References and Notes

1. L. D. Jaffe *et al.*, *Science* **152**, 1737 (1966); E. A. Whitaker, *ibid.* **153**, 1550 (1966).
2. Stereometric contours were compiled by the U.S. Air Force Aeronautical Chart and Information Center in January 1967 during preparation of a chart of the region on a scale of 1:100,000.
3. L. D. Jaffe *et al.*, *Jet Propulsion Lab. TR No. 32-1023* (1966), part 2, pp. 61–67; W. E. Brown, *J. Geophys. Res.* **72**, 791 (1967).

* Co-investigators with L.H.S.

25 April 1967

Sea Levels 7,000 to 20,000 Years Ago

Abstract. *Relative sea levels for early post-Pleistocene time are best known from radiocarbon dates of sediments on the continental shelves off Texas and off northeastern United States. Differences in indicated rates of the rise of relative sea level and in depths of the shelf-breaks reveal differential vertical movement of the two shelves during this time, with the result that the Atlantic shelf has sunk with respect to the Texas shelf.*

During the past decade several hundred radiocarbon age determinations of sediment from continental shelves and from coastal bore holes have provided information on the position of sea level during post-Pleistocene times. Most of the measurements are for the past 6000 years. They show a slow rise that began 2000 to 4000 years ago, lasted until the present, and was preceded by a faster rise. Regional or local differences in the apparent rate of rise and of the date at which the rise slowed (*1*) have been interpreted as resulting from variations in the rate of eustatic rise of sea level and from the effects of local isostatic movements of the coastal zone due to relief of ice load, to weighting by deltaic sediments, and to weighting by sea water that deepened on the continental shelves as glaciers melted (*2*).

Dates for sea levels older than 6000 years are relatively sparse. There are 13 such dates for the continental shelf off Texas (*3*, *4*)—the largest published set of appropriate radiocarbon measurements covering this period. These extend back about 17,000 years and are based on shells, partly those of *Crassostrea virginica* (Gmelin), the common edible oyster that lives in bays that generally are less than about 4 m deep.

Since 1965 additional dates have been obtained for shells of *C. virginica* from the Atlantic continental shelf between Cape Hatteras and Georges Bank (*5–7*). One date was obtained for a deeply submerged peat deposit that contained some salt-marsh material (*8*). These 11 dates for oyster shells and peat, most of which were available in 1965 (Table 1 and Fig. 1), indicated relative positions of sea level for the Atlantic shelf that are lower than those for the Texas shelf during the same period; however, the oldest dates were only 11,000 years and the greatest depths were only 59 m for the Atlantic shelf, and data from the two shelves (Fig. 2) exhibited considerable overlap.

During 1966 Garrison obtained five more dates that included several from older and deeper deposits of the Atlantic shelf (Table 1). These dates are for shells found in piston cores collected aboard the University of Rhode Island's research vessel *Trident*. A shallow-water environment is indicated by some of the shells (although others are from mollusks that live in a wide range of depths) and also by the nature of the sediment that encloses the shells. Accordingly, a description of the sediment is appropriate.

Core T 228 consists of sediments that are shown by seismic subbottom profiling to lie atop a 145-m terrace just east of Hudson Canyon (*9*, *10*). The core (80 cm long) contained layers of clay balls in a sandy matrix alternating with layers of very silty fine- to medium-grained sand. Several large fragments of the sea scallop, *Placopecten magellanicus* Gmelin, enclosed within a silt sand layer at 46 to 63 cm were dated. This mollusk lives in a wide range of depths and is common at 100 m; however, the clay balls deposited with these shells probably were derived from the erosion of another terrace that lies at about 120 m, when sea level was slightly above that terrace.

Core T 203 was from the flank of a small ridge that has a relief of 5 to 10 m and rises above an erosional terrace whose average depth is about 120 m. The core consisted of 100 cm of grayish-brown sand underlying 12 cm of greenish sandy silt. This sand was fine- to medium-grained and well sorted at the top but became coarser and pebbly near the bottom. Shell fragments, mostly of *Mesodesma arctatum* (Conrad), were abundant throughout the lower 100 cm, but many whole valves were strongly imbricated in the bottom 15 cm of the core. The species is common on exposed beaches, especially adjacent to the mouths of streams and tidal inlets. Only the imbricated shells were removed and dated by their content of radiocarbon.

Core T 206 was 110 cm long. The uppermost 10 cm consisted of fine-grained sand and silt with abundant planktonic foraminifera. Below a sharp break at 10 cm, the lower part of the core was fine- to medium-grained subround sand that was very clean and well sorted. A date was obtained on a collection of shell fragments between 63 and 83 cm, including specimens of *M. arctatum*. Both sand and shells are indicative of shallow water, and the date probably relates to the destructive phase of a former delta, on the surface of which the core was obtained.

Core T 147, 117 cm in length, contained medium- to coarse-grained grayish-brown sand underlying sandy silt above a sharp contact at 47 cm. A date was determined for shells of *M. arctatum* enclosed in the sand at 107 to 117 cm. This sand may be a Holocene transgressive deposit atop a reworked Pleistocene surface and beneath the southern part of a large silt body in this area (*10*, *11*). The coarse-grained, well-sorted nature of the sand in this core suggests that it was deposited no more than about 10 m below sea level, in agreement with the restricted habitat of *M. arctatum*.

Core T 307 has the same stratigraphic relations as core T 147, except that it came from the northern edge of the silt body. This core had clean fine- to medium-grained gray sand sharply overlain by 30 cm of silty, very fine sand. A date was obtained for fragments of the razor clam, *Ensis directus* Conrad, in the lower sand at 55 to 65 cm; this mollusk is typical of sand flats but occurs as deep as 15 m.

The assemblage of dates shown in Fig. 2 indicates conclusively that relative sea level was lower for the Atlantic than for the Texas shelf, or in reality that the shelves have undergone differential movement during at least the past 16,000 years. Such movement could be accompanied by broad warps or sharper irregularities in the region of movement. Although the available dates for nearshore mol-

Table 1. Radiocarbon dates for indicators of ancient sea levels of the continental shelf off northeastern United States.

Symbol	Ship and station	Material	Location	Depth (m)	Source	Age	Lab. No.
IN 1	*Invader* 1	*C. virginica**	40°59′N,69°44′W	45	(*26*)	7,310 ± 300	W-1981
D 7	*Delaware* 7-1	*C. virginica**	36°09′N,75°20′W	33	(*7*)	8,130 ± 400	W-1402
M 27	Bridge boring	*C. virginica**	36°59′N,76°06′W	21	(*5*)	8,135 ± 160	ML-196
T 307	*Trident* 307	*E. directus*†	40°50′N,70°52′W	55	(*27*)	9,150 ± 220	I-2475
AEV 1	*A. E. Verrill* 1	*C. virginica**	41°18′N,71°00′W	34	(*28*)	9,300 ± 250	W-2013
D 60	*Delaware* 60-7	*C. virginica**	37°24′N,74°39′W	64	(*29*)	9,600 ± 600	L-948
D 26	*Delaware* 26	*C. virginica**	38°49′N,73°39′W	55	(*7*)	9,780 ± 400	W-1403
D 45	*Delaware* 45	*C. virginica**	40°43′N,72°25′W	37	(*7*)	9,920 ± 400	W-1400
S 210	?	*C. virginica**	41°55′N,67°35′W	46	(*30*)	10,300 ± 150	S-210
S 186	?	*C. virginica**	42°05′N,67°15′W	53	(*6*)	10,600 ± 130	S-186
D 47	*Delaware* 47	*C. virginica**	40°40′N,71°59′W	51	(*7*)	10,850 ± 500	W-1401
T 206	*Trident* 206	*Astarte* sp. *M. arctatum*‡	40°10′N,71°26′W	86	(*27*)	10,850 ± 150	I-2474
RL 1	*Ruth Lea* 1	Peat, partly salt-marsh	41°09′N,68°43′W	59	(*8*)	11,000 ± 350	W-1491
T 228	*Trident* 228	*P. magellanicus*§	39°37′N,72°07′W	147	(*27*)	13,200 ± 210	I-2545
T 147	*Trident* 147	*M. arctatum*‡	40°09′N,70°29′W	122	(*27*)	13,420 ± 210	I-2473
T 203	*Trident* 203	*M. arctatum*‡	40°06′N,70°32′W	130	(*27*)	14,850 ± 250	I-2544

* *Crassostrea virginica* (Gmelin). † *Ensis directus* Conrad. ‡ *Mesodesma arctatum* (Conard). § *Placopecten magellanicus* Gmelin.

lusks and peat span a 550-km length of the Atlantic continental shelf, no longitudinal tilt is apparent. Moreover, the data indicate no differential vertical movement on either side of the large strike-slip fault that presumably crosses the shelf off New York (*12*).

Least-squares straight lines were drawn through the 13 Texas and the 16 Atlantic data points of Fig. 2 (the sea level for core T 228 was taken as 120 m). These lines have slopes of 8 m and 16 m per thousand years, respectively. Clearly, a straight line is not the most reasonable depiction of the rise of relative sea level, but the scarcity of points does not justify the drawing of a compound curve—especially not the many irregularities shown by Fairbridge (*13*) and to a lesser extent by Curray (*3*), who deduced the irregularities of his curve largely from other evidence. The rise of sea level must have slowed gradually after about 7000 years ago to reach the almost constant low rate that began about 4000 years ago. Similarly, this rise must have been slow just after the sea level departed from its lowest level, about 123 m according to estimates (*14*) based on ice volumes. This lowest level is generally considered to have been reached about 19,000 years

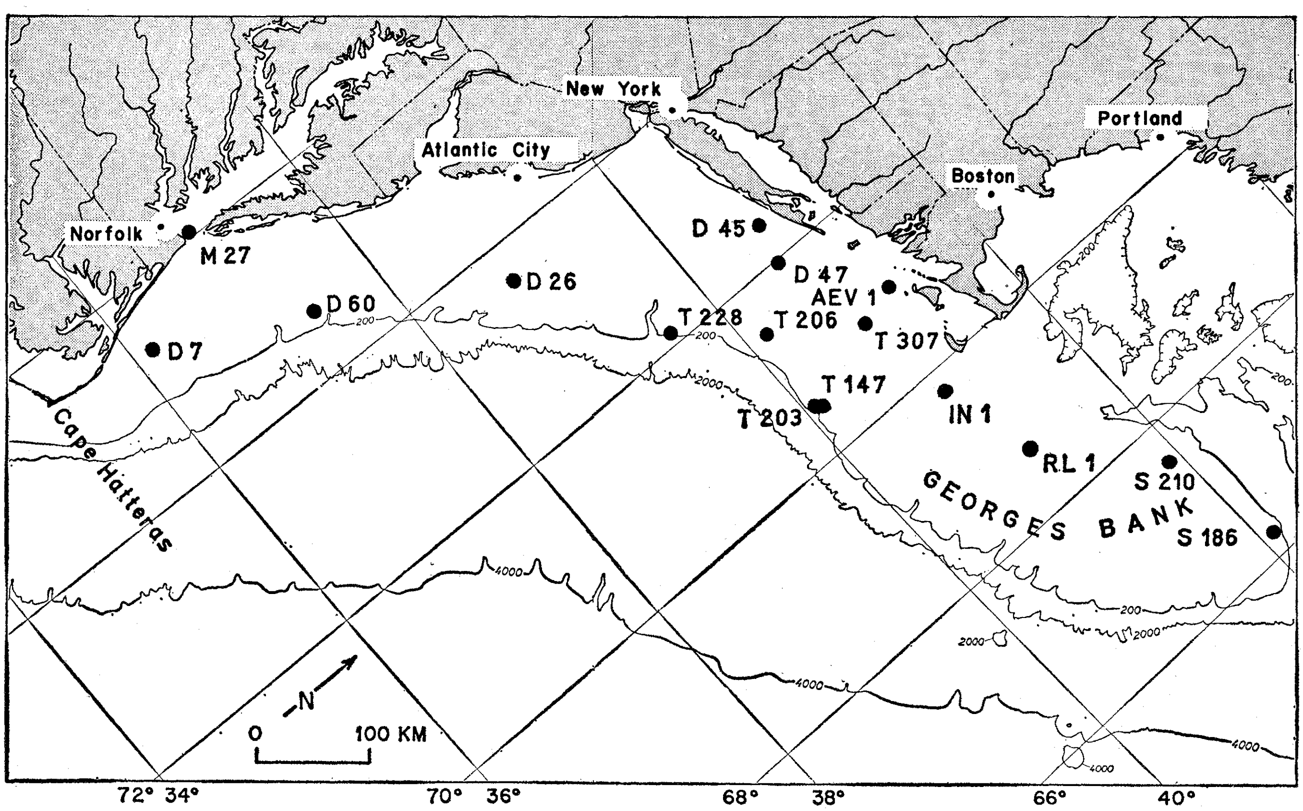
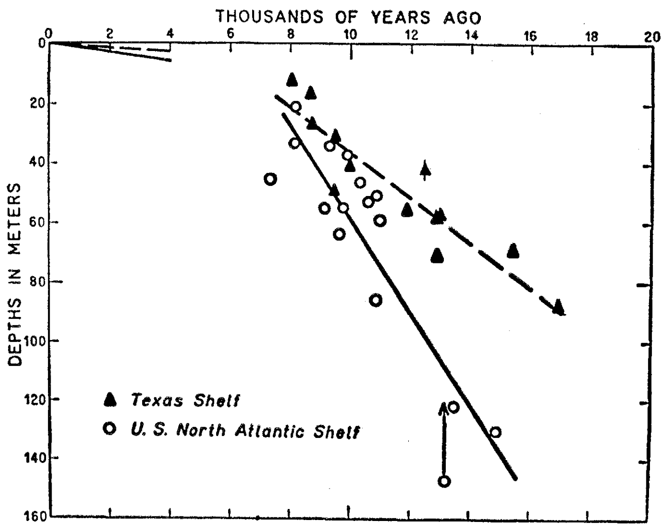


Fig. 1. Positions of Atlantic shelf samples that contain materials indicative of sea levels 7000 to 15,000 years ago, according to radiocarbon dating.



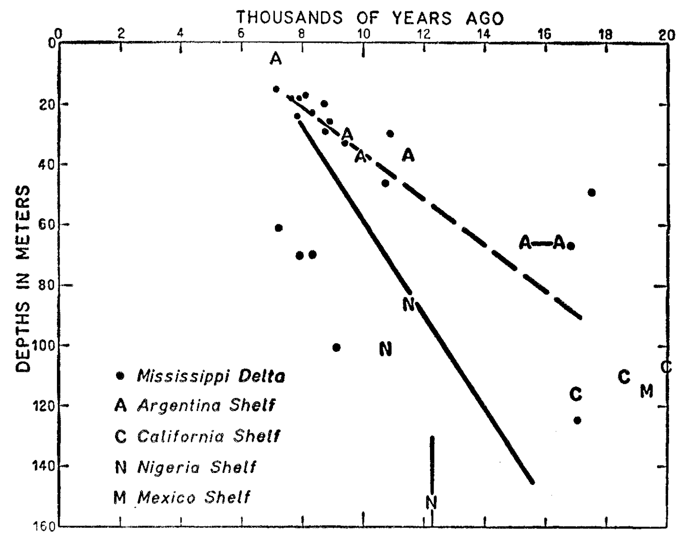


Fig. 2 (left). Radiocarbon ages of the period 7000 to 17,000 years ago for salt-marsh peat and shallow-water (0 to 4 m) shells from the Texas continental shelf and the Atlantic shelf of the northeastern United States. The least-squares best-fit straight lines for each set of dates are indicated. Lines at the upper left represent positions of sea level during the past 4000 years for the Gulf coast (dashed) and for the New England coast (solid line) according to Redfield (*1*). Fig. 3 (right). Comparison of the straight lines of Fig. 2 with dates of 7000 to 20,000 years for sea levels in various areas of the world.

ago, from considerations of the date for maximum extent of glaciers on land and of the temperatures indicated by pollen profiles and by isotopic and faunal measurements of deep-sea sediments (*15*). Prior to 19,000 years ago sea level was high; 25,000 or 30,000 years ago it may even have been above the present level.

In order to establish which of the two shelves was the more mobile, a literature search was made for reliable dates and depths for relative sea levels 7000 to 20,000 years ago on shelves elsewhere in the world. Most complete are the 122 dates for the Mississippi Delta that were published by McFarlan (*16*). Nineteen of these, the ones for shells or peat that were believed to have accumulated within 4 m of sea level, are plotted in Fig. 3. The wide scatter of data points is attributed to subsidence and compaction of the deltaic sediments, coupled with uplift across a hinge line, as discussed in detail by McFarlan. Six more dates came from the Argentine shelf; four of these are for peat samples plotted by Shepard (*4*). Two dates are for a single sample of abraded shells that include the shallow-water *Littoridina charruana* (d'Orbigny) and *Chione gayi* (Hupe) (*17*); four other dates older than 7000 years were listed, but these were for shells having uncertain depth ranges. For the California shelf, Emery (*18*) published four dates for calcareous red algae, three of which are shown on Fig. 3; the fourth, at about the same depth, is 24,500 years old and is equally acceptable but beyond the limits of the graph. The shelf off Nigeria was studied by Allen (*19*), who reported three dates older than 7000 years for calcareous algae and for shells of uncertain depth range, but probably of shallow water because they are closely associated with submerged terraces. A single date for shells of *Strombus grannulatis* (habitat, 2 to 20 m) was reported (*20*) for the shelf off western Mexico. Another single date was reported (*21*) for a bridge test boring in British Guiana, but the depth is shallow (22 m) and the date is young (8590 years), so it was not included in Fig. 3.

Transfer of the two best-fit lines from Fig. 2 to Fig. 3 permits a comparison of the Texas and Atlantic dates with those of other areas of the world. The relative rise of sea level off Texas is reasonably close to the rise that might be inferred from the fewer measurements for the shelves off Argentina, California, and Mexico. The rise for the Atlantic shelf is similar only to that off Nigeria; however, the Nigerian data are somewhat suspect because of uncertainty in the original water depths of the dated materials. Some data for the Mississippi Delta lie close to the line for Texas and some are closer to that for the Atlantic shelf, but they are suspect because of the known deformation of the delta region.

Related information is the depth of the shelf-break within each of the regions of radiocarbon dating of past sea levels. As shown by Dietz and Menard (*22*), where the shelf-break is erosional it probably was formed when sea level was so low that the water was only about 10 m deep. In many areas the erosional shelf-break has been thickly covered by later sediments, as revealed by seismic profiling. The shelf-break off Texas lies at about 110 m, according to contours by Uchupi (*23*). This depth is somewhat similar to the depths of the shelf-break off Argentina [an average of 125 m for 13 sounding profiles of Fray and Ewing (*17*)], Mexico [110 m, according to contours of Moore and Curray (*24*)], and California [80 m, according to six profiles by Emery (*18*)]. In comparison with other profiles in the region, this part of southern California is undergoing rapid uplift. Off the Atlantic coast the shelf-break is deeper; for the region having the oldest radiocarbon dates of Table 1, the shelf-break ranges from about 100 to 145 m, with an average of about 140 m, as shown by detailed contours of Garrison and McMaster (*10*). Similar depths of 145 m characterize the shelf-break off Nigeria (*19*). According to Shepard (*25*), the average depth of the shelf-break on a worldwide basis is 72 fathoms, or 132 m. The depth for the part of the Atlantic shelf that contains most of the dated materials is nearer this worldwide average than is the depth of the shelf off Texas.

The relations between apparent rates of rise of sea level and depths of the shelf-breaks implies that the shelves off Texas, Argentina, California, and Mexico have risen during the past 20,000 years, or that the shelves off the Atlantic and Nigerian coasts have sunk during that period. The difference between the apparent rates (8 in contrast to 16 m per thousand years) and between the depths of the shelf-breaks (110 in contrast to 140 m) are large enough to demand explanation. Relative subsidence of the New England coast with respect to areas farther south is also shown by Redfield's (*1*) studies of salt-marsh dates of the past 4000 years. For both studies the subsidence is nearly twice the rate of eustatic rise of sea level, if the southern areas having lower rates of relative rise of sea level are assumed to be tectonically stable.

If subsidence of the New England (Atlantic) shelf and coast with respect to other areas did occur, perhaps it can be attributed to landward flow of subcrustal material required for the known uplift of the land areas after melting of their load of glacial ice. However, we believe that further speculation is useless in attempts to arrive at the cause of the difference between the relative rise of sea level on the Texas and the Atlantic shelves and that the existing data are inadequate even for determining which area was the more mobile. For the present, we merely wish to inject a note of caution against the acceptance of measurements of past relative sea levels on any single continental shelf as an indication of absolute changes of sea levels throughout the world ocean.

K. O. EMERY
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
LOUIS E. GARRISON
Graduate School of Oceanography, University of Rhode Island, Kingston

References and Notes

1. A. C. Redfield, *Science*, this issue.
2. A. L. Bloom, *Bull. Geol. Soc. Amer.*, in press.
3. J. R. Curray, in *Recent Sediments, Northwest Gulf of Mexico* (American Assoc. of Petroleum Geologists, Tulsa, 1960), p. 221.
4. F. P. Shepard, in *ibid.*, p. 338; ———, in *Essays in Marine Geology* (Hancock Foundation, Univ. of Southern California, Los Angeles, 1963), p. 1.
5. W. Harrison, R. J. Malloy, G. A. Rusnak, J. Terasmae, *J. Geol.* **73**, 201 (1965).
6. J. C. Medcof, A. H. Clarke, Jr., J. S. Erskine, *J. Fish. Res. Bd. Can.* **22** (2), 631 (1965).
7. A. S. Merrill, K. O. Emery, M. Rubin, *Science* **147**, 398 (1965).
8. K. O. Emery, R. L. Wigley, M. Rubin, *Limnol. Oceanogr.* **10**, suppl. R97 (1965).
9. J. Ewing, X. Le Pichon, M Ewing, *J. Geophys. Res.* **68**, 6303 (1963).
10. L. E. Garrison and R. L. McMaster, *Mar. Geol.* **4**, 273 (1966).
11. E. Uchupi, *U.S. Geol. Surv. Prof. Papers No. 475-C* (1963), p. 132.
12. C. L. Drake, J. Heirtzler, J. Hirshman, *J. Geophys. Res* **68**, 5259 (1963).
13. R. W. Fairbridge, in *Physics and Chemistry of the Earth*, L. H. Ahrens *et al.*, Eds. (Pergamon, London, 1961), vol. 4, p. 99.
14. W. L. Donn, W. R. Farrand, M. Ewing, *J. Geol.* **70**, 206 (1962).
15. W. Broecker, *Bull. Geol. Soc. Amer.* **72**, 159 (1961).
16. E. McFarlan, Jr., *ibid.*, p. 129.
17. C. Fray and M. Ewing, *Proc. Acad. Natur. Sci. Phila.* **115**, 113 (1963); H. G. Richards and J. R. Craig, *ibid.*, p. 127.
18. K. O. Emery, *Bull. Geol. Soc. Amer.* **69**, 39 (1958).
19. J. R. L. Allen, *Mar. Geol.* **1**, 289 (1964).
20. J. R. Curray, *Bull. Geol. Soc. Amer.* **72**, 1707 (1961).
21. T. van der Hammen, *Leidse Geol. Mededel.* **29**, 125 (1963).
22. R. S. Dietz and H. W. Menard, *Bull. Amer. Ass. Petrol. Geol.* **35**, 1994 (1951).
23. E. Uchupi, *Misc. Geol. Invest. Map I-521* (U.S. Geological Survey, Washington, D.C., in press).
24. D. G. Moore and J. R. Curray, in *Deltaic and Shallow Marine Deposits*, L. M. J. U. van Straaten, Ed. (Elsevier, Amsterdam, 1964), p. 275.
25. F. P. Shepard, *Submarine Geology* (Harper & Row, ed. 2, New York, 1963).
26. Capt. Norman Lepire.
27. L. E. Garrison.
28. Marine Biological Laboratory.
29. A. S. Merrill.
30. J. C. Medcof.
31. We are indebted to W. J. Clench, J. D. Davis, and R. L. Wigley for identification of molluscan shells and to A. C. Redfield and R. L. Wigley for their critical reading of the manuscript. Contribution No. 1926 of the Woods Hole Oceanographic Institution. Contribution of the Graduate School of Oceanography, University of Rhode Island.

6 April 1967

Postglacial Change in Sea Level in the Western North Atlantic Ocean

Abstract. *Radioactive carbon determinations of the age of peat indicate that at Bermuda, southern Florida, North Carolina, and Louisiana the relative sea level has risen at approximately the same rate, 2.5 $\times$ 10^{-3} foot per year (0.76 $\times$ 10^{-3} meter per year), during the past 4000 years. It is proposed tentatively that this is the rate of eustatic change in sea level. The rise in sea level along the northeastern coast of the United States has been at a rate much greater than this, indicating local subsidence of the land. Between Cape Cod and northern Virginia, coastal subsidence of 13 feet appears to have occurred between 4000 and 2000 years ago and has continued at a rate of about 1 $\times$ 10^{-3} foot per year since then. On the northeastern coast of Massachusetts, subsidence of 6 feet occurred between 4000 and 3000 years ago; since then sea level has risen at about the eustatic rate. Between 12,000 and 4000 years ago, sea level rose at an average of about 11 $\times$ 10^{-3} foot per year. The part played by local subsidence or temporary departures from the average rate during this period is uncertain.*

The trend of changing sea level during postglacial times, based on radiocarbon determination of the age of submerged organic material, has been reviewed by Shepard (*1*). Data indicate a continuous rise in level, amounting to about 100 feet during the past 10,000 years, at a rate which decreased markedly about 5000 years ago. Individual measurements scatter rather widely from the curve describing the general trend, and it is not possible to distinguish effects due to the general eustatic change in sea level from those arising from local tectonic changes in the elevation of the land, from errors in measurement, or from the displacement of the materials (shells, tree stumps, and so forth) since their formation at the dated time.

This study is an attempt to distinguish between these effects and to determine more precisely the recent eustatic rise in sea level. Consideration has been given only to data based on analysis of peat, because it is less subject to displacement since formation than logs, shells, and so forth are. Since some error is inherent in the interpretation of measurements on peat, only those data are considered that are consistent with others secured at the same locality, and only those localities are included from which the selected measurements are supported by similar measurements from other places.

During the past decade a number of determinations of the age of peat, recovered from various depths at localities on the eastern coast of the United States, have been published. Additional data from Bermuda, North Carolina, and the New England coast are reported herein.

Each investigator secures samples of peat from a series of depths measured from some local datum near which it is believed peat is now forming. By plotting the ages of the samples against these depths, curves have been drawn that are considered to show the time course of the rise in sea level at the locality in question. In comparing data from different locations, difficulty arises if a different local datum has been employed in different places. Local datum has been taken as the surface of the marsh or from some measured tide level. In either case, the relation of datum to depth, relative to mean sea