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by J.T. Gray and the late R.J.E. Brown

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The influence of terrain factors on the distribution of permafrost bodies in the Chic-Choc Mountains, Gaspésie, Québec

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Ground temperature studies revealed the presence of several contemporary bodies of discontinuous permafrost on the windswept treeless summits of the Chic-Choc Mountains in Gaspésie. One such permafrost body on Mont Jacques-Cartier is 45 to 60 m thick and related to a mean annual ground surface temperature of −1 to −1.5°C. Snow cover is the principal terrain factor governing the presence or absence of permafrost. Snow depth indices derived from long-term data from a similar climatic region in central Québec–Labrador permitted the Mont Jacques-Cartier permafrost to be plotted on the basis of snow cover. The rapid increase in snow depth as one crosses from the tundra into the krümmholz zone enabled a close correlation to be made between the permafrost boundary and the tree-line and this facilitated regional mapping of permafrost bodies thoughout the Chic-Choc Mountains. This correlation is not perfect, however. First, local tree-lines occur below the critical altitude at which the mean annual air temperature is sufficiently low to induce the development of permafrost, either due to local lithologic, microclimatic, or geomorphological conditions. Secondly, in the tundra zone large topographic hollows on the leeward side of summits harbour a deep winter snow pack which inhibits permafrost development. Thirdly, below the regional tree-line, lenses of permafrost occur in rock glaciers at the base of steep slopes. In one case, an ice lens 5 to 10 m thick was observed during excavations at the toe of the rock glacier.

Des études de la température du sol ont révélé la présence de plusieurs poches de pergélisol discontinu sur les sommets sans arbres balayés par les vents des monts Chic-Choc en Gaspésie. Une de ces masses de pergélisol sur le mont Jacques-Cartier atteint une épaisseur de 45 à 60 m alors que la température moyenne annuelle de surface y est de −1 à −1,5°C. La couverture nivale est le principal facteur dont dépend la présence ou l'absence de pergélisol. Des indices d'épaisseur de neige, dérivés de données portant sur de longues périodes pour une région climatique comparable dans le centre du Québec et du Labrador, ont permis de déterminer l'étendue de pergélisol du mont Jacques-Cartier en fonction de la couverture nivale. L'épaisseur de neige augmentant rapidement entre la zone de toundra et la zone de krummholz, on a pu établir une étroite corrélation entre la limite du pergélisol et la limite des arbres, qui a facilité la cartographie régionale des étendues de pergélisol dans l'ensemble des monts Chic-Choc. Cette corrélation n'est toutefois pas parfaite pour trois raisons: premièrement, il existe des limites des arbres locales à des altitudes inférieures à l'altitude critique à laquelle la température annuelle moyenne de l'air est assez peu élevée pour qu'il y ait formation de pergélisol en raison des caractéristiques lithologiques, micro-climatiques ou géomorphologiques locales; deuxièmement, dans la zone de toundra de grandes dépressions situées du côté sous le vent des sommets subissent en hiver un enneigement important qui empêche la formation de pergélisol; enfin, on trouve, en-deçà de la limite régionale des arbres, des lentilles de pergélisol dans les glaciers rocheux à la base des pentes raides. Dans un cas on a trouvé pendant des travaux d'excavation, une lentille de glace de 5 à 10 m à la base d'un glacier rocheux.

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Introduction

Despite the relative accessibility of the Chic-Choc Mountains and the numerous field studies of glacial geomorphology in the region over the past 100 years, there has been little discussion of the periglacial landforms and even less mention of the possible existence of permafrost or perennially frozen ground. This, despite the cold climate and treeless nature of the highest summit domes and plateaux. Passing reference was made by McGerrigle (1952) to the probably widespread distribution of permafrost in the eastern Chic-Choc Mountains (in the vicinity of Mont Jacques-Cartier). However, McGerrigle was actually able to prove the existence of frozen ground at only one location.

"This was close to the base of the valley wall east of the Salmon Branch of Grand Cascapedia River where the Bathurst Company Road turns to cross the branch. Here, talus from adjacent cliffs lies under a cover of moss and scrubby tree growth. The upper four feet of the talus deposit was too tightly bound by frost (August 1944) to be removed by bulldozer. The depth of the frozen ground is not known. The elevation is 975 feet" (McGerrigle 1952, p. 49).

Subsequently de Römer (1977), while commenting on periglacial features such as stone nets and stripes near the summit of Mont Jacques-Cartier in the eastern Chic-Choc Mountains, and on rock glacier-like lobes and semi-permanent snow banks on several of the eastern slopes, indicated that he was "reasonably sure that there are no large areas of perennially frozen ground". No positive proof for the validity of this statement is brought forward by de Römer, however, although he did state that the periglacial environment with its frost-generated features could reflect cold climates without necessarily implying permafrost.

During separate visits to the summit of Mont Jacques-Cartier, the present authors were struck by the treeless nature of the plateaux, resembling very closely the tundra and rock desert surfaces of northern Canada underlain by contemporary permafrost. They were also impressed by the periglacial features in the summit regions and subsequently undertook studies of the ground temperature regime which now establish the existence of contemporary permafrost bodies on a number of these summits (Gray and Brown 1979).

The present paper defines the various thermal parameters of one such permafrost body on Mont Jacques-Cartier and attempts to relate the permafrost distribution on a regional basis to various terrain factors, principally snow cover. Finally, since the operation of these terrain factors is somewhat influenced by the nature of the vegetation cover through microclimatic effects, the relationship between permafrost and tree-line throughout the Chic-Choc region is examined.

The Study Area

The Chic-Choc Mountains form the backbone of the northern Gaspé Peninsula (Figure 1). The area of high summits, exceeding 900 m, extends for 80 km from the vicinity of Matane to the eastern front of the McGerrigle massif. The mountain range follows the Appalachian structural trend from WSW to ENE and is for the most part composed of Cambrian to Devonian rocks of sedimentary and volcanic origin, intruded locally by magmatic material. The largest of these intrusions, at the eastern end of the range, is the McGerrigle pluton, composed in part of granitic and in part of hybrid rocks, particularly syenite, monzonite, and granodiorite. A second intrusive mass, of peridotite composition, forms the Mont Albert massif and the Chic-Choc Range proper, to the west of Mont Albert.

Topographically the McGerrigle Mountains consist, in reality, of a large interior plateau at an altitude of 900 to 1100 m from which several summit domes rise to altitudes of about 1200 m. Mont Jacques-Cartier, the highest summit in south-eastern Canada, attains an elevation of 1268 m. The Mont Albert massif is a large undulating plateau ranging in elevation from 900 to 1150 m. The Chic-Choc Range proper, to the west, consists of a succession of dome-like summits rising to 900 to 1100 m from the broad interior

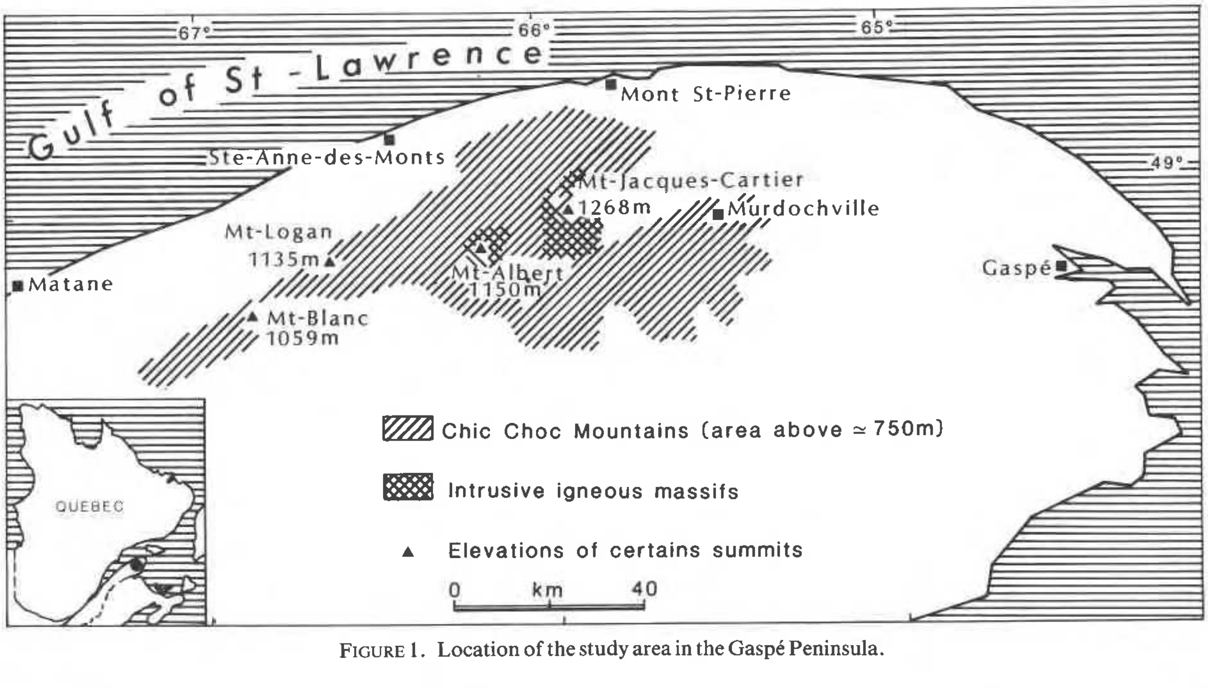

FIGURE 1. Location of the study area in the Gaspé Peninsula.

FIGURE 2. Krümmholz zone on east flank of Mont Jacques-Cartier. Note the stone stream in the foreground. The turf embankment beyond the terminus of the feature is an indicator of gravitational movement of the boulders downslope.

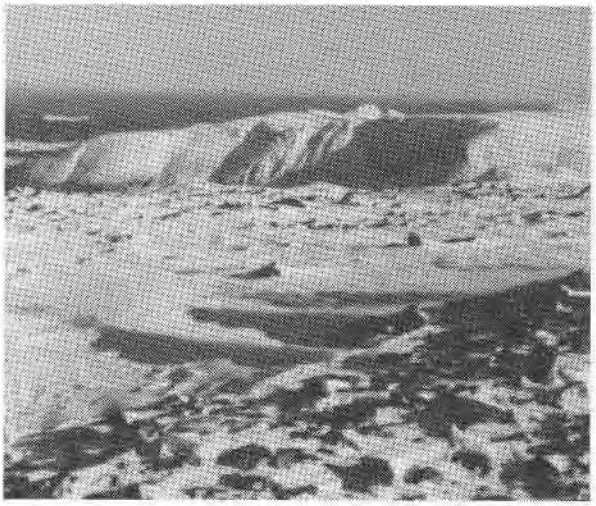

FIGURE 3. Frost-shattered bedrock in the tundra zone on the east flank of the summit dome of Mont Jacques-Cartier.

plateau described by McGerrigle (1952) as the Gaspé Upland. The highest of these summits is Mont Logan situated at 1130 m. Topographic contrasts are accentuated by glacial erosion, which has carved out large cirques and steep-sided valleys on the margins of the highland massifs.

The Tree-line in the Chic-Choc Mountains

Previous permafrost studies have placed considerable emphasis on the role of forest and shrub growth with respect to permafrost distribution and development, through their effects on snow cover and radiation input in summer (Brown 1966; Ives 1974, 1979). Some comments are therefore in order, concerning the altitude and character of the tree-line in the high mountains of Gaspésie. Studies by Boudreau and Payette (1974) in the Mont Jacques-Cartier area have demonstrated that a climatically controlled transition from a subalpine forest dominated by white spruce (*Picea glauca*) to an alpine tundra takes place through a transitional zone of krümmholz. The transitional zone, which extends from about 1000 to 1100 m, is characterized by very tightly packed stands of stunted white spruce (*Picea glauca*) and black spruce (*picea mariana*). As one moves from the true forest to the true tundra, individual stands become increasingly isolated and individual trees more stunted (Figure 2). In the true alpine tundra, the clumps of krümmholz are very sparsely distributed, covering less than one per cent of the terrain. Despite the absence of trees, the surface cover in the tundra zone is very varied, depending to a large extent on the nature of the surface sediment cover. Large areas consist of coarse frost-shattered debris with a sparse moss and lichen cover (Figure 3). Where a finer grained sediment mantle exists, grasses and flowering plants grow, albeit, subject to disturbance associated with frost churning in the soil. In the more humid depressions characterized by late-lying snow patches, a continuous turf cover has been able to develop, giving true alpine meadow characterized by various herbaceous species (Figure 4).

The Mont Albert massif is characterized by a dramatic transition from forest cover to an alpine tundra at 1000 m near the north rim of the plateau. The sharp transition with no change of altitude, the relationship to a lithological boundary between amphibolite to the north and peridotite to the south, and the generally low elevation of the transition, compared with the Mont Jacques-Cartier area, indicates that climate alone is not responsible for the tree-line. The high concentrations of olivine in the soils of the peridotite zone are toxic to tree growth, suggesting that an edaphic contrast is the main reason for the sharp transition from forest to tundra. As a result most of the plateau of Mont Albert is treeless.

In the western zone, very few summits attain the climatically controlled tree-line and most are covered by dense, almost impenetrable, krümmholz. The tundra zone is reached only on the highest and steepest summit domes such as Mont Logan.

In all three zones in the high mountains of Gaspésie, another treeless situation may occur locally, where contemporary or recent geomorphological processes have inhibited colonization by vegetation. Such areas are found generally on and below glacially steepened slopes characterized by cliffs and coarse debris accumulations such as talus cones and rock glaciers.

Climate

Climatic records for this mountainous region are sparse and of short duration. The Meteorological Service of the Ministère des Richesses Naturelles du Québec studied the regional climate of the western Chic-Choc Mountains between 1966 and 1969 by locating numerous semi-automatic stations at various altitudes (Gagnon 1970). Apart from these records, there are data of varying quality from a few isolated stations throughout the mountainous region. This includes records for the summit of Mont Jacques-Cartier (1268 m) between 1943 and 1945, compiled by the Canadian Armed Forces and cited in Boudreau and Payette (1974); for the summit of Mont Logan (1135 m), 55 km to the west, between 1963 and 1973; for the Mines de la Madeleine (850 m), 10 km to the west, between 1974 and 1977; and for Murdochville (550 m), 40 km to the east, between 1952 and 1976.

Among the most significant elements from the point of view of the ground temperature regime, may be cited temperature and precipitation parameters, particularly mean annual air temperature and the build-up of snow cover. The mean annual air temperature for Mont Jacques-Cartier for 1943 to 1945 was $-3°C$. If one takes into account the mean adiabatic lapse rate of $0.6°C/100$ m, calculated very accurately for the region by Gagnon (1970), it is possible to extrapolate the Mont Logan data to the summit of Mont Jacques-Cartier. A mean annual air temperature of $-4.5°C$ is thereby obtained for the latter summit for the decade 1963 to 1973. It can be concluded that the mean annual air temperatures of the Gaspesian summits in the tundra zone are within the approximate range of -3 to $-5°C$.

Gagnon's maps (Gagnon 1970) indicate a total annual precipitation of more than 1600 mm for the summits above 1100 m and an annual snowfall in excess of 6250 mm. The snow cover lasts for 260 to 290 days, disappearing between the 15th and 30th of June. The plateau surfaces above the tree-line are windswept in the winter and snow accumulation is relatively small. Snow surveys were carried out on the summit dome of Mont Jacques-Cartier by a group from the Université de Montréal in the springs of 1978 and 1979, which were years of successively very high and very low snow accumulation in the region. Average snow depths in these two years were 66 and 38 cm respectively. Individual values ranged from a few centimetres to 120 cm for 64 sample points in the two years, variations within each year's sample population being mainly due to topographic irregularities and to contrasts in aspect. Despite these variations, the difference between the snow accumulation in the two years is statistically significant at a confidence level of 99.9 per cent. On the moderate to steep slope on the eastern, leeward side of the summit ridge, snow annually accumulates to a depth of several metres, and may occasionally persist through the summer season into the following winter, as was the case in 1977 (Figure 5). Below the tree-line the krümmholz and subalpine forest are characterized by a thicker snow cover than was observed for the sum-

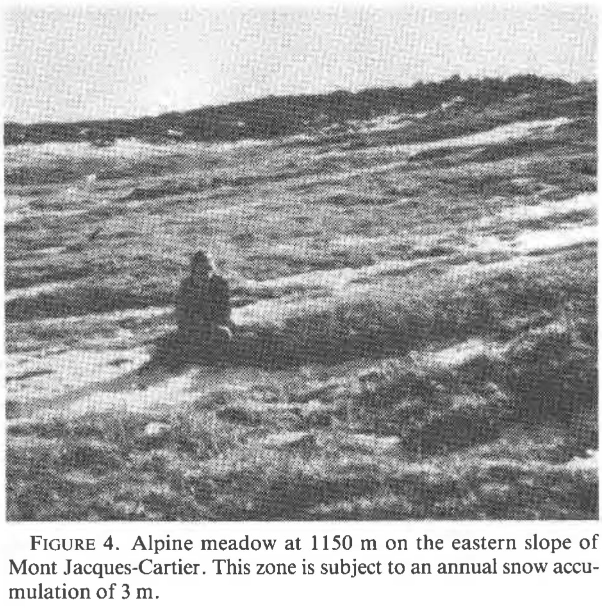

FIGURE 4. Alpine meadow at 1150 m on the eastern slope of Mont Jacques-Cartier. This zone is subject to an annual snow accumulation of 3 m.

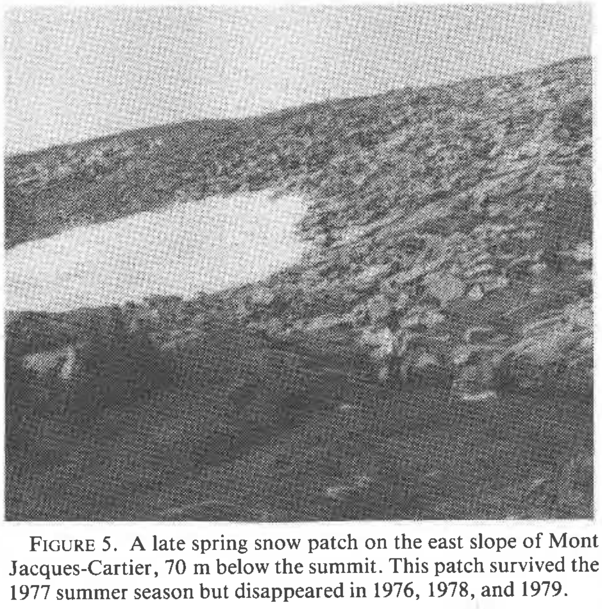

FIGURE 5. A late spring snow patch on the east slope of Mont Jacques-Cartier, 70 m below the summit. This patch survived the 1977 summer season but disappeared in 1976, 1978, and 1979.

mit of Mont Jacques-Cartier in the tundra zone. An eleven-point transect carried out over a distance of 300 m in the Lac à René area, 2 km north of the summit, at an elevation of about 1125 m, in the spring of 1979, gave snow depths ranging from 95 to 235 cm, with a mean depth of 150 cm.

Field Programme

In September 1977, a hole 22 mm in diameter was drilled through 3 m of weathered bedrock, and a further 27 m into the underlying competent bedrock at a site close to the summit of Mont Jacques-Cartier. A multi-thermistor cable 30 m long was installed in the freshly completed water-filled hole, and readings were taken at the time of the installation and throughout the summers of 1978, 1979, and 1980.

A second 30-m cable was installed in a well 15 cm in diameter near the summit of Mont Logan, in the same month, and readings have been taken at intervals since the installation. In addition, sporadic temperature readings were obtained with flexible cables and rigid probes in old drill holes on Mont Notre-Dame, Mont Jacques-Cartier, and Mont Albert.

Thermal conductivity and heat production analyses were carried out on core samples by A.S. Judge, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa.

In an effort to relate the thermal data to snow distribution, in order to determine the probable boundaries of permafrost bodies on Mont Jacques-Cartier, snow surveys were carried out in April 1978 and 1979. In addition, the late-winter thermal regime to the base of the snow pack was ascertained for three contrasting sites.

Finally, the surfaces of three rock glaciers were examined for signs of recent activity and the presence or absence of ice bodies which would reveal the presence of sporadic permafrost well below the regional tree-line.

Derivation of Significant Geothermal Parameters

Temperature profiles have been obtained on twelve occasions over the two-year interval since cable installation at the summit of Mont Jacques-Cartier. To date, all readings have been obtained for spring, summer, and fall conditions, with the exception of two late-winter readings, obtained in April 1979 and March 1980.

Four of these temperature profiles (Figure 6) clearly demonstrate the presence of a permafrost body at the summit of Mont Jacques-Cartier. The drilling process appears to have caused minimal disturbance, and a rapid return to thermal stability is indicated by the convergence of the lower parts of the profiles. The wide variations in the top few metres of the profiles (with the exception of two profiles logged immediately after the cessation of the drilling operation), are related to seasonal temperature fluctuations at the surface.

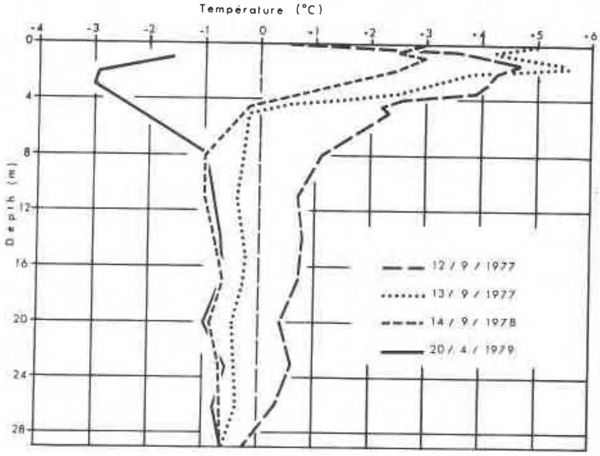

FIGURE 6. Temperature profiles in the 30-m drill-hole at the summit of Mont Jacques-Cartier.

Analysis of all the available data permits definition of several important thermal parameters, which can then be used to derive conclusions on the thickness of the permafrost and the associated active layer, as well as on its spatial extent and contemporaneity. These parameters are the depth of zero annual amplitude, the geothermal gradient, and the mean annual ground surface temperature.

The depth of zero annual amplitude is difficult to estimate precisely due to the limited precision of the temperature bridges used, even when frequently calibrated (± 0.1°C), and due to the lack of winter data, but available logs indicate that 11 to 14 m represents a reasonable approximation. This is a rather shallow depth for bedrock but the insulative role of 3 m of frost-shattered bedrock with the contained voids and fines must be borne in mind.

The geothermal gradient may be calculated directly from the temperature data, or it may be derived indirectly from a number of geothermal parameters. The direct approach simply graphs observed ground temperatures against depths (Figure 7), for the section of the profile XY beyond the depth of zero annual amplitude, revealing a geothermal gradient of 17°C/km (or 0.017 K/m). In the indirect approach, the geothermal gradient must be derived from available estimates of the geothermal flux in the Appalachian structural province, and from analysis of the thermal conductivity of the local bedrock.

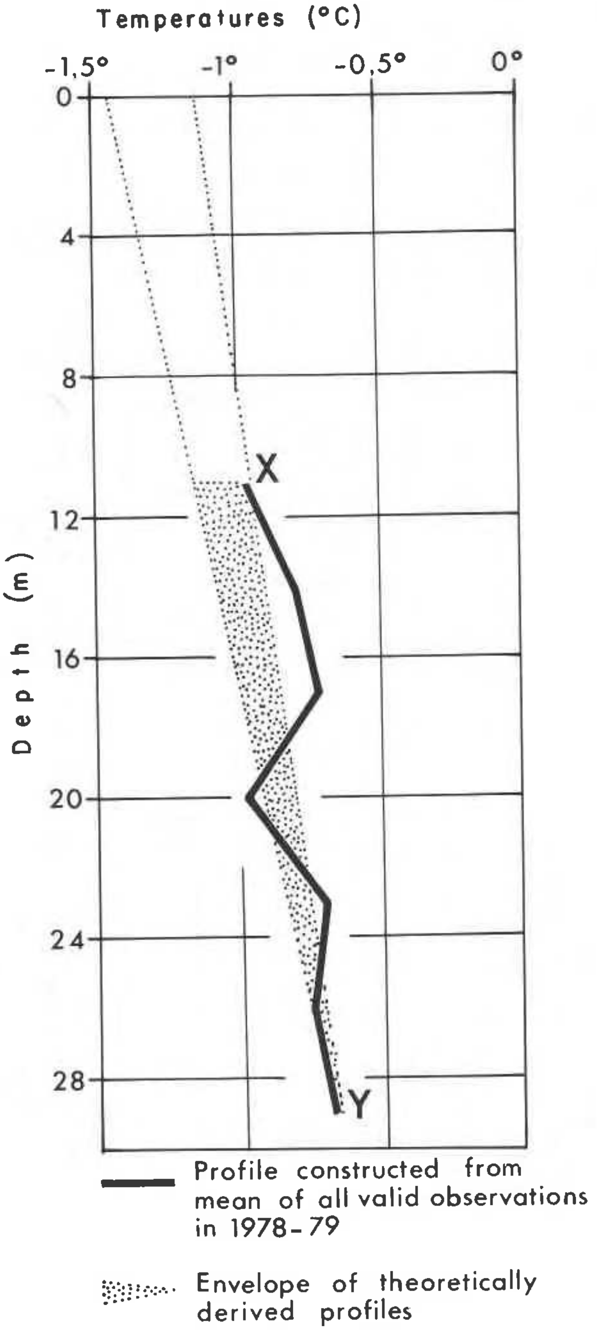

FIGURE 7. Geothermal gradients for the Mont Jacques-Cartier drill-hole between 11 and 29 m.

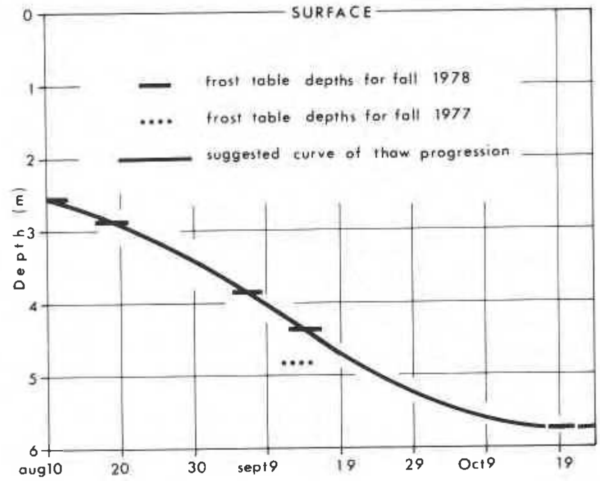

FIGURE 8. Active layer progression during the fall of 1978 at the summit of Mont Jacques-Cartier.

The geothermal flux is the heat flow from the mantle through the crustal rocks to the surface, supplemented by heat production due to radioactive decay of elements within the crustal rocks. Broad limits of 48 to 64 mW/m^2 for the geothermal flux for the Appalachian structural province can be estimated from data compiled by Hyndman *et al.* (1979) given measured heat production values of 1.97 W/m^3 for a core sample from the Mont Jacques-Cartier drill-hole (Figure 8). Thermal conductivity values for core samples of the crystalline bedrock from the Mont Jacques-Cartier drill-hole range from values of 2.47–2.95 W/m · K with a mean value of 2.65 W/m · K.

The geothermal gradient is then calculated by dividing the estimated geothermal flux (in mW/m^2) by the measured thermal conductivity of samples (in W/m · K) (Judge 1973).

With the given ranges of values for thermal conductivity and geothermal flux, maximum and minimum values for geothermal gradient are 26 and 16°C/km respectively.

This indirectly derived range of geothermal gradients when plotted linearly (*see* Figure 7) shows a general correspondence with the directly observed temperature gradient. The small-scale fluctuations evident in the latter are the result of small cumulative shifts in ground surface temperatures in a positive or negative sense over time spans exceeding one year, and are, perhaps, also the result of unrecorded variations in thermal conductivity.

A mean annual ground surface temperature below 0°C, measured over several years, is critical for the existence of contemporary permafrost. It was felt that, if this parameter could be estimated for the summit of Mont Jacques-Cartier, reasonable projections to lower altitudes, using statistically determined lapse rates, could then form a basis for establishing lower altitudinal limits of permafrost for similar terrain conditions.

The very short-term record of surface temperatures at the cable site, coupled with the lack of winter data do not permit direct calculation of the mean annual ground surface temperature. Furthermore, the latter cannot be derived indirectly from air temperature data due to the absence of detailed information on microclimatic factors such as albedo, snow cover, and evapotranspirative effects on heat exchange.

The only recourse, therefore, is to the subsurface temperature data. The previously determined mean, maximum, and minimum geothermal gradients for the lower section of the drill-hole may reasonably be extrapolated upwards to the surface through the zone subject to seasonal temperature fluctuations. If no correction to these gradients is made to allow for a change in thermal conductivity associated with the 3 m of frost shattered debris at the surface, maximum and minimum values of −1.1 and −1.4°C are obtained (*see* Figure 7). If allowance is made for a reduction in thermal conductivity by a very liberal estimate of 50 per cent for this highest zone due to an entrapped mixture of air, fine debris, and moisture, the values suffer an insignificant reduction of about 0.1°C. Thus, within reasonable error limits, a mean annual ground surface temperature of −1 to −1.5°C can be assessed for the summit plateau of Mont Jacques-Cartier. This range of values is 2 to 3.5°C higher than the mean annual air temperatures for the site derived earlier in this paper.

Thickness of the Active Layer and the Contemporary Permafrost

Temperature observations taken through the fall of 1978 indicate downward progression of the thaw zone to a depth of almost 6 m in late October (*see* Figure 8). The surprising element here is the relatively rapid late fall progression of the thaw front, despite the small positive, and sometimes negative, heat flux into the ground after early September. The explanation is probably to be found in the passage of the thaw front in the fall, from frost-shattered bedrock, with a fine sediment fraction and a moderate ice content, into competent bedrock, with a very low moisture content. The phase change from ice to water then becomes of insignificant importance in absorbing latent heat, and hence in retarding penetration of the thaw front. No fall readings were available after late October and so 6 m represents only a reasonable minimum value for the active layer thickness at the site.

Reasonable values of 52 to 65 m for the base of the permafrost are obtained when the indirectly derived geothermal gradients are linearly extrapolated downwards from the observed temperature at the base of

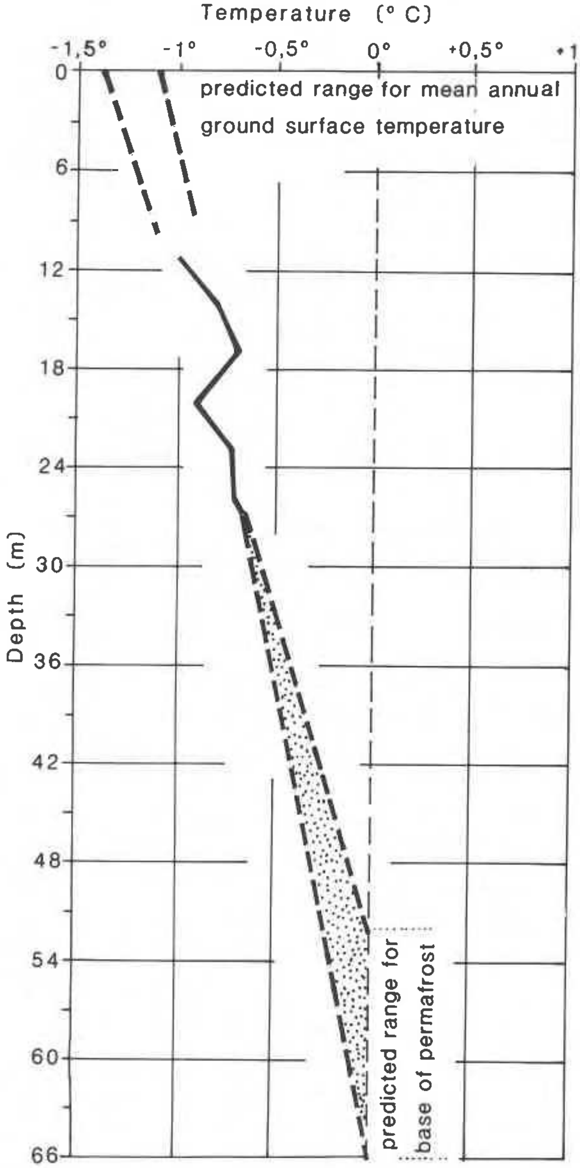

FIGURE 9. Extrapolation of geothermal gradients downwards to the base of the permafrost body and upwards to the ground surface for the Mont Jacques-Cartier site.

the hole (Figure 9).

Undoubtedly some error is introduced into such extrapolations due to perturbations in the temperature profiles related to recent climatic change or to variations in thermal conductivity. However available climatic data from nearby Murdochville shows no evidence of a cumulative shift in air temperatures or snowfall values and, by implication, in ground surface temperatures over the last 25 years. This is certainly valid evidence in support of the suggested linearity of the temperature gradients for the upper few tens of metres at the Mont Jacques-Cartier site, well beyond the range of extrapolation to the suggested permafrost base. Thermal conductivity variations over such a short vertical range are also likely to be slight as there are no major lithological discontinuities in the vicinity of the drill-hole.

Thus, from information on the active layer depth and the permafrost base it can be concluded that Mont Jacques-Cartier permafrost body has a thickness beneath the plateau summit of 45 to 60 m.

The available evidence indicates clearly that the permafrost is contemporary and not relict in nature. In the first place, the permafrost table is only about 6 m below the surface. If the permafrost body had developed only in response to a colder phase than that prevailing at the present day (such as during the historically recent "little ice age") thermal diffusivity of the bedrock would have been sufficiently great for a rapid descent of the permafrost table, far beyond 6 m, within only a few decades of the onset of a warming trend. In the second place, the mean annual surface temperature of -1 to $-1.5°C$ deduced above for the site, and the mean annual air temperature of -3 to $-5°C$, clearly support the conclusion that the present day climate favours contemporary permafrost on the summit plateau.

Spatial Distribution of Permafrost in the Chic-Choc Mountains in Relation to Climatic and Terrain Factors

If the adiabatic lapse rate of 0.6°C/100 m is used in association with the derived mean annual surface temperature at the summit of Mont Jacques-Cartier to assess the lower limits of permafrost in the Chic Choc Mountains, a hypothetical altitude of 1000 to 1100 m above sea level is obtained. This would permit the existence of many small permafrost bodies but would be a valid conclusion only for surfaces where terrain factors resemble very closely those of the Mont Jacques-Cartier summit plateau.

Indeed for the Gaspésie summits, where mean annual air temperatures are only marginally below 0°C, the presence or absence of contemporary permafrost at a given site becomes mainly a function of the specific micro-climatic conditions induced by various terrain factors. The latter include aspect, topography, vegetation cover, soil cover, and winter snow cover. Whilst not in a position to evaluate quantitatively the role of all those factors on the annual heat budget it is clear that the variability in thickness of the snow cover is largely responsible for lateral variations and indeed discontinuities in permafrost bodies. Windswept surfaces such as those of the Mont Jacques-Cartier summit plateau are not usually very extensive and exhibit considerable topographic contrasts around the margins, leading to an insulative snow blanket of variable thickness. An even more important cause of snow cover variations is the rapid altitudinal transition from tundra through krümmholz to forest vegetation. As cited earlier, snow depths increase rapidly, three- to four-fold, as one passes below the tree-line. It therefore seems reasonable at first glance to use the tree-line as an index to aid in the regional mapping of permafrost distribution, rather than simply relying on the given altitude of 1000 to 1100 m derived from ground temperature at a single site.

Caution is required, however, in such an exercise. Permafrost mapping using the tree-line cannot be carried out indiscriminately without regard for local topographical and geological conditions. In some instances these conditions suggest that non permafrost zones exist above the local tree-line. In other instances, on the contrary, small permafrost bodies appear to exist well below the tree-line.

Non-Permafrost Conditions in Treeless Zones

With regard to non-permafrost conditions in treeless zones, the summit plateaux of Mont Jacques-Cartier and Mont Albert illustrate the range of possibilities that exist. The summit dome of Mont Jacques-Cartier in relation to a proposed permafrost boundary is shown in Figure 10. The surface conditions of the plateau are maintained with considerable uniformity in a long, narrow zone extending from NNE to SSW, but elevations drop off rapidly towards the ESE, where an important lee situation, favourable to a very deep winter snow cover, exists just below the summit dome. In March 1980, the acumulation attained a maximum depth of 4 m. The zone of heavy snow accumulation favours higher sub-nival winter temperatures. In fact, the profiles (Figure 11) suggest late winter ground temperatures only barely below 0°C when the seasonal cold wave would be expected to have penetrated to the base of the snow pack. The snow depth obviously far exceeds the critical depth for permafrost. This critical depth has still to be calculated for the site, but, based on studies by Nicholson (1979) carried out in the climatically similar plateau region north-west of Schefferville, a depth of about 0.75 to 1 m may be sufficient to cause taliks provided that the topographic hollows are sufficiently large in their lateral dimension.

The aspect and moderate inclination of this south-eastern flank of Mont Jacques-Cartier also favour relatively high ground temperatures in summer

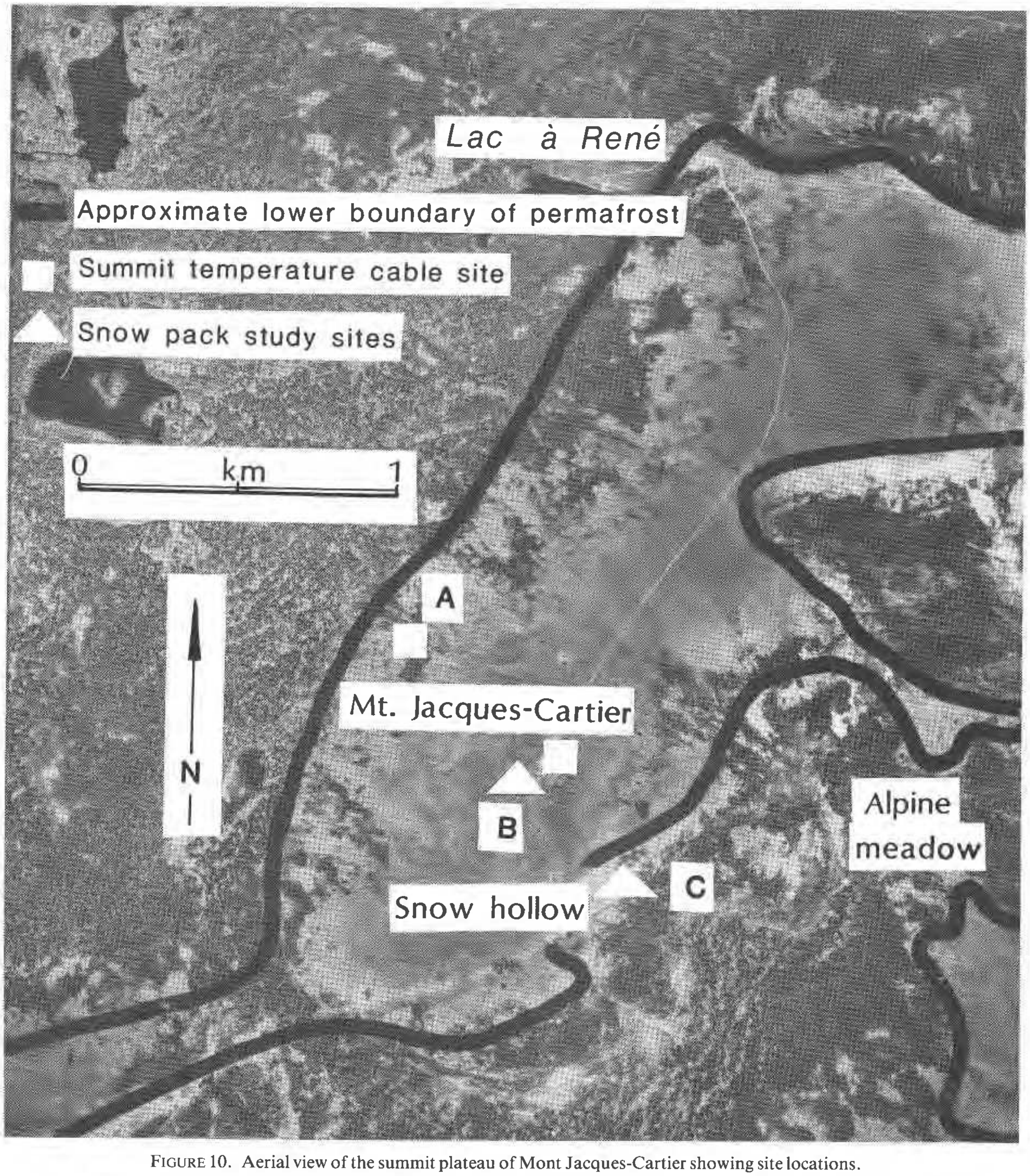

FIGURE 10. Aerial view of the summit plateau of Mont Jacques-Cartier showing site locations.

(except where the snowbanks are deepest and persist until mid or late summer). Thus, permafrost is clearly absent from this zone, despite its high altitude. The total absence of ground ice right to the base of a pit 4 m deep, excavated by Payette (*pers. commun.*) beneath an alpine meadow on this slope late in August 1978, supports this conclusion.

For the more exposed northern, north-western, and south-western slopes the permafrost boundary has been traced (*see* Figure 10) along a line where the krümmholz becomes relatively continuous. However, on the steep slopes of cirques east of the Mont

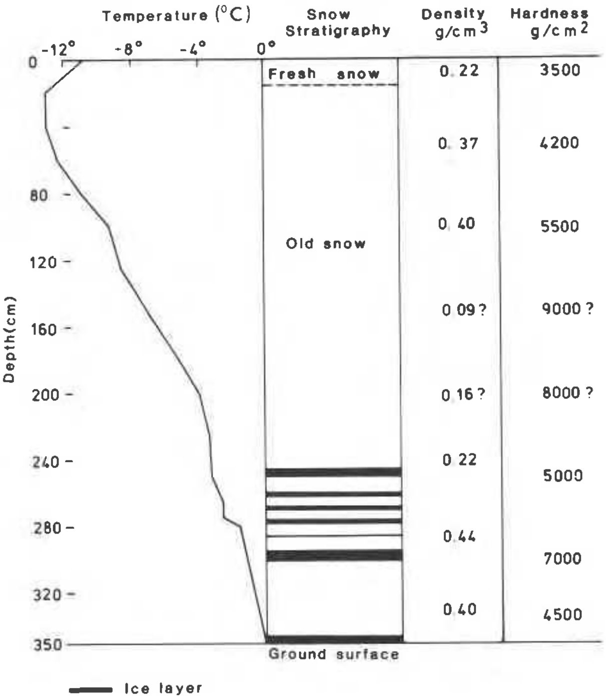

FIGURE 11. Temperature profiles and stratigraphy of the snow pack at site C in a topographic hollow to the east of the summit of Mont Jacques-Cartier on March 20th, 1980.

Jacques-Cartier massif, the permafrost boundary was traced well above the local tree-line. This is because these slopes are characterised by a rather mobile and coarse-textured regolith which does not permit rapid colonisation by vegetation. This consideration is a valid one, of course, for all steep slopes throughout the Chic-Choc Mountains.

The plateau of Mont Albert illustrates in striking fashion the existence of a large treeless area, extending well below the permafrost boundary of 1000 to 1100 m established from the Mont Jacques-Cartier data. On Mont Albert the tree-line is situated some 200 m below the regional tree-line on account of the toxic effect on tree vegetation of the local olivine-rich bedrock. Temperature profiles obtained for four old drill-holes in a col at 1000 m between the north and south summits (Figure 12) indicate that permafrost is absent on the lower part of the plateau. Widespread permafrost does probably exist, however, at the highest altitudes on the plateau, beneath the wind-blasted south summit, at 1150 m.

Permafrost Islands in the Forest Zone.

With regard to the existence of permafrost islands in the forest zone, well below the tree-line, the authors considered the case of coarse boulder accumulations at the base of steep slopes, in glacially carved cirques and valleys, and identified a number of

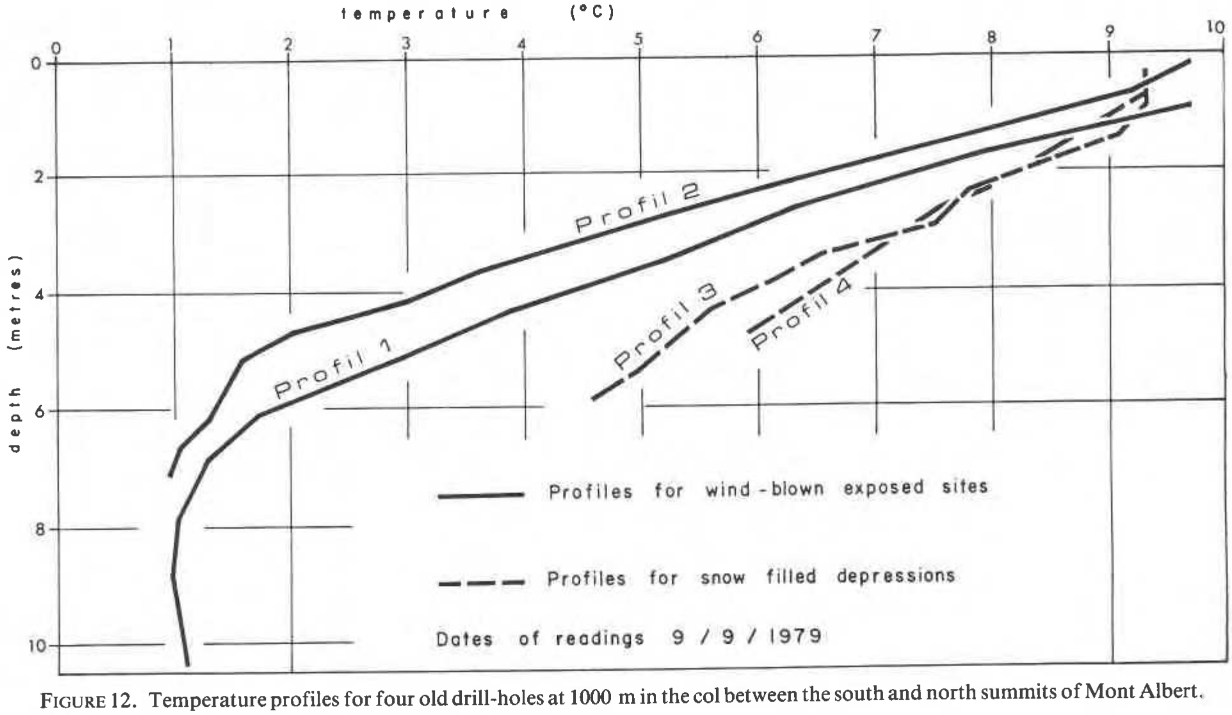

FIGURE 12. Temperature profiles for four old drill-holes at 1000 m in the col between the south and north summits of Mont Albert.

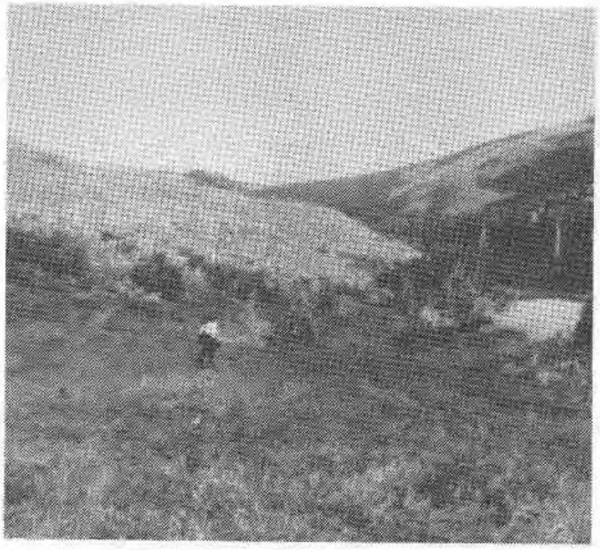

FIGURE 13. Rock glacier like accumulation below the north-facing slope of one of the cirques on the eastern margins of the McGerrigle massif, approximately 4 km to the north of Mont Jacques-Cartier.

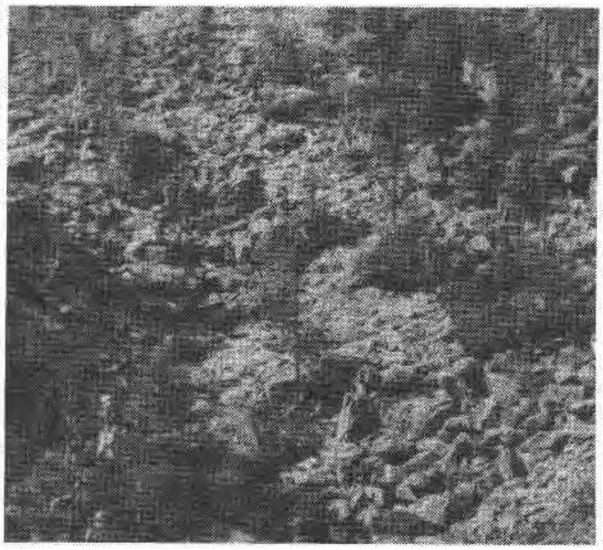

FIGURE 14. Surface of rock glacier on the east side of the Cascapedia Valley on the Trans-Gaspé Highway. The temperature profile (*see* Figure 15) was obtained at the bottom of the thermokarst hollow in the foreground.

these debris accumulations as rock glaciers (Figures 13 and 14). They were initially built up by rock-falls, avalanches, debris flows, and debris creep and perhaps, in some instances, as lateral moraines in the late glacial and postglacial period. The lobate form of the rock glaciers and the fact that they frequently extend out over the cirque floors suggests that they have been quite active in the Holocene period.

Reconnaissance studies carried out on three of these rock glaciers in the summer of 1980 provided several indications that permafrost lenses, either relict or contemporary in nature, exist in the interior of many of these debris accumulations.

The toe of one of these rock glaciers, is situated at only 250 m in altitude on the east side of the Cascapedia Valley on the Trans-Gaspésie highway. A large ice lens about 5 to 10 m thick was exposed in 1979 by a Québec Ministry of Transport excavation in the front. By the summer of 1980, the ice lens had melted back and was no longer visible. A short temperature profile obtained in late July, however, in the interstices between boulders at the base of a thermokarst hollow on the rock glacier surface suggests the proximity of a frozen body to the surface (Figure 15). This discovery of a thick ice body at such a low altitude substantiates McGerrigle's discovery of frost-bound talus at an elevation of only 297 m, alluded to at the beginning of this paper (McGerrigle 1952). It is also very interesting in the light of the recent discovery, through deep drilling by Hydro-Québec personnel, of a thick zone of buried interstitial ice in a rock glacier at 540 m in the Parc des Laurentides, north of Québec City (Grumich and Thibeault 1979).

In the case of the two other rock glaciers located at a much higher altitude (about 800 m), permafrost islands are even more likely to be present although deep excavations are not available to reveal the evidence. Except in one instance where buried ice was

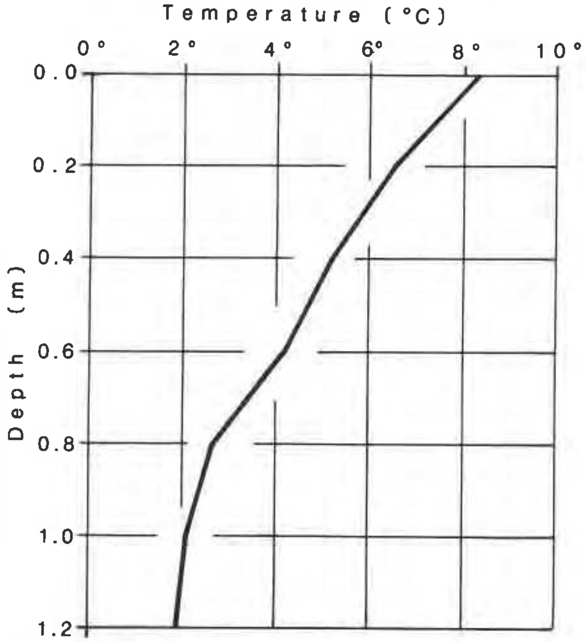

FIGURE 15. Temperature profile in the interstices between boulders on the surface of the rock glacier shown in Figure 14.

observed within 2 m of the surface and might have been seasonal, the evidence for ice bodies is circumstantial. It is tied to indices of recent activity. Variability of the forest cover and lichen cover on the surfaces reveal that some zones are more active than others. In places, sharp contrasts in lichen cover corresponding to topographic breaks suggest overriding of older lobes by lobes active more recently. Excavations in the toe of the rock glacier (*see* Figure 13) revealed recent lichen kill on boulder surfaces and boulders which had clearly been overturned by recent advance of the rock glacier toe.

Permafrost Map of the Chic-Choc Mountains

Despite these topographically and lithologically induced irregularities, the climatically controlled treeline does give a reasonable idea of regional permafrost distribution (Figure 16). The Alpine permafrost in the Chic-Choc Mountains is obviously very discontinuous in nature. Because the individual permafrost bodies are relatively thin, never exceeding the thickness of 60 m predicted for Mont Jacques-Cartier, spatial transitions from non-permafrost to permafrost conditions are likely to be very rapid, reflecting very faithfully the topographic and vegetation transitions visible at the surface.

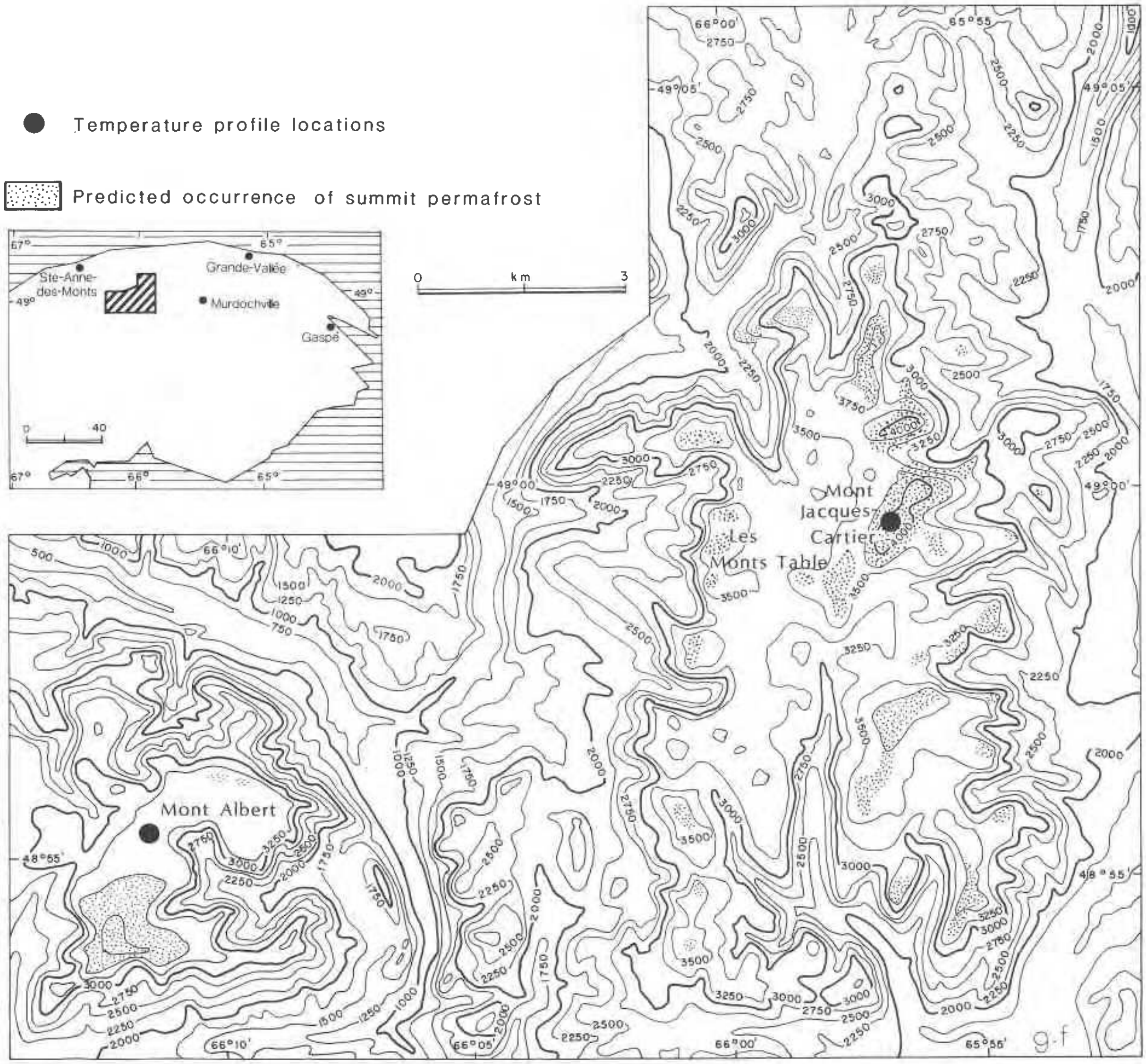

FIGURE 16. Probable distribution of extensive permafrost bodies in the summit regions of the eastern Chic-Choc Mountains, Gaspésie.

Permafrost Elsewhere in the Appalachian Region

Whilst the Chic-Choc Mountains probably possess the most extensive and thickest bodies of permafrost in the Appalachian region, other summits in New England and in Newfoundland protrude above the tree-line, and a few of those summits may be underlain by permafrost. In New England, this is definitely the case for Mount Washington, in the Presidential Range of the White Mountains of New Hampshire, which attains an elevation of 1915 m. There, the mean annual air temperature is −2.8°C, and below-freezing temperatures were measured at considerable depths in a deep well drilled at the summit (Howe 1971). Mount Katahdin in Maine, and Mount Marcy, in the Adirondack Mountains in New York State, the only two other mountain areas of New England which attain elevations in excess of 1500 m, are, nonetheless, 300 m below the altitude of Mount Washington, and permafrost probably does not underlie their summits. In Long Range, in western Newfoundland, initial measurements of ground temperatures have been obtained by Brookes and Brown (*pers. commun.*) for a drill-hole 18 m deep at an elevation of 550 m. Ground temperatures decreased steadily with depth to 1.5°C at the base of the drill-hole, suggesting that the freezing point may be very closely approached at slightly greater depths, and therefore, that the highest summits, at altitudes of almost 800 m, may be underlain by permafrost.

Conclusion

A permafrost body, approximately 60 m thick, underlies the summit of Mont Jacques-Cartier in the Chic-Choc Mountains, Gaspésie. Temperature measurements and heat production and conductivity data, available to a depth of 29 m, indicate that the permafrost is contemporary and that a mean surface temperature of −1 to −1.5°C can be estimated. The altitude, extent, and probable form of the permafrost body on Mont Jacques-Cartier was outlined on the basis of temperature lapse rates and terrain factors. This type of analysis was then applied throughout the region, leading to a map of the treeless summits of the eastern Chic-Chocs which are potentially underlain by permafrost. For such exposed situations, 1000 to 1100 m appears to be the critical lower limit for extensive permafrost. Sporadic areas of thin permafrost do exist below the regional limit, in several coarse debris accumulations or rock glaciers, at sites receiving little insolation because of their northerly aspect or their situation at the base of deeply incised valleys.

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References

BOUDREAU, F. ET PAYETTE, S. 1974. Le mont Jacques-Cartier, Parc de la Gaspésie, De toute urgence, Québec. vol. 5, no. 1, pp. 3–18.

BROWN, R.J.E. 1966. Influence of vegetation on permafrost. *In*: Proc. 1st Int. Conf. on Permafrost, Nat. Acad. Sci. Nat. Res. Counc. Pub. 1287, pp. 20–25.

DE RÖMER, H.S. 1977. Région des Monts McGerrigle. Rapport géologique no. 174, Min. des Richesses Naturelles, Québec, 233 p.

GAGNON, R.M. 1970. Climat des Chic-Chocs. M.P. 36, Service de la Météorologie, Min. des Richesses Naturelles, Québec, 103 p.

GRAY, J.T. AND BROWN, R.J.E. 1979. Permafrost presence and distribution in the Chic-Choc Mountains, Gaspésie, Québec. Geogr. Phys. Quat., vol. 33, nos. 3-4, pp. 299–316.

GRUMICH, J. ET THIBEAULT, L. 1979. Projet Lac Louis — centrale à réserve pompée: Investigation géologique 1977-78. Rapport du Service de géologie et géotechnique, Hydro-Québec, Place Dupuis, Montréal.

HOWE, J. 1971. Temperature readings in test bore holes. Mount Washington Observatory News Bull., vol. 12, no. 2, pp. 37–40.

HYNDMAN, R.D., JESSOP, A.M., AND JUDGE, A.S. 1979. Heat flow in the Maritime Provinces of Canada. Can. J. Earth Sci., vol. 16, no. 6, pp. 1154–1165.

IVES, J.D. 1974. Permafrost. *In*: Arctic and Alpine Environments. Ives, J.D. and Barry, R.G. (eds.), Methuen, London, pp. 159–194.

———. 1979. A proposed history of permafrost development in Labrador–Ungava. Geogr. Phys. Quat., vol. 33, nos. 3-4, pp. 233–244.

JUDGE, A.S. 1973. The prediction of permafrost thickness. Can. Geotech. J. vol. 10, no. 1, pp. 1–11.

MCGERRIGLE, J.W. 1952. Pleistocene glaciation of Gaspé Peninsula. Trans. Roy. Soc. Can., vol. 66, series 111, pp. 37–51.

NICHOLSON, F.H. 1979. Permafrost spatial and temporal variations near Schefferville, Nouveau-Québec. Geog. Phys. Quat., vol. 33, nos. 3-4, pp. 265–278.