Plate V. Maximum glaciated areas in North America during the Great Ice Age.

The Great Ice Age in Vermont

ELBRIDGE C. JACOBS

The subject of glaciology is one of the most fascinating in the whole field of geology and, moreover, most of its concepts are easily comprehended by the lay reader while illustrative material is seen, in this north country, on every hand. This article represents one more effort on the part of the State Geologist to arouse interest among the citizens of Vermont and elsewhere, and especially among the young people, in the wonderfully varied geology of the State. With this brief story of glaciology in mind they will be the better fitted to read, study, and observe the many glacial phenomena of this region. Furthermore, the article will serve as an introduction to Professor Chapman's brilliant paper on the glacial history of Lake Champlain which follows.

At least three times in the geological history of the earth hundreds of thousands, and even millions, of square miles of its surface have been deeply buried by ice-sheets which, persisting for hundreds of thousands of years, have profoundly modified the land, eroding its bed rock, moving tremendous quantities of unconsolidated rock material, damming up lake basins, deranging old river systems, modifying climates, causing considerable changes in sea and land levels and, on melting, leaving immense quantities of débris in characteristic glacial forms.

The glacial epochs, as they are called, are irregularly spaced as to time, the oldest occurring in the Proterozoic Era roughly a billion years ago, and leaving its evidences in the country north of the Great Lakes, in Australia, South Africa, and other regions.

The second great glaciation occurred in Permo-Carboniferous times, some 230,000,000 years ago, and was especially remarkable for its occurrence in tropical areas of South America, Africa, and in Australia, as well as in regions remote from the equator. In North America this glacial epoch is definitely known only on the coast of Massachusetts (at Squantum, near Boston) but there may be other areas in some of our other states, in Alaska, and Canada.

The latest glacial epoch is called the Pleistocene, or Great Ice Age. Geologists believe that it began about a million years ago and its waning stages are still with us. Plate V[1] shows the area of maximum glaciation in North America during which about 5,920,000 square miles of the continent were covered by the ice-sheet. The Pleistocene also extended over some 1,350,000 square miles of Europe, 5,200,000 square miles of Antarctica, and smaller areas in Asia, New Zealand, and Patagonia, giving a total glaciation for the earth, according to Daly (1), of 12,900,000 square miles, or about 13 percent of the surface of our planet. These maximum areas in the different continents were not necessarily contemporaneous.

[1] Reproduced from Tarr & Martin's College Physiography by kind permission of the Macmillan Company, New York City.

Today the ice-sheets in Greenland and Antarctica and the smaller ice-caps on Ellesmere and Grinnell lands, in the Arctic, cover about 6,000,000 square miles, so that the Great Ice Age is only approximately half over and the earth is slowly returning to the more genial climes of its normal condition.

In the Pleistocene there were several great areas of ice accumulation of which the two largest are known as the Keewatin and the Labrador ice sheets (Plate V). From these centers the ice, which had accumulated on the relatively low lands of Canada (today about 1,000 feet above sea level) spread out in all directions. In the mountainous and plateau regions of the far west mountain glaciation (see p. 33) first appeared and gradually spread to the plateaus and valleys forming what is called by some writers the Cordilleran-sheet. According to Coleman (2) the Keewatin-sheet covered over 1,500,000 square miles while the Labrador-sheet, which formed later, had an area of some 2,000,000 square miles; these two sheets ultimately coalesced. The Cordilleran glaciation reached an elevation, according to the same writer, of 8,000 feet, for glacial phenomena appear on the mountains up to this elevation. Above this ice-sheet many mountain tops projected as islands, called nunataks. The Labrador sheet covered eastern Canada, New England, New York, and the present Great Lakes region, overriding all our New England mountains, as well as the Adirondacks, and extending for considerable distances into the ocean.

The southern border of the ice sheet, the terminal moraine, is shown on Plate V extending along the southern shore of Long Island, crossing Pennsylvania, and following the courses of the Ohio and Missouri rivers and thence westward to the Pacific coast. It is noted that a large part of Alaska is unglaciated—this because of deficient precipitation.

Geologists estimate that the ice sheet, at maximum, was some 10,000 feet in thickness. It either killed or drove to the south all living things and must have presented a desolate waste if there had been human eyes to see it.

Daly (1) estimates that if all the Pleistocene ice-sheets reached their maximum size simultaneously, the ocean lost about 240 feet of depth, which would have extended the Atlantic coast line considerably to the eastward. On the other hand, should all the ice-sheets of the earth today be melted the ocean would gain about 160 feet in depth and many of our coastal cities would be submerged.

In North America and Europe, owing to climatic fluctuations, there were four advances of the ice-sheet, separated by three interglacial stages. In the United States the sequence, from oldest to youngest, included the first advance, called the Nebraskan, followed by the Aftonian interglacial stage; the second advance, known as the Kansan, followed by the Yarmouth interglacial; the third, of Illinoian advance, followed by the Sangamon interglacial; and the latest, or Wisconsin advance, followed by the Post-Glacial stage, in which we live. It is an interesting speculation whether we are in a fourth interglacial stage and if, say in a few hundred thousand years, another ice-sheet will descend upon the earth.

The interglacial stages were hundreds of thousands of years in duration and in them the ice-sheets were melted back to varying degrees, and animal and plant life again flourished in the formerly ice-ridden areas. In the Yarmouth interglacial, which was the longest in duration, it is thought that the earth was warmer than it is now.

In New England the glaciation belongs very largely to the Wisconsin advance and was a part of the Labrador Ice-Sheet.

With the coming of the Post-Glacial stage the ice-sheet slowly melted ("rotted") and its front retreated northward, where it is found today on borders of Greenland and in Ellesmere and Grinnell lands. Antevs (3) shows that it required 4,100 years for the ice front to retreat from Hartford, Conn., to St. Johnsbury, Vermont, a distance of about 185 miles; this is at the rate of one mile in twenty two years (see p. 39). Daly (1) estimates the time required for the retreat of the ice front from Long Island to the center of dispersion at James Bay (the southern end of Hudson Bay) at about 30,000 years.

It may be mentioned, in passing, that primitive man probably first appeared in the Pleistocene Epoch.

GLACIERS

Glaciers form in those regions where more snow falls in the winter than can be melted in the following summer. With successive snow falls and the effect of moisture the snow assumes a granular texture and is slowly consolidated into ice. The progress can be observed in your back yard, in spring, where the transition from granular snow to solid ice is clearly seen. The granular snow is called the névé.

Ice is a crystalline substance similar in its optical properties to mineral crystals (it crystallizes in the hexagonal system), and glacial motion, caused primarily by gravity, is not that of a viscous substance, like tar, but is a very complicated affair which, like the cause of glacial epochs, need not be gone into here. Glaciers carry, frozen into their bottoms, rock débris from their scouring action and, on their surfaces, enormous amounts of rock wastage of all sizes, including boulders often of huge dimensions, plucked from the rock surfaces in their course, together with soil and vegetable growth. The rock débris, of all sizes, is called *glacial drift*. The glacial ice wastes by evaporation and by melting. Streams of melt-water flow in and under the glacier and the sediments carried and deposited by them give rise to characteristic glacial forms. A glacier acts something like a huge belt conveyor, bringing the rock débris to a position where ice melting is equal to ice "making." Here it forms a temporary *terminal moraine*. Streams from the ice, working over this morainal material, sort it, carrying away the finer material and leaving *outwash plains*. The material under the glacier forms the *ground moraine;* in mountain glaciers *lateral moraines* also form.

Hence a region like Vermont shows many evidences of former glaciation, as will be shown.

Like water-streams glaciers erode and transport, and deposit their loads.

GLACIAL EROSION

The erosive action of glaciers is due to abrasion, and quarrying or plucking. Ice is too soft a substance to erode rock by itself but needs "tools," as rivers do in their erosive action. But, whereas the tools of a stream are sediments carried in the water, the glacial tools are rocks frozen into the under surface of the moving ice—something like the action of a diamond drill with its black diamonds (bort) embedded in the end of the bit, only of course the motion of the ice is not circular but longitudinal. Thus equipped the glacier moves ponderously forward under the action of gravity, smoothing, fashioning, striating, and gouging the rock surfaces below. These smoothed surfaces are very common in this State, projecting above the soil mantle and drift and bearing upon them striations and grooves. Some of these rounded rock surfaces resemble a longitudinal section of a cigar with the tapering end towards the advancing ice (the stoss side) while the butt end (or lee side) is cut off abruptly by the plucking action, to be presently described. These surfaces form asymmetrical rock hills, with their gently sloping stoss slopes and abrupt lee ends. All these rounded rock forms are called *rôches moutonnées,* from the fancied resemblance to a sheep's back.

Striations and grooves are found almost everywhere in Vermont: on the mountain tops and in the lowlands, and their compass courses, or trends, tell us the direction in which the ice was moving. These trends are mostly from west of north to east of south but cross-striae on the same surface, and even east-to-west trending markings, in some places, testify to cross-currents in the ice-sheet. On Mount Mansfield, near the hotel, the smooth rock surface bears striae trending North 37° West, while along the summit ridge other striae trend in the same general direction. But along Hell Brook Trail, which ascends the east side of the mountain from Smugglers Notch, striations are noted trending about north and south. Without doubt all the mountains of the State bear glacial striae. The most astonishing display that the writer has seen is on the summit of Mount Hunger, in the Worcester Range, which shows thousands of such markings. They trend from N. 6° to 24° E. There are said to be similar striated surfaces on the neighboring Burnt Mountain. In East Putney there is a glaciated surface, peering out from under its drift mantle and striated.

Glacial grooves are also numerous. On Isle La Motte the Trenton limestone shows such depressions a foot wide with parallel striae in them: A specimen from here, at the University of Vermont, has such a groove a foot wide, with striae cutting an Ordovician fossil snail (*Macluria magna*).

In the 1861 Geology of Vermont hundreds of striae are listed with trends ranging from N. 70° W. to N. 70° E. The accuracy of these figures is questionable. Glacial grooves are also listed, the largest (in Whiting) is "several feet long"; other dimensions are not given. Another is located along the Missisquoi River, north of Troy: "six inches wide, three feet deep, and three or four rods long," trending southerly.

Besides striations and grooves, "chatter marks" are found. These are horseshoe-like gougings caused by the rasping action of the ice-held tools cutting out rock chips—like those made on wood by a chisel too lightly held. The 1861 Geology locates such "chatters" "along the shore of Lake Champlain," which is delightfully vague.

Glacial quarrying, or *plucking,* by which masses of rocks, often in the form of joint blocks, are loosened and carried away from their parent rock, is due to the prying action of freezing melt-water which has penetrated the joints and fractures of the bedrock. This action may go on beneath the ice-sheet as well as on exposed rock surfaces. Plucking gives rise to *glacial troughs* and *cirques.* Glacial troughs are U-shaped depressions, often of vast cross-section and great length. They usually occupy pre-glacial stream valleys to which they add the U-section. The tortuous courses of the old valleys become straightened out by the snubbing action of the ice-sheet. A good many stream valleys in Vermont show this modifiying action; the Black River Valley, in Coventry, is a case in point.

GLACIAL TROUGHS

The finest glacial trough in Vermont was carved out of the limestone ridge, intruded by granite, which crosses southern Westmore, in Orleans County, from northeast to southwest and forms the divide between the St. Lawrence and the Connecticut River drainages. This great U-shaped cut, trending northwest and southeast, is a striking feature of the region and is visible for many miles; even on a clear day, from Mount Washington. In it lies the upper portion of Lake Willoughby (4), one of the most beautiful bodies of water in the State. This lake is about five miles long and somewhat less than a mile in maximum width. Its surface is 1,170 feet above sea-level, while from its eastern shore Mt. Pisgah rises to 2,761 feet, and from its western border Mt. Hor reaches 2,648 feet. The lake basin, in cross section, increases gradually in depth from the eastern shore to about 200 feet, at one-third the width of the lake, and then descends precipitously forming an inner gorge 250 to 330 feet wide and 96 feet deep, giving the lake a total depth of 296 feet.

Now this trough was probably not carved from a preexisting stream valley but owes its existence wholly to the plucking action of the glacier; for most of the glacial débris is found as a high morainal embankment some distance south of the lake and 130 feet above its surface, while the glacial dam at the northern end of the lake is composed of sand only twenty-seven feet above the lake level. These facts and the deep, inner gorge seem to show that the trough was excavated by the southward movement of the ice-sheet. The outlet of the lake is controlled by a dam; the overflow empties into the Willoughby River, a tributary to the Barton River.

To the west of the lake lies Wheeler Mountain, a granite "boss" glacially smoothed, with a steep escarpment on its eastern border caused by the "snubbing" action of the ice. Several other eminences in the neighborhood show the same effect.

About four and one-half miles to the west, in Barton, Crystal Lake lies in a similar but less spectacular trough. Its surface is 945 feet above sea level. Lake Willoughby is shown partly on the Lyndonville and partly on the Memphremagog topographic quadrangles; Crystal Lake is wholly on the former.

The Averill Lakes, in Essex County, also lie in rocky basins carved out by glacial action.

Fig. 4. The glacial trough near Peacham, Vermont.

There is another large glacial trough in Underhill, Chittenden County, lying between Macomber Mountain and the western spurs of Mt. Mansfield, but there is no lake in it. The glacial trough southeast of Peacham, Caledonia County, is shown on Figure 4. Probably other troughs exist in the State.

SMUGGLERS NOTCH

Smugglers Notch was originally formed by stream action in the great fold (an anticline) which once included Mt. Mansfield and Stirling Mountain; its course is north and south. The highest point in the Notch is 1,803 feet above sea level and forms the divide between the Brewster River, flowing north to the Lamoille, and the West Branch, or Waterbury River, which empties into the Winooski.

The valleys of these rivers are heavily glaciated: great deposits of till are seen along the highway through the Notch. It has already been noted that, along the Hell Brook trail, glacial striae are still to be seen, trending generally

north and south; other glacial features may well have been obliterated by the great rock falls from the valley walls. It is clear that a tongue of the ice-sheet passed through the Notch.

A GLACIAL POTHOLE

Ordinary potholes are round or cylindrical excavations in bedrock caused by the swirling motion, or eddys, in streams laden with their "tools" which may consist of sand, gravel, or even boulders of considerable size. The pothole stones are themselves rounded by the abrasion. Such potholes are very common in our streams; one of the best series of such holes is seen along the lower course of the Huntington River in Richmond.

That streams of melt-water, high up in the ice-sheet, produced this type of erosion is shown by the glacial pothole not far from the summit of Burnt Rock Mountain in Fayston, Washington County. This pothole is four feet in diameter, about thirty inches deep, and 2,820 feet above sea level. It is described by Professor Doll (5).

MOUNTAIN OR ALPINE GLACIATION

If mountains are sufficiently lofty to extend above the snow line, glaciers form on their surfaces and move down the valleys, which they modify as stated above. The Alps, Himalayas, Rockies, and many other mountains in various parts of the earth show this type of glaciation.

On such mountains there are formed, by the quarrying action of the ice, snowshoe-shaped depressions with their broad, convex ends towards the mountain crests and their narrower ends extending down the slopes. The upper ends form steep head-walls, often thousands of feet high. Such depressions are called *cirques*. The glaciers, whose quarrying action forms the cirques, are "nourished" by the snow fields above and these must of course be extensive, hence only on large mountain masses are cirques found. Often two cirques form on opposite slopes of a mountain and quarry towards each other, so that often only a narrow ridge of the rock remains. Such a residual ridge is known as an *arête*. If three or more cirques approach one another, a pyramidal erosion remnant remains, often thousands of feet high; this is called a *horn*. The Matterhorn, in Switzerland, is probably the most famous example.

The Presidential Range, in New Hampshire, is today far below the permanent snow line but, during the Pleistocene Epoch, as the ice-sheet approached the range, Alpine glaciation was induced and eight cirques were formed. These are indicated on the Mt. Washington topographic quadrangle. They are in order: Tuckermans Ravine, Huntington Ravine, the Great Gulf, Jefferson Ravine, Madison Gulf, Castle (Gulf), King Ravine, and Bumpus Basin. All except Castle (Gulf) lie east of the Crawford Path-Appalachian Trail. Whether one could consider the ridge along which the trail runs an arête is open to question. Further information concerning New Hampshire glaciation can be found in Professor Goldthwait's valuable book (6). This author states that: "Strongly developed cirques have been reported on Mt. Katahdin, Maine." No cirques exist on the Green Mountains, the explanation being that the crests were not sufficiently high or extensive to furnish adequate snow fields for circation.

Fig. 5. Glacial erratic in Underhill.

TRANSPORTATION

Glaciers gather in their courses and transport enormous amounts of rock material of the most diverse form and size: from great boulders, called *erratics*, to gravel, sand, and clay; the clay may arise also from the decomposition of the feldspathic minerals in the rocks. All this glacial matter, as we find it today, is called *drift* or *till*. In its unmodified state the drift is unsorted, the larger pieces often lying on the finer material.

Glacial erratics, often of enormous size, are found everywhere in a glaciated region. The largest ever discovered is known as the Madison Boulder and lies in the woods in Madison, N. H., about half a mile west of New Hampshire Route No. 13. It measures 83 by 37 by 23 feet and is estimated to weigh 7,650 tons. It is a single block of granite which Goldthwait states was evidently brought by the ice-sheet from the ledges in Albany, N. H., about two miles from its present resting place.

In Vermont erratics are found on every hand, from the mountain tops to the shores of Lake Champlain, and on the islands in the lake. The largest ever reported was found in West Whitingham. The 1861 Geology of Vermont gives the dimensions as 41 feet long, 32 feet wide, and 125 feet in circumference, with an estimated weight of 3,400 tons. It is known as the Vermont Giant; the material is not stated. Another huge erratic, called Rock Raymond, is recorded in the same volume as lying in Stamford. It is 12 feet high, 20 feet long, and 18 feet wide. Others are found in Searsburg, along the Deerfield River, from 6 to 25 feet in diameter, and in the region between Bennington and Brattleboro. Numerous erratics occur on the flanks of Mt. Ascutney.

Probably most of the erratics have been transported only short distances but some have traveled far. Thus, on Mt. Mansfield, east of the summit ridge, the largest boulder, over 30 feet long by about 20 feet high; and another, 21 feet long by 8 feet wide, and 9 feet high, are of Green Mountain gneiss and probably of local origin; but a smaller erratic is composed of syenite which is not found in the Champain valley but probably came from Canada. Unfortunately it was removed, years ago, to the Stowe cemetery as a war memorial.

In Underhill, a few rods south of the summit of the road which leads from the Center to Stevensville, there is a great erratic (Figure 5) 19 by 15 by 10 feet, made up of serpentine studded with shining black octahedral crystals of magnetite and showing on its surface elliptical markings which are characteristic of pillow lava. On the roadside opposite the Shaw cottage there are several others. The nearest sources of this type of igneous rock are on Owls Head and Bear Mountain, near Newport, Vt., some forty miles in an air line to the northeast. Professor Doll describes an erratic on the Clyde River (Figure 3).

Sometimes erratics are so delicately poised that they can be tilted by hand; they are then called balanced rocks. There is one, reported in the Geology of Vermont (1861) in Greensboro, weighing seventy tons. Another boulder here, not balanced, is 41 feet long, 22 feet wide, and 22 feet high.

BOULDER TRAINS

Erratics sometimes form boulder trains, or trails, of the same kind of rock, extending over considerable distances. The largest one in the State is made up of syenite boulders (syenite is quartzless granite) from Mt. Ascutney. From this source it spreads out, fan like, in a widening arc across southern Vermont, western New Hampshire, as far east, according to Goldthwait, as East Jaffrey and Peterboro, and as far south as Bernardston, Mass. Pieces of the syenite are now found in the stone walls along the course of the train. Goldthwait states that this fanning out was probably due to the changing in direction of the glacial flow, and this is borne out by the varying compass directions of the striae and grooves in the bedrock.

In Craftsbury, Vt., there are huge erratics composed of biotite granite containing more or less spherical segregations of biotite, an inch or less in diameter. This is called orbicular granite; prune granite is a local term. Similar erratics have been found in Irasburg and in Stanstead, Quebec. A boulder train is thus suggested but it has not yet been studied.

The most striking formation in northwestern Vermont is the red Monkton quartzite which extends from Snake Mountain, near Middlebury, to Roods Pond, in Milton. Rocks from this formation are easily recognized and have been found to form a boulder train. One of Professor Goldthwait's students has plotted this train and found that it fans out from its source, over an area extending from eastern New York nearly to the Connecticut River.

A smaller train of syenite boulders fans out from Cuttingsville, Rutland County, to the southeast.

DEPOSITION

The extreme southern border of the Pleistocene ice-sheet is marked by ramparts of glacial débris which extend along the southern part of Long Island and thence across the continent as shown in Plate V. They represent the results of the conveyor-belt-action, already referred to, and make up the *terminal moraine.* The material left by the glacier along its course, after it melted, is known as the *ground moraine.* This morainal stuff is seen in boulder-strewn upland pastures and it was in other places before the farmers cleared the land and built stonewalls which became veritable outdoor museums of glacial débris. It has already been seen that the source of the Ascutney boulder train was determined from the material of such walls.

In temporary halting places of the glacier *intermediate moraines* were formed. One crosses the Third Branch of the White River, north of Roxbury, while another is seen in the White River valley near Granville.

LAKES

In Vermont, and of course in other glaciated regions, there are hundreds of lakes, great and small, probably all due to glacial action. They are found in many parts of the State: in the lowlands, St. Catharine, Bomoseen, Dunmore, Carmi, and others; and even on Mt. Mansfield, where the tiny Lake of the Clouds lies about 3,900 feet above sea level and, farther south, Lake Mansfield, a considerably larger body, has an elevation of 1,140 feet. But the Vermont Piedmont, the region east of the Green Mountains, is the lake country *par excellence* of the State, especially that part north of the White River and its tributaries. Here are hundreds of lakes of which the largest are Morey, Fairlee, Willoughby, Crystal, Seymour, Echo, Island Pond, Maidstone, and the Averill Lakes. Of course the largest, Memphremagog, lies only about one-fifth in Vermont.

Some of these bodies of water, such as the Lake of the Clouds, Willoughby Lake, and the Averill Lakes, lie in depressions plucked out of the bedrock and

bordered by glacial embankments, while others have resulted from the glacial damming of preexisting valleys. During the last glacial epoch tongues of ice lay in these valleys and around these tongues, and to a lesser extent upon them, the glacial till accumulated. When the ice tongues rotted away melt-water filled the depressions and formed the lakes. Small ponds so formed are called *kettles;* they usually have no outlets. Childs Pond, in Thetford; Gut Pond, in Eden; Roods Pond, in Milton; Colchester Pond; and Small Pond, in Newport, are kettles.

On the melting of the ice-tongue which filled the Connecticut River valley (7), a great lake, 157 miles long, was formed by glacial damming in the narrow gorge of the river near Middletown, Conn., and its extension northward to Lyme, N. H., was made possible by the downwarping which the earth's crust had undergone under the enormous and long continued pressure of the ice cap, "so that the floor of the valley actually sloped northward towards the ice." "The width of this lake in New Hampshire and Vermont was only two or three miles, but in Massachuetts and Connecticut it attained a width of ten or twelve miles." This body of water, which was named for President Edward Hitchcock, the co-author of the Geology of Vermont (1861) endured for about 4,000 years when it was suddenly drained, probably by the failure of the glacial dam near Middletown.

Of more local interest to us is Lake Upham, which formed after the abrupt lowering of Lake Hitchcock, at 90 feet lower elevation. With the continued retreat of the ice-sheet this lake expanded like the branches of a tree to the north, with one branch reaching North Stratford; another up the valley of the Passumpsic River, past Woodsville and St. Johnsbury, and reaching nearly to West Burke; while a third branch reached Randolph where it received the waters of Lake Winooski, near Montpelier. Lake Upham endured for at least 600 years at Hanover and for 1,600 years near Haverhill and Woodsville. Enough of the old shore lines remain in sufficient degree to permit their delineation.

As the ice-sheet withdrew across Vermont the large streams of melt-water issuing from it greatly increased the size of old valleys which, today, are much too large for the streams flowing in them. Such enlarged valleys may be seen from Route 7, on the way from Burlington to Charlotte, and doubtless in other places. The waters formed ancient lakes fragments of whose shore terraces still remain. Some of these occur along Route 2, going out from Burlington; another on the road from Underhill to Underhill Center.

A long glacial lake formed in the valley of the Black River and extended from Plymouth to Cavendish where it was dammed by a ridge extending across the valley and by glacial drift. When the ice in the lake melted the water overflowed the southern end of the ridge and formed a post-glacial gorge, across which, not many years ago, a dam was built for power purposes. Cavendish Village lies on the old lake bottom on the northern side of the valley. During the fateful November third, 1927 (8), the swollen river, held back by the dam, flooded the old valley, while streams coming down from the north burst the storm sewers which had been built east of the village for its protection, carried away the glacial fill, and revealed the old preglacial gorge of the river. On the polished bedrock were seen striae trending N. 45° E., which showed that a tongue of the ice-sheet had moved down the valley. A similar condition was disclosed in the White River Valley, near Gaysville, where it was seen that the river had been driven from its pre-glacial gorge and was flowing in a post-glacial gorge, which had also been dammed, when the 1927 flood occurred.

Several other glacial lakes, long since drained, have been described by Merwin (9), and C. H. Hitchcock (10), while Bigelow (11) gives the evidence for the existence of a former glacial lake in the Barrows Valley of Stowe.

DERANGED DRAINAGE SYSTEMS

In the glaciated areas of the Pleistocene many rivers have changed their courses, some of them reversed in their flow, by the ice-sheet and the rise of the land following its retreat. The post-glacial channels of the Black River, at Cavendish, and the White River, at Gaysville, have already been noted. Hitchcock (12) states that, at one time, the glacial lake in the Stowe valley was high enough to discharge its waters through the Williamstown Gulf into the Connecticut River, whereas the present streams of the Stowe valley flow into the Winooski. The same author believes that Lake Memphremagog, which now discharges into the St. Francis River and thence into the St. Lawrence, once drained through Eligo Pond, in Hardwick, and thence into the Lamoille River. Moreover he claims that the glacial Lamoille was reversed in its flow and emptied into the Winooski and that the latter stream, also reversed in its course, poured through Williamstown Gulf into the White River and thence into the Connecticut. This was due to the ice tongue which "filled up Lake Champlain so high that there was no chance for the waters to discharge except into an eastern outlet." Without doubt many other Vermont streams were similarly diverted.

GLACIO - FLUVIATILE DEPOSITS

DELTAS

Sediment laden streams flowing into quiet water bodies deposit their loads and form deltas. On these deltas characteristic arrangements of the material are noted: the "top set," horizontal; the "fore set," sloping towards the deep water; and the "bottom set," also horizontal. Of these the "fore sets" are by their inclination the most easily recognized on what may be called fossil deltas (deltas high and dry). Gravel banks have been opened up here and there by the road makers and these foreset beds disclosed. Such indications of former lakes have been noted especially in the Barre-Montpelier region.

The great Bristol delta which the New Haven River formed as it entered Glacial Lake Champlain is of notable interest. Other Champlain deltas will be found discussed in Professor Chapman's paper which follows this article. The Quechee delta, near Deweys Mills, in Hartford, one of the best preserved in

the State, has been described by Goldthwait (13). Quechee Gulf, a narrow, post-glacial gorge is described in the same paper.

VARVES

Streams of melt-water, flowing from a ground moraine, sort the material, carrying the lighter stuff away and leaving the coarser conglomeration of boulders, gravel, pebbles as an outwash plain. The lighter silt and clay are deposited in lakes and ponds, where the stream velocity is checked, forming alternate strata of light-colored silt and dark, greasy clay. These banded strata are called *varves*. The explanation is that, in the warmer seasons of the year, the coarser material settles to the bottom while the finer stuff is held in suspension (colloidal suspension). During the winter months when the ponds are frozen at the surface and the water beneath is stagnant, this colloidal material settles and forms the dark, greasy layer. Thus a coarser and a finer layer, taken together, are the product of one year's deposition. If a varved deposit is sliced smoothly and a strip of paper is fastened against it the varves can be graphed, the age of the deposit in years, told, and by the width of the varves, something about the prevailing temperature determined. Furthermore de Geer, the Swedish geologist who discovered the phenomenon, found that each varve overlaps its predecessor in the direction of the glacial recession—like the slates on a roof which overlap towards the ridge pole.

There is not found an unbroken succession of varves but, by measuring sets of them in all available places, they can be correlated and a chronological series established. Then the number of double varves between the ends of the series will equal the number of years needed for their deposition. The number of double varves between two points along the line of retreat of the ice-sheet will give the number of years taken by the ice-sheet to retreat from the first point to the second.

The varve method affords the most accurate ice-sheet chronology that we have.

Ernst Antevs (3) has carried on the de Geer method of varve study in many parts of North America; some of his earliest studies were undertaken in New England. He determined an equivalent series of 4,100 double varves between Hartford, Conn., and St. Johnsbury, Vt., which meant that it required 4,100 years for the ice-sheet to retreat between these places, a distance of 185 miles, or an average retreat of 238 feet a year. Similar studies by Lougee and others were used to determine the "life" of Lake Hitchcock, Lake Upham, and other glacial water bodies.

Varved deposits are found in many parts of Vermont; in some places they are the only indications remaining of the former existence old lakes and ponds. Several brick-making companies use varved clays.

ESKERS, DRUMLINS, KAMES, KAME TERRACES

The process or processes by which these glacio-fluviatile features were formed has largely to be inferred, since the ice-sheets under which they were produced have disappeeard and the ice-caps of the world today conceal those that are probably forming under them.

ESKERS

Eskers are long, low, sinuous ridges, made up of more or less water-sorted morainal material (sand, gravel, and boulders, great and small) extending along the valleys in the general direction of the ice movement. They are seldom over 75 or 100 feet high, a few rods wide and often less than a mile long, although some are many miles in length. They look like old railroad embankments except that they are too crooked.

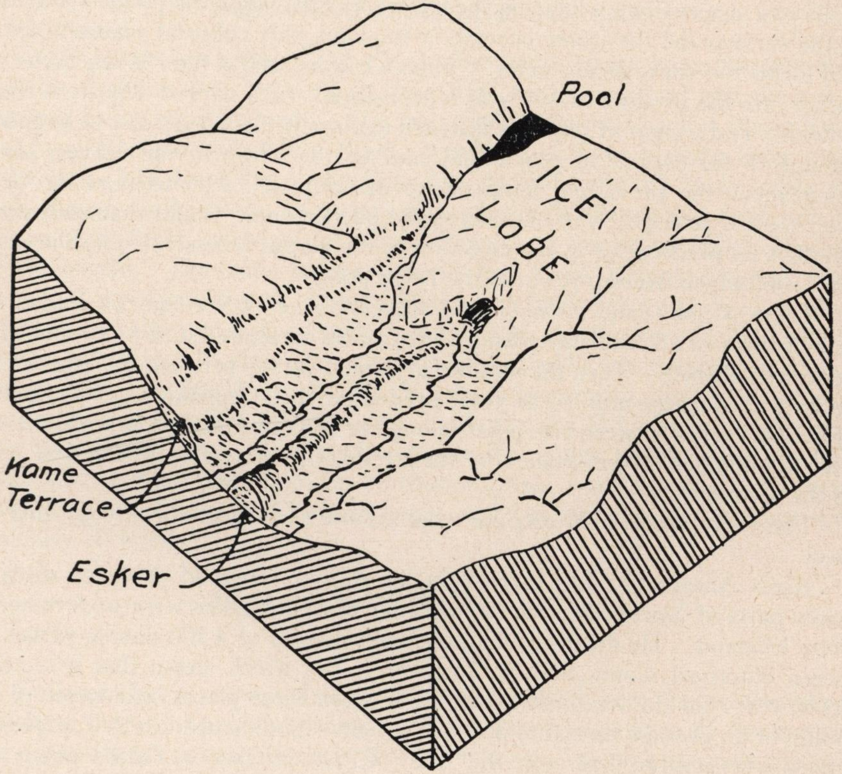

Fig. 6. Block diagram illustrating the way in which eskers and kame terraces are formed during the ice recession.

ORIGIN

The origin of eskers may be explained by an analogy. The Rhone River rises in a glacial trough far up in the Alps Mountains. The glacier itself, whose front forms a huge wall across the valley, is criss-crossed with crevasses and bears on its surface some of the rock débris which it has plucked in its onward

movement. In the glacial front there is a large tunnel worn by the melt-water and flowing from this orifice is the stream which forms the very beginning of the Rhone. The Rhone Glacier has retreated about a mile from its farthest advance and strewn along its old bed one sees the outwash plain, or valley train, made up of englaciated material which had worked down through the crevasses and been swept along the tunnel by the rushing stream. This material is more or less water-sorted: the coarser near the source of supply; the finer farther away; the finest, carried in suspension, gives the milky hue to the river all the way along its course to the quiet water of Lake Geneva, where it settles and is forming a delta. All this is of course the work of an Alpine glacier.

Fig. 7. The esker at West Burke.

A similar action must have taken place in the lobes of the continental ice-sheet which lay in our valleys, but with this difference: Towards the end of the glacial epoch, when forward motion had ceased, sub-glacial tunnels entered glacial lakes which bathed the glacier front and the streams carrying englaciated material were checked in their velocity so that their loads were deposited and the tunnels became choked with rock débris, more or less sorted, forming *eskers*. With the final disappearance of the ice the esker remained with its typical serpentine form. The whole picture is admirably shown in Figure 6, reproduced by kind permisson of Professor Goldthwait.

EXAMPLES

On the way down the valley from Lake Willoughby to West Burke the road cuts across a typical esker (Figure 7), a few rods wide, perhaps twenty feet high and of undetermined length. The cross section shows that the esker is made up of sand, gravel, and small boulders.

Another esker is seen by the roadside in Groton along Route U. S. 302. Goldthwait (13) describes an esker at Bridgewater Corners (Woodstock quadrangle) and another in the northwest corner of Plymouth Township, which forms "a peninsula over a quarter of a mile long and only a few hundred feet wide, extending from the north into Woodward Reservoir" (Rutland quadrangle). Richardson (14) describes an esker, a quarter of a mile long, in the northwest part of Coventry, between two small ponds.

The largest known esker in New England extends on either side of the Connecticut River for twenty-four miles, from Windsor, Vt., to Lyme, N. H. It is unbroken save where the river has cut across it.

There are without doubt many eskers in Vermont which should be located. The readers of this article are asked to aid in this interesting quest.

DRUMLINS

These are elongated, oval hills of morainal material, "stream-lined" in current parlance, with their long axes parallel to the direction of the ice movement. They are commonly 50 to 200 feet high and from one-quarter of a mile to one mile long, athough many are much larger. Drumlins are made up of compacted, unsorted drift and, unlike eskers and kames, were evidently not deposited by streams of melt-water flowing in or under the ice; rather they seem to represent till that had been passed over and fashiond by the ice-sheet. One gets some such effect by sweeping wet snow with a broom. Drumlins may occur singly or in groups.

ORIGIN

The origin of drumlins is uncertain. Goldthwait (6) describes them as "thick masses of till, plastered on and rubbed down smoothly by the ice-sheet, near the close of the epoch when forward motion was still strong but downward pressure had been reduced by decrease in thickness." W. M. Davis, on the other hand, likens them to sand banks in a river, formed under the ice where the topography favored accumulations of till, which were left when the ice-sheet melted away.

EXAMPLES

Massachusetts has thousands of drumlins, of which the largest forms Corey Hill, in Brookline; Beacon Hill, on which the State House stands, in Boston; and Breeds Hill, on which the Battle of Bunker Hill was fought, in Charlestown. Many island drumlins are found in Boston Harbor.

In New York, between Syracuse and Rochester, there are thousands of drumlins and they are also abundant in eastern Wisconsin, near Fond du Lac. Goldthwait states that drumlins in New Hampshire are most abundant in a wide belt that stretches from near Mount Monadnock, in Jaffrey and Rindge, northeastward to Pittsfield and Barnstead. The New Hampshire quadrangles, Monadnock and Peterboro, show many of these. From the Vermont topographical quadrangles there appear to be drumlins in Berkshire, Grand Isle, North Hero, Alburg, Isle La Motte, Weybridge, Ferrisburg, Panton, Springfield, Pawlet, and Wells; these have not yet been investigated.

KAMES

As one goes about the State he sees hundreds of graceful, grass-covered hills of rounded outline or elongated form. They occur either isolated or in groups. Where they have been cut into for road material it is seen that they are made up of glacial material: in some cases of sand alone; in others, of sand, gravel, and small boulders. The material is generally sorted but not in all cases. They are called *kames.*

ORIGIN

Kames are made up of englaciated material which has been carried downward through the ice-sheet by melt-water flowing through crevasses and have accumulated under stagnant ice—else they would have been destroyed by ice motion. They are, therefore, generally water-sorted. An artificial kame can be formed by pouring sand through a funnel.

Some writers also ascribe them to accumulations formed by débris-laden streams of melt-water which deposit the morainal material as they emerge from the margins of mountain glaciers. They are reported to be in process of formation on the margins of some of the Alaskan glaciers.

EXAMPLES

There is a fine sand kame some fifty feet high, in the eastern part of Brownington, on the country road from the Center to the highway (Figure 8). Other kames occur in the neighborhood. Several low gravel kames are seen just west of Hardwick. In Underhill, north of the road to Underhill village, there are several huge kames. Chipman Hill, in Middlebury, is probably a kame; it rises about 400 feet above the surrounding country. Southeast of it is a smaller one. It will be interesting for readers of this article exactly to locate other kames and report them to the State Geologist.

KAME TERRACES

Ice lobes remained in the valleys long after the ice-sheet had melted away from the higher ground. The glacial débris left behind was carried by streams of melt-water and deposited between the ice tongue and the valley walls. When the tongue finally melted this accumulated débris slumped and formed even-topped kame terraces (Figure 6).

Goldthwait (13) describes a kame terrace where Pinny Hollow Brook joins Hale Hollow Pond, in Plymouth township, and another at Bridgewater Corners, on the south side of the Ottauquechee River. Chapman, in the following article, has much to say about kame terraces in the Champlain

Valley. In the narrow valley of the Winooski River, between Middlesex and Waterbury, kame terraces occur on either side. The Central Vermont Railroad is built on the northern terrace.

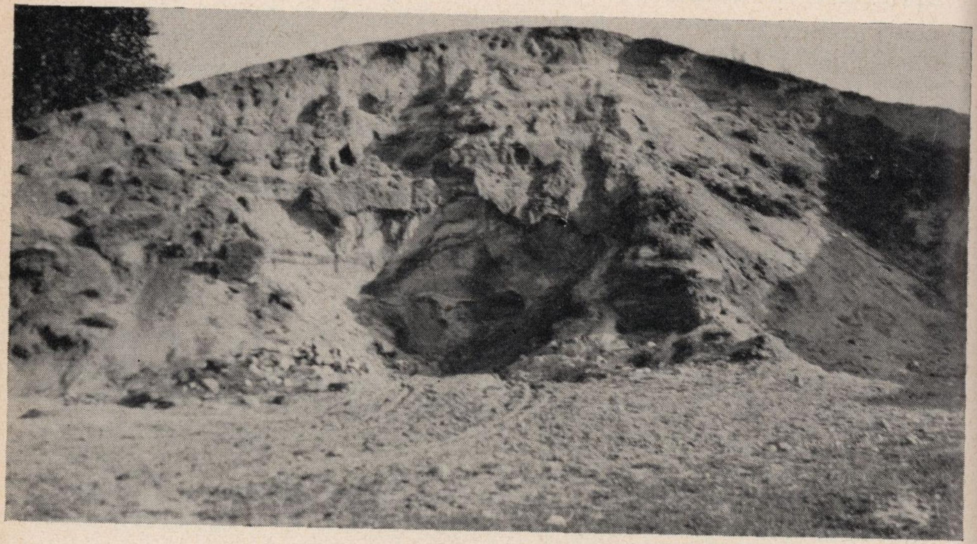

Fig. 8. The sand kame in Brownington.

THE GREAT LAKES

The glacial history of the Great Lakes is a long and involved one and only a brief outline can be given here. Several excellent books may be consulted by those desiring a fuller discussion. The present outline is based chiefly on Professor Daly's treatise.

Plate 5 shows the lobated, terminal moraine of the Pleistocene ice-sheet which crosses Long Island and Pennsylvania, extends down the course of the Ohio and up the Missouri rivers, thence northward along the eastern borders of the Rocky Mountains where it meets the mountain and piedmont glaciation.

The earth is an elastic body and, under the tremendous load of ice, its surface was depressed for hundreds of feet. As the load was gradually removed by the melting of the ice, the surface slowly rebounded, not steadily but spasmodically, with long still-stands in between. Evidences of this uplift are seen at Battery Park, Burlington, a great sand bank which stands a hundred feet above the present lake level, as well as along the lake shore to the north. Cobble Hill, in Milton, whose summit is now 860 feet above sea level, shows a "bench" at 527 feet, made by the waters of the Champlain Sea; several neighboring hills or mountains have similar benches on their flanks. On the slopes of Mount Royal, Quebec, there are found numerous beaches of shell-bearing sands and gravels, about 600 feet above sea level, which show that this eminence was once

at the level of the Champlain Sea. This uplift of the land, therefore, increases from sea level, at New York City to 527 feet, at Cobble Hill, and to about 600 feet at Montreal. Old strand lines along the shores of the Great Lakes furnish further evidences of uplift.

The sites of the Great Lakes, in pre-glacial times, are thought to have been rocky basins which, as Daly puts it, "controlled the set of the glacial currents."

As the ice melted and the ice-sheet retreated to the northeast, great volumes of melt-water were formed which eroded new stream channels or flowed through old ones. The Ohio, Missouri, Illinois, Wabash, and Mississippi rivers received much of this drainage.

With the recession of the ice-sheet small glacial lakes were impounded, the earliest of which was Glacial Lake Maume, which lay just east of Fort Wayne, Ind., and discharged into the Wabash River. As the ice farther receded the southern end of the Lake Michigan basin was exposed and in it another small body of water was formed which is known as Glacial Lake Chicago. This lake found an outlet into the Illinois River and thence into the Mississippi. This outlet, excavated in modern times, now forms the Chicago drainage canal, whose level has to be controlled to prevent a general lowering of the Great Lakes. Meanwhile, Glacial Lake Maumee increased in size as far as Cleveland, on the east, and as far as Imlay, Mich., on the north, where it discovered a new outlet into Lake Chicago.

The ice-sheet continued to retreat to the northeast and Glacial Lake Whittlesey was formed in the modern Lake Erie basin, extending from western Ohio northeastward to Buffalo, N. Y., and from Cleveland, on the south, to Port Huron, Mich., and Toronto, on the north. This lake included the older Lake Maumee. Lake Whittlesey, with the further recession of the ice-sheet, found a lower outlet across western New York and possibly into the Susquehanna River, but a readvance of the ice closed this outlet and forced the drainage back through the old Imlay outlet to Glacial Lake Chicago and the Illinois River. Glacial Lakes Warren and Lundy were later stages of Lake Whittlesey. The former extended into the Finger Lakes region of New York.

The continued retreat of the ice-sheet enlarged Glacial Lake Chicago into the present Lake Michigan and formed Glacial Lake Duluth, in the western half of the Lake Superior basin, which drained through the St. Croix outlet into the Mississippi River. Further recession of the ice-sheet to the northeast gave rise to the giant Glacial Lake Algonquin which included the present lakes Superior, Michigan, and Huron.

Meanwhile the old Glacial Lake Whittlesey had grown from Buffalo to Rome, N. Y., and had become divided into Glacial Lake Erie, and Glacial Lake Iroquois, which was a much larger body of water than the modern Lake Ontario and drained through the Mohawk Valley into the Hudson River valley which, with the retreat of the ice northward, had become an estuary of the Atlantic Ocean.

In regard to the Lake Erie, B. F. Taylor (15), an eminent glacialist, wrote: "After Lake Erie became separated from Lake Ontario it ceased to be a glacial lake, and from that time was entirely independent of the ice-sheet. By the time the separation had been accomplished, following the fall of Lake Lundy, the basin of Lake Erie had probably been brought nearly to its present size. In this time it had two low stages, during which it was not receiving the discharge of the upper lakes. These times were when the Kirkfield and North Bay outlets were active."

To go back somewhat, Glacial Lake Algonquin found an outlet at Kirkfield, Ontario, east of Georgian Bay, through which its waters flowed into Glacial Lake Iroquois and thence into the Atlantic Ocean.

Released of its ice burden the land rose along a hinge line extending northwestward across southwestern Ontario and gradually closed the Kirkfield outlet, forcing the water of Glacial Lake Algonquin to find a new escape in the St. Clair River channel, Lake St. Clair and Lake Erie, at the eastern end of which it spilled over the escarpment between this lake and Lake Ontario and partly excavated the Niagara gorge, forming Niagara Falls, 160 feet high, but the falls, at this time, were seven miles down the river at Lewiston. During the twenty-five or thirty thousand years that have elapsed, the falls have receded up the river to their present position.

Next, the continued withdrawal of the ice-sheet opened a new outlet for the waters of Lake Algonquin through a spillway that followed the course of the present Ottawa River, from North Bay to the *CHAMPLAIN SEA,* a great body of salt water which, in the depressed state of the land in that region, had made its way up the St. Lawrence River, invaded the St. Lawrence Plain and the Lake Ontario basin, and extended into the northern part of the Lake Champlain Valley, as Professor Chapman's paper, following this, will show. According to the older textbooks Glacial Lake Champlain connected with the Hudson estuary and made an island of New England. Chapman shows this theory to be false.

That the Champlain Sea was salt is proved by the multitude of salt water fossil shells that occur along the northern shores of Lake Champlain and by the discovery in the township of Charlotte, in 1849, of the skeleton of a small whale (*Delphinapterus vermontanus*). This skeleton is now in the State Cabinet, in Montpelier. Other fossil whale skeletons have been found in Ontario and Quebec.

With the further recession of the ice-sheet and the rise of the land the Ottawa outlet was abandoned and the present size and drainage of the Great Lakes were established. Many more details and numerous illustrations of the glacial history of the Great Lakes may be obtained from the works cited.

Gutenburg estimates that present tilting of the region between Chicago and the northeastern part of the Great Lakes region is about two-fifths of an inch a year. Other seismologists see in the gradual recovery of the earth's crust from its bowed-down condition during the Great Ice Age a possible explanation for the earthquakes which occur in this northern region from time to time.

Coleman thinks that the ultimate disappearance of the present ice-sheets of the earth may take a million years or more.

The Pleistocene glaciation was the latest great geological event in the earth's history. The glacial forms which have been discussed have suffered only slight erosion and remain practically in the same condition in which they were formed. Bedrock has been but little decomposed and our soils are largely of glacial origin—and so are "sour" and need much limestone "sweetening." If we could compare pre-glacial Vermont with its present topography we would be amazed at the changes that the Great Ice Age wrought: Instead of "ever fair Champlain" there would be the Champlain(?) River with the present western Vermont and eastern New York streams as tributaries; other streams would probably differ in their courses from those which they now take; our beautiful lakes would be missing; the graceful *rôches moutonnées,* eskers, kames, and drumlins (if there are any) would be absent; and, in place of the great mantle of drift with its stony fields, great erratics, and clay banks, we would have—who knows?

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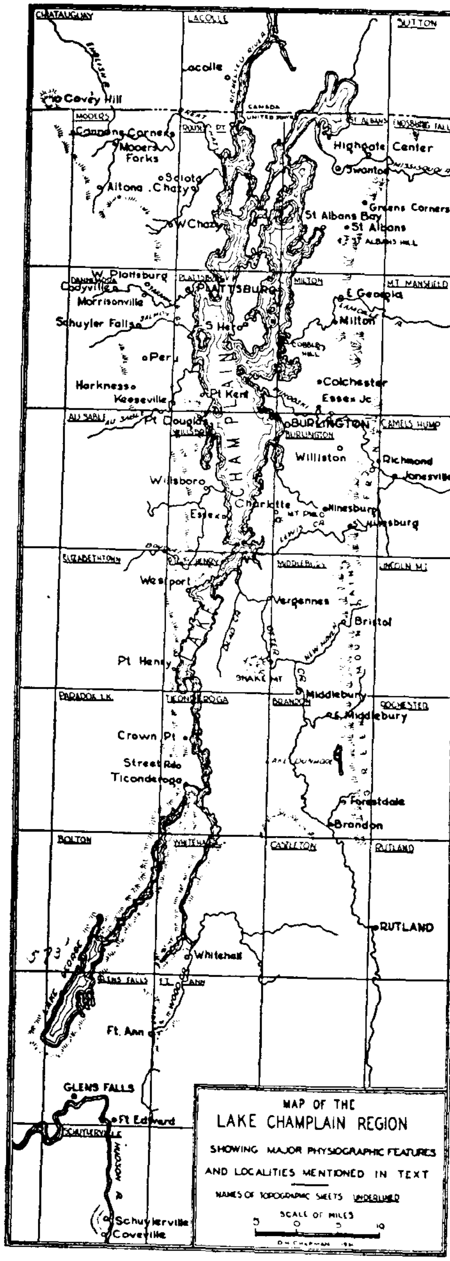

Fig. 9. Map of the Lake Champlain region, showing the major physiographic features and localities mentioned in the text.

Late-Glacial and Post-glacial History of the Champlain Valley [1]

DONALD H. CHAPMAN

University of New Hampshire

ABSTRACT

Precise levelling of the elevated shore features on both sides of the Champlain valley shows clearly two stages of glacial Lake Vermont, while, later, the sea flooded the valley southward from the St. Lawrence estuary only as far as Whitehall, N. Y. Thus New England was never cut off as an island in the late-glacial sea. Parallelism of the three major water planes in the valley shows that there was a long period of stability which ended soon after the marine water invaded the valley. This period of stability during the life history of Lake Vermont corresponds to stability in the Great Lakes region during Algonquin time while the period of tilting initiated soon after the marine invasion corresponds to tilting in late Algonquin time. Isobases drawn across the area are in harmony with those already drawn for northeastern North America.

INTRODUCTION

Lake Champlain,[2] occupying the bottom of a preglacial trough[3] between the Adirondack Mountains of New York and the Green Mountains of Vermont, is a very long and narrow body of water, exceeding a width of ten miles only in the latitude of Burlington, Vt. The level of the lake is held at 92.5 feet above the sea by the threshold across which the Richelieu River carries the outlet waters north to the St. Lawrence. Southward there are two narrow passes into the Hudson Valley; one at the southern tip of Lake George (573 feet) and a much lower one several miles north of Fort Edward, N. Y. (147 feet). North of Ticonderoga, the lake is bordered by clay lowlands, continuous with those of the St. Lawrence. These low rolling clay plains are much broader on the Vermont side of the valley and here they are interrupted by occasional hard rock hills rising out of them like islands out of the sea.

During the "Great Ice Age," the climate of North America, together with that of the rest of the world, grew colder. Ice accumulated over parts of Canada and, nourished by continuous snowfalls, spread southward over northern United States. When the ice-sheet reached maximum size, it extended southward along the Atlantic Coast as far as Long Island, and buried

1 The original article has been considerably changed by Professor Chapman in order to adapt it to this Report. It appeared in the American Journal of Science, vol. 34 (1937) and is reproduced by courtesy of this Journal.

2 The lake is 107 miles in maximum length and it extends five miles into Canada. The maximum width is ten miles, this at about the latitude of Burlington. The lake is about 92.5 feet above mean sea level.

There are some eighty islands, of which Grand Isle, North Hero, Isle La Motte, and Valcour are the largest.

The area of the lake is, in New York, 151 square miles; in Vermont, 322; in Canada, 17; total, 490 square miles. The combined areas of the twelve largest islands is 55 square miles, leaving the water surface, 435 square miles. (U. S. Coast & Geodetic Survey data.)

The deepest channel of Champlain runs a sinuous course, first between the New York shore and Isle La Motte and Grand Isle, then nearer the middle of the lake to Split Rock and Thompson's Point, south of which, it trends more towards the New York side as far as the latitude of Port Henry, beyond which it continues south through the narrow part of the lake and up East Bay to Poultney River. The deepest sounding, 399 feet, is a little over two miles north of Split Rock Point.

3 In pre-glacial times a river must have run through this trough, probably southward.