Permafrost and the shallow thermal regime at Alert, N.W.T.

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In 1978, a shallow permafrost and terrain analysis study was started at Canadian Forces Station Alert, N.W.T. (82°30'N, 62°26'W). Five holes, drilled to depths down to 60 m, were instrumented with multi-thermistor cables, and temperature measurements have been taken every two or three weeks for the last three years by DND personnel.

The drilling sites were chosen to cover various terrain types accessible from the Alert station. Preliminary air-photo analysis indicates that the principal landforms are of glacial and marine origin. A 60 m temperature cable (site 1), installed within 100 m of a shore-line emerging due to glacial unloading, yields temperatures 4 to 5 K warmer than two similar cables installed on inland plateau sites (sites 2 and 3). An analysis of these three sites suggests the higher subsurface temperatures at the shore site result as much from its proximity to the sea as from the period of submergence prior to 3000 years ago. Temperature cables installed in two 15 m holes (sites 4 and 5) on gentle north- and south-facing slopes have shown that aspect has little influence on temperatures at this extreme latitude.

Un projet pour étudier les caractéristiques du pergélisol en surface et la géomorphologie des environs de la station des forces armées canadienne Alert, T.N.-O. (82°30'N, 62°26'W) a débuté en 1978 par le forage de 5 trous dont certains ont une profondeur de 60 m. Le personnel du ministère de la Défense a, par la suite, effectué des relevés des profils de température à un intervalle de 2 à 3 semaines à l'aide des cables à thermistors multiples installés lors du forage.

Les divers types de terrain disponibles à partir de la station d'Alert ont été le facteur prédominant dans le choix de l'emplacement des sites. Les dépôts surficiels de la région sont surtout d'origine glacière et marine. Un cable de 60 m (site 1) installé à moins de 100 m du rivage en voie d'émergence suite à la déglaciation, montre des températures de 4 à 5 K plus chaude que les deux autres cables de 60 m (site 2 et 3) localisés, eux, sur des plateaux à l'intérieur des terres. Une analyse de ces trois sites suggère que les températures plus chaudes trouvées au site 1 sont tout autant dues aux effets résiduels de la période d'immersion qu'à la proximité de l'océan.

Les profils de température relevés aux deux autres trous, profonds de 15 m (site 4 et 5), sur des pentes douces à exposition nord et sud nous permettent d'affirmer qu'à cette latitude extrême la présentation azimutale de la surface n'a qu'un rôle négligeable sur les profils de température dans le sol.

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Introduction

At a number of sites in Canada's north, intensive studies have been undertaken on surficial aspects of permafrost. Of interest have been studies that examine the variability of permafrost and subsurface temperatures and the influence of climate and terrain. Such investigations have increased our understanding of the processes that have formed the landscape and that are presently active in the Arctic.

Brown (1973) combined an analysis of vegetation and surficial materials with measurements of shallow subsurface temperatures at three locations in northern Canada: Thompson, Manitoba in the southern part of the discontinuous permafrost zone, Yellowknife, N.W.T. in the northern part of the discontinuous permafrost zone, and Devon Island in the northern continuous permafrost zone. Similar studies were undertaken in the Keewatin in the southern part of the continuous permafrost zone (Brown 1978), in the Mackenzie Valley (Judge 1973*b*), and in the Rocky Mountains, as part of an alpine permafrost study (Harris and Brown 1982). Other scientists have recognized the complementary nature of surficial studies and ground temperatures (e.g. Mackay 1974; Nicholson 1978*b*).

It seemed natural, when the opportunity presented itself several years ago, to extend this type of study to the northern limit of continuous permafrost on the North American continent, to Canadian Forces Station Alert, N.W.T., at 82°30'N, 62°26'W (Figure 1). Five holes were drilled in 1978 and an extensive set of

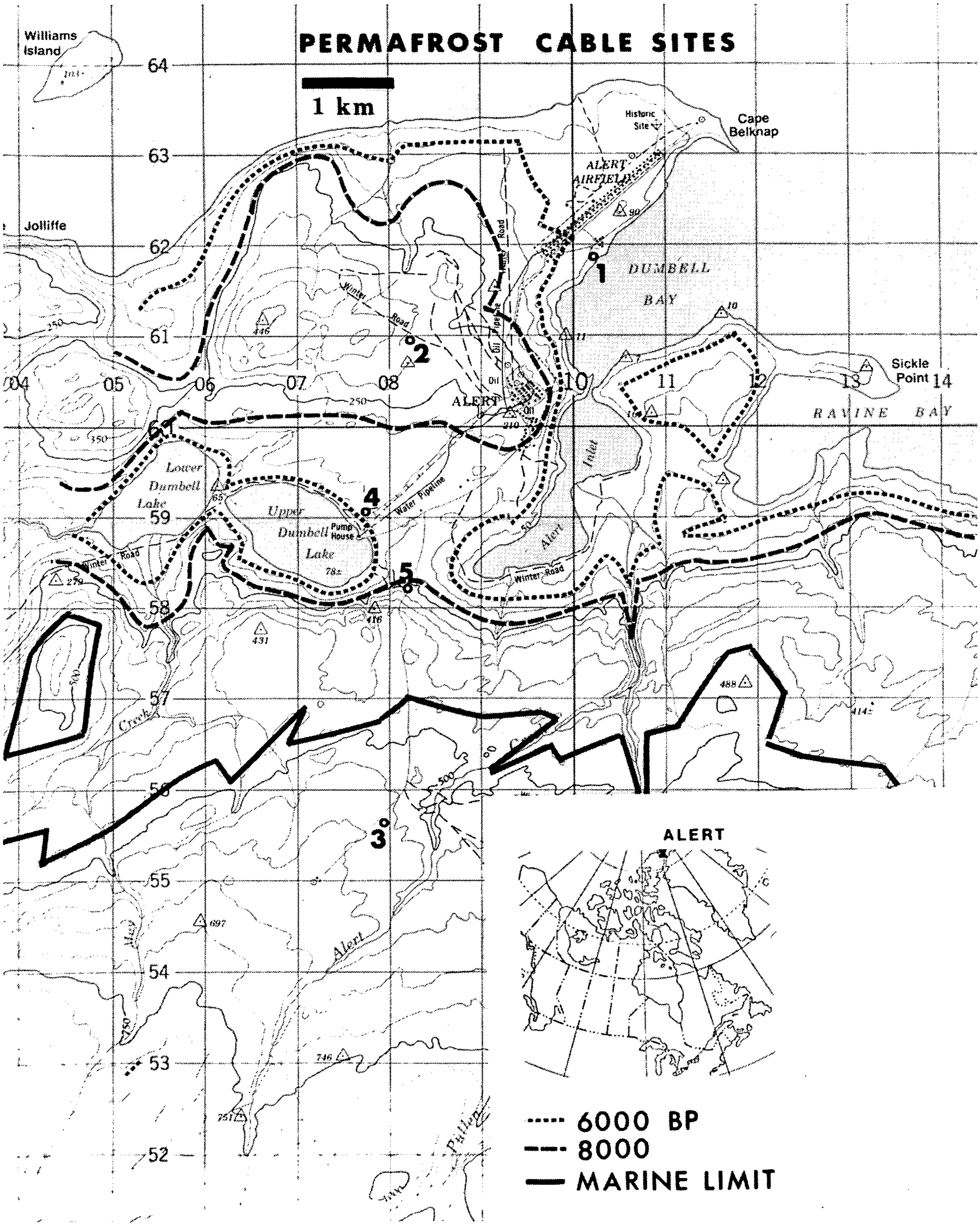

FIGURE 1. Map showing the location of Alert, Ellesmere Island, and the five drillholes. Contour interval: 50 ft = 15 m. Dashed contours: approximate position of shore-line 6000 and 8000 years ago (*after* England 1976*b*). Solid line: maximum marine invasion limit at 135 m derived from air-photo interpretation.

ground temperatures has since been acquired. This temperature measurement program was put in place at the beginning of the project to ensure a good data base for geomorphological studies to follow, while providing subsurface thermal data of immediate scientific and engineering interest.

This project is the most northerly geothermal/geomorphological study in the world. One cannot imagine a more ideal location to study extreme permafrost conditions, since Alert experiences one of the shortest frost-free periods in Canada, only four days, on average (Table 1).

TABLE 1. Meteorological data for Alert, N.W.T.

Parameter	Data
Mean annual air temperature[1]	−18.0°C
Extreme maximum temperature[1]	+20.0°C
Extreme minimum temperature[1]	−49.4°C
Freezing Index, Celsius Degree Days[2]	6700
Thawing Index, Celsius Degree Days[2]	220
Mean annual snowfall[3]	145 cm
Mean date of snow cover formation[4]	Sept. 1 ± 10 days
Mean date of snow cover loss[4]	July 1 ± 12 days
Mean duration of snow cover of at least 2.5 cm[4]	320 ± 12 days
Mean annual rainfall[3]	1.9 cm

[1] Environment Canada 1975*a*.
[2] Boyd 1973.
[3] Environment Canada 1975*b*.
[4] Maxwell 1980; Figures 3.127, 3.144, 3.161, and Tables 2.6 and 3.26

The Project

This investigation has been undertaken jointly by the Department of National Defence, the National Research Council of Canada, and the Department of Energy, Mines and Resources. The project commenced in September, 1978, with Canadian Longyear drilling three holes to 61 m (sites 1, 2, and 3 *see* Figure 1) and two holes to 15 m (sites 4 and 5 *see* Figure 1) in areas that would demonstrate any diversity in permafrost conditions at Alert. Drill-core samples were selected for geological identification and for laboratory measurements of physical and thermal properties. Cables containing 10 to 12 thermistors each were installed in the drillholes and temperature measurements have since been taken by DND personnel every two or three weeks. More than two years of data (over 250 individual logs of 10 to 12 temperatures each) are now available for analysis. Thermistors are calibrated to an absolute value of ± 0.1 K but changes better than ± 0.01 K are being resolved, a credit to the great care with which the measurements are being taken. With temperature data as accurate and frequent as these, an attempt is being made to determine thermal properties *in situ*; this study will be published elsewhere.

Further details of the drilling program, and preliminary analyses of the temperature measurements are contained in two previous reports (Brown *et al.* 1979; Taylor 1980). A up-to-date set of the temperature measurements may be obtained from the first author.

Geology and Surficial Deposits

The Alert area lies near the northern limit of the Franklinian Geosyncline, within the Imina Formation of Ordovician age. Sediments of this formation were deposited in a deep-sea environment and consist mainly of calcareous greywackes, siltstones, and shales. This deposition was followed by a final orogeny which occurred in middle or late Tertiary time (Trettin 1971).

In drilling the five sites, two dominant rock types were encountered: a varved argillite, a fine-grained rock consisting of quartz and calcite; and calcareous greywacke, a coarser rock. Layering is generally vertical with some indication of folding and a number of small faults. Some of the latter were up to 2 cm wide and filled with ice; smaller fractures, occurring to a depth of 48 m, were cemented with ice. Table 2 summarizes the bedrock lithology at each site.

In more recent times, the landscape around Alert has been very much influenced by glacial and periglacial events (Figure 2). Preliminary air-photo interpre-

TABLE 2. Drill core descriptions[1]

Site	Depth interval (m)	Rock
1	0 - 3.8	Overburden and shattered rock, poor sample recovery
	3.8 - 61.0	Argillite
2	0 - 3.0	Overburden and shattered rock, infilled with ice
	3.0 - 61.0	Argillite; fine fractures between 30 and 48 m cemented with ice
3	0 - 2.4	Overburden and shattered rock, infilled with ice up to 2 cm thick
	2.4 - 12.8	Argillite
	12.8 - 60.0	Greywacke; some ice up to 2 cm around 18 and 38 m
4	0 - 3.0	Overburden and shattered rock
	3.0 - 7.9	Greywacke
	7.9 - 15.2	Argillite
5	0 - 2.4	Overburden and shattered rock, infilled with ice up to 3 cm thick
	2.4 - 15.2	Argillite

[1] logged in field; lithologic identification by Gratton-Bellew (Brown *et al.* 1979).

FIGURE 2. A typical glacially-sculptured valley near Alert in August.

tation has distinguished the general distribution of sediments of glacial, fluvioglacial, and marine origin (Figure 3). The field area may be generally described by the following major classes: (i) thin till-mantled plateaus and slopes, subject to varying degrees of modification since deposition by solifluction and cryoturbation; (ii) gravel terraces and fans of deltaic or flood-plain origin subjected, since deposition, to solifluction, cryoturbation, and fluvial erosion; (iii) marine sediments derived from wave washing of glacial till and fluvial sediments; (iv) raised beaches composed of sands and gravels along the shore; and (v) felsenmeer derived from the local bedrock by gelifraction, cryoturbation, and solifluction. Relatively little bedrock is exposed. In drilling the five sites, about 2 to 3 m of highly fractured rock was generally encountered before reaching competent bedrock. The rock was held together by ice frequently of the order of 1 cm in thickness but occasionally up to 2 or 3 cm. Similar depths of frost shattering were encountered at Resolute (Cook 1955).

Post-glacial Quarternary History

The Innuitian Ice sheet covered the Alert area during the Quaternary, although its extent and thickness is not well known (Blake 1970; England 1976*a*; Prest 1970). The possibility of parts of Northern Ellesmere Island being ice-free refugia during the Wisconsin glaciation has been widely discussed (e.g. Brassard 1971). In particular, Schuster *et al.* (1959) suggests that glaciation in the Alert area was local and incomplete. Otherwise, estimations for the deglaciation of northern Ellesmere Island vary from 10,000 to 13,000 years B.P. (Lyons and Mielke 1973) to as recent as 7500 to 8100 years B.P. (England 1974), the latter date being based on the time of initial post-glacial emergence from the surrounding ocean. Shell and driftwood collected from raised beaches in the Alert area have established an emergence curve since that time, suggesting about 30 m emergence in the past 6000 years and up to 60 m since 8000 years B.P. (England 1976*b*). Shore-line positions at these dates (*see* Figure 1) show the considerable land area around Alert that remained submerged following deglaciation until recent times.

In this study, geomorphological evidence (surficial material wash limits) obtained from air photos indicate a maximum marine invasion limit at Alert of

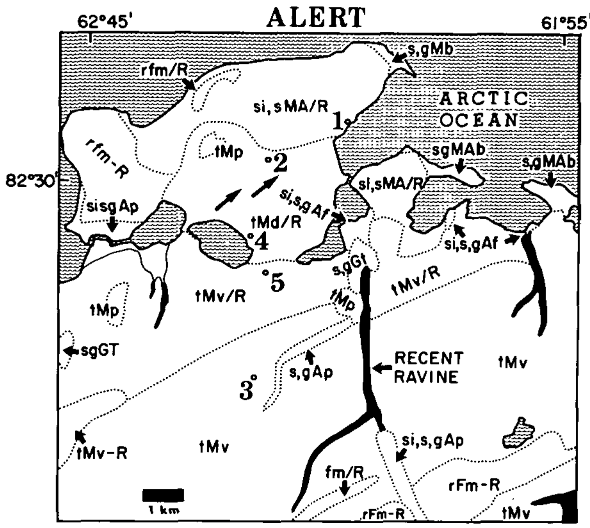

FIGURE 3. Map of surficial geology showing the general distribution of the sediments of glacial, glaciofluvial, marine, and bedrock origin. The temperature measurement sites are shown (numbers 1 to 5).

Legend

t Mp	=	till moraine plain
t Mv	=	till moraine veneer
t Mv/R	=	till moraine veneer with < 25% bedrock outcrops
t Mv-R	=	till moraine veneer with < 50% bedrock outcrops
t Mf/R	=	till moraine fluted with < 25% bedrock outcrops
si, s, g Ap	=	silt, sand, gravel alluvial plain
si, s, g Af	=	silt, sand, gravel alluvial fan
s, g Gt	=	sand, gravel glaciofluvial terraces
r Fm-R	=	felsenmeer with < 50% bedrock outcrops

Notes:

Prefixes stand for type of material

t	=	till
si	=	silt
s	=	sand
g	=	gravel
r	=	rock debris

Large central letter stands for the geomorphological process

M	=	moraine
A	=	alluvial
G	=	glaciofluvial
MA	=	marine
R	=	bedrock

Suffixes stand for the geomorphological form

p	=	plain
v	=	veneer
f	=	fan
t	=	terrace
b	=	beaches
d	=	fluted/drumlinized
/	=	a > 5% but < 25% component
-	=	a > 25% but > 50% component

Arrows indicate direction of general glacial fluting.

approximately 135 m above sea level, excluding eustatic considerations. Although this limit is undated and may apply to an earlier glacial epoch, it indicates that only one of our study areas (*see* site 3, Figure 1) has not been subjected to a marine invasion at some time in the past. On the other hand, site 1, now less than 100 m from the sea and at an estimated 10 m elevation, was underwater for about 5000 years after ice retreat, emerging only 3000 years ago according to England's (1976*b*) emergence curve. Site 4 (elevation about 38 m) had emerged by 7000 years B.P. suggesting a relatively short marine episode.

Together, the maps (*see* Figures 1 and 3) illustrate the diversity in the study sites with respect to glacial and post-glacial history. The following sections describe the variations in the subsurface thermal regime attributable to these diverse histories and varied lithologies.

Subsurface Temperatures

Temperatures typical of summer and winter at the five sites are shown in Figure 4, illustrating the "whiplash" of temperatures at shallow depths from warmer to cooler values in response to seasonal change. While temperatures in the upper several metres follow the seasonal variation quite closely, deeper temperatures lag by progressively greater amounts due to the low thermal diffusivity of the ground. Annual variation is negligible below 20 m. Temperatures in the deeper portion of the curves will reflect climatic conditions of the past hundreds to thousands of years. The spread in temperature values among the sites attests to the variability of sursurface regimes over an area of a few kilometres. Even the two plateau sites (Nos. 2 and 3) differ by 1 K and the shore site (No. 1) is about 4 to 5 K warmer than the others at 60 m.

Differences among the sites in the upper 8 m can be better analyzed from a plot of the temperature ranges and means for the one-year period beginning in August, 1979 (Figure 5). This period was chosen since it was the first year with a complete temperature data set; the data from the succeeding year exhibited similar trends in general. Of the two plateau sites, temperatures measured at site 3 have yielded a mean temperature over a year about 1 K higher than, and a maximum range one-half to two-thirds that of, site 2. The mean temperature at site 1 is up to 3 K higher than the other sites; the annual range is intermediate between the small range at site 3 and the other sites. Extrapolating the shallow mean temperatures to the surface yields similar trends; the mean ground surface temperatures for 1979-80 are − 14.0°C at site 1, and − 15.7 to − 16.5°C at the other sites (Table 3).

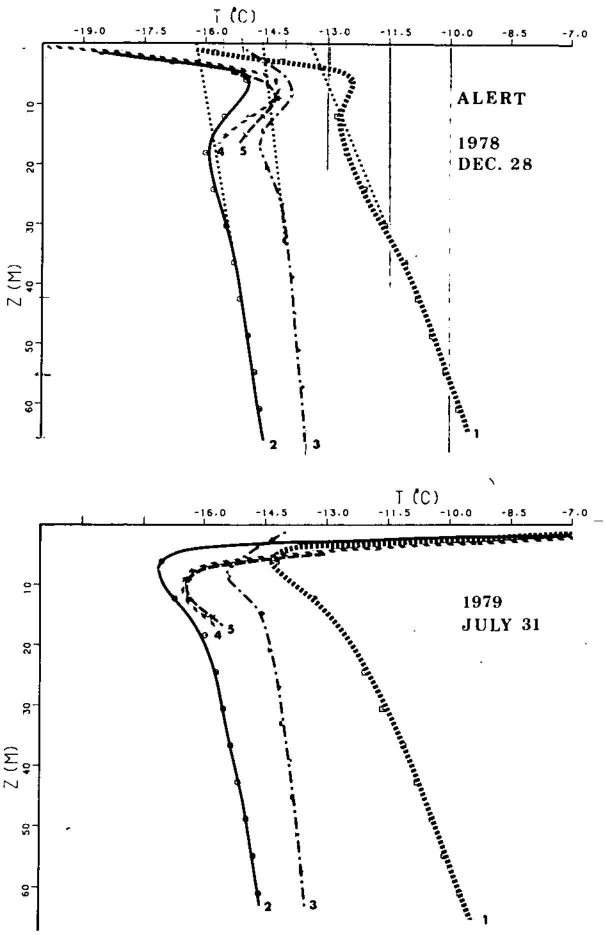

FIGURE 4. Typical summer and winter ground temperatures measured at Alert for each site. Temperatures deeper than 20 m exhibit negligible seasonal change and have been extrapolated to show the variation in long-term mean surface temperatures occurring over a few kilometres.

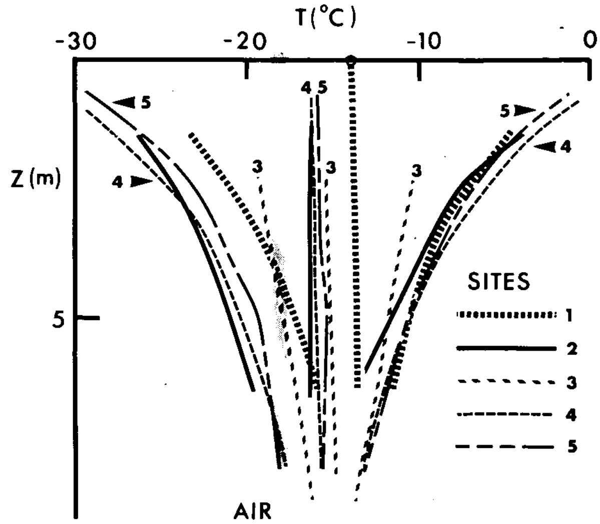

FIGURE 5. Maximum-minimum ground temperature envelopes for August, 1979 to August, 1980. The central, near vertical lines are mean temperatures for the year; the broad stippled line is the mean air temperature (−18°C) for the period from the Alert weather station; the mean monthly air temperatures ranged 21 K above to 15 K below this mean.

There is little evidence to explain these variations in other than a qualitative way. Using the simple heat conduction model, Gold and Lachenbruch (1973) described the gross features of subsurface temperature fields in the zone of the annual variation. The annual range depends on the temperature amplitude impressed on the ground surface and decreases exponentially with depth as a function of the rock thermal diffusivity. Because of its insulating property, snow cover lessens the surface temperature amplitude; variation in surface materials among the sites may also result in significant differences in the thermal diffusivity in the upper metre or so.

While a detailed examination of surface materials at each site must await a summer visit, snow depths and densities have been measured at each site along with the ground temperatures. Snow depths have generally been less than those measured at the Alert weather station, as recorded on the Monthly Climatological Summary Sheets of the Atmospheric Environment Service. Sites 4 and 5 had the least depth of snow, mostly less than 10 cm over the year beginning in August, 1979 (Figure 6), although somewhat more the following year. Snow accumulation at sites 1, 2, and 3 was somewhat greater, generally less than 20 cm but reaching 30 to 40 cm in the spring of the year in question (*see* Table 3).

There seems to be little correlation between ground temperature variations among the sites and the snow depths measured at each. The high mean temperatures at site 1 are not accompanied by significantly greater depths of snow. The small annual range of annual subsurface temperatures at site 3 cannot be explained by a greater snow thickness limiting the surface temperature amplitude. At a much more southerly latitudes, Nicholson (1978*a*) found in excess of 50 cm snow cover is required to cause significant increase in subsurface winter temperatures near Schefferville, while Judge (1973*b*) observed that the autumn decrease in ground temperatures at Fort Good Hope was slower after a 20 cm snow cover had accumulated. The difficulty in linking snow cover as a winter insulator to subsurface temperatures at high latitudes lies in the tendency for snow to be constantly redistributed by wind (Cook 1955). The lighter snow cover measured at sites 4 and 5 might result from the wind keeping these areas more snow-free; these sites lie on opposite sides of an east–west valley (*see* Fig-

TABLE 3. Summary of thermal parameters measured at each site (79/8 to 80/8)

Parameter	Alert AES[1]	Site 1	Site 2	Site 3	Site 4	Site 5
MAAT(°C)[2]	−18.0					
MAGT(°C)		−14.0	−16.4	−15.7	−16.5	−16.0
Min. temp. at 1.5 m (°C)		−23.0	−26.2	−19.6[3] (2.4 m)	−27.2	−25.6
Max. temp. at 1.5 m (°C)		−4.9	−4.2	−10.6 (2.4 m)	−3.7	−4.4
Temp. range at 1.5 m (K)		18.1	22.0	9.0 (2.4 m)	23.5	21.2
Z(0.1 K) (m)		21-24	21-24	≈21		
average snow depth (cm) 79/10-80/6	23.3 ± 11.3	16.6 ± 6.1	12.7 ± 6.2	12.2 ± 8.7	3.9 ± 2.8	4.7 ± 3.9
max. snow depth (cm) and date	38 80/5/30	29 80/5/1	31 80/5/30	39 80/5/30	10 80/5/30	18 80/5/30
snow density at same date (kg/m³)		300-400	200-300	290-330	270	220

[1] Environment Canada, Monthly Climatological Summary Sheets, 79/8 to 80/8.
[2] MAAT, mean annual air temperature,
MAGT, mean annual ground temperature
[3] At site 3, the thermistor nearest surface is at 2.4 m.

ure 1), a direction similar to the prevailing winter winds at Alert (Maxwell 1980).

At the Devon sites, Brown (1977) found that the north slope of a beach ridge had higher mean annual ground temperatures than the top or the south-facing slope. He attributed the higher temperatures to the insulating property of winter snow cover that more than compensated for the lower ground temperatures expected for a north slope in summer. Two sites at Alert were located on south- and north-facing slopes to test this observation at an even higher latitude. Site 4 (*see* Figure 1) lies part way down a gentle slope of approximately 4° and faces south; site 5 lies on a more rugged slope varying in steepness from 9 to 17° and faces north. Ranges and means at these two sites are very similar, although ground temperatures at the north-facing slope (site 5) are slightly higher on average than at the south slope (site 4). Snow depths measured at these two sites were comparable over the year, being less than 10 cm except for a period in May, 1980. As expected, the south-facing site does have slightly higher maximum subsurface temperatures in the summer.

The role of vegetation in moderating subsurface temperatures may be substantial, as illustrated by Brown (1973) at vegetated sites at Yellowknife. The effect at Alert is expected to be insignificant, however; Schuster *et al.* (1959) estimated that more than 90 per cent of the area around Alert is devoid of plant cover. The extent of vegetation at each site is not known at present.

A distinctive feature is the similarity in general shape of the cold and warm side of the temperature envelope at each site (*see* Figure 5). One tends to be the mirror image of the other, although there is not perfect symmetry about the mean. While this similarity in the minimum and maximum envelopes was evident at the Devon island sites (Brown 1977), it is generally not observed at locations further south. At Schefferville in discontinuous permafrost, the envelopes are very asymmetric, either the highest, or the lowest ground temperatures at a site being constrained by the freezing point (Nicholson and Thom 1973). At non-bedrock sites near Yellowknife and Thompson, Brown (1973) observed similar one-sidedness to the ground temperature envelopes. At southerly sites in the discontinuous permafrost zone, these effects arise from abundant soil water present in the active layer allowing a zero curtain to develop and to last for some time.

The symmetry of the temperature envelopes at Alert suggests a zero curtain is not a prominent phenomenon there, since the active layer has little apparent effect in shielding deeper temperatures from normal seasonal variation. Further evidence may be taken *from* Figure 6, which illustrates the subsurface response to seasonal and shorter-term variations in air temperature at site 4. The small, distinct asymmetry in the summer temperature waveform may reflect a refreezing active layer in both years (*note* the attenuated August temperatures and the abrupt decrease in September). A similar asymmetry is observed in deeper temperatures at Schefferville, where a zero curtain persists for several months (Nicholson 1978*a*). Ground temperature data at Barrow, Alaska, taken at a frequency and at depths simi-

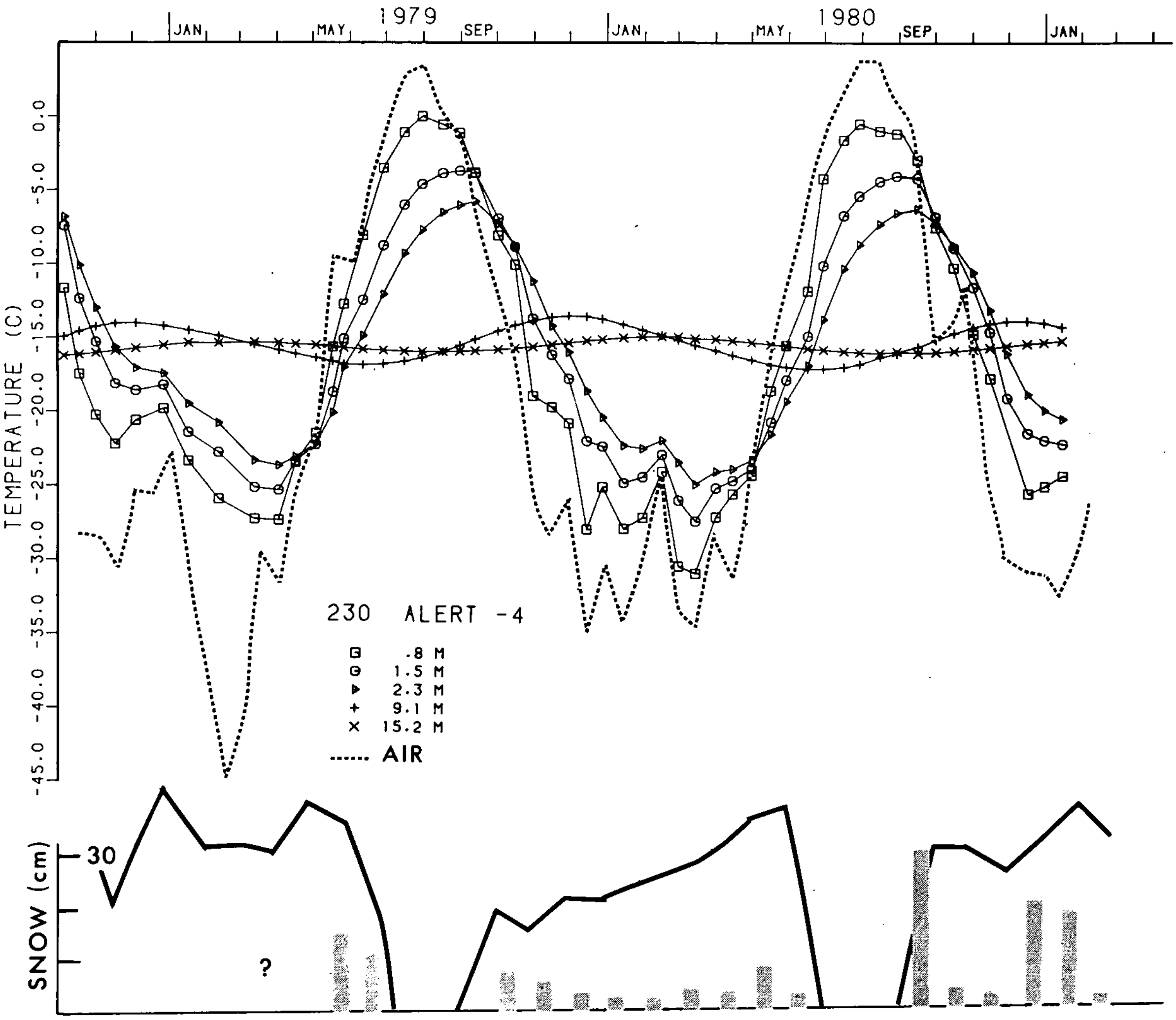

FIGURE 6. Subsurface temperatures measured at selected depths, site 4. The air temperatures are 15-day means extracted from the Atmospheric Environment Service's Monthly Climatological Summary Sheets. Snow depths (bars) are averages of three probings in the vicinity of the hole, compared with month-end depths (solid line) taken at the Alert weather station (AES Sheets).

lar to the Alert data, show a degree of asymmetry most prominent at depths of 3.0 and 6.4 m (Brewer 1958). This effect was attributed to the difference in the manner of heat passage through the active layer during periods of thaw and freeze-up. Brewer suggests permafrost is temporarily shielded from decreasing air temperatures in the fall by latent heat given off during refreezing of the active layer.

The top thermistor in the cables at Alert is at 0.8 m (sites 4 and 5), 1.5 m (sites 1 and 2), and 2.4 m (site 3); in two and a half years, no positive temperatures have been recorded. Although no data are available at present on the active layer around Alert, it is obviously more shallow than these depths.

Table 4 summarizes pertinent ground temperature data at the various Canadian sites discussed above in relation to similar data at Alert. All sites have mean ground temperatures several degrees higher than mean air temperatures, a common phenomena discussed by Judge (1973*a*) and attributed largely to winter snow cover. While these mean ground temperatures are lower at northern stations, the annual range in bedrock varies considerably but does not show any particular dependence on latitude, being roughly related to the annual amplitude in air temperature.

Subsurface Temperature Gradients

In addition to the variation in subsurface temperatures, the temperature gradients vary from site to site as well (*see* Figure 4). Considering only the tempera-

TABLE 4. Meteorological and ground thermal regime parameters for a number of Canadian sites taken from the literature, compared to Alert

Parameters	Sites					
	SCHEFFERVILLE	THOMPSON	YELLOWKNIFE	RESOLUTE	DEVON	ALERT
Location	54°48'N, 66°48'W	55°48'N, 97°52'W	62°28'N, 114°27'W	74°41'N, 94°54'W	75°33'N, 84°40'W	82°30'N, 62°26'W
Date of study	1971-75	1969-70	1970-71	early 1950's	1972/5-1973/5	1979/8-1980/8
Mean annual air temperature	−6.5 to −4.6°C	−3.3°C	−5.6°C	−16.4°C	(−18.7°C)[1]	−18.0°C
Mean monthly range and (amplitude)	−22.7 to 12.6°C (35 K)	−24.1 to 16.8°C (41 K)	−28.6 to 16.0°C (45 K)	−33.5 to 4.3°C (38 K)	(−35.1 to 2.8°C) (38 K)	−33.3 to 3.9°C (37 K)
Mean ground surface temperature	−2 to 4°C	−1 to 4°C	−2 to 2°C	−12°C	−15 to −17°C	−14 to −16°C
Annual temperature range at 6 m						
in bedrock	NA	4.5 K	9.0 K	NA	6 to 14 K	5 to 8 K
in non-bedrock	NA	2 K	3 K	NA	NA	NA
Permafrost	discontinuous, up to 100 m	discontinuous, up to 15 m or more	discontinuous, up to 50 m; none in exposed bedrock	continuous, 380-600 m	continuous, est. 210 m (coastal) to 659 m (uplands)	continuous, est. 600 m + at inland areas
Active layer	0.5 m (peat) 1.8 to 4 m generally	0.5 to 2 m	1 m in peat	0.6 m in shattered rock	0.6 to 1.7 m in bedrock	less than 0.8 m
Maximum duration of zero curtain	4 to 10 weeks			23 days		
Reference	Nicholson 1978*a*, 1978*b*	Brown 1973	Brown 1973	Cook 1955; Misener *et al.* 1956; Judge *et al.* 1981	Brown 1977; Judge 1977	this study

[1]Air temperature data for Devon is not available; quoted values are for Resolute for the same period, extracted from Atmospheric Environment Services Monthly Climatological Summary Sheets.

tures below the seasonal variation (about 20 m), it is apparent that the largest increase of temperature with depth occurs at site 1, while the smallest gradient is measured at site 3. These variations in gradient may be attributed to differences in rock thermal conductivity among the sites and to differing surface temperature histories over the past few thousand years.

A reconstruction of the palaeoclimate will be left to a following paper when the authors have had a chance to visit the area in the summer and examine the location of each site relative to shorelines. However, some preliminary observations may be made here to support the air-photo interpretation and to emphasize the relationship between surface history and the subsurface regime.

The geothermal analysis is based on the premise that the terrestrial heat flux from distinct tectonic regions is reasonably constant over a large area (Judge 1973*a*). Temperatures in the upper thousand or so metres of the earth's crust are strongly influenced by the ground surface temperature history: by mathematical analysis, these transitory effects may be stripped from the temperature profiles, leaving a thermal regime reflecting solely the earth's heat flux from deeper regions of the earth.

Judge (1973*a*) postulates an equilibrium heat flux for the Alert region of 50 to 67 mW/m^2. The temperature gradients measured at plateau sites 2 and 3 (*see* Figure 4) are approximately 26 and 20 mK/m, respectively. This contrast in temperature gradient is approximately inversely proportional to the average values of thermal conductivity measured in the laboratory (2.8 W/mK at site 2 and 3.3 W/mK at site 3), resulting in the product of gradient and conductivity (the heat flux) being approximately equal for the two sites (68 mW/m^2). The gradient measured at the near-shore site (60 mK/m) and the measured thermal conductivity (3.0 W/mK) suggests an apparent terrestrial heat flux almost three times the flux at the plateau sites. Preliminary calculations show that the enhancement of the heat flux (and hence the gradient) at site 1 is perhaps a result, about equally, of two factors: first, its proximity to the sea since emergence about 3000 years B.P. (the "lake" or "topographic" correction of heat flow studies), and secondly, residual heat still being dissipated from the time prior to that date when the site was submerged or covered by glacial ice and hence had a much higher surface temperature (the "climatic" or "glacial" correction).

Although the measured heat flux of 68 mW/m^2 is at the top of the range expected for this geological environment, the value may change somewhat as the effect of recent surface history is eliminated. For instance, if the ice base temperature during the most recent glaciation was higher than present ground temperatures (e.g. at pressure melting point), the corrected heat flux would be somewhat lower.

The derivation of heat flux values from such shallow temperatures is generally less reliable than from much deeper temperatures because of the strong influence of relatively recent surface histories. The thermal regime is very sensitive, as noted, to the shoreline history at site 1, where the contrast in subaerial and sub-sea conditions is more than 10 K. Judge (1973*a*) described how the heat flux may be used to calculate permafrost thickness. Because of the limited depth of the original data, predicting permafrost thicknesses at Alert is fraught with uncertainties similar to those encountered during a similar calculation for Devon Island (Judge 1977). The method suggests, however, that permafrost is over 600 m thick at inland areas around Alert, a result of the low surface temperatures, moderate rock thermal conductivities and expected moderate terrestrial heat flux.

Conclusion

Temperatures measured at Alert in five shallow holes to 61 m in depth have demonstrated the subsurface thermal response to the seasons and the variability of permafrost temperatures from site to site.

Sites on gentle north- and south-facing slopes show that aspect has little influence on subsurface temperatures at this extreme latitude. One site, emergent from the sea due to isostatic rebound in the past several thousand years and presently within 100 m of the shore, is 4 to 5 K warmer at 60 m depth than two inland sites. Surface temperatures were extrapolated from average temperatures in the upper 8 m at each site; four of these are about 2 K warmer than the mean annual air temperature while the shore site is 4 K warmer, a reflection of a less severe microclimate in the vicinity of the ocean.

Temperatures and their gradients are consistent with a geological environment that would be expected to have a moderate terrestrial heat flux. The near-shore site exhibits a temperature gradient more than twice the inland sites; since thermal conductivities are comparable, this is an indication that its historical surface temperatures have been considerably higher than today, due to a substantial period of submergence by the sea.

Through the continued co-operation of DND and their personnel taking the readings, the authors propose to continue the collection of these detailed temperature data at Alert and to expand the program along the following lines.

Automatic temperature recorders permit data to be gathered at a much greater frequency. It is proposed to install such devices on at least one cable at Alert within a year. This will record the short-period response of the ground to air temperature variations and facilitate the calculation of the ground thermal diffusivity directly from the periodic variation of subsurface temperatures. With automatic recording, it would also be feasible to install short (one metre) cables to study temperature variations in the active layer.

A summer visit would yield a detailed description of the geomorphological environment of each site, and would provide ground check of the air-photo analysis. A large-scale map of features and surface materials in the Alert area would assist DND's operation and would provide further insight to the post-glacial history.

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