Research Report 259

FORMATION OF A MODERN ICE-PUSH RIDGE BY THERMAL EXPANSION OF LAKE ICE IN SOUTHEASTERN CONNECTICUT

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PREFACE

This report was prepared by Mr. Fred Pessl, Jr., of the U.S. Geological Survey, Boston, Massachusetts. It covers a study conducted in cooperation with the State of Connecticut Geological and Natural History Survey and the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL). This report was published under DA Task 1T061102B52A02.

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FORMATION OF A MODERN ICE-PUSH RIDGE BY THERMAL EXPANSION OF LAKE ICE IN SOUTHEASTERN CONNECTICUT

by

Fred Pessl, Jr.

INTRODUCTION

Well-developed, modern* ice-push ridges occur on the northwest shore of Gardner Lake in southeastern Connecticut (Pessl, 1966). Gardner Lake is approximately 2.8 km long, 0.8 km wide and elongate north-south (Fig. 1). The maximum depth of the lake is about 14 m near the southeast corner; the northwest part of the lake has a gently sloping bottom. The best developed ice-push ridges are found along the northwest shore. The shores are composed of glaciofluvial deposits, except for the northeast shore which is composed of till. The ice-push ridges of Gardner Lake consist of reworked beach deposits derived from glaciofluvial materials.

The level of Gardner Lake is artificially controlled by a dam at the northeast end of the lake that functions in both winter and summer. The original extent of the lake is approximately defined by its 12-ft (3.7-m) bottom contour (Fig. 1). A dam constructed in the early 1880's raised the lake to its present level. The beaches and the ice-push ridges along the present shore of Gardner Lake therefore postdate the construction of the dam. The absence of any recognizable soil profile on the ice-push ridges, except for a thin humus layer, also attests to their recent formation.

PREVIOUS WORK

Many authors have described ice-push phenomena on lake shorelines and coastlines in cold regions (e.g., Kindle, 1924; Washburn, 1947, p. 76; Nichols, 1953, 1961, p. 107-108; Hume and Schalk, 1964; Peterson, 1965, p. 191-193). Others have described similar features along lakes in the Rocky Mountains (Montagne, 1963), in midwestern United States (Fenneman, 1902; Zumberge, 1952, p. 59-63), and in New England (Goldthwait *et al.*, 1951, p. 62-64). Two hypotheses have commonly been proposed as the cause of shoreward thrust of ice to form ice-push deposits: 1) wind action and 2) thermal expansion. Wind action has most often been cited as effective along coastal areas and the shores of large lakes (Tyrrell, 1910; Leffingwell, 1919, p. 174). Thermal expansion, on the other hand, is probably limited to relatively small bodies of water or to confined parts of larger bodies of water such as restricted bays and narrow arms.

Gilbert (1890, p. 71-72) and Buckley (1901) recognized the role of thermal expansion in the formation of ice-push deposits. Hobbs (1911) and Scott (1927) enlarged upon the earlier discussions and firmly established the principles involved. Ice, like other solids, contracts on cooling

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*As used in this report, "modern" refers to a feature that has either just recently been formed or is currently being formed.

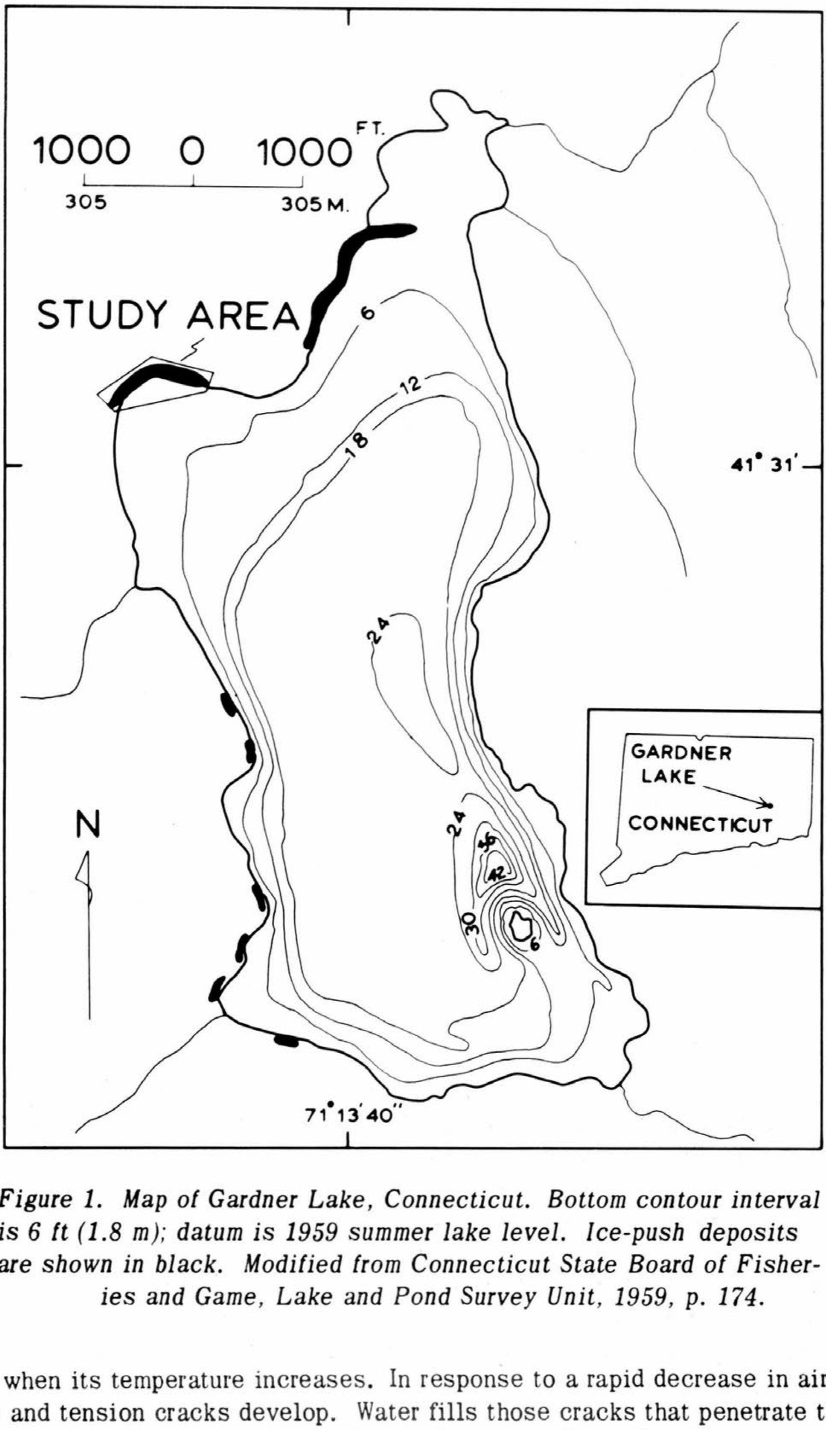

Figure 1. Map of Gardner Lake, Connecticut. Bottom contour interval is 6 ft (1.8 m); datum is 1959 summer lake level. Ice-push deposits are shown in black. Modified from Connecticut State Board of Fisheries and Game, Lake and Pond Survey Unit, 1959, p. 174.

and expands when its temperature increases. In response to a rapid decrease in air temperature, lake ice contracts and tension cracks develop. Water fills those cracks that penetrate the total ice thickness and freezes, thereby increasing the total amount of ice. A subsequent increase in air temperature causes the ice sheet to expand, and a new cycle is started. If the ice margin is in contact with the shore, the expansion transmits compressive forces to the shore area and, under favorable conditions, pushes the shore material into a ridge.

Zumberge and Wilson (1953) conducted a study in southern Michigan to determine the direction of expansive forces in lake ice and the correlation of the amount of expansion with air-temperature change. They reported a 2-ft (0.6-m) net shoreward movement of the ice surface during a

38-day period and indicated that an air-temperature increase of 1C/hour for 12 hours was sufficient to induce ice thrust. The present study follows the field procedures of Zumberge and Wilson and in addition presents ice temperature and solar radiation data.

STUDY AREA

The ice-push ridge at the northwest corner of Gardner Lake was chosen for detailed study because: 1) it is the best developed ridge on the lake; 2) it appears to be currently undergoing modification by ice push; 3) it is easily accessible; and 4) the shape of the shoreline permits the establishment of reference points inland from the zone of ice push and along an unobstructed line of sight. This ice-push ridge is broadly arcuate in plan, is parallel to the shoreline, and is 0.6 - 1.2 m high (Fig. 2, 3). It is 1.2 - 3.1 m wide and asymmetric in transverse profile; its back (landward) slope commonly is steeper than its front (lakeward) slope. The ice-push ridge and the beach are bounded on the north by a swamp. Perennial vegetation is well established on the ridge and on the beach where the ridge provides protection from wave action.

The ice-push deposit is composed of poorly sorted pebbly sand, small cobbles, and sparsely scattered boulders as much as 0.6 m in diameter. Interbedded organic-rich, fine- to medium-grained sand is a minor constituent. Disrupted root masses are commonly present on the ridge crest and back slope. Sediments in the ridge are crudely stratified; the stratification is subparallel to the beach slope and steepens landward, subparallel to the front slope of the ridge (Fig. 4).

Figure 2. Old ice-push ridge, west part of study area, northwest shore of Gardner Lake.

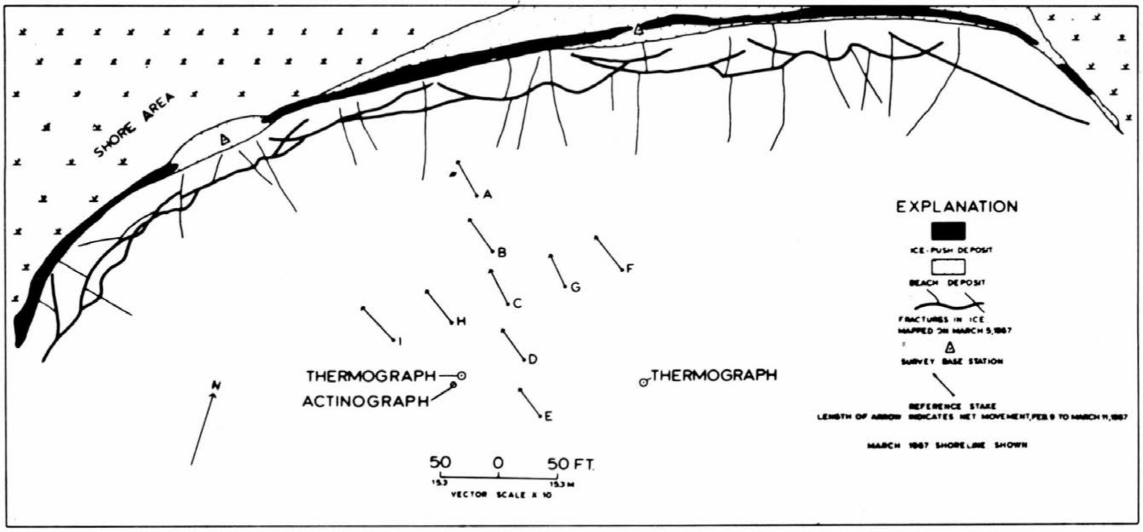

Figure 3. Map of study area, northwest shore of Gardner Lake, Connecticut.

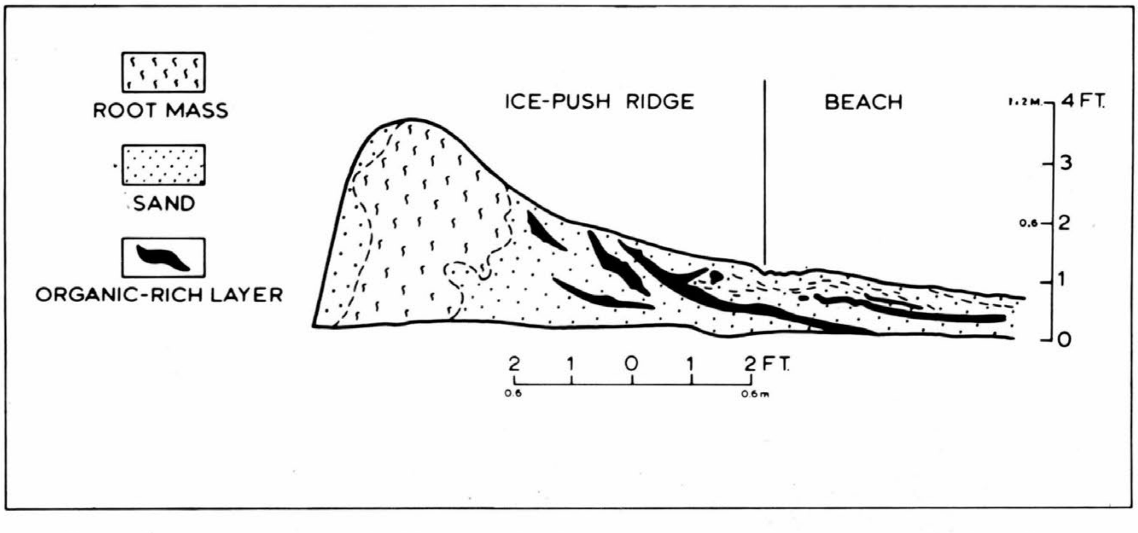

Figure 4. Cross section of old ice-push ridge in west part of study area, Gardner Lake.

FIELD PROCEDURES

Two iron pipes were driven into the ground on shore to serve as survey base stations. Wooden dowels, 0.9 m long and 2.5 cm in diameter, were placed in holes drilled through the ice and were supported at the ice surface by a 20.3-cm-wide wooden platform. Nine such reference stakes to measure ice movement were arranged approximately 15.3 m apart in a cross pattern; the nearest stake was approximately 30.5 m from the shoreline (Fig. 3).

Two thermographs, each having three independently recording temperature-sensitive elements, were installed on the ice at the beginning of the observation period (Fig. 3). Two elements from

Figure 5. Actinograph, thermograph stand, and ice-movement stakes on Gardner Lake. Note thermograph leads (dark lines in ice) extending to right and left of thermograph stand. View north to northwest shore. Melt water on ice surface due to thaw at time of photograph, 15 February 1967.

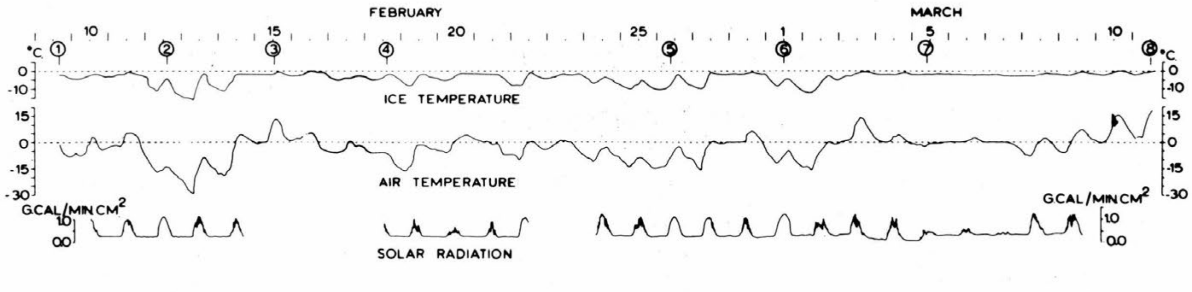

Figure 6. Thermograph and actinograph records, 9 February to 11 March 1967. Circled numbers at top of figure are observation numbers that indicate dates on which reference stakes were surveyed.

each thermograph were buried in the ice 2.5-5.1 cm below the ice/air interface (Fig. 5). Slight changes were noted in the depths of the thermograph leads relative to the ice/snow interface during the winter but precise measurements were not made. The remaining element from each thermograph was suspended approximately 15.2 cm above the ice surface. Thus, at each thermograph, two continuous records of ice temperature and one of air temperature were maintained throughout the period of observation. Air and ice temperatures recorded by different elements were essentially the same throughout the season. Near one of the thermograph stations, a continuously recording actinograph was placed on the ice to record the intensity and duration of solar radiation received at the lake ice surface (Fig. 5). The information obtained from these instruments is summarized in Figure 6.

RESULTS AND DISCUSSION

During the period of observation, 9 February to 11 March 1967, ice cover on Gardner Lake was continuous, and the ice margin was frozen to the shore along the entire perimeter of the lake. On only three occasions was there a continuous snow cover of more than a few centimeters. Maximum snow cover of 15.2 cm occurred on the lake on 7 March and had decreased to 7.6 cm by 11 March. The relatively flat trace obtained from the actinograph on 5 March to 7 March (Fig. 6) indicates that the instrument was probably covered with snow. Average depth of snow cover on the lake was 2.5 cm.

The direction and magnitude of the net movement of the reference stakes are shown in Figure 3. The average net movement for the period of observation was 1.0 m. Net movements of individual reference stakes between observations and from the beginning to the end of the observations are shown in Figure 7; the magnitudes of stake movements between observations are given in Table I. Although the pattern of movement varies from one stake to another, the similarity in the direction and magnitude of the net movements is striking and confirms similar results of Zumberge and Wilson (1953).

At ice temperatures below –5C, changes in ice temperature correspond rather directly to changes in air temperature. As the ice temperature approaches the melting point (above –5C), changes in ice temperature are less evident with respect to changes in air temperature (Fig. 6). Figure 8 compares the total degrees increase in air temperature and ice temperature per day. The difference in the slopes of the air temperature and ice temperature curves such as on 11-13, 16-18, 24-25 February and 6-11 March shows that air temperature does not accurately indicate thermal conditions in ice. Ice-temperature data are summarized in Table II.

Table I. Stake-movement data, 1967.

Distances moved between observations (m). Numbers in parentheses are observation numbers as shown in Figure 6.

Stake	*9-12 Feb (1-2)*	*12-15 Feb (2-3)*	*15-18 Feb (3-4)*	*18-26 Feb (4-5)*	*26 Feb-1 Mar (5-6)*	*1-5 Mar (6-7)*	*5-11 Mar (7-8)*
A	0.06	0.37	0.15	0.15	0.35	0.08	0.12
B	0.00	0.36	0.12	0.34	0.22	0.06	0.09
C	0.11	0.36	0.30	0.34	0.24	0.12	0.13
D	0.12	0.41	0.15	0.31	0.23	0.12	0.06
E	0.10	0.48	0.06	0.24	0.26	0.13	0.11
F	0.09	0.39	0.23	0.37	0.52	0.08	0.00
G	0.06	0.38	0.20	0.28	0.22	0.06	0.06
H	0.16	0.44	0.20	0.20	0.22	0.11	0.19
I	0.09	0.39	0.09	0.22	0.23	0.10	0.12
Average	0.09	0.40	0.17	0.27	0.28	0.10	0.10

Table II. Data on increases in ice temperature.

Observation interval	*Date (1967)*	*Increase (°C)*	*Duration (hr)*	*Rate (°C/hr)*
1-2	10 Feb	2.70	12	0.23
	11 Feb	1.30	5	0.26
	11 Feb	1.30	3	0.43
	12 Feb	6.67	7	0.95
		Total 11.97	Total 27	Average 0.47
2-3	13 Feb	14.33	7	2.05
	14 Feb	9.00	8	1.13
	15 Feb	0.67	1	0.67
		Total 24.00	Total 16	Average 1.28
3-4	15 Feb	0.67	2	0.34
	16 Feb	2.67	8	0.33
	17 Feb	1.00	5	0.20
	17 Feb	1.00	3	0.33
	18 Feb	2.67	7	0.38
		Total 8.01	Total 25	Average 0.32
4-5	18 Feb.	0.67	2	0.34
	19 Feb	6.67	8	0.85
	20 Feb	3.67	8	0.45
	22 Feb	7.00	6	1.17
	23 Feb	2.33	10	0.23
	24 Feb	3.67	7	0.52
	25 Feb	5.00	7	0.71
		Total 29.01	Total 48	Average 0.61
5-6	26 Feb	5.33	5	1.07
	27 Feb	9.00	6	1.50
	28 Feb	1.00	5	0.20
	1 Mar	3.00	4	0.75
		Total 18.33	Total 20	Average 0.88
6-7	1 Mar	0.67	2	0.34
	2 Mar	9.00	11	0.82
	3 Mar	2.00	6	0.33
	3 Mar	2.00	7	0.29
	4 Mar	1.00	7	0.14
		Total 14.67	Total 33	Average 0.38
7-8	8 Mar	1.33	3	0.44
	8 Mar	0.67	2	0.34
	9 Mar	1.67	8	0.21
	10 Mar	2.33	9	0.26
	11 Mar	2.00	10	0.20
		Total 8.00	Total 32	Average 0.29

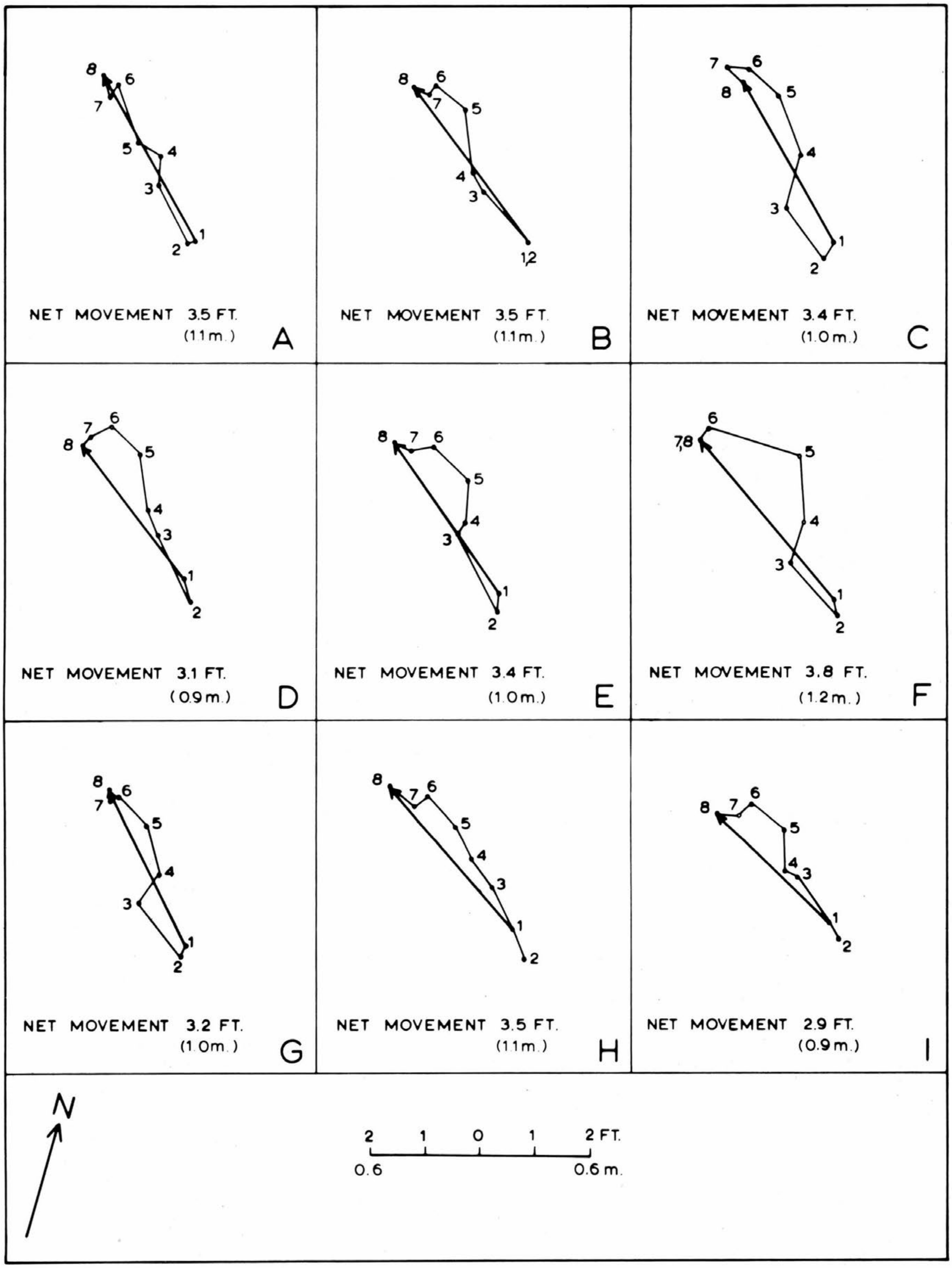

Figure 7. Map diagrams showing net movements of reference stakes between observations, and net movements (heavy line) from beginning to end of observations, 9 February to 11 March 1967. Position of each stake is shown by letter symbol on Figure 3.

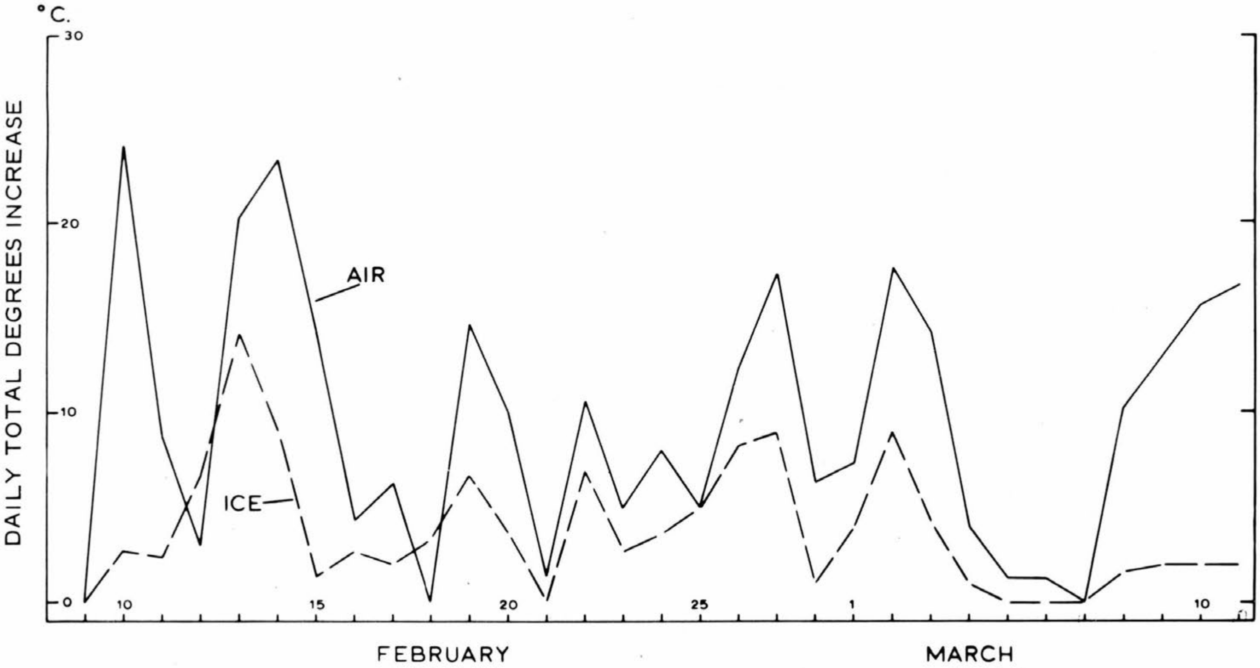

Figure 8. Graph of daily total degrees increase in air temperature and ice temperature, 9 February to 11 March 1967.

Figure 6 shows that solar radiation can, under certain conditions, have a considerable effect on increasing the temperature of the ice; e.g., in 6 hr on 12 February, the air temperature increased approximately 3C, but ice temperature increased almost 7C. Figure 6 shows that the solar radiation on 12 February was intense in contrast to that of the preceding and following days. The abrupt change in ice temperature on 12 February, consequently, may have been caused by solar radiation. However, intense solar radiation was also observed on 22 February, 26 February, and 1 March but no increase in the ice temperature was noted. Such factors as the extent of snow cover, the physical properties of the ice, and the presence of surface melt water have not been evaluated and are important considerations in the effect of solar radiation on ice temperature (Bilello, 1967).

Figure 3 shows the fracture pattern in ice as of 5 March 1967. Throughout the observation period, fractures similar to those shown were observed in the ice-marginal zone. Earlier fractures were healed by refreezing, and a few fractures seemed to have been reopened and rehealed several times. The fractures approximately normal to the shoreline were narrower, ranging from hairline cracks to about 2.5 cm in width.

Although the formation of the fractures was not observed, it seems likely that both sets of fractures are tension cracks which developed during periods of rapid cooling. The wider fractures are probably due to subsequent melting and collapse in those parts of the ice sheet where shear is most active, such as the marginal zone where the ice sheet is frozen to the lake bottom, and where the ice sheet moves up the gently inclined beach slope. Contraction cracks developed in the offshore ice as well as in the near-shore zone, but most fractures were observed near the ice margin. Addition of new ice to the original ice sheet by filling and refreezing of fractures is therefore concentrated in the marginal zone.

Figure 9 presents two histograms that compare average increasing ice-temperature changes with the average net movement of the nine reference stakes during the same intervals. These histograms show that a rough correlation exists between the measured average increasing temperature changes in ice and the amounts of stake movements. The highest average rate of ice-temperature

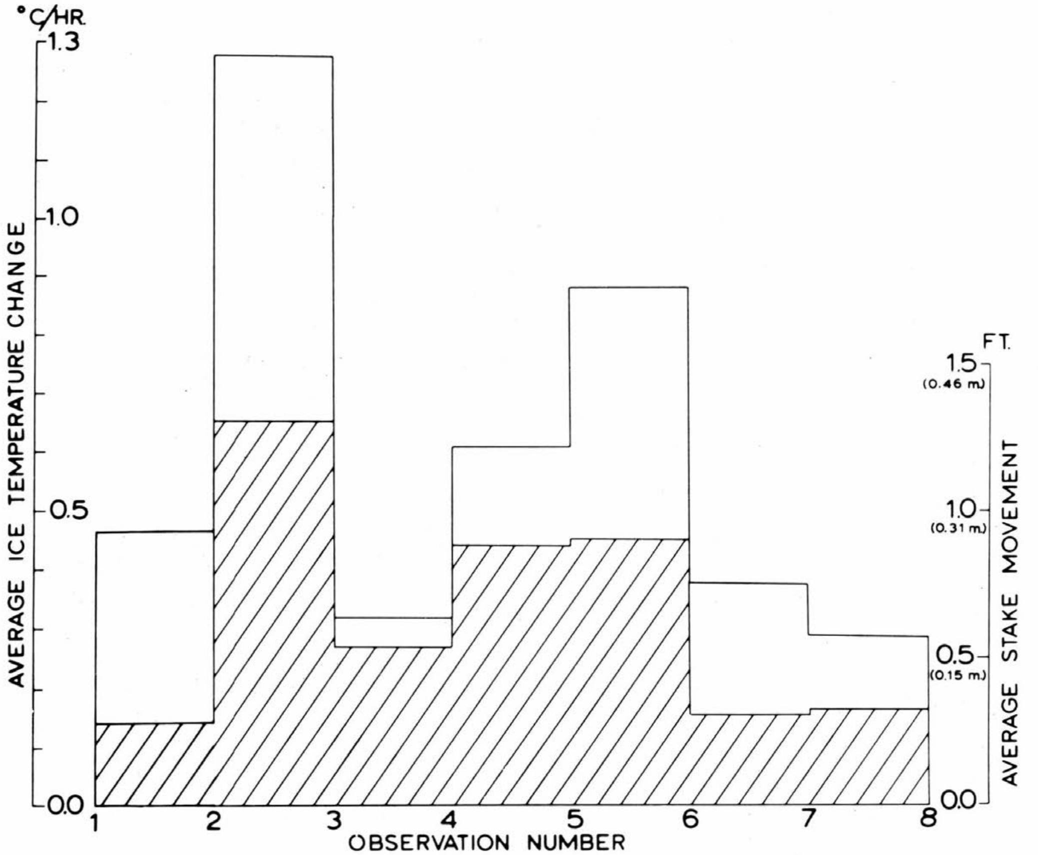

Figure 9. Histograms comparing average net distance stakes moved between observations (ruled pattern) and average increasing ice-temperature change between observations.

change occurred between observations 2 and 3; the greatest stake movement also took place during this time. Similarly, the intervals between observations 4 and 5, and 5 and 6 show relatively high rates of average ice-temperature change and correspondingly large stake movements.

This correlation is only a general one, however, and the quantitative differences in average increasing ice-temperature changes between observations are not proportional to the distances of stake movements for the same intervals (Fig. 9). Even allowing for errors in thermograph sensitivity and surveying procedures, a better correlation between ice-temperature changes and stake movement is not to be expected unless continuous observation of stake movement is made. The surveyed position of each stake establishes only the net movement of that stake between observations. Probably the total movement of a stake between observations is much greater than the net movement and is the sum of numerous individual movements widely divergent in direction and magnitude.

Ice expansion against the shore was observed on 12 February, 26 February, and 2 March. Increasing ice temperature during these times was respectively 1.0C/hr for 7 hr, 1.1C/hr for 5 hr, and 0.8C/hr for 11 hr (Table II). An increase in ice temperature of approximately 1C/hr for 5 to 11 hr appears sufficient to induce ice thrusting against the shore.

During the intervals of observed ice expansion, when ice temperature was increasing at approximately 1C/hr, rates of increase in air temperature varied by a factor of almost three (0.5 C/hr, 0.8C/hr, 1.3C/hr). This suggests that changes in air temperature are not dependable indications of changes in ice temperature as related to ice-thrust capability.

Figure 10. Small ice-push ridge formed during January 1967. Note parallelism of smaller ridge to ice margin, right background. Shovel handle is 20 in. (50.8 cm) long.

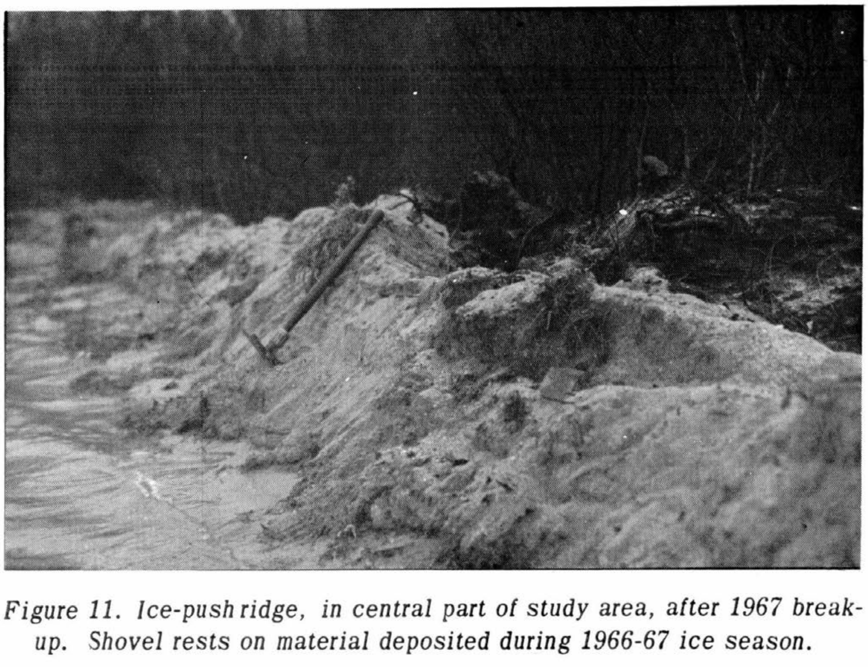

Figure 11. Ice-push ridge, in central part of study area, after 1967 break-up. Shovel rests on material deposited during 1966-67 ice season.

Early in the ice season of the 1966-67 winter, small (15.2-25.4-cm-high) ice-push ridges developed on the beach (Fig. 10). These ridges were overridden by subsequent ice thrusting, and the materials were incorporated in a larger ice-push ridge which was deposited farther shoreward at the base and on the front slope of the old ice-push ridge (Fig. 11). During the 1966-67 winter, approximately 14 m^3 of beach material was reworked and deposited as a discontinuous ice-push ridge along 260 m of shoreline in the study area. An estimated 90% of this freshly deposited material was within the zone of wave action and was removed by wave erosion before the 1967-68 ice season.

CONCLUSIONS

Although air temperature is the principal factor controlling the temperature of lake ice, under conditions of no snow cover solar radiation can also have a significant effect on ice temperature. Changes in ice temperature more closely follow air-temperature changes when ice temperature is below –5C than when ice temperature is above –5C. An increase in ice temperature of approximately 1C/hr for 6 hr is sufficient to induce ice thrusting. In a 30-day period, the average net shoreward movement of the surveyed area of the ice surface on Gardner Lake was 1.0 m.

Because the ice margin was frozen to the entire perimeter of Gardner Lake during the period of observations, it is unlikely that wind-induced ice thrusting effectively contributed to the observed movement of the ice surface. Even during a late-winter gale (1 March 1967) when a northwest wind exceeded 48.3 km/hr, the lake ice remained frozen to the northern shore of the lake and no leads were opened in the ice sheet. The observed ice movements and consequent reworking of beach materials by ice thrust are believed to be the result of thermal expansion of the ice. Breakup occurred on 2-4 April 1967 (personal communication, E.L. Witchie, 1967) and was accompanied by strong (27.4-56.4 km/hr) northwest winds which prevented ice action against the northwest shore of the lake. Although during other years wind-driven floating ice may have contributed to the formation of ice-push ridges on Gardner Lake, the observations made during the 1966-67 winter strongly support the hypothesis of thermal expansion as the principal cause of ice thrusting in the study area.

Active ice thrusting was observed along the shores of other small lakes and ponds in southern New England during the 1966-67 winter. This process is probably active throughout regions in which conditions permit the development of lake ice, and it is intensified during periods of rapidly increasing temperatures. Preservation of the ice-push deposits, however, depends primarily on the fortuitous location of the deposits beyond the zone of wave action and above the normal fluctuations of lake level.

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13. ABSTRACT

A modern ice-push ridge on the northwest shore of Gardner Lake in southeastern Connecticut is 0.6-1.2 m high and 1.2-3.1 m wide. In February and March 1967, the positions of survey stakes placed on the lake ice were measured periodically. During the same period, air and ice temperature and solar radiation intensity were also recorded. Analysis of the data supports the hypothesis that thermal expansion of the lake ice rather than wind action, was the principal cause of ice push. An ice-temperature change of approximately 1C/hr increase for 6 hr was sufficient to induce ice thrust. In a 30-day period, the average net shoreward movement of the surveyed area of the ice surface was 1.0 m. During the 1966-67 winter, approximately 14 m^3 of beach material was reworked and deposited, forming a discontinuous ice-push ridge along 260 m of shoreline.

14. Key Words

Air temperature
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Ice formation
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Thermal expansion

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