TABLE I (*cont.*)

Group		Name of Cwm	Altitude Feet	Altitude Metres	Aspect
WEST SNOWDON	1.	Cwm Du	1200	365	0
	2.	Cwm Silin	1100	335	0
	3.	Trum y Ddisgl	1200	365	0
	4.	,, ,,	1100	335	0
SNOWDON	5.	Cwm Dwythwch	1300	395	45
	6.	,, ,,	900	275	45
	7.	Cwm Cynghorion	1500	455	45
	8.	Cwm D'ur Arddu	1700	520	0
	9.	Cwm Clogwyn	1700	520	320
	10.	Cwm Tregalen	1600	490	140
	11.	Cwm Dyli	2000	610	90
	12.	,, ,,	1400	425	90
	13.	,, ,,	1000	305	100
	14.	Cwm Glas	1400	425	45
	15.	,, ,,	900	275	45
GLYDER	16.	Marchlyn Bach	1600	490	50
	17.	Marchlyn Mawr	2000	610	350
	* 18.	Cwm Graianog	1240	380	40
	* 19.	Cwm Perfedd	1970	600	90–100
	* 20.	Cwm Bual	1760	540	55–65
	* 21.	Cwm Goch	1640	500	50–55
	* 22.	Cwm Cywion	2050	625	70–75
	* 23.	Cwm Clyd	2300	700	70
	* 24a.	Cwm Idwal	1280	390	15–20
	* 24b.	,, ,,	1250	380	15–20
	25.	Cwm Bochlwyd	1800	550	0
	26.	Cwm Tryfan	1400	425	20
CARNEDD	27.	Cwm Ffynnon Lloer	2200	670	120
	28.	Cwm Ffynnon Llugwy	1800	550	180
	29.	Cwm Llafar	2100	640	350
	30.	Cwm Ffynnon Caseg	2400	730	45
	31.	Cwm Melynllyn	2100	640	90
	32.	Cwm Dulyn	1800	550	90
	33.	Cwm Anafon	1600	490	45

ICE ACTION ON NEW ENGLAND LAKES

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ABSTRACT. Motion produced by ice expansion and by wind-blown ice cakes has modified the shores of lakes in northern New England, U.S.A. Twenty-six lakes have been studied, the processes observed, and measurements made of the rate and extent of ice action. Conclusions as to the effectiveness of the two processes are brought out.

ZUSAMMENFASSUNG. Die durch Ausdehnung von Eis und durch windgewehte Eiskuchen hervorgerufene Bewegung hat die Ufer von Seen in Nord-Neu-England, U.S.A., modifiziert. Sechsundzwanzig Seen wurden untersucht, die Prozesse beobachtet, und Messungen vom Verlauf und Ausmass der Eisaktion gemacht. Schlussfolgerungen inbezug auf die Wirksamkeit der beiden Prozesse wurden gezogen.

INTRODUCTION

The shores of many lakes are altered by the action of expanding ice cover and wind-blown ice cakes. As far back as 1822 Lee [1] reported moving rocks in Connecticut. Later many articles have dealt with the origin of ice action features, notably articles by Buckley [2] and by Gilbert [3] on Wisconsin, by Tyrrell [4] on northern Canada, and by Hellaakoski [5] on Finland. Recently Stanley [6] described the dragging of boulders in the Death Valley region in California by wind-blown ice

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cakes. Many questions remain unanswered as to the nature and rate of ice action. This paper records the results of field observations and experiments made on lakes in northern New England.

Observations

The 26 lakes studied are located in Maine, New Hampshire and Vermont and range in size from Rockybound Pond, roughly 0·8 by 0·32 km. to Lake Winnepesaukee, which is over 29 km. long. Normal maximum ice thickness is between 40 and 60 cm. However, the range of effective ice action over the years is considerably greater than 60 cm. because of the fluctuation of lake level often as much as 1 m. Furthermore, many of these lakes have been artificially raised or lowered during the last two centuries.

As the ice moves ashore as a result of wind push or of expansion, it tends to catch the larger rocks and drag them ashore. These accumulate higher on the shore leaving the smaller ones lower, thus forming a sorted pavement of rocks. Such pavements are found in all but 7 of the 26 lakes studied, the 7 being the smallest. Minimum lake size for definite indications of ice action is approximately 1·2 by 0·4 km.

Permanent dirt ramparts form where ice pushes against gently sloping glacial till or gravel. Rocks and dirt are heaped and buckled into a ridge commonly 0·5 to 1·5 m. high parallel to the shore. Ramparts are common features of the lake shores and may be found on any shore regardless of the direction it faces. Some lakes, such as Little Lake Sunapee, New Hampshire, are nearly ringed with ramparts. Fig. 1 (p. 103) shows a cake of ice after being pushed ashore. The ice was loaded with debris, and the shove was great enough to buckle and crack a road pavement 2 m. from the road edge. In this particular case, in the spring of 1949, the ice covered the lake, and expansion resulted from one warm-cold-warm temperature cycle completed within 48 hours. This and other comparable situations suggests that the most violent ice push is produced by the expansion process.

Ice moving along or onto the shore may either grasp by freezing or drag the larger rocks. Of the dozens of moved rocks studied over the last twenty years, there has been no indication of rolling. The rocks not only keep the same upright position, but the heaps of debris on the front side of the rocks indicates a plowing action that leaves a trail behind. Fig. 2 (p. 103) illustrates ice pushed up on edge (by expansion in this case) and retaining the sand and rocks grasped from the lake floor. This method of transportation of rocks has been observed repeatedly on the lakes of northern New England.

Generally the direction of the boulder trail is onshore or slightly diagonal to the shore. Fig. 3 (p. 101) illustrates the directions taken by boulders shoved by the ice in Lake Wentworth, New Hampshire. The trails selected were made by rocks usually over a meter in one dimension and appreciably larger than the pavement around them. The fact that the motion is strongly onshore suggests expansion as the process causing the moving of these larger rocks. The pattern of trails certainly implies that there was not just one center of radial expansion but many centers, each operating as an independent unit. The frequent development of ice-buckled ridges dividing the ice cover of the lake into several units further suggests this. If the trails were formed by wind-blown cakes one would expect to find numerous trails nearly parallel to the shore, and they are not.

None of the trails observed were curved, many were straight, and some were zigzag trails. The zigzag trails suggest that either the centers of expansion change or that the effective wind direction shifts.

Some remarkably long trails have been produced on shallow shelving lake floors. One trail in Lake Wentworth measures a total of 32 m., 20 m. of which is straight, the rest zigzags within 18 degrees of the straight portion. The granodiorite boulder making this long trail measured $4{\cdot}5\times2{\cdot}5\times2{\cdot}1$ m. The largest trail-producing rock measured in these lakes is $5{\cdot}8\times2{\cdot}5\times2$ m. or approximately 29 $m.^3$. Its trail is 6·5 m. long and about 65 cm. deep. It is unlikely that wind-blown ice cakes would be able to move rocks of such size after they have been weakened and rotted by melting in the Spring. It probably was done by expansion of hard ice.

EXPERIMENTS

Little Lake Sunapee, an oval lake about 2·8 × 1 km., is nearly bisected by an esker. Water only a meter or less deep separates the end of the esker from the south shore, a distance of about 30 m. On both the east and west sides of the end of the esker 5 rocks were placed on the sandy lake floor, spaced 1·2 m. apart on lines at roughly right angles to the shore. Each of the 10 rocks was about 25 cm. in diameter and within reach of winter ice. After one winter these rocks were carefully relocated.

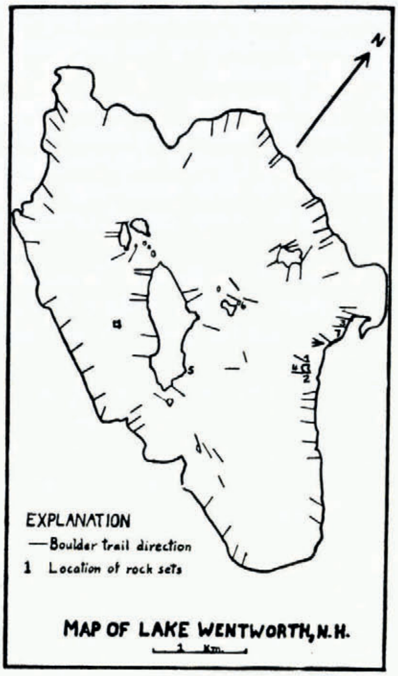

Fig. 3. Map of Lake Wentworth, New Hampshire. Straight lines indicate directions of rock trails. Numbers refer to locations of sets of rocks planted to indicate action of moving ice

All the rocks moved. With one exception they moved diagonally onto the point and along it (south) from both east and west sides. One rock moved along and outward slightly. The maximum motion was 36 cm., the minimum 10 cm. Ice action thus tends to extend the point southward and accounts for the accumulation of boulders in the form of a narrow rampart (see Fig. 4, p. 103) extending south from the esker to the shore.

In Lake Wentworth at locations, numbered 1 and 2 on Fig. 3, 8 boulders having trails were mapped annually over a period of 5 years. They ranged in size from 2·5 × 1·5 × 0·8 m. to 100 × 45 × 22 cm., and were at various depths of water. Over the 5 years there were 40 possible moves. Actually 18 moves took place. In 1949 all the rocks moved, while in 1952 only two did. The longest move was 146 cm., the median move was 25 cm. This was an unusually active group of rocks since each year a number of the rocks would not have been reached by the ice at all because of the fluctuating lake level and of different depths in the water.

Each rock moved independently of the others in amount as well as in direction. Although the majority of moves were diagonally onshore 5 moved offshore as much as 23 cm. The mechanism causing such motion is uncertain. Possibly as the ice chilled and shrank it would withdraw from the shore in places, but such motion has not been observed. A wind blowing along the shore at times causes cakes of ice to drag and rotate, possibly moving rocks out a limited amount. At the time of ice break-up, the cakes tend to pulsate back and forth as the water rises and falls in slow swells, moving small rocks outward by this mechanism. It is doubted however whether such action could move a rock 1·5×1·2×0·6 m. as much as 23 cm. on a rocky floor.

Four sets of rocks were set out at locations numbered 3 and 6 on Fig. 3. Each of the sets consisted of 5 marked 23 cm. boulders about equally spaced in shallow water to a depth of 1 m. The locations of the rocks were mapped each year for 5 years.

Of the 20 rocks set out, 9 moved, and there were 13 moves greater than 7 cm. The greatest number of moves in one year was 4 and the smallest 1. Two reasons are suggested for the inactivity of many of the rocks. The depth range of the rocks was considerably greater than the normal ice thickness; as a result several of the rocks were either above or below the reach of the ice. Also the rocks used were nearly the size of the rocks already making up the pavements and therefore unlikely to be caught by the ice as it moved over the pavement.

At the location numbered 7 on Fig. 3 11 rocks averaging 30 cm. in diameter were mapped annually. They had a depth range of 1·7 m. and this shore was sandy with small cobbles. In 5 years all rocks moved with a total of 21 moves. The greatest displacement was 4·9 m. with a median move of 31 cm. All motion was onshore. The high percentage and unusual length of moves suggests the importance of the large size of the rocks moved compared to the relatively fine texture of the pavement beneath.

Two rocks that were placed in shallow water on a sandy floor are illustrated in Fig. 5 (p. 103) (location 7 on Fig. 3). The broken mass of ice cakes extended offshore an estimated 40 m. with open water beyond and with a maximum fetch for waves of 4 km. On the day when these rocks moved, having remained unmoved all winter, there was a strong onshore wind, somewhat variable in direction. Shoving by the wind-blown ice cakes was slow, pulsating and with considerable direction shift. Paths formed in the sand by the moving boulders were about 5 cm. deep. One path was nearly straight for 1·8 m. and the other was zigzag for a total of 4·9 m. Shortly after motion ceased the ice cakes withdrew from shore about 8 m. This was a clear example of ice shove by wind-blown cakes producing a zigzag trail within a period of one hour.

Conclusions

Two processes involving ice action are effective in altering shores of lakes in northern New England. Contraction and expansion of ice due to temperature changes appear to be the dominant processes in moving the larger boulders. Wind-blown ice cakes produce the same kinds of changes on these lakes on a smaller scale. The rate at which boulders are moved, and therefore the time needed for the formation of sorted boulder pavements, certainly indicates that the lakes of northern New England have not been at their present levels for much of the time since glacierization and the formation of these lakes. The greatest motion occurs where boulders are appreciably larger than those surrounding and where the floor is smooth and gently sloping. The dominant direction of rock migration is diagonally or directly onshore with occasional motion offshore. The force of the moving ice is sufficient to plow granitic rocks as large as 29 $m.^3$ on a rocky floor.

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Fig. 1 (above left). Partially melted cake of ice pushed up by ice expansion
Fig. 2 (above right). Rocks and finer debris imbedded in upended cake of ice
Fig. 4 (below left). Rampart formed by ice action at Little Lake Sunapee, New Hampshire
Fig. 5 (below right). Boulder shoved by wind-blown ice cakes on the shore of Lake Wentworth, New Hampshire. Part of the trail in the sand may be seen behind the boulder where the ice was cut away

Fig. 7. Tent used by party at SP-2 when rediscovered three years later. See following pages. (Photograph by Arkticheskiy Nauchno-Issledovatel'skiy Institut)

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