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Les variations spatio-temporelles du pergélisol à Schefferville, Nouveau-Québec
Räumliche und zeitliche Variationen des Dauerfrostes bei Schefferville, Nouveau-Québec

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Résumé de l'article

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PERMAFROST SPATIAL AND TEMPORAL VARIATIONS NEAR SCHEFFERVILLE, NOUVEAU-QUÉBEC

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ABSTRACT Specially detailed studies of permafrost have developed at Schefferville because of the availability of long term data and the economic stimulus of the effect of permafrost on the iron mines. Knowledge of the three dimensional distribution of permafrost has been greatly expanded and energy budget studies have given confidence to many aspects of interpretation. Although the mean annual temperatures are −5 to −6.5°, large areas remain free of permafrost due to the winter insulation provided by deep snow which accumulates where snow drifting is subdued (*e.g.* in woodland). There are large year to year variations of frozen ground temperature in the upper 25 m (due to variations of snow conditions) and active layer depth (related to variations of summer weather conditions). Suprapermafrost groundwater movement is often concentrated along specific channels and transported heat causes very deep active layers (up to 12 m) or even maintains unfrozen zones (up to 30 m). On simple sites the active layer is primarily related to % vegetation cover, with mean depth ranging from 2.3 m under 100% vegetation to 3.6 m under bare ground. Considerable effort has been devoted to quantifying snow data for permafrost prediction and good results have been obtained from quantitatively relating ground temperatures to snow and a simulated groundwater measure. The permafrost is generally in balance with the present climate and new permafrost has developed in mine waste dumps.

RÉSUMÉ *Les variations spatio-temporelles du pergélisol à Schefferville, Nouveau-Québec.* On a pu entreprendre, dans cette région, des études particulièrement détaillées grâce à l'existence de données sur une longue période et de l'importance de ces études sur les mines de fer. Les connaissances sur la répartition tri-dimensionnelle du pergélisol se sont grandement accrues, et les études du bilan thermique ont permis une meilleure interprétation générale des données. Malgré une température moyenne annuelle de −5 à −6,5° C, de vastes espaces demeurent non pergélisolés grâce au pouvoir isolant de la neige (dans les boisés notamment). La température du sol varie considérablement dans les 25 premiers mètres (suivant l'épaisseur du couvert nival) ainsi que l'épaisseur du mollisol (suivant les températures estivales). La circulation de l'eau souterraine se fait le long de canaux particuliers, et le transfert de chaleur ainsi provoqué permet le développement d'épaisseurs considérables de mollisol (jusqu'à 12 m) et même de taliks (jusqu'à 30 m). Dans les sites, où il n'y a pas de circulation souterraine, l'épaisseur du mollisol dépend de la densité du couvert végétal, l'épaisseur moyenne étant de 2,3 m lorsque la couverture est totale et de 3,6 m sous un sol dénudé. Beaucoup d'efforts ont été consacrés à la quantification des données afin d'en arriver à une meilleure interprétation des caractéristiques du pergélisol; les résultats obtenus sont intéressants. On en conclut que le pergélisol est habituellement en équilibre avec le climat actuel.

ZUSAMMENFASSUNG *Räumliche und zeitliche Variationen des Dauerfrostes bei Schefferville, Nouveau-Québec.* Eingehende Forschungen des Dauerfrostes haben sich in Schefferville auf Grund der Verfügbarkeit von «long term» Daten und des wirtschaftlichen Anreizes, den die Folgen des Dauerfrostes auf die Eisenminen haben, entwickelt. Die Kentnisse der dreidimensionellen Verteilung des Dauerfrostes haben sich sehr verbreitet, und Studien des Energiebudgets haben sich auf viele Aspekte der Interpretation verlassen. Obgleich die jährlichen Mitteltemperaturen bei −5 bis −6,5°C liegen, bleiben grosse Gebiete auf Grund der Winterisolation der dicken Schneedecke, die sich dort ansammelt wo Schneetreiben verhindert ist (Waldland) dauerfrostfrei. Die Bodenfrosttemperaturen der oberen 25 m, (auf Grund der Variationen der Schneeverhältnisse) sowie die Tiefe der Auftauzone (von den sommerlichen Wetterverhältnissen abhängig) zeigen grosse jährliche Veränderungen. Superdauerfrost-Grundwasser-Bewegungen sind oft um spezifische Kanäle konzentriert und transportierte Wärme verursacht sehr tiefe Auftauzonen (bis zu 12 m) oder erhält sogar ungefrorene Zonen (bis zu 30 m). In einfachen Gebieten ist die Auftauzone hauptsächlich in Verbindung mit dem % satz der Vegetationsdecke, mit durchschnittlicher Tiefe von 2.3 m bei 100% Vegetation und 3.6 m unter kahlem Boden. Beträchtliche Bemühungen wurden gemacht, die Schneemengen einzuschätzen, um Dauerfrostvorhersagen machen zu können, und gute Resultate wurden durch Mengenvergleiche zwischen Bodentemperatur und Schnee und einer simulierten Grundwassermessung erreicht.

INTRODUCTION

The presence of widespread permafrost in the Schefferville area was not obvious without detailed study. In consequence when the decision was made to open the iron mines of the Schefferville area permafrost was not taken into account (IVES, 1962). Palsas are the only definite surface indication of permafrost conditions and these are very restricted in their distribution. Certainly they do not indicate the widespread permafrost which caused severe problems in some mines and stimulated a series of studies in the fifties and sixties (BONNLANDER, 1958; IVES, 1960, 1961, 1962; BONNLANDER and MAJOR-MAROTHY, 1964; ANNERSTEN, 1964, 1966; THOM 1969). These studies were especially valuable because of the availability of exploration drill holes up to 100 m deep for temperature observations and also because of the economic stimulus to maintain observations over a relatively long period. Based on this foundation, an expanded and more accurate observation program has been developed in the seventies and forms the basis of the results reported here.

REGIONAL SETTING

The study area lies on the west side of the Labrador Trough characterised by geologically controlled parallel valleys and ridges trending northwest to southeast, ranging from 500 m to 750 m above sea level. The mean annual temperature varies from $-5°$ to $-6.5°$ in general relation to the local elevation, and these temperatures would result in continuous permafrost in many more westerly areas of the continent. However, annual snowfall is 350 cm and there is extensive snowcover for 7 or 8 months of the year. Snowdrifting causes considerable local variations in the thickness of the snowcover. A cover of snow insulates the ground and reduces winter heat loss. Where the snow cover is sufficiently deep the heat retained may prevent permafrost formation, despite the mean annual air temperature. For example a woodland environment greatly reduces snowdrifting so that normally a layer about 1.5 m deep will accumulate during the winter and the total insulation effect is sufficient to prevent permafrost. Schefferville lies in the transition zone from boreal woodland to tundra. In this transition zone woodland and tundra habitats are found in close proximity with the woodland habitat in more favoured sites and the tundra habitat (with occasional stunted krummholtz trees) on less favoured, exposed sites. Thus it is not surprising that there are extensive areas near Schefferville that are free of permafrost and other areas where permafrost is widespread. In general, woodland predominates south of Schefferville and permafrost is confined to localised exposed areas. North of Schefferville the woodland environment occupies a declining percentage of the terrain and there is widespread permafrost (see Fig. 1). The generalised permafrost distribution in the Québec-Labrador Peninsula was first clearly explained in these terms by IVES (1960, 1961, 1962), and BROWN (1975) has published other broad scale information on the permafrost distribution.

VISUAL CHARACTER AND PHYSICAL PROPERTIES OF THE PERMAFROST

The characteristics of the frozen ground can be examined in mines immediately after a mine blast. The amount of ice and its distribution varies very widely with the materials. Unaltered iron formation is predominantly chert with variable iron content (taconite), but the soft iron ores of the Schefferville area were formed by leaching of the primary iron formation which reduced the silica content and increased the percentage of iron. The leaching also changed the physical properties of the iron formation and adjacent formations, the large increase in porosity being of particular significance. Since the leaching is very variable in three dimensions, porosity and hence permafrost physical properties are

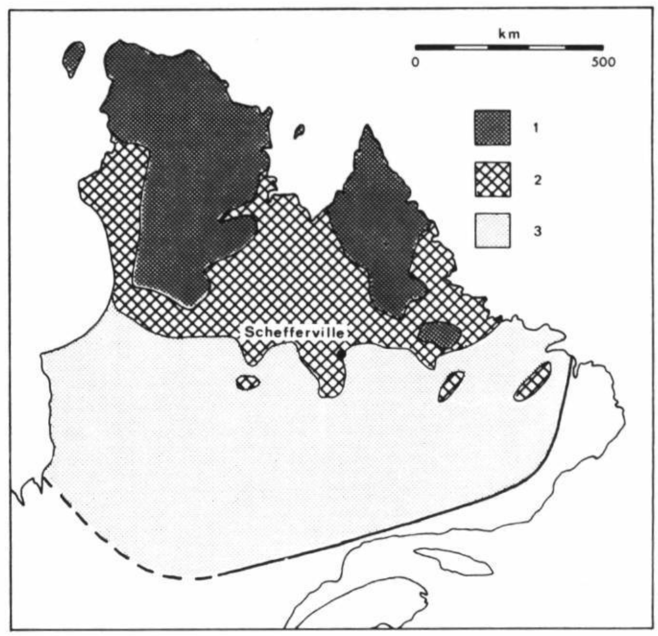

FIGURE 1. Location of Schefferville in relation to the general permafrost distribution. 1. Continuous permafrost or very widespread discontinuous permafrost. 2. Widespread discontinuous permafrost. 3. Occasional to rare patches of discontinuous permafrost. (After IVES 1962, BROWN 1975, NICHOLSON, 1976).

La localisation de Schefferville et la répartition du pergélisol: 1) le pergélisol continu ou très peu discontinu; 2) le pergélisol discontinu; 3) le pergélisol sporadique (d'après IVES, 1962; BROWN, 1975; NICHOLSON, 1976).

also very variable. The other rock types are predominantly slates, quartzite and dolomite, and often there is a variable till cover up to 2 or 3 m thick. The ice content is most commonly in the order of 15% by volume but variations from 3% to 40% have been recorded. Usually the ice content does not exceed the overall porosity and thus, although there is sufficient moisture to cause problems for the mining, there is usually no change of rock volume on thawing. The form of the ice is closely related to the rock texture, varying from veins in impermeable slatey material to intergranular ice in many earthy (leached) materials, in which the ice crystals are often so fine that even with a moisture content of 15% the ice is invisible. Large veins and irregular masses of ice are relatively infrequent. The geophysical properties of the permafrost have been described by GARG (1973) and SEGUIN (1974). Various physical properties of the frozen material have been investigated by WILLIAMS (1967) and YAP (1972).

THERMAL REGIME AND HEAT BALANCE

The general thermal regime is well known from the wealth of available temperature data and the heat balance has been investigated in special detail on a typical site. Although the permafrost is frequently 80 or 100 m thick the mean temperature is usually between 0° and −1°, and temperatures lower than −2° are almost always restricted to the uppermost 20 m. Near to the surface there is a large seasonal temperature fluctuation and annual fluctuations of up to 0.1° commonly occur to depths of 25 m.

Figure 2a shows seasonal temperature fluctuations at the detailed study site. This figure shows the normal pattern of ground temperature penetration with reduction of size of the temperature fluctuations with depth and also progressive delay in the time of maximum and minimum temperatures at increasing depths. The approximate depth of the active layer can be seen from the temperature curve for depth 2.5 m, which shows that in summer 1975 the ground thawed rather deeper than 2.5 m and in summer 1976 the ground thawed to only a little over 2.5 m (precise figures are given in Table 3). In the period October to December (O, N, D on Fig. 2a) a major irregularity in the temperature curves for shallower depths can be seen. This is due to the release of latent heat from water in the active

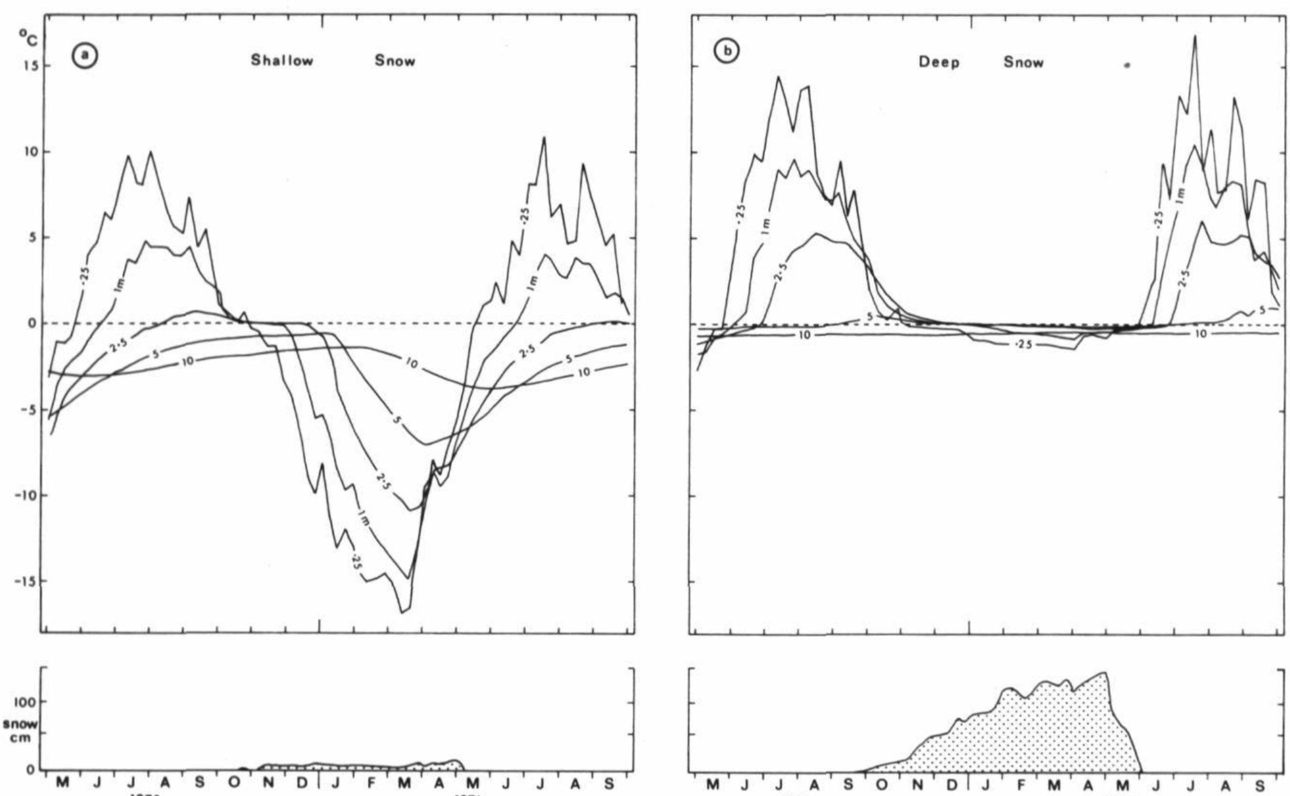

FIGURE 2. The change of ground temperatures through time at sites with (a) shallow snowcover and (b) deep snowcover (by using snow fences). Winter heat loss is greatly reduced by the insulating effect of deep snow.

Les variations de la température du sol au fil des années aux sites (a) peu enneigés, et (b) très enneigés (protégés par des clôtures à neige). Une épaisse couverture de neige réduit considérablement la perte de chaleur hivernale.

layer holding the temperatures near 0°C although considerable heat is being lost from the active layer at this time (the "zero curtain effect"). After the ground freezes at a particular depth the temperatures fall rapidly with approximately the same rate of heat loss as previously. Temperatures were also monitored at an adjacent similar site where snow depth was artificially increased by use of snowfences. Figure 2b shows the dramatic change in the thermal regime when there is a deep insulating blanket of snow in winter which greatly reduces winter heat loss. Detailed examination of the data shows that the zero curtain effect occurs at −.02° to −.03° rather than exactly at zero. This depression of freezing point corresponds to that due to material in solution in the groundwater, as measured by WILLIAMS (1967, p. 17).

On the special test site a range of micrometeorological instrumentation was operated and the physical properties of the ground materials were determined. A summary of the heat budget and allied data is given in Table I. The heat budgets were calculated in two separate ways: (i) change in total heat content; (ii) heat movement by conduction, calculated from continuous temperature data (NICHOLSON, 1976). Variations of the thermal budget from year to year can be expected and Table I is based on the mean of several years of data. The thermal regime and heat budget will also vary from place to place particularly with variations in snow conditions, groundwater conditions, vegetation cover and physical properties of the ground materials. However, the thermal budget data compiled during the course of permafrost thermal amelioration studies (NICHOLSON, 1976) demonstrate clearly that the permafrost on the site is in balance with the present climate and that a major change in the thermal budget is needed to produce significant thawing. Comparison with temperature data from other sites indicates that all of the extensive areas of deep permafrost are also in balance with the present climate. This is further borne out by the fact that new permafrost is actively developing in mine waste dumps (NICHOLSON, 1976). During the early stages of the permafrost studies in the Schefferville area it was suggested that the permafrost was in balance with the present climate (BONNLANDER, 1958, IVES, 1961) though the data collected by ANNERSTEN (1964) raised some doubts (see the following section). It is satisfying that these early contentions have now been confirmed by two independent lines of evidence.

VARIATIONS OF THERMAL REGIME FROM YEAR TO YEAR

Variations in weather from year to year produce variations in the thermal regime. Figure 3 shows the variations in temperature at 10 m depth over a 6 year

TABLE I

Mean Thermal Budget Data for Typical Permafrost Site
(Most data based on 5 or 6 year means)

Surface cover: 5 cm thick tundra mat with abundant frost scars		
Annual air temperature	−6.2°C	
Depth of permafrost	100 m	
Elevation	708 m	
Snowfall	352 mm	
Peak snow depth	12 cm	
Winter snowcover	2322 cm days	
Global radiation	4030×10^6 Jm^{-2}	
Net radiation (R_N)	1250×10^6 JM^{-2}	
Evapotranspiration	$375\text{-}500 \times 10^6$ JM^{-2}	35-45% of R_N
Heat necessary to melt snowfall	117×10^6 JM^{-2}	9% of R_N
Active layer depth	2.8 m	
Seasonal heat gain and loss to active layer (including latent heat)	200×10^6 JM^{-2}	16% of R_N
Latent heat gain and loss in active layer	132×10^6 JM^{-2}	11% of R_N
Seasonal heat flux through base of active layer (mean annual downward flux = mean upward flux)	46×10^6 JM^{-2}	4% of R_N
Seasonal heat flux at 10 m depth	11×10^6 JM^{-2}	1% of R_N
Temperature at 10 m depth	−2.3 C	
Thermal conductivity (frozen ground)	5.5 W m^{-1} K^{-1}	
Thermal diffusivity	1.95×10^{-6} m^{2}s^{-1}	

Data from the Timmins 4 Permafrost Amelioration Test Site, mainly calculated from primary data collected by, or under the supervision of, the author, between 1971 and 1977 (methods outlined in NICHOLSON, 1976, and NICHOLSON and LEWIS, 1976). Snowfall from McGill Subarctic Research Station records; global radiation from PETZOLD (1974) and a corroborative value for thermal conductivity from A. Judge, Heat Flow Group, Department of Energy Mines and Resources (pers. comm.).

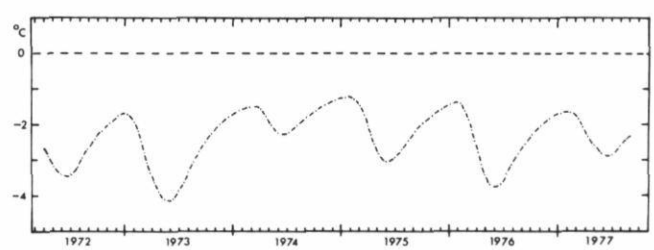

FIGURE 3. Temperature change through time at 10 m depth on a typical site (cf. Table II).

Les variations annuelles de la température d'un site caractéristique à 10 m de profondeur (voir le tabl. II).

period. The minimum temperatures fluctuate much more than the maximum temperatures. Reference to Table II shows that the minimum temperatures are closely correlated with winter snowcover conditions ($r = .94$). There is also some relationship between minimum ground temperature at 10 m and mean winter air temperature ($r = .59$) but the relationship to snow depth is very much closer. There is a much greater uniformity of maximum ground temperatures at 10 m depth mainly because the base of the active layer in summer is always at the same temperature (0°) some 7 to 7.5 m above the 10 m depth, and similar temperature gradients are established each year. Thus, in general, variations in summer heat input from year to year do not greatly affect mean temperatures of the ground remaining frozen, but they rather produce variations in active layer depth, as discussed later.

TABLE II

Winter snow and temperature data for the site used in Fig. 3 and Table I

	1971 −72	1972 −73	1973 −74	1974 −75	1975 −76	1976 −77
Peak snow depth (cm)	6	3	20	13	8	20
Cumulative snowcover (cm days)	1050	731	4566	3266	1690	2632
Winter mean air temperature (Oct.-Mar.)	−16.1	−18.1	−14.9	−16.8	−16.0	−13.8

The importance of recognising the influence of short term fluctuations is illustrated from early interpretations of Schefferville data. In 1964 ANNERSTEN, with only one years data available, produced the mean temperature curves shown in Figure 4a. These were interpreted as indicating a general degrading of the permafrost. However, long term data (14 years) show that there is no degrading of the permafrost (Fig. 4b). In hindsight it is clear that the year of ANNERSTEN's initial observations was one when shallow temperatures were higher than average (perhaps similar to 1974 in Fig. 3) probably the result of one or two winters of above average snowcover. The large changes of shallow temperatures from year to year at modest depths (as shown in Fig. 3) cause important errors if short period data are used to compile mean temperature profiles. Experience in the Schefferville area indicates that in the absence of control data from long term observations the form of mean temperature profiles for the uppermost 20 to 30 m in the frozen ground cannot be reliably interpreted with less than 5 years data.

The active layer depth varies considerably from year to year, as shown in Table III. Although year to year variations of the frozen ground are most strongly controlled by variations of snowcover, *i.e.* by variations of winter conditions, the important lower boundary of the active layer is controlled by depth of thaw and this is primarily related to summer conditions, rather than winter conditions. Winter heat loss is more than adequate to freeze all unfrozen ground above the permafrost on most sites (the exception being limited areas strongly affected by groundwater movement, as discussed later). Once all latent heat has been lost on freezing a relatively small further heat loss will cause a large temperature drop and similarly a relatively small heat gain will raise ground temperatures from winter minimum to near freezing point. Thus the absolute value of the previous winters minimum has little effect on active layer depth. Much of the variation of active layer depth from year to year can be explained by variations of summer heat input, but some variations do not seem to be related to heat input variations. It seems probable that variations in the moisture content when it froze the previous year may be a second important factor affecting depth of active layer in a particular year.

TABLE III

Year to year variations of active layer depth at the site used in Fig. 3 and Table I

1972	1973	1974	1975	1976
2.3 m	2.9 m	3.0 m	3.0 m	2.6 m

Year to year variations in frozen ground in muskegs are of special importance to persons carrying out reconnaissance surveys by probing. In the Schefferville area the amount and persistance of frozen ground in muskegs is highly variable from year to year. In most years by late summer no frozen ground can be detected in muskegs except in palsas. However, in one year (1976) extensive frozen ground persisted until the following winter so that according to the strict definition of permafrost there was temporarily a major increase in the areal cover of permafrost in the Schefferville region! This type of observation indicates the need for caution in interpreting single season probing data, and it is clearly desirable to relate such single season data to longer term observations if at all possible.

SPATIAL VARIATIONS OF ACTIVE LAYER DEPTH

The active layer depth has been reliably measured at 37 varied sites for periods of 2 to 5 years and a wide range of supportive data has been collected. Two main factors affecting spatial variations of active layer depth have been identified, viz variations in vegetation cover

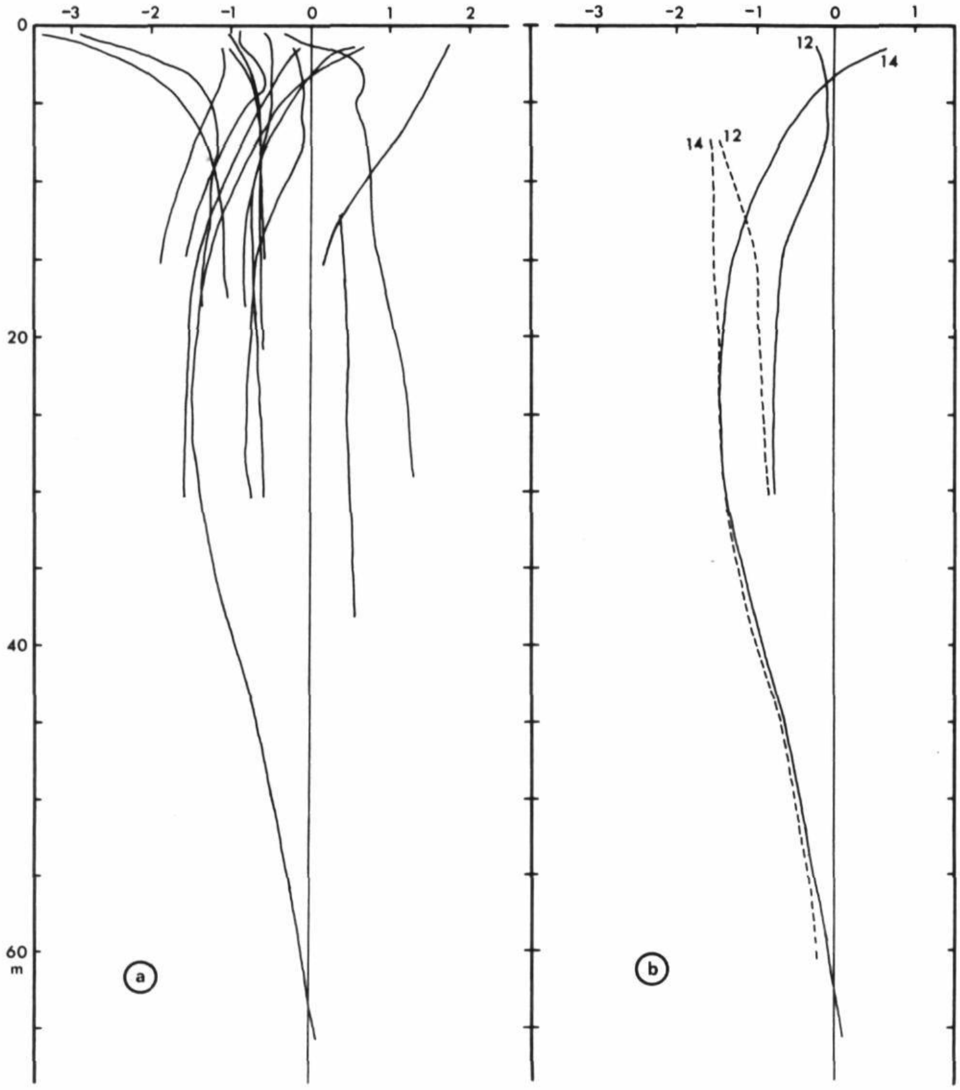

FIGURE 4 (a). Mean temperature curves compiled by ANNERSTEN (1964) with only one year's data available. (b) Solid lines show two of Annersten's original curves as in (a), broken lines show revised mean temperature profiles for the same sites compiled from 14 years data. Note that although (a) suggests a degradation of the permafrost, the longer period data show no warming trend. This emphasises the problems of interpreting short period data.

a) Les courbes de température moyenne dressées par ANNERSTEN (1964) basées sur les données d'une seule année. b) Les lignes continues représentent deux des courbes originelles d'Annersten, tandis que les tirets représentent les courbes de température moyenne, corrigées et basées sur quatorze ans de données. Bien que (a) suggère une dégradation du pergélisol, les données basées sur une plus longue observation ne fournissent aucun indice de réchauffement. Ce cas illustre bien les dangers d'interprétation à partir de données trop partielles.

including vegetation absence and the effect of suprapermafrost groundwater movement where it is concentrated along restricted flow "channels".

The influence of vegetation cover on active layer depth is shown in Figure 5. On sites not specially affected by groundwater the active layer depths vary from 1.8 to 4 m. The calculated regression line indicates that 2.3 m depth is typical under a complete vegetation cover compared to 3.6 m for sites with completely bare ground. The important effect of vegetation in reducing the flow of heat into the ground has been described in earlier permafrost studies (BAKAKIN and PORKHAEV, 1959; ANNERSTEN, 1964; BLISS and WEIN, 1971) and clearly demonstrated again in the Schefferville area. Table IV gives the results of shallow ground temperature measurements in midsummer. It seems that both vegetation cover and vegetation density are important. There is little doubt that this effect of vegetation is due to interception of radiation by the vegetation and subsequent rapid loss of energy gained, mainly to the air above. Studies at test plots of ground artificially stripped of vegetation, compared to lichen covered plots (NICHOLSON, 1976), show that the vegetation is relatively ineffective in reducing heat loss in the autumn.

The active layer is strongly affected where there is a concentration of the suprapermafrost groundwater movement in "wet lines" or subsurface "channels". These lines of concentrated suprapermafrost groundwater flow are generally from 3 to 20 m wide at the surface and may be in small, well marked valleys or they may have only very slight surface relief. Temperature measurements from drill holes at these sites show much higher temperatures in the upper part of the profile, usually with mean temperatures above freezing

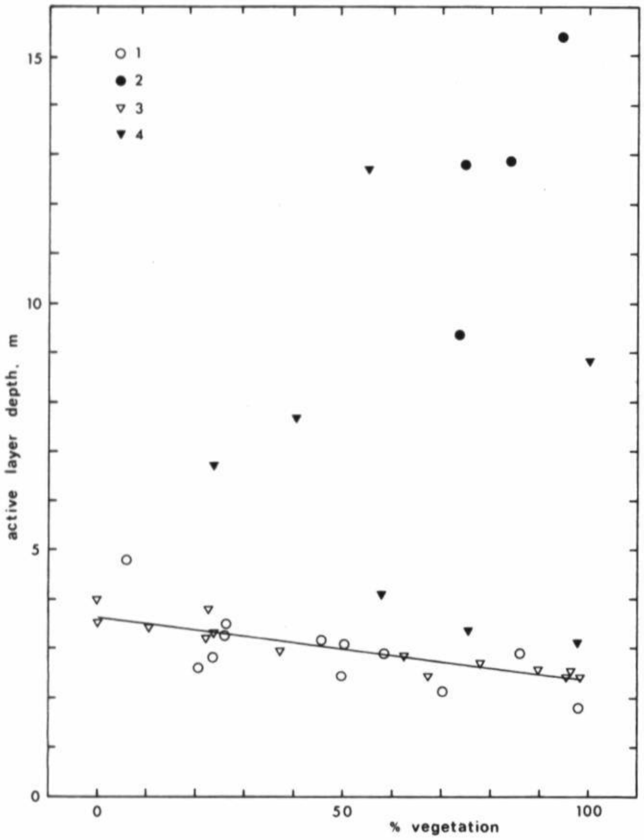

FIGURE 5. Relationship of active layer depth to per cent vegetation cover (relative to bare soil). Solid symbols are sites especially affected by suprapermafrost groundwater (2 and 4), open symbol sites are not (1 and 3). Circles for Timmins 4 area; Triangles for Fleming 7 area. The plotted regression line is for non groundwater affected sites only.

La relation entre l'épaisseur du mollisol et la densité du couvert végétal. Les symboles noirs représentent des sites particulièrement affectés par la circulation d'eau souterraine au-dessus du pergélisol (2 et 4), les symboles blancs représentent des sites qui n'en sont pas affectés (1 et 3). Cercles: région de Timmins 4; triangles: région de Fleming 7. La courbe de régression ne vaut que pour les sites non affectés par la circulation souterraine.

TABLE IV

Mean midsummer temperatures at 50 cm depth under typical cover types

	Mean Temperature °C	Standard Deviation
Bare ground (natural)	6.1	0.5
Bare ground (artificial)	6.2	0.3
Lichen mat	4.7	0.8
Brush	3.6	1.2
Krummholtz spruce	3.0	1.2
Wet lines	4.9	1.2
Ephemeral ponds	7.5	1.3

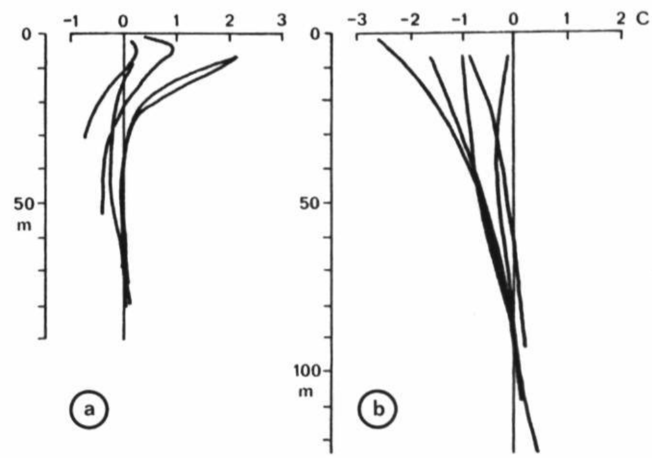

FIGURE 6. Vertical mean temperature profiles measured in drill holes. (a) "Wet line" or suprapermafrost groundwater drainage line sites. (b) "Simple" sites, *i.e.* neither near suprapermafrost drainage lines nor showing strong effects of complex lateral heat flow.

Profils thermiques tels que mesurés dans des trous de forage creusés dans: a) sites complexes affectés par un drainage souterrain au-dessus du pergélisol; b) sites simples éloignés des canaux de drainage souterrains et non affectés par des courants de chaleur latéraux.

(Fig. 6). This upper warm portion may freeze and thaw each year, and thus be the active layer, or there may be a zone that remains permanently unfrozen (a talik). Active layer depths of up to 12 m have been demonstrated by temperature measurement over several years. Taliks associated with wet lines range up to 30 m depth. On one site a mechanically excavated trench across a suprapermafrost ground water channel where there was also deep temperature data available showed the form drawn in Figure 7. This remarkable abrupt plunge of the frost table at the margin of the wet line has been directly observed in trenches on several other occasions. The depth of the active layer or talik in a wet line is quite variable as seen in Figure 5. This measured variation may be due to real variation in the maximum depth (caused by such factors as volume of flow, permeability or geometry of the channel), but much of the variability is probably due to using single drill holes to quantify features with a relatively narrow and variable form in cross section.

Several other factors that may affect spatial variations in active layer depth were considered. Variability of materials is undoubtedly important. However, almost all of the test sites are in till (mainly stoney clay) or porous bedrock (usually earthy), so that thermal properties are probably crudely similar. Solid bedrock with higher thermal conductivity and low porosity (*e.g.* un-

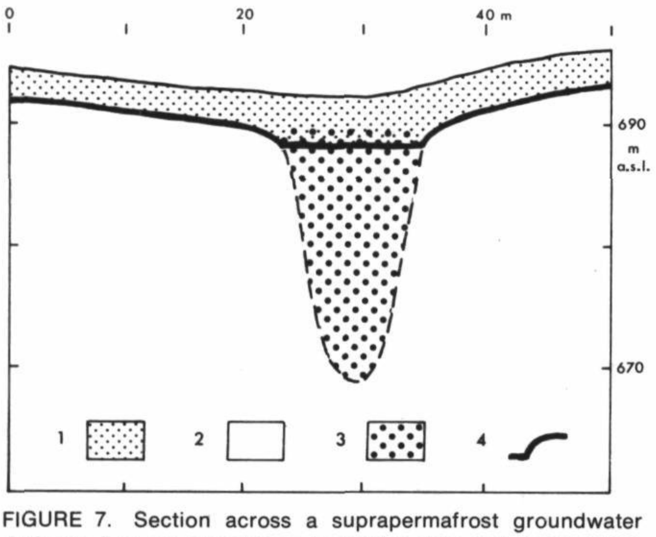

FIGURE 7. Section across a suprapermafrost groundwater drainage line produced from trenching data and temperature data measured in drill holes. 1. Active layer; 2. Permafrost; 3. Unfrozen ground; 4. Bottom of trench.

Coupe d'un canal de drainage souterrain au-dessus du pergélisol d'après les données obtenues d'une tranchée et des mesures de température dans des trous de forage. 1) mollisol; 2) pergélisol; 3) sol dégelé; 4) fond de la tranchée.

leached iron formation or quartzite) would have a notably thicker active layer, but in materials of low porosity and permeability this would have relatively little significance to physical or biological processes. On palsas, in peats, the active layer in the Schefferville area is typically between 50 and 80 cm, and again a thinner active layer is found under vegetation covered palsa surfaces than under bare peat palsa surfaces. The influence of slope orientation on active layer thickness in the Schefferville area was suggested by ANNERSTEN (1964) and a tentative decrease of one third on north east facing slopes was indicated. The sites investigated in this study were not suitable for making comparisons of different slope orientations. In theory, since the main heat input is in the high sun period at a relatively low latitude (54°N), aspect controlled differences of radiation receipt are at a minimum, and major variations in active layer thickness should not be expected on gentle slopes.

SPATIAL VARIATIONS OF PERMAFROST DISTRIBUTION

Sustained effort has been devoted to study of the spatial distribution of the permafrost (IVES, 1962; ANNERSTEN, 1964; GRAY, 1966; THOM, 1969; NICHOLSON and GRANBERG, 1973; JONES 1976). On a local scale the three dimensional distribution of permafrost in the Schefferville area has been investigated in detail using temperature measurements in drill holes. A selection of this information is given in Figures 8 and 9. It is immediately obvious that a wide variety of temperature profiles may be measured on a single site and unless conditions are exceptionally uniform the three dimensional thermal pattern must be taken into account in the interpretation of any single profile. Usually when boundaries of a frozen area are delimited with precision it is found that the boundary is very steep, as shown in Figure 8a and c. The highest ground temperatures measured away from the surface (up to 5° at 50 m depth) were under a lake, yet permafrost was measured less than 50 m from the lakeshore. Observations indicate that stable horizontal temperature gradients of up to one degree in fifteen metres are not exceptional. Frequently drill holes do not extend below the base of the permafrost, but on a site where many holes do traverse the entire permafrost thickness the base shows considerable relief (see Fig. 9a). The influence of suprapermafrost groundwater in "wet lines" or subsurface channels was discussed in relation to active layers (Figs. 6 and 7), and the very strong influence on local permafrost distribution is obvious in Figures 8b, c and 9. In places the permafrost extends well below the general water table and the piezometric surface may be high in the permafrost, whereas elsewhere it may be well below the base of the permafrost. The relationships of the permafrost with the general groundwater table are very different from those with suprapermafrost groundwater.

The quantitative relationships between ground temperature, snow and other factors have been studied in detail over the past few years in an attempt to develop quantitative predictions to aid mining operations. A major program of ground temperature measurement was developed based on past results in the area. The quantification of snow data to relate to ground temperature is a major task in itself. Snow depths are very variable over short distances and thus detailed snow information is needed to relate to the temperature data. Manual field survey of snow is far too tedious to be practical for more than pilot studies. Two methods of obtaining large scale snow data were developed and tested by GRANBERG (1973), one using sequential aerial photographs taken at intervals during the snowmelt period and one using computer modelling based on stepwise multiple regression of snow data and relief information. Further snowcourses were established and monitored over several years to give a better idea of broad scale variations over a longer period. The method of using sequential aerial photographs taken at intervals through the snowmelt period is more adaptable to large scale work and is less liable to gross error in the absence of local ground control. This method was refined over several seasons and large areas photographed for future use (NICHOLSON, 1975). For the

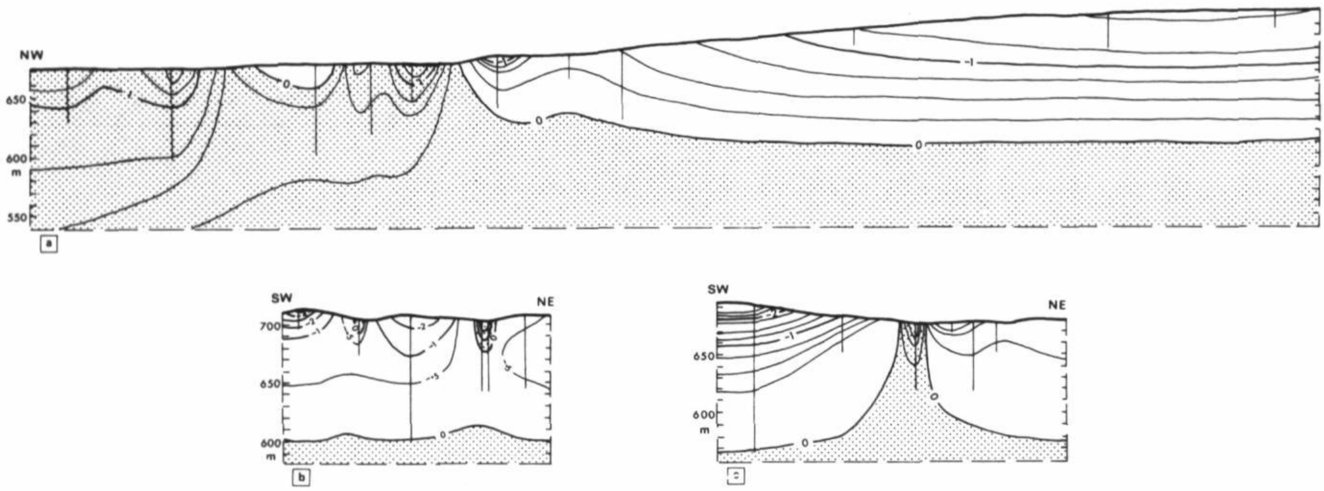

FIGURE 8. Cross sections at Timmins 4 site showing permafrost distribution (unfrozen ground is shaded). Vertical lines mark temperature profile measurement sites. Horizontal = Vertical scale.

Coupes effectuées au site de Timmins 4 qui montrent la répartition du pergélisol (zone non pergélisolée en grisé). Les lignes verticales marquent l'emplacement des sites où l'on a dressé des profils thermiques. L'échelle horizontale est la même que l'échelle verticale.

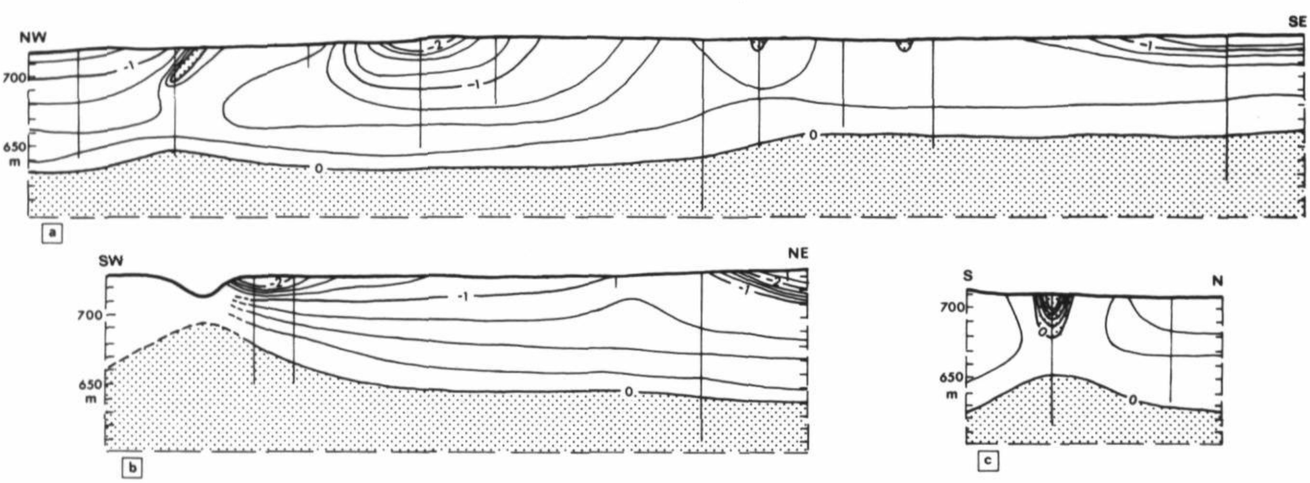

FIGURE 9. Cross sections at the Timmins 3/Fleming 7 site showing permafrost distribution (unfrozen ground is shaded). Vertical lines mark temperature profile measurement sites. Horizontal = Vertical scale.

Coupes effectuées au site Timmins 3 - Fleming 7 montrant la répartition du pergélisol (zone non pergélisolée en grisé). Les lignes verticales marquent l'emplacement des sites où l'on a dressé des profils thermiques. L'échelle horizontale est la même que l'échelle verticale.

main sites where temperature data are available detailed snow depth maps at a scale of 1:1200 were compiled and 15 m interval grid snow depth values were transferred to a computor.

Various models were used to relate snow depth to ground temperature. Using simple measures of snow the best correlations were obtained when the ground temperatures at a particular depth were related to mean snow depth over a circular area with radius equal to twice that depth (NICHOLSON and GRANBERG, 1973). This measure was termed the "2D" snow measure.

Later an improved physical model was developed based on a theoretical model by GOLD and LACHENBRUCH (1973) for calculating the influence of areas of known surface temperature on ground temperatures at some depth. GOLD and LACHENBRUCH describe the proportioning of areas of surface temperature anomaly according to the solid angle subtended at the point in the ground where the influence is to be calculated (see Fig. 10). Preliminary correlations indicated that snow up to perhaps 300 m from the temperature measurement drill hole was significantly affecting ground temperatures and thus, with a 15 m grid of snow data points,

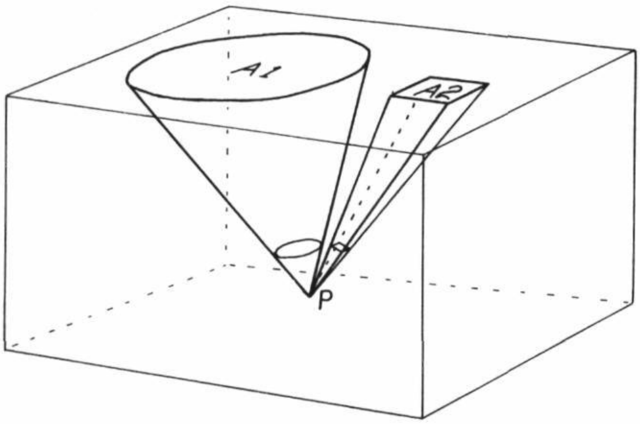

FIGURE 10. Diagrammatic representation of the solid angle subtended by two surface areas (A1 and A2) at a point of influence (P). Under equilibrium conditions if areas A1 and A2 have anomalous surface temperatures then the influence of the anomalous temperatures on point P will be in proportion to the solid angle subtended at P (following GOLD and LACHENBRUCH, 1973).

Représentation graphique de l'angle solide (SA) sous-tendu par deux surfaces (A1 et A2) à partir du sommet P. Dans des conditions d'équilibre, si les surfaces A1 et A2 connaissent des températures anormales, l'incidence de ces températures au point P sera proportionnelle à l'angle solide fermé au sommet P (d'après GOLD et LACHENBRUCH, 1973).

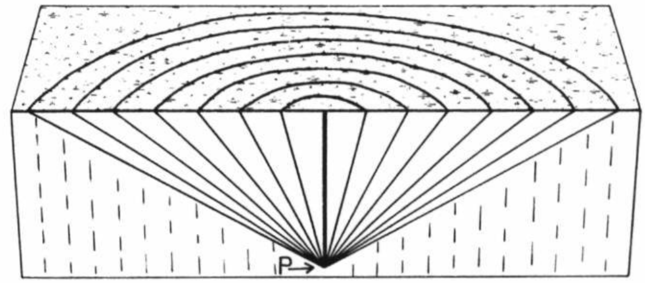

FIGURE 11. Diagram to show how the "SA" measure is calculated for a selected depth ("P"). Mean snow depths are compiled in concentric rings (7 shown here but 20 used normally). The solid angle subtended by the area of each ring projected to "P" is calculated and this value is applied as a weighting factor to the snow depth value for the respective ring. The sum of the weighted snow values for all rings is the "SA" snow measure.

Schéma du mode de calcul de l'angle solide pour une profondeur donnée (P). Les épaisseurs moyennes du couvert nival sont réparties en anneaux concentriques (habituellement 20). On calcule l'angle solide sous-tendu par la surface de chacun des anneaux projeté vers le point P et on applique ce résultat, considéré comme un facteur de pondération, à la valeur obtenue pour l'épaisseur du couvert nival de l'anneau. La somme des valeurs de tous les anneaux ainsi pondérées devient la mesure de l'angle solide.

over 1000 need to be considered for each temperature measurement profile. Some simplifying procedure was needed to handle this amount of data. Thus the first step in handling the snow data in relation to any profile was to condense the data by compiling snow depths for successive concentric rings around each profile location (see Fig. 11). Mean snow values for 20 fifteen metre wide rings were calculated for each profile, the rings extending to a maximum radius of 300 m. The final data were calculated in relation to temperature measurement or prediction points at fixed depth intervals (7.5 m, 15 m, 30 m, 45 m, etc.). For each depth the solid angle subtended by every one of the 20 rings was calculated and from these a set of 20 factors were derived which give the relative influence of each ring. These factors can then be applied to the mean snow values calculated for each ring and the 20 products are then summed to give an overall snow value for that depth (Fig. 11) This was termed the "SA" snow measure — the snow depth value weighted according to the solid angle subtended at the measurement point. A different set of 20 factors are needed for each fixed depth, but the same factors can be used for all profiles since deliberately no other non uniform site factor was built into the snow measure.

Temperature data from all sites for which snow data were compiled (75 sites) were regressed against the simple "2D" and the improved "SA" snow measures and the best results were with the "SA" snow measure (snow influence weighted according to the subtended solid angle at the temperature depth point). The "SA" results are given in Table V and the results for one depth are illustrated in Figure 12a. Tests were also made weighting the snow areas for both solid angle subtended at the temperature depth point and the distance of the snow areas (rings) from the depth point. This was termed the "SAD" measure. This latter measure gave lower correlation coefficients than the SA measure. Since the SA model is appropriate to an equilibrium situation and the SAD model for a non equilibrium situation (GOLD and LACHENBRUCH, 1973) this better correlation with the SA measure supports the conclusion that the permafrost of the area is generally in equilibrium with present climatic conditions.

The regression coefficients using snow were much better than those obtained correlating temperature with any other single factor (various relief measures, vegetation, geology or putative thermal conductivity measures and groundwater). Whilst the regressions given in Table V are far from perfect the consistency of the results from site to site and with increasing depth suggests that they are generally reliable for the range of conditions tested (tundra and tundra margin).

The "critical snow depth" which will prevent permafrost formation (*i.e.* the depth of snow for which a 0° temperature is predicted) can be calculated from the regressions and these values are given in the final

TABLE V

Linear regression of ground temperature (T) with snow depth (S)

Depth (m)	Regression Equation	Coefficient "r"	Snow when T = 0°
7.5	T = .0472 S − 3.82	.79	81
15	T = .0419 S − 3.30	.76	79
30	T = .0358 S − 2.74	.74	77
45	T = .0302 S − 2.27	.73	75
60	T = .0250 S − 1.78	.74	71
75	T = .0198 S − 1.32	.72	67

"S" for each depth is weighted in proportion to the solid angle subtended at the prediction point by each area of varying snow depth within 300 m ("SA" in text). "Snow when T = 0" is the snow depth which corresponds to ground temperature 0° according to the particular regression equation.

column of Table V. It can be seen that this snow depth corresponding to a ground temperature of 0° decreases progressively for deeper ground temperatures, which is a reflection of the geothermal gradient and is also a quantitative expression of the fact that shallower snow is needed to produce deeper permafrost. The precise critical depth of snow needed to prevent any permafrost development (81 cm in Table V) varies with the particular snow data and measure. Relative errors for prediction are greatly reduced by using comparable snow data and all the results given here are based on the 1974 sequential snowmelt aerial photography, calibrated from long term mean data. In general, using a variety of snow measures, the critical snow depth which will prevent the formation of permafrost seems to be a mean peak snow depth about 75 to 80 cm.

To quantify suprapermafrost groundwater influence a different approach was used. Field data indicate that the influence of suprapermafrost groundwater is concentrated along "wet lines" or subsurface channels. On the ground or on air photographs "wet lines" are easily recognised from their characteristic vegetation. It was reasoned that the thermal influence of a wet line would be proportional to the volume of groundwater flow, which in turn would be proportional to the catchment area. For suprapermafrost drainage the surface topography can be used to estimate catchment area, probably with reasonable accuracy except where relief is very slight and the drainage pattern very complex. Various measures were tried but the best correlations with residuals after regression of temperature with snow were obtained with the square root of the catchment area. Adjustment for varying distance from the channel was made by making the index inversely proportional to the square root of the distance from the channel. This groundwater measure was used with

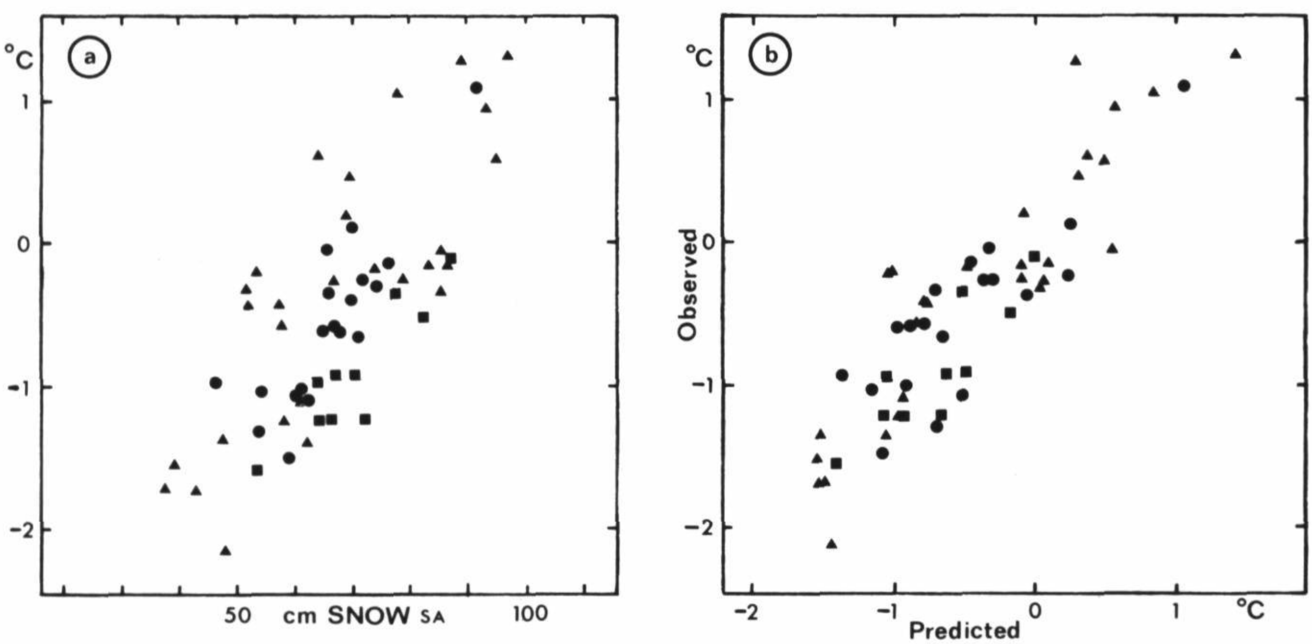

FIGURE 12(a). The relationship between snow (SA measure) and ground temperatures at 15 m depth for 3 different areas, shown by 3 different symbols (r = .76; see Table V). (b) Improved relationships for the same sites when both snow and groundwater are used as in Table VI (r = .89).

a) Rapports entre l'épaisseur de la neige (mesure de l'angle solide) et la température du sol à 15 m de profondeur dans trois sites différents identifiés par trois symboles différents (r = 0,76; voir le tabl. V); b) rapports améliorés lorsque l'on ajoute aux calculs les mesures de l'eau souterraine (r= 0,89; voir le tabl. VI).

snow for multiple regression with temperature which gave significant improvement over the use of snow alone (see Table VI and Fig. 12 b). Multiple regressions of snow and other factors gave markedly inferior results. Regressions using thermal conductivity should improve results, but the very limited thermal conductivity data available and problems of relating these values to available geological information probably accounts for the very poor results obtained. Thermal conductivity rather than thermal diffusivity measures are thought to be the most appropriate since the permafrost seems to be in an approximately equilibrium condition. Attempts to further refine predictions are hampered by the problems of producing sufficiently accurate data on the necessary scale. Known errors in the accuracy of the basic snow data are probably in the order of the magnitude of the size of influence of the next most important factor. However, the results given in Tables V and VI are very useful in their present form for prediction for the mining industry.

TABLE VI

Multiple linear regression of ground temperature (T) with snow depth (S) and a groundwater factor (G)

Depth (m)	Regression Equation	Coefficient "r"
7.5	$T = .0395\ S + .673\ G - 3.77$	.87
15	$T = .0334\ S + .579\ G - 3.26$	.89
30	$T = .0213\ S + .352\ G - 2.19$	.87
45	$T = .0203\ S + .238\ G - 1.84$	.84
60	$T = .0221\ S + .144\ G - 1.74$	.81
75	$T = .0136\ S + .144\ G - 1.03$	.81

CONCLUSION

A greatly intensified field observation program in the Schefferville area in recent years has led to considerable advances in our understanding of spatial and temporal variations of the permafrost. The general thermal budget has been quantified and the results allow greater confidence in making spatial interpretations. Snow has indeed proved to be an extremely important factor affecting permafrost distribution. Year to year variations of active layer depth are mainly controlled by summer weather conditions and spatial variations are most closely related to vegetation cover. Heat transported by suprapermafrost groundwater concentrated into "wet lines" or subsurface channels affects both unfrozen ground (active layers and taliks) and frozen ground in the vicinity of the channels. Permafrost in the Schefferville area is in a general state of equilibrium as demonstrated both by the close relationship between thermal conditions and the natural environmental conditions and by the changes that occur when the natural conditions are modified (*e.g.* by changing snow cover, hydrological conditions or vegetation cover). Undoubtedly the current knowledge of permafrost conditions in the Schefferville area provides a springboard for further research. From a practical viewpoint there is a need to ensure that available knowledge is used in the operational situation.

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