Géographie physique et Quaternaire

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Vergleich thermaler und radaraktiver Schichten Messungs Techniken in der Leaf-Bay Gegend, Neues Québec

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Volume 33, Number 3-4, 1979

URI: https://id.erudit.org/iderudit/1000367ar
DOI: https://doi.org/10.7202/1000367ar

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Publisher(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (print)
1492-143X (digital)

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Cite this article

Pilon, J. A., Annan, A. P., Davis, J. L. & Gray, J. T. (1979). Comparison of thermal and radar active layer measurement techniques in the Leaf Bay area, Nouveau-Québec. *Géographie physique et Quaternaire*, *33*(3-4), 317–326. https://doi.org/10.7202/1000367ar

Article abstract

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Géogr. phys. Quat., 1979, vol. XXXIII, nos 3-4, p. 317-326.

COMPARISON OF THERMAL AND RADAR ACTIVE LAYER MEASUREMENT TECHNIQUES IN THE LEAF BAY AREA, NOUVEAU-QUÉBEC

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ABSTRACT Continuous profiles of the frost table for a series of traverses in unconsolidated sediments in the Leaf Bay area, Ungava, were obtained using an all terrain vehicle borne impulse radar system. The results correlate extremely well with data obtained by the insertion of rigid temperature probes at frequent intervals along the traverses. Each of the two systems has its own particular advantages and disadvantages. The radar profiling system provides more continuous information and can be carried out more rapidly than the system using the temperature probes. However, it requires some local ground control as regards soil moisture profiles and values for soil texture and soil temperature. A definite advantage of the rigid temperature probe is that it produces a temperature curve as a by-product and this can be used to assess the effect of different terrain factors on heat flow in the soil. It is, furthermore, a much cheaper and less bulky apparatus than the radar equipment, requiring no auxiliary logistical support for field use. Neither method can be applied universally for thaw zone and active layer determination. The trials in the tidal flats were a failure, the earth materials being too stony for the temperature probe and the salt water in the soil not permitting proper signal propagation for the radar. Neither method is suitable for penetrating bedrock and, in such a case, reliance has to be placed on temperature measurements in drillholes.

RÉSUMÉ *Comparaison de deux méthodes de mesure de la couche active dans la région de la baie aux Feuilles, Nouveau-Québec.* Des profils continus du niveau supérieur du pergélisol dans des sédiments non consolidés le long d'un certain nombre de transects ont été obtenus à l'aide d'un appareil radar léger et de transport facile. Les résultats obtenus concordent bien avec les données recueillies par des sondes rigides installées à intervalles rapprochés le long des transects. Chacune des deux méthodes présentent des avantages et des désavantages. Le radar fournit des renseignements plus rapidement et sur une base plus continue que les sondes. Cependant cette technique doit être accompagnée de vérifications supplémentaires: profil d'humidité du sol, analyses granulométriques et mesures de température. La sonde est beaucoup plus utile à cet égard puisqu'elle fournit également un profil thermique qui permet d'évaluer l'influence de certains facteurs sur le flux de chaleur issu du sous-sol. Les sondes sont également moins chères et de manipulation plus facile que l'appareil radar puisqu'elles ne requièrent pas de moyens logistiques compliqués. Aucune des deux méthodes, cependant, ne peut servir dans tous les cas à délimiter la couche active. Les essais dans les battures, par exemple, ont échoué, le sol étant trop rocheux pour les sondes et l'eau salée ayant gêné la propagation des signaux de radar. En outre, aucune des deux méthodes n'est efficace dans la roche en place; il faut alors s'en tenir aux mesures de température qui proviennent des trous de forage.

ZUSAMMENFASSUNG *Vergleich thermaler und radaraktiver Schichten Messungs Techniken in der Leaf-Bay Gegend, Neues Québec.* Fortlaufende Profile einer Serie von Querschnitten in losen Sedimenten in der Leaf-Bay Gegend, Ungava, erhielt man durch den Gebrauch eines Impuls-Radarsystems von einem Geländefahrzeug aus. Die resultate stimmen sehr genau mit den von steifen Temperatursonden erhaltenen Daten überein. Jedes der beiden Systeme hat seine Vor- und Nachteile. Das Radar-Profil-System ergibt eine mehr fortlaufende Information und kann schneller funktionieren als ein System mit Temperatursonden. Jedoch benötigt es etwas örtliche Bodenkontrolle, wie Bodenfeuchtigkeitsprofile und Angaben über Bodenbeschaffenheit und-temperatur. Ein grosser Vorteil der steifen Temperatursonde ist die so erhaltene Temperaturkurve, die zur Bestimmung des Einflusses von verschiedenen Bodenfaktoren auf die Wärmebewegung im Boden dienen kann. Es ist überdies ein viel billigerer und weniger unhandlicher Apparat als die Radarausrüstung, der kein besonderes Transportmittel für seinen Gebrauch benötigt. Keine der beiden Methoden lässt sich universal zur Bestimmung der Auftauzone und des Auftaubodens anwenden. Die Versuche im Wattenmeer waren ein Fehlschlag, das Erdmaterial war zu steinig für die Temperatursonde und das Salzwasser im Boden liess eine angemessene Signalfortpflanzung des Radars nicht zu. Keine der beiden Methoden eignet sich für Felsen, in diesem Falle muss man auf Temperaturmessungen in Bohrlöchern zurückgreifen.

INTRODUCTION

For the past three years, an active layer development study in Leaf Bay has been conducted by J. A. Pilon as part of a doctoral project under the direction of J. Gray, Département de Géographie, Université de Montréal, Québec. One of the objectives was to obtain profiles of active layer depth through various geomorphological units. These profiles were obtained at isolated locations through the use of the DREO developed rigid temperature probe (PICHETTE and PILON, 1978). At the completion of the operation, a certain amount of uncertainty remained as to the accuracy of the active layer portrayal in a spatial sense. A method was sought that would generate a continuous profile of the frost table which could then be used to assess the spatial representativity of a limited number of active layer measurements measured at discrete points using the temperature probes. In the spring of 1977, discussions with A. P. Annan and J. L. Davis of the Resource Geophysics and Geochemistry Division, Geological Survey of Canada, led to consideration of the use of VHF impulse radar method (ANNAN *et al.*, 1975a, 1975b; ANNAN and DAVIS, 1976; DAVIS *et al.*, 1976; ANNAN and DAVIS, 1978). A field experiment was carried out in early August 1977 and this paper presents the main results of this comparative analysis.

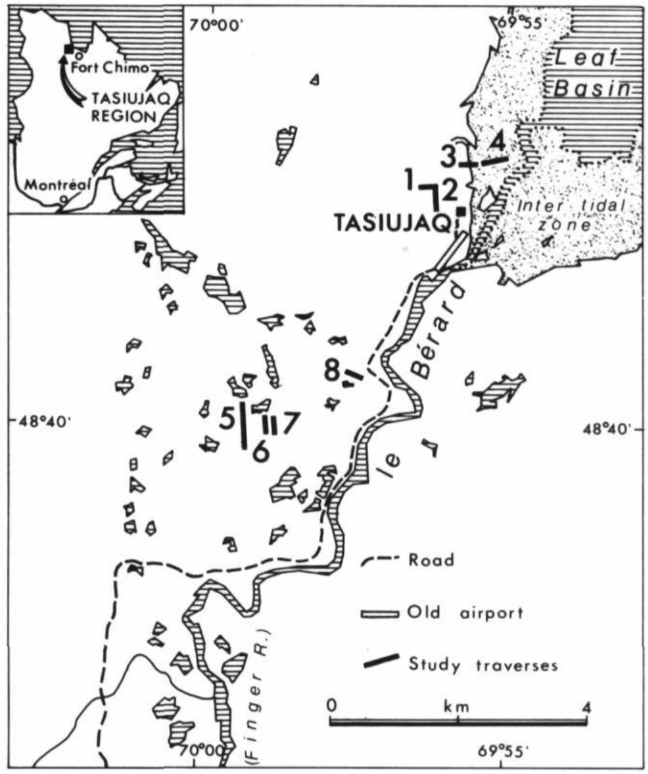


FIGURE 1. Location of field research, with geophysical traverses shown.
Localisation de la région étudiée et sites des transects.

REGIONAL SETTING

The field area is situated approximately 110 km northwest of Fort Chimo in the tidal estuary of the Leaf River known as the Leaf Basin. A map of the area is shown in Figure 1.

Geologically, the estuary of the Leaf River traverses the north-south trending sedimentary and volcanic rocks of the Labrador Trough, which include rich iron, copper and nickel formations. The topography follows the structural trend, long north-south trending ridges, 100-300 m in elevation, alternating with wide lake studded valleys. The lower parts of the valley tributary to Leaf Bay lie below high tide level and form long inlets or bays.

The area studied lies in the tundra zone approximately 50 km north of the treeline in the Labrador Trough. In detail the zone straddles HARE's (1959) subclasses of sedge tundra in the wide valleys and rock lichen tundra on the better drained slopes and summits of the ridges.

No climatic information is available for the immediate vicinity of Leaf Bay but certain facts can be inferred from statistics available for the Fort Chimo weather station, 100 km to the southeast, and from a temporary weather station at Payne Bay, 160 km to the north. The mean annual air temperature for Tasiujaq, on Leaf Basin, probably lies between the figures of −5°C and −7°C recorded for Fort Chimo and Payne Bay respectively. Mean total precipitation and snowfall figures are very difficult to interpolate due to great local variability. Comparison of snow survey data from Leaf Bay and Fort Chimo for the spring of 1977 suggest that the long term snowfall and total precipitation water equivalent figures of 237 cm and 48 cm at Fort Chimo considerably exceed the long term values for Leaf Bay. Previous studies by GRAY and PILON (1976) have determined that permafrost is everywhere present in terrestrial situations, and exceeds 200 m in thickness in exposed localities (GRAY and PILON, 1978; GRAY, PILON and POITEVIN, 1979).

The surficial materials in the area are very much influenced by glacial and periglacial events and comprise the following major classes of importance to the active layer study: 1) wave washed bedrock usually found on moderate to steep slopes below the marine limit of circa 180 m above mean sea level; 2) till mantled plateaux and slopes — subject to varying degrees of modification since deposition, by solifluction, and/or wave washing; 3) silty clays of marine origin on the valley floors; 4) raised beaches composed of sand and gravel; 5) sands and gravels of deltaic and floodplain origin; 6) intertidal mud flats strewn with boulders; 7) organic deposits (represented by peat hummocks).

FIELD METHODS

The equipment used for field work to obtain the active layer temperature profile was the DREO developed rigid soil temperature probe. It consisted of a small diameter (7 mm) long (150 cm) stainless steel tube with a removable point as illustrated in Figures 2 and 3. A thermistor bead is embedded at the end of the tip to sense the ambient temperature. The probes were used in conjunction with an Atkins direct temperature reading Wheatstone Bridge, calibrated in 1/10°C, to obtain the temperature profile. The probes are pushed 1 cm into the ground, left to stabilize (*circa* 45 seconds) at one level and then pushed in by successive increments of 10 cm until the tip reaches the frost level. A soil temperature profile is thus obtained. In three years of field use, experience has shown that it took an exceptionally stony soil to render the use of these probes impractical. In such situations, however, the profiles can be linearly extrapolated provided that data is available at least beyond the diurnal fluctuation zone (less than 20% of the profiles required such extrapolation).

The radar data were obtained through the use of an impulse radar system constructed by Geophysical Survey Systems Inc. A block diagram of the system is shown in Figure 4. A clock circuit with a 50 KHz repetition rate drives an impulse voltage source generating 70 volt impulses with a 500 MHz bandwidth. The impulses are fed to the transmitting (Tx) antenna and radiated after modification by the antenna spectral characteristics. The antenna transforms the impulse into a wavelet with centre frequency of about 300 MHz. The peak radiated power is about 5 watts and the dynamic range of the system is about 80 dB. Part of the radiated signal penetrates into the ground and is either reflected, scattered or absorbed by the earth materials. The amount of the signal reflected back to the surface is related to the electric properties of these earth materials (ANNAN and DAVIS, 1978). The signal at the receiving (Rx) antenna is composed of energy radiated directly from the Tx antenna to the Rx antenna and energy re-radiated by surface or subsurface scattering structures. The received signal is fed to a sampling head which uses the repetitive nature of the signal to slow down the VHF signal to an audio frequency fascimile. The low frequency signal is then displayed on an oscilloscope and a graphic recorder. The data are also recorded on an instrumentation tape recorder for future replay and data enhancement.

The location of eight geophysical traverses carried out using this system are shown in Figure 1. For ease of operation, the Tx and Rx antennas were rigidly mounted on a toboggan and towed over the ground. The antennas were housed in the two boxes on the toboggan. The antenna separation was 30 cm from centre to centre. The electronics and recording equipment were mounted in an all-terrain trailer. In this fashion, several hundred meters of line at different sites could be profiled in a day.

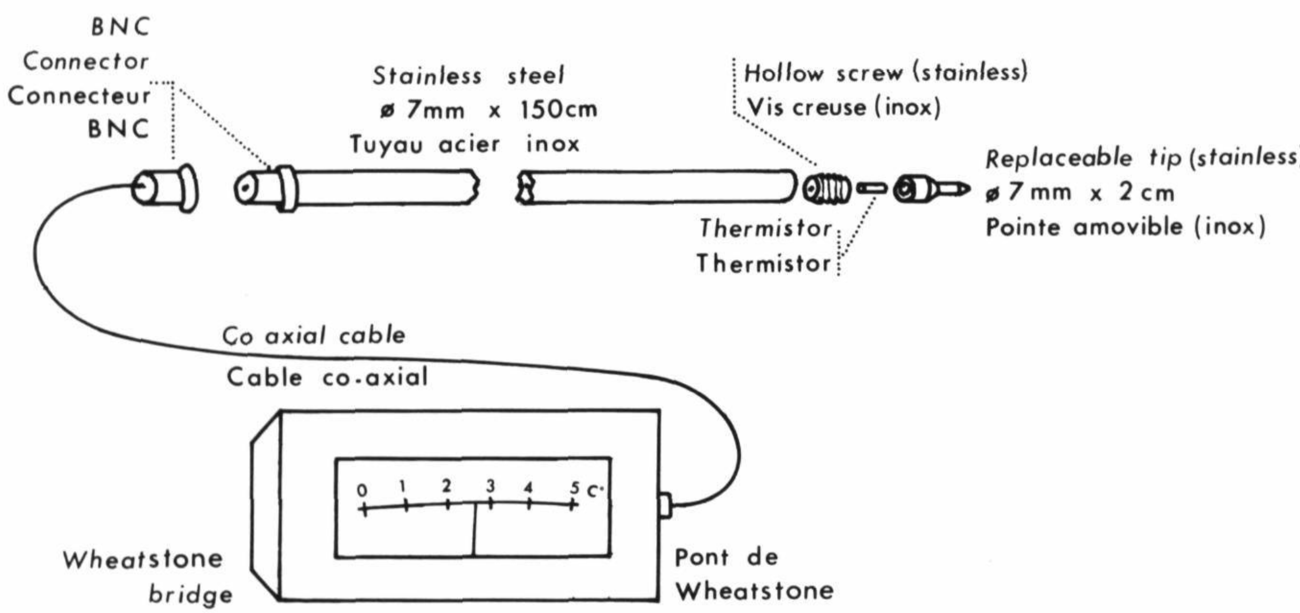


FIGURE 2. Diagrammatic representation of the DREO rigid temperature probe.

Schéma de la sonde du C.R.D.O. servant à mesurer les températures.

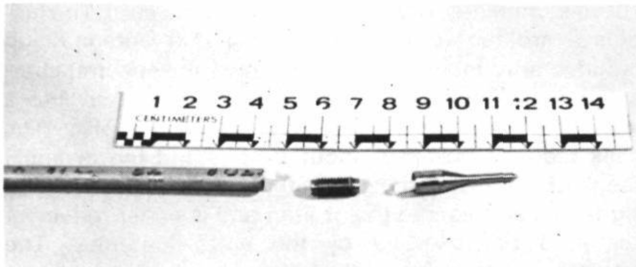


FIGURE 3. Close-up view of point of DREO probe.
Gros plan de la pointe de la sonde du C.R.D.O.

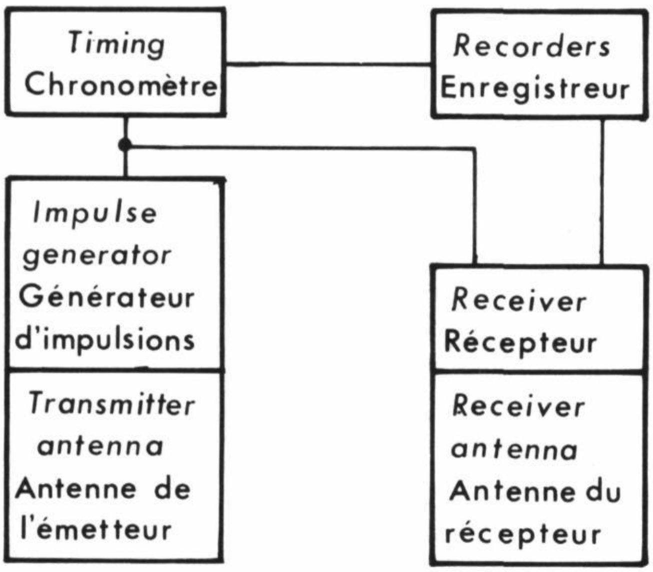


FIGURE 4. Radar system used in the research.
L'appareil radar utilisé sur le terrain.

After the traverses were completed and marked, the surface elevations were accurately profiled in 10 to 50 cm increments with a theodolite. Vegetation data, soil water content profiles, and grain size analyses were obtained at selected intervals along the traverses. Temperature profiles down to the frost table were also obtained in order to allow comparison of the thermal and radar sounding methods of determining the thickness of the thawed zone. It should be mentioned here that, although the surveys were carried out in early August, studies of thaw penetration throughout the season reveal that the thawed zone at this time and for this area represents about 80% of the total thickness of the active layer at the end of the thaw season in September. Strictly speaking, the discussion in this paper concerns the thawed zone at a particular date, but of course, the results have direct applicability to active layer variations and to actual values for active layer thickness if the appropriate parameters of heat input, conductivity and diffusivity are applied through to the end of the thaw season.

Table I summarizes the basic parameters for all eight traverses. Two traverses were carried out for each geomorphological situation in order to ensure that representative data were collected.

PRESENTATION OF RESULTS

Problems were experienced with traverses 3 and 4 in the intertidal mud-flats. Both traverses were saturated semi-diurnally with salt water which resulted in extreme attenuation of the radar signal. As a result, the radar soundings produced little information. It also proved

TABLE I

Basic parameters for the active layer traverses at Leaf Bay

Traverse No.	Length (m)	Interval for the temperature probe measurements (m)	No. of grain size analyses	No. of moisture content profiles	Geomorphological unit
1	50	5	0	0	Marine terrace
2	85	3.4	4	4	Marine terrace
3	45	5	0	0	Beach and upper intertidal zone
4	50	—	—	—	Intertidal zone
5	225	12.5	3	3	Washed till with thin cover of deltaic sediments
6	104	0	0	0	Abandoned air strip on sand and gravel terrace
7	101	0	0	0	Abandoned air strip on sand and gravel terrace
8	9	18	1	2	Sand on old delta surface

impossible to obtain rigid probe profiles for this zone because of the extremely stony nature of the ground (Fig. 5).

The remaining six traverses in the terrestrial situation were successful. Three of these have been selected for detailed discussion here. One profile was chosen from each of the geomorphological units shown in Table I. The traverses presented here are numbered 2, 5 and 8. The numbering scheme represents the time sequence of the survey work.

The top half of Figures 6, 7 and 8 show the topographic and active layer profiles as they were measured with the theodolite and the rigid temperature probes. The location of points where moisture profiles were obtained are also indicated. The bottom half of Figures 6, 7 and 8 portray the raw radar signal as recorded for the three chosen traverses during the survey. One should note that the reference marks (known fixed distances on the ground) at intervals along the trace are not at constant spacing. This results from slight variations in speed at which the survey toboggan was towed over the terrain surface. The scale relationship between the upper and lower halves of each graph is therefore not exact, but they are fairly close to one another. The soil water content profiles are illustrated in Figure 9. At selected points, grain size analyses were also carried out and these are shown in Table II.

FIGURE 5. Inter-tidal mud-flats at Tasiujaq, Leaf Basin, Note the high density of boulders.
La slikke vaseuse à Tasiujaq (bassin aux Feuilles). À noter la grande quantité de blocs.

The terrain characteristics along each of the traverses is summarized below. Traverse 2 is an 85 m long profile across a low terrace of marine origin capped by silty sand and by large isolated boulders (Fig. 10). Its surface is characterized by low peat hummocks (30-50 cm in height) possessing a lichen and dwarf shrub cover, and by intervening wet fen depressions possessing a cover of *carex* spp and other sedge grasses. A small stream flows across the southern end of the traverse.

Traverse 5 is a 225 m long profile across an old airstrip built in the early 1950s by the Fenimore Iron Ore Company. The central part of the profile, the airstrip itself, is situated on a small alluvial fan or delta of sand and gravel composition. The alluvial deposits are mostly overlain by a vegetal cover of mosses and sedge with some patches of lichen covered peat. Where it

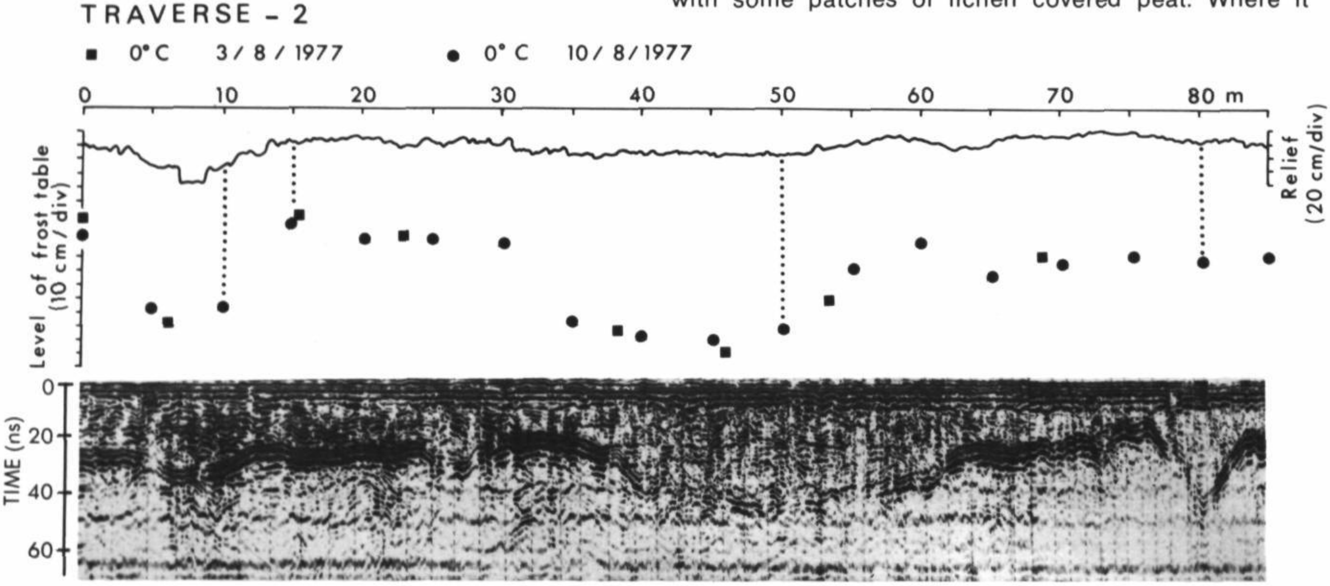


FIGURE 6. Topographic profile and trace for traverse 2. The locations of temperature and humidity profiles and measured active layer depths are also plotted.

Le profil topographique et l'enregistrement radar du transect n° 2. La localisation des profils de température et d'humidité ainsi que les profondeurs de la couche active sont indiquées.

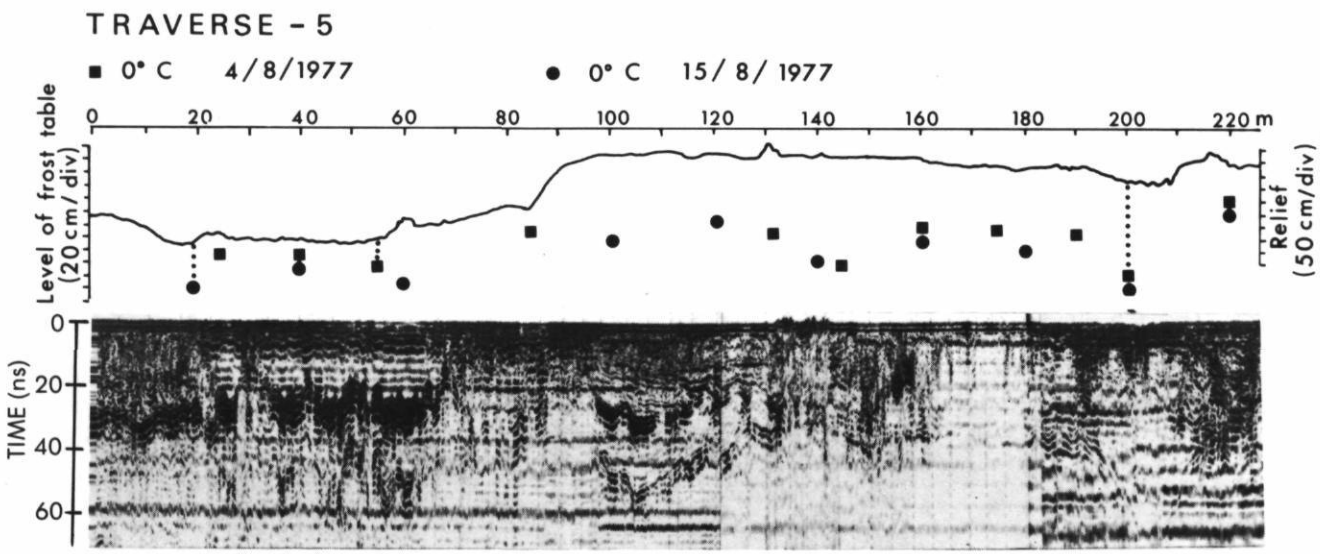


FIGURE 7. Topographic profile and radar trace for traverse 5. The locations of temperature and humidity profiles and measured active layer depths are also plotted.

Le profil topographique et l'enregistrement radar du transect n° 5. La localisation des profils de température et d'humidité ainsi que les profondeurs de la couche active sont indiquées.

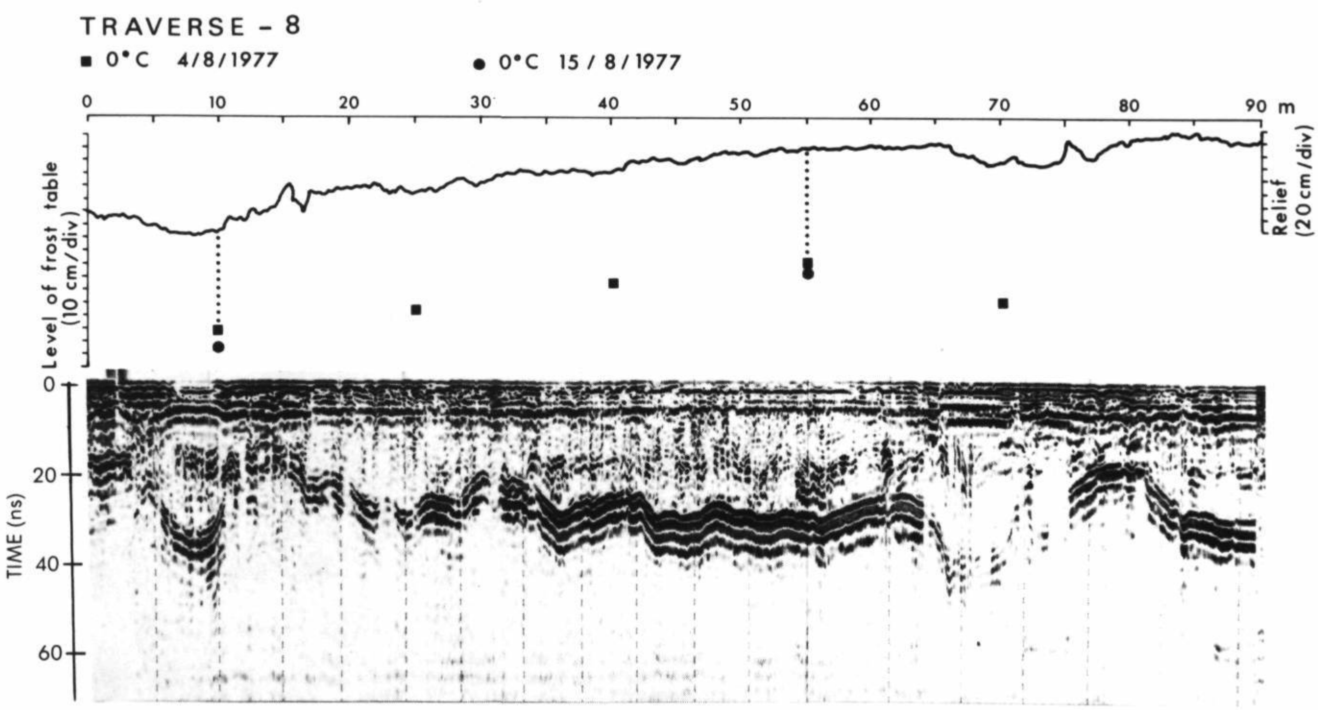


FIGURE 8. Topographic profile and radar trace for traverse 8. The locations of temperature and humidity profiles and measured active layer depths are also plotted.

Le profil topographique et l'enregistrement radar du transect n° 8. La localisation des profils de température et d'humidité ainsi que les profondeurs de la couche active sont indiquées.

is undisturbed, the gravel fan is covered by a thin lichen mantle. In the areas disturbed by the airstrip, tall grasses and dwarf shrubs have colonized since the strip was abandoned 20 years ago.

Traverse 8 is a 90 m long profile across a marine terrace, whose surface is characterized by large, well defined, raised centre polygons and small scattered depressions, dotted with shallow lakes of thermokarstic

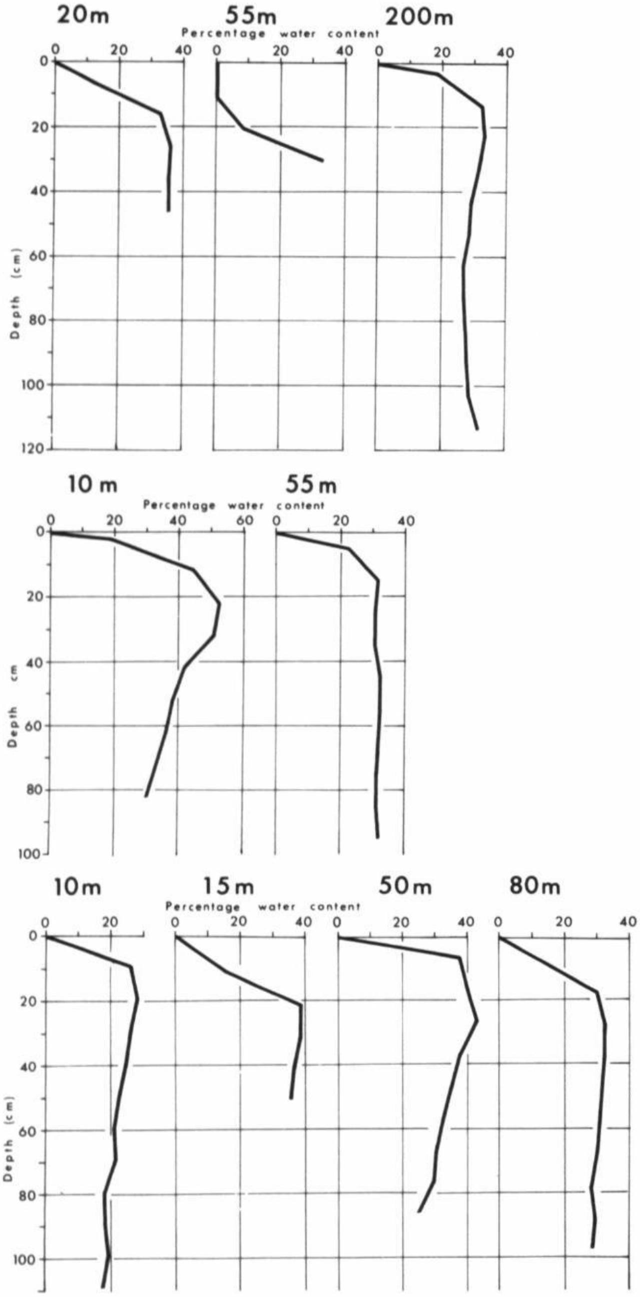


FIGURE 9. Soil moisture profiles at selected sites on traverses, 2, 5 and 8.
Les profils d'humidité enregistrés à certains endroits choisis des transects nos 2, 5 et 8.

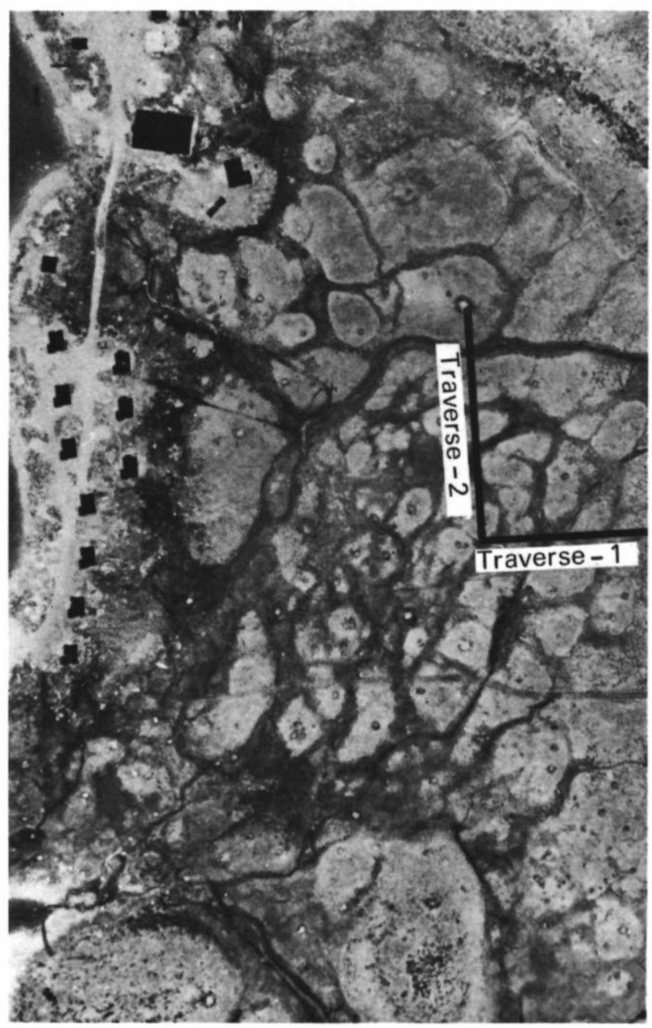
FIGURE 10. Vertical view of traverse 2 from 1,200 m altitude.
Vue en plan du transect n° 2 à 1 200 m d'altitude. ⟶

TABLE II

Grain size analyses for traverses sites
(% by weight in each grain size category)

	Gravel	*Coarse sand*	*Med. sand*	*Fine sand*	*Silt*	*Clay*
Traverse						
15 m	0.8	5.1	10	25.9	58.2	Trace
60 m	—	10.3	26.3	19	41.4	3
80 m	2.9	9.8	13.4	33.8	39.1	1
Traverse 5						
10 m	5.6	41.1	33.6	10.7	9.2	trace
20 m	3.2	17.6	20.1	29.6	29.5	trace
200 m	—	—	33.6	26.7	27.1	12.7
Traverse 8						
55 m	—	28.1	26.5	37.9	7.5	trace

Grain size according to M.I.S. classification.



origin. The centres of the polygons are of sandy composition whereas the margins contain a much higher proportion of silty material. The vegetation cover on the polygons consists essentially of a thin lichen carpet; in the marginal depressions the vegetation is mostly mosses, sedges and dwarf willows.

DISCUSSION AND INTERPRETATION OF DATA

The data obtained with the thermal probe are relatively simple to understand and little interpretation is required. In areas where probe refusal was encountered, the depth of the frost table is obtained by extrapolating the temperature gradient to 0°C. Table III summarizes the depth of the frost table for the three traverses.

The radar data yields a very graphic display of the relative variations in the depth of the frost table. The radar record displays the depth of the frost table in terms of the two-way travel time required for propagation of the radar signal down to the freeze-thaw boundary. In order to convert the travel time into estimates of depth, the propagation of velocity of the radar signal in the unfrozen zone must be known. In soils, the propagation velocity is controlled by the volumetric water content of the soil (DAVIS, TOPP and ANNAN, 1977). The water content of the soil along a traverse varies and causes a variation in the propagation velocity with position.

In order to interpret the radar data, the propagation velocity was determined in three different manners. First, the radar system was deployed in the wide angle reflection and refraction mode (ANNAN and DAVIS, 1976) to obtain velocity estimated at points along the traverses. Second, the time domain reflectometry method (DAVIS and CHUDOBIAK, 1975) was used to estimate the propagation velocity and water content of the soil on some of the traverses. A third measure of velocity was inferred from the measured volumetric water contents.

The propagation velocity of the signal, V, is related to the bulk dielectric constant, K, by the relationship

$$v = c/\sqrt{K} \quad (1)$$

where C is the velocity of light, 3×10^8 m/s. The bulk dielectric constant is related to the volumetric water content, θ, by the empirical formula

$$K = 2.26 + 17.6\,\theta_v + 106\,\theta_v^2 \quad (2)$$

derived by DAVIS, TOPP and ANNAN (1977). The highest velocity and lowest dielectric constant were found in well drained areas of the traverses. The lowest velocity and highest dielectric constant were found in poorly drained areas which usually had free-standing water on the surface. In general,

TABLE III

Depth of thaw zone on 10/8/77 for traverses 2,5 and 8.

Traverse 2		Traverse 5		Traverse 8	
Position on traverse (m)	Thaw depth (cm)	Position on traverse (m)	Thaw depth (cm)	Position on traverse (m)	Thaw depth (cm)
0	61	20	70	10	79
55	103	40	43	25	90
10	110	60	96	40	90
15	58	100	140	55	93
20	73	120	112	70	107
25	70	140	170	$\bar{x}$ =	91.8
30	70	160	135	δ =	10.0
35	122	180	130		
40	130	200	170		
45	137	220	170		
50	126	$\bar{x}$ =	115		
55	92	δ =	41.9		
60	75				
65	98				
70	93				
75	93				
80	91				
85	89				
$\bar{x}$ =	93.9				
δ =	23.9				

K varied between 10 and 25 and V varied between 0.60 and 0.94 m/ns.

The radar data was digitized and a computer program which combines surface elevation and estimated propagation velocity was used to automatically generate interpretations for the radar traverse data. Since the water content was variable along most of the traverses, the interpretation of the radar data was made using the extreme values of velocity. The resulting interpretation yields upper and lower bounds for the depth of the frost table. The interpretations for traverses 2, 5 and 8 are shown in Figure 11. For traverses 2 and 5 the shaded band gives the estimated frost table range inferred from the radar data. For traverse 8 the frost table is indicated by a broken line only. The starred points indicate the thermal measurements of frost table for all traverses.

The freeze-thaw boundary is a strong radar reflector since there is a large and abrupt velocity change at the freeze-thaw boundary (ANNAN and DAVIS, 1978). The reason for the change is that liquid water has a dielectric constant of about 80 while ice has a dielectric constant of about 3. In the Leaf Bay area, the water content usually is largest at the freeze-thaw boundary since water tends to drain downward. The propagation velocity in the frozen soil was inferred to be about 0.14 m/ns from wide angle sounding data. The velocity increases at the freeze-thaw

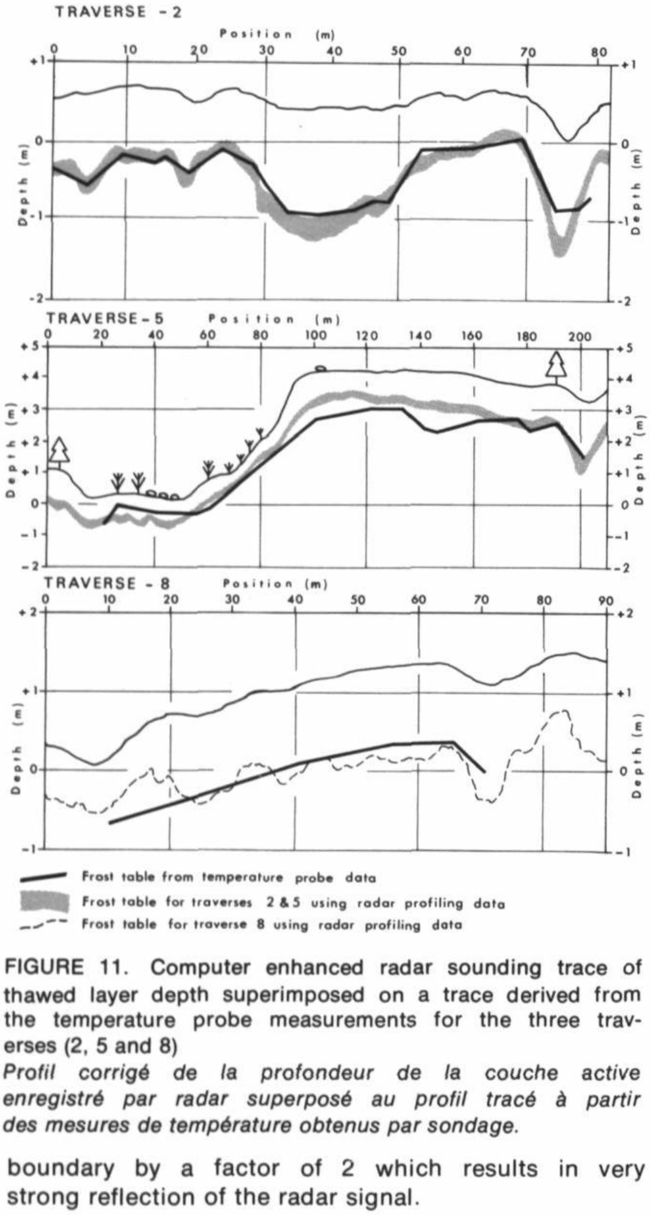


FIGURE 11. Computer enhanced radar sounding trace of thawed layer depth superimposed on a trace derived from the temperature probe measurements for the three traverses (2, 5 and 8)

Profil corrigé de la profondeur de la couche active enregistré par radar superposé au profil tracé à partir des mesures de température obtenus par sondage.

boundary by a factor of 2 which results in very strong reflection of the radar signal.

The correlation of data obtained by the two techniques is clearly good. Along traverse 2 where it was possible to push the probes all the way to the frost table and where there are 18 data points spaced at 5 m intervals the correlation is almost perfect. Along traverse 5 there is some divergence where the profiles cross the abandoned airstrip, between 100 and 160 m. This may be due to inaccuracy in the temperature probe values for active layer depths at individual data points. At these points the temperature probes could only be pushed down in the gravels and sands to 60 cm depth, necessitating extrapolation to the approximate position of the 0°C isotherm using a relatively short linear temperature profile of only 30 cm beneath the zone subject to diurnal fluctuations.

It is not the intent of this paper to explain in detail the role of the various terrain factors in causing variability in the position of the frost table and, ultimately, the active layer thickness. There is, however, a strong correlation between terrain type and frost table depth. The frost table generally lies at a depth of about 25-60 cm beneath peat hummocks on the silty sand terrace surfaces, about 80-120 cm on the sandy terrace surfaces and about 140-175 cm on the bare sand and gravel surface of the old airstrip.

CONCLUSION

Determination of the thickness of the thawed zone above permafrost obtained by temperature probe measurements and impulse radar profiles reveal good correlation between the two methods. The use of the rigid probe to profile the active layer in late summer is a viable method for characterization of permafrost in the various geomorphological units of a region. One must allow for the slight increase in thickness of the thawed zone at the end of the summer period. The temperature probe method may have an advantage over the radar profiling method on moderate to steep slopes on account of less stringent requirements for accessibility. Drainage may also be too effective on such slopes and reduce the radar reflectivity of the frost table although this is very unlikely. The rigid temperature probe also produces a temperature curve as a by-product and this can be used to assess the effect of different terrain factors on heat flow in the soil. It is, furthermore, a much cheaper and less bulky apparatus than the radar equipment, requiring no auxiliary logistical support for field use.

On the other hand, the radar profiling method provides more continuous information and can be carried out more rapidly than the temperature probe method. The radar method does require some local ground control as regards soil water profiles. Wide angle reflection and refraction soundings can be used to estimate the soil water content. Radar would appear to have a definite advantage if one wished to prepare a detailed map of the active layer for a small section of terrain such as a route location or a townsite.

This system might also prove more convenient in more southerly areas of the permafrost zone where active layers exceed 3-4 m, thus creating problems for temperature probe penetration, or in situations such as these found at the abandoned airstrip where the stony nature of the soil stopped the temperature probes after only 60 cm. The radar system would have even more applicability for large area traverses in the future if a method could be found of making the instrumentation airborne without a large loss in resolution. The radar system used in these tests was a general purpose instrument. A light, field portable, unit should be designed for future active layer analysis.

It should be noted that neither method can be applied universally for thaw zone and active layer determinations. As an example, the trials in the tidal flat were a failure. The earth materials were too stony for the temperature probe and the high conductivity of the salt water in the soil strongly attenuated the radar signal.

Ultimately, the choice of a survey method for active layer profiling must depend on the intended objectives of the survey and on its logistical, economic and time constraints.

ACKNOWLEDGEMENTS

Many agencies and individuals have contributed to the geothermal studies at Leaf Bay from 1975-1978. Thanks are extended to the Geological Survey of Canada for their financial support through research grant No. 2239-4-239-77 awarded to J. Gray, and to the Department of Indian Affairs and Northern Development for their assistance through the northern training grants programme. The financial assistance of the Centre d'ingénierie nordique de l'École polytechnique and of the Université de Montréal is also gratefully acknowledged. The geophysical work was made possible through the logistical aid provided by the Electrical Methods Section, Resource Geophysics and Geochemistry Division of the Geological Survey of Canada. The field work was carried out with the assistance of D. Pichette, J. Carmichael, J. Thériault and B. Allen. Finally, gratitude is expressed to the Inuit community of Tasiujaq for their kind hospitality during field work in the Leaf Bay area.

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