FROST HEAVE IN LAKE-BOTTOM SEDIMENTS, MACKENZIE DELTA, NORTHWEST TERRITORIES.

C.R. BURN

Department of Geography, University of British Columbia, Vancouver, B.C. V6T 1W5.

Abstract

The frost-heave regime of lake-bottom sediments has been studied during winters 1987-88 and 1988-89 at a lake connected seasonally with the Mackenzie River near Inuvik, N.W.T. Sub-ice frost heave was measured with telescoping tubes and by precise levelling; the lake-bottom thermal regime was monitored with thermistor cables. Air temperatures were similar during both winters, but a thinner snowcover during 1988-89 led to thicker primary ice, greater frost penetration into lake-bottom sediments, and greater frost heave than during 1987-88. In 1988-89, maximum measurements of ice thickness, frost penetration and frost heave were 77 cm, 180 cm and 30 cm respectively. About 10% of segregational frost heave occurred in frozen sediment some distance above the frost front. During 1987-88 lake water, under pressure due to recharge, was injected into freezing sediment to form intrusive ice. Little evidence of intrusive ice was found in 1988-89 because recharge was lower than during 1987-88.

Résumé

Le régime de soulèvement par le gel des sédiments de fond de lac a été étudié au cours des hivers 1987-88 et 1988-89, dans un lac rattaché annuellement au Fleuve Mackenzie près d'Inuvik, T.N-O. Le soulèvement par le gel sous la glace a été mesuré au moyen de tubes téléscopiques et par nivellement de précision; le régime thermique du fond lacustre a été suivi à l'aide de câbles à thermistors. Les températures de l'air étaient semblables pendant les deux hivers, mais une couverture nivale mince en 1988-89 a favorisé la croissance d'une glace plus épaisse, une pénétration plus profonde du gel dans les sédiments lacustres, et un soulèvement par le gel plus important que pendant 1987-88. En 1988-89, les mesures maximales de l'épaisseur de la glace, de la pénétration du gel, et du soulèvement par le gel ont été de 77 cm, 180 cm et 30 cm. Environ 10% du soulèvement par le gel s'est produit par ségrégation de glace dans les sédiments gelés à quelque distance au dessus du front de gel. En 1987-88 de l'eau lacustre, pressurisée par le rechargement, fut injectée dans les sédiments gelés et forma de la glace intrusive. Peu d'évidences de la glace intrusive étaient observées en 1988-89 parce que le rechargement était moindre qu'en 1987-88.

Introduction

During winter, after water has frozen to the bottom in shallow parts of arctic lakes, the frost line may penetrate underlying sediments. Mackay (1967, pp. 39-43) demonstrated that considerable frost heave may occur on exposed surfaces of drained lakes and that some frost action may take place beneath an ice cover. Patterned ground on the bottoms of some lakes in the Districts of Mackenzie and Keewatin may have formed by sub-ice frost action (Mackay, 1967; Shilts and Dean, 1975). Lake bottoms are environments conducive to frost heave because the sediments are saturated and the temperature gradient is low beneath the lake ice and snow cover. The fine-grained lake sediments of the Mackenzie Delta provide an excellent environment for field observations of frost heave because of their frost susceptibility and the long freezing season (October to May).

Frost heave in lake-bottom sediments was examined during winter 1987-88 at two lakes in the Mackenzie Delta near Inuvik, N.W.T (Burn, 1989; see Fig. 1). Maximum measured frost penetration into lake sediments was 130 cm, including 10 cm of segregated ice (frost heave); lake-bottom heave of up to 20 cm was observed over the winter at four instrumented sites. Segregated ice lenses 0.5 to 2 cm thick were common in frozen lake sediments that were drilled during March 1988. At Lake 2 the elevation of lake ice increased after December 1987, possibly due to groundwater recharge. Intrusive ice masses were observed in drill core collected from this lake close to the limit of grounded surface ice.

Investigations during winter 1988-89 along a transect at Lake 2 studied in 1987-88 where lakewater recharge was apparent are reported in this paper. During 1988-89, the principal intentions were:

(1) to determine total frost heave and the amount of segregational heave at four sites along the transect;

(2) to compare frost heave measured at the sites in 1988-89 with observations from 1987-88; and

(3) to examine in detail the movement of water in frozen soil.

Site Conditions

Lake 2 is 16 km downstream from Inuvik along the East Channel of the Mackenzie River (Fig. 1). The lake is one of a cluster of lakes bounded to the east by the escarpment of the Caribou Hills. Thermokarst erosion of lake shores has led to interconnection of most of the lakes and has breached the bank of East Channel. During summer, small boats may enter the lake without difficulty. After freeze-up, however, as the Mackenzie stage falls, water drains from the lake into East Channel. The duration of drainage depends on the stage at freeze-up, and the thickness of water column to be frozen before the outlet is sealed. In 1988-89, water level at freeze-up was 50 cm higher than during 1987-88. As a result, drainage continued longer into the winter, and any continuing groundwater discharge into the lake was released. Lake-ice rupture leading to surface icing, and the development of intrusive ice in lake sediment, both observed during 1987-88 due to elevated lake-water pressures (Burn, 1989), were not observed in 1988-89.

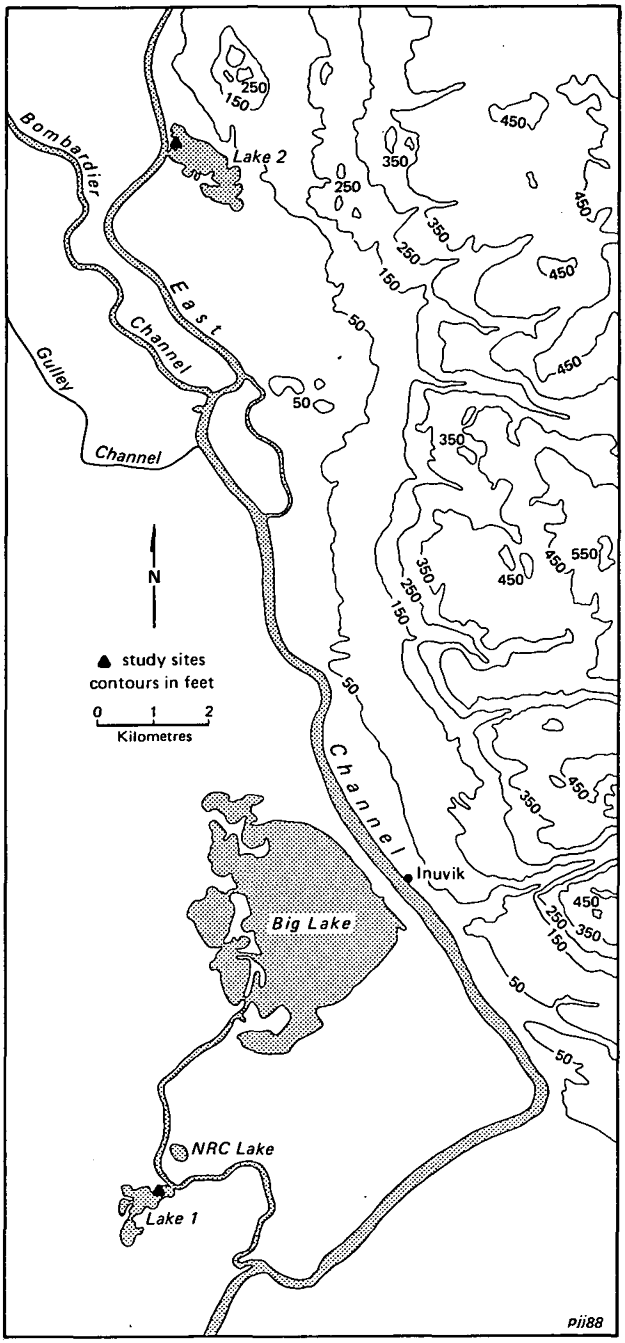

Fig. 1. Location map. Observations reported in this paper are from Lake 2.

It is possible that the depth of water at the outlet may also have increased due to bed erosion. However, stream velocity at this point is low, and it is likely that deposition rather than scouring occurs (P. Marsh, personal communication, 1989). Indeed, a bar 50 m from the outlet was built up over 1 m between April and November 1988. Therefore, the Mackenzie stage during freeze-up may be a critical determinant of cryotic processes in lake-bottom sediments at this site.

The bottom sediments are mostly silt (75 % silt; 25 % clay), and are classified ML under the Unified Soil Classification (Burn, 1989). The freezing characteristic curve for the sediment, determined by Time Domain Reflectometry, is presented in Figure 2. The clay content of the sediment ensures that below 0 °C a considerable proportion of the total water content of the soil is in the liquid phase. For instance, at -1 °C, over 20 % of the soil water is liquid. In such a matrix, water migration and frost heave may continue at temperatures well below 0 °C (Mackay *et al.*, 1979; Smith, 1985; Smith and Patterson, 1989).

Air temperatures during the study period in 1988-89 were closer to normal, i.e. generally cooler, than in 1987-88, except during mild conditions in February (Table I). Total precipitation was also closer to normal, in particular, snowfall during November and December was lower during 1988 than in 1987. As a result, snow accumulation over the winter was lower during 1988-89 than in 1987-88, and lake-ice thickness, excluding icing, was greater. In late March 1988, maximum ice thickness measured, excluding icing, was 72 cm; by mid-April 1989, a maximum thickness of 77 cm had formed without icing.

Table I
Mean monthly temperatures and total precipitation at Inuvik Airport, winters 1987/88 and 1988/89.

Mean monthly temperature (°C)

	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
Normal	3.1	-8.1	-20.7	-27.2	-29.6	-28.9	-25.0
1987/88	4.7	-3.2	-21.7	-21.4	-26.6	-25.0	-19.7
1988/89	3.7	-10.6	-28.1	-20.5	-32.4	-12.8	-23.5

Total precipitation (mm water equivalent)

	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
Normal	23.9	33.4	17.9	17.4	17.9	10.5	12.0
1987/88	21.7	9.1	34.1	23.7	5.5	8.0	11.3
1988/89	15.8	30.7	17.3	11.7	14.7	16.7	4.4

Normals from Environment Canada (1982).

Field Techniques

Lake-bottom temperatures and associated frost heave were monitored with equipment installed during early November and December 1988. Study sites were located lakeward from the edge of ice, continuing a cutline established in 1987 from a benchmark anchored in permafrost. The benchmark comprised 1.25 cm steel rod, 3.5 m long, covered in the active layer and near-surface permafrost by a 2 m-long sleeve of close-fitting, greased aluminum tube. Collars on the rod protruded into permafrost.

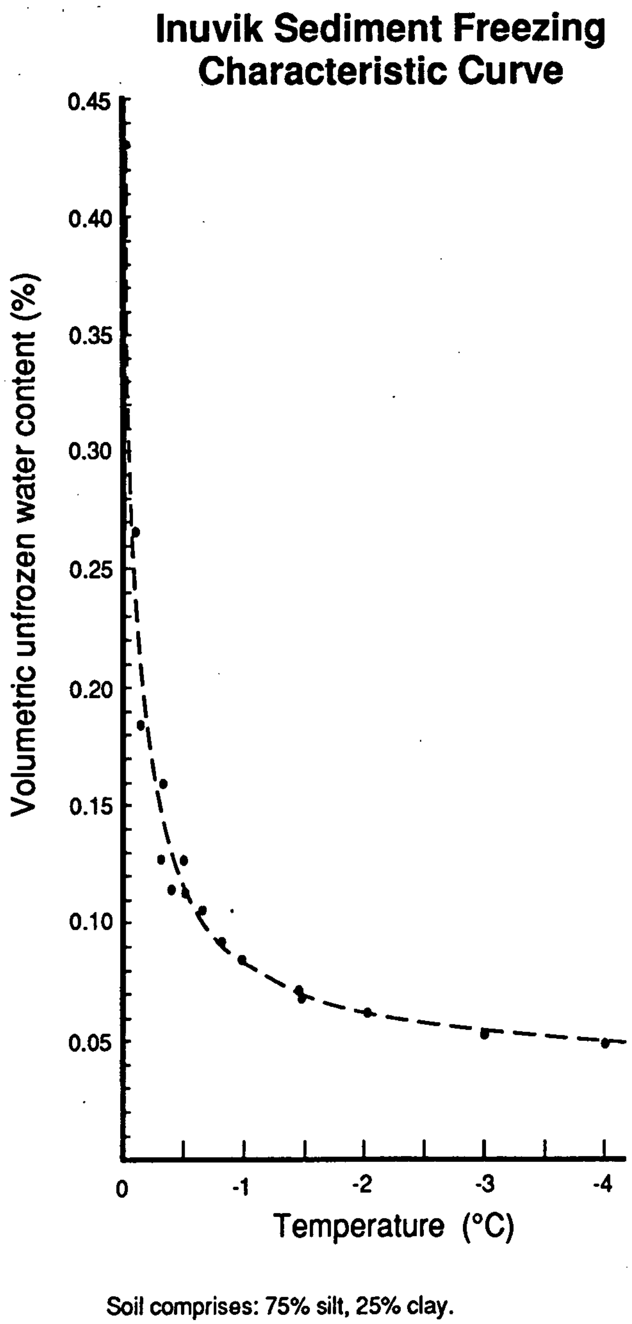

Fig. 2. Freezing characteristic curve for lake-bottom sediment, determined by Time Domain Reflectometry.

The benchmark is assumed to have heaved little; in any event, levelling of the lake surface with respect to the benchmark provided a *minimum* estimate of total lake-bottom heave after the water column had frozen through.

Fourteen sites were established at 10 m intervals lakeward from the shoreline for levelling over the winter. The sites were numbered 0 to 13, beginning at the ice line. At each site tin cans 3 cm high were frozen to the ice surface during November for use as level markers.

At sites 0, 2, 5, and 8, thermistor cables and telescoping heave tubes were installed to monitor lake-bottom temperatures and frost heave (Mackay *et al.*, 1979). Thermistor cables and heave tubes were installed at sites 0, 2, and 5 on November 2. Thermistors (YSI 44033) were placed at the ice/sediment interface and at depths of 10, 25, 45, 70, 100 and 150 cm in the sediments. The thermistors were calibrated before installation and could be read near 0°C to ± 0.03°C. A cable with 11 thermistors spaced 15 cm apart from the sediment surface to 150 cm was installed at site 8 on 10 December.

The telescoping heave tubes were placed in one-inch diameter holes augered into unfrozen sediments beneath the surface ice. The holes were augered to 150 cm, and the tubes were pushed in a further 50 cm. The bottoms of the tubes at sites 0, 2, and 5 were located 25, 50, 75, 100, 150 and 200 cm below the sediment surface, to provide measurements of frost heave in the upper 150 cm of sediment. The tubes terminated 40, 80, 120 and 160 cm below the ice/sediment interface at site 8.

The sites chosen for equipment installation indicated the range of subaqueous conditions at the lake. Site 0 was located at the shoreline, where on 2 November the frostline had penetrated 45 cm. At site 2 the ice thickness was 25 cm, and underlying sediment had just begun to freeze; at site 5, 22 cm of ice covered a 30 cm water column. At site 8 the sediments underlying 42 cm of ice had just begun to freeze in mid-December.

Measurements of frost heave and sediment temperature were made during visits to the sites in mid-December, February and April. In addition, each site was drilled in April to determine the depth of frost penetration along the transect.

Results

TRANSECT BATHYMETRY

A lake-bottom profile compiled from data collected on 4 November is presented in Figure 3. The ice surface elevation was obtained by levelling; the ice thickness and depth to sediment were measured after holes were chiselled through the ice. On this date, lake level had fallen by approximately 60 cm from the stage when freezing began. The surface of floating ice on November 4 was 65 cm below the ice surface at the shoreline (Site 0), but some heave may have occurred at site 0 during freezing of 45 cm of sediment.

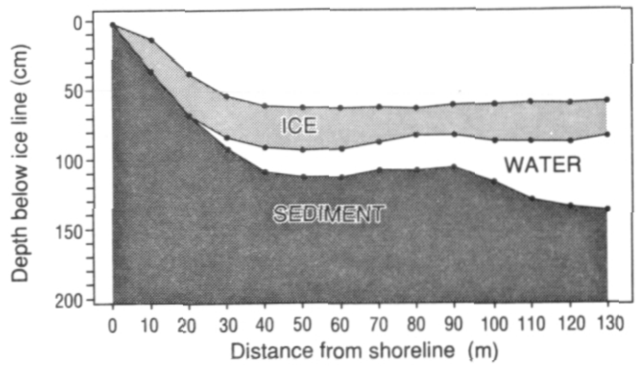

Fig. 3. Bathymetric profile of transect, 4 November 1988.

The lake-bottom transect may be divided into three sections (Fig. 3): (1) a slope from shoreline to 40 m, of average gradient 0.03; (2) a relatively flat bench from 40 m to 90 m; and (3) a slope lakeward of 90 m, with gradient 0.01. By 10 December water had frozen to the bottom of section 1. The bench was frozen through by 18 February. The maximum extent of grounded ice lay between 100 and 110 m during 1989, and most of the third section remained unfrozen throughout the winter. Grounded ice extended almost to 130 m in March 1988, due to a lower water level at the beginning of winter 1987-88 (see Burn, 1989, Fig. 5).

Frost penetration

The frost penetration into lake-bottom sediments in mid-April, determined by examining drill core for the deepest ice in lake sediments, is presented in Figure 4. The thickness of frozen sediment declined with distance from the shoreline, where the maximum frost penetration (1.8 m) was measured.

Lake-bottom temperature profiles

The most detailed temperature profiles were obtained from site 8. The record at this site intersected the frostline throughout the period of observation, while at the other instrumented sites the 0 °C isotherm penetrated past 150 cm.

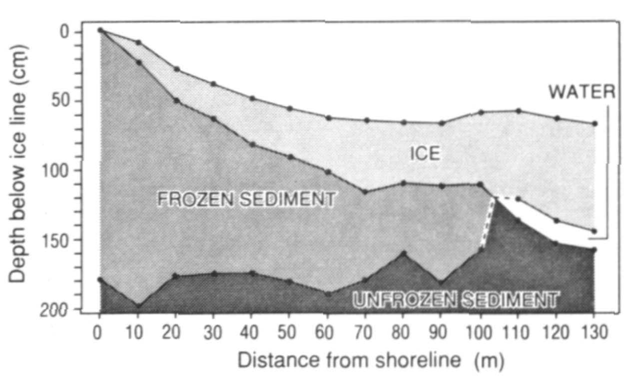

Fig. 4. Frost penetration along transect, 17 April 1989.

Temperature gradients in unfrozen sediment were on the order of 1 °C/m throughout the winter (Fig. 5). At temperatures below -1 °C, the gradient increased to between 3 °C/m and 4 °C/m. The change in temperature gradient at site 8 from unfrozen to frozen soil occurred from -0.1 °C to –0.6 °C, corresponding to the temperatures at which most freezing occurs in this sediment (see Fig. 2). For the profiles displayed in Figure 5, the freezing zone occupied a vertical interval of between 18 and 26 cm.

Miller (1978) uses the term "frozen fringe" for the interval between warmest pore ice and the warmest ice lens in freezing soils. In our case, the frozen fringe indicated by the temperature data is the zone of phase transition, because the sediment contains sufficient clay-size particles to prevent formation of a rigid, continuous ice lattice on the cold side of the warmest ice lens (cf. O'Neill and Miller, 1985). Drill core collected near, but above, the warmest ice lens was frequently not ice-bonded.

Frost heave

Changes in lake-surface elevation between 2 November and 15 April due to frost heave are indicated in Table II. Maximum displacement, 29 cm, was observed at site 3, where 110 cm of sediment contained visible ice. More than

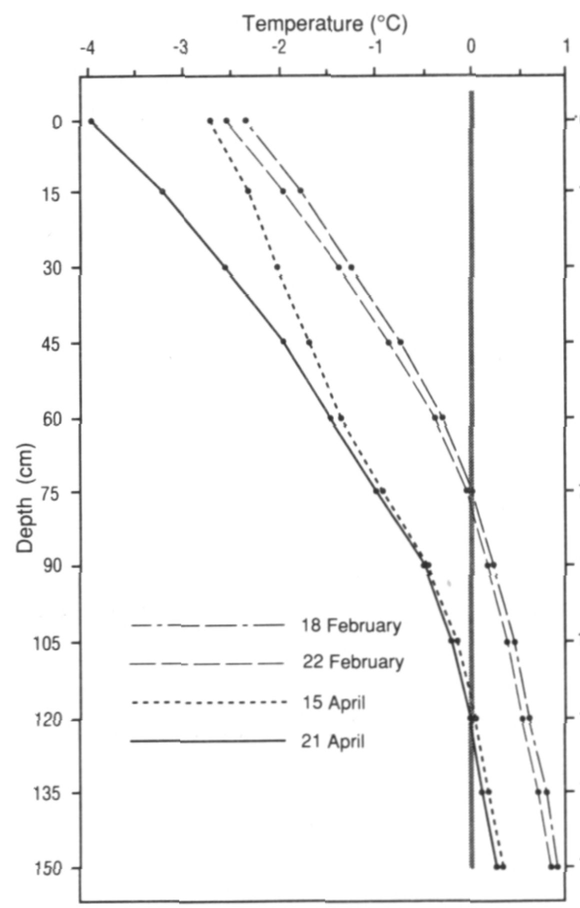

Fig. 5. Sediment temperature profiles at site 8, February and April 1989.

Table II
Soil strain over winter 1988/89

Site	Total Heave (cm)	Frost penetration (cm)	Strain (%)
0	13.9	180	8.4
1	16.8	175	10.6
2	23.4	125	23.0
3	28.9	110	35.6
4	28.2	92	44.2
5	22.4	90	33.1
6	17.1	88	24.1
7	16.7	64	35.5
8	19.6	52*	60.5
9	14.2	70	25.4
10	8.6**	48	21.8
11	0.0	0	0.0

Strain = (Total heave)/(Frost penetration - Total heave)

* Frost penetration probably underestimated, possibly by a factor of 2; see Fig. 5.
** Includes a component due to water injection, possibly 2 cm.

20 cm of heave were measured between 20 and 50 m in sediments that froze for over 5 months. The greatest soil strain was also observed in this portion of the transect (Table II), since the strain at site 8 is likely overestimated due to inaccurate estimation of frost penetration depth at this site (cf. Fig. 5). The strain levels at these sites reflect the optimal conditions for temperature-induced water migration in lake-bottom sediments.

It is important to note that these are conservative estimates of soil strain, since the total heave was measured from the lowest levelled elevation of the lake surface. After surveys in November and December, the ice surface may have been lowered further due to continuing drainage and therefore the heave would be underestimated.

Table III
Total heave (cm) measured between dates of level surveys by levelling and heave tubes, winter 1988/89

Dates	2/11-10/12	10/12-18/2	18/2-15/4	2/11-15/4
Site 0				
Level	8.1	6.8	2.0	16.9
Tubes	6.8	4.4	2.1	13.3
Site 2				
Level	12.9	8.1	2.4	23.4
Tubes	-	-	-	-
Site 5				
Level	4.1	13.6	4.7	22.4
Tubes	6.3	13.7	6.1	26.1
Site 8				
Level	-	15.5	4.1	19.6
Tubes	-	12.9	3.7	16.6

Measurements of total heave by levelling and with heave tubes at sites 0, 2, 5 and 8 are presented in Table III. Unfortunately the tubes at site 2 jammed, and did not register any displacement over the winter. At the other sites, however, there is good agreement between the techniques. Therefore, the heave tubes may be considered reliable indicators of displacement at the sites. Some of the discrepancy between tube measurements and levelled changes during the first interval may be due to settling and adjustment of tubes after installation.

Detailed frost heave measurements at sites 0, 5 and 8 provide intriguing observations of moisture movement in frozen soil. Measurements of tube displacement were made with calipers, and could be replicated to +0.01 cm. During visits in December, February and April, tubes were measured almost daily. Small movements of the tubes were confirmed by measurements of continuous change over several days.

Displacement (heave) of soil during freezing is due to two processes: (1) freezing and 9% expansion of soil water *in situ*, as indicated by the freezing characteristic curve (Fig. 2); and (2) segregational heave due to water migration and freezing behind the frost front to form ice lenses.

There are two principal models of segregational heave. The Rigid Ice model (e.g. Miller, 1978; O'Neill and Miller, 1985) proposes that all volume is added to frozen soil during the growth of the warmest ice lens. At cooler temperatures, thermally-induced regelation may lead to purification of the ice matrix found in frozen soil, so that bands of ice purified of soil particles may appear as growing ice lenses. However, this process does not involve addition of mass to frozen soil.

On the other hand, Mackay *et al.* (1979), Smith (1985), Smith and Patterson (1989) and various laboratory studies, for instance Yoneyama *et al.* (1983) and Ohrai and Yamamoto (1985), suggest that segregational heave may occur in frozen soil, on the cold side of the warmest ice lens. These studies suggest that water may move into frozen soil either by regelation across the warmest ice lens or via capillaries that are not truncated by ice lenses, and contribute to the growth of ice lenses in frozen soil. In addition, redistribution of liquid and freezing at ice lenses within a closed-system of frozen soil may cause up to 12 times more heave than the 9% expansion upon freezing of capillary water (1.09: 0.09), because ice lenses are loci of supersaturated conditions. While there is no doubt that most segregational heave is associated with the growth of the warmest ice lens, there is not agreement on the nature and magnitude of heave that continues to occur in frozen soil.

The data collected during winter 1988-89 are relevant to this discussion. However, in order to determine segregational heave in frozen soil from measurements of total heave, it is necessary to account for displacement due to *in situ* freezing of pore water. This may be done by examining the depth interval where heave occurs, determining the change in sediment temperature from thermistor measurements, and applying these to the soil freezing characteristic (cf. Smith, 1985). The results in Table IV indicate segregational heave, measured at sites 0, 5 and 8 at various depths during the

Table IV
Segregational heave (cm) of separate layers at sites 0, 5 and 8, winter 1988/89

Dates	10/12-14/12	14/12-18/2	18/2-23/2	23/2-15/4	15/4-21/4
Site 0					
77-110	0.10	2.19	0.01	0.12	0.00
110-150	0.00	0.49	0.03	1.61	0.11
Site 5					
31-56	0.05	0.04	0.00	0.00	0.00
56-86	0.54	2.65	0.03	0.42	0.02
86-118	0.00	7.12	0.40	4.40	0.10
Site 8					
0-51	-	9.27	0.03	0.12	0.00
51-95	-	1.36	0.20	2.13	0.09

Table V
Percentage of total segregational heave in frozen soil

	18/2-23/2	23/2-15/4	15/4-21/4
Site 0	25.0	6.9	0.0
Site 5*	7.0	8.7	16.6
Site 8	13.0	5.3	0.0

* For sediment depths up to 118 cm.

winter. Considerable displacement was measured in sediment layers behind the freezing front, where most heave occurred (Table V).

The results in Tables IV and V indicate that ice segregation appears to continue in frozen soil at temperatures below those of the warmest ice lens. The clearest measurements of this process were made on 15 April, summarizing heave over seven weeks after 23 February. The continuing segregational heave comprised between 5 and 10 % of total segregational heave during this interval. Over shorter periods, the continuing heave effected a greater proportion of total heave (Table V).

It is not possible to determine whether the continuing heave is due to a transfer of moisture from unfrozen soil through the zone of initial heaving to the cold sediment, or if it is due to redistribution within the frozen soil. Comparison of the maximum depth of ice recovered during drilling with temperature measurements suggests that ice lenses may form at -0.2 °C, but considerable liquid water is present at cooler temperatures, indicating that the water may still be mobile. Chamberlain (1983, p. 121) noticed that the active freezing zone in saline soil is "thick... with many ice lens growth sites". It is possible that in clay-rich soils, which possess freezing characteristics similar to saline soils (e.g. Tice *et al.*, 1981, Fig. 2), ice lenses may grow simultaneously within a considerable thickness of freezing soil.

Total frost heave measured along the transect during 1988-89 was approximately twice the amount observed in

Table VI
Comparison of total frost heave (cm) measured at transect sites during 1987/88 and 1988/89

Site	1987/88	1988/89
2	10.3	23.4
4	9.0	28.2
6	7.5	17.1
9	9.8	14.2
10	22.0*	8.6
11	28.4*	0.0

* Including 15 - 20 cm of injected lake ice and intrusive ground ice.

1987-88 (Table VI). This was due to the longer interval between first and last observations during 1988-89, and to deeper frost penetration in 1988-89 because of a shallower snow cover. However, the freezing zone extended about 20 m further lakeward during 1987-88, as a result of lower lake level at freeze-up.

Summary and Conclusions

The following conclusions may be drawn from the fieldwork conducted during 1988-89:

(1) The Mackenzie stage during freeze-up determines the nature of cryotic processes that occur over the winter at the site. Continuing discharge over the winter into the lake may lead to water pressures sufficient to rupture lake ice or to form intrusive ice. Only segregated ice may form if the recharge rate is low.

(2) Maximum frost penetration into lake-bottom sediments is approximately 180 cm, and maximum frost heave is 30 cm. The freezing zone may be strained by over 40 % due to ice segregation.

(3)There is evidence that approximately 10 % of total segregational heave may occur in frozen soil on the cold side of the warmest ice lens.

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