

LATE GLACIAL MARINE LIMIT IN MASSACHUSETTS.

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INTRODUCTION.

The late-Quaternary changes of the shore line in Massachusetts, the southeastern corner of the glaciated area in North America, have been studied and debated for eighty years. Yet, such a fundamental question as the altitude of the late-glacial marine limit, the highest elevated shore line, is not settled. Thus, according to Fairchild (1919, Fig. 2, p. 616), the marine limit rises rather evenly from an altitude of 100 feet at Nantucket to that of 400 feet just south of the New Hampshire border; while, according to Goldthwait (1922, 1924, Fig. 17, p. 150), it ascends from sea level at a point on the coast some twenty miles southeast of Boston to 50 feet just south of Cape Ann and 100 feet on the New Hampshire line.¹ The position of Goldthwait's zero-isobase is not determined by observation, but by extrapolation. The former view is founded on numerous observations by Fairchild (1919, 1925). The latter view is largely based on the conditions on Cape Ann described by Tarr and Woodworth (1903) and on Goldthwait's (1925) thorough studies in New Hampshire, and is supported by the investigations of the marine limit in Maine, and of the distribution of varved clay in New England carried out by Antevs (1922, 1928, 1928a) and by R. W. Sayles. The

¹ Several different opinions on the marine limit in New England and adjacent regions are quoted by De Geer, 1892, pp. 462-463.

observations presented on the following pages also confirm the view of Goldthwait and others.

Determination of the marine limit is necessary for a profit-

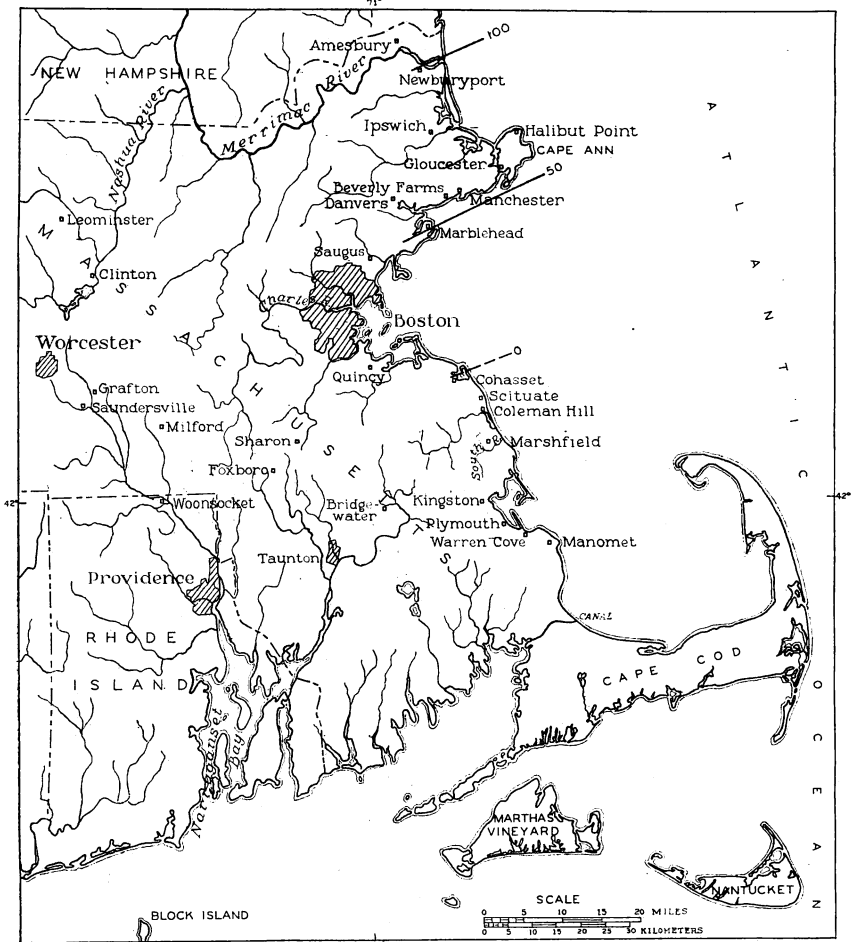


Fig. 1. Map showing localities discussed, and approximate isobases.

able discussion of the Quaternary changes of level which are so important a part of the late-Quaternary history, and also furnish data for an interpretation of the physical state of the earth.

The present study was undertaken at the suggestion of Dr. Ernst Antevs, who has also given much good advice, participated in some field trips, and helped in the preparation of the manuscript. The work, which was made possible by scholarships from the Sverige-Amerika Stiftelsen in Stockholm and the University of Uppsala, has also been facilitated by the kind hospitality of the Division of Geology at Harvard University and by the helpful interest of Professor R. A. Daly, Professor Kirk Bryan, Mr. Robert W. Sayles, and Professor J. W. Goldthwait.

PREVIOUS DETERMINATIONS OF THE MARINE LIMIT.

Here are summarized only such previous determinations as refer to what, in the opinion of the writer, is the real marine limit. Observations formerly supposed to indicate higher altitudes of the marine limit will be discussed in a later section.

Tarr (1903) found undisputable evidence that the sea has covered the coastal region of Cape Ann up to an elevation of at least 40 to 60 feet above sea level. A very distinct beach (B on Tarr's map, 1903, Pl. 1) on Eastern Point at Gloucester has a maximum altitude of 41 feet, but it "reaches . . . some low rocky hills which have the appearance of having been stripped of their drift cover." The altitude of the base of the hills is from 42 to 47 feet (l.c., p. 187). Other beaches on Eastern Point were found to have an elevation of 50 feet and 52 feet. A delta northeast of Gloucester (F on Tarr's map) stands at about 50 feet (l.c., p. 184). Tarr was undecided whether the shore line stood higher than indicated by beaches and deltas, though bare rocks and boulders seemed to him to suggest that this was the case. Bare ledges are described as frequent at altitudes from 40 to 90 feet.

Woodworth (1903), with an aneroid, determined the height of a beach at Whale Cove, east of Rockport, at about 65 feet. This was the highest beach known to him on Cape Ann. However, a nearby bar, as determined by aneroid readings and hand-level determinations, rose to an altitude of 77 to 78 feet (l.c., p. 193). Farther south, weak gravel bars, stretching amid rock knobs, are stated to occur at about the 90-foot level (l.c., p. 193). Between the rocky cliffs all along the shore, from an altitude of 80 or 90 feet downward, there is sand overlaid by rubble (l.c., p. 192). On Pigeon Hill, a drumlin about a mile north of Rockport, no signs of wave action were

found by Woodworth above the 100-foot contour. Thus, Woodworth seems inclined to put the marine limit on Cape Ann at about 90 feet. This figure may be somewhat too high as suggested in the following paragraphs.

FIELD STUDIES BY THE PRESENT WRITER.

Shore Phenomena Due To Erosion.

(1) *Halibut Point, North end of Cape Ann (Gloucester quadrangle).* The top of the gently sloping, rocky hill, forming the northern end of Cape Ann has a thin and incomplete mantle of typical till. Under even a thin cover of till the rock still shows glacial striation. The lower hillsides, on the other hand, entirely lack a till cover. The only soil here consists of a small quantity of loose rock fragments formed by post-glacial disintegration of the underlying granite on which all finer glacial pattern has been destroyed. Without doubt, also these lower slopes were once covered by till, which had been washed away by the waves. But the waves cannot have reached the highest parts of the hill, for then the thin and loose till cover would necessarily also have been removed. The slightly indefinite lower limit of the till cap was found by spirit-leveling to lie about 70 to 75 feet above present sea level.

(2) *Half a mile south-southwest of Gap Head, Cape Ann (Gloucester quadrangle).* On the northern slope of the hill at the road curve shown on the topographic map, there is a faint bench in the till at an altitude of some 55 to 60 feet.² It is probably wave-cut. North of this terrace is a small rock knob, marked on the topographic map by a small ring of the 80 feet contour, though in fact it seems to lie slightly lower than the bench. The top of the knob is free from loose material, as if washed clean by waves. On the lee side are accumulations of cobbles and pebbles without fine material. Though hardly rounded at all, the pebbles seem to be rearranged by the waves.

Features that may represent wave-cut benches, although they seem less convincing, were found at corresponding elevations on Pigeon Hill, at Magnolia (Gloucester sheet) and at other places.

² Where not otherwise stated, the determinations of altitude have been made by an aneroid barometer, or by hand leveling; datum: mean sea-level. No reduction has been made for the height of the different shore features above the mean water level at time of their formation.

Shore Phenomena Due to Accumulation by Waves.

The marine limit is also registered by beaches formed by the accumulative work of the waves. The ancient beaches on Cape Ann, described by Tarr and Woodworth (1903), have already been referred to. As known from Goldthwait's studies (1925), there are numerous well developed beaches at the marine limit in adjacent New Hampshire. A thorough search between Cape Ann and the New Hampshire border would probably reveal several beaches at the highest late-glacial shore. On the rocky coast between Gloucester and Boston the conditions as a rule were not favorable for formation of beaches or sand bars and only a few have been observed.

(1) *Amesbury (Newburyport quadrangle)*. Monday Hill is connected with its neighbor hill in the south by a ridge of sand and gravel, as called to my attention by Professor Goldthwait. Part of the superficial material in the ridge may have been thrown up by waves. The elevation has not been determined by the writer, but the topographic map indicates 80 to 100 feet.

(2) *Marblehead Neck (Boston Bay quadrangle)*. Where, near the southeastern corner of the neck, the road curves towards the southwest, it follows an old beach for several hundred feet. The beach has an altitude of slightly over 40 feet.

(3) *Saugus (Boston quadrangle)*. At the southern foot of Baker Hill, near the old race track, water-laid cobbly gravel probably represents a shore formation. The comparatively level highest parts of its surface reach 45 to 50 feet above sea level.

No Raised Shore Features South of Boston.

South of Boston no traces of ancient wave action above the present shore were observed by the writer. Part of the region is not very favorable for the development and preservation of shore features, but there are parts that are decidedly so. The modern shore features of the region are strongly developed in unconsolidated material. Topography and material are such as to insure similar development of shore features at a higher shore line.

When, therefore, on Mann Hill in Scituate (Abington quadrangle), the loose till above the modern shore line shows no influence of waves, it seems evident that the shore has never

stood higher since the formation of the till. Only at Musquashiat Pond were shore features developed before the spot became protected by the formation of the existing large bay-bar, now damming the pond. These older shore phenomena, though, lie at practically the same altitude as the modern beaches. Also on adjacent seaward-facing slopes, from Hope Pool Hill (Abington quadrangle) to the region of Scituate Harbor raised shore lines were sought in vain.

Deltas and Sand Plains Formed in the Sea.

An ancient water level may be registered not only by erosion and accumulation by the waves, but also by its control of the top surface of deltas formed by inflowing rivers and brooks. Some of the deltas formed when the sea lay at the marine limit have been visited.

(1) *Amesbury (Newburyport quadrangle)*. At the southwestern end of the hill just east of Amesbury there is a fairly well developed sand plain occupied by a cemetery. The elevation of the plain corresponding to the ancient sea level is about 110 feet. Also west of Powow River is a similar plain on the hillside. Both deposits are glacio-fluvial wash plains. On the south side of Merrimac River, southwest of Amesbury, and probably also between Merrimac and Amesbury, there seem to be several similar sand plains at about the same elevation, though the writer has not had an opportunity to study them.

(2) *Newburyport (Newburyport quadrangle)*. The glacio-fluvial deposits in the southern part of the city of Newburyport have an irregular topography with knobs and kettles. Some higher portions at an altitude of nearly 100 feet, for instance, that are occupied by the cemetery between the main railroad and the turnpike, are comparatively flat, but it seems doubtful whether they were completely built up to the level of the sea.

(3) *Ipswich (Salem quadrangle)*. On the northeast side of the road, a mile south of Heartbreak Hill in Ipswich, there is a small glacio-fluvial delta at an altitude of about 70 to 75 feet.

(4) *Gloucester (Gloucester quadrangle)*. In Stage Fort Park southwest of Gloucester, 700 yards southwest of the highway bridge there is a small glacio-fluvial delta with depressions due to melting of buried ice. The top of the delta lies at about 60 feet. On the road from Gloucester to Rockport there is another delta of better development at an altitude of about 50 feet (Tarr, 1903, p. 184).

(5) *Manchester-by-the-Sea (Salem quadrangle)*. In the northern part of the village there is a small delta with a level surface. According to information kindly furnished by Mr. Reynold C. Allen of Manchester, the elevation as determined by spirit leveling is 50 to 55 feet.

(6) *Beverly Farms (Salem quadrangle)*. In the village of Beverly Farms there are on both sides of the brook sand terraces representing deltas. On the west side the surface reaches an altitude of 45 to 50 feet.

(7) *North Beverly (Salem quadrangle)*. A somewhat undulating sedimentary plain south of Wenham Lake, and at an approximate elevation of 50 feet, possibly corresponds to the highest shore line.

(8) *Danvers (Salem quadrangle)*. North of Beaver Brook, at the cemetery a mile northwest of the old railroad junction, there is a tiny sand terrace that is probably part of a diminutive delta. It has an altitude according to the map of about 60 feet.

(9) *Saugus (Boston quadrangle)*. Lily's Pond in Saugus—on the map called Prankers Pond—is towards the south dammed by outwash, which reaches an altitude of about 50 feet. Many similar features may be found in the coastal region north of Boston.

Plains in Greater Boston Possibly Marking the Late Glacial Sea Level.

Most of the wash plains described above have a position open to the sea. No higher glacio-fluvial deposits were found in analogous positions in the same region. The fact that the elevation of the deltas corresponds to that of the highest shore features due to wave action, shows that the sea was the controlling water body.

In the Boston region the possibilities for isolation of lakes at the time of the ice recession were greater; and several sand plains in the southern and southwestern parts of Greater Boston were built up in ice-dammed lakes (Crosby and Grabau 1896; Grabau 1900; Clapp 1901, 1904; Crosby 1903). However some deposits in the area may have been formed in the sea.

(1) *Arlington*. The part of the town that lies south of Mystic Lakes stands on outwash the surface of which is mostly at an altitude of 20 to 40 feet. At the very end of the lake the

gravel rises to slightly over 40 feet. The terrain here is not level and no old water level is distinctly registered in the topography.

(2) *West Medford.* East of the southern Mystic Lake the conditions are similar to those at Arlington. The surface of the outwash is as a rule not quite even, especially so above the elevation of the 40-foot contour.

(3) *Cambridge.* The sedimentary plains in the city of Cambridge have been so much changed by man that it is not possible to get a satisfactory idea of the original conditions. Their surfaces are mostly found between the contour lines of 20 to 40 feet above sea level.

According to oral information from Mr. R. W. Sayles, varved clay was found in the excavation for the new Chemical building of Harvard University on Oxford Street. There were only about 20 varves; and their thickness showed that the mouth of the glacial river was quite near when the clay was deposited. Varves are best formed in fresh water; but they may also be developed in slightly brackish water, as in the sea in the immediate vicinity of a glacial river. On the whole the clays in Cambridge seem to lack varves. The sediments in Cambridge, Medford, and Arlington may have been formed in a bay of the sea. (Cf. Woodworth, 1897, p. 103.) The sand and gravel deposits on Mystic Lakes possibly correspond to a marine limit at an altitude of about 40 feet.

Probably Supramarine Sediments South of Boston.

Localities Discussed.

(1) *Quincy-Hingham.* Even the deltas formed in the ice-dammed lakes south of Boston give some indirect information regarding the late-glacial sea level. Since the lake surfaces could not be lower than the contemporaneous sea, the lowest water levels of these lakes give a maximum possible height of the synchronous marine shore line. The lowest level of glacial Lake Bouvé registered by glacio-fluvial deltas is, according to Grabau (1900), about 25 feet above the present sea surface. Even if the deltas in Weymouth are not sufficiently well developed and even-topped to prove fully a water level at 25 feet, the water level at 40 feet elevation seems well established by the accordant surfaces of the "Quincy plains." Therefore the sea level synchronous with Lake Bouvé was lower than the present 40 feet altitude.

(2) *Cohasset (Abington quadrangle)*. The village of Cohasset is in part built on glacio-fluvial sand and gravel deposits. The surface is uneven, but presents small, fairly flat areas at an altitude of about 30 feet. Half a mile west of the village square, on the south side of the road, there is a gravel pit showing gravel with some sand. The structure of the deposits, which at the time of visit was visible only on a few small spots, showed nearly horizontal stratification, even in the deeper part of the cut. The characteristic fore-set structure of a sub-aquatic delta was not observed. It is therefore uncertain whether the Cohasset sand and gravel was deposited in a water body or on land. If there was a water body, it must have been either the sea or a lake that was dammed up by ice remnants, which perhaps lay in Cohasset Cove and The Gulf. The till slopes between and Cohasset and Scituate harbor, though exposed to the sea, do not show any traces of wave action. The sea seems in post-glacial time never to have extended higher on the land than it does now.

(3) *Coleman Hill (Duxbury quadrangle)*. Coleman Hill, a mile south of Scituate village, consists of sand and gravel. The interior structure of the deposit is exposed in a huge pit. The eastern part of the large cut shows an upper horizontal bed of coarse material, there under steeply inclined fore-set beds, and at the base gently sloping strata. In the central part of the southern wall the dip of the beds is southward and gentle, being mostly about 10° . A cut near Greenbush station showed a very fine silty sand. The structure of Coleman Hill suggests that it was formed in water; and the fairly equal elevation of the highest parts as well as the typical topset bed seem to indicate that the ancient water surface stood at a level of about 100 to 110 feet above the present shore line.

(4) *Marshfield (Abington and Duxbury quadrangles)*. In the hilly region of Marshfield, between North River and South River, there occur sand and finer-grained sediments and, in places, gravel also. The bulk of the sediments stand below the hundred foot level. At the east-west road, three-quarters of a mile from Littleton, mo, or a very fine sand, is found at least as high as an elevation of 150 feet. It is here covered by till. Also at some other localities till was found on top of sand. Two and a half miles south-southeast of the Marshfield-Norwell bridge, and a mile east of North River, at an elevation of a little more than a hundred feet, a small clay pit shows a distinctly varved clay with about 50 varves, mostly from one-

third inch to one inch thick. The varves, apparently formed in fresh water, are much distorted either by land slides, or more probably by overriding by the ice. Although this clay must have been deposited in a lake, no abandoned shore features were observed among the hills and "Highlands of Marshfield."

(5) *South River region, Marshfield and Duxbury (Abington and Duxbury quadrangles).* A considerable area around South River consists of kames and undulating or nearly level sand deposits. As a rule the kames and the undulating areas do not reach the 100-foot contour.

One and a half to two miles southwest of Marshfield Center station, a sand-plain, with a partly level surface, rises to an altitude of about 100 feet. South of South River at the village of Marshfield there is a partly level wash plain reaching an altitude of 100 feet or slightly higher. A small sand pit in the northern or proximal end, near the Marshfield village bridge, showed the following profile:

Topmost, till	6-10 feet
Waterlaid sand containing scattered cobbles and some gravel. Strata dipping towards the south, occasionally as much as 25° in places	25 feet
Bottom concealed.	

To the south this plain gradually changes into a gently undulating sand region at a lower elevation. Just east of North Duxbury a hillock rises gently to the 100-foot contour, but without forming a level surface. The material seems here to be partly till and partly outwash, and may represent a poorly developed moraine. Between half a mile and a mile south of North Duxbury there is another small sand plain attaining an altitude of about 100 feet. A pit at the northern end shows gravelly sand. One to two miles northwest of Island Creek station there is a large sand plain which is fairly level, in contrast with the very irregular kame area farther south.

None of the sand plains in the South River region shows fully typical topographic features of a sub-aquatic delta. No characteristic distal slope was seen. On the other hand nothing was observed to indicate that the sand plains were formed on land. The few cuts did not give information enough to settle the question.

The rough correspondence of the elevations of the upper surfaces of the sand plains might suggest that they were controlled by a water level at about 100 feet. Very likely water

bodies were dammed and in places nearly surrounded by remnants of the disintegrating ice. Kame areas and pitted plains testify that the ice sheet became highly dissected, and lend plausibility to this explanation.

(6) *Region of Kingston, Plymouth, and Warren Cove (Plymouth quadrangle).* In this region with complex kames and moraines no indication of any general water level was found. The lack of regularity in the altitude of the sand deposits is striking. Evidently, the ice border was much disintegrated and most of the sediments were deposited between lobes or blocks of ice, or between the ice and elevations of the ground. Here temporary fresh water lakes were formed, as shown by the distinctly varved sediments, exposed in the present sea cliffs on the southern shore of Warren Cove, especially at the Pilgrim Hotel and at the Plymouth Country Club. The ice-dammed lake may here have been almost filled with sediments, as the material grows coarser upwards, grading from clay into gravelly sand.

(7) *Manomet (Plymouth quadrangle).* The topography of some of the sand deposit near the village of Manomet is comparatively simple, and might suggest uncomplicated conditions of formations in a water body. However, the present wave-cut cliff on Cape Cod Bay, which is 60 to 80 feet high, presents a complex interior structure. The sand and gravel, forming the topmost parts of the deposit, is of varying thickness, but averages about 30 to 40 feet. The stratification is mostly flat, varying somewhat in direction and inclination, and does not resemble that of a subaqueous delta. Beneath the covering sand are beds and large lenses of clay, sand, and mo in alternation. The lower strata are at several places disturbed, mostly, no doubt, from overriding by the ice. The upper layers of some clay beds are locally folded, and sand and gravel are kneaded into them. Some till also occurs. Probably only part of the Manomet deposits were formed during the withdrawal of the last ice. The core, like certain other glacial deposits in southeastern Massachusetts, may be older.

(8) *Cape Cod and adjacent regions.* During my reconnaissance in southeastern Massachusetts no indications of a general elevated water level have been observed. It should be remembered, however, that the search for abandoned shore features in broad areas of this region is rendered difficult by the dense growth of bushes.

Extensive sand plains of Cape Cod are very level indeed, and call to mind the surfaces of subaquatic deltas. Essential

characteristics of these latter are, however, lacking. Seen as a whole the sandy plains of Cape Cod resemble more closely Iceland's Sandr and Jutland's Hedesletter, flat sand deposits formed on land by rivers issuing from under the ice.

Some of the valleys occurring in the wash plains must date from the time when the glacial streams poured their water over the sand. As many of these valleys are now drowned, they indicate a rise of the shore line since their formation. This feature is well illustrated by the U. S. Geological Survey's topographical map of Nantucket, Martha's Vineyard, and the southern shore of Cape Cod. (See also Relief Map of Nantucket, Wilson, 1906, Pl. I.)

Summary of the Conditions South of Boston.

The undisturbed till at Mann Hill, 20 miles southeast of central Boston, seems to indicate that the sea level in post-Wisconsin time never stood higher in relation to the land than it does now. The lack of raised shore features between Cohasset and Coleman Hill, Scituate, supports this view. Coleman Hill, 16 miles north of Plymouth, seems to have been formed in a water body whose surface coincided with the present 100 or 110-foot contour. Some sand plains near South River may indicate water levels at about the same elevation. South of Kingston and Plymouth no elevated shore features were observed.

The water body indicated by Coleman Hill, and those possibly indicated by the South River plains cannot very well have been the sea, for the conditions south of and immediately north of the localities indicate that, after the withdrawal of the ice, the marine shore line has not stood higher than it does now. The ancient waters that may have existed around Coleman Hill and South River thus seem to have been local lakes. They must, then, have been dammed up by ice remnants, though it is difficult to visualize how this could take place.

There may be a slight possibility that exceptional tilt, due to bulging up of the marginal belt of the ice cap, caused a ponding of a glacial lake in Cape Cod Bay, in front of an ice barrier in the north, to such a height that the crest of Coleman Hill and possibly the sand plains near the South River correspond to its surface. However, such an explanation seems unlikely, and no observations in favor of it were made.

Supposed Shore Features Above the Marine Limit.

Thus, as touched upon in the introduction, the results arrived at in the present study on the marine limit in Massachusetts confirm the opinions of Tarr, Woodworth, Goldthwait, Sayles, Antevs, and others. They contradict Fairchild's view of extensive submergence in late glacial times.

But what is then the explanation of the various phenomena at higher levels, held by Fairchild to be of marine origin? The present writer has visited, partly in the company of Dr. Antevs, most of Fairchild's localities on the mainland of Massachusetts and attempts to answer this question will be made in the following section.

"Summit deltas" and "summit-level sand plains" of Fairchild. Some formations described under these headings appear simply to be more or less irregular outwash deposits lacking essential characteristics of subaquatic deltas. Thus the so-called delta on Mill River, west of Milford (Blackstone quadrangle) (Fairchild, 1919, p. 606), consists (northwest of Hopedale) of an uneven deposit, a few feet thick, largely of coarse gravel resting on bed-rock. On West River northwest of West Upton (Blackstone quadrangle) (Fairchild, l.c., p. 606), only hummocks of outwash and a typical, though minute, esker were found.

The supposedly marine deltas and other deposits at Clinton in the Nashua valleys, as pointed out by W. O. Crosby (1899, 1903-04) and Alden (1924, pp. 60-73), were formed in a well-defined, ice-dammed lake, Glacial Lake Nashua. The distinct varvity of the clay of the lower plains (Alden, 1924, Pl. XX B) shows that the sea did not enter the valley. Also the Leominster sand plains (Fairchild, l.c., pp. 606, 620) were formed in Glacial Lake Nashua though outside the area mapped by Alden. Similarly the sand plain of Woonsocket, Rhode Island (Burillsville quadrangle) (Fairchild, l.c., pp. 607, 627), was formed in a small ice-dammed lake in the Cherry Brook valley. The deposit is a fine, level wash-plain with steep ice-contact slope and a typical delta structure. A sand pit shows a gravelly top-set bed, 6 feet thick, underlain by a sandy fore-set bed with a southward slope.

The formation during the ice retreat of temporary lakes in drainage systems that slope towards the ice border, that is, in the region here discussed towards the north, is a simple and well known phenomenon. The formation of lakes in areas now drained southward may appear less natural. Yet the

existence of lake sediments in valleys sloping to the south indicates many lakes of this kind. The lakes may have been caused by greater depression of the northern part of the areas compared with the southern part, which because of the progress of early, probably mostly elastic uplift after the removal of the ice (Daly, 1925) may have risen sooner. Such a lake existed in the Narragansett Bay inside a barrier on the line Montauk Point-Block Island-Martha's Vineyard. Its shore, according to R. W. Sayles (Antevs, 1928, p. 84), rises from the modern sea level near the mouth of the bay to about 120 feet at Providence. In this very lake the deposits of gravel and sand at Saundersville (Blackstone quadrangle), considered by Fairchild (p. 606, 622-623) to be marine deltas of Blackstone and Quinsigamond Rivers, may have been formed. The glacio-fluvial delta on the southeastern shore of Goddard Pond, and about half a mile northwest of Grafton, seems to correspond, at least roughly, to this old water level. The delta shows in an exposure a gravelly topset bed, 6 to 10 feet thick, underlain by southwardly dipping strata.

However, northward inclination of the earth's surface was probably not the sole cause of damming of temporary water bodies in valleys now sloping away from the then ice cap. The ponding may in some instances have been due to ice remnants, moraines, or sediments.

"Water-laid deposits facing the sea." At Manomet Hill (Plymouth quadrangle), considered by Fairchild (l.c., p. 608) as a critical locality, a broad gravel plain at an elevation of about 230 feet should indicate the ancient sea level. However, as far as could be seen in good fresh road cuts, the material is a very sandy and gravelly till, possibly derived from over-ridden outwash. No shore features or change in the nature of the material were observed at the 230-foot level; in fact, no shore features were noticed on any part of the hill seen by the writer.

"Sand-plains of inferior level." Some sand-plains below Fairchild's supposed marine limit, but above the marine limit as held in this paper, have been described as glacio-fluvial deltas, deposited in ice-dammed lakes (Grabau, 1900; Clapp, 1901, 1904; Crosby, 1903; Fuller, 1904; Goldthwait, 1905). In many cases it is so evident that the deposits are deltas, built up to a water level, that further discussion is superfluous. This holds, for instance, for the Newtonville sand plain (Gulliver, 1893). Even if the shape of several deltas were not so well developed and preserved as to exclude all doubt regarding

the origin of the plains, and even if we did not have the cuts now exposing the characteristic delta structure (for instance, west of Braintree, and half a mile southeast of South Braintree), it would hardly be possible to explain the plain surface by the leveling effect of waves (cf. Fairchild, l.c., pp. 609-610). In many cases, also, erosive action by waves would have been prevented by breakwaters protecting these areas. The Newtonville plain and one near Blue Hill, for instance, would not have been sufficiently exposed to wave work to have been leveled even if the sea had reached over them.

Water-laid clays. A supposed evidence for a much higher marine limit than that advocated in this paper is the occurrence of water-laid clays (Fairchild, l.c., p. 611). However, several of the clay deposits in the coastal region of southern Massachusetts are probably older than the retreat of the last ice sheet, as held by Marbut and Woodworth (in Shaler, Woodworth, and Marbut, 1896, pp. 994-995), Fuller (1906, 1914, p. 219 ff) and others (see also Clapp, 1908). Furthermore, many of the late-glacial clays of Massachusetts and Rhode Island are typical fresh-water deposits. The clays in open situation on the Narragansett Bay are distinctly varved and were deposited in a glacial lake formed because of northward inclination of the earth's surface as compared with the modern stand (Antevs, 1928, p. 84). And the clays in the interior, as for instance those at Taunton, Bridgewater, and Marshfield, are also varved and were deposited in temporary lakes.

Unexplained Features.

Several of the features used as arguments for a higher marine limit than that advocated in this paper are thus clearly non-marine. South of Boston, however, some questions relating to the existence of ancient water bodies and some problems of sedimentation on land still remain unsolved. The difficulties in explaining the conditions of formations of the great moraines and accompanying glacio-fluvial deposits on Cape Cod and in the Plymouth regions, etc., have already been touched upon. The mode of formation evidently is very complicated, involving repeated oscillations of the ice border and perhaps even different glaciations.

Other unexplained features are the Sharon-Foxboro washplains (Dedham and Franklin quadrangles), considered by Fairchild (1919, p. 623-624) as good indications of a late gla-

cial submergence of about 300 feet. That the plains are not marine may, however, be safely concluded from the observations in adjacent areas, treated above. If, in late Wisconsin time, the sea did not reach the elevation of 300 feet, the glacio-fluvial plains may either have been formed on land, as promorainal sand-plains of southern Cape Cod, Martha's Vineyard, and Nantucket are thought to be, or else they may have been formed in a temporary lake. The topography does not give a definite answer as to which explanation is correct. The surface is in some places almost horizontal and in others somewhat undulating. No sure or characteristically distal slope was found. The stratification was not sufficiently exposed to give the solution, the fresh cuts observed being all superficial. The observed strata were flat or almost horizontal and may represent topset beds. Only in a minute exposure in the large abandoned gravel pit on the west side of the railroad north of Sharon heights were seen more inclined layers, dipping 15° to 20° east-southeast or southeast. Northwest of Foxboro, southwest of the bay of Neponset Reservoir, and west of the railroad are small cuts in fine silty sand with a somewhat wavy stratification. The material is slightly consolidated. In the sand there are some boulders suggesting the existence of a late-glacial water body deep enough to allow ice-rafting.

If the Foxboro-Sharon plains were formed in a lake, the damming of this water body at the south is difficult to explain; for the slope from the region towards the south is so steep that it cannot very well have been surpassed by the greater late-glacial depression in the north.³ On the other hand as the region is very open towards the south, ponding by ice remnants seems very improbable.

When the difficulties in explaining some deposits are here pointed out, it should also be mentioned that even Fairchild's extremely high marine limit fails to explain some still higher sand plains in south-facing valleys. As examples may be taken the plains in the Enfield-Greenwich-Millington area (Belchertown quadrangle, and Alden's map, 1924, Pl. VI).

³ Six miles south of the Sharon plain, in east Mansfield, there are some sand deposits suggesting by their topography and structure formation in standing water with the level at 140 to 150 feet. If the Sharon-Foxboro plains were formed in the same water body, the later warping would be about 22 to 26 feet to the mile. However, such a gradient is extremely improbable, the tilt of the shore of Glacial Lake Narraganset being $5\frac{1}{2}$ feet a mile (R. W. Sayles quoted by Antevs, 1928, p. 84) and that of the marine limit in northeastern Massachusetts being only about 3 feet a mile.

Elevated Shore Features Below the Marine Limit.

In several localities, features, possibly caused by wave action, have been observed, but none that could be correlated from place to place. No typical well-developed deltas below the marine limit, but some sedimentary terraces and sand-plains that suggest deltas have been observed. One was seen at an altitude of 25 feet in Manchester-by-the-Sea (Salem quadrangle). A somewhat uneven sedimentary plain in Beverly Farms stands at about 30 feet.

Drowned Shore Line.

It is a well known fact that the New England shore line during some period of the post-glacial time lay lower than it does now (Sears, 1894; Townsend, 1911; Shimer, 1918; Johnson, 1925, p. 585; Goldthwait, 1925, pp. 69-71; Antevs, 1928, pp. 92-93; 1928a; and others). Drowned valleys testifying to this fact occur along the whole coast of Massachusetts. Peat reaching below the present sea level has been described from several localities, and was observed south of Third Cliff in Scituate, north of the mouth of North River (Duxbury quadrangle), and on the Cape Cod canal west of Sagamore (Plymouth quadrangle).

RÉSUMÉ OF LATE-GLACIAL AND POST-GLACIAL CHANGES OF
THE SHORE LINE.

Thus the shore line, recorded as the ice sheet withdrew, coincides with the modern shore on the coast 20 miles southeast of Boston. South of that point the late-glacial shore lay outside; north of Boston it lay inside the present strand line. The marine limit rises from the modern sea level 20 miles south of Boston to about 40 feet at Marblehead, 50 to 60 feet at Gloucester, and 110 feet at Amesbury, 35 miles north of Boston. The marine limit is recorded by features produced by the action of the sea waves and by deltas built up to the former sea level. The erosional features are mostly very weak at the higher levels, even in loose material with free exposure to the sea; well developed beaches are scarce. The raised shore forms a striking contrast to the modern shore line with its deeply cliffed and truncated drumlins and enormous beaches. The conditions indicate that the waves worked only for a very short time at the marine limit.

The absence of well developed water-marks between the marine limit and the present shore suggests that the entire uplift was rapid and without pronounced interruptions. The shore may have reached its modern position fairly soon. Similar conclusions were reached by Goldthwait (1925, p. 69) and Antevs (1928a) regarding New Hampshire and Maine. From the distribution of sub-fossil molluscs, as known from investigations by C. H. Hitchcock and A. S. Packard, Antevs (1928a) concluded that in Maine, "the shore line seems to have retreated to below 40 per cent of the marine limit before molluscs that now reach their northern limits in the Gulf of St. Lawrence immigrated in Maine and to below the modern stand before the modern fauna appeared. The withdrawal of the shore line from the marine limit to the modern stand may consequently have taken only part of the time that has elapsed since the uncovering from the ice. . ."

The shore line even withdrew beyond the present stand (see above). According to Shimer (1918, p. 457) the shore at Boston may have stood at least 43 feet below the modern position. The rapid regression and the numerous and, in some cases, rather good-sized deposits of peat below the present sea level suggest that the shore lay outside its present position for a considerable time.

At length the regression of the shore line was followed by transgression, drowning peat bogs and river valleys situated at low levels, and ultimately shifting the shore to its present position.

Some idea of the time of the recent transgression is obtained from the deposits in Boston, especially the following section on Boylston and Berkeley Streets, described by Shimer (1918, pp. 446, 460):

- Top of deposits at 3 feet below low tide or 13 feet below high tide.
- (a) 8 feet dark-gray silt with modern mollusc fauna.
 - (b) 4 feet dark-gray silt with rich molluscan fauna resembling that now living off the coast of Virginia.
 - (c) Glacial clay at 15 feet below low tide.

In bed *b* was a fish-weir, whose vertical rods reached down into the underlying clay. The lowest horizontal sticks were about 1½ feet above the glacial clay, i. e. at 13½ feet below low tide. If we may judge from the practice of to-day, the weir was erected when the locality was exposed or almost

exposed at low tide. If so, the shore line at the time stood 13 to 15 feet (not 16 to 18 feet as Shimer states on page 462) lower than to-day. This stand of the shore was taken, as the "warm" fauna of the bed *b* shows, during the post-glacial temperature maximum, which is indicated by various kinds of evidence in Europe and in North America, and which according to studies made in Sweden prevailed from about 7,000 years ago to 3,500 or 2,500 years ago (Sandegren, 1924, pp. 43, 52; Antevs, 1925, p. 64-65; Auer, 1927).

The time of the marked temperature fall concluding the warm age is recorded in the section given above by the transition from bed *b* to bed *a* at 11 feet below low tide. It is also recorded in a section on Exeter Street (Shimer, 1918, p. 445) by a similar transition at 7½ feet below low tide. At this time the shore line lay less than 7 feet below its present position, and had possibly reached its modern position.

To sum up: when the region was released from the ice, the shore line in northeastern Massachusetts lay higher than at present. It withdrew rapidly to below the present stand, reaching in the Boston region at least the level of — 43 feet. Finally it transgressed to its present position.

South of a point on the modern coast 20 miles southeast of Boston no marine features have been observed above the present sea level; but the late-glacial shore line lay outside the modern shore with an amount increasing in south-southeastward direction, and it remained outside until the existing relation was attained not more than a few thousand years ago.

Only records of transgression exist in this part of Massachusetts, but this transgression was very likely preceded by regression as it was in the northern part of the state.

CHANGES OF LEVEL OF LAND AND SEA.

Thus far, we have considered only the movements of the shore line without discussing the relative rôle of the vertical movements of the earth's crust and of sea level.

At the climax of the last glaciation sea level stood much lower than at present, because great quantities of water were stored in the ice sheets. The amount of the lowering of the sea has been variously estimated (see Daly, 1925, p. 285). It has been calculated by Antevs (1928, p. 81), after survey of the quantity of the ice, at about 300 feet. As the ice sheets melted, the sea level rose to its present stand, i. e., probably

some 300 feet. An attempt at reconstruction of this rise, based on the present knowledge of the rate of waning of the ice sheets and the length of the late-Quaternary time, has been made by Antevs (1928a, 1928b). This rise of sea level has obviously caused transgression on all land that has remained stable or risen by a less amount than the rise of sea level.

Regression of the shore since the release from the ice is thus due to an isostatic and elastic uplift of the earth's crust in response to the unloading of the ice which is greater or more rapid than the rise of sea level.

When the ice front had withdrawn to the region south of Boston, the sea level had risen somewhat, probably about 25 feet. The point at which the late-glacial and modern shore lines cross each other—the isobase of zero—under the above assumption now stands 275 feet higher than it did when uncovered. Suppose that the sea level, when the high shore line was registered near the Massachusetts-New Hampshire border, stood 250 feet lower than at present. As the marine limit here lies at 110 feet, the land would now stand 250 plus 110 (= 360) feet higher.⁴ South of the isobase of zero the rise of the land has been less than that of sea level; and the amount gradually decreases in a south-southeastward direction.

To our best knowledge, the rise of land was most rapid when the ice load waned, and decreased gradually in rate towards the present time. Thus, in the region discussed, the land uplift in late-glacial time may have been faster than the rise of sea level, causing the shore line of north-eastern Massachusetts to withdraw to and below the present position before the land had reached its modern level. Later the rise of the ocean level may have been faster than that of the land, submerging peat bogs, river valleys, etc.

A deposit at Boston (Shimer, 1918, pp. 459-462, see above) implies that the shore line here stood 13 to 15 feet below the present position during the post-glacial warmth period and after the sea level in all probability had risen to its modern stand or higher. This suggests that the land actually rose above its present level and that the last transgression was partly

⁴In the present discussion the problem of the distortion of the sea-level by the gravitative pull of the mass of the ice sheet has been omitted. Woodward (1888) has mathematically computed the local rise in the sea-level attributable to ice caps. This calculation, however, was made under the assumption that the earth's crust did not yield to the pressure of the ice (l.c. 60). But the earth's surface evidently yielded. There may have been so nearly isostatic equilibrium that there was no excess mass to cause an important distortion of the sea surface.

due to land sinking. If sea level at the time mentioned was already as high as to-day, the land sinking amounted to about 13 to 15 feet. If sea level before the post-glacial temperature fall some 3,000 years ago was 16 feet higher, as held by Daly, the sinking amounted to at least 30 feet. Whether the shore line is now stable and has been for several thousands of years as held by Johnson (several papers, see 1925, p. 585), is not clear (see also Antevs, 1928a). The reason why Daly's (1920; 1920a, 1925; 1926, p. 174; 1927, p. 80, 81) 16-foot bench does not occur in Massachusetts as far as known may be its having been drowned by a greater sinking of the land. The 16-foot shore line is recorded on the coasts of many different seas, and is held by Daly to be due to an eustatic sinking of sea level, caused by absorption of water in glaciers and ice sheets during the temperature fall that set in at the close of the post-glacial warmth period some 3,000 years ago. However, a world-wide sinking of the sea level as cause of the shore line has been questioned (Johnston 1923, 1926; Johnson, 1925, p. 233).

The superelevation and subsequent sinking of the New England coast was perhaps due to the tendency of the earth's crust to bulge up along the borders of large glaciated areas, and then, at de-glaciation, to sink again because of sub-crustal flow of material and elastic response (cf. Barrell 1915, p. 13; Daly 1921, p. 389; 1925; 1926, pp. 180-200).

Further knowledge of the late-glacial and post-glacial changes of level in our region and of the number, amount, and date of different movements on the shore line, may be gained through a more detailed study of physiographic features, of the stratigraphy of the sediments, and of the megascopic and microscopic organic remains in peat bogs, etc. In Europe plants remains, especially pollen, are being used with great success for dating late-Quaternary deposits.

It is evident that a detailed knowledge of the changes of level in these border regions of the glaciated area would have an importance far beyond the local interest, especially by shedding light on the behavior of the earth's crust on the removal of a local load.

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