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LATE-PLEISTOCENE FLUCTUATIONS OF SEALEVEL AND POSTGLACIAL CRUSTAL REBOUND IN COASTAL MAINE

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ABSTRACT. Deglaciation and postglacial crustal rebound near Portland, Maine took place during a time of generally rising sealevel. The relative positions of land and sealevel at several points in time are indicated in part by: (1) glacial-fluvial deposits buried by marine silty clay to depths of 70 feet below present sealevel, (2) radiocarbon-dated shells from emerged marine beds 160 to 250 feet above present sealevel, (3) pollen-stratigraphic profiles of coastal sites underlain by marine sediment, which lack the late-glacial and early postglacial portion of the record, and (4) submerged tree stumps dating back to 4200 years B.P. The position of a reference point in Maine with respect to changing sealevel is graphically shown, using several alternative interpretations of late-Pleistocene eustatic rise of sealevel as base lines. Only one of the constructions can be reasonably interpreted in terms of postglacial crustal rebound, demonstrating that areas of known crustal deformation can be useful in interpreting eustatic sealevel fluctuations.

INTRODUCTION

A strip of land a few tens of miles wide (fig. 1) inland from the coastline of southwestern Maine displays evidence of both emergence and submergence during late Pleistocene time. The region was described by Davis (1912, p. 532) as an unusual type of emerged coastal plain because it has only a discontinuous cover of late-glacial marine sediment partially filling valleys and lapping up on highlands to the altitude of maximum postglacial marine submergence. In contradiction to such obvious evidence of emergence, topographic maps of the area, especially the Boothbay Quadrangle, are used in many geology classes to illustrate the characteristics of a submerged coast.

The late-glacial and postglacial history of coastal Maine can be summarized as follows: the weight of glacier ice isostatically depressed the region, then postglacial eustatic rise of sealevel submerged a fringe of land extending inland from the present shoreline to about the 200- or 300-foot contour, and finally, lagging postglacial crustal rebound caused re-emergence. Marine sedimentation was not sufficient to blanket completely the crystalline basement rocks and thus did not convert the coastal region into the monotonous lowland that is envisioned by the elementary definition of a coastal plain.

The present report is an attempt to fill in the details of the late-glacial and postglacial history, with emphasis on the interrelation of glacial-eustatic and glacial-isostatic movements. Work was supported during the 1957 and 1958 field seasons by the Office of Naval Research and during 1959 by the Maine Geological Survey. The stimulating discussion of the Friends of the Pleistocene during their annual meeting in May, 1961 is gratefully acknowledged.

The plan of attack is as follows: relative movements of land and sealevel in the vicinity of Portland, Maine are reviewed; then models are constructed, showing the position of a hypothetical bench mark relative to sealevel during late Pleistocene time; finally, the difficulties of the constructions are discussed and points of interest noted. The model presented as the most satisfactory is only one of an infinite number of possible interpretations, but it appears to be in best accord with the facts now available. The intent is to illustrate a method of analyzing interrelated land and sealevel movements as well as to elucidate

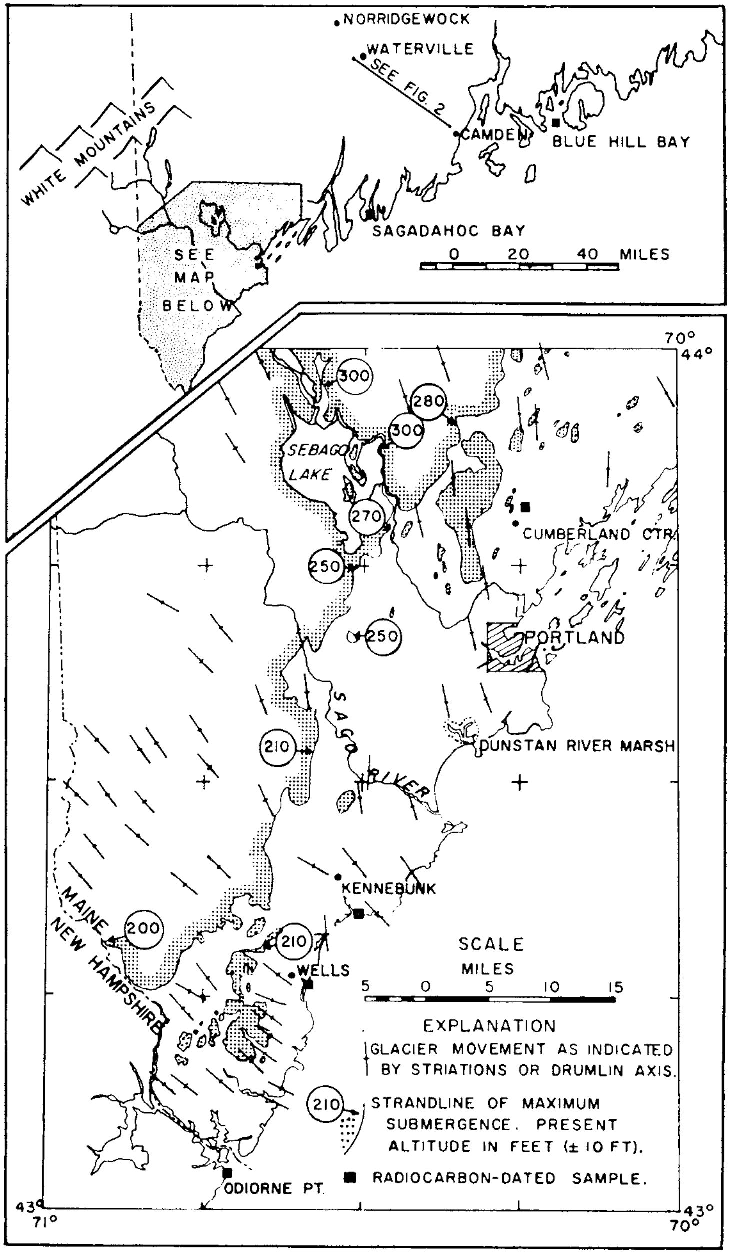

Fig. 1. Map of southern Maine showing places and features described in the text.

the history of a region. For more detailed description of the late-Pleistocene geology of the region, the reader is referred to Bloom (1960).

LATE-GLACIAL HISTORY

The term "late glacial" is used here in an informal sense as encompassing that part of late Pleistocene time when southwestern Maine was being deglaciated for the last time. Not all of the area was deglaciated simultaneously, but even though one locality had been deglaciated and was thus in its "postglacial" environment at the same time that another locality was still covered with glacier ice, as long as some part of the region was characterized by some glacier-controlled regimen, the term "late glacial" is appropriate. The term "postglacial" is used to describe events that followed regional deglaciation. Such terms avoid the problem of defining an artificial Pleistocene-Recent boundary in the continuous series of events to be described. Because events in Maine form a continuum, it is preferable to refer the entire sequence to late Pleistocene time and to use the term "recent" in the informal sense proposed by Flint (1957, p. 283).

Mode of deglaciation.—Till is not abundantly exposed in southwestern Maine. It forms drumlins, locally abundant, and both downglacier tails and upglacier ramps against bedrock hills. In addition, clusters of closely spaced till ridges, or washboard moraines, cross several areas (Bloom, 1960, p. 28). The predominant amount of drift has been stratified or sorted by running water, and takes the form of kames, kame terraces, eskers, ice-contact deltas, and outwash fans. In the vicinity of Portland, many deltaic deposits show ice-contact stratigraphy on their north or northwest sides grading into deltaic foreset beds of sand dipping south or southeast. The surface form of these ice-contact deltas has been completely masked or destroyed by subsequent marine erosion or deposition, but abundant artificial exposures indicate that ice-contact deltas are regionally abundant forms.

The significance of the regional abundance of stratified drift lies in the fact that both the stratification and sorting indicate deposition in meltwater streams or ice-dammed lakes. Through-flowing drainage enabled most of the silt and clay-size sediment to be flushed from the drift, leaving a profusion of sand and gravel deposits. The fact that finer-sized sediment constituted a part of the glacier load is evidenced by exposures of compact fissile till, rich in silt and clay. The general lack of fines in the stratified drift, except for silt lenses that mark local meltwater ponds, emphasizes the through-flowing nature of the meltwater streams. The sea, the ultimate base-level of stream flow as well as the ultimate settling basin for flocculated glacial rock flour, must have been lower than the lowest-known deposit of coarse, well sorted stratified drift. The log of an engineering testhole near Portland (Bloom, 1960, p. 58) reported sand at 64 to 68 feet below present sea level in a buried valley, overlain by gray silty clay. Another testhole log reported, "coarse sand and gravel; hole caves" between –62.2 and –70.2 feet, beneath 63 feet of marine fine sand, silt, and clay (Maine Turnpike Authority, boring 2148+44, Nonesuch River Bridge, unpublished). Although a subaerial origin for these deeply buried sand and gravel beds can not be proved, it seems unlikely that well sorted sand or gravel would be deposited in a sea that was receiving great quantities of silt- and clay-sized rock flour from a melting ice sheet. Marine reworking of previously deposited drift, well shown in figure 3 by a lens of mixed sand, silt, and clay underlying marine silty clay and thinning over the crests of buried hills, is additional evidence that valley floors now well below sealevel were subaerially exposed during deglaciation, prior to marine submergence. Sealevel, relative to the land, must have been at least 70 feet below present during some part of late-glacial time.

Marine submergence.—Stratified glacial drift and till in the vicinity of Portland are unconformably overlain by gray sandy, silty clay of marine origin. The marine sediment has been named the Presumpscot Formation (Bloom, 1960, p. 55) from exposures in the valley of the Presumpscot River near Portland. Fossils from the type area were described as early as 1842 (Mighels and Adams, 1842) and the marine deposit, referred to by various terms such as "the Portland clays" (Hitchcock, 1861, p. 275), "the Leda clay" (Katz and Keith, 1917, p. 29), and "clay of the Champlain submergence" (Meserve, 1919, p. 207), has been well known ever since. A formation name has been given the unit in order to prevent unwarranted assumptions of its stratigraphic equivalence (as was done in referring it the Champlain submergence) and also to define a mappable unit of regional extent.

The Presumpscot Formation is composed of poorly sorted, glacially abraded sediment deposited in a transgressing sea of late-Pleistocene age. The average grain size of 43 samples (Goldthwait, 1951, p. 25) was 23.5 percent sand, 37.5 percent silt, and 39 percent clay, although extreme variations are common. Fossils are locally abundant, converting some beds to veritable coquina. All 30 species of macrofossils collected (Bloom, 1960, fig. 3) from the formation are extant today. Most species are described in reference works as circumpolar or arctic forms, although eleven species are found in deep water as far south as Cape Hatteras, and several inhabit coastal waters to southern Georgia.

Two of the most common species of pelecypods in the Presumpscot Formation, *Yoldia arctica* and *Nucula expansa*, are not found today south of Cape Breton Island. Another less common species, *Astarte arctica*, is not found south of the Labrador coast. The general aspect of the fauna suggests that the environment of deposition of the Presumpscot Formation was comparable to present conditions about seven degrees latitude farther north, in southern Labrador. The faunal evidence of a colder climate is compatible with abundant ice-rafted erratics and ice-thrust features in the formation that confirm a periglacial marine origin.

In the vicinity of Portland the Presumpscot Formation overlies with regional unconformity stratified and sorted glacial drift. As is to be expected, the angle-of-rest slopes of sand and gravel that formed part of the newly deglaciated landscape were unstable when submerged, and reworking and mixing of subaerially deposited drift into the base of the Presumpscot Formation was common. Gravel pits opened in stratified drift on the coastal plain commonly show sandy basal beds of the Presumpscot Formation dipping radially off buried former hills at angles approaching 30°. No buried soil profile or other evidence of postglacial, pre-submergence weathering has been found on the surface of buried glacial deposits.

Near the inland limit of marine submergence the Presumpscot Formation intertongues with, rather than unconformably overlies, subaerially deposited drift. Delta fans, each several miles long on radii that converge on major gaps in the foothills at the back of the coastal plain, trend in a line northeastward across southwestern Maine (Bloom, 1960, p. 42). At their heads, the delta fans are composed of poorly sorted, but usually well-rounded, cobble gravel that passes transitionally inland into ice-contact stratified drift. Several of the delta fans head at eskers that follow sinuous courses northwestward into the foothills of the White Mountains.

At their distal margins the delta fans are composed of fine sand, commonly rhythmically interbedded with silt and clay typical of the Presumpscot Formation. Thus, while deglaciation was apparently pre-marine on the coastal plain near Portland, at the inland limit of marine submergence deglaciation and the maximum marine transgression were synchronous. The late glacial transgressing sea apparently "caught up" with deglaciation.

Radiocarbon dates on the marine submergence not only measure the transgression of the Presumpscot sea, but also give maximum dates for the final deglaciation of southwestern Maine. Three dates are now available, two from the vicinity of Waterville, Maine, 75 miles north of Portland, and one from Cumberland Center, 10 miles north of Portland. All three dates were determined on shells of shallow water or even intertidal mollusks (*Mytilus edulis, Panomya arctica*). They are as follows, listed with sample number, locality, height above sealevel, and reference:

W-737	11,800 ± 240	Waterville	ca. 186 ft.	(Rubin and Alexander, 1960, p. 130)
W-947	11,950 ± 350	Norridgewock	ca. 250 ft.	(Rubin, 1961, written communication)
L-678	12,100 ± 300	Cumberland Center	ca. 160 ft.	(Broecker, 1961, written communication)

The limit of marine submergence in the Waterville-Norridgewock area is about 320 feet (C. F. Hickox, 1959, written communication), and near Cumberland Center it is about 260 to 280 feet. Thus the shallow-water fauna of all three radiocarbon-dated sites shows that the dates are older than the time of maximum marine transgression and final deglaciation.

All the dates are from localities north of Portland that have been uplifted more than Portland by postglacial isostatic recovery. The limitations of attempting to project former water levels can be illustrated by an example: The maximum amount of submergence measurable at Portland is 160 feet, the height of the highest hills in the city. Actual submergence was probably greater. If 12.100 years ago the sea was about 100 feet below the level of maximum submergence at Cumberland Center (the difference between the present altitude of the marine limit there and the present altitude of the dated shell bed) then at the same time Portland must have been submerged more than 60 feet (100 feet less than the measurable submergence), but how much more is indeterminate. The extent of submergence at Portland at the times indicated by the more northerly sites cannot even be estimated because of the uncertainty of the amount of differential uplift over a distance of 75 miles.

POSTGLACIAL HISTORY

Re-emergence of the coastal plain.—It would be hard to improve upon the description by Davis (1912, p. 532-539) of the morphological changes that followed re-emergence of the coastal plain. The newly exposed Presumpscot Formation had partially filled the valleys and reduced the local relief considerably. Wave erosion of the previously submerged landscape during the re-emergence through the surf zone was minimized by the blanket of marine sediment. Nevertheless, the newly emerged, fine-grained Presumpscot Formation was much more susceptible to subaerial erosion than were the permeable sand and gravel deposits of the upland valleys, and a fine-textured drainage pattern quickly developed on the clayey lowlands. Major streams generally followed the axes of partially filled valleys across the coastal plain. A marked change in drainage texture marks the inland edge of marine deposition.

Marine submergence and subsequent re-emergence involved a transgressive and a regressive phase. The Presumpscot Formation was deposited during the transgressive phase in the proximity of melting ice, as witnessed by: (1) its basic character as a deposit of glacial rock flour, (2) its cold-water marine fauna, (3) abundance of ice-rafted erratics in it, and (4) intertonguing of the formation with outwash along the inland edge of submergence. The maximum transgression coincided with regional deglaciation. Thus re-emergence must have been a postglacial event. This inference is supported by the pollen stratigraphy of two ponds in Maine that are floored by the Presumpscot Formation. In both ponds (Potzger and Friesner, 1948, p. 181, and Deevey, 1951, p. 192) blue-gray silty clay of the Presumpscot Formation is overlain by freshwater organic sediments that bear a dominant percentage of pine pollen. The late-glacial and early postglacial sequence of tundra and spruce-birch pollen that typically precedes the pine maximum in the pollen stratigraphy of New England (Deevey, 1958) is missing on the coastal plain of Maine. Therefore, re-emergence apparently did not take place until pine dominated the pollen accumulation in swamps and ponds. The pine zone (zone B of pollen stratigraphers) is not radiocarbon dated in southern Maine, but zone B in south-central New England, subdivided into B1 and B2, dates from 6000 to 8500 B.P., and in northern Maine and Nova Scotia the undifferentiated zone B dates from 6000 to 7000 years B.P. (Deevey, 1958, p. 34). Therefore, a tentative date of 7000 to 8000 years B.P. for the re-emergence of southern Maine is proposed.

As is shown by figure 2, the ponds used in the pollen-stratigraphic studies now stand 250 feet and 140 feet above sealevel. To the degree of accuracy with

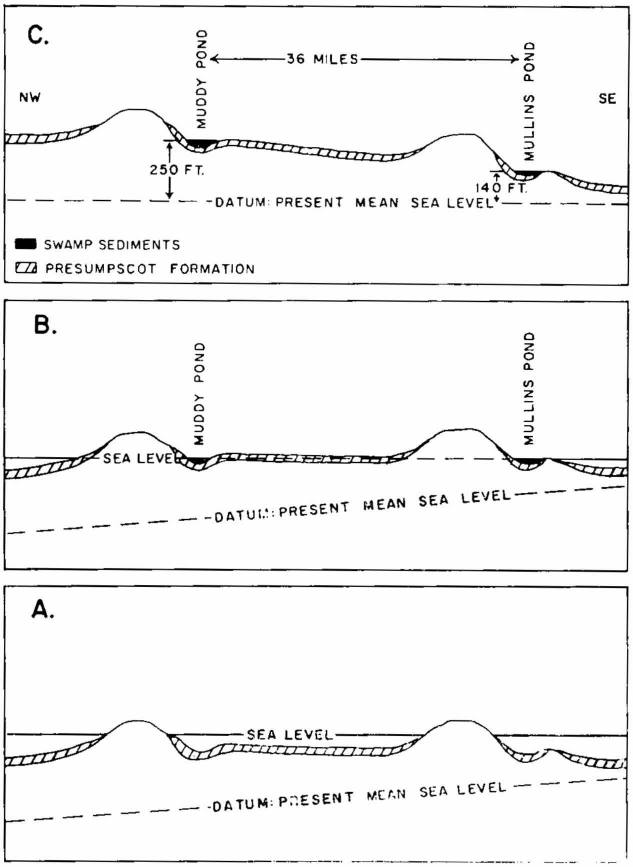

Fig. 2. Episodes in the differential postglacial upwarping of south-central Maine. Diagrammatic only; vertical scale greatly exaggerated. Note that earliest episode A is at the bottom. A. Maximum marine submergence, <11,800, >7000 to 8000 years ago. B. Re-emergence of Muddy Pond and Mullins Pond, 7000 to 8000 years ago. C. Present altitudes.

which the pollen stratigraphy permits an estimate of simultaneous emergence, in the same length of postglacial time Muddy Pond, near Waterville (Deevey, 1951, p. 192) has been elevated 110 feet more than Mullins Pond, near Camden (Potzger and Friesner, 1948, p. 181). Thus differential upwarping of about 3 feet per mile toward the northwest has accompanied re-emergence during the last 7000 to 8000 years. The differential uplift, greatest in the direction of thickest glacier ice as inferred from directions of ice movement, supports the idea that re-emergence was caused by postglacial crustal rebound. The total amount of postglacial rebound is unknown, as only the last 7000 to 8000 years are subject to measurement. Furthermore, the northwestern component of 3 feet per mile is not necessarily the maximum component of uplift.

Recent submergence.—Renewed submergence of at least 35 feet has followed the postglacial re-emergence. Evidence of this recent submergence consists of: (1) subaerially weathered sediments now submerged, (2) the well known "drowned forests" of coastal Maine and adjacent regions, and (3) tide-gauge records.

The following quotation is from an engineering report (Gray, 1954a, p. 1) on the problem of roadbed subsidence of U. S. Route 1 across the Dunstan River tidal marsh, 7 miles southwest of Portland. It illustrates the economic importance of a significant geologic feature—a weathered zone on the Presumpscot Formation now below sealevel.

> There exists over the greater part of the marsh a surficial layer of up to 20 feet in thickness which is composed essentially of organic material. This organic substratum does contain variable quantities of sand, but in spite of this it is very soft and unstable . . . Underlying the organic stratum in numerous localities is a layer of firm weathered silty clay. It is characterized by its consistency and frequently by a brownish color. At the southwest end of the section this clay appears at the ground surface. Elsewhere it is buried at depths varying from 10 to 20 or more feet. It appears to represent the weathered surface zone of a much thicker stratum [Presumpscot Formation] which was formerly exposed to atmospheric conditions . . .

Figure 3 (generalized from Gray, 1954b, pl. II) is a cross section constructed from highway borings 2.5 miles southeast of U. S. Route 1 on the Pine Point Road, across another branch of the Dunstan River marsh. Note that tidal-marsh peat has accumulated to a thickness of 15 feet. Moreover, stiff, mottled brown and gray clay, interpreted by highway engineers as a weathered zone on the Presumpscot Formation, extends 35 feet below the high-tide marsh surface. Thus, at some time subsequent to the deposition of the Presumpscot Formation, the Portland area must have been emerged at least

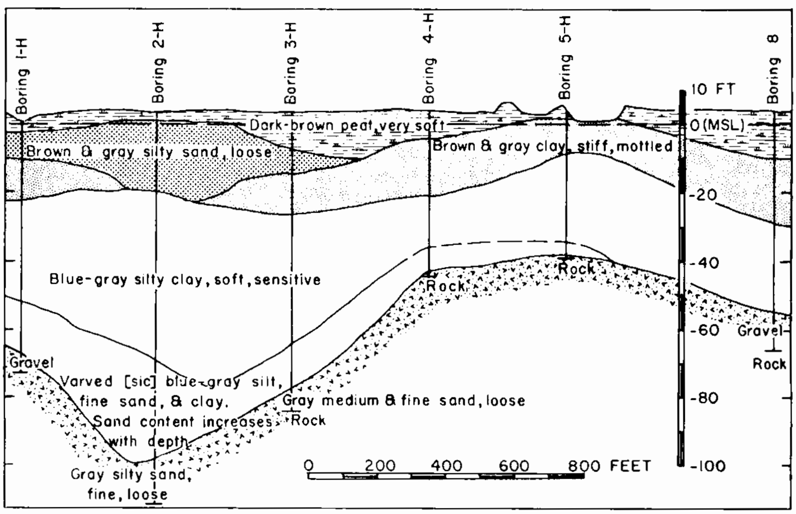

Fig. 3. Cross section of the Dunstan River tidal marsh, Scarboro, Maine, along Pine Point Road. Stiff, mottled brown and gray clay, interpreted by highway engineers as a weathered zone on the Presumpscot Formation, extends to 35 feet below high-tide marsh surface. Interbedded silt, sand, and clay in the buried valley is interpreted as marine-reworked glacial drift.

35 feet more than present, for it seems doubtful that the Presumpscot Formation could be discolored and partly cemented with oxidized iron in the reducing environment of a tidal marsh. The testhole logs of this section recorded an abrupt decrease in the number of blows required for a foot of penetration from 64 to 88 in "partly weathered firm brown and blue clay and silt" to 10 to 20 in the underlying blue-gray silty clay.

Additional evidence of recent submergence is to be found in radiocarbon dates from rooted tree stumps exposed on tidal flats or in the banks of tidal-marsh channels. The following list of radiocarbon-dated stumps gives the minimum amount of submergence indicated, on the assumption that all trees grew with their roots above the high-tide level.

W-396	2980 ± 180	Wells Marsh (2 to 3 ft)	(Hussey, 1959)
W-508	2810 ± 200	Wells Beach (6 ft)	(Hussey, 1959)
W-509	1280 ± 200	Kennebunk Beach West (10 to 13 ft)	(Hussey, 1959)
W-510	3250 ± 200	Kennebunk Beach East (7 to 13 ft)	(Hussey, 1959)
L-118	4150 ± 200	Sagadahoc Bay (9 ft)	(Bradley, 1953)
Y-156	4190 ± 70	Odiorne Point, N. H. (7.6 ft)	(Deevey, Gralenski, and Hoffren, 1959, p. 145)
Y-773	2970 ± 140	Blue Hill Bay (13.5 ft)	(Stuiver and Deevey, 1961, p. 127)

The dates show no consistent relationship of age and amount of submergence. Some of the stumps are rooted in peat that has been overridden and compacted by the landward retreat of a barrier beach; the amount of submergence indicated by such stumps is excessive. Nevertheless the total evidence of the stumps is for submergence, perhaps of different amounts at different localities, and perhaps proceeding at an irregular rate, during the last 4200 years. The maximum amount of submergence indicated by an intertidal stump, 13.5 feet at Blue Hill Bay, is less than half the amount indicated by the engineering data of marsh borings. However, lobstermen's tales of other stumps farther offshore suggest that the intertidal stumps are only the visible part of a more extensive occurrence.

Submergence has continued to the present decade on the Atlantic coast. Disney (1955) summarized tide-gauge records and concluded that submergence at a mean annual rate of 0.007 feet had been in progress at Portland since 1912, when the record began. The rate of submergence indicated at Portland by the tide-gauge record is only about half that indicated by tide gauges in other Atlantic Coast cities from Boston southward.

RELATIVE MOVEMENTS OF LAND AND SEALEVEL

A summary of the preceding description of late-glacial and postglacial events in southwestern Maine contains the following points of interest to the problem of relative movements of land and sealevel at Portland:

1. During deglaciation the area around Portland was emerged at least 70 feet greater than present, because stratified drift was deposited in valleys now that far below sealevel.

2. Submergence was in progress 12,100 years ago, with rapid marine transgression over a newly deglaciated landscape. The result was a transgressive wedge of glacial-marine, fine-grained sediment, the Presumpscot Formation. By 12,100 years ago Portland was submerged at least 60 feet greater than present.

3. Some time less than 11,800 years ago the maximum submergence took place. Late-glacial conditions still persisted along the inland edge of marine submergence. Sealevel at Portland was at least 160 feet higher than present relative to the land at the time of maximum submergence.

4. Postglacial re-emergence, accompanied by differential crustal upwarping toward the northwest, was in progress 7000 to 8000 years ago. Ponds now 140 and 250 feet above sealevel re-emerged then, and localities now at lower altitudes, including the Portland area, probably re-emerged late in this interval.

5. Postglacial re-emergence apparently continued until areas seaward of the present shoreline were emerged, producing a relative sealevel at least 35 feet lower than present in the vicinity of Portland. The weathered zone of the Presumpscot Formation below present sealevel and the submerged rooted stumps along the Maine coast are the record of this greater emergence. Radiocarbon-dated stumps suggest that the greater emergence dates back to at least 4200 years ago.

6. Since at least 4200 years ago, sealevel relative to the coast of Maine has been rising. Radiocarbon-dated stumps and tide-gauge records indicate that submergence has continued to the present decade.

A graphic model.—The time span of the events summarized above covers an interval when, according to widely accepted theory and substantial evidence, eustatic (worldwide) sealevel was rising rapidly. Sealevel during the maximum Wisconsin Glaciation was at least 300 feet below present, and deglaciation must have resulted in a rapid rise as water was returned to the sea. Several graphic interpretations of successive positions of sealevel during late Pleistocene time have been published (for example, Shepard, 1960; McFarlan, 1961; Fairbridge, 1961). The data supporting all these graphs are inadequate, and caution is invariably urged in their use. It is instructive, nevertheless, to apply the information on fluctuations of relative level in Maine to the various interpretations of glacial-eustatic sealevel.

In figure 4, the locus of a point now at mean sea level near the city of Portland, Maine has been plotted with respect to the sealevel curve proposed by Shepard (1960). Shepard's curve is based primarily on studies in the northwestern part of the Gulf of Mexico (Curray, 1960) an area considered to be tectonically stable. The curve is not in conflict with radiocarbon-dated sealevel positions reported from other areas, but it is not a "best fitted" curve through a collection of reference points from many areas. Maxima and minima on the curve are based on local stratigraphic and topographic evidence in the northwest Gulf of Mexico.

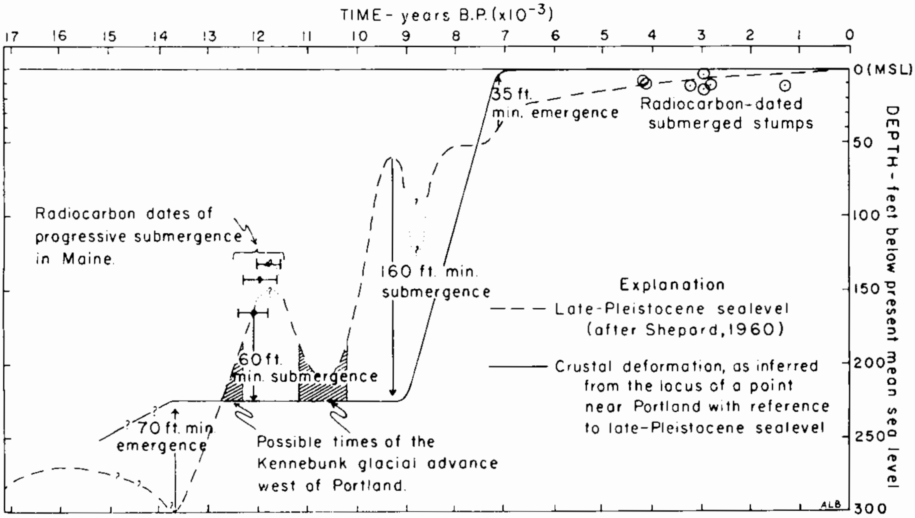

Fig. 4. Position of a reference point now at mean sea level near Portland, Maine, relative to late-Pleistocene sealevel as interpreted by Shepard. Arrows indicate the amount of emergence or submergence of the reference point at various times.

The major consideration in drawing figure 4 was to fit a curve of crustal deformation at Portland, Maine, to the curve of eustatic sealevel in such a way that at least 70 feet of late-glacial emergence and subsequently at least 160 feet of late-glacial submergence could be reasonably accounted for prior to 7000 to 8000 years ago. In other words, relative vertical displacement of coastal Maine and the sea amounted to a minimum of 230 feet in the late-glacial interval. Based on Shepard's curve, 70 feet of emergence a little less than 14,000 years ago and 160 feet of submergence a little more than 9000 years ago can be accounted for by drawing a horizontal line about 225 feet below present sealevel.

There is no evidence for the age of deglaciation in the Portland area. The 14,000 year date suggested in figure 4 is used only because 70 feet of emergence at that time does not require downwarping of the crust to account for a subsequent 160 feet of submergence. However, deglaciation 14,000 years ago is not inappropriate for the Portland area. Southern Connecticut was deglaciated more than 13,500 years ago, judging by radiocarbon ages of peat samples from near the bottom of bogs; similar evidence suggests that central Massachusetts was deglaciated an estimated 13,000 years ago (Deevey, 1958, p. 34-36.) A minimum age for deglaciation of the Portland area is 12,100 years, the radiocarbon age of marine shells from Cumberland Center (L-678).

A horizontal curve of crustal deformation fixed by the two points defined above is compatible with two other features of the late-Pleistocene history of Maine. First, the radiocarbon date of 12,100 years B.P. on shells from Cumberland Center has been shown in a previous part of this paper to represent at least 60 feet of submergence at Portland. Shepard's sealevel curve is almost exactly 60 feet above the curve of crustal deformation at 12,100 years B.P. The two other radiocarbon dates of the marine transgression in Maine also fall on a steeply ascending limb of Shepard's curve.

Second, there is evidence of a late advance of glacier ice 15 to 20 miles west of Portland that entered the sea (Bloom, 1959). Kennebunk, the type locality for this ice advance, was submerged about 40 feet at the time, because marine sediment now that far above sealevel was deformed by ice movement. Kennebunk is southwest of Portland and has probably been uplifted about the same amount by differential postglacial rebound. Thus at the time of the Kennebunk advance, Portland also would have been submerged about 40 feet. Shepard's sealevel curve lies less than 40 feet above the curve of crustal deformation at only three times on figure 4, and the youngest of these is in postglacial time. Therefore 12,300 to 12,800 and 10,200 to 11,200 years ago are the times of the Kennebunk advance permitted by the construction. Both sets of dates narrowly bracket times of significant ice readvances in the north-central United States, the earlier dates bracketing the Port Huron advance, and the later the Valders advance. The lesser age is more likely because of the evidence that late-glacial conditions persisted at the inland limit of marine transgression until the time of maximum submergence, which would have been about 9,300 years ago by the construction.

The suggested correlation of the Kennebunk advance in Maine with the Valders readvance in Wisconsin raises a larger question of significance to New England Pleistocene geology. If, as is now believed (Karrow, Clark, and Terasmae, 1961) the St. Lawrence lowland was ice-free during Valders time, then a Kennebunk advance of Valders age would have been from an independent ice cap over the White Mountains. Ice of the Kennebunk advance did indeed move over southwestern Maine from a northwesterly direction (the direction of the White Mountains) in contrast to the southward-moving ice sheet that covered the Portland area prior to marine submergence (fig. 1).

The fact that figure 4 permits an ice advance in Maine at times of known glacier expansion in central United States is permissive evidence for the validity of the construction. It is emphasized that this placement of the Kennebunk advance is not a basis for the construction of figure 4, but the result of the construction.

No evidence reported from Maine supports the fall of sealevel indicated by Shepard as culminating about 10,700 years ago. However, some visitors to a field conference in Maine (Friends of the Pleistocene, 1961) argued that the sand overlying highly fossiliferous Presumpscot Formation at the Dowdy Gravel Pit, near Cumberland Center (Bloom, 1961, p. 5) represents a regressive episode. Shells from that pit were subsequently radiocarbon dated as 12.100 years old (L-678, p. 866). Thus it is possible that a fall of sealevel coinciding with the Valders (= Kennebunk?) readvance produced a temporary marine regression in parts of coastal Maine that had already been submerged. Regional evidence for or against the hypothesized regressive episode has been destroyed or buried by subsequent more extensive submergence.

Southwestern Maine records little evidence of final re-emergence. Reemergence apparently began very shortly after the time of maximum submergence, for the erosional and depositional forms along the strandline of maximum submergence are few and poorly developed. Furthermore, re-emergence must have been caused primarily by crustal rebound, as evidenced by the differential upwarping described on a previous page.

The segment of the crustal deformation curve in figure 4 between 9300 and 7000 years ago is drawn as a straight line intersecting the sealevel curve at 7500 years B.P., midway in the thousand-year period of probable re-emergence. Between 9300 and 8000 years ago Shepard's curve, based on data from Curray (1960, p. 257) shows a substantial drop to a low stand of at least –90 feet (–15 fathoms) and possibly –126 feet (–21 fathoms). Curray (1960, p. 263) followed Fairbridge in attributing this temporary lowering of sealevel to the "Cochrane and Bothnian ice return". If sealevel fell only to –90 feet 8700 years ago, then by figure 4, from 9300 to about 7000 years ago re-emergence in Maine would have been continuous although at a variable rate. However, if sealevel reached the extreme low level of –126 feet suggested for this period by Curray, then from 8700 to about 8000 years ago crustal rebound in Maine and rise of sealevel would have been nearly synchronous, and a relative still-stand of the sea in Maine, about 75 to 90 feet above present sealevel, would have resulted. No strandline features from this altitude have been found in Maine. Therefore, on the basis of the model being considered, the evidence in Maine favors the higher alternative stand of the sea shown by Shepard at 8700 years B.P.

Re-emergence of the reference point about 7500 years ago permits adequate space above Shepard's curve for the 35 feet of greater-than-present emergence recorded by the buried submarsh weathered zone on the Presumpscot Formation. If crustal deformation ceased about 7000 years ago, and sealevel continued its slow rise to the present as interpreted by Shepard, then radiocarbon-dated submerged stumps ought to plot on figure 4 along Shepard's curve, with younger stumps showing progressively less submergence. That they do not raises the possibility of either minor fluctuations in one or both of the variables or, equally likely, differential post-depositional compaction of the submerged stumps. The substratum of only one of the stumps (W-396, Hussey, 1959) has escaped probable compaction by a migrating barrier beach. Some of the dated stumps may not be in place; there is considerable room for uncertainty concerning the validity of criteria used to demonstrate that stumps are in an undisturbed growth position. About all that can be said for submerged stumps is that they demonstrate submergence; how much and at what rate remain open questions.

In summary, the following points concerning figure 4 can be noted:

1. A simple curve of crustal rebound, horizontal between 14,000 and 9000 years ago, then rising 225 feet in about 2000 years (about 0.1 ft/yr.), then horizontal from 7000 years ago to the present, when superimposed on Shepard's curve of late-Pleistocene eustatic sealevel, accounts for all of the known late-glacial and postglacial relative fluctuations of land and sealevel in southwestern Maine.

2. Deglaciation of the Portland area by about 14,000 years ago is required by the construction.

3. The model permits the Kennebunk ice advance to have occurred at either of two favorable times. The younger of these times, correlative with the Valders advance in the north-central states, is favored because of the evidence that melting glacier ice persisted until the time of maximum submergence.

4. Re-emergence caused by rapid crustal uplift began immediately after regional deglaciation, and abruptly reversed the previous submergent trend.

5. The evidence of submergence during the last 4200 years and probably longer is accounted for by crustal stability and a eustatic rise of sealevel. Minor fluctuations in either variable could account for departures from the linear trend.

6. Crustal rebound near Portland of 225 feet could be caused by postglacial isostatic recovery from an ice sheet three times as thick, or about 675 feet. The latter value is too small by an order of magnitude for the total thickness of New England glacier ice, which is known to have covered Mt. Washington, with a height above the surrounding country of 5000 feet. However, the ice of the Kennebunk advance west of Portland was thin, and during deglaciation the Kennebunk ice must have ceased movement and melted in place when its thickness no longer exceeded the local relief of 1000 feet. Regional stagnation of Kennebunk ice over a zone at least 25 miles wide in southwestern Maine is indicated by the profusion of ice-contact stratified drift in the valleys. It is possible that the model shows only the rebound at Portland attributable to the removal of about 1000 feet of Kennebunk ice from a region 15 to 40 miles to the west, earlier rebound having accompanied deglaciation of the Portland area by 14,000 years ago.

Other possible models.—It is obvious that an infinite number of sets of intertwining curves can be drawn to explain the relative movements of land

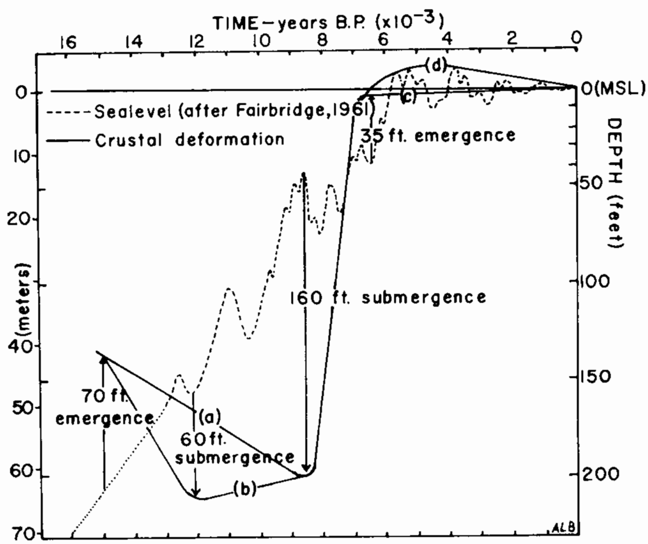

Fig. 5. Interrelation of land and sealevel near Portland, based on a curve of eustatic sealevel by Fairbridge. The data and method of construction are the same as used in figure 4.

and sealevel in Maine. Most of them would be unrelated to the meager data we possess concerning the absolute position of either variable with time. However, it is possible to use the data from Maine to test hypotheses of eustatic sealevel fluctuation. Figure 5 illustrates one such test, applied to a curve by Fairbridge (1961, p. 156). The method of construction and the data are the same as those used in figure 4.

Alternative constructions are made for parts of the crustal deformation curve in figure 5. Alternative (a) represents a straight line between an early episode of 70 feet of emergence at Portland and a subsequent episode of 160 feet of submergence. Even though these values are minimal, the construction requires a negative slope of the crustal deformation curve, indicating continued crustal downwarping until the time of maximum submergence, which has been shown to coincide with final regional deglaciation. The negative slope could only be eliminated by assuming an unreasonably early deglaciation of the Portland region. Furthermore, although alternative (a) would provide for progressive submergence during the 12,100 to 11,800 year interval dated by radiocarbon, the magnitude of the submergence would be far too small to reach the altitudes of any of the dated sites. Alternative (a) would date the advance of Kennebunk ice into the shallow transgressing sea at 11,300 to 13,000 years ago; while in terms of glacial chronology this is an admissable time range, it is hard to visualize how the thin ice of the advance could have persisted in the region for several thousand years until the time of maximum submergence. Furthermore, if the maximum advance of the Kennebunk ice were some 12,000 years old, and the ice subsequently lingered stagnant in the foothills, what force can be invoked to explain continued crustal subsidence during the entire late-glacial interval?

Alternative (b) is an attempt to remove some of the difficulties presented above. Specifically, the locus of the Portland reference point is set 60 feet below sealevel at 12,100 years B.P. in order to allow for submergence of the radiocarbon-dated sites to the north and at higher altitudes. This difficulty being removed, the shallow submergence correlated with the Kennebunk advance must be pushed still farther back to more than 13,000 years ago, and the problems of accounting for lingering ice cover and continued crustal subsidence during deglaciation become even more serious. The major criticism of Fairbridge's eustatic sealevel curve in this time range is that it does not have sufficient amplitude to account for the minimum estimate of 230 feet of relative movement in Maine without requiring an unexplained negative slope for the curve of crustal deformation.

Re-emergence between 7,000 and 8,000 years B.P. is easily shown by a curve of crustal rebound intersecting Fairbridge's eustatic sealevel curve at the appropriate time. The 35 feet of emergence greater than present and subsequent submergence can be accounted for by hypothesizing either (alternative c) crustal stability during the last 6800 years or (alternative d) overcompensated glacial rebound and subsequent crustal subsidence. Alternative (c) would predict numerous emerged shoreline features along the Maine coast correlated with the remarkably detailed fluctuations Fairbridge described for this interval.

No emerged marine features of this young age have been found. Therefore, alternative (c) seems highly unlikely.

The lack of emerged shoreline features can be accounted for by arching the curve of crustal rebound over Fairbridge's emergent peaks. A curve of this shape recalls the now discredited idea of marginal superelevation, but it could be explained by hypothesizing crustal subsidence not related to glacial isostasy superimposed on the curve of postglacial recovery. However, the magnitude and rate of the submergence seem excessive for a non-glacial tectonic phenomena, when one considers the geologic terrane involved.

Another construction is attempted in figure 6. As a basis for this model, a eustatic sealevel curve published by McFarlan (1961, p. 145) is used. McFarlan drew two curves, (1) a mean based on all plotted sealevel positions in the Mississippi delta region, many of which were corrected for structural movement, and (2) a curve based on the fewer points provided by "hingeline" samples that required no structural adjustment. The hinge-line curve is used here because the mean curve does not have sufficient amplitude to accommodate 230 feet of relative movement in Maine prior to 7000 to 8000 years ago. Broecker (1961, p. 160) in discussing McFarlan's data, also preferred the hinge-line curve in spite of the fact that it is based on fewer points and cannot be expected to show much detail.

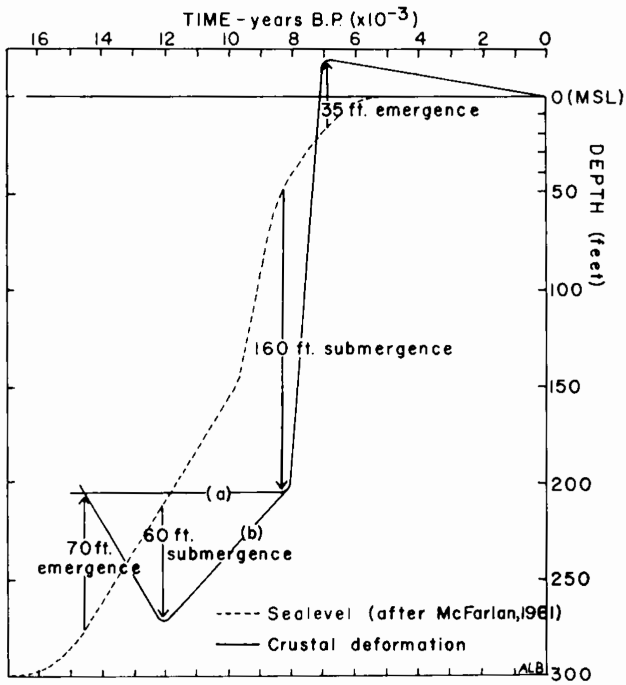

Fig. 6. Interrelation of land and sealevel near Portland, based on a curve of eustatic sealevel by McFarlan. The data and method of construction are the same as used in figure 4.

It is possible to draw in figure 6 a line of crustal deformation that does not have a negative slope between 14,000 and 9000 years ago. Alternative interpretation (a) shows that line, 70 feet above sealevel 14,600 or more years ago and 160 feet below sealevel about 8400 years ago. By this construction the sealevel reference point at Portland would not have been submerged until less than 12,000 years ago, whereas radiocarbon dates show submergence in progress to much higher altitudes by that time. Therefore, even though the interpretation would date the Kennebunk advance into the shallow sea at a reasonable time of about 10,000 to 12,000 years ago, the construction must be rejected as not satisfying the known facts. Alternative curve (b) provides for the submergence indicated by radiocarbon dates about 12,000 years ago, but requires either excessively early deglaciation at Portland, or an unexplained crustal downwarping during the time of deglaciation.

Re-emergence of the Portland area 7000 to 8000 years ago, 35 feet of emergence greater than present, and subsequent slow submergence are illustrated as in the preceding models. McFarlan's curve requires postglacial rebound to superelevate the reference point. However, McFarlan noted in an addendum (1961, p. 148) new evidence that suggests sealevel rose from 17 feet below its present level 5650 years ago to its present level about 3000 years ago. If his curve of eustatic sealevel based on hinge-line samples were to be revised in accordance with this new evidence, no postglacial crustal superelevation and subsequent downwarping would be required to account for relative changes of sealevel in Maine during the last 6000 to 7000 years.

CONCLUSIONS

A method of using relative changes of land and sealevel in a glaciated region to test the validity of various interpretations of postglacial eustatic fluctuations of sealevel is demonstrated. A simple curve of postglacial isostatic rebound in southwestern Maine, compatible with the time of deglaciation and estimated ice thickness, is superimposed on the curve of late-Pleistocene eustatic rise of sealevel proposed by Shepard. The result provides a remarkably complete explanation of late-Pleistocene events in southwestern Maine, restricts the possible times of an otherwise undated glacier advance, and accounts for all known relative changes of level.

Two other models are constructed to illustrate the method of analysis, but neither of them can be made to fit the observed facts. Although only one of three models is found acceptable, this is not to imply that it is the ultimate solution. Data from mobile areas, especially glaciated regions where a late-Pleistocene chronology can be established, can be useful in studying the difficult problem of glacial-eustatic sealevel fluctuations.

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