# THE UNCOVERING OF NEW HAMPSHIRE BY THE LAST ICE SHEET.

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ABSTRACT.

The detailed mapping of lateglacial ice marginal deposits and outwash on some fifty newly contoured quadrangles in New Hampshire for the State Highway Department, since 1925, has led to a complete revision of opinion regarding the way in which the last ice sheet disappeared.

Downwastage of the ice surface appears to have been fully as important as backward wasting of the periphery. In the hilly interior, it produced utterly ragged ice borders which shrank down in disorderly fashion until at last there were narrow tongues and remnants in the valleys, where kame terraces and crevasse fillings appear. Over the coastal lowland, seaward-flowing systems of meltwater drainage developed, which left strong parallel lines of kettled outwash and kames but no recessional moraine deposits and very few signs of sweeping by waves and shore currents. Thinning seems to have continued even while marine clay was being spread.

What was formerly thought to be a slanting marine waterplane that registered the exact amount and direction of lateglacial upwarping is now regarded as a waterplane of meltwater drainage, seeking escape from confining ice walls, and building deposits which show the touch of shore agencies only locally where areas of thin ice were least continuous. Field observations indicate similar features in Maine and Essex County, Massachusetts.

If downwastage played this large rôle in ice removal over wide areas, it is difficult to estimate the full amount of crustal upwarping, and to account for it by recovery from ice load; also, it is difficult to time successive stages in lateglacial rise of sealevel.

## INTRODUCTION.

The manner in which the ice sheet uncovered New Hampshire, at the close of the last glaciation, is a question that has grown in interest during the last fifteen years. Antevs' extraordinary studies of varved clays in 1921-22 afforded what appeared to be exact rates of northward recession of the ice edge up the Merrimac, Connecticut and Hudson valleys. With these parallel records correlated, year for year, it was easy to draw lines across the intervening spaces transverse to glacial movement and parallel to such fragmentary "moraines" as were then recognized, so as to produce a map of the recession of the last ice sheet from New England and New York.[1] But enthusiasm for this new technique did not entirely shut our eyes to the fact that deglaciation is a three-dimensional process

[1] Antevs, E.: The recession of the last ice sheet in New England, Amer. Geogr. Soc., Research Series No. 11, 1922; with map, Plate 6, compiled by J. W. Goldthwait.

involving downward wastage of the surface as well as back wastage of the margin. A single paragraph written in 1925 puts it thus:—

"The wasting of the ice sheet consisted in: (a) a melting back of its edge at rates usually between 200 and 600 feet a year; and (b) a thinning out of the sheet by slow downward melting of its surface at a rate as yet unknown, so as to expose the mountain tops and hillsides and leave irregular tongues of ice in the valleys. Water gathered in pools and larger lakes some of which were dammed by the ice sheet and consequently found new outlets as the edge of the ice receded, so that they spread forward or drained away or coalesced to form larger lakes, in a highly kaleidoscopic fashion. Valleys not flooded by lakes were occupied by outflowing rivers larger than those of today, and generally overburdened with sediment, which was spread out in various forms of 'outwash'. . . ."[2]

Since this paragraph was written, the complete contour mapping of New Hampshire by the U. S. Geological Survey and a detailed survey of gravel deposits for the State Highway Department by the writer and several assistants have afforded better opportunity to judge the relative importance of downward and backward melting of the ice. Meanwhile, emphasis upon stagnation and downwastage in Connecticut with possibility of very irregular removal of the final scraps, as first suggested by Flint,[3] has called for critical review of evidence from New Hampshire. Fortunately our field studies of sands and gravels over this State have come at a time of rapid development of pits and sections for highway construction, permitting old inferences from details of slope and form to be checked by actual exposure of structure at literally thousands of places.

The result of field observations here since 1925 may be summarized briefly as follows: In the hilly interior of the State, our mapping of ice-marginal kames and kame terraces, which outnumber all other types of gravel deposits, and of marginal stream channels cut across till slopes, indicates a long continued lowering of the surface of the ice while its thin and irregular edge shifted unevenly from contour to contour. Although deglaciation in general seems to have proceeded northward or northwestward, locally it was toward the east or west, accord-

[2] Goldthwait, J. W.: The geology of New Hampshire, N. H. Acad. Sci. Handbook No. 1, p. 29, 1925.

[3] Flint, R. F.: The stagnation and dissipation of the last ice sheet, Geogr. Review, Vol. 19, pp. 256-289, 1929; also, The glacial geology of Connecticut, Conn. Geol. Surv. Bull. 47, 1930; and Deglaciation of the Connecticut Valley, This Journal, Vol. 24, pp. 152-156, 1932.

ing to the direction of upland slopes. In this rough terrain the ice seems nowhere to have had a well-defined "front" transverse to the ice motion of and more active stages of glaciation. How long and how general the ice lay stagnant in lateglacial stages it is not yet possible to say. Recessional moraines, if present at all, are mere scraps, not in line. Local groups of sharply defined ridges, formerly thought to mark halts in the retreat of the margin of an ice lobe,[4] seem now more likely to be crevasse fillings, formed at unknown distances within the wasting icefield and wholly without seasonal or climatic significance.[5] Some consist of till, while others are of gravel, sand, or even stratified silt. As for the valley deposits generally, ice contacts appear on any or all sides of them. Plains, terraces, mounds and ridges thus bounded, lie scattered plentifully along valleys where meltwater escaped southward and southeastward. They are much more strongly aligned in the direction of ice motion than transverse to it. Both individually and collectively these records of lateglacial drainage imply downwastage of the ice surface almost to the valley floors instead of orderly "retreat" of a single wall or "front." The overlapping of thin marginal ice by glaciofluvial deposits of sand and gravel, followed by slumping, is abundantly suggested by gently undulating surfaces. Downvalley gradients of former stream profiles marked by outwash plains and ice-marginal terraces in branch valleys are so unlike in slope and direction as to be inconsistent with the idea that long open lakes were uncovered by ice retreating from end to end, and that their horizontal waterplanes were later upwarped; on the contrary, the record strongly favors the theory that stagnant remnants of ice impeded southward escape of meltwater over a zone of considerable width. More particularly in the low-lying coastal district of southeastern New Hampshire, detailed mapping of the lateglacial deposits has led to a complete revision of views regarding conditions of ice removal, marine submergence, and crustal upwarping.

This shifting of emphasis from *recession* to *downwastage* recalls doubts felt by the writer some thirty-five years ago, when his study of sandplains in the Sudbury valley of eastern Massachusetts and a similar study by F. G. Clapp in the adjoining valley of the Charles River left unsettled the question

[4] Goldthwait, J. W.: Op. cit., pp. 49-51.

[5] Flint, R. F.: Eskers and crevasse fillings, This Journal, Vol. 15, pp. 410-416, 1928.

whether the last ice sheet had receded so as to leave wide, open lakes or had wasted downward into fragments, as Clapp supposed, creating irregular groups of ice-bound pools with fluctuating levels.[6] The writer's uncertainty was increased later, when outwash deposits near Twin Mountain House on the northwest side of the White Mountains were found to have an intricate ice-contact pattern, implying highly irregular downwastage of the ice.[7] This example of downwastage, quoted by Flint[8] is now much more accurately contoured on the new Whitefield quadrangle (survey of 1934-35) and is seen to be closely associated with other icemarginal drainage features.

Among the long-accepted items of lateglacial history of New Hampshire which our revised views lead us to discard are: (a) three lines of halt or readvance of the ice edge, known as the Newington moraine, the Claremont-Winnepesaukee line, and the Bethlehem moraine; (b) wide, open lakes in the Winnepesaukee, Merrimac-Pemigewasset, Contocook and Ashuelot valleys; (c) the reconstructed waterplane and shoreline of the lateglacial or "Champlain" sea, as shown by "beaches" and "wave-cut cliffs" in the coastal area, and the computed crustal upwarping of that waterplane.

## RECORDS OF THE INTERIOR.

### *"Recessional Moraines."*

While Antevs was computing definite rates of annual recession of the ice margin in the Connecticut and Merrimac valleys by means of varved clays, in 1921, the writer discussed with him all known signs of temporary halting and readvance of an ice front in New Hampshire and made a rapid search in the field for more. There was hope of discovering important oscillations of climate during deglaciation in New England which might be correlated with those registered by the moraines in western New York State and the Great Lakes region, studied by Taylor and others.[9]

[6] Clapp, F. G.: Relations of gravel deposits in the northern part of Glacial Lake Charles, Massachusetts, Jour. Geol., Vol. 12, pp. 198-214, 1904; and Goldthwait, J. W.: The sandplains of Glacial Lake Sudbury, Bull. Mus. Comp. Zool., Vol. 42, pp. 263-301, 1905.

[7] Goldthwait, J. W.: Glaciation in the White Mountains of New Hampshire, Bull. Geol. Soc. Am., Vol. 27, pp. 263-294, 1916.

[8] Flint, R. F.: Op. cit., p. 279, 1929.

[9] Taylor, F. B.: The glacial and postglacial lakes of the Great Lakes region, Ann. Rept. Smithsonian Inst. for 1912, pp. 291-327, 1913.

### *The Line of the Bethlehem "Moraine."*

A zone of massive kettled outwash had already been studied in Bethlehem and Littleton, in northern New Hampshire[10] and intepreted as a recessional moraine, although its climatic significance had not been particularly stressed. Varved clay sections at Fifteen Mile Falls, ten miles west of Littleton, indicated to Antevs a halt of the ice margin and readvance after some 280 years, at a point nearly in line with the Bethlehem "moraine."[11] Deep excavations during the construction of the Comerford Dam at East Barnet, several years later, clearly exposed two sheets of till and the interbedded varved sediments, by which Lougee was able to confirm Antevs' measure of the time interval for the halt and readvance.[12]

Meanwhile Crosby, who had made elaborate studies of the drift in and near the Fifteen Mile Falls project for the New England Power Company, urged correlation of these records with ice-marginal kames midway between them and the Littleton end of the Bethlehem moraine and with a body of stratified silts overriden by till many miles farther east, in the Peabody River valley south of Gorham.[13] Thus, it seemed, the supposed halt represented by the Bethlehem moraine might be traced along a wide front. Now that our gravel survey on the new contour maps has been completed and has found ice-marginal kames, ridges and terraces abundantly both north and south of Crosby's line, and has shown that these features persistently occupy the main valleys regardless of valley orientation, and hence were localized by the preglacial topography, it seems no longer reasonable to interpret any of these stratified drift deposits as moraines. The thick, kettled outwash with boulder-strewn surface between Littleton and Bethlehem, which first gave rise to the idea of an icefront standing in deep water along this eastward segment of the Ammonoosuc Valley, can now be mapped more correctly on the newly contoured quadrangle and appears not only much less continuous than was once thought but also much less definitely ridgelike in detail than descriptions by Agassiz, Upham and the writer implied. The general east-west course of this zone of outwash can be attributed to the east-west trend of this particular segment of

[10] Goldthwait, J. W.: Op. cit., pp. 263-294, 1916.
[11] Antevs: Op. cit., pp. 83-84.
[12] Lougee, R. J.: Time measurements of an ice readvance at Littleton, N. H. Proc. Nat'l Acad. Sci., Vol. 21, pp. 36-41, 1935.
[13] Crosby, I. B.: Extension of the Bethlehem, New Hampshire, moraine, Jour. Geol., Vol. 42, pp. 411-421, 1934.

the valley. As for Crosby's correlation of the over-ridden silts near Gorham with those at Fifteen Mile Falls, one must object that, if they are varved, these have not been measured and matched, and that the two localities are 25 miles apart; moreover, in the rough country that separates them, kame terraces and kames follow opposite sides of the deep valleys along a winding course at a nearly uniform elevation for long distances, especially in the township of Jefferson, thus indicating the downwastage of a thin and ragged ice margin instead of the northward retreat of a high ice "front."[14]

### *The Claremont-Winnepesaukee "Line of Halt."*

Antevs found reason to suspect a line of halt and readvance farther south, near Claremont, New Hampshire, in a district where varved clay sections did not match and where one section of lake silt especially was covered discordantly by four feet of coarse cobbly gravel, like outwash from a readvancing ice front.[15] Starting from this point in the Connecticut Valley, scattered ice-contact deposits were picked up by the writer in reconnaissance eastward and northeastward at Lempster, Lake Sunapee, Winnisquam and Laconia, toward Lake Winnepesaukee, where Upham, fifty years earlier, had reported laminated clays overlain by till at Weirs, Alton, and Wolfeboro. The only section exposed there in 1921—the one at Weirs—was measured by Antevs; but the clay beds were found to be much distorted and disturbed by sliding or ice pressure and could not be matched with the varve sections in the Merrimac Valley. There seemed to be about 200 varves in the Weirs section. Hummocky deposits of sand near Center Tuftonboro, just east of the lake, were accepted as another mark of a lingering ice border. On various grounds, Antevs assumed a time interval of from 200 to 400 years for oscillations on this Claremont-Winnepesaukee line; but he could not find a record of the halt either in moraine deposits or in varved clay in the Merrimac Valley, nor any in the Hudson and Mohawk Valleys.

A somewhat detailed description of these features was given a few years later in the writer's "Geology of New Hampshire."[16] It was already realized then that the moraines "do not form a continuous line by any means, but seem to have

[14] The mapping of these features on the new Mt. Washington and Whitefield quadrangles by R. P. Goldthwait will be discussed by him in a forthcoming paper.
[15] Antevs, E.: Op. cit., pp. 81-82.
[16] Op. cit., pp. 49-52.

been built only at points where conditions were most favorable. The recognition of this line of halt is recent and its full significance is as yet uncertain." Particular attention was called to a series of ten or twelve distinct ridges of bouldery till, supposedly stadial moraines, at the south end of Lake Sunapee[17] and to a less orderly cluster of ridges and hummocks partly of till and partly of silt at Laconia.[18] "While these moraine scraps are separated by gaps of fifteen or twenty miles, where the ice edge either left no good mark on the hills or where the marks lie undiscovered, evidence seems to justify the view that there was a halt of some duration here, during the recession. There are few places north or south of the zone mentioned where deposits like them have been noted, although searched for."[19]

The uncertainty thus expressed in 1925 has steadily grown, with the progress of field work on new contour maps, until it can now be said positively that the correlation of these features across the State from Claremont to Winnepesaukee is not justified. Although the ridges near Lake Sunapee resemble the so-called stadial moraines of the Finger Lakes region,[20] the Berkshires [21] and central Massachusetts,[22] they are better explained as crevasse fillings than as ice-border embankments. Their diagonal courses down the steep side slopes of the basin might of course be due either to the slanting contact of an ice lobe with the mountain side or to crevasses opened by strain of ice movement within a lobe. The distance between successive ridges is not very different from that of annual recession as computed by Antevs from varved clays in the Connecticut Valley. But the ridges have side slopes that are equally steep, as if both were determined by contact with the ice. They are broken and less diagrammatic than first supposed. The Laconia ridges seem even more surely to be crevasse fillings, for they consist largely of fine, laminated lake sediments, and they trend in various directions. Still more significant is the discovery that sets of ridges like these are not limited to the Claremont-Winnepesaukee zone, as first supposed, but occur at a number of places off that line,—for example, near the Orange Sum-

[17] Op. cit., Figure 15.

[18] Op. cit., Figure 12.

[19] Op. cit., pp. 50-51.

[20] Tarr, R. S.: Watkins Glen-Catatatonk Folio, U. S. Geol. Surv., No. 169, 1909.

[21] Taylor, F. B.: The correlation and reconstruction of recessional ice borders in Berkshire County, Mass., Journ. Geol., Vol. 11, pp. 323-364, 1903.

[22] Alden, W. C.: The physical features of Central Massachusetts, U. S. Geol. Surv. Bull. 760B, 1924.

mit, and in Lebanon, South Danbury, Orford, Newfound Lake and East Andover, quite without alignment and apparently dependent upon local topographic conditions. Finally, the four feet of cobbly gravel overlying the lake beds at North Charlestown, which Antevs was inclined to interpret as outwash from a readvancing ice edge, now appears instead to be a sheet of river channel gravel spread across truncated lake beds during the period of emergence and terracing of the valley floor. Although the concept of an important ice-margin oscillation along a Claremont-Winnepesaukee line has won a place in the literature[23] there seems to be little ground for retaining it.

### *Valley Outwash.*

Field studies before 1925 were chiefly in "lateglacial lake" areas of the Winnepesaukee, Merrimac and Connecticut valleys, and in the lowland of southeastern New Hampshire, where valleys were ill defined and contour maps obsolete. Lateglacial conditions in tributary valleys of the interior were suggested, however, by the case of the Cocheco River in the towns of Farmington and Rochester, where "swift flowing rivers running through ice canyons and tunnels built a fine chain of eskers and kames in midvalley and an almost continuous line of kame terraces against the hillsides."[24] These deposits were thought to have accumulated in pools of water on opposite sides of a short ice tongue, forming one by one as the ice drew back. The down-valley gradient of terraces in the Cocheco valley was about 20 feet to the mile,—much steeper than the slant due to crustal warping, which was estimated to be six feet per mile in the same direction.

Since this was written, the State Highway Department's gravel survey has carried the detailed study of glacio-fluvial deposits into every significant valley in the state, as fast as new contour maps were available. Features like those of the Cocheco were found in most valleys that drain toward the south or southeast. The lateglacial stream gradients range from ten to 25 feet per mile, with little regard to compass direction, showing that the water in them was flowing toward the trunk lines of drainage, with stream profiles governed by ice on the one hand and till or rock slopes on the other.

[23] Goldthwait: Loc. cit.
Antevs: Loc. cit., also The last glaciation, Amer. Geogr. Soc. Research Series No. 17, pp. 152-153, 1928.

[24] Goldthwait: Op. cit., p. 35, 1925.

Gravel terraces are largely if not wholly constructional, with conspicuous ice contacts facing valley axes. Usually there seems to be but one ice-contact terrace in a valley, in contrast with conditions reported from the lower Connecticut.[25] There is little if any sign of lateral cutting by ice-marginal streams into till slopes or of scouring of ground between ice-marginal pools. This implies that drainage at that stage was almost wholly through or across thin crevassed ice. Gently undulating borders of plains commonly suggest a slow collapse of deposits laid on thin ice. In particular, the descent of a lateglacial stream profile down a valley appears to be uniform for long distances, without abrupt drops over temporary thresholds.

While the familiar hypothesis of construction of kame terraces by up-valley growth of deposits at the end of a receding tongue of ice may still be invoked to explain these facts, we are nevertheless troubled by the question,—what was the form of the central ice tongue? Was it short, steep and wide, or long, low and slender? Was the ice in the valley wasting away more by backward recession or by thinning over a zone five, twenty-five, or fifty miles wide? So far as the kame terraces have substantial continuity and rather steady downvalley gradients, they suggest thin, slender tongues of ice bordered by long pools that were fully connected by passages through the ice. This is conspicuously the case, for example, in the Soucook valley in the town of Loudon, in the Lamprey River valley in Deerfield and Raymond, and in the valley of Beaver Brook in Windham and Pelham. The zone of thinned ice during late stages of wastage would seem to have been much wider than formerly assumed by the writer and others, and more nearly comparable to the conditions described by Flint in Connecticut.

At the same time, it seems certain that in these New Hampshire valleys, as in Connecticut,[26] the removal of ice proceeded in a northerly or northwesterly direction. Evidence lies in the sharp contrast between deposits in valleys that discharge in opposite directions. Those which drain northward usually contain ice-contact deposits that register ponding of deep meltwater behind thresholds of rock and till with overflow in a southerly direction. The waterlevel to the north is marked by nearly accordant tops of kame terraces, deltas and general upper limit of outwash, adjusted to the controlling threshold;

[25] Flint, R. F.: Op. cit., 1929, 1930.
[26] Flint, R. F.: Op. cit., p. 155, 1932.

the southward discharge, where structure was not too resistant, is indicated by a spillway channel with sometimes a boulder pavement or potholes in the stream bed, and by rapid descent to the much gentler long profiles of the more freely flowing southward drainage lines. Even in these cases, however, the drainage basins on the north and northwest sides of divides appear to have been occupied by thinned and ragged ice during the accumulation of sediment, and not for any length of time by open water, if one may judge from the prevalence of kames and marginal kame terrace deposits around their borders and an almost complete absence of lake-bottom sediment from their floors.

### *Marginal Drainage Channels.*

Inasmuch as detailed field work before 1925 had been limited largely to the lowland areas of southeastern New Hampshire and to the poorly contoured areas around Lake Winnepesaukee, Lake Sunapee and the White Mountains, channels cut by overflow from highlevel drainage basins had not been found in large numbers and were not given much place in the account of that date. The Handbook did, however, describe gaps cut across till barriers by westward discharge of "Glacial Lake Winnepesaukee" at Winnisquam and Lakeport, and a pair of newly discovered "spillways" that led from "Glacial Lake Belknap" toward Laconia. It was intimated that future studies in districts similarly situated would probably reveal many cases like them.[27] That expectation has been abundantly fulfilled with new contour maps to expedite discovery. But in many instances drainage channels have turned up in situations not easily accounted for by the hypothesis of a retreating ice front and bordering lakes. There are many marginal river channels; but few if any lake spillways.

While mapping the gravel deposits on the old Whitefield quadrangle south of Lancaster for the State Highway Department in 1930, Richard Lougee found a group of district channels traversing the long till slope and terminating in a long kame terrace near the Connecticut River. The generalized contours gave no suggestion of these details, which Lougee interpreted as marks of a westward escape of ice-marginal waters from a lake in the Israel River basin. This discovery led to another, at Jefferson Highlands on the Mt. Washington quadrangle, where several channels cut the slope that separates

[27] Goldthwait, J. W.: Op. cit., pp. 39-42, and Figure 12, 1925.

Stag Hollow from the Israel River lowland. New surveys of these two quadrangles in 1934-35 have made it possible to trace out and map the details of channel cutting and terrace building here with greater accuracy than before, and to find in them an indication of downwastage of ragged ice margins against the mountains.[28]

On quadrangles farther south our gravel survey has revealed many examples of marginal channels descending into kame terraces. Thus, Lougee found lines of former drainage on the west and north sides of Hubbard Hill in North Charlestown (Claremont Quadrangle), and George W. White located an important channel and kame deposit near the Contocook River in Henniker (Hillsboro Quadrangle). Small but unmistakable channels had been noted on the Wolfeboro quadrangle by the writer as early as 1920; but these could not be satisfactorily explained until the weight of evidence brought recognition of extreme irregularity of icemargins fitted to upland slopes in all directions. Some thirty such channels have been located by the writer and his associates on the Mt. Cube, Mascoma, Cardigan, Winnepesaukee and Wolfeboro quadrangles. In nearly all cases the channeling indicates escape to the south or east or west; but in one or two instances it was toward the north. The cutting in nearly every case is through till or against kame gravels; rock has been channeled only in Jefferson and in Lyme. It seems, then, that these streams were short lived. Boulder pavements are not so common nor so good on channel floors as one might expect from the plentiful supply in the drift. Steepened banks and gently graded floors are often rather typical, blending upstream into slopes that either rimmed an old lake or more likely a basin occupied by downwasting ice when the stream found this course. Nowhere have we found direct evidence of wide open lakes; on the contrary the deposits in these basins are scattered kames and kame terraces, more often marginal than central in their positions. Some channels are so related to slopes as to deny origin from lakes and require a river flowing off the ice. Others which might be regarded as spillways from proglacial lakes show strange inconsistencies of altitude. Thus near East Plainfield (Mascoma quadrangle) at the southern end of Great Brook drainage basin, where overflow from an ice dammed lake would be expected to have followed a gap on the Claremont road at about 1,230 feet, there is no sign of river scour, although a higher gap only a

[28] Goldthwait, Richard P.: unpublished studies, 1937.

half-mile to the east has a channel sharply cut through till. The initial surface of the till here was fully 40 feet higher than that in the other gap and the finished channel floor is 15 feet above it, or 1,245 feet by precise leveling. If there was a lake ready to spill through these gaps, then the lower of the two was blocked by ice all the time the upper one was being channeled. It seems more likely that the higher gap was channeled by a superglacial stream which became superimposed on that col, and that no lake developed to select a lower outlet. In other places, channels occur far up hillsides on open slopes rather than in cols, where it is impossible to relate them to proglacial lakes.

### *Ultimate Northward Recession in the Connecticut and Merrimac Valleys.*

Whatever the indications of general downwastage of the ice on to the upland surface and thinning down into the lowest valleys, a final northward deglaciation in Merrimac and Connecticut Valleys seems to have been established by Antevs' measurements and matchings of varved sediments. Independent measurements of newly exposed sections of varves around Hanover, at points in the White River Valley and at Fifteen Mile Falls, by students at Dartmouth, notably by R. J. Lougee, corroborate Antevs' original matching. In spite of the fact that he actually reached "bottom" at only a few localities,[29] there can be little doubt that the varves overlap northward, as Antevs first claimed in 1921, showing that the deglaciation proceeded generally in that direction. The approximate correspondence in rates of retreat in the parallel valleys, Connecticut and Merrimac, as worked out from varved sediments, at least as far north as the line Cohoes, New York—Putney, Vermont—Boscawen, New Hampshire, lends some plausibility to the reconstruction of successive positions of a straight ice "front" across the wide intervening spaces, as originally drawn by Antevs[30] but the correctness of such representation of many successive ice fronts is seriously open to question, in view of the extremely ragged ice margins required by the features already described. Indeed, ice-contact slopes are not lacking in the thick sandy deposits of the Merrimac Valley.

After all, there is no contradiction between the varved

[29] DeGeer, G.: Geochronology as based on solar radiation, Science, Vol. 66, p. 459, 1927.

[30] Antevs, E.: Op. cit., Plate 6 and pp. 67 and 74, 1922.

deposits and the icemarginal features. It is conceivable that ablation may have thinned the ice down to almost nothing, with gentle southward slope over wide areas of upland while ice still remained fairly thick and partly stagnant in the broader and deeper valleys; and that finally the extremities of the valley remnants wasted northward at the rates which Antevs has worked out.

## RECORDS OF THE COASTAL REGION.

### *"Recessional Moraines."*

Just before the writer's study of southeastern New Hampshire began, in 1917, Katz and Keith had traced a deposit of stratified drift from Biddeford, Maine, southwestward across New Hampshire to Newburyport, Massachusetts, and had called it the "Newington moraine."[31] They took this to mark an important halt in retreat of the ice border from the seacoast. Without accepting this broken, zigzag line of kames as a single continuous moraine, the writer attached some significance to that portion known as Merriland Ridge in the township of Wells, Maine, and sought for its southwestern extension across the towns of Dover, Madbury and Lee, New Hampshire. A map (Fig. 8) in the handbook and brief statements show that this search met with indifferent success.

"As it receded across the submerged zone, the ice edge halted from time to time, building some large morainic embankments, such as Pudding Hill in Madbury and the Glenwood Ave. ridge north of Dover. These have typical knob and kettle topography like the terminal moraine on Long Island; and like it, also, each moraine has a smooth frontal apron along its seaward margin where sands were spread forward from the ice border. These aprons match closely in altitude the raised beaches near them. Other mounds and ridges of morainic nature in Barrington and Lee probably mark the two lines of halting noted above (coarse dotted pattern) and form a natural continuation of the moraine which has been traced from Biddeford, Maine, to Berwick and Dover by Keith and Katz, called by them the 'Newington moraine.'[32]

"The recession of the ice border across this submerged zone was unsteady and interrupted by halts. Where the edge stood still, morainic banks or ridges were heaped up, with aprons of sand washed forward, like the great terminal moraine and outwash

[31] Katz, F. J., and Keith, A.: The Newington moraine, Maine, New Hampshire and Massachusetts, U. S. Geol. Surv. Prof. Paper, 108-B, 1917.

[32] Op. cit., p. 30.

apron on Long Island but on a much smaller scale. These are so small and scattered as to suggest that the ice border never stood long at any one line, in this part of the State. The two best examples . . . . Pudding Hill and the Dover moraine ridge mark two positions of the ice edge, about five miles apart; and are very nearly in line with a moraine that has been traced through southern Maine from Saco and Biddeford westward to North Berwick. This was named the Newington moraine . . . . . by Keith and Katz because of its supposed extension down past Dover Point to the town of Newington. Since the two moraine banks and aprons, described above, at Dover and Madbury resemble the Maine moraine closely in form and structure and lie in direct line with it, while the Dover Point and Newington deposits are dissimilar and out of line as well as out of harmony with the direction of ice-flow of the continental glacier, there is good ground for regarding them as fragments of the Saco-North Berwick moraine line. Repeated search for an extension of these ice border deposits southwestward through the townships of Barrington, Lee, Nottingham and Epping, where excellent topographic maps can be used, has failed to bring to light any good records there, although in Fremont and the southern part of Raymond are several strongly marked lines of moraine, both gravelly and rocky, which Hitchcock long ago noticed. These too are only scraps, somewhat scattered, and not in every case distinguishable from glacial deposits of other origin. It seems fairly certain that they mark the same zone of retardation in ice recession as the Saco-Berwick moraine. No one has yet traced this line west of Fremont; but it presumably extends across the lines of glacial flow, in a southwesterly direction past Nashua to join a well defined zone of halt and readvance at Amherst and Northampton, Massachusetts. According to Antevs, the halt there occupied two or three hundred years."[33]

This forecast of what might in time be found along the extension of the Saco-Dover-Fremont line grew out of a fancied resemblance of the New England features to the famous Salpausselkä moraines in Finland. The Merriland Ridge and the Pudding Hill deposits were suggestive, indeed, but disappointingly discontinuous. Field work during the next decade revealed no additional records that could be used to extend these moraines over into Massachusetts. With detailed mapping of gravels completed, it is now clear enough that no such halt of an ice front is registered. The "moraine ridges" in the town of Raymond and the kettled kamefield in the town of Fremont, separated from each other and from the Madbury

[33] Op. cit., pp. 33-34.

embankment by several miles, are no more related to them than they are to kames and outwash plains to the north and south.

The "moraine embankments" of Dover and Madbury differ only in size and linear trend from ice-marginal plains and kames of great diversity and number. From the first, the outwash deposits of the coastal area have been hard to relate to an orderly receding ice edge bathed by the Champlain Sea. The general southeastward slant of their surfaces, accompanied as it often is by diminishing coarseness of sediment and by dipping foreset beds gives reason indeed to regard them as built by powerful and persistent flow of meltwater; but the proximal edges of the plains are often ill defined, unlike ice contacts, and the distal margins with rarely a trace of distributary lobes are as irregular as the rest. Kettles in some cases are deep and steep sided, in others shallow and indefinite; but these and the irregular ice contacts suggest accumulations within and upon a thinned and discontinuous mass of land ice which lacked any sharply defined edge.

Very large outwash plains such as those at Rochester, poorly shown on the contour sheets of fifty years ago, lack the simplicity formerly attributed to them. They seem to be complex in form and in date of origin. What is more, their internal structure, better seen now in enlarged gravel pits than it was twelve years ago, leaves considerable doubt about the exact elevation of the water surface at which or beneath which they were spread. Comparison of these old contour maps with the excellent new Haverhill and Newburyport quadrangles shows that plains like these are smaller, more numerous and more irregular in outline than they formerly appeared to be. Like the other marginal deposits, they do not fall into lines transverse to ice movement, but lie conspicuously parallel to it.

Indeed, on purely theoretical grounds, continuous recessional moraines are scarcely to be expected in a region as hilly as this. Exposures of overridden varved clays at Amherst, Massachusetts, Fifteen Mile Falls, New Hampshire, and other places show that locally, at least, the ice had active motion even at its edge. But the rates of motion may have been very different within short distances on the ice margin, when the ice sheet had thinned down close to the uneven rock surface, and increasingly variable and diverse as downwastage continued. Concentration of drift into a terminal moraine required an approximate balance between forward movement and backward wastage of ice. Both processes may well have been variable at different points along a given sector, movement being influenced by irregular topography as just suggested, and melting being fast or slow because of irregularly distributed load of drift gathered from the hilly terrain itself. Balance then between the two variables would be unlikely for any distance along the ice edge and moraine deposits would be discontinuous. In smoother country like the Great Lakes region, where movement would be steadier and drift content and ablation more uniform, approximate balance between the two processes would result in relatively continuous moraine ridges. Granted that stagnation of ice over New Hampshire in late-glacial stages is highly probable as the result of thinning by surface ablation, it is not necessarily implied by the absence of recessional moraines.

### *Other Ice-Marginal Deposits.*

The "moraine embankments" discussed in the foregoing section cannot be satisfactorily differentiated from outwash deposits of other types. Although their distinctive features were supposed to be (a) linear trend at right angles to ice movement, (b) kettled ice margin on the north and seaward slope to the south, and (c) coarser and more crumpled beds in the proximal zone grading to finer and more uniform beds in the distal portions, the best of these "moraines" fails to meet specifications. For example, (a) the Pudding Hill and Dover ridges run nearly east and west, or diagonal to glacier movement. Katz and Keith, seeking a nearly continuous line for their "Newington moraine" but missing the two ridges just mentioned, mapped it as turning abruptly at right angles at Dover and as running several miles south-southeastward to Dover Point, beyond which it turned again into a northeast-southwest course through Portsmouth to Newburyport. There again it seemed to follow a line of kettled drift southeastward. Their supposed moraine was thus markedly zigzag instead of consistently transverse to ice motion. Forty years earlier, Upham had interpreted the Dover-Newington section as a great kame, built by a glacial river that ran between ice walls on a course parallel to ice motion and to the seaward slope of the ice surface. This would seem today to be the better explanation. (b) While kettled surfaces mark the crests or backbones of the best "embankments," they are plentiful as well in outwash plains that lack linear form or transverse trend—plains which seem as often to have steep slopes on the south, east, or west sides as on the north. Examples include the plain at Barbadoes Pond in the town of Madbury and Spruce Hole in Durham. In some cases, kettles are as conspicuous in the central or southern portions as in the northern. (c) Although southward slope of surface and gradation from gravel into sand indicate flow toward the south in many instances, there are plenty of striking exceptions. Steep westerly or northwesterly dips of foreset beds covered by thin horizontal topsets are exposed over wide areas and to great depth in the plains of Newmarket, Greenland and North Hampton. Beds jammed and wrinkled as if by ice shove can be seen at the southwest corner of a wash plain near Back River School in Madbury. The great diversity of form and structure and in direction of growth of these delta-like aprons of outwash is easy to account for if the wastage of the ice consisted chiefly in downmelting of an uneven surface with broad passageways and pools to catch sediment delivered to them from one side or the other; it is hard to explain as a record of successive retreats and halts of a single ice wall or "front."

The fact is, alignment of these deposits is definitely along northwest-southeast lines, *parallel with* ice motion. The small-scale map of our gravel survey of the southeastern part of the State makes this clear. (Fig. 1.) Beginning with the line which comes down along the Maine-New Hampshire boundary in Milton and becomes part of the "Newington moraine" near Dover Point, one can count nine or ten definite lines of concentrated outwash, approximately parallel and about five miles apart. It seems easier to explain this persistence of lines of kame and outwash plain construction by seaward-flowing systems of glacial drainage consequent upon a thinning ice sheet than to try to relate them to backward recession of an ice front. It must be pointed out, also, that the southeastward courses of the lateglacial drainage lines, here, are wholly independent of control by the present slopes and drainage of the area. The region is an undulating lowland, and the stream systems arborescent, with very crooked main stems, quite disorderly in pattern.

Farther inland, where the upland rises and takes on stronger relief, with valleys, which may or may not follow a southeasterly course, the lines of outwash shift their direction to conform to the topographic control. Thus, as seen on Fig. 1, we find the pronounced line of kames, terraces, and outwash plains of the Soucook Valley running due south for some 20

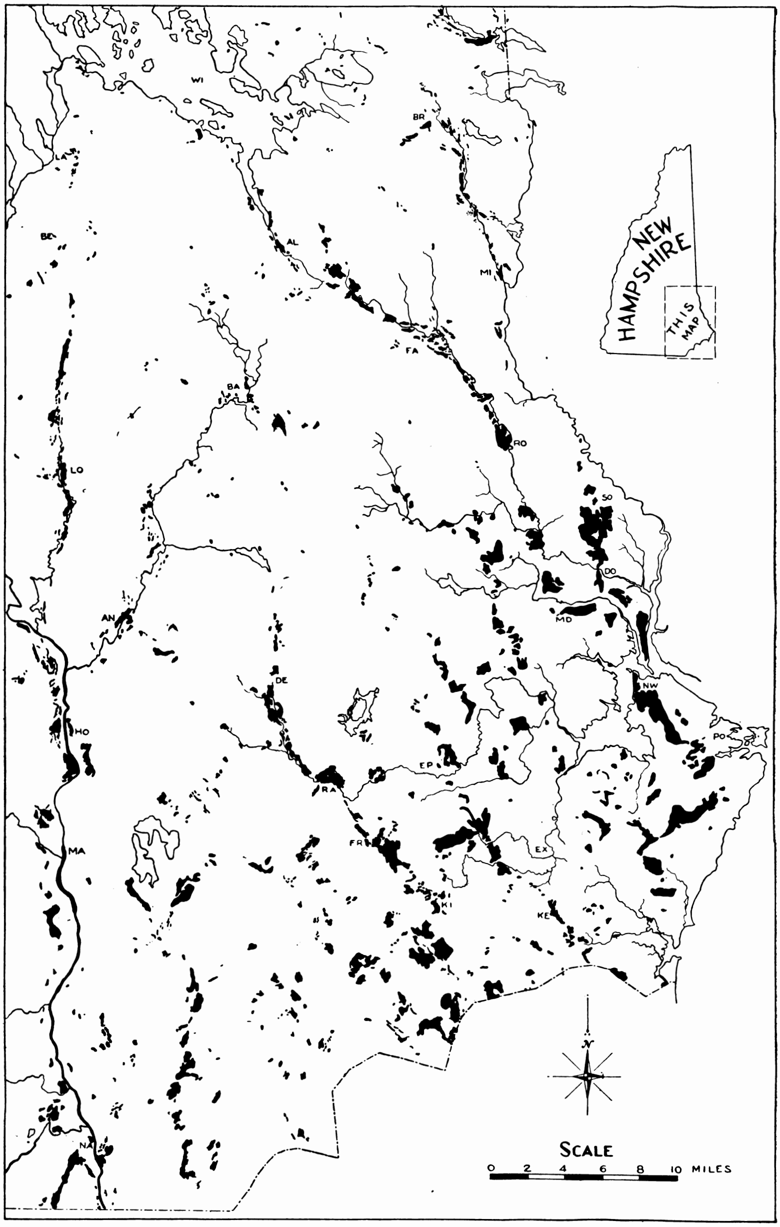
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Fig. 1.

miles from Belmont to Pembroke and continuing down the Merrimac eight miles more to Hooksett. One of the southeastward lines of outwash of the coastal area which enters Fremont from Raymond is seen to have its source farther up the valley of Lamprey River in Deerfield, where the trend of the deposits is from north to south in obedience to topography. The southeasterly course of kames from Alton Bay to Farmington and North Rochester is undoubtedly due more to guidance by the long valley of Cocheco River than to the surface slope or movement of the ice sheet. Over central and northern New Hampshire, as explained on earlier pages, outwash deposits follow the valleys more and more closely with greater relief as the controlling factor.

## *Emerged Marine Strandlines* (?)

Records of lateglacial submergence of the New Hampshire coast were described in 1925 as follows:

"As the ice edge melted back from the coast of New Hampshire the sea spread inland fifteen or twenty miles beyond the present shoreline, flooding Portsmouth, Dover, Newmarket, Exeter and a score of adjoining towns . . . . Islands singly and in clusters lay in the sea. . . Many of them were drumlins, standing knee-deep in water; and on their exposed ends and sides the waves . . . cut cliffs and built bars and beaches. The submergence appears to have been rather short-lived here and elsewhere along the coast of New England and the Maritime Provinces. The watermark at the 'upper marine limit' is distinct only in those places where there was full exposure to the sea, ground easy for waves to cut into, material easy for shore currents to move, and a slope favorable to wave action and undertow. Where sea cliffs were cut in the

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Fig. 1. Map of southeastern New Hampshire, showing 750 gravel deposits as mapped by the State Highway Department on U. S. Geological Survey quadrangles. Deposits containing only sand are not included. Localities shown by initial letters as follows:

(In northern part) WI, Lake Winnepesaukee; LA, Laconia; BE, Belmont; AL, Alton; BR, Brookfield; MI, Milton.

(On Cocheco River) FA, Farmington; RO, Rochester; DO, Dover.

(Eastern corner) SO, Somersworth; MD, Madbury; NW, Newington; PO, Portsmouth.

(Southeastern part) EX, Exeter; KE, Kensington; FR, Fremont; KI, Kingston.

(On Lamprey River) DE, Deerfield; RA, Raymond; EP, Epping.

(Western part—on Soucook River) LO, Loudon.

(On Suncook River) BA, Barnstead; AN, Allenstown.

(On Merrimac River) HO, Hooksett; MA, Manchester; NA, Nashua.

seaward ends of drumlins . . . the cliffs are no longer steep banks, but have been softened by frost creep, slump or rainwash. Platforms developed in front of these cliffed headlands or islands are in some places simply wave-swept slopes of till, paved with cobbles and boulders; in other places they have a thin mantle of gravel or sand such as would be expected more generally along a well developed shoreline. Some islands, like Long Hill and Barker's Hill in Stratham were tied together or connected with the mainland by bars where beach drifting was active, or had hooked spits built out on their sheltered ends, like Stratham Hill. Gravel pits in these show typical rolled and stratified beach gravels and sands. . . Measurements of the present altitudes of the marine limit indicate that the points which according to theory once registered a common level or waterplane no longer agree in level but fit rather closely a plane that slants southeastward at a rate of between five and six feet to the mile. . . That this emergence was already in progress when the coast was uncovered is suggested by the delicacy with which wave work is registered at the marine limit; that it was both steady and rapid is suggested by the lack of any strongly defined shoreline between the marine limit and the present shore."[34]

This interpretation of former strandlines needs revision: for our mapping of the gravel deposits on the newly contoured sheets and the study of sections exposed in scores of new gravel pits since 1925 convinces us that many of the "shoreline features" are largely—and perhaps wholly—of glaciofluvial origin. What were once regarded as seacliffs on drumlins may in some cases be terraces cut by ice marginal streams; in other cases they are abnormally steep initial slopes of drumlins abutting on icemarginal outwash deposits. Two of these deserve special mention: a flat topped triangular terrace at the west end of Newfound Hill in Kensington and a narrower one at the east end of Moulton Ridge in the same town. Although both the form and the vertical position of these justified consideration of them as watermarks of the upper limit of marine submergence before sections were opened, and one of them, accordingly, had been carefully measured and used as one of the points for reconstructing the marine waterplane, deep gravel pits that have been opened in them since that time show convincingly by their structure that they are ice-contact deposits built in small pools against the drumlin ends. Since their elevations approximately match those of other outwash deposits of diverse shapes and sizes in their vicinity, falling into line

[34] Goldthwait: Op. cit., pp. 29-32.

with them on the map, as already described, we may infer that such pools in the ice formed a well connected system draining seaward in thinned and wasting ice and not much above the sealevel of the time.

Most of the "beach ridges" lack perfect horizontality: they rise and fall gently, instead, after the manner of kame deposits. Their internal structure now abundantly exposed often shows poor sorting, slumped crossbedding, boulder beds, and isolated boulders. Rarely do they display that thorough layering, with separation of shingle from sand, which distinguishes shore drift from outwash. Still more disconcerting is the fact that a number of these beach-like features occur in most unlikely situations, without proper associations or characteristic curvature, while those drumlins which according to the theory stood most openly exposed to the sea furnish the least convincing watermarks of all. Of course, one may argue that even waveswept sediment might have been rendered irregular by shore ice which crowded rocks ashore and became so involved in deposits as to cause sagging or pitting of the surface after crustal warping had brought it above the reach of the sea; but the extent to which such a modifying factor is called for leaves little place for normal shore processes. Where so many things point to downwastage of the ice and well organized drainage systems sweeping gravels and sands into pools and pockets, it appears wise to reject all but the clearest cases of shore forms. A hooked spit at the west end of the Stratham Hill drumlin[35] is one of these.

## *Sea-Floor Clay.*

Belief in lateglacial submergence of the coastal area depends not only upon the widespread deposits of sand and gravel but also on associated deposits of clay, used for brickmaking at Rochester, Gonic, Epping and Exeter. These were long ago described by Upham and Hitchcock, and assigned to marine origin because of the presence in them of fossil shellfish, particularly *Leda*.[36] Although no authentic discovery of such shells has been reported since Upham's time, from New Hampshire clays, there seems to be no reason to doubt the older record. The clays closely resemble known marine clays of the

[35] Op. cit., p. 31 and Figure 7.
[36] Hitchcock, C. H.: The geology of New Hampshire, Part 3, with Chapter 1, Modified drift by Warren Upham, pp. 165-167, 1878.

St. Lawrence Valley and other regions in their utter lack of textural lamination, in contrast with the varved clays of fresh-water areas. Their continuity northeastward through Maine past Portland and Brunswick, where they spread far inland, become more continuous, reach greater altitudes and are associated with shell-bearing sands and gravels leaves little doubt of their marine origin.

Since fine sediments collect only in quiet water, it is not likely that the clays reach up to the limit of submergence anywhere. At the Epping brickyards, however, broad clay flats lie at 140-150 feet elevation, or within ten or twenty feet of such watermarks as have hitherto been taken to mark late-glacial sealevel. Near Exeter they are much lower, while at Gonic they reach 200 feet.

If the removal of ice from the coast consisted, as we have come to think, of downwasting over a wide area, so that the waves and shore currents had little chance to mark out shorelines, then the detail of topography of these clays acquires fresh interest, inasmuch as lingering masses of ice might be expected to have imposed their outline on the seafloor sediments as well as upon the coarser sediments of shallow water. No thoroughgoing study of the morphologic detail of the clays has been made. That some tracts are level and others definitely undulating and of variable thickness is obvious enough; but it is not certain how far the unevenness is due to thin clay deposits on an uneven base and how far, possibly, to lingering ice preventing uniform deposition.

A more promising field than New Hampshire for testing this hypothesis is in Cumberland County, Maine, where clays are much thicker and more widespread, but associated, as in New Hampshire, with high pitted plains and kames of gravel and sand. Wide areas of sag-and-swell topography in marine clay are traversed by highways in the townships of Buxton, North Yarmouth, and Waterboro, for example. Although elaborate stream dissection if carried far beyond the mature stage of the cycle can produce hummocks and hillocks very much like ice-contact features, that, in the writer's opinion, is not the case in the areas just mentioned. Nor can the sags and swells be attributed to artificial grading of clay areas that were formerly worked as brickyards: these examples lie far beyond the reach of sites thus used. One hesitates to resort to the theory that the sag-and-swell surface was produced by glacial readvance over a seafloor; for there seems to be no deposit of till, boulders, or coarser material on top of the clays. And deep road cuts seem to prove that the clay deposit is much too thick to undulate over a still more uneven till and rock surface. It seems more likely that the surface was produced by sedimentation in contact with lingering areas of thin ice.

## IMPLICATIONS OF THE THEORY OF DOWNWASTAGE.

Inasmuch as the features described here as characteristic of New Hampshire can be seen also in Maine and the Maritime Provinces and as the hypothesis of downwastage applies equally to all, the possible consequences of it are of more than local interest. Moreover they touch our conception of lateglacial crustal upwarping and of rates of rise of sealevel.

### *Why the "Marine Limit" is so Obscure.*

The strange discontinuity and obscurity of strandlines at the upper limit of lateglacial marine submergence has been remarked by almost every investigator of the records, from Quebec and Nova Scotia down to Massachusetts. Search for emerged beaches and measurements of their elevations by the writer, begun in 1909 for the Geological Survey of Canada, extended up and down the St. Lawrence and Ottawa valleys, around the coast of Gaspé, New Brunswick, Prince Edward Island and Nova Scotia, and concluded in 1926, together with scattered observations on the coast of Maine and more detailed studies in southeastern New Hampshire and in Essex County, Massachusetts, have confirmed the opinion that true records of wave and shore-current action above the old seafloor deposits are not only scarce but impossible to distinguish from icemarginal deposits of stratified drift. A favorite theory to account for this obscurity of watermarks, namely, a rapid and uninterrupted emergence of the coast when uncovered by the ice has never been really satisfactory, in view of the probability that even on an emerging coast violent storms must occasionally leave strong strandlines at favorable places. The alternative theory of an ice-bound coast without effective wave action has been entertained by many writers, although the existence of shore ice so continuous and lasting for so long a time was not explained, and the only direct evidence of its presence seemed to be the removal of erratic boulders from the zone of emergence. If now we apply the theory that the ice sheet uncovered the coast by thinning down upon it, the lateglacial blanket of ice comes to have a new meaning, and the zone thus shielded from wave action acquires a breadth and degree of permanency that seems adequate.

Still we are left with the problem of reconstructing the waterplane of the lateglacial sea. To solve this we have a very limited number of what seem to be reliable shoreline features, built by waves and currents at sealevel, and mostly at or near the upper "limit"; less definitely and accurately we have the much larger number of watermarks presented by ice-marginal kames, washplains and embankments, with all their variety of form and structure. Their approximations to flatness at elevations not wholly out of accord with the accepted "beaches" and with one another, and their internal composition and structure, especially the unconformities that separate topset beds from foresets,—all these, if considered carefully as indicators of the local waterlevels to which they were related, may ultimately fix the position of the lateglacial sea as closely as we have until now thought it fixed. But until the record is more fully analyzed, it seems best to adopt the view that the southeastward gradient of these lines of lateglacial outwash is as much an initial slope of meltwater as it is an upwarped waterplane of the sea.

### *Ice Thinning as a Cause of Crustal Upwarping.*

Both in North America and in Fennoscandia, studies of lateglacial upwarping have led to general acceptance of the theory that these crustal movements were caused by removal of ice load. Particularly in Fennoscandia the argument seems strong: for (a) the unwarped area is approximately the area formerly covered by ice; (b) the upwarping was greater where the ice was thicker, with a few low flattish domes of uplift simulating the former higher dome of ice which centered over the Baltic Sea; and (c) the uplift came promptly with ice recession, and proceeded fast for centuries. Though slowing down greatly, it seems to have continued even to the present time. The remarkable analyses of rates of recession of the ice border over Sweden by DeGeer and over Finland by Sauramo, together with the extraordinarily detailed studies of upwarped waterplanes by investigators of both countries present a strong case for this view of cause and effect. It has recently been reviewed by Daly.[37]

In North America Antevs' studies of ice retreat along lines of varved sediments in western New England and New York and in the Sudbury-Cochrane district of Ontario, filled out by rough estimates of longer time intervals during ice recession across the gaps that separate and lie beyond these lines, have renewed the emphasis on the classic theory of orderly ice recession, leaving almost unmentioned the probable lowering of the surface of the ice sheet by areal wastage. If thinning down of the ice proceeded so far as we are led to suppose it did in New Hampshire before the overspreading of the lowlands by sea or lakes, and if response of the crust to removal of load was as prompt as all have thought, then it seems likely that a large part of the crustal upwarping came before waterplanes were registered. Thus the total amount of uplift may be much greater than hitherto figured from the deformed shorelines of the lateglacial seas and lakes,—which adds to the difficulty of attributing so great a crustal movement to an ice sheet from 5,000 to 10,000 feet thick.

### *Ice Thinning and Rise of Sealevel.*

Changes of sealevel accompanying the waxing and waning of ice sheets have been taken more and more seriously with fuller knowledge of the maximum areal extent of the ice caps and with more definite measures of their actual or minimum thicknesses. Antevs and Daly, particularly, have computed the vertical oscillations of sealevel or "eustatic changes" of the last glacial stage. Correct analysis of postglacial drowning of the coast, not only on opposite sides of the Atlantic but throughout the world is of wide consequence; for upon it may depend the proper correlation, for instance, of prehistoric human records in Europe and America. Also eustatic movements must be disentangled from regional crustal oscillations of lateglacial time, supposedly due to unloading. If it should appear that the amount of water delivered to the sea by ice melting during the decline of the ice age depended more upon downwastage of the surface than upon final recession of the ice margin, it is not easy to judge correctly the stage reached by rising sealevel for

[37] Daly, R. A.: The changing world of the ice age, New Haven, Chapters II, III, 1936.

any given position of the ice border. If, for example, one wished to estimate the stage reached by rising sealevel when the ice uncovered Boston, it would be useless to figure out a ratio between the distance from Nantucket moraine to Boston and the total distance from Nantucket to the center of glaciation in Canada. Vertical and horizontal wastage may not have been at all proportional.

## CONCLUSION.

It was natural that glacial geologists in New England, impressed by the elaborate mapping of recessional moraines in the Great Lakes region for several decades, sought to interpret their own lateglacial records accordingly. So fully were our minds accustomed to the theory of a single great ice front across New England that there was danger of ignoring the downwastage that must have accompanied it. Sufficient thinning by ablation to produce lobes in the deeper valleys was conceded, indeed; but wholesale fragmentation of lingering ice masses was suggested only in rare instances, such as Clapp's study of Glacial Lake Charles. In New Hampshire, so long as detailed studies covered small areas and reconnaissance was handicapped by poorly contoured maps, it was easy to imagine correlations of hummocky moraine-like banks of drift, or of scraps of ice contact deposits found in lines transverse to ice flow, and to grasp at these eagerly as promising signs that the favorite theory would finally find full illustration in northern New England.

Especially when DeGeer's key to lateglacial chronology—the matching of varves—was skillfully applied to New England and Canada by Antevs in the early 1920's, previous doubts were all but forgotten and lines of ice front were plotted boldly across broad belts of hilly country from the Hudson to the Connecticut and from the Connecticut to the Merrimac. At last we had "aequicesses" like those drawn by DeGeer in southern Sweden and by Sauramo in Finland. But the gaps between these rivers were very wide, the terrain highly irregular, and the "moraine" fragments obscure and as yet little explored.

The first real challenge to the theory of orderly recession in New England came in 1929, when Flint held that the "recessional moraines" of this region were fictitious and that the deposits of western Massachusetts and Connecticut required stagnation and irregular downwastage of the ice.

During this interesting decade or two, all of New Hampshire has been freshly contoured, the State Highway Department's gravel survey has examined and mapped several thousand deposits, and an effort has been made to account for them, singly and collectively. Ice-contact features almost everywhere have proved to be irregular and to trend north, east, west or south, with little preference, instead of transverse to ice flow. Kame terraces arranged on opposite sides of valleys are the dominant type of stratified drift; and their persistence is remarkable. Associated kames of great variety of size and shape, and crevasse fillings, strengthen further the impression that in this hilly region we are not dealing with one continuous ice edge that receded in orderly fashion across country but rather with a maze of downwasting, thinning ice which lay stagnant or nearly so when these gravels and sands finally accumulated, occupying areas so utterly ragged in outline and so unstable in pattern that one can hardly reconstruct successive stages of ice removal on the maps.

Three lines of supposed halt and readvance in New Hampshire, plausible enough so long as reconnaissance followed selected zones and gave certain forms and structures false significance, have had to be abandoned as fuller mapping on the new quadrangles and study of many new exposures brought out the abundance of ice-marginal forms and showed their marked tendency to lie along lines of meltwater drainage, parallel to ice motion rather than transverse to it. Particularly this has been the case in the coastal region, where ice-molded kames and pitted plains run in parallel systems, seaward, as if directed by the evenly slanting surface of an ice sheet that had thinned down almost to sealevel but was traversed by parallel ice canyons.

These characteristics of kettled and ice-banked outwash material are not peculiar to New Hampshire alone; they prevail also in Maine, though not yet mapped in detail there. On the surrounding lowland the sag-and-swell surface of marine clay invites the idea that downwastage of ice continued even until the last fine sediments were spread. The obscurity of shoreline features at the marine limit may thus be explained. But in adopting this view of the lateglacial records we give up the long cherished basis for figuring accurately the amount of lateglacial upwarping.

Finally, in admitting downwastage as a large factor in the removal of ice from the surface of New England, we add an unrecorded amount of lateglacial deformation to what has hitherto been figured, and thus increase the difficulty of accounting for so much uplift by the removal of ice load. We also complicate the problem of timing the lateglacial rise of sealevel, since that may be less closely related to horizontal shifts of an ice margin than we have thought.

In spite of these disturbing consequences, it is the writer's slowly formed conviction that the evidence from New Hampshire and adjoining states favors the theory that ice removal here was accomplished largely by thinning.

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