surface water was isolated from the deep sea. The mixing rates required by this hypothesis are an order of magnitude lower than those that explain the vertical distribution of natural radiocarbon [see Broecker (*4*)]. Chow and Goldberg (*5*) have suggested that the deficiency is generated in much the same way as that for silicon and phosphorus. Radium in surface water is fixed onto particulate matter that sinks to the deep ocean where the radium redissolves. Their demonstration that, in the Pacific, barium shows a fourfold enrichment in deep relative to surface water strongly supports this alternate hypothesis.

Despite the difference in the deep-to-surface anomaly for radium in the two oceans the same particulate extraction rate, I, is required for both. Material balance requires that $I = R(C_D - C_S)$. The rate of transfer, R, of water across the main thermocline is given by

$$R = \frac{\hbar}{t_M(C_D' - C_S'/C_D')}$$

where $\hbar$ is the mean depth of the ocean; C_D' and C_S' are the C^{14}/C^{12} ratios in the deep and surface ocean;