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Frost Blisters of the Bear Rock Spring Area near Fort Norman, N.W.T.

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ABSTRACT. Frost mounds of the frost blister type form every winter at the site of a group of cold mineralized springs on the east side of Bear Rock near Fort Norman, Northwest Territories, Canada. During each of four years of observation (1975-1978) three to five frost blisters formed, with measured heights ranging from 1.4 to 4.9 m, and with horizontal dimensions between 20 and 65 m. Locations of the blisters varied somewhat, presumably in response to differences in temperature regime and snow cover. Mature frost blisters consisted of a layer of frozen ground (20-85 cm thick) and a layer of ice (25-85 cm thick), covering a cavity which in some cases was over 4.0 m high. The cavities contained water during formation of the frost blisters; they were empty by spring. Time-lapse photography revealed that frost blisters can grow as fast as 0.55 m·day^{-1}, and that some of them fracture, drain and partially subside one or more times before reaching their full height. During the summer, degradation occurs as a result of thawing and slumping of the soil cover and by melting and collapse of the ice layer; portions of the ice layer, or an uncollapsed section of a frost blister, can survive until the second summer after their formation. Water chemistry and isotope studies revealed that the frost blisters are formed by pressure build-up in subsurface water below seasonal frost and that the ice layers accumulate by gradual downward freezing in a closed (or intermittently opened) system filled with water derived from the Bear Rock spring system. Similar frost blisters are found in other areas of groundwater discharge in a variety of locations.

Key words: frost blisters, hydraulic uplift, springs, icings, permafrost, environmental isotopes, time-lapse photography

RÉSUMÉ. Un groupe de sources froides minéralisées du côté est de Bear Rock, près de Fort Norman, dans les Territoires du Nord-Ouest au Canada, est chaque hiver en butte à des tertres de gel sous forme de talus gélis. Au cours de quatre années d'observation (1975 à 1978), la formation de trois à cinq talus a été notée, ceux-ci mesurant entre 1,4 et 4,9 m de hauteur et d'un diamètre variant entre 20 et 65 m. L'emplacement des talus variait quelque peu, probablement en raison des différences dans les régimes de température et la couverture de neige. Les talus gélis complètement développés consistaient d'une couche de terre gelée (20 à 85 cm d'épaisseur) et d'une couche de glace (25 à 85 cm d'épaisseur), couvrant une cavité qui faisait dans certains cas jusqu'à 4,0 m en hauteur. Ces cavités renfermaient de l'eau durant la formation des talus et se vidaient avant l'arrivée du printemps. Des photographies accélérées ont indiqué que les talus peuvent grandir jusqu'à 0,55 m·jour^{-1}, et que certains d'entre eux se fracturent, s'écoulent et s'effondrent en partie une ou plusieurs fois avant d'atteidre leur hauteur maximale. Il s'ensuit une dégradation au cours de l'été par suite du dégel et de l'affaissement de la couverture de sol et de la fonte et de l'effondrement de la couche de glace; des portions de la couche de glace ou des sections non effondrées du talus gélis peuvent demeurer intactes jusqu'au deuxième été suivant leur formation. La chimie hydrique et l'étude d'isotopes ont signalé que les talus sont formés par une augmentation de la pression hydraulique sousterraine sous la couche de glace saisonnière et aussi que les couches de glaces accumulées lors d'un gel progressif vers le bas dans un système clos (ou ouvert par intervalles) se gonflent d'eau tirée du réseau de sources de Bear Rock. Des talus semblables ont été trouvés dans d'autres régions de déchargement d'eau sous-terrestre, dans divers milieux.

Mots clés: talus gélis, levée hydraulique, sources, glaçages, pergélisol, isotopes de l'environnement, photographie accélérée

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INTRODUCTION

Bear Rock, forming the extreme southeastern portion of the Norman Range, is situated north of the Mackenzie River just west of the confluence of Great Bear River (Fig. 1). Three groups of sulfurous mineral springs occur around Bear Rock (Fig. 2). Two of these were briefly described by Hume (1954) and by Hughes *et al.* (1973); their water chemistry and stable-isotope composition were discussed by Michel (1977).

In early June 1975, several frost mounds were found at one of the spring sites (Lat. 64°55′22″N, Long. 125°39′22″), on the east side of Bear Rock, about 4 km WNW of Fort Norman. Observations and surveys during 1975 and 1976 revealed that (1) new mounds formed in slightly different positions during consecutive winters; (2) they degraded partially or completely during the summer; and (3) they contained an empty cavity under a frozen dome consisting of a layer of frozen ground underlain by a layer of ice. A tentative explanation of the mechanism of their formation was given by van Everdingen (1978), who suggested that the term *frost blister* (Muller, 1945:59) be reserved for this type of frost mound.

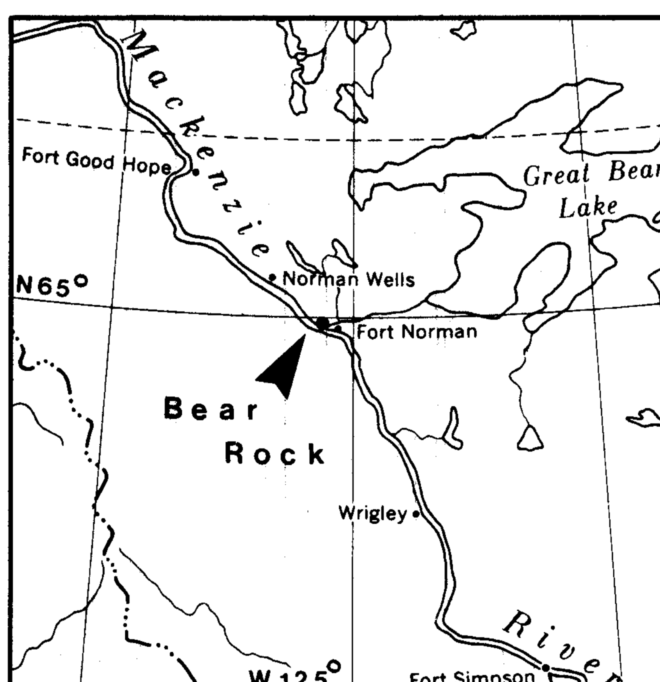

FIG. 1. Location of the Bear Rock area.

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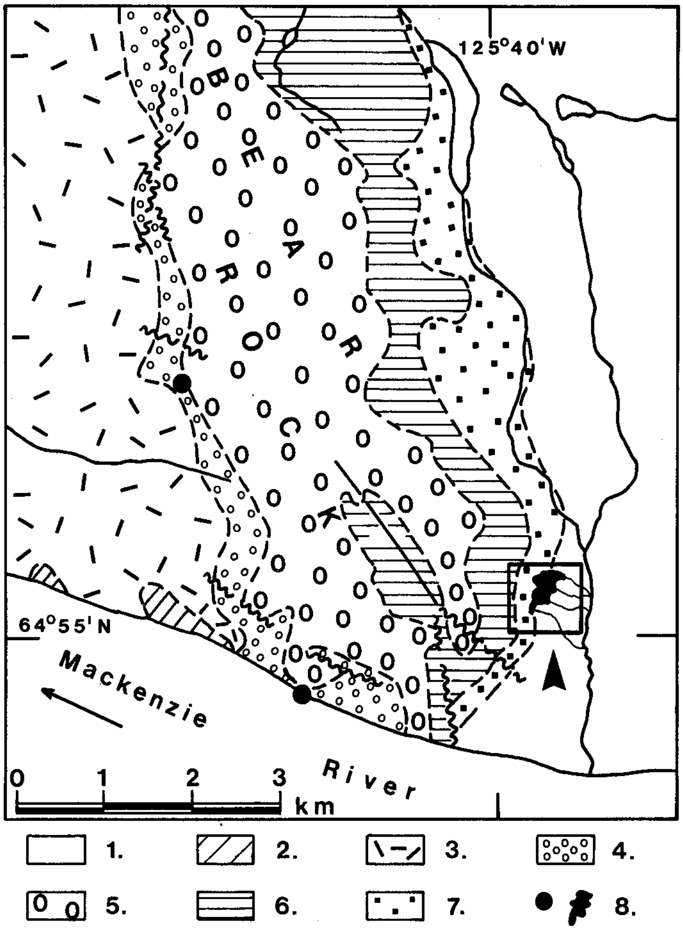


FIG. 2. Geology of the Bear Rock area (after Hume, 1954). (1) Tertiary; (2) Cretaceous; (3) Upper Devonian shales; (4) Middle Devonian limestones; (5) Lower Devonian Bear Rock Formation; (6) Lower Devonian-Upper Cambrian dolomites; (7) Upper Cambrian Saline River Formation; (8) spring area. Arrowhead indicates study area.

Field observations and surveys of the Bear Rock frost mounds were continued intermittently through 1978. Daily time-lapse photography was successfully used during the period September 1977 to May 1978 to record the timing and rate of growth of the frost mounds (van Everdingen and Banner, 1979). The photography was continued into September 1978 to record the timing and mode of degradation. Samples from the ice layers in several of the frost mounds were analysed for stable isotopes of oxygen and hydrogen in an attempt to elucidate further the process of frost-blister formation.

This paper presents a summary of the observations during the period from June 1975 to October 1978, with emphasis on the annual variations in shapes, dimensions and positions of the frost mounds in the spring area; an interpretation of a full year of time-lapse photography in terms of timing and rate of growth, and timing and mode of decay of the frost mounds; and an interpretation of the environmental isotope data. The final section of the paper identifies a number of other frost-blister occurrences, based on the author's observations and on descriptions in the literature.

THE SPRINGS AT BEAR ROCK

Setting

The cold mineralized springs on the east side of Bear Rock emerge from moss-covered rocky talus overlying red beds and evaporites of the Upper Cambrian Saline River Formation along the base of the mountain (Fig. 2, after Hume, 1954). The talus is derived from Lower Devonian and Upper Cambrian dolomites exposed in cliffs above the spring site. The spring outlets are situated along the edge of a large grass-and-sedge-covered glade in the forest (Fig. 3). Discharge from the springs traverses the glade in several runoff channels that join a large stream channel draining into the Mackenzie River south of the spring site (Fig. 2). Mineral precipitates are deposited by the spring water along some of the runoff channels. A large part of the spring deposit in the northern portion of the glade is devoid of vegetation other than mosses and lichens. The glade and the surrounding forest are underlain by permafrost.

The springs are perennial. During the winter their discharge freezes to form icings, locally up to 1.5 m thick, that cover the glade and the discharge channels and may extend onto the ice cover of the Mackenzie River. Most of

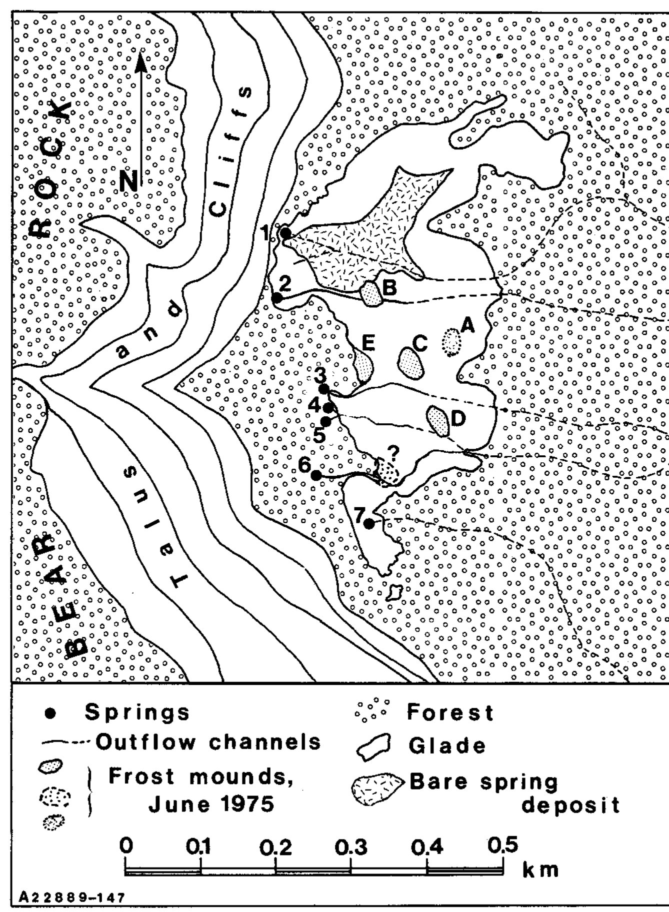


FIG. 3. Sketch map of the spring area at Bear Rock (after van Everdingen, 1978).

TABLE 1. Physical and chemical data for the Bear Rock springs

Source	Spring No. 1	Spring No. 2		Spring No. 3			Spring No. 4		Spring No. 5		Spring No. 6	
Date	9-9-75	9-9-75	13-9-78	9-9-75	11-5-76[b]	13-9-78	11-6-75	13-9-78	9-9-75	13-9-78	9-9-75	13-9-78
Temp., °C	1.6	2.6	4.8	1.9	0.1	4.9	1.7	5.0	2.8	4.3	3.1	4.0
pH, units	7.5	7.5	7.6	7.5	7.5	7.5	7.6	7.5	7.5	7.6	7.5	7.5
Cond.[a]	2210	1650	1536	1500	1638	1529	1620	1989	2025	2110	1500	1434
Ca	594	413	310	358	371	327	392	436	528	473	352	289
Mg	40.2	39.0	37.9	37.0	40.0	32.8	27.2	33.9	34.2	32.0	44.0	38.8
Na	5.5	2.5	2.0	2.3	2.0	1.9	1.9	2.0	3.0	3.1	2.5	1.9
K	1.8	1.3	1.2	1.2	1.1	1.1	1.1	1.2	1.5	1.2	1.4	1.2
Fe	0.18	0.15	0.12	0.05	0.22	0.04	0.14	<0.04	0.16	0.04	0.14	0.07
HCO_3	332	320	320	312	317	305	271	293	295	301	303	295
SO_4	1050	830	660	740	736	680	880	940	1090	1000	750	600
Cl	1.0	1.9	0.5	2.0	1.0	0.5	0.7	0.5	2.2	0.7	2.1	0.7
F	0.43	0.58	0.65	0.50	—	0.60	0.38	0.63	0.42	0.52	0.58	0.77
SiO_2	4.0	4.0	4.3	3.8	4.4	4.2	3.8	4.3	4.0	4.4	4.0	4.5
Sum	2029	1612	1336	1457	1473	1353	1578	1711	1959	1816	1459	1232
Degrees of saturation, log (Q/K):												
Calcite	+0.38	+0.26	+0.31	+0.18	+0.17	+0.20	+0.25	+0.28	+0.30	+0.41	+0.18	+0.14
Dolomite	-0.16	-0.25	-0.02	-0.36	-0.38	-0.31	-0.41	-0.27	-0.33	-0.08	-0.28	-0.34
Gypsum	+0.13	-0.06	-0.24	-0.15	-0.14	-0.21	-0.05	-0.00	+0.11	+0.04	-0.15	-0.30

[a]Conductivity in $\mu S \cdot cm^{-1}$; ionic concentrations in $mg \cdot l^{-1}$.
[b]Flow from fracture in icing mound E76.

the dissolved-mineral content of the spring water is precipitated during freezing; it is found as a powdery coating on rocks and vegetation in the glade after melting of the icings.

Hydrochemistry

Water samples for chemical analysis were collected from the Bear Rock springs in 1975 (Michel, 1977; van Everdingen, 1978) and again in late 1978. Water temperature, conductivity and pH were measured in the field at the time of sampling. The results of the field measurements and the chemical analyses are listed in Table 1.

The water of the Bear Rock springs is a Ca(Mg)-$SO_4(HCO_3)$ water. The data in Table 1 show appreciable variation in concentration between samples taken from the different springs at the same time, and also between samples taken from the same spring at different times. Relative compositions, however, are similar.

The results of equilibrium calculations (log Q/K in Table 1) indicate that the water from the springs is supersaturated with respect to calcite and that the water of springs nos. 1 and 5 is supersaturated with respect to gypsum. None of the spring waters show supersaturation with respect to dolomite.

The main active spring deposit outlined in Figure 3 was found to consist of calcite (92%), quartz (5%) and dolomite (2%). A mineral evaporite found locally on mosses and other low plants consists of gypsum (95%) and calcite (5%); the powdery precipitate left behind after melting of the icings in the glade is similar to the evaporite with more than 95% gypsum and minor calcite.

It is likely that the Bear Rock springs derive their water from recharge through brecciated dolomite (and possibly gypsum or anhydrite) of the Bear Rock Formation, and through dolomites of the Franklin Mountain Formation, both of which are exposed on Bear Rock at elevations between 300 and 450 m above sea level. The spring site, at an elevation of approximately 125 m above sea level, overlies red beds and evaporites of the Saline River Formation. The significant dissolved calcium and sulfate contents of the spring water could thus be derived, through dissolution of gypsum or anhydrite, from evaporite beds in either the Bear Rock or the Saline River Formation, or both.

Environmental Isotopes

The waters of the Bear Rock springs have been analysed for a number of environmental isotopes, including sulfur-34, deuterium (^2H), oxygen-18 and tritium (^3H), to determine the source of the dissolved sulfate, the source of the water and the approximate residence time of the water in the subsurface flow system.

Sulfur-isotope analyses of dissolved sulfate collected from five of the springs in 1975 gave $\delta^{34}S$ values ranging from +25.1 to +32.7‰ (van Everdingen, 1978; expressed as per mil deviations relative to the usual standard, Cañon Diablo meteorite troilite). Analyses of a second set of samples, collected in 1978, gave similar values. These results indicate that the Saline River Formation, with a mean $\delta^{34}S$ value for evaporite sulfate of $+29.7 \pm 2.2‰$ (van Everdingen *et al.*, 1982) is the main source for the dissolved sulfate, and that the contribution of sulfate from the Bear Rock Formation, with a mean $\delta^{34}S$ value of $+17.8 \pm 1.8‰$ (van Everdingen *et al.*, 1982) is negligible.

Deuterium and oxygen-18 analyses have been made on samples of spring water collected in 1975 (Michel, 1977; van Everdingen, 1978) and in 1978. The results are listed in Table 2 as isotope abundances δ^2H and $\delta^{18}O$, expressed as per mil deviations from Standard Mean Ocean Water (SMOW), and they are illustrated by Figure 4a.

As the most likely source of the spring water is atmospheric precipitation (recharging the flow system through infiltration of rain and snowmelt), samples of precipitation collected at Norman Wells have also been analysed for ^2H and ^{18}O abundances; the results are listed in Table 2 and illustrated by Figure 4b. The least-squares best fit to the precipitation data is represented by dashed lines in Figures 4a and 4b; lines marked "Fort Smith" represent the least-squares best fit to isotope data for precipitation that fell between 1961 and 1967 at Fort Smith, N.W.T., the nearest station for which such background data are available. Both the Fort Smith and Norman Wells lines differ only slightly from the general relationship between the two isotopes in meteoric waters, described by the equation $\delta^2H = A\delta^{18}O + B$, where A is generally 8 ± 0.1 and B is approximately 10 ± 10 (Craig, 1961).

TABLE 2. Environmental isotope data for the Bear Rock springs

Source	Date	$\delta^{18}O$, ‰ SMOW	δ^2H, ‰ SMOW	^3H, units
Spring No. 1	9-9-75	-22.9	-177.1	207 ± 58
Spring No. 2	9-9-75	-22.9	-176.6	209 ± 79
	13-9-78	-23.1	-175.0	117 ± 8
Spring No. 3	9-9-75	-22.8	-175.3	195 ± 33
	13-9-78	-23.1	-176.0	117 ± 8
Spring No. 4	13-9-78	-23.6	-178.0	116 ± 8
Spring No. 5	11-6-75	-23.6	-179.2	218 ± 44
	9-9-75	-23.2	-178.4	217 ± 53
	13-9-78	-23.4	-181.0	123 ± 8
Spring No. 6	9-9-75	-22.4	-176.3	220 ± 70
	13-9-78	-22.9	-178.8	143 ± 8
Precipitation at Norman Wells				
Rain	22-9-77	-24.5	-186.5	—
Snow	23-9-77	-20.3	-155.6	99 ± 10
Snow	23-9-77	-20.2	-157.7	100 ± 10
Snow	1-10-78	-20.0	-156.4	—
Snow	7-10-78	-24.2	-190.4	69 ± 8
Snow	7-10-78	-22.8	-180.5	41 ± 12
Snow	10-10-78	-31.5	-244.5	27 ± 12
Snow	10-10-78	-31.9	-250.0	19 ± 8

Analyses by F.A. Michel, Department of Earth Sciences, University of Waterloo.

Figures 4a and 4b show that precipitation is the source of the Bear Rock spring water. The detailed plot (Fig. 4a) illustrates the magnitude of variations in δ^2H (3.1 to 6.0‰) and in $\delta^{18}O$ (0.7 to 0.8‰) between samples of the various springs collected on the same date, and those between samples from a single spring collected on different dates (up to 2.6‰ for δ^2H and up to 0.5‰ for $\delta^{18}O$). The variations between springs likely reflect varying additions of shallow fresh-water seepage to the discharge; the smaller temporal variations could easily result from variations in the isotopic composition of the recharge (see ranges of δ^2H and $\delta^{18}O$ for precipitation samples in Table 2 and Fig. 4b).

Tritium analyses for the spring water and precipitation samples are listed in Table 2. They are illustrated by Figure 4c which also shows the range of natural tritium levels and a plot of the tritium levels found in monthly precipitation collected at Fort Smith, N.W.T. (between 1961 and 1969) and at Ottawa, Ontario (between 1968 and 1975). The high ^3H concentrations during this period, with a very high peak around 1963, reflect man-made additions of tritium from atmospheric testing of nuclear weapons.

The ^3H values for precipitation sampled at Norman Wells in 1977 and 1978 conform reasonably well to the trend of gradually decreasing ^3H values indicated by the historic data. The ^3H values for the 1975 spring-water samples suggest that the water was derived from precipitation that fell at some time during the period 1961 to 1972. The decline in ^3H concentrations in the spring water, from an average of 210 T.U. in September 1975 to an average of 123 T.U. in September 1978, suggests that the water represents precipitation that fell around 1969 or 1970.

The ^2H, ^3H and ^{18}O data thus indicate that the Bear Rock springs discharge water that fell as precipitation some five or six years earlier. The relatively short residence time is interpreted as reflecting a relatively short flow system. The sulfur-isotope data show that the water derived its dissolved sulfate from evaporite of the Saline River Formation, indicating that the flow system is not restricted to flow in the active layer and that the discharge must ascend through a talik or taliks in the permafrost.

THE FROST BLISTERS AT BEAR ROCK

Incidental Observations

Several frost mounds form each year in the glade of the Bear Rock spring site. The photographs in Figure 5, taken in late winter or early spring, show the frost mounds that formed in three consecutive winters.

The new frost mounds that form during a particular winter are usually covered with icing ice, indicating that the ground in the glade is covered by icing before the frost mounds start growing. Remnants of frost mounds from previous winters may not be covered by icing, if they are high enough (e.g. the 1975 mound D in Fig. 5b).

Some thickness of frozen soil, with its vegetation cover, is apparently lifted up during the formation of the frost

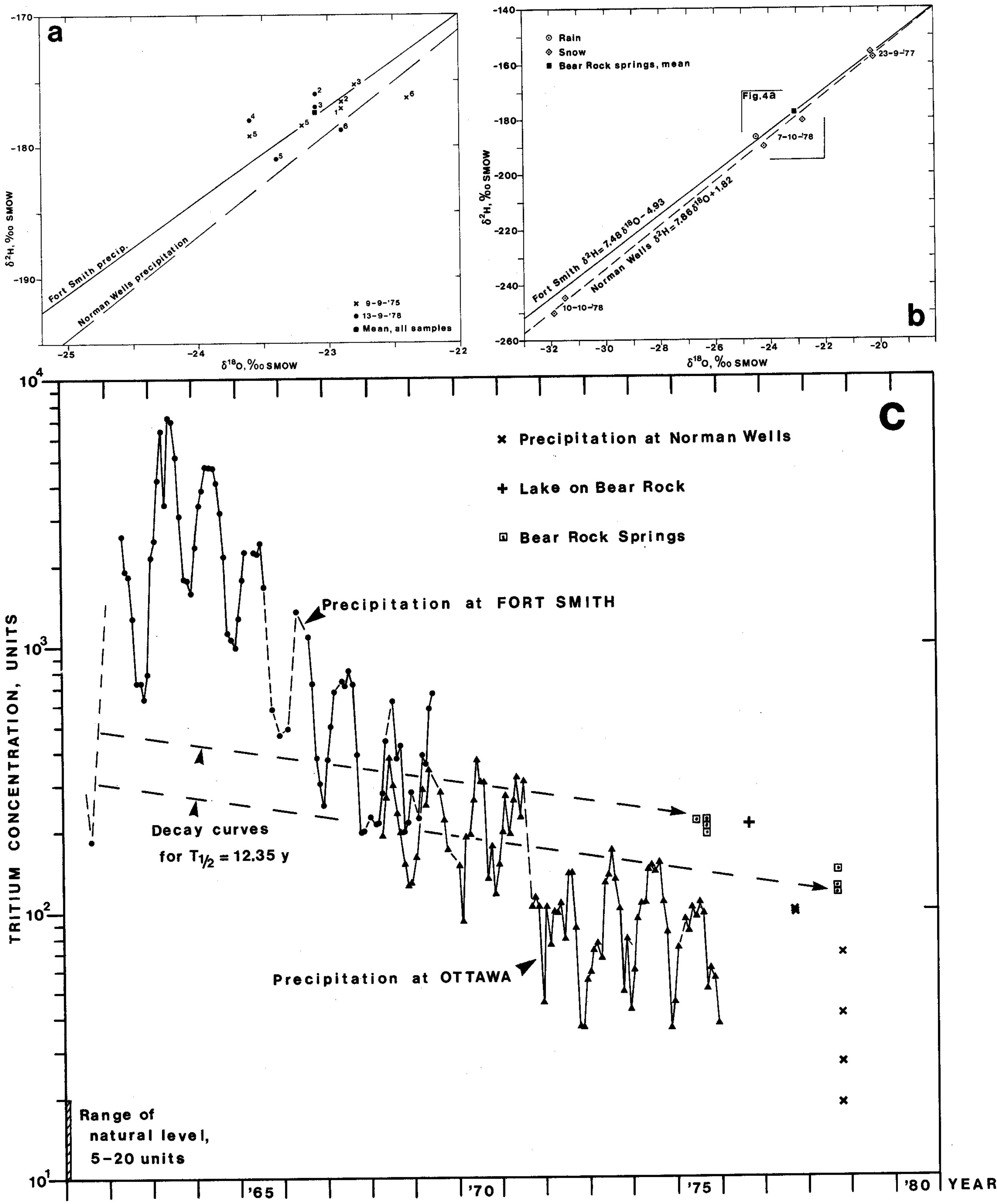
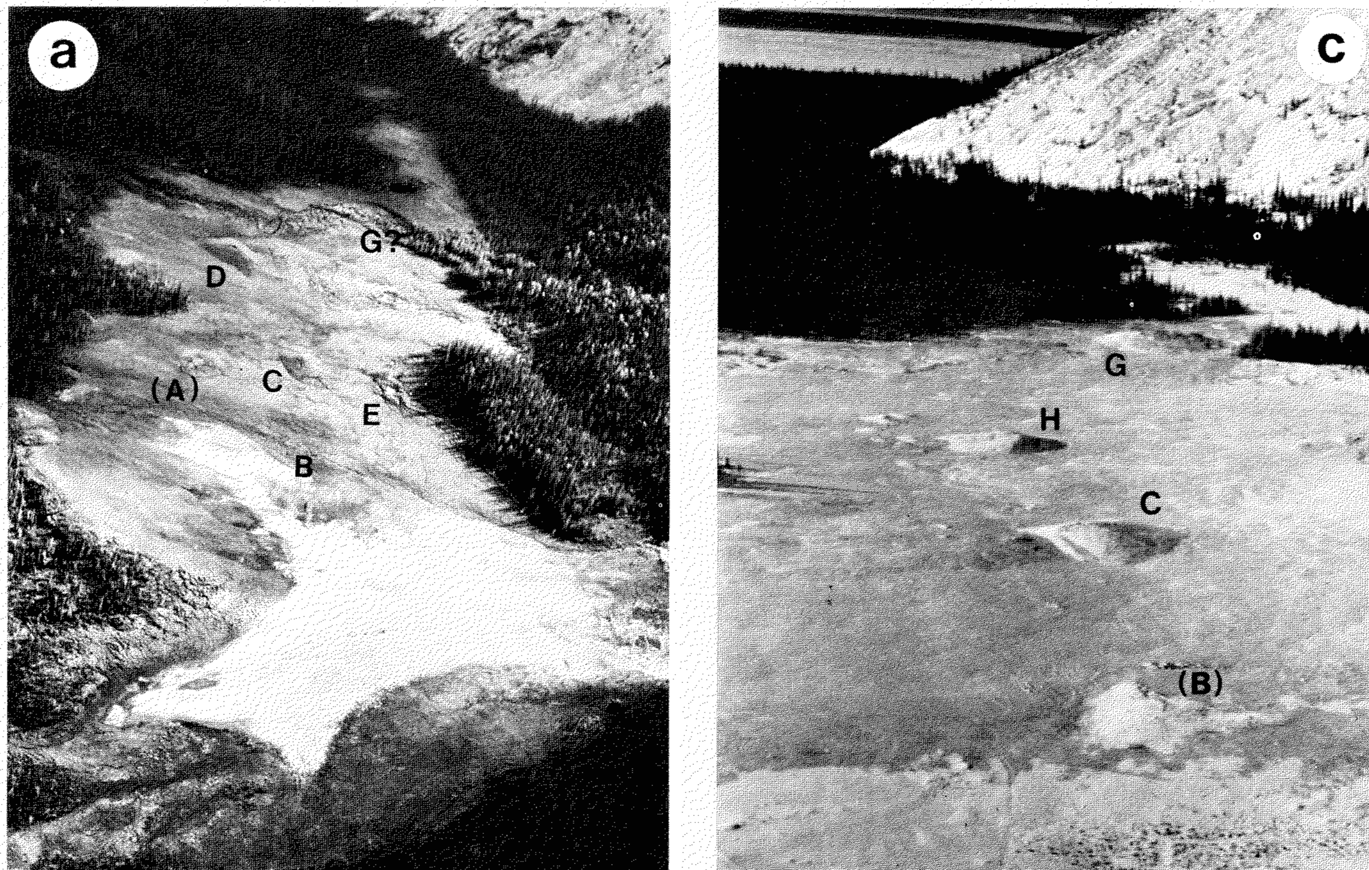


FIG. 4. Environmental isotope data: (a) δ^2H *vs.* $\delta^{18}O$ for the Bear Rock springs (numbers refer to Fig. 3); (b) δ^2H *vs.* $\delta^{18}O$ for precipitation at Norman Wells (line representing precipitation at Fort Smith is based on data for the period 1961-1967, IAEA Environmental Isotope Data Series); (c) tritium data for the Bear Rock springs and for precipitation (Fort Smith and Ottawa data from IAEA Environmental Isotope Data Series).



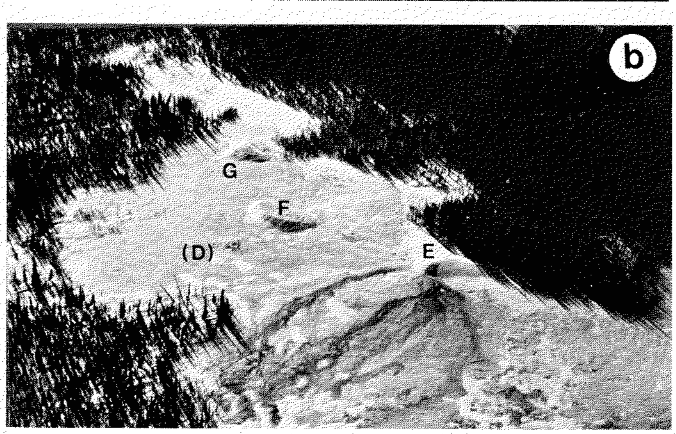


FIG. 5. Aerial views of frost mounds (indicated by letters) in spring area at Bear Rock: (a) 3 July 1975, looking south; (b) 21 March 1976, looking southwest; (c) 27 March 1977, looking south. Letters in brackets indicate remnants from previous years.

mounds, as shown by the small bushes protruding through the icing cover of frost mound F in March 1976 (Fig. 6). This becomes more obvious in early summer after snow and icing ice have melted (Fig. 7a). Thawing of the frozen soil covering the mounds leads to their degradation; at some stage during this process the frost mounds may start collapsing in sections, as shown in Figure 7b.

Inspection of partially collapsed frost mounds reveals their internal structure (Fig. 8). The layer of frozen soil (partially or completely thawed by late summer) can range in thickness from 20 to 85 cm; the lower 10 to 15 cm often contain lenses of segrated ice (Fig. 8b). The frozen soil is underlain by a layer of clean ice from 25 to 85 cm thick. It should be noted that the maximum combined thickness of soil and ice observed in frost mounds at Bear Rock did not exceed 1.4 m. The ice layer covers an empty cavity. The greatest cavity height measured was 1.1 m, at the edge of a collapsed section about 6 m from the highest point of the 1977 frost mound C (5 August 1977).

During the formation of the frost mounds the cavities are apparently filled with water. Horizontal water-level marks on the inner ice surface have been observed in a number of the mounds after partial collapse. During the

FIG. 6. Frost blister F76 at Bear Rock, 20 March 1976, looking south; note small bushes raised during formation of blister.

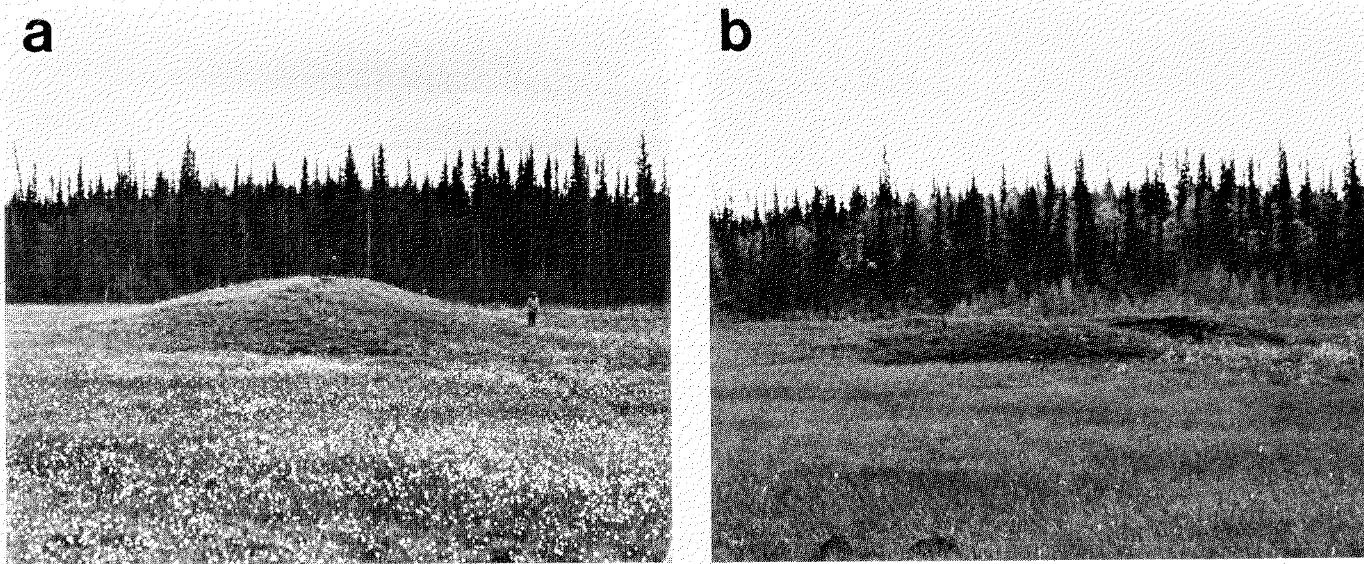


FIG. 7. Decay of frost blister D75 at Bear Rock: (a) 2 July 1975; (b) 9 September 1975 (both photographs taken from same point, looking south).

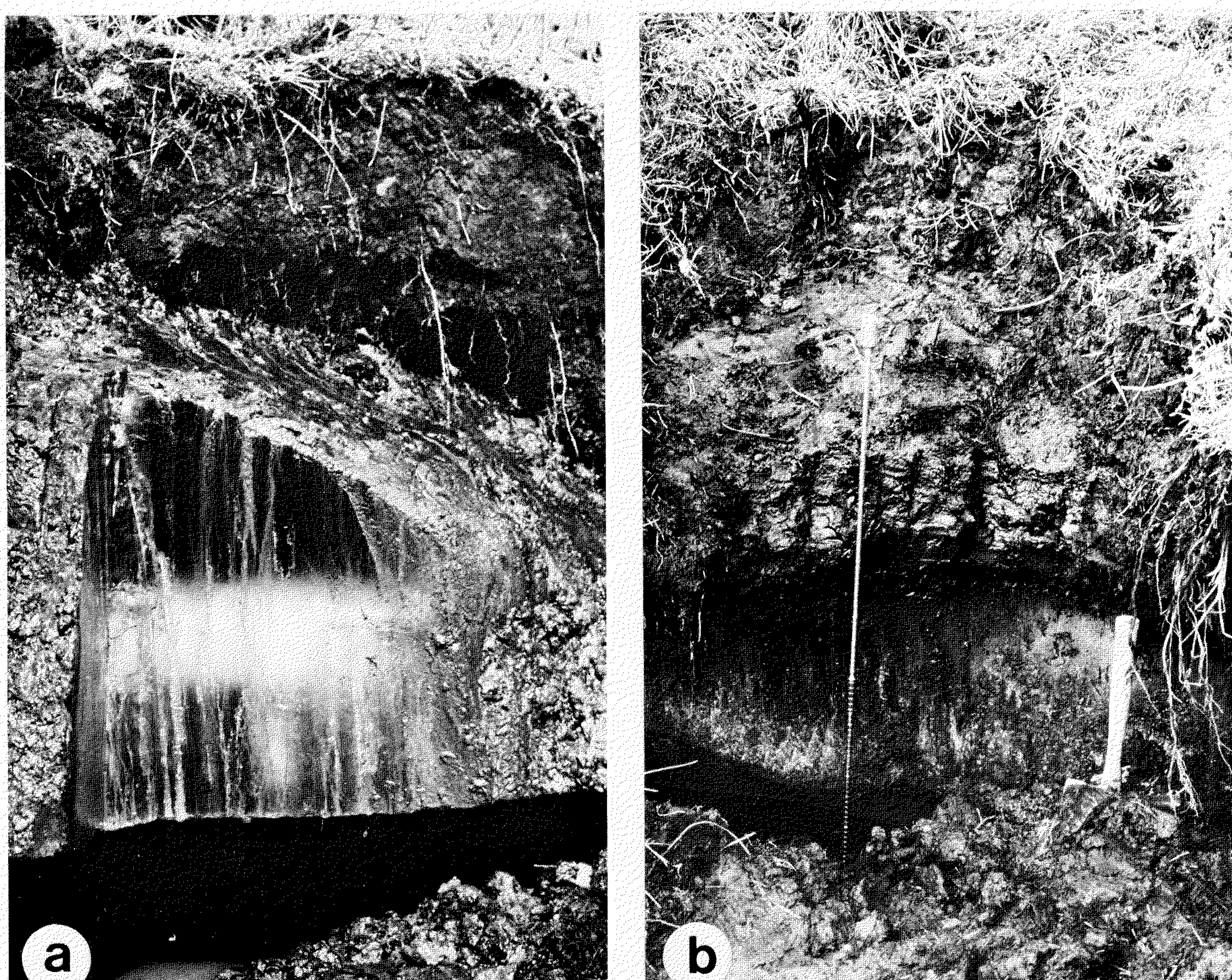


FIG. 8. Cavities below the ice layers inside two of the Bear Rock frost blisters (16 June 1976): (a) E76, portion of ice cut away; (b) F76, showing lenses of segregated ice in soil just above ice layer.

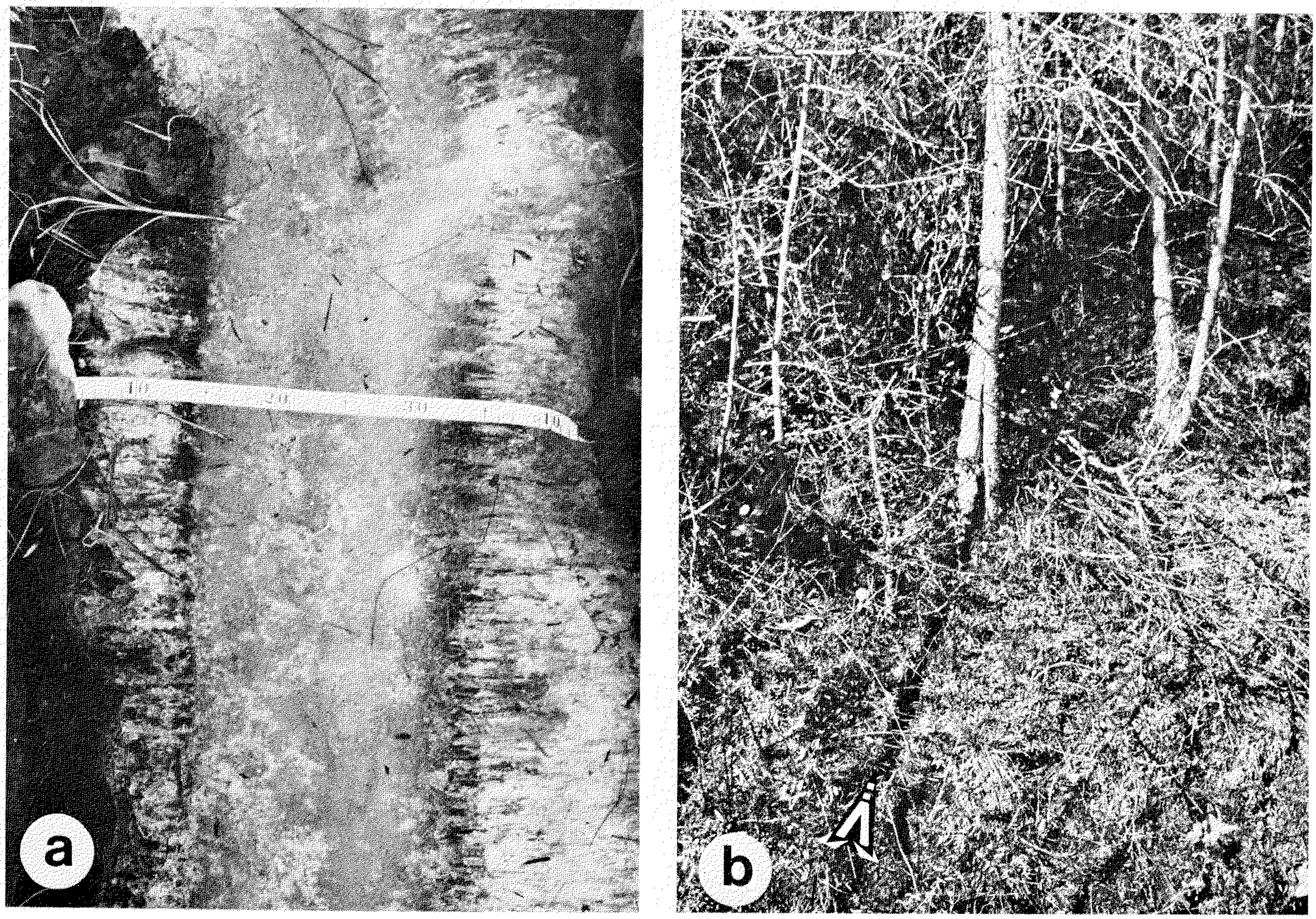


FIG. 9. Fractures associated with the Bear Rock frost blisters: (a) ice-filled fracture along the crest of frost blister F76, 11 May 1976, viewed straight down (tape shows centimetres); (b) tree trunk split by fracturing of frozen ground near frost blister G76, 16 June 1976.

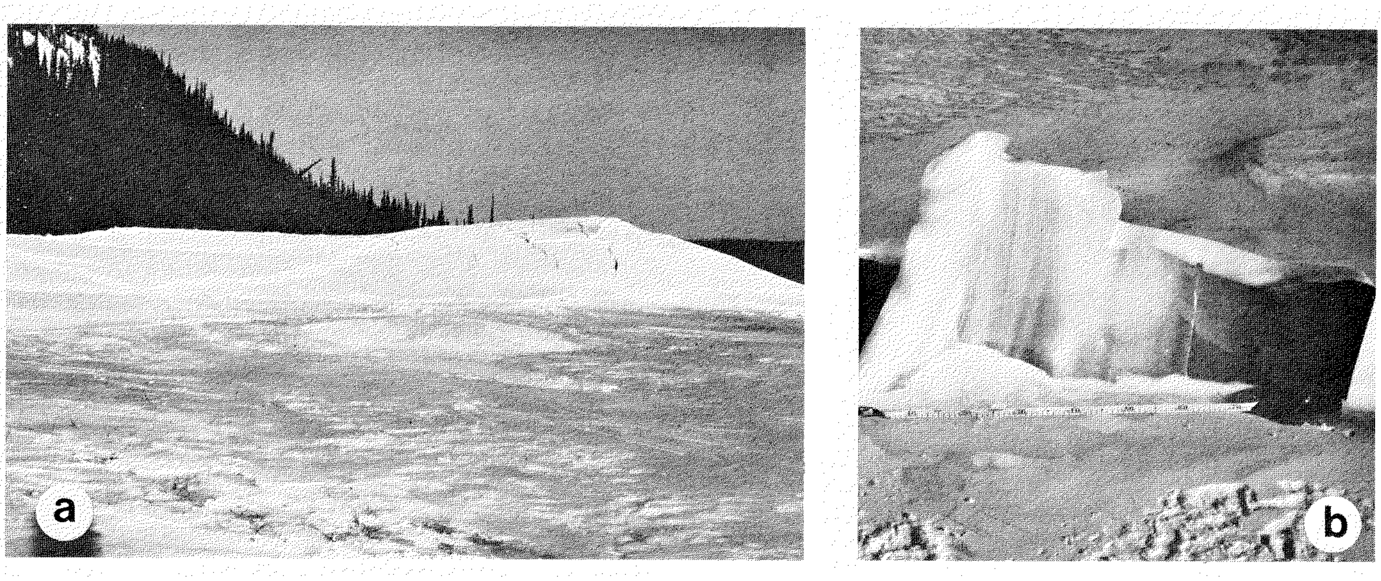


FIG. 10. Icing blister E76: (a) ground-level view looking north, 22 March 1976 (note absence of bushes on blister); (b) block of ice produced by rupture, 20 March 1976 (top is at left, tape shows centimetres).

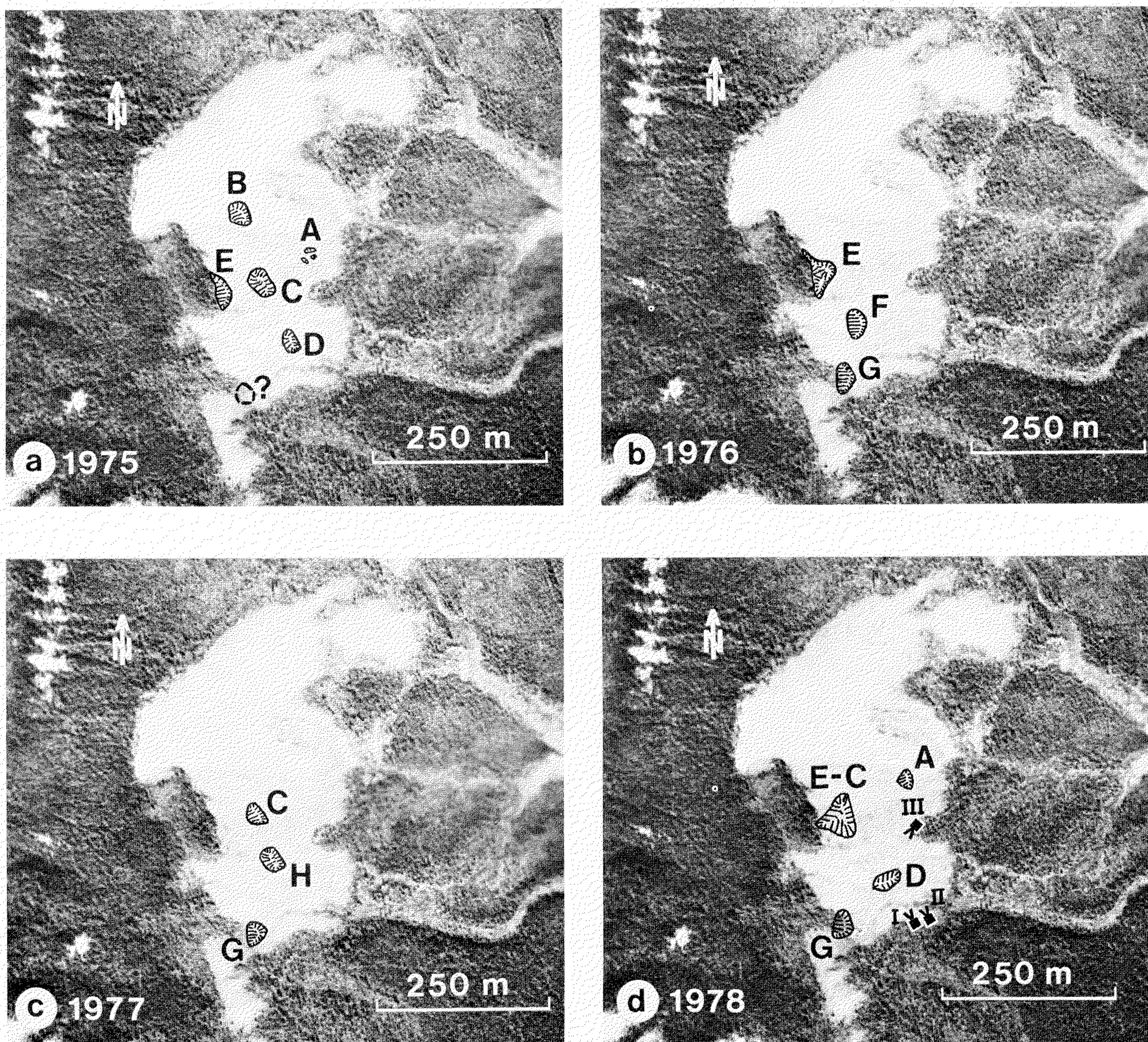


FIG. 11. Locations of frost mounds at Bear Rock: (a) spring 1975; (b) spring 1976; (c) spring 1977; (d) spring 1978 (plotted on airphoto A22889-147).

early stages of their formation the water in the frost-mound cavities is under pressure; in some cases rupturing of the cover of ice and frozen ground allows part or all of the water to drain out. Evidence of such draining is visible in Figure 5b, downslope from mound E; on two occasions small lobes of icing were found on either side of a fracture along the crest of a previously ruptured frost mound. The fractures may subsequently heal by freezing if water refills the cavity, as illustrated by the ice-filled fracture shown in Figure 9a. The fractures, extending through the frozen ground, cut through roots and on occasion split the trunks of small trees that happen to be in their path (Fig. 9b). The apparent involvement of free water in the formation of these frost mounds led to the suggestion of the term *frost blister* for this type of frost mound (van Everdingen, 1978).

Only once during the study period, in the 1975/76 winter, a frost mound was formed that did not show grass or small bushes protruding through its cover of icing and snow (Fig. 10a). At the time the photograph was taken, the mound had just ruptured, a large amount of water had drained out, and the left-hand portion of the mound had subsided by 1.4 m. Measurements through a fracture in the top of the mound revealed a 1.5 m thick ice layer overlying an empty cavity, 0.9 m high, with a floor of ice. Observations during the spring of 1976 found that the ice floor of the cavity had in turn overlain domed layers of frozen ground and ice covering a second cavity. This mound was apparently a composite, consisting of an *icing blister* overlying a frost blister (van Everdingen, 1978).

Near the base of the composite mound several large blocks of ice were found frozen into the icing surface. It was assumed that these ice blocks were part of the original icing cover of the mound, broken off and pushed out during an earlier rupture episode. One of the blocks is shown in Figure 10b. Its upper portion consisted of layered icing ice (55 cm), its lower portion of clear massive ice (28 cm), similar to that formed by freezing of a pool of water.

Variations in Position and Dimensions

Surveys were carried out periodically in the Bear Rock spring area to determine the position and height of new frost blisters, and to monitor their decay. It was found that the frost blisters form in slightly different positions in consecutive winters and that their shapes and sizes vary from year to year. This is illustrated by the four airphoto plots in Figure 11, which show the positions and approximate outlines of the frost blisters found in the spring of each year from 1975 to 1978.

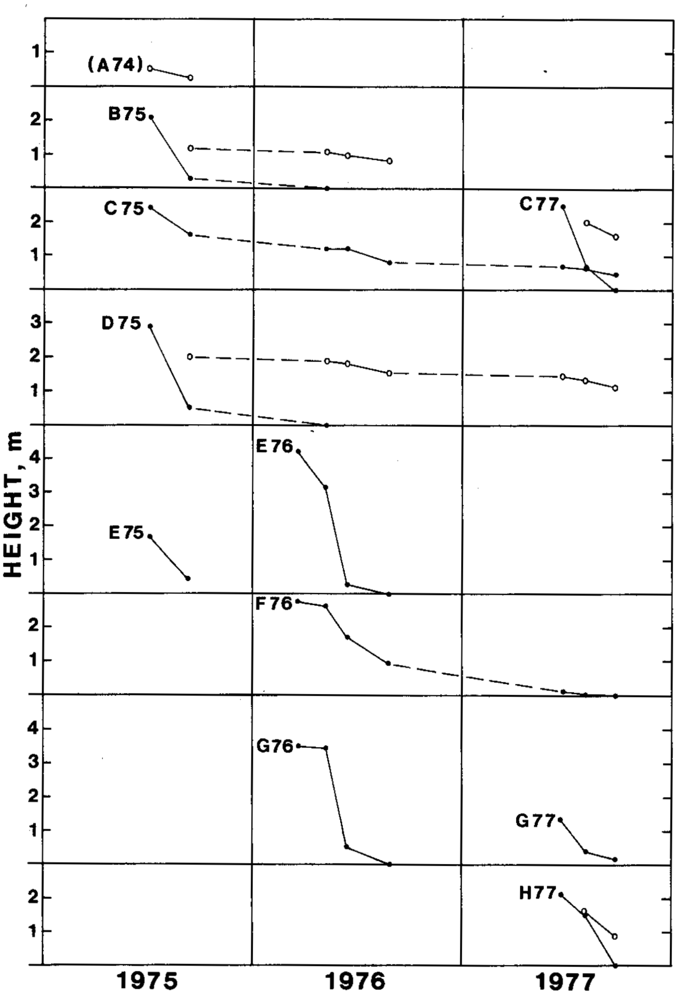


FIG. 12. Summary of frost blister surveys, 1975 through 1977. Dots indicate height of the original highest point of each frost blister above average terrain; open circles indicate remaining high point after partial collapse.

In June 1975 four fresh frost blisters (B to E) were present. A fifth one may have existed at the location marked with a question mark in Figure 11a, where fresh collapse scars were evident. Remnants of a small frost blister (marked A on Fig. 11) were presumed to date back to the 1973/74 winter. Three frost blisters formed during the 1975/76 winter; three during the 1976/77 winter; and four during the 1977/78 winter.

Comparison of the four plots of Figure 11 indicates that a frost blister formed at G in three (possibly four) consecutive winters. During the period of observation, frost blisters were formed only once at A (1978), at B (1975), at F (1976) and at H (1977); twice in similar positions at C (1975 and 1977), at D (1975 and 1978) and at E (1975 and 1976); and once in a position straddling the approximate positions C and E (1978).

The position with the most frequent recurrence of a frost blister (G) is situated on the outflow channel of spring no. 6 (Fig. 3); positions D and F are situated on the channel carrying outflow from springs no. 4 and 5; position H is situated on the outflow channel of spring no.3 and position B on that of spring no. 2. The positions of frost blisters C, E and E-C are not situated on any obvious outflow channel.

Most of the frost blisters observed at Bear Rock in the period 1975 to 1978 were somewhat elongated in outline (Fig. 11). Their horizontal dimensions ranged from a minimum of about 20 m for their short axis to a maximum of about 65 m for their long axis. In many cases the frost blisters were strongly asymmetric in cross section, with the ENE-facing slopes (facing downhill, away from the springs) much steeper than the WSW-facing slopes (Figs. 5b, 6). Similar asymmetry of frost blisters was observed in Mongolia by Froehlich and Slupik (1978c).

Elevation data for individual frost blisters, identified by their position and year of formation, are summarized in Figure 12, which also shows the maximum height determined for each blister on the basis of the surveys. It should be stressed that the maximum heights (with the exception of those for the 1976 frost blisters E, F and G) are probably less than the full original heights, because elevations were not measured until early May or later, when some subsidence could already have occurred.

The height of a frost blister, as determined from surveys made before the occurrence of significant subsidence and again after collapse and melting of the ice layer, is equivalent to the thickness of its ice layer plus the height of the blister cavity. For example, the measured height of frost blister C77 (2.48 m, Fig. 12) and its approximate ice thickness (0.60 m, below a 0.50 m thick soil cover) indicate that the cavity in this frost blister must have been at least 1.88 m high at its centre, which is considerably more than the 1.1 m measured on 5 August 1977 (cf. under Incidental Observations). Moreover, some subsidence had undoubtedly already taken place when it was first surveyed on 26 June 1977. Similarly, cavity-centre heights of at least 2.74 m

FIG. 13. Time-lapse camera system installed on a tree; main batteries visible at the base of the tree.

and 2.84 m, are indicated for frost blisters E-C78 and G78 respectively, on the basis of the survey data (assuming ice thickness was equal to the maximum of 0.85 m measured at Bear Rock).

Growth and Decay of Frost Blisters during the 1977/78 Cycle

The progressive degradation of frost blisters in the summer after their formation had become well documented by the end of 1976. Nothing was known, however, about the timing and rate of their formation, with the exception of the fact that the 1975/76 frost blisters were well developed by 20 March 1976. In December 1976 it was decided that the growth of frost blisters at the Bear Rock spring site could only be monitored through the use of *time-lapse photography*.

A battery-powered automatic time-lapse camera system was developed for this purpose during early 1977 (Banner and van Everdingen, 1979). Final installation of three cameras, on suitably positioned trees at the south and east edges of the Bear Rock glade, took place on 26 September 1977 (van Everdingen and Banner, 1979). Camera locations are indicated in the 1978 portion of Figure 11; Figure 13 shows one of the systems in early May 1978. All three cameras were set to expose three frames each day at solar noon.

Twenty plywood targets, 30.5 cm square and painted half black and half white for maximum visibility under most ground conditions, were installed on and between remnants of earlier frost blisters to allow photogrammetric measurements. The targets were subsequently surveyed, using a WILD T2 Universal Theodolite.

The first set of time-lapse films was retrieved on 3 May 1978. Recharged batteries and cameras with fresh film were installed in the three systems on 6 May, to monitor the decay of the frost blisters. All the targets and the four new frost blisters that had formed during the winter were surveyed on the next day. The time-lapse photography was terminated and the systems retrieved on 13 September 1978, after a total of 351 days of operation. Targets and frost-mound remnants were re-surveyed on 15 September; the targets and other survey markers were subsequently removed.

The daily negatives from cameras I and III (Fig. 11d) were printed on 12.5 × 20 cm black and white photographic paper; examples are shown in Figure 14. The prints were used to determine the starting dates and the daily growth of frost blisters E-C78, D78 and G 78 (frost blister A78 was located outside the field of view of the cameras). The targets and a few identifiable fixed objects in the photographs served as reference points for the measurements of daily changes in the elevations of the highest points of the frost blisters throughout the period covered by the photography. Available resolution varied from about 2 cm for frost blister D78, closest to the cameras, to about 8 cm for frost blister E-C78, farthest from the cameras. The results of the measurements are shown in Figure 15b. A comparison with the results of the 7 May 1978 survey indicated an accuracy of the order ±10 cm (van Everdingen and Banner, 1979).

The time-lapse record revealed a number of interesting aspects of the growth of frost blisters at Bear Rock during the 1977/78 winter and it confirmed some inferences that had been based on the earlier incidental observations. Frost blister D78 started growing on 12 December and reached a height of 2.9 m by 24 December, indicating an average increase in height of 0.22 m·day^{-1}. It attained its maximum height of 3.38 m by 30 January; two days later it ruptured and subsided by approximate 0.25 m; its height remained relatively constant after that, until the end of the freezing period.

The second frost blister, E-C78, developed during the period between 9 January and 22 April. Its growth was interrupted three times by the occurrence of rupturing and subsidence of as much as 0.55 m, before it reached its full height of 3.95 m. Smaller fluctuations in height after the main subsidence events may reflect further minor leakage episodes.

The third frost blister, G78, did not start developing until 27 February. It underwent partial subsidence twice

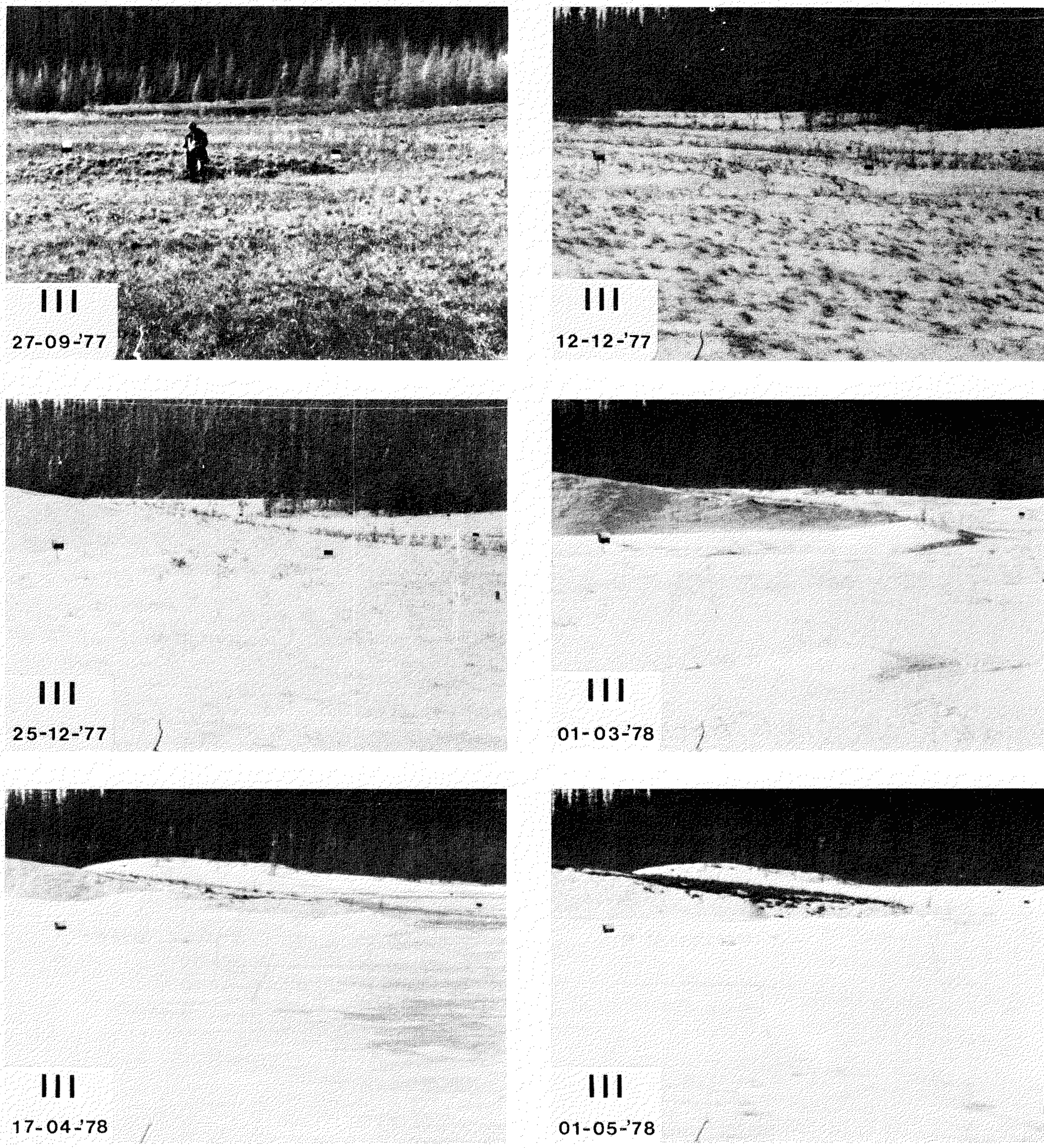


FIG. 14. Selected frames from time-lapse films from the west-looking camera No. III.

(up to 0.85 m) before reaching its full height of 4.92 m on 18 April. It had suffered considerable subsidence (1.23 m) by the time of the survey on 7 May; frost blisters D78 and E-C78 showed only minor subsidence (0.31 m and 0.36 m, respectively) by that time.

The time-lapse photography indicated increases in height of up to 0.55 m·day^{-1} during the early stages of development of the frost blisters. These growth rates, as well as the maximum heights reached by the frost blisters, far exceed the rates and maximum heights shown by ordinary *frost heaving* during a single winter.

The spring and summer portions of the time-lapse photography revealed three slightly different modes of decay. Frost blister G78 subsided rapidly and relatively smoothly

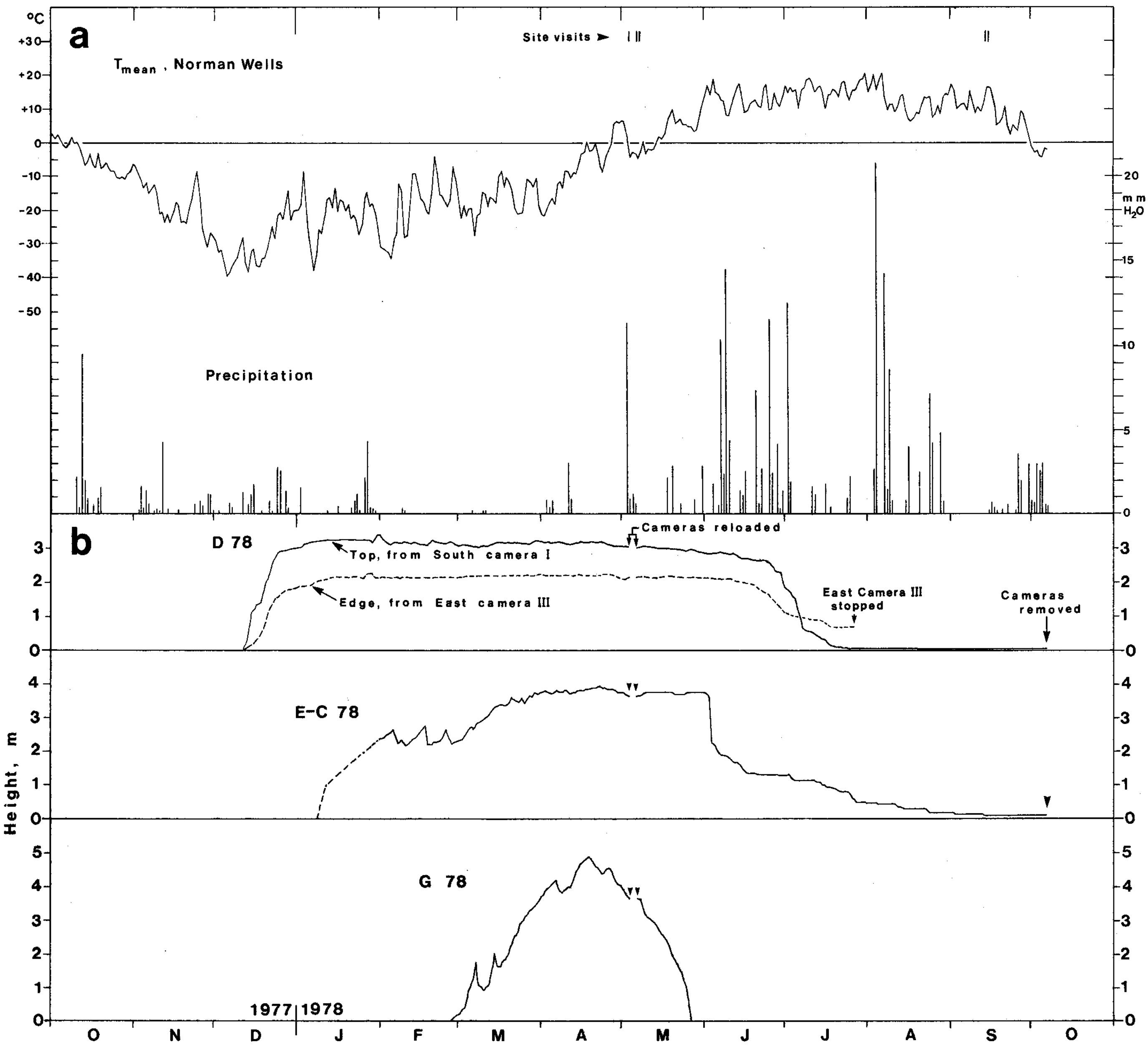


FIG. 15. The 1977/1978 frost-blister cycle at Bear Rock: (a) daily mean temperatures and daily precipitation at Norman Wells airport; (b) growth and decay curves for frost blisters D78, E-C78 and G78, from time-lapse photography.

and was obliterated by 26 May. Frost blister E-C78 remained essentially unaffected until 2 June, when it underwent a sudden subsidence of about 1.35 m. It deteriorated in a stepwise fashion after that. A few minor elevated portions remained by the middle of September.

Frost blister D78 subsided slowly until about mid-June; subsidence of the central part was accelerated during the last two weeks of June and the first week of July. On 18 July, a low "scarp" developed on the west side of the collapsed centre; this scarp retreated in stages, reaching the edge of the blister by mid-September. Only a small portion of the frost blister, about 0.7 m high (equal to the thickness of its ice layer), remained by 13 September.

The time-lapse photography confirmed that surveys to determine the full height of frost blisters have to be carried out during the winter. It also revealed that different frost blisters would have to be surveyed for this purpose at different times (e.g. frost blister D78 on 30 January, frost blister G78 on 18 April and frost blister E-C78 on 22 April). The maximum heights determined for those three frost blisters on the basis of the time-lapse photography are from 0.3 to 1.2 m higher than those determined on the basis of the 7 May survey. It should be added here that the height of about 4.9 m determined for frost blister G78 implies a maximum height of its cavity of over 4.0 m, if the thickness of its ice layer did not exceed the maximum of 0.85 m measured at Bear Rock during the study period.

Influence of Temperature and Snow Cover

It was presumed that the main factors influencing the development (position, dimensions, timing and rate of growth) of frost blisters at Bear Rock would be the temperature regime during the winter and the timing and extent of snow cover. Temperature and precipitation data for the Norman Wells Airport (the nearest weather station) have been used to investigate possible correlations between these weather factors and various aspects of frost-blister growth.

A plot of mean daily temperature and daily precipitation for the period 1 October 1977 to 31 October 1978 was presented earlier in Figure 15. A summary of the potentially significant parameters (length of period with mean temperature continuously below 0°C; total degree-days of freezing; extreme minimum temperature, with date of occurrence; and total precipitation, rain and snow), covering the period from 1 September to 31 August for 1974/75, 1975/76 and 1976/77, is given in Table 3. Graphs of cumulative degree-days of freezing and cumulative snowfall for the four winters are presented in Figure 16 to simplify comparisons between the winters.

Comparison of the data in Table 3 and in Figures 15a and 16 with Figure 11 reveals no obvious connection between the weather factors and the numbers, positions or dimensions of the resulting frost blisters. Several frost blisters developed during each of the four winters, with freezing indices ranging from 3544 to 4334 degree-days of freezing and with the total snowfall ranging from 82.7 to 155.5 mm H_2O. During the coldest winter with the highest snowfall (1974/75), four or five blisters developed; during the mild winter with the least snowfall (1977/78), four blisters developed; only three blisters developed during the relatively cold winter with moderate snowfall (1975/76) and during the relatively mild winter with somewhat higher snowfall (1976/77).

TABLE 3. Summary of temperature and precipitation data for Norman Wells for the period September 1974 to September 1978

	Periods			
	9/74-9/75	9/75-9/76	9/76-9/77	9/77-9/78
Period with T_{mean} <0°C continuously, days	202	186	184	189
Freezing index, °C-days, based on T_{mean}	4334	4252	3544	3560
Extreme T_{min}, °C	−49.4	−47.9	−46.7	−41.2
Date of occurrence	14-1-75	11-12-75	9-12-76	5-12-77
Precipitation, mm H_2O	271.5	250.0	231.1	266.9
Rain, mm H_2O	116.0	149.1	120.8	184.2
Snow, mm H_2O	155.5	100.9	110.3	82.7

The potential effect of *snow cover* would normally be much attenuated at the Bear Rock spring site as a result of incorporation of the snowfall in icings forming in the glade, which eliminates most of the insulating capacity of the snow. Even during the 1974/75 winter the total snowfall (155.5 mm H_2O) would only have contributed between 10 and 15 percent to the thickness of the icing (ranging in thickness from 1.1 to 1.5 m), thus adding relatively little to the overall thermal resistance. No evidence was found to indicate that wind conditions had significantly increased the snow cover in the glade through drifting during any of the four winters. Incorporation of drifting snow into the icings would in any case have cancelled out most of the potential increase in insulation. The tops of developing frost blisters are usually kept relatively snow-free by wind.

Comparison of parts a and b of Figure 15 indicates that the first frost blister of the 1977/78 winter (D78) started developing approximately 63 days after the start of the period with daily mean temperatures continuously below 0°C. By that time the *freezing index* had reached 1115 degree-days and freezing could easily have penetrated into the ground as deep as 0.6 m, the average thickness of frozen soil on this frost blister.

The freezing index reached the same value of approximately 1115 degree-days on 5 December in both the 1974/75 and 1975/76 winters and on 20 December in the 1976/77 winter, according to Figure 16. This suggests that the starting date for the development of frost blisters at Bear Rock probably varies by not more than about 15 days. The much heavier early snowfall in the 1974/75 winter (more than 80 cm by 5 December, compared to between 30 and 45 cm in the three other winters) might have delayed the start of frost blistering, but only if a significant proportion of the snow had not yet been incorporated into icings forming in the glade.

Five of the seven notable subsidence events recorded by the time-lapse photography during the 1977/78 winter coincided with sudden drops in the daily mean temperature (Fig. 15). This is regarded as an indication that partial subsidence of frost blisters during the winter results from draining of part of the contained water as a consequence of rupturing triggered by contraction-cracking of frozen ground and ice, which is itself caused by a sudden lowering of temperature.

Frost-blister development stopped, according to the time-lapse photography, on 22 April 1978, when frost blister E-C78 attained its maximum height; this date coincides with the end of the period with daily mean temperatures continuously below 0°C.

Distribution of Environmental Isotopes in Frost-Blister Ice

Ice samples from the frost blisters at Bear Rock have been analysed for deuterium and oxygen-18, to determine whether the ice layers in the frost blisters form by freezing in an open system (continuously replenished by flow-through), in a closed system (with inflow only), or in an

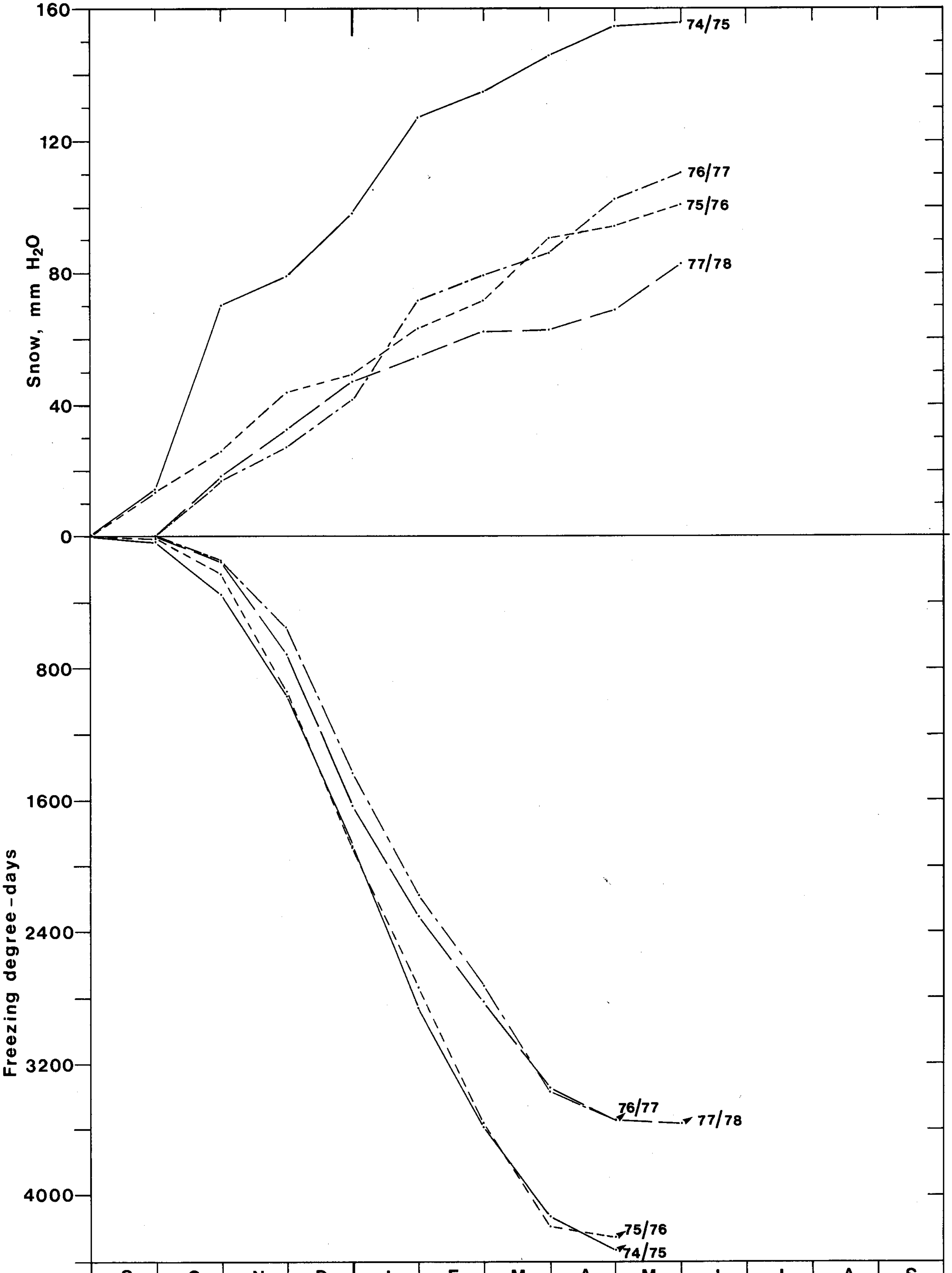


FIG. 16. Cumulative freezing degree-days and cumulative snow cover for the Norman Wells area, for the winters 1974/75, 1975/76, 1976/77 and 1977/78.

intermittently leaky system, and to determine the source of the water that formed the ice.

Water molecules containing the lower-energy, heavy isotopes (^2H and ^{18}O) are preferentially incorporated in the solid phase during freezing, while the residual liquid becomes depleted with respect to those isotopes. Laboratory experiments by Suzuoki and Kimura (1973) have shown that the $\delta^{18}O$ and δ^2H values for ice formed in equilibrium with water will show positive shifts of about 3‰ and 21‰, respectively, relative to the $\delta^{18}O$ and δ^2H of the original water. Equilibrium is apparently not reached if the freezing rate exceeds 2 $mm \cdot h^{-1}$, or if the residual water is not vigorously agitated during the process; at a freezing rate of 5 $mm \cdot h^{-1}$, isotopic fractionations reached only about 50% of the equilibrium values.

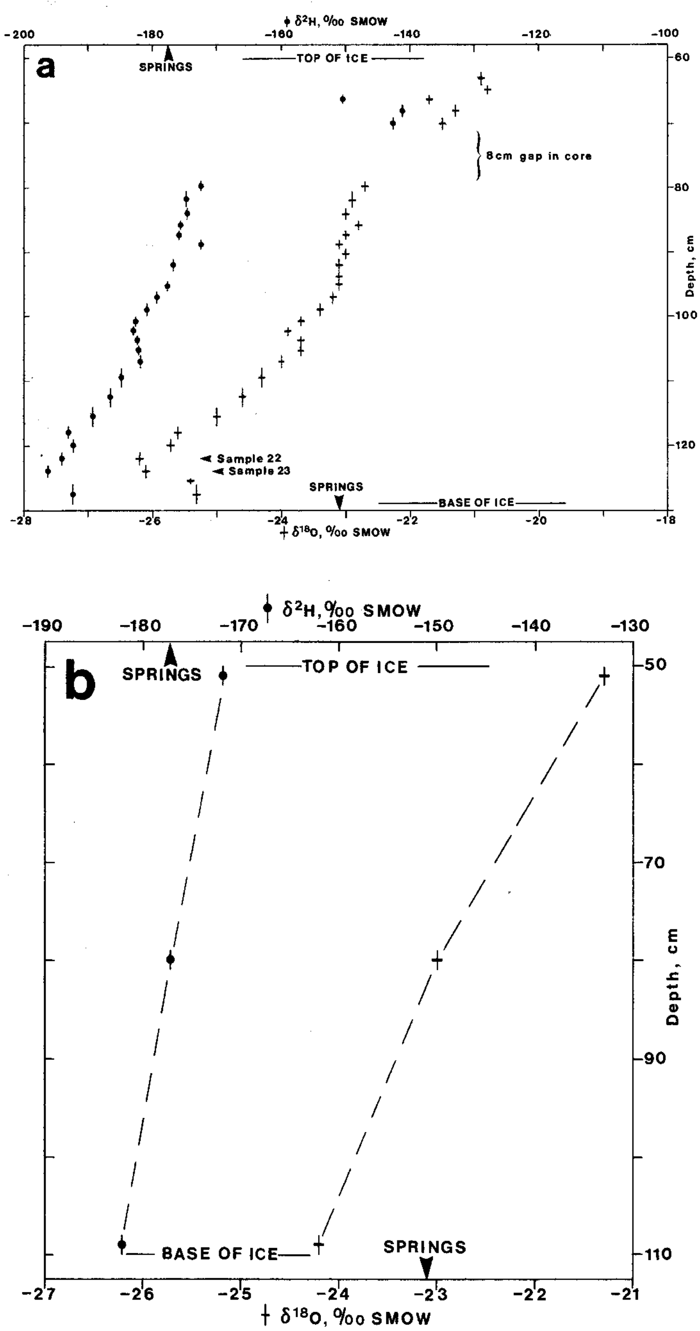


FIG. 17. δ^2H and $\delta^{18}O$ *vs.* depth for ice layers in Bear Rock frost blisters: (a) samples from drill core from C75; (b) samples from hole cut in top of H77.

In the case of frost blisters, with the ice forming below a layer of frozen soil (and possibly snow), the rate of ice formation is likely to be less than 2 $mm \cdot h^{-1}$ (less than 5 cm in 24 hours), but it is unlikely that the remaining water will be agitated vigorously. Therefore one would expect to find isotopic shifts of less than +3‰ (in $\delta^{18}O$) and +21‰ (in δ^2H) relative to the spring water, if the frost-blister ice were formed in an open system. If the frost-blister ice were formed in equilibrium with the water in a closed system, however, continued slow freezing of the shrinking reservoir would result in progressive depletion of the remaining water with respect to the heavy isotopes; the ice, although enriched relative to the remaining water, would also reflect the progressive depletion relative to the original water. This effect would accelerate as the liquid reservoir shrinks and the fractionation effects would be most strongly displayed by the last ice formed.

The $\delta^{18}O$ values for ice samples cut from a drill core obtained from frost blister C75 were reported by Fritz and Michel (1977) and discussed by van Everdingen (1978); δ^2H values for the same samples were reported by Michel and Fritz (1978). Figure 17a presents a plot of $\delta^{18}O$ and δ^2H *vs.* depth for these samples. Results of isotope analyses for ice samples collected in 1977 from the top, centre and base of the ice layer in frost blister H77 are presented in Figure 17b. The mean isotopic composition of the spring water is indicated in Figures 17a and 17b for comparison.

The isotope data for frost-blister C75 can only be interpreted as resulting from slow freezing in a closed system (Fritz and Michel, 1977; Michel and Fritz, 1978; van Everdingen, 1978). The samples in the upper part of the core show values less negative than those for the spring water, reflecting the positive fractionation of δ^2H and $\delta^{18}O$ during freezing of the spring water; the increasingly more negative values in the lower part of the core result from continued freezing of the shrinking reservoir that is progressively being depleted with respect to the heavier isotopes. The most negative values found in ice from this core (−26.2‰ and −196.2‰ for $\delta^{18}O$ and δ^2H, respectively) indicate that the $\delta^{18}O$ and δ^2H values in the final residual reservoir may have fallen as low as −29‰ and −215‰ respectively.

The bottom 18 cm of the lower core from frost blister C75 consisted of frozen silt, sand and fine gravel; no cavity was found between the ice and the frozen soil materials. The latter are presumed to represent the permafrost that underlies the Bear Rock glade; frozen ground was encountered at depths ranging from 65 to 85 cm on 24 September 1977 and on 14 September 1978. The core hole was located near the edge of the frost blister and it is therefore possible that the ice at this point completely filled the space created between the seasonally frozen soil and the permafrost during development of the frost blister. This tentative explanation is supported by the isotope data in Figure 17a which indicate that samples 22 and 23 (with the most negative isotope values) correspond to the last aliquot of water from the residual reservoir to be turned into ice (Michel and Fritz, 1978). Most of the ice (above sample 23) was formed by freezing from the top downwards in response to negative air temperatures; a minor portion of the ice (samples 23 to 25) may have formed by freezing advancing upwards from the permafrost.

The isotope data for the samples from frost blister H77 show a pattern similar to that shown by the ice from frost blister C75 above sample 23. The main difference between the two is the considerably flatter slope exhibited by the δ^2H *vs.* $\delta^{18}O$ line calculated for H77 (about 3.5) as compared to the approximate slope of that line for the lower portion of the C75 core (about 6.3). Both slopes, as expected, are flatter than the slope of the meteoric water line (7.5 for Fort Smith; 8.0 ± 0.1 world-wide). Weighted-mean values of $\delta^{18}O$ and δ^2H for the samples from frost-blister C75 (−23.3‰ and −170.3‰) and for the samples from frost blister H77 (−22.8‰ and −177.1‰) are similar to the mean values for the spring water (−23.1‰ and −177.4‰), confirming that the ice layers are formed from the spring water.

The isotope data thus indicate that the frost-blister ice is formed from spring water in a closed system. Evidence from the time-lapse photography, supported by field observations, indicates that some frost blisters may rupture, drain and refill during their development. Such an event would be reflected in the isotope curves for the ice by a sudden return to values somewhat less negative than the spring-water values, followed by a renewed progressive depletion with depth.

THE FROST-BLISTER PHENOMENON

The Model

The environmental conditions that are required to enable the formation of frost blisters were identified by van Everdingen (1978) as: perennial discharge of groundwater with a low temperature; presence of a layer of very low permeability (such as perennially frozen ground) close to the surface; and a long winter with daily mean temperatures below freezing. On the basis of the 1978 data presented above, it should be added that a freezing index exceeding 1100 degree-days appears to be required to initiate frost-blister development under the discharge and ground conditions prevailing at Bear Rock.

An outline of the sequence of events during the formation and degradation of frost blisters (and icing blisters) was also given by van Everdingen (1978), starting with the situation in the fall (Fig. 18/1). During early winter, freezing penetrates progressively into the saturated active layer underlying the glade, reducing both the transmissivity and storage and restricting water movement; freezing of spring water on the surface starts forming icings (Fig. 18/2). Continued freezing of the ground and formation of icing may eventually freeze the spring outlets. Increasing restriction of water movement in the remaining nonfrozen portion of the active layer leads to increases in the hydraulic potential to a magnitude that will eventually enable uplifting of the seasonally frozen ground and any overlying icing (Fig. 18/3a). Actual uplifting will occur at the point or points where the most favourable combination of relatively low resistance to deformation of the frozen ground and relatively rapid supply of water is found. The observations since 1975 indicate that such points are located primarily on the outflow channels of the springs.

It is possible that the distribution of frost blisters at the Bear Rock spring site reflects the existence of a system of small taliks, each feeding a minor seep, in addition to the main taliks that feed the springs identified in Figures 3 and 18. Such small taliks would locally provide the favourable combination of water supply and excess pressure (relative to deformation resistance) referred to above. If that is the case, then the icings in the glade would represent discharge from the main springs, whereas discharge from the seeps would be responsible for the growth of the frost blisters. It would perhaps also explain why frost blisters appear to be a permafrost phenomenon; groups of small permeable taliks in permafrost are more likely to be self-maintaining than small seeps in non-permafrost low-permeability materials.

The water injected into a frost blister during the uplift freezes gradually from the top down, forming clean massive ice. It was presumed by van Everdingen (1978) that uplifting would proceed slowly; that the ice layer developing in a frost blister would deform plastically rather than by fracturing; and that the strength of the seasonally frozen soil would prevent sudden deformation. The 1978 observations, however, indicate that uplifting may proceed as fast as 0.55 $m \cdot day^{-1}$. It is therefore not surprising that developing frost blisters do on some occasions rupture (Fig. 18/4a); contraction fractures induced by sudden cold periods may provide the triggering mechanism (Fig. 15). Depending on fracture location, part or all of the water may drain out, leading to partial subsidence of the then unsupported frozen soil and ice cover of the blister. Gradual refilling with water will allow the fractures to heal, as shown in Figure 9a.

When the daily mean temperature rises above 0°C, frost penetration and encroachment will stop, halting further increases in hydraulic potential. Consequently, frost-blister growth will also stop, as observed during the 1977/78 winter. Initial thawing around the spring orifices will tend to relieve hydraulic potential, especially in the frost blister that was formed last, encouraging subsidence (cf. frost blister G78, Fig. 15).

Melting of snow and icing in springtime exposes the actual frost blister (Fig. 18/5a). The cover of frozen soil is

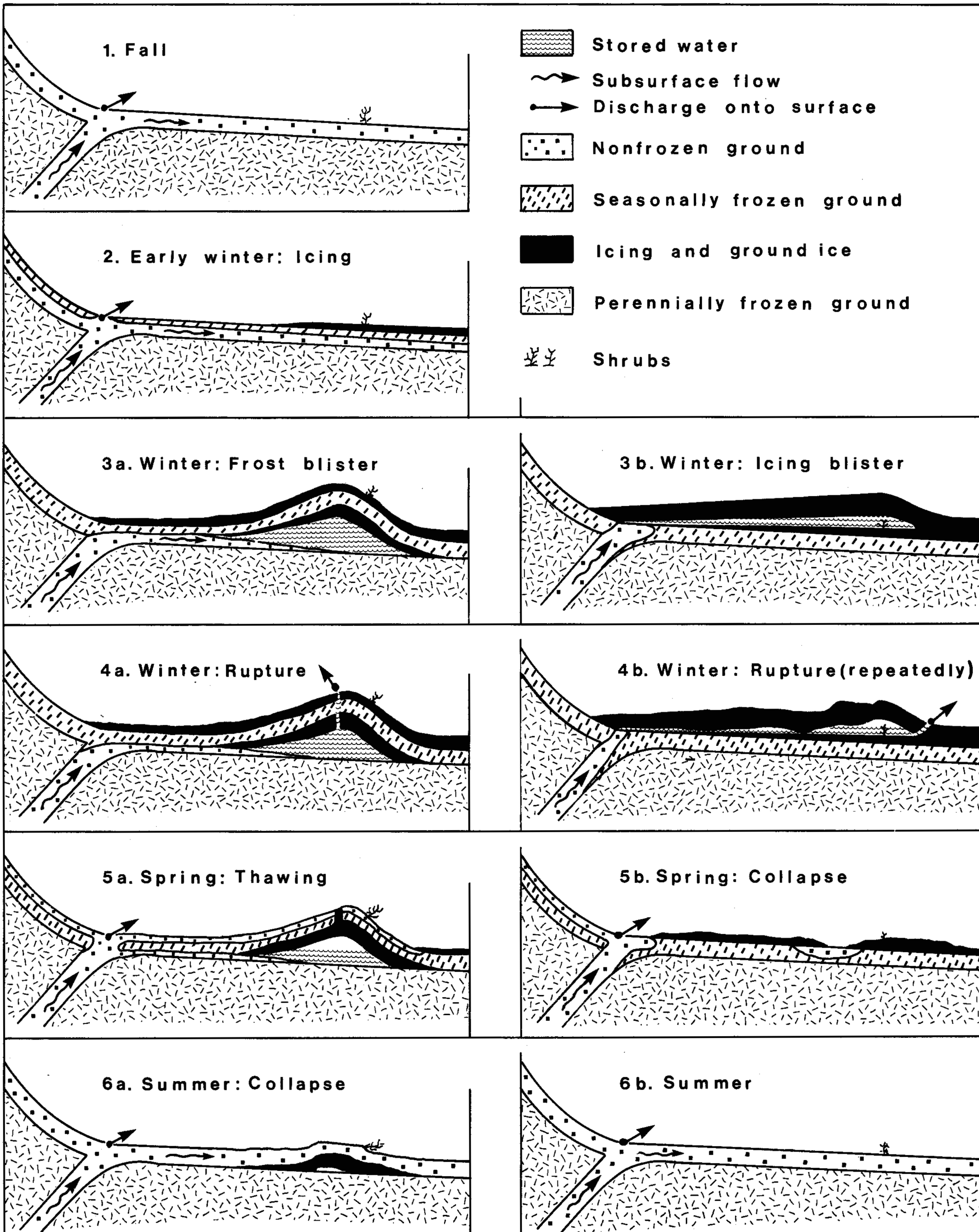


FIG. 18. The sequence of events in the formation and decay of frost blisters and icing blisters (from van Everdingen, 1978).

gradually weakened by thawing, leading to subsidence and/or collapse (Fig. 18/6a). Portions of the ice layer in the frost blister may last through the summer and sometimes well into the second summer after its formation.

Diagrams illustrating the formation of a frost blister, as a result of freezing that impedes percolation of water in the active layer, were presented by Muller (1945: Fig. 29, modified after Nikiforoff, undated). The one objection to those diagrams is that they show a nonfrozen portion of the active layer being lifted by the water in the cavity.

Formation of icing blisters is similar to that of frost blisters, the main difference being that no frozen ground is being lifted but only icing ice, by water channeling between icing layers (Fig. 18/3b). As the cover of an icing blister lacks the strength provided by a layer of frozen ground, icing blisters are likely to rupture more readily than frost blisters (Fig. 18/4b). Rupturing, followed by partial subsidence, resealing and renewed uplift, are therefore likely to be experienced more frequently by icing blisters. Icing blisters are destroyed more rapidly than frost blisters (Fig. 18/5b); by the summer little or no evidence is left of their earlier existence (Fig. 18/6b).

In cases where the fractures formed during rupture of a frost blister or icing blister are located low on its flanks, air may be entrapped inside the blister when the fractures are resealed by freezing. Compression of the entrapped air would make future rupture of such a blister explosive in character. Accumulation of gases carried in the groundwater could lead to a similar effect. Such explosive ruptures have been described in the literature from several places (e.g. Sloan *et al.*, 1976).

Minimum Required Water Pressures

During the formation of a frost blister significant forces are required to overcome the resistance against deformation of the gradually thickening layer of ice in the blister, as well as of the layers of seasonally frozen ground and icing covering the blister, and to support and lift them.

Using the heights shown in Figure 12 for two of the frost blisters (D75 and E76) and the thicknesses of the various materials overlying their respective cavities, van Everdingen (1978) calculated minimum hydraulic potentials, at the bottom of the water-filled cavities in these frost blisters, that would be required just to support the overlying materials towards the end of their growth cycle, as 2.65 m H_2O and 4.90 m H_2O, respectively. Resistance to deformation of the frozen materials was not taken into account.

The results of the calculations published by van Everdingen (1978) were incorrect because of erroneous interpretation of the stratigraphy of the blisters. A reinterpretation of the data shows that frost blister D75 (2.91 m high) contained a cavity about 2.06 m high, below an ice layer of 0.85 m and a soil cover of 0.50 m. Assuming densities of 0.9 for ice, 1.6 for saturated frozen soil and 1.0 for water, the minimum required hydraulic potential at the bottom of the water-filled cavity would be 3.63 m H_2O (35.5 kPa). Similarly, one finds a minimum required hydraulic potential of 4.31 m H_2O (42.2 kPa) for the composite icing blister and frost blister E76 (4.20 m high; consisting, from top to bottom, of 1.5 m icing, a 0.9 m high cavity, 0.2 m soil, approximately 0.6 m ice and a 1.2 m high cavity). The highest frost blister observed at Bear Rock, G78 (approximately 4.9 m high, with a soil cover of about 0.6 m and an ice layer approximately 0.75 m thick) would have required a hydraulic potential of about 5.8 m H_2O (56.8 kPa).

The forces required to overcome the deformation resistance of the cover of a frost blister are more difficult to determine; both elastic and plastic deformation presumably play a role in the process. The strength of the layer of frozen soil is dependent on a number of factors such as ice content, grain-size distribution and grain shape, strain rate and temperature distribution. The strength of the frost-blister ice depends on its degree of homogeneity, the prevailing temperatures and the strain rate; the gradual increase in the thickness of the ice-layer with time presents an additional complication. None of the factors involved are known in much detail; their relative influence is difficult to define with any degree of reliability. It is likely, however, that the actual deformation of the frost-blister cover at any one point is minor, because of the small ratios between vertical and horizontal dimensions.

It appears possible, nevertheless, to determine the approximate magnitude of the hydraulic forces involved. A frost blister occupies only a small portion of a large area subject to both frost penetration and, potentially, buildup of hydraulic pressure. As stated earlier, frost blisters form at points where the combination of deformation resistance and water supply is most favourable, e.g. where the depth of freezing is slightly less because of somewhat higher convective heat supply by moving groundwater. When water is being injected into a developing frost blister, that frost blister must constitute a point of lower potential compared to the surrounding area, otherwise the groundwater would not move toward and into it; instead, it would lift the whole area. Growth of the frost blister stops when the potentials in the water in the frost blister and in the surrounding area have been equalized. It can therefore be concluded that the hydraulic potentials calculated earlier, equal to the weight per unit area of the overburden plus the water column in the frost blister, are adequate to overcome the deformation resistance. In the case of frost blister G78, for example, the overburden would be supported initially by a force equivalent to 0.96 m H_2O (9.4 kPa), increasing to 1.64 m H_2O (16.1 kPa), leaving a force decreasing from 4.84 m H_2O (47.4 kPa) to 4.16 m H_2O (40.7 kPa) to overcome the deformation resistance.

The actual magnitude of the hydraulic potentials involved in frost-blister development could presumably be determined by drilling and pressure measurements. However, no reliable method has yet been devised to seal a pressure-measuring device into the ice layer of a frost blister for a period long enough to allow full recovery of the pressure loss occasioned by drilling and installation of the device.

At the Bear Rock spring site, the increased hydraulic potentials occur only during the winter; they are provided by the groundwater flow system that feeds the springs. As the discharge from the springs is gradually impeded by reduction of transmissivity caused by freezing of the ground, progressively higher hydraulic potentials will be automatically transmitted to the discharge area, because other outlets with lower overall hydraulic resistance apparently do not exist.

The Influence of Grain-Size Distribution

The observations at Bear Rock indicate that frost blisters up to 4.9 m high, with ice layers up to 0.85 m thick, can be formed in a single winter if a supply of groundwater with a sufficiently high hydraulic potential is available. Grain-size distribution, which appears to play a limiting role in the formation of many occurrences of subsurface segregated ice, does not appear to have a limiting influence on the occurrence of frost blisters.

Results of grain-size analyses of soil materials overlying the ice layer in three of the Bear Rock frost blisters, B75, C75 and D75 (van Everdingen, 1978) are shown in Figure 19. Grain-size analyses for material overlying the ice in a frost blister at a spring site 21 km northeast of Turton Lake, about 70 km north of Norman Wells (van Everdingen, 1978) and for materials underlying and overlying the ice layer of a frost blister along the Alaska Highway near Donjek River, Yukon (van Everdingen, 1982) have been included in Figure 19 for comparison. Frost blisters can apparently form in materials with a wide range of grain-size distributions, provided that the water-supply and temperature conditions are satisfied.

Other Occurrences of Frost Blisters

From the foregoing it is clear that the occurrence of frost blisters is not restricted to the Bear Rock spring site. Frost blisters can form wherever the required conditions of water supply, permeability and temperature are satisfied. One example, at the spring site northeast of Turton Lake (65°53′15″N, 126°30′W), was mentioned above; soil conditions there are similar to those at Bear Rock (Fig. 19).

A second example is located on the north shore near the east end of Kelly Lake (65°24′19″N, 126°05′45″W), where a low *gravel*-covered frost blister was found in the unvegetated outflow area of a group of springs described by Michel (1977).

Groups of small frost mounds (1.0 to 3.7 m high and 6 to 30 m in diameter) form every winter in the valley of East Blackstone River just north of North Fork Pass, Yukon (64°35′49″N, 138°18′34″W). These were interpreted as frost

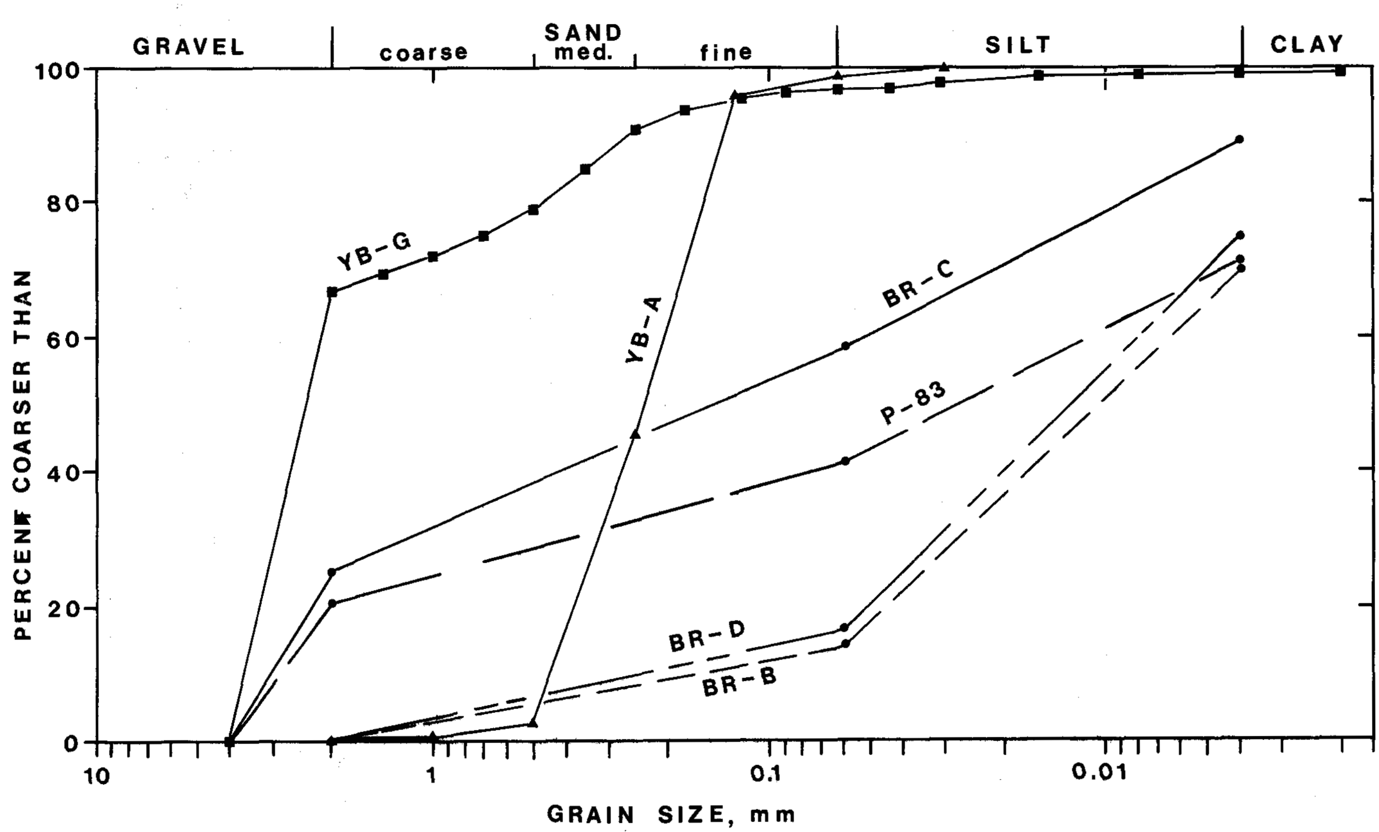


FIG. 19. Grain-size distribution: BR-B, BR-C and BR-D for materials overlying the ice layers in Bear Rock frost blisters B75, C75 and D75; P-83 for material overlying the ice layer in a frost blister 21 km NE of Turton Lake; YB-A and YB-G for materials overlying the ice and underlying the cavity in a frost blister near km 1817.5, Alaska Highway, Yukon.

blisters by van Everdingen (1978); fresh frost blisters that had formed in the 1977/78 winter at this site were described by Hughes and van Everdingen (1979). Their topographic setting is similar to the Bear Rock occurrence: a short distance downslope from springs at the base of the mountains. Their cover, however, consists primarily of sedge *peat*. They are the subject of a detailed study by W. H. Pollard, University of Ottawa; the stone-free nature of their cover makes drilling and, we hope, measurement of water pressures in their cavities, more practical than at Bear Rock.

A recent example of an *exploded* frost blister, in the valley of Fish Creek near the Trans-Alaska pipeline route (66°32′N, 150°44′E, approximately), was reported by Sloane *et al.* (1976), who described it as an "exploded hillside icing mound". An up-ended soil and ice block shown in their Figure 5 (Sloane *et al.*, 1976:7) can be seen to consist of, from top to bottom (left to right in the photograph): approximately 40 cm of layered icing ice, 35 cm of frozen soil and 30 cm of massive (frost blister) ice. The topographic setting was apparently similar to those described above; details about the soil materials involved were not given.

Both frost blisters and icing blisters have recently been described from the Olgoin-gol river valley in the southern part of the Bayan-Nuurin-khotnor basin, Khangai Mountains, Mongolia (47°N, 100°E, approximately) by Froehlich and Slupik (1978 a, b and c) and by Froehlich *et al.* (1978). Terms used by those authors to describe the frost blisters were: seasonal earth mound, seasonal "winter pingo", seasonal frost mound, ice-covered ground mound and ice-cored mound covered with ice (Froehlich *et al.*, 1978); seasonal pingo mound and seasonal pingo-type mound (Froehlich and Slupik, 1978a); ice mound, ice-covered ground mound, "winter pingo"-type ice mound and "winter pingo"-type seasonal ice-mound (Froehlich and Slupik, 1978b); and frost blister, seasonal hydrolaccolith, ice-cored mound, ice-cored earth mound and "winter pingo" (Froehlich and Slupik, 1978c). Although translation difficulties undoubtedly compounded this profusion of terms it is no worse than the terminological confusion observed in the North American literature. The term *frost blister* still appears to be one of the handiest; the term *seasonal pingo* used by Froehlich and Slupik (1978a) for the seasonal frost mounds of the same type in Mongolia may be equally appropriate.

An "icing mound" on the Tuktoyaktuk Peninsula, N.W.T., described by Mackay (1977:213-214), which formed in the 1975/76 winter and collapsed in August 1976, contained a cavity, 1.65 m high at the centre and 12 by 15 m across, showing horizontal water-level marks on the inside ice surface. On the basis of this description the mound was interpreted as being a frost blister by van Everdingen (1978). The mound was located near the edge of a pingo, in the basin of a drained lake; the material was sandy lake-bottom sediment. A second "icing mound" described by Mackay (1975:473, Fig. 2) as having grown during the 1973/74 winter and again by Mackay (1977:212, Fig. 5) as having grown during the 1974/75 winter, may also have been a frost blister.

The "ice mound" described by Porsild (1938:53-54) from near the lower east branch of the Mackenzie Delta was interpreted as a frost blister by van Everdingen (1978) on the basis of its vegetation cover shown on a photograph published by Porsild (1938: Fig. 2). It may also have been a very young pingo.

The above examples describe natural occurrences of frost blisters and icing blisters which may present a hazard to construction projects if not recognized in time. Man-induced changes in the groundwater and thermal regimes may inadvertently create the combination of conditions required for formation of frost blisters at locations where they do not occur under natural conditions. One such occurrence, on the Dempster Highway about 6 km east of Fort McPherson, N.W.T., was described by van Everdingen (1978). During the first winter after construction of the highway embankment, differential uplifting affected an area more than 100 m wide along the highway and extending more than 200 m upstream from where the highway crosses a shallow drainage depression. Compaction of water-bearing materials under the weight of the embankment fill and, possibly, aggradation of permafrost below the embankment, reduced the transmissivity, thereby impeding subsurface drainage from an unnamed lake upstream, southeast of the highway. The resulting increase in hydraulic potential caused uplift, followed by repeated rupture of the seasonally frozen surficial materials, and buildup of icing that overtopped the embankment.

A similar occurrence, along a 4.5 km long section of the Alaska Highway west of Tanacross in Alaska, during the 1943/44 winter, was described by Eager and Pryor (1945:63-67).

A low, wide frost blister was suspected to have formed during the 1979/80 winter in the upstream portion of an icing area at km 1817.5 on the Alaska Highway (61°38′36″N, 139°43′14″W) just east of Donjek River (van Everdingen, 1982). The ice of this frost blister was covered by peat and volcanic ash; gravelly sandy "till" formed the floor of a low cavity below the ice. Grain-size analyses for the ash and the "till" are included in Figure 19.

Finally, uncontrolled flow of subpermafrost water from artesian wells may create the water-supply condition required for the formation of frost blisters, as shown by Linell (1973). A water-supply well drilled in the Farmers Loop Road Research Area, Fairbanks, Alaska, became uncontrolled when artesian water was encountered at a depth of 32.9 m on 3 May 1946. Although efforts to control the flow appeared to have been successful, surface icings, extending several kilometres from the well site, formed during the 1948/49 winter; a frost blister had developed by early April 1949 at a point about 4 km from the well. A crack 2.5 to 12.7 cm wide, extending over 45 m along the ridge of the blister, was found to be sealed with ice over most of its length, but water was flowing from it in several places. An idealized section of the frost blister published by Linell (1973: Fig. 4) shows 0.3 to 0.6 m icing, 0.2 m of frozen moss and 0.5 m of seasonally frozen silt overlying an upward bulge of the permafrost; water under "hydrostatic head" is shown occupying a small pear-shaped closed talik at the centre of the permafrost bulge. It should be regarded as unlikely that such a bulge existed in the permafrost; it is more likely that the "talik" was a wide, flat-bottomed and dome-shaped, water-filled cavity, similar to those found in the Bear Rock frost blisters; and that an ice layer was present between the frozen silt and the talik (at a depth of 1.0 to 1.3 m below the icing surface).

SUMMARY AND CONCLUSIONS

Several frost blisters develop every winter at the Bear Rock spring site, reaching heights of up to 4.9 m and horizontal dimensions up to 20 by 65 m. They consist of a layer of frozen soil 20-85 cm thick, overlying a layer of ice 25-85 cm thick, which in turn covers a cavity with a maximum calculated height of 4.16 m. Positions and dimensions vary from year to year without apparent correlation with differences in temperature regime and snow cover.

Time-lapse photography during the 1977/78 winter revealed that the first frost blister started growing on 12 December 1977 when the freezing index had reached 1115 degree-days; that height increased in some instances as fast as 0.55 $m \cdot day^{-1}$; that growth was interrupted several times by subsidence of as much as 0.85 m; and that development of the last frost blister stopped when mean daily temperatures rose above 0°C. The subsidence events during the winter, following rupture and partial draining, appear to be triggered by rapid lowering of air temperatures. It is regarded as likely that the starting date of frost-blister development at Bear Rock does not vary by more than about 15 days (5 December to 20 December).

Results of isotope analyses indicated that the frost-blister ice forms by freezing of spring water in a closed system.

The frost blisters are formed, through hydraulic lifting of frozen soil and a gradually thickening ice layer, by groundwater under pressure. Hydraulic potentials involved in frost-blister development are relatively low; the highest frost blister at Bear Rock is thought to have required the equivalent of 1.64 m H_2O for support of the soil and ice layers and the equivalent of 4.16 m H_2O to overcome the deformation resistance of its cover.

The requirements for development of frost blisters are: perennial discharge of groundwater with a low temperature; presence of limited conduits in a layer of very low permeability (e.g. taliks in permafrost) in the shallow subsurface, and a long period with daily mean temperatures below freezing. Grain-size distribution apparently does not have a limiting influence on the occurrence of frost blisters. They can form in a variety of settings as long as the basic requirements are satisfied.

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