BASAL ICE LAYERS OF VERY COLD ARCTIC SNOWPACKS

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ABSTRACT

In the Canadian High Arctic, both the snowpack and the ground temperatures are extremely low throughout winter. During the melt period, meltwater percolating through the cold pack will refreeze as ice layers, thus releasing heat to the lower parts of the pack. When water reaches the bottom of the pack, the cold substrate again refreezes the meltwater to produce a basal ice layer. The growth of this layer will continue until meltwater supply is depleted or until the extreme coldness of the ground is removed. When the basal ice is exposed, its destruction is accomplished by surface melting or by rills eroding on the ice.

Basal ice formation is an efficient mechanism that transfers heat through the cold snowpacks and to the cold substrate. Hydrologically, multiple freezing and melting of water through ice formation and destruction complicate the snowmelt-runoff relationship. Where basal ice layers are abundant, basin storage is prolonged and they contribute to streamflow during the drier Arctic summers.

INTRODUCTION

In very cold regions such as the Canadian High Arctic, a layer of ice is frequently encountered at the base of the melting snowpacks. This ice is formed by a refreezing of the percolating meltwater as it encounters a cold substrate. Most basal ice layers remelt after the original snowpack has disappeared. In some cases, however, this ice persists throughout summer and can grow into multi-year ice, an example of which is the superimposed ice commonly observed on glaciers (Koerner, 1970; Wakahama et al., 1976). This paper will discuss the processes which produce the basal ice layers in snowpacks, and will examine the effects of basal ice upon the hydrology of cold regions.

STUDY AREA AND SNOW CONDITIONS

Field observations were carried out in eastern Queen Elizabeth Islands, mainly in the vicinity of Resolute, Cornwallis Island; Eidsbotn Fiord, Devon Island; and Vendom Fiord, Ellesmere Island (Fig. 1). The area is charcterized by a lack of vegetation and an uneven snow distribution in winter. Most valleys tend to have deep snowpacks but the exposed ridge-tops and steep slopes have little snow (Woo and Marsh, 1978). The annual snow cover duration is nine months or more, with negligible melting during the long polar winters.

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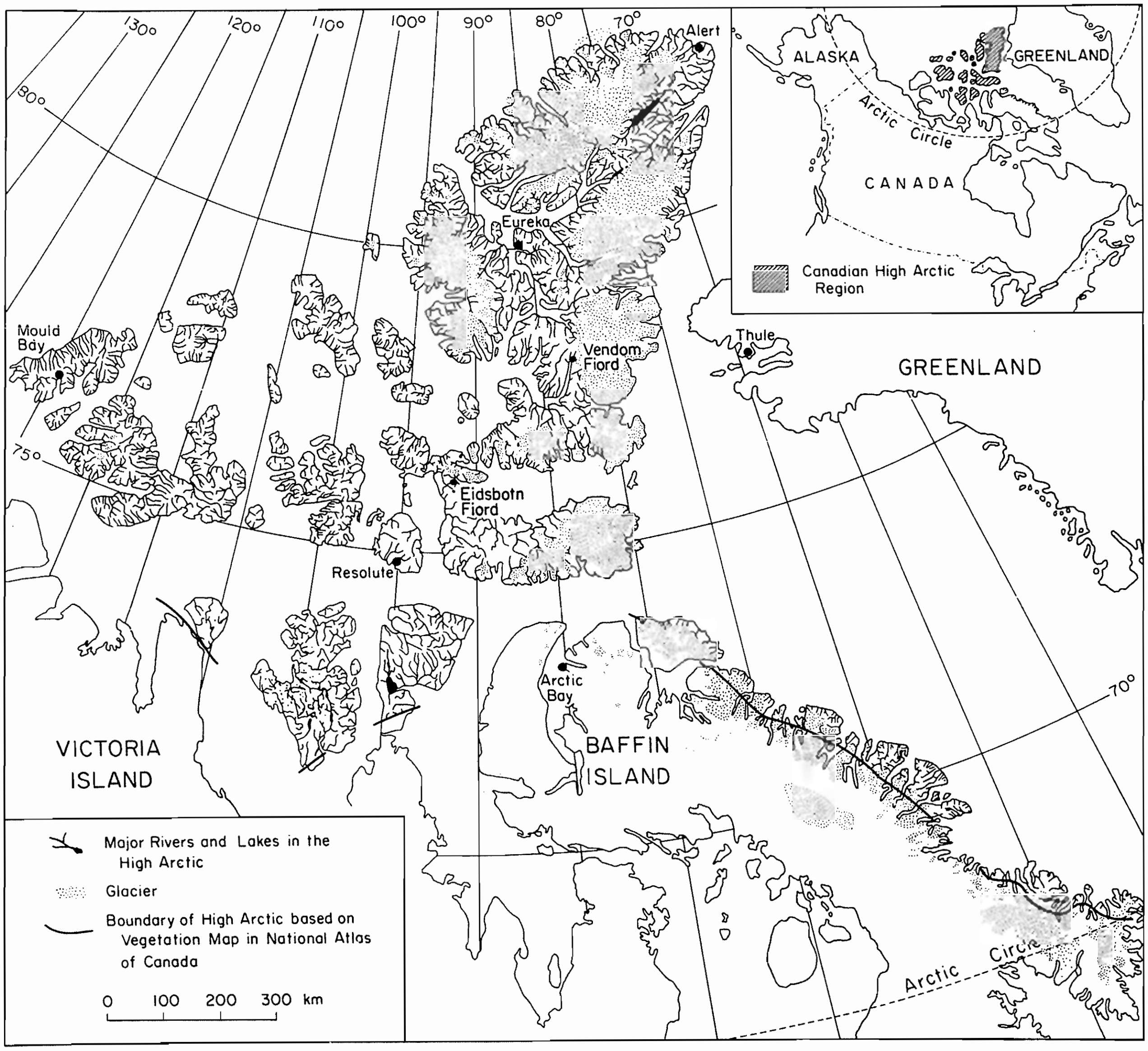

Fig. 1 Map showing the Canadian High Arctic and location of major study areas.

In late May, it is common to find the snowpacks at temperatures below -15°C. After the air temperature has risen to 0°C, shallow packs warm up quickly and attain isothermal conditions soon after the commencement of melt. In deeper packs, subfreezing conditions are maintained for days after melting has started at the snow surface. Ground melt is completely absent because the entire area is underlain by permafrost at shallow depths. Typical ground surface temperatures during mid-May vary from -15 to - 20°C, and ground thaw does not occur until the snow has disappeared.

Surface snowmelt begins in late May or June. Downward movement of meltwater often concentrates along flow fingers, and percolation is locally retarded by the layering structure of the pack. This is shown by the path of dye injected at the surface of a typical snowpack at Eidsbotn Fiord on June 4, 1980 (Fig. 2). The photograph was taken at 11:45, about 10 minutes after dye injection. Note that the snowpack was still very cold, but some of the dye was able to penetrate to the bottom of the pack along vertical fingers.

FORMATION OF BASAL ICE LAYER

As meltwater released from the surface of the snowpack percolates through the cold snow, subfreezing temperatures of the pack can refreeze the meltwater into ice lenses and vertical ice pipes (Fig. 3). This in turn releases latent heat which warms up the snow adjacent to the lenses or pipes. Figure 4 is an example from a snow-pit dig during the 1980 melt season at Eidsbotn Fiord. As meltwater refroze, the snow temperature immediately above and below the ice lens was raised by approximately 1°C. The cold snowpack ripens mainly through conduction and latent heat transfer.

As meltwater moves further down to reach the base of the pack, a layer of ice may be formed if the following conditions are satisfied.

(1) the availability of meltwater to the base of the snowpack must exceed the losses through infiltration, lateral runoff or sublimation.

(2) temperature of the substrate must be below 0°C and the latent heat released should be effectively dissipated by conduction to a colder zone such as the permafrost or the glacier ice.

The relative importance of these conditions can be demonstrated by comparing the basal ice growth rate over two types of substrates: bog and lake ice. Observations on ground temperature, snow ablation and basal ice growth were made at Resolute during June 1980 (Fig. 5). Long before basal ice was formed, the substrates were gradually warmed by heat conduction. For two days before initial ice growth at the bog site (13th - 14th June) ground temperature rose rapidly, at a rate unattainable by heat conduction alone. Such abrupt warming of the frozen boggy ground is attributed to an infiltration of meltwater into the pores of the frozen soil, and a subsequent release of latent heat to the ground (Woo and Heron, 1981; Wright, 1980). Infilitration probably continued until the pores were sealed by the refrozen meltwater. Afterwards, further infiltration was inhibited and meltwater began to refreeze at the bottom of the snowpack to form a basal ice layer. In contrast to bogs, lake ice is relatively impermeable and meltwater from the overlying snowpack cannot penetrate into the ice. Thus, meltwater reaching the snow-lake ice interface was immediately refrozen by the cold ice, accompanied by a release of latent heat to warm the underlying ice (14th June). These two examples show that basal ice formation is delayed when meltwater is lost to infiltration. Otherwise, ice growth continues so long as meltwater supply lasts and a subfreezing substrate is maintained.

In topographic depressions at the bottom of some slopes, lateral drainage can supply a considerable amount of meltwater. If the ground is cold, the meltwater will con-

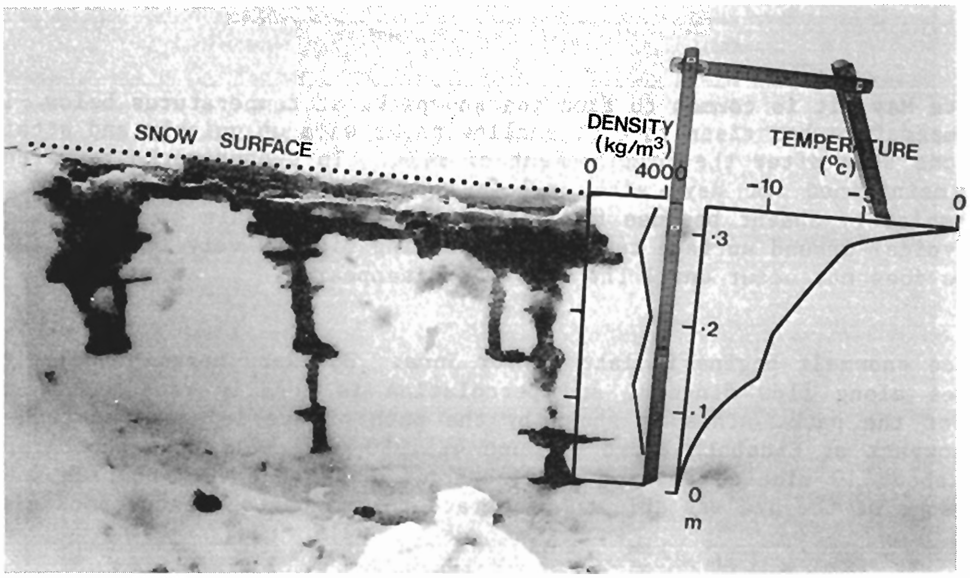

Fig. 2 Movement of dye injected into a cold, Arctic snowpack at Eidsbotn Fiord showing dye concentration along vertical flow fingers and horizontal lenses. Also shown are snow temperature, and snow density.

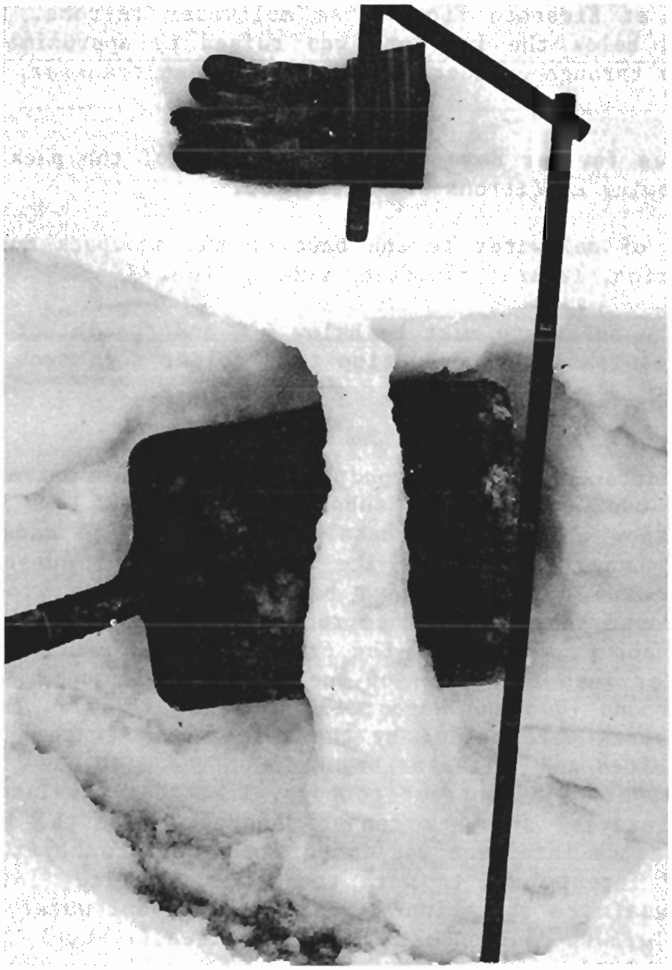

Fig. 3 Ice pipe and ice lenses formed by a refreezing of meltwater in a cold snowpack at Eidsbotn Fiord. Basal ice layer is shown at the bottom of the pack.

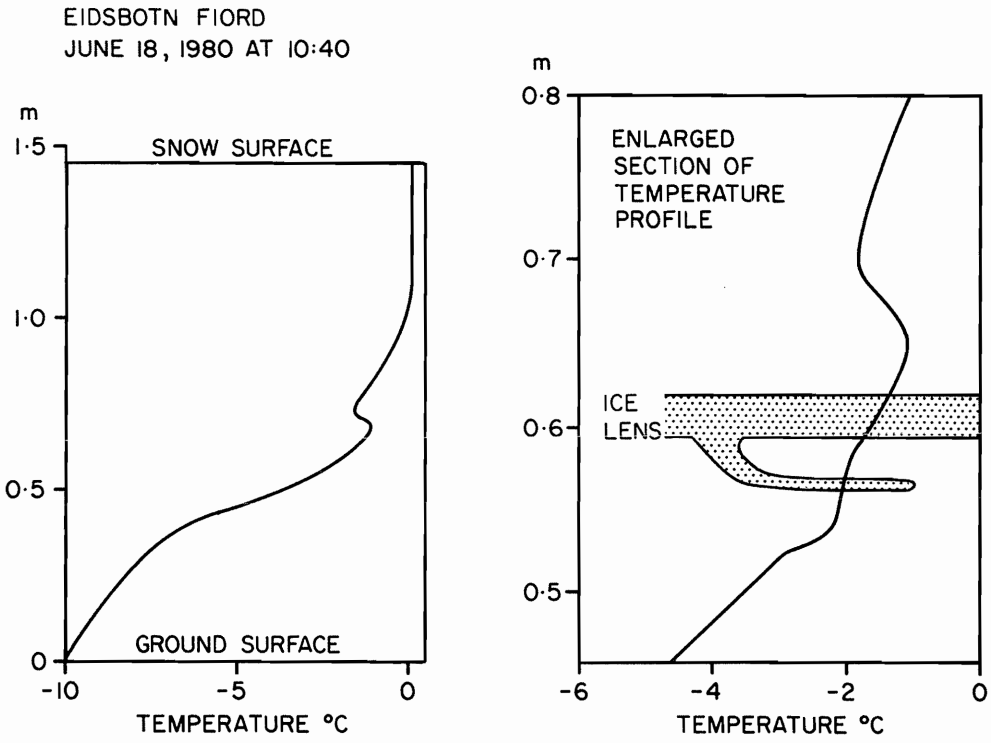

Fig. 4 Temperature of an Eidsbotn Fiord snowpack undergoing melt metamorphism. Note that the formation of an ice lens in the pack raised the snow temperature locally.

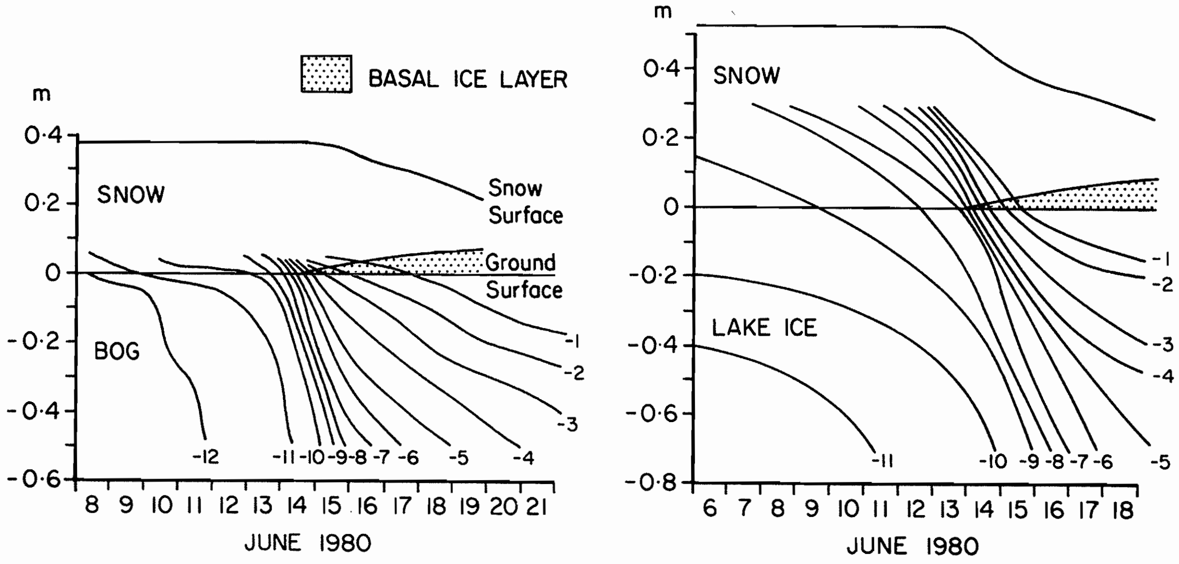

Fig. 5 Formation of basal ice layer over bog and lake ice near Resolute, and the resultant rapid temperature rise in the substrate due to latent heat transfer.

tinue to refreeze, producing substantial thickness of basal ice. Similarly, in some valleys with deep snowpack and low ground temperatures, portion of the flow can freeze at the base of the snow jams (Woo, 1979) to produce a thick layer of ice.

FATE OF BASAL ICE

By mid or late summer, most basal ice layers are destroyed. The destruction of basal ice layers is accomplished (1) by melting of the ice after the overlying snow has disappeared, and (2) by the formation and enlargement of runnels in the ice. These processes tend to reinforce each other: differential melting of the ice surface enhances runnel formation, and dissection of the ice accelerates melting of the disintegrated ice segments. Figure 6 shows part of a decaying basal ice layer on a slope at Vendom Fiord observed on 27th June 1975. Differential melting was caused by an uneven cover of organic debris which insulated portions of the ice surface. Rills were then formed between the insulated patches, and a concentration of meltwater runoff further perpetuated the rill network.

During cool summers, some of the basal ice may not melt completely. In the following spring, this ice would be buried by snow and a new layer of basal ice will form on top. A semi-permanent snowbank may be created, comprising a varying number of layers of refrozen meltwater. In a similar manner, basal ice layer occurring in the snow which overlies a glacier may be incorporated as part of the glacier. Such ice is commonly known as superimposed ice in glaciological literature (Koerner, 1970).

HYDROLOGIC IMPORTANCE OF BASAL ICE

Below the basal ice layers, ground temperature cannot exceed 0°C, and the ice layer therefore prevents the ground from thawing. Hydrologically, the occurrence of basal ice layers complicates the snowmelt-runoff relationship by adding a storage component with a duration that varies according to the ice thickness. Through refreezing, meltwater runoff is delayed and flow does not occur for days after the snow has begun to melt.

The storage effect of basal ice layers is demonstrated by the hydrographs from an experimental slope located near Resolute. For this site, snowmelt was computed using an energy balance approach (Heron and Woo, 1978) and weighted by the areal snow cover on the slope (Fig. 7). Snowmelt began on 13th June 1980 and basal ice formation commenced two days later. Groundwater movement was restricted to the snow and ice free areas. Only a limited amount of runoff was observed throughout the early parts of the melt period because the bulk of the meltwater refroze as basal ice. The ground remained frozen beneath the ice, but thawed rapidly once the ice disappeared. As the basal ice began to melt, a large quantity of water was finally released to runoff. However, the thinly thawed ground could not accomodate this supply of water and overland flow prevailed (Dingman, 1973) during the period between 22nd June and 1st July. In this way, the basal ice sustained runoff long after the bulk of the snowpack has disappeared, thus effectively prolonging the melt season.

As basin storage, basal ice is particularly important during cool summers and where the basin elevation is high. There, streamflow can be maintained by the abundant snowbanks throughout summer. The resultant runoff pattern is similar to that of a proglacial regime (Marsh and Woo, in press).

CONCLUSION

At the base of very cold Arctic snowpacks, a layer of ice is often formed by a refreezing of the percolating meltwater. The necessary conditions leading to basal ice

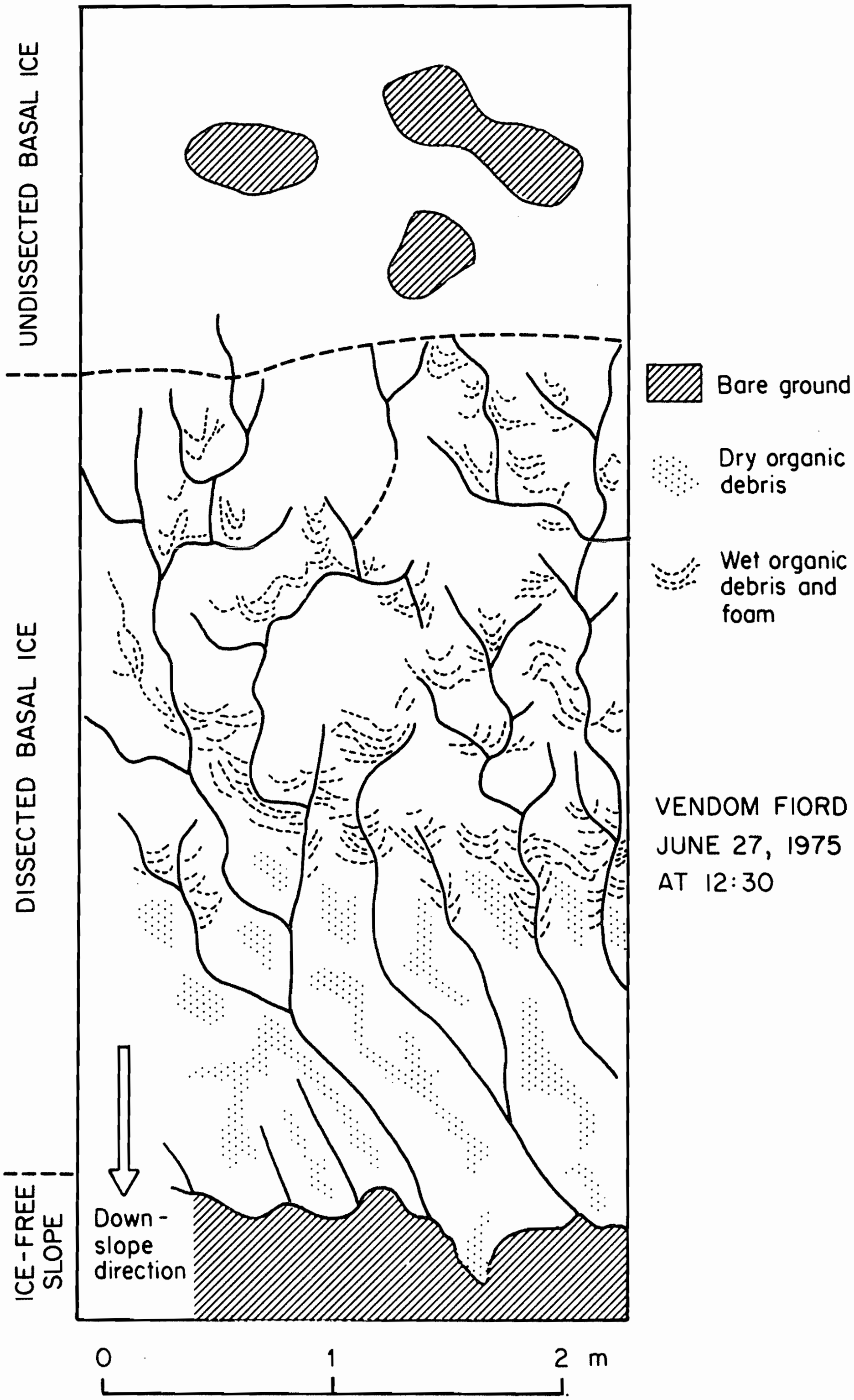

Fig. 6 Rill pattern developed on basal ice layer occurring on a slope at Vendom Fiord.

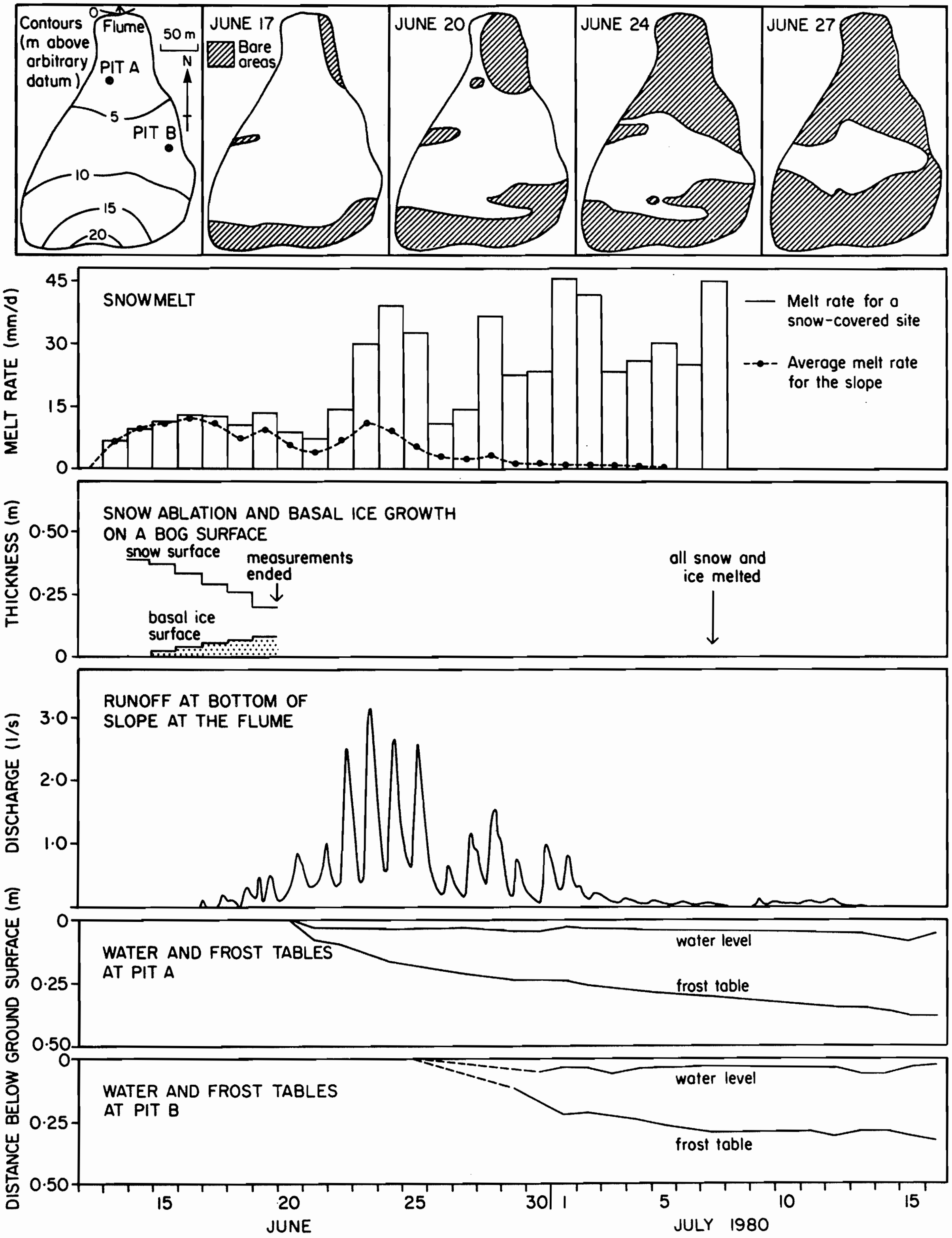

Fig. 7 Snow cover, snowmelt, suprapermafrost groundwater tables and runoff from a slope near Resolute during the melt season of 1980.

formation are (1) the meltwater supply should be adequate to sustain ice growth, (2) a cold substrate should be maintained to dissipate the latent heat released. Through latent heat transfer, basal ice formation provides an important mechanism that rapidly warms the substrate beneath the snow.

Destruction of the basal ice layers is accomplished by surface melt or by the formations of runnels on ice. Sometimes, the ice may not be totally ablated, but is incorporated as multi-year ice of semi-permanent snowbanks. In this mode of occurrence, basal ice becomes a form of long term storage in drainage basins.

Hydrologically, the presence of ice layers complicates the snowmelt-runoff relationship. Runoff response to snowmelt is delayed until basal ice formation ceases. Overland flow is enhanced at the zone in front of the ice. Once runoff begins, however, melting of the exhumed basal ice prolongs the flow, sometimes well into the drier summer period.

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