RELATIONSHIPS BETWEEN RUNOFF GENERATION AND ACTIVE LAYER DEVELOPMENT NEAR SCHEFFERVILLE, QUEBEC

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The generation of runoff in areas underlain by permafrost is similar to that of temperate regions, but is distinguished by the seasonal changes in the extent, shape, and thickness of the areas generating runoff as well as the storage and transfer of small amounts of water by frost-related mechanisms. Studies conducted near Schefferville, Quebec have shown that these mechanisms can significantly alter the development of the active layer. The development of the active layer partially controls the distribution of saturated surfaces in a given catchment, and thus its hydrologic response to runoff-generating events. This phenomenon is similar to the variable-source area runoff generating mechanism of temperate regions, except that the ratio of stormflow to baseflow is also partially controlled by the depth and extent of the active layer. A detailed study of a small catchment at Schefferville has demonstrated that consideration of these effects can increase the precision of models of runoff-generation from such catchments.

INTRODUCTION

The movement of moisture within the active layer is an important component of both the moisture and thermal balances in northern regions. The rate of moisture movement through the active layer largely controls the distribution of saturated surfaces in a given catchment, which inturn, controls the rate at which runoff leaves the catchment. At the same time, the vertical and horizontal fluxes of moisture within the active layer transfer both sensible and latent heat, thereby influencing the rate and depth of thaw. There is therefore a degree of feedback between the rate of runoff generation and the rate of active layer development. This paper will present some observations of the processes of active layer development at Schefferville, and discuss the implications of those processes for modelling subarctic water balances.

The results presented in this paper are only a part of the information obtained in a study carried out near Schefferville, Quebec during the period 1976-1979. The primary goal of the project was the accurate representation of the water balance of a lichen tundra underlain by permafrost. In line with that project, some data were collected about the ground thermal regime. The results of the water balance investigations have been reported elsewhere (Wright 1981,1982). This paper will present, in more detail, some observations of the development of the active layer and the generation of runoff.

ACTIVE LAYER DEVELOPMENT

The study's primary objective was accurate characterization of the water balance, but data about the ground thermal regime were required for the accurate estimation of the amount of suprapermafrost groundwater. It was initially thought that point determinations of the depth of the active layer could be made from interpolation of the discrete temperature measurements along a thermocable while the areal estimates of the depth of the active layer could be achieved by applying a known relationship between maximum active layer depth and the distribution of vegetation at the surface (Nicholson 1978). Significant problems were encountered, however, due to the importance of latent energy transfer, which had been implicitly ignored in the estimation procedures.

The transfer of sensible and latent energy can result from moisture movement in either the liquid or gaseous phases. The transfer of sensible heat by water vapor is probably of little importance in cold regions, but the transfer of sensible heat by liquid water movement appears to be of considerable importance. Although it can be shown that the vertical transfer of sensible heat is of little moment, Lewis' (1977) study at Timmins 4 indicates that the lateral concentration into the very permeable wetlines (areas of slight to moderate topographic depression and concentrated subsurface flow) of the latent and sensible heat associated with suprapermafrost groundwater can lead to active layers up to 10 m deep. Nicholson (1978) improved the accuracy of his model of permafrost distribution in the Schefferville area by adding a groundwater flow component.

The problem of adequately explaining the physics of latent heat transfer within a partially-frozen soil is one that has attracted considerable attention in recent years. Much of the attention has been focussed on accurately modeling the phenomenon in the laboratory and, while considerable success has been achieved (e.g., Jame and Norum 1980), it is not clear whether such models are applicable under the range of conditions normally found in the field.

One of the effects associated with latent energy transfer is the well-known "zero-curtain", where a significant portion of the freezing or thawing active layer assumes temperatures at the freezing point due to the large amount of latent energy involved in the fusion of water. The near-zero temperatures produced during the phase change of the soil water reflects conditions under which water exists in two phases. Under those conditions, it is difficult to accurately determine the thermal and hydraulic properties of the ground.

The relative changes in moisture content and phase over the depth of the active layer also influence the rate and depth of thaw. The magnitudes of the thermal conductivity and apparent specific heat will vary over the depth of the soil column according to changes in the composition and structure of the inorganic matrix, the amount and distribution of organic matter, and the proportions and distribution of frozen and unfrozen water within the soil column. Since the variation of soil moisture content is a function of both depth and time, the rate and depth of thaw is a function not only of the heat flux at the surface, but is also a function of the distribution and state of water within the active layer.

In general, models of active layer development (e.g. Nakano and Brown 1972, Smith 1975, McGaw et al 1978) have assumed that soil thermal properties are double-valued; i.e. one value would hold in the 'frozen' state and another value would hold in the 'thawed' state. The transition between the two states was presumed to be instantaneous, occurring when the soil temperature passed through the freezing point. The data collected in this study clearly demonstrates that heat transfer is not solely by conduction and that the active layer is not sharply demarcated into frozen and unfrozen zones.

THE FIELD AREA

The bulk of the results presented in this paper were collected near Schefferville, Quebec (54°51'N, 67°01'W,; 520 m a.s.l.). Located within the Labrador Trough in central Ungava, the area is composed largely of Poterozoic metamorphosed rocks (Figure 1). The region is characterized by broad, permafrost-free valleys and long, narrow ridges underlain by extensive permafrost. The valley bottoms are largely covered by spruce woodlands and lakes, while the ridgetops are dominantly lichen tundra. Mean annual air temperature at Timmins 4 is -6.2°C. Mean annual precipitation at the Schefferville townsite (15 km SE of the main research site) is 785 mm, of which 407 mm falls as rain and the rest falls as snow (Barr and Wright 1981).

The main research site (Hematite, Figure 2) is at an altitude of 685 m a.s.l. The area is typical of lichen-heath tundra in central Ungava. The surface over 80% of the site is a 5-10 cm thick lichen mat (predominantly Cladonia and Cladina spp.) with scattered dwarf birch (Betula glandulosa). The remaining 20% of the surface is bare, frost-scarred ground, partially paved with frost-shattered debris. The bedrock, which is typically overlain by 1-2 m of very stony till, is weakly metamorphosed sediments. Permafrost underlies the entire site to a depth of at least 30 m. The annual depth of thaw ranges from 2.0 m under thick lichen mat to

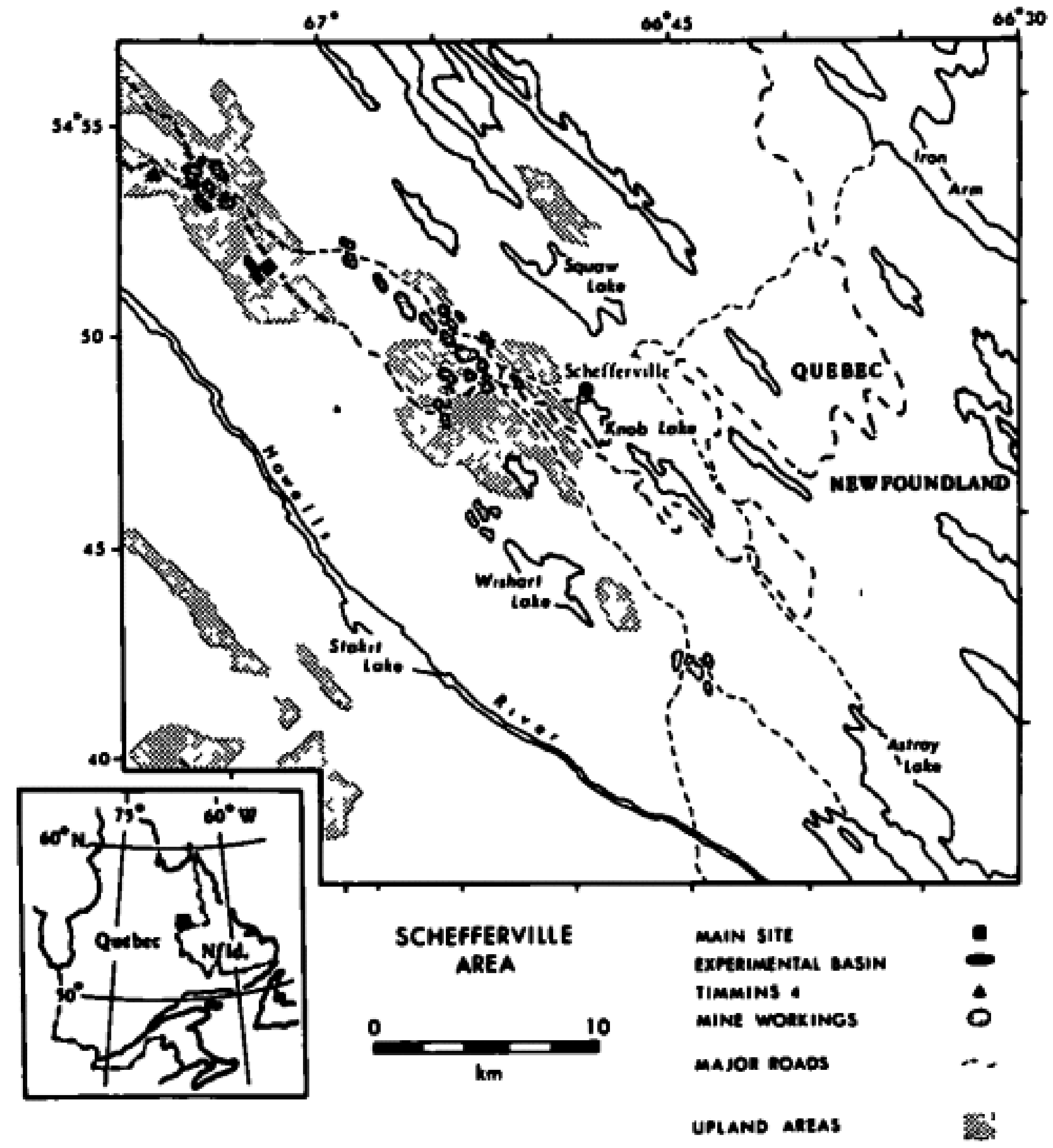

FIGURE 1 Location of Schefferville and the study sites.

3.0 m under bare surfaces. Two areas of special interest at Hematite are locations One and Two. Both are located in an area of lichen-heath tundra, but the surface of One is slightly convex and is stripped of vegetation. Location Two is relatively flat and has an undisturbed lichen mat.

Data were collected at the main site from December 1976 through August 1979, though the frequency of observation varied from daily during the summers of 1977 and 1978 to monthly or bimonthly during the winter. Intensive data collection was carried out from May through September in 1977 and 1978 as well as frequent observations during the freeze-up of 1977. Daily observations (during the thaw season) included air temperature and humidity at screen height, ground temperatures, incoming and net radiation, evapotranspiration, and rainfall (Wright 1981). In addition, soil moisture contents were monitored with a neutron moisture probe through the freeze-up of 1977 and the summer of 1978.

Observations at the main site in 1978 were paralleled by observations of the water budget of a small basin adjacent to the main site (Bazilchuk 1979). The basin is, like most of the Schefferville region, strongly controlled by the underlying geology. Permafrost is estimated to underlie approximately 80% of the basin, being absent beneath the lake and possibly the lower reaches of the creek. The distribution of vegetation in the basin is controlled by aspect, exposure, and drainage. Low-lying, often-saturated areas are dominated by birch-willow scrub while better sites are dominated by lichen-heath tundra.

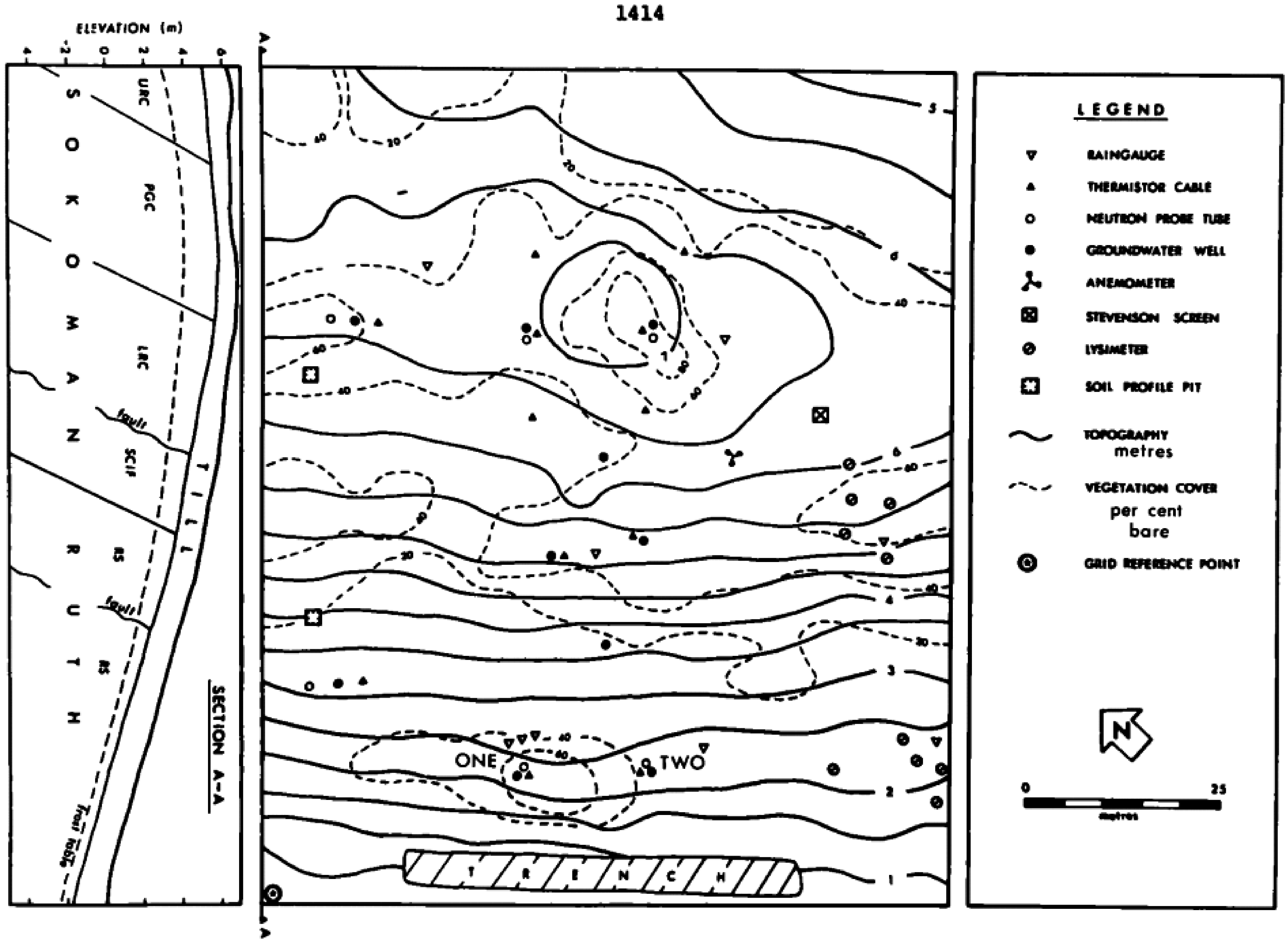

Figure 2 Map and cross-section of Hematite, the main research site. Geological data courtesy IOCC.

RESULTS

Freeze-up

In the Schefferville region, when the surface of the mineral soil freezes, an essentially impermeable barrier is formed between the atmosphere and the active layer. The development of a well-defined zero-curtain was observed at all cables at Hematite in 1977. Zero-curtain temperatures observed during freeze-up ranged from -0.02°to -0.08° C with the most frequently observed value being -0.06° C.

The magnitude of the freezing point depression increases as the solute content of the soil water increases and as the grain size of the matrix decreases. It can be shown that (in the active layer) the effect of solutes in the pore water is trivial, but it is difficult to accurately characterize the effect of a given grain size distribution. The values observed at Hematite are slightly lower than the values observed at Timmins 4 (Nicholson 1978), but the slight difference is probably due to instrumental error, though it may also be partially attributable to the deeper, finer-grained till cover at Hematite.

The unsaturated part of the active layer is usually at or near field capacity at the beginning of freeze-up because that period tends to be cool and moist in central Ungava. In addition, late season rainfall is usually augmented by the melting of an early snowpack and that may lead to a large soil moisture content as freeze-up commences. It seems unlikely, however, that freeze-up could be completed with soil moistures in excess of field capacity unless the drainage of the soil were poor or nonexistent. For example, the complete melting of a 15 cm snowpack and heavy rainfall (approximately 20 mm) in late October 1977 produced a saturated zone up to 2 m thick at Hematite, but, despite a relatively rapid freeze-up, the saturated zone quickly disappeared.

The reduction of the saturated zone during freeze-up is largely due to suprapermafrost groundwater flow, but there is also a minor amount of moisture transport from the lower part of the active layer towards the surface. The upwards transport result from the water potential gradient set up by the freezing process itself. The gradient is caused by the attenuation of the interfacial liquid films on the soil particles as the ice crystals forming within the pores abstract the less tightly-held soil water (Dirksen and Miller 1966). It follows that a finite amount of moisture transport should take place within a freezing soil; such transport has been detected in the laboratory (e.g. Hoekstra 1967, Jame and Norum 1980), but only limited field observations are available (e.g. Woo and Heron 1981).

Field data demonstrating these phenomena are shown in Figure 3, which depicts the moisture and temperature data collected at Hematite from November 1977 to February 1978. The precision of the temperature measurements is quite high (± 0 03°C), but the interpolations between the discrete

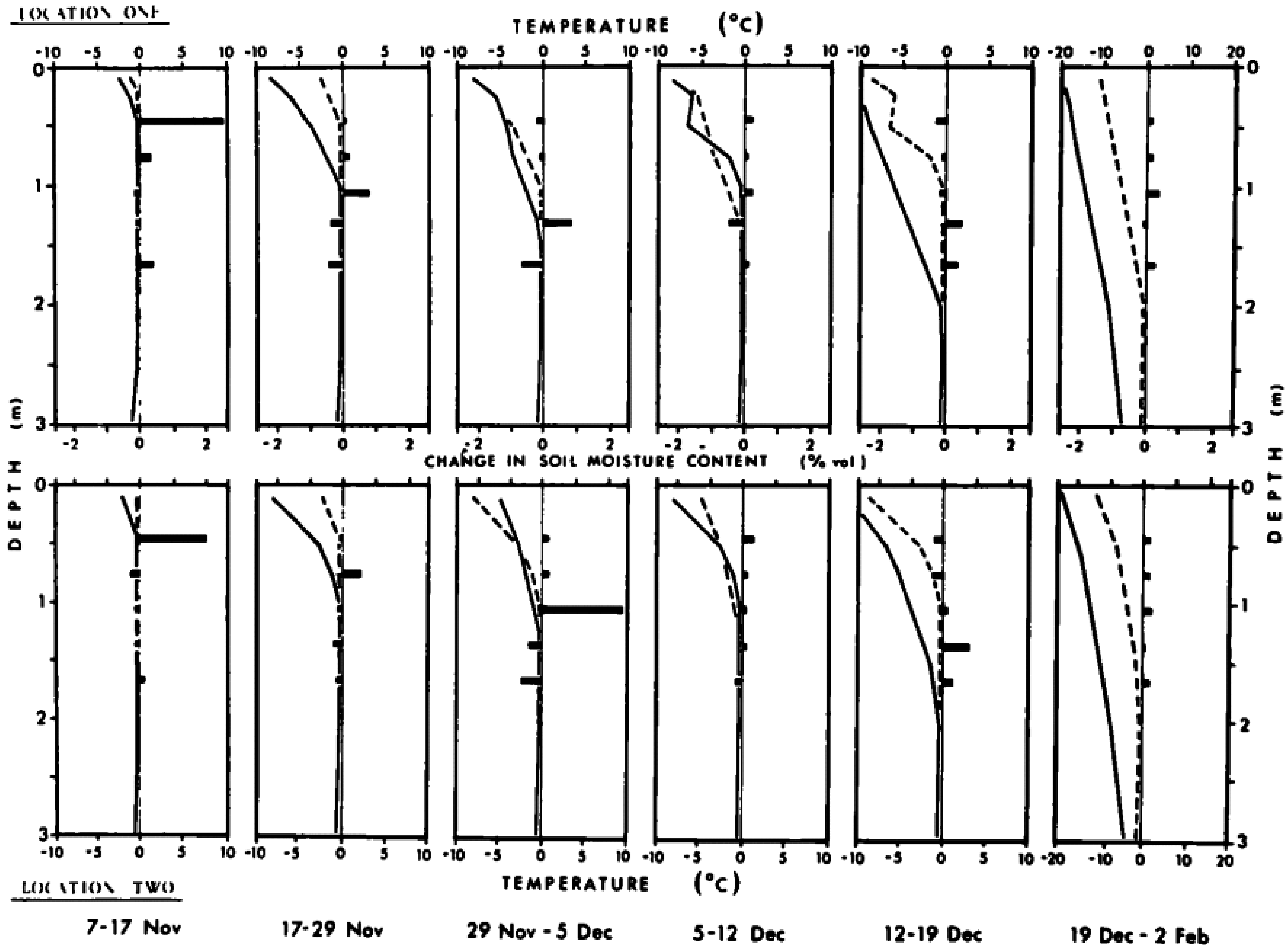

FIGURE 3 Temperature and soil moisture profiles observed at Locations One and Two during freeze-up 1977. Dashed lines represent the temperature profile on the first date indicated while the solid line is for the second date indicated. The bars represent the change in soil moisture content between the two indicated dates.

temperature measurement points are approximate, particularly in the vicinity of the freezing front. The changes in moisture contents, though relatively small, show quite clearly that the moisture transport is correlated with changes in the ground thermal regime. The large transfers took place between 12 November and 5 December and between 12 and 29 December. Both of those periods were characterized by rapidly decreasing air and surface temperatures, leading to strong temperature gradients toward the surface.

The data clearly demonstrate that there is detectable moisture transport during freeze-up and that those changes are closely associated with the ground temperature field within the active layer. The changes in moisture content are presumably the result of the unsaturated flow induced by the increased soil matrix suction developed during the freezing process. However, attempts by the author to numerically model the presumed relationships between soil moisture contents and the temperature field have been unsatisfactory, primarily because of an inability to adequately characterize the properties of the active layer during the freezing process.

Thaw Season

It was initially thought that soon after the ground began to thaw there were three zones within the active layer that possessed significantly different thermal and hydraulic properties: unsaturated unfrozen, saturated unfrozen, and unsaturated frozen. The difference in thermal properties between the saturated and unsaturated unfrozen materials is probably not very large because of the genrally low porosity of the till and bedrock in the Schefferville area, but the higher thermal conductivity and lower specific heat of the frozen ground should give it a significantly higher thermal diffusivity with respect to the unfrozen materials. It follows that the temperature wave should be strongly attenuated with depth, especially in the frozen material. That conclusion is based, however, on the assumption that the transfer of heat is solely by conduction and that there is no significant transfer of heat by moisture transport. The data collected at Hematite during June and July of 1978 clearly demonstrate that those assumtions are not warranted.

Although the phenomena indicating latent heat transfer were observed at all main thermistor cables during 1977, 1978, and 1979, the following discussion is based on the data from Locations One and Two during 1978 since those sites and periods have the most complete data records.

Following the completion of freeze-up in 1977, soil moisture contents remained essentially constant until the following spring. Ground temperature patterns observed during the spring of 1978 were characterized by decreasing amplitude of the temperature wave with depth, indicating that heat transfer was primarily conductive.

In early June, however, when active layer depths were approximately 35 cm and completely saturated, abrupt and substantial increases in temperature were observed at Location Two. Those temperature increases coincided with increases in moisture content of the still-frozen part of the active layer. A week later, a very similar sequence of events was observed at Location One, when percolation from a thick saturated zone led to large moisture increases in the still-frozen ground and those moisture changes were coincident with sharp temperature increases in the still-frozen ground. The amount of percolated water was quite large, equivalent up to 30 mm of water at Location One. The magnitude of the temperature increase was not attenuated with depth, but was instead a function of the initial temperature with respect 0°C (Figure 4). The closer the initial temperature to the freezing point, the smaller was the temperature increase. This is attributed to the sharp increase in the apparent specific heat of frozen materials as the freezing point is approached (Williams 1967).

A related phenomenon was the existence of a zero-curtain throughout the thaw season. Its presence was indicated by a pause (at -0.02° to -0.08°C) in the passage of each temperature measurement point through the freezing point. The transition was frequently observed to coincide with the occurrence of a thick saturated zone in the thawed portion of the active layer. In periods when the saturated zone was thin or absent, the zero-curtain appeared to descend slowly. The zero-curtains were observed at every thermocable, although the duration of a particular temperature measurement point at the freezing point varied.

These phenomena indicate that there is significant penetration of suprapermafrost groundwater into the still-frozen parts of the active layer. When the amounts of water are large, the zero-curtain is well developed, but when the pore pressures at the thawing front are small or negative, only a very small amount of water penetrates the still-frozen material. Presumably, such percolation is self-limiting, since the penetration and re-freezing of the water would tend to reduce the effective permeability of the soil.

DISCUSSION

It is clear that heat transfer in at least some frozen soils is not solely by conduction and that the traditional view of the active layer is not always adequate; the transition from frozen ground to unfrozen is shown to be gradational in nature both thermally and hydraulically. It follows, then, that simple models of active layer development will not give accurate results unless latent heat transfer

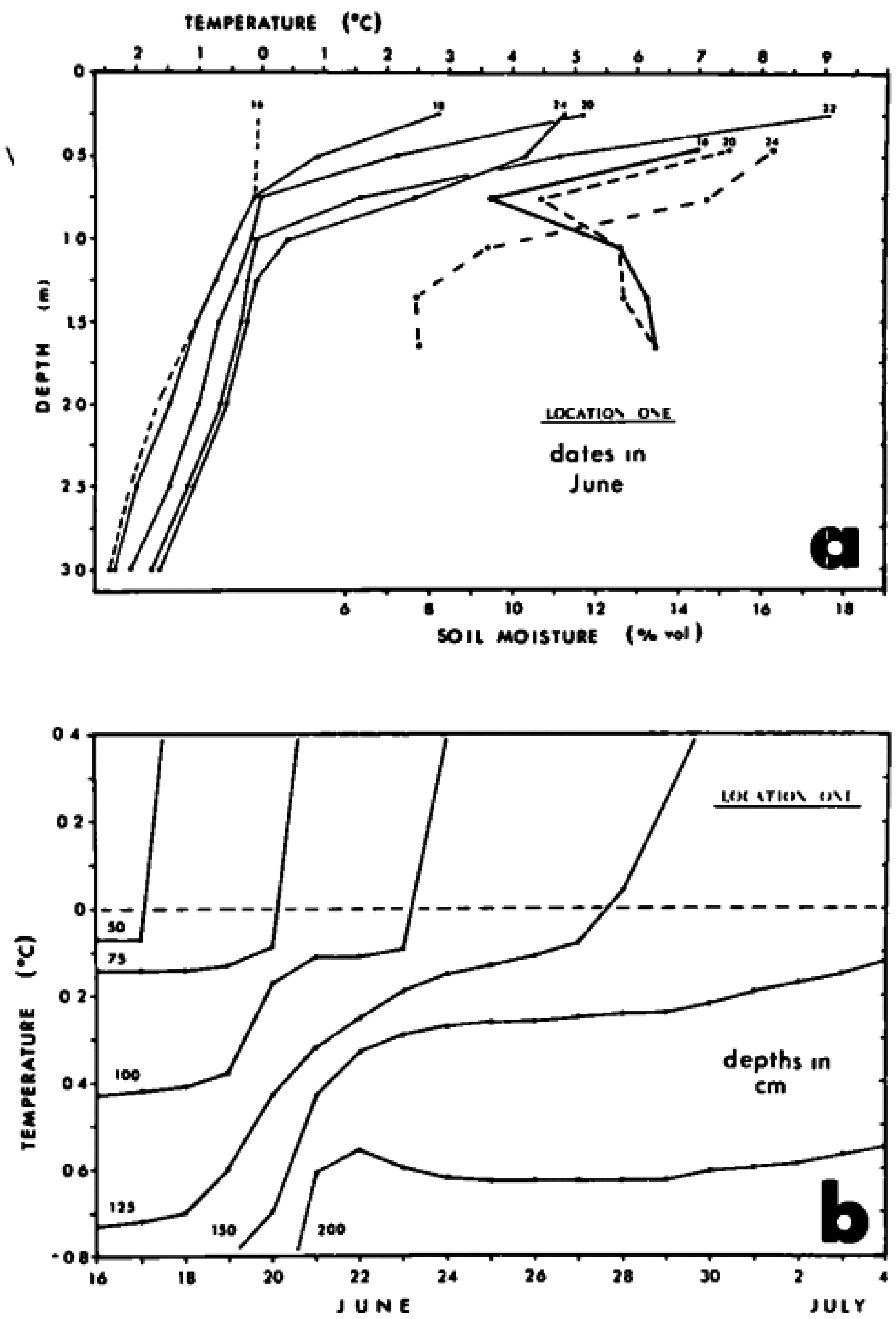

Figure 4 (a) Temperature and soil moisture profiles observed at Location One during June 1978. (b) Temperature patterns through time at Location One during June 1978.

is somehow inhibited (e.g., the frozen material is effectively impermeable) Heat budget models based upon time-dependent heat storage will give adequate results only if the zero-curtain zone and the variation in moisture storage can be accurately approximated or if the time interval is sufficiently long that those effects can be neglected.

For example, in non-wetline areas (i.e. those areas that are little affected by suprapermafrost groundwater flow), there is a good correlation between the percentage of bare ground in a given area and the maximum active layer depth (Nicholson 1978), which indicates that conduction of surface heat is the dominant mode of heat transport over an entire thaw season. On the other hand, in the low-lying wetline areas the saturated zone tends to be much thicker, so the pore pressures at the thawing front are much higher than on adjacent slopes. The higher pore pressures, in conjunction with the higher permeabilities of the wetlines, leads to significant amounts of suprapremafrost groundwater percolating to relatively great depths within the still-frozen ground The influence of latent heat transfer therefore extends well below the zone in which conductive transfer is dominant and the magnitude of the latent heat transfer probably exceeds that of conduction. It is for these reasons that the active layer depths in the wetlines do not correspond to the vegetation distribution at the surface. Accurate prediction of active layer depths along the wetlines requires some measure of the magnitude of the latent heat transfer, either through a budget type of procedure (e.g., Lewis 1977, Wright 1981) or through actual knowledge of the pore pressure distribution within the wetline.

There are two main areas in which the development of the active layer can strongly influence the generation of runoff in subarctic areas. First and most important is in controlling the effective depth to which percolating water can penetrate. The depth of the effectively permeable portion of the active layer strongly controls the distribution of saturated surfaces within a given catchment and that, in turn, controls the rate at which runoff reaches the outlet of the catchment. Thus, the rate and depth of thaw in a given area can influence the response time of that area to a given runoff-generating event.

The second area in which development of the active layer affects the water balance is through the percolation of suprapermafrost groundwater into the still-frozen part of the active layer. As noted above, the amounts percolated at Location One equalled up to 30 mm of water. If the same processes take place along the wetlines, the amount of abstracted water could be quite significant That such percolation does take place is indicated by the very deep wetlines themselves. Water stored in this fashion would presumably be released only when the depth of thaw had reached the depth of the percolation. Attempts to incorporate such an effect in subarctic water balance models have been partially successful (Wright 1982). Good correlation is achieved between observed and predicted runoff volumes, but few data are available on subsurface moisture storage over the course of a thaw season, so it is difficult to assess the realism of such a model.

CONCLUSION

The results presented here constitute strong qualitative evidence of the importance of latent heat transfer to the development of the active layer. It is clear that such effects can significantly affect the rate and depth of thaw and, indirectly, the rate of runoff generation. The rate and depth of thaw control the rate at which runoff is generated and, in turn, patterns of moisture flow and storage influence the thermal behavior of the ground.

These results represent only the first step in quantifying the thermal and hydrologic behavior of the active layer. The prime needs at this time are for a more detailed picture of of the distribution of heat and moisture within a wetline over an entire thaw season and the development of a model which can adequately describe the three-dimensional flow of heat and moisture within a partially thawed active layer. It may well be that the present numerical models of these processes can be adapted to the far less homogeneous conditions of the field. That will certainly require a more complete description of the temperature and moisture distributions within a wetline, a project which the author has recently begun in central Ungava.

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