ARCTIC
VOL. 44, SUPP. 1 (1991) P. 40-48

Remote Sensing of Permafrost by Ground-Penetrating Radar at Two Airports in Arctic Canada

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(Received 5 September 1990; accepted in revised form 29 July 1991)

ABSTRACT. Over a cycle of seasons, ground-penetrating radar studies were carried out at Inuvik and Rankin Inlet, Northwest Territories. The two airports are part of the Forward Operating Location (FOL) program of the Department of National Defence and have been slated for significant upgrading of runways, taxiways and parking aprons. This provided a good opportunity to investigate the extent of permafrost and its seasonal variation at two locations distributed over a wide geographic area. The study method involved specific and repeated traverses with a Pulse EKKO III ground-penetrating radar unit. The survey was successful in locating massive ice bodies, imaging several existing problem areas beneath runways and mapping the seasonal depth of thaw in permafrost. The study results imply that future monitoring at FOL sites should be continued in light of suggested ground stability problems due to global warming.

Key words: Canadian Arctic, ground-penetrating radar, permafrost, global warming, airport, Forward Operating Location

RÉSUMÉ. Une série d'analyses des sols menées à l'aide d'un géoradar ont été effectuées sur une période d'un an à Inuvik et Rankin Inlet, TN-O. Les deux aéroports font partie du programme d'Emplacement Avancé d'Opérations (EAO) du ministère de la Défense nationale. Ils ont été sélectionnés afin de subir des modifications importantes de leurs pistes d'envol, de leurs bretelles d'accès et de leurs aires de stationnement. Ces circonstances ont offert une excellente occasion d'analyser le pergélisol et ses variations saisonnières dans deux endroits géographiquement différents. La méthode de recherche choisie prévoyait l'usage systématique d'un géoradar de type "Pulse EKKO III". L'étude a ainsi permis la localisation d'importants dépôts de glace ainsi que l'établissement de cartes décrivant la variation saisonnière du dégel au sein du permafrost. La recherche dans son ensemble a démontré que ce type d'analyse doit continuer à exister pour le futur même si l'on doit tenir compte du problème de la stabilité des sols posés par le réchauffement général de la planète.

Mot clés: Arctic canadien, géoradar, pergélisol, réchauffement atmosphéric, aéroport, Emplacement Avancés d'Opérations

INTRODUCTION

During April and September 1988 and September 1989 ground-penetrating radar surveys were carried out at two arctic runway sites: Inuvik and Rankin Inlet, Northwest Territories (N.W.T.) (Fig. 1). There were several reasons for conducting the study. From a practical point of view the sites are part of the Forward Operating Location (FOL) program of the Department of National Defence, Canada, and as such are slated for runway extensions and upgrading of taxiways and parking aprons. This was considered to be a good opportunity to evaluate ground-penetrating radar as a tool with which to predetermine the extent of permafrost and seasonal variation before construction began and to investigate several post-construction problems.

The conclusions presented herein are preliminary and are part of an ongoing study that will assess the stability of permafrost at the two sites over the longer term. Further results will be incorporated in the "Mackenzie Basin Impacts Study," which is being organized by the Canadian Climate Centre of Atmospheric Environment Services Canada to assess the significance of global climate change on the Mackenzie, Peace and Athabasca river basins of northwest Canada.

STUDY AREAS

Inuvik

The town of Inuvik is located on the boundary between the modern Mackenzie Delta to the west and the Anderson Plain to the east (Mackay, 1963). It is situated on the north flank of the Campbell Uplift, leading to a fairly complex bedrock geology in the study area, as described by Norris and Calverly (1978). The vicinity of the airport is underlain by quartzites, shales and dolomites of Precambrian to Devonian age. The shales are rarely exposed and generally occur beneath a thin veneer of more recent surficial deposits that are related to the Wisconsinan ice sheet and subsequent deglaciation (Rampton, 1988; Johnston, 1982).

The town site, including the airport area, is located within the continuous permafrost zone, which extends to depths in excess of 100 m (Judge, 1973, 1987). Ground temperatures within the community have been found to range from –3 to –4°C at a depth of 6 m during late September (Philainen, 1962; Rowley *et al.*, 1973; Johnston, 1982). The maximum depth of seasonal thaw ranges from about 0.5 m in poorly drained areas to as much as 2.5 m where well-drained granular

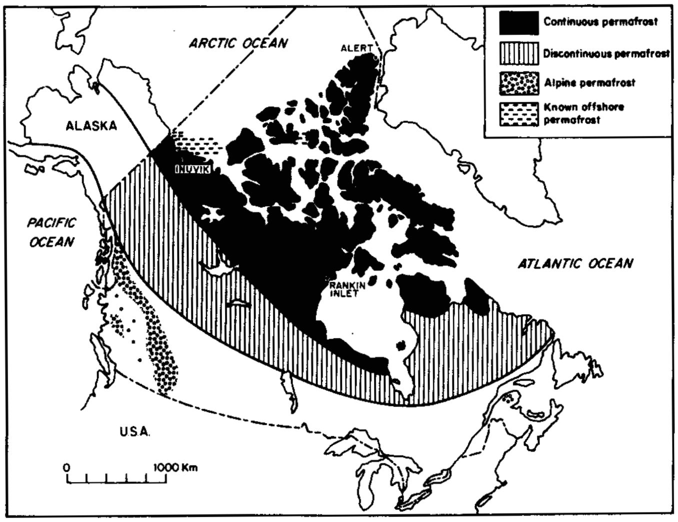

FIG. 1. Location map, showing Inuvik and Rankin Inlet on a background of the distribution of permafrost.

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materials are present at the ground surface. In contrast, mean March temperatures range from -6 to -8°C at 6 m depths. The ice content of surficial materials in this area is generally high. Thermokarst features due to thaw settlement are common.

The existing runway was constructed on a topographic high. According to Johnston (1982), the stratigraphy consists of peat underlain by ice-rich clay till, and the runway was, therefore, constructed by placing quarried rock over the undisturbed ground surface to a thickness reported to range from a minimum of 2.5 m to a maximum of about 4.3 m. Insulation was not used in the construction of the runway and taxiways. In a few locations, most notably the main taxiway, the surface has settled up to 1.5 m, partly due to thaw degradation.

The FOL extension examined in this study is located in an area north of the east end of the runway. The general area is characterized by a series of drumlinoid ridges believed to be bedrock controlled. The site has fair to poor drainage and is covered by stunted black spruce. Groundwater is confined within the thawed active layer by the underlying permafrost. Because of poor local drainage, water is ponded adjacent to the edge of the runway fill.

From Thurber's preliminary study (Thurber Consultants Ltd., 1988a), the stratigraphic sequence below the FOL site consists of several major units. Compressible peat, ranging from 0.5 to 1.5 m in thickness, is present over virtually the entire study area. The peat is underlain by a silty clay till containing occasional boulders, cobbles and gravel. In other locations near the airport, the clay till has been found to contain significant quantities of massive and wedged ground ice. The till is underlain by a shale bedrock, which in turn is underlain by dolomite. The dolomite is exposed in the quarries at the west end of the runway, where it is hard, grey in colour and well jointed (Norris and Calverly, 1978). The depth to dolomite below the study area is not known, but because the dolomite contact is an ancient erosional surface, it is probably highly variable. The upper few metres of the dolomite is weathered and fractured.

Rankin Inlet

The hamlet of Rankin Inlet, the administrative centre for the Keewatin Region of the Northwest Territories, is situated at the head of Rankin Inlet on the northwest shore of Hudson Bay. James (1970, 1972) and Thurber Consultants Ltd. (1988b) have summarized the physiography and geology of the study area. Rankin Inlet is part of the Kazen Upland, a major physiographic unit of the northwestern Canadian Shield. The Rankin Inlet area is underlain by Precambrian volcanic and sedimentary rock comprised of basalt, andesite, sandstone greywacke, argillite and other metamorphosed sedimentary rocks (Tella *et al.*, 1986). The bedrock surface is very irregular, and overburden thickness can vary significantly over short distances.

The hamlet is located on a narrow, irregularly shaped peninsula devoid of significant oriented glacial landforms (Shilts and Boydell, 1974; Shilts *et al.*, 1979). Because of its low elevation (30 m a.s.l.), all of the area was submerged during the postglacial period (Lee, 1962; Andrews, 1989). Much of the terrain surrounding the airport is composed of marine reworked sand and silt till. At several locations, some degree of local sorting has occurred, with fine silt and sand having been winnowed out to lower areas. A number of thin beach ridges and deposits have proven to be important sources of sand and gravel for the community, including major construction projects such as the FOL site.

Rankin Inlet is situated in the continuous permafrost zone, with an estimated permafrost thickness of about 300 m. Ground temperature monitoring carried out by the Division of Building Research of the National Research Council (Brown, 1978) has indicated that the mean annual ground temperature in the Rankin Inlet area is -10°C. Ground temperatures within the community have been found to range from -7 to -9°C at a depth of 6 m during late July and -7 to -15°C in March (Thurber Consultants Ltd., 1988b).

The maximum depth of annual thaw varies greatly depending on the thickness of organic cover, soil type and seasonal variations of the thawing index. An average depth of thaw of slightly more than 1 m has been calculated for the area. The depth of thaw in well-drained gravels is in the order of 2.5 m, though it may increase to more than 3 m in areas where organic surface cover has been removed or on bedrock outcrops.

Ground ice is present in the form of segregated ice, ice wedges and ice wedge polygons. These features commonly occur in poorly drained beach deposits and are often concentrated in drained lakes or ponds. Some evidence of permafrost degradation is visible in the vicinity of the hamlet where disturbance of the organic cover has occurred due to construction activity (Thurber Consultants Ltd., 1988b).

The original airstrip at Rankin Inlet was constructed in the late 1950s to serve the North Rankin Nickel Mine and was upgraded in 1975. It is situated on a topographic high, on which relatively thin sand and gravel beach deposits were present. The runway was constructed by placing granular fill over the existing ground surface.

The main study site is located at the north end of the runway and extends approximately 300 m onto the tundra. It slopes downward towards the north. Although the overall slope is stable, minor shallow sloughing (due to oversteepening and thaw degradation) has occurred in some very localized areas (Thurber Consultants Ltd., 1988b). The terrain surrounding the end of the runway is relatively smooth and is about 15 m lower than the centre line of the existing runway.

The site is generally well drained, though a number of depressions containing small ponds are present nearby. The low-lying area north of the runway is poorly drained, and at the end of Runway 31 lake water level is within 2 m of the runway surface. Groundwater is confined to the thawed active layer by the underlying permafrost.

The stratigraphic sequence beneath the runway extension consists of several units. The near-surface materials consist of sands and gravels developed by wave washing and reworking of the underlying till. These deposits are typically thin, in the range of 1-2 m. Beach deposits are underlain by till consisting of gravel and cobble- to boulder-sized bedrock fragments in a silty sand matrix. The till contains only a minor amount of ground ice, except possibly in the form of vertical ice wedges. The depth to bedrock is variable and could range up to 20 m or more. According to Thurber Consultants Ltd.(1988b), the depth of thaw was found to range from 1 to 1.9 m in test pits excavated on the site in early September. Because of postglacial emergence from proto-Hudson Bay, it is probable that saline permafrost occurs within the Rankin Inlet townsite, which would increase attenuation and decrease the depth of penetration of signals obtained from the ground-penetrating radar unit.

METHODS

The study method involved specific traverses repeated at different times of the year using a Pulse EKKO III ground-penetrating radar unit, designed and developed for the Geological Survey of Canada by Sensors and Software Inc., and shown in Figure 2 operating on the apron at the Inuvik airport. Ground-penetrating radar is a relatively new geophysical tool; the first commercial unit only became available in the mid-1970s. Impulse radars such as the Pulse EKKO III operate on the principle that a short pulse of electromagnetic energy is emitted by a transmitter antenna, reflects off a distant electrical boundary, and the reflected pulse is picked up by a receiver antenna. The time taken for the pulse to travel from the transmitter to the receiver antenna via a reflector or a series of reflectors is measured. The distance to an individual reflector can be calculated when the propagation speed of the pulse in the material is known. Presentation of information is similar to optimum offset reflection seismic surveys (McCann *et al.*, 1988). The propagation velocity can be measured *in situ* by conducting a common mid-point (CMP) or a wide angle reflection and refraction (WARR) survey (Annan and Davis, 1976). In air, the pulse travels at the speed of light (0.3 $\mathrm{m{\cdot}ns^{-1}}$). In the subsurface, the pulse travels at a velocity dependent upon the electrical properties of the material traversed. This velocity will be some appreciable fraction of the speed of light, typically varying from 0.05 to 0.16 $\mathrm{m{\cdot}ns^{-1}}$, higher in frozen or dry soils and lower in wet materials.

Reflectors detected with a ground-penetrating radar system result from dielectric contrast between subsurface materials. Common causes of subsurface reflections are material interfaces (overburden/rock, sand/clay, etc.), the water table, boundaries between ice and unfrozen water, cavities, boulders and ice lenses. A large dielectric contrast exists between liquid water and most geologic materials, including ice. The presence or absence of free moisture controls to a large degree the subsurface propagation characteristics of the radar pulse. Thus, the ability of a material to retain water within its pore structure and its degree of saturation are important factors in the determination of its bulk electrical properties.

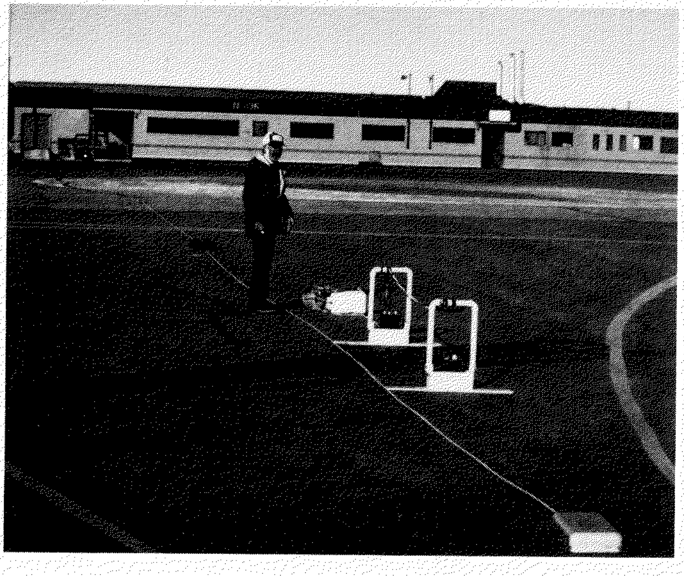

FIG. 2. Pulse EKKO III ground-penetrating radar in use at Inuvik airport.

The depth to which a radar pulse will effectively penetrate is dependent upon the power of the system, number and strength of reflecting interfaces and electromagnetic absorption properties, i.e., attenuation properties, of the subsurface materials. More complete descriptions of the field methodology and design parameters for the radar unit are given in Annan and Davis (1976), LaFlèche *et al.* (1987) and Davis and Annan (1989). For our purposes, it is sufficient to document that the Pulse EKKO III system used in this study is a fully digital unit incorporating fibre optic couplings between the antennas and the console, signal stacking and digital data processing. Limited processing was applied to the profiles; to enable simpler visual interpretation, the upper portions of the profiles were expanded such that the full resolution of the recorded data was displayed and weak signals at depth were enhanced differentially by applying automatic gain control. A prediction error filter was applied trace by trace to remove some of the generally higher "noise levels" on the spring profiles.

The antennas used during the various field studies had nominal or centre frequencies of 50-100 MHz, antenna separation was 1 m (100 MHz) or 2 m (50 MHz) and the spacing used between traces was 1 m. Not all of the survey results are shown here; rather, several representative examples are displayed to represent certain features.

Weather and survey conditions varied considerably from location to location and survey to survey. During the April survey, snow off the runway at the Inuvik site was loosely packed and had drifted in places to more than 1 m thick. Daytime air temperatures were in the range of –15 to –20°C. Conditions at Rankin Inlet were significantly worse. Snow around the airport was very densely packed into ridges about 30-40 cm high, with intermediate bare ground. Temperatures during the day were about –25 to –30°C, with strong winds from the northeast causing ground drifting of snow. Conditions during the September surveys were less varied. Ground conditions at both Inuvik and Rankin Inlet were generally wet, with daytime air temperatures in the range of 6-8°C. In spite of the severe spring conditions, no serious problems were encountered with routine operations of the Pulse EKKO III.

Two profiles were recorded at the Inuvik FOL site. One was acquired in the early spring (mid-April) to determine winter conditions (Fig. 3A), and a second (Fig. 3B) was obtained in early September to show maximum thaw conditions. In each case, the profiles were started at the northeast corner of the tarmac of runway 23 and proceeded in a direction perpendicular to the existing runway for a distance of approximately 210 m. The location of the profiles is shown in Figure 4.

Two sets of profiles were obtained at Rankin Inlet in time frames similar to those of the Inuvik study. In this instance, however, one set was obtained on the existing runway because preliminary discussions with airport officials had indicated that there might have been a historic problem with ground ice thaw beneath one section. The profiles were recorded at a starting point in the middle of the runway at landing light number 9, counting from the end of runway 13 and moving towards runway 31 for a distance of 130 m. A second set of profiles was obtained in the area slated for extension — i.e., from the button of runway 13 for a distance of 300 m in a general northeast direction parallel to the airstrip. As in the previ-

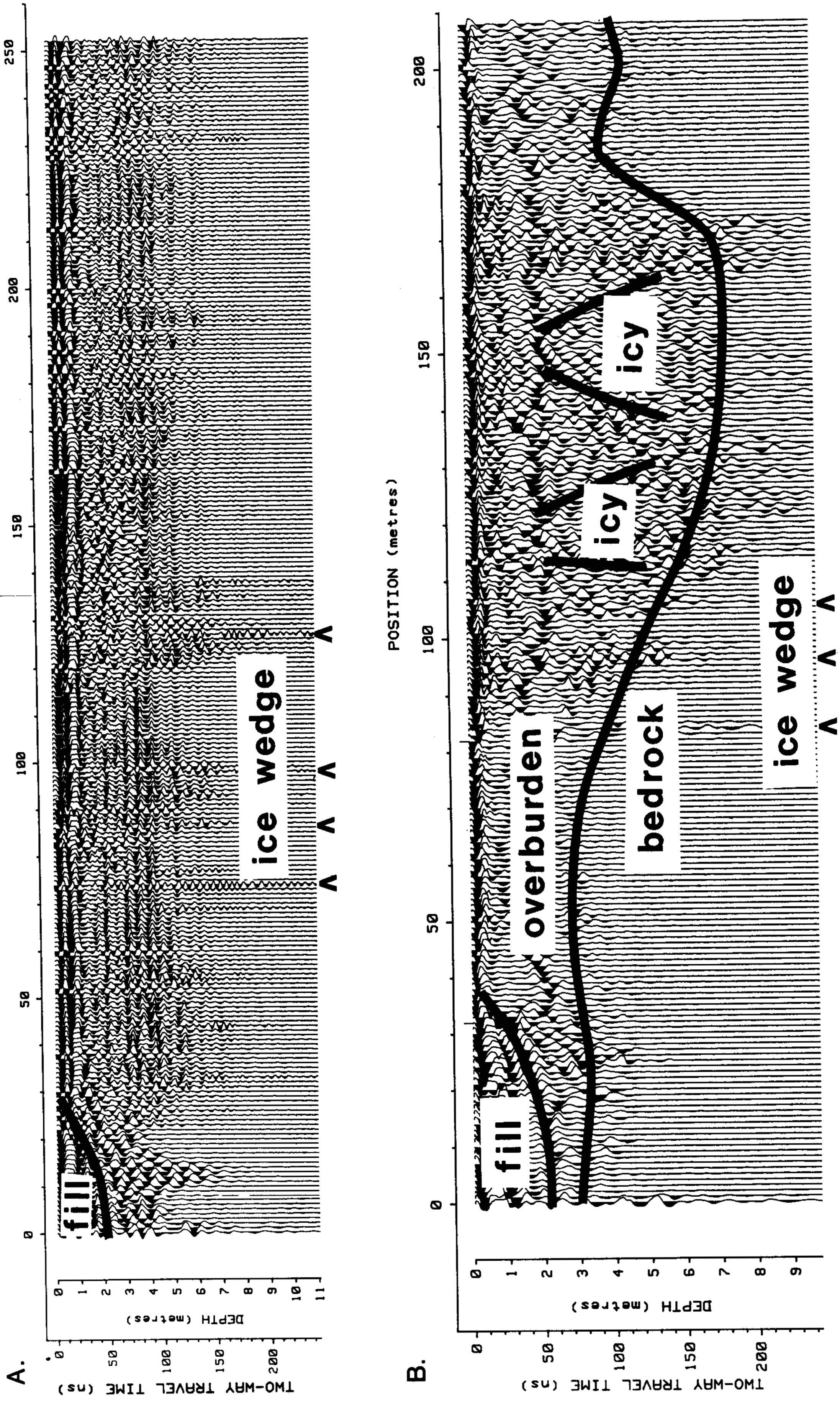

FIG. 3. A) Inuvik airport, spring FOL profile. B) Inuvik Airport, fall FOL profile. For profile locations see schematic on Figure 4.

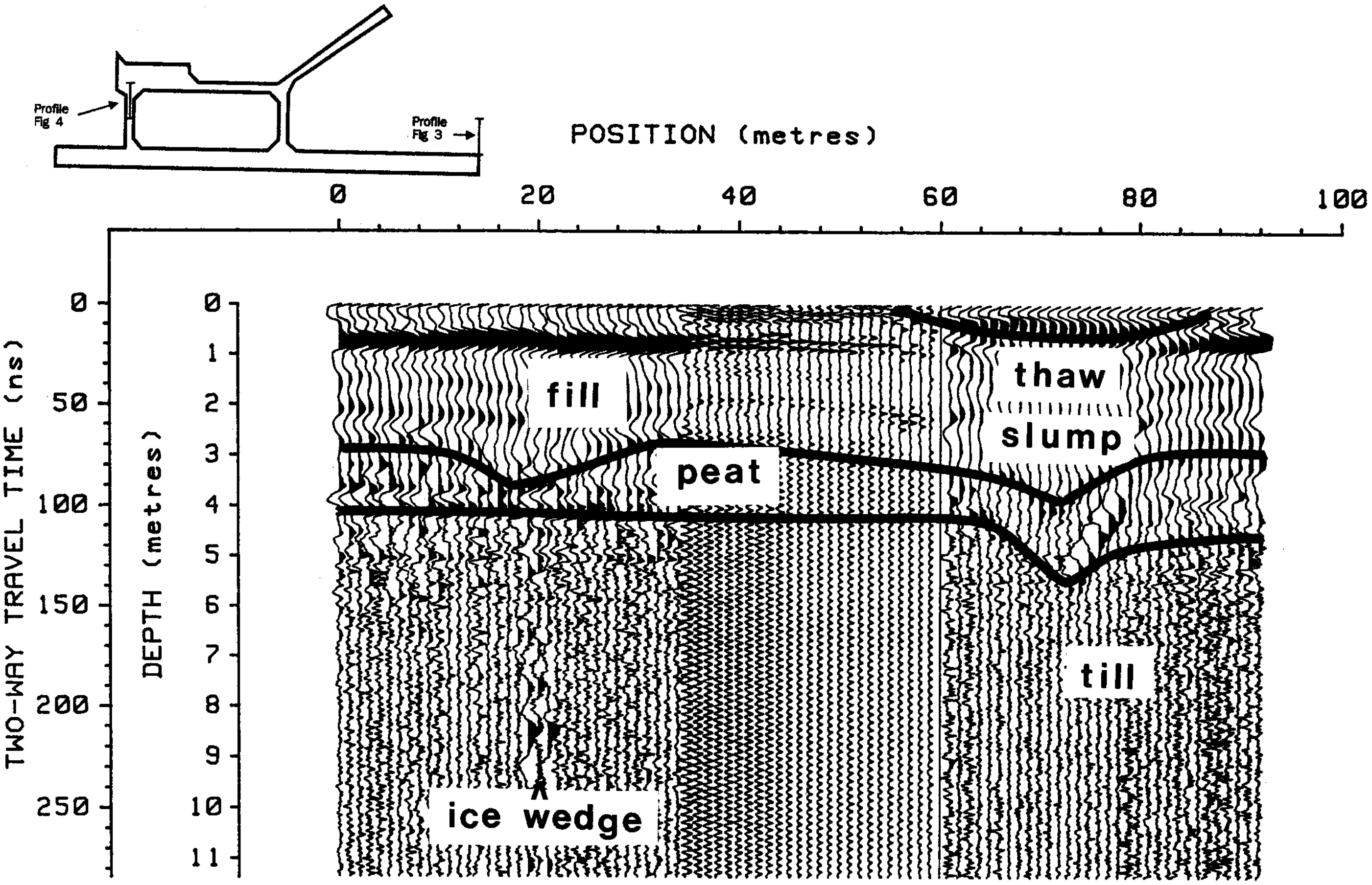

FIG. 4. Inuvik airport schematic with fall taxiway profiles.

ous example, the profile followed the centre line of the runway. CMPs were carried out on the airstrip and on the surrounding terrain. The results from these measurements presented an experimental dilemma on long profiles. Because velocities vary as surface and subsurface conditions change, they in turn can yield false depth when applied to the profiles. As a general caution, the calculated depth scale should only be accepted as an approximation, as there is a degree of uncertainty due to variations in both the velocity depth structure and the near-surface velocity because of irregular surface and subsurface conditions.

RESULTS

Inuvik

The Inuvik spring profile (Fig. 3A) is noteworthy in several respects. Starting at about the 25 m point on the horizontal scale, a well-developed horizon occurs at 0.5 m below the surface. This is considered to be the base of snow cover, from which the radar signal shows a strong to saturated train of returns caused by reverberation of the electromagnetic energy within the snow cover. Little energy has penetrated below this horizon, and despite enhanced processing, only minor subsurface detail is recognizable. One exception is a group of shadows (train of multiple reflections on several sequential traces) that occur at 43, 79, 100, 109 and 120 m along the section. Several of these shadows appear to coincide with the tops of ice wedges and are more readily apparent on the fall profile.

As previously noted, the fall data required significantly less processing to reveal the major subsurface features. The strongest reflecting horizon is located at a depth of about 3 m beneath the runway and extends to as much as 8 m in depth near the 145 m point. This has been interpreted as the surficial material to bedrock contact. The profile indicates that the bedrock is rather hummocky in nature, as suggested above. A more poorly defined horizon is located at a depth of approximately 1 m near the starting point and continues in a generally sub-horizontal fashion across the profile. It corresponds with the thaw front or base of the active layer, and because of the season, is probably close to its maximum development. Evidence for a deeper seasonal thaw beneath the area of ponded water is evident on the radar profile shown in Figure 3B. However, the depth of thaw shown on the profiles is exaggerated. This is because water will modify the velocity of the radar signal and hence magnify the perceived underlying permafrost by as much as a factor of two. A slight deepening at between 38 and 45 m along the profile corresponds to the same process of ponding of water adjacent to the runway fill. Another reflecting horizon is visible at a depth of 2 m at the origin. At 38 m along the horizontal axis it tapers out at the surface, which suggests the feature is the base of fill used in runway construction. Distinct ice wedges are visible at 80-87 m, 96-98 m, 104-108 m and 165-172 m. Ice-rich zones commencing at least 2 m below the surface and extending as much as 4 m in depth are interpreted at the 123 and 145 m marks. These results, at least from a materials point of view, agree well with the local borehole stratigraphy described by Thurber Consultants Ltd. (1988a).

Johnston (1982), in his description of the construction and subsequent performance of the Inuvik runway, apron and taxiways, describes a problem related to slumping of a section of the northwest taxiway. A short radar section 90 m in length was profiled in September 1989 in the hope of shedding some light on the cause of this problem. Figure 4 depicts the profile obtained, and although the middle section is obscured by interference from navigation equipment, the subsided portion from 60 to 85 m is very clear. Although no drill hole information is available for the taxiway, Johnston (1982) does show a geological section for the nearby apron indicating peat, ice and a stony, silty clay underlying the rock fill. The slump seems to be at least in part caused by a melting out of an icy horizon above the till and, perhaps, also within the till itself. This horizon is preserved in the 0-35 m section of the profile and, in fact, an intact ice wedge is apparent beneath the till at the 20 m station. Since the active layer is at a depth of 2 m across the profile, the thaw has probably not originated from directly above and through the runway surface, but is more likely water moving sub-horizontally in summer from an adjacent source roughly perpendicular to the radar profile. Additional surveys are planned to verify the cause of the settlement on the taxiways. Such case histories may prove important, for example, in assessing the impact of global warming on northern infrastructure resulting from a combination of higher air temperatures and increased precipitation.

Rankin Inlet

In neither of the seasonal profiles compiled for the existing runway were massive ice bodies noted (Figs. 5A,B). A reasonably distinct horizon occurring at about 7 m below the surface at the origin and descending to 11 m at the 105 m position is interpreted as the bedrock contact on both profiles. The bottom of runway fill is discernible in both profiles at about the 1.5-2.5 m level, and on the fall profile, or maximum thaw stage, a possible sand/gravel interface is delineated at a depth of 4.5 m. This marker is verified by the stratigraphy provided from Transport Canada (1988) studies.

The spring survey of the Rankin Inlet runway extension profile (Fig. 6A) does not indicate reflecting horizons as clearly as had been hoped. Strong specular reflections from within the shallow section tend to mask the continuous horizons easily identifiable on the fall profile. This may be due to seasonal freeze/thaw processes, which enhance signal penetration and/or dispersion. From the runway end of the profile to a break in slope at approximately 85 m, a distinct horizon of fill is visible on the profile to a depth of 2.5 m. Below this, a discontinuous horizon is present at a depth of 2.5-4.5 m. This may be a surficial material/bedrock contact. Between the 70 and 140 m positions approximately 0.5 m of hard-packed snow was present along the top of the profile. The consistency of the radar pulses would indicate that there were very few voids in the snow and that its properties were approaching those of the ground immediately below. A major break in the traces exists at 140-150 m. This occurred because of a flaw in data reception. Batteries and data tapes for the Pulse Ekko III were changed at this point, and just prior to the change very noisy data were being received.

The fall profiling of the runway extension (Fig. 6B) produced mixed results. Again, as in the spring, the fill material is visible to about 2.5 m, internal layering in surficial material shows at about 4.5 m and a break in slope, or tapering off of fill, shows at the 80-90 m position. One can trace the bedrock contact through the whole profile. However, perhaps because no well-defined horizons exist within the largely reworked surficial materials, internal stratigraphic detail in the overburden is less clear.

DISCUSSION

The preceding sections discuss the various stratigraphic sequences from a synergistic point of view using information from multiple sources (several seasonal profiles and nearby drill records). Profiles on details created solely from the ground-penetrating radar study (Table 1) are not as definitive. This reveals one of the present shortcomings of the ground-penetrating radar system common to all geophysical methods. Radar, like all geophysical techniques, responds to the physical properties of the ground and does not indicate the actual composition of the soil or rock generating the response. As a result it is not possible to infer the exact composition of the subsurface materials without supplementary information, such as from drilling. The real utility of the method, as shown in the preceding sections, is gained from its ability to delineate interfaces. The various profiles also illustrate the ability of the Pulse Ekko III to locate ice wedges and other forms of massive ground ice and to map the depth of seasonal thaw in permafrost zones. Although material types are not as readily identified, some interesting characteristics do emerge.

The ground wave velocities calculated for each of the CMP profiles are presented in Table 2. It is clear that there is significant variation both spatially and seasonally, especially as materials near the surface changed in texture. The spatial variability in velocity leads to uncertain conversion of time scale to depth. One possible remedy for this problem might be to run surveys with an increased frequency of CMPs on each profile. Then long profiles can later be divided into shorter sections of similar or constant velocity for processing.

The ground-penetrating radar study at the two arctic airports proved to be very instructive. Ground-penetrating radar, with the aid of borehole information, was able to define stratigraphic units fairly precisely in a two-dimensional sense. Closely staggered profiles could easily extend this to three dimensions. One of the potentially most useful tasks for the ground-penetrating radar is as a tool for stratigraphic mapping. Further work is needed, however, on enhancing the accuracy of depth scales from borehole-determined velocity structures. More development of a methodology for surveying in deeply snow-covered areas is also required. In situations such as the Inuvik spring survey, signal strength was lost to the snow blanket.

Nevertheless, in areas slated for major construction projects or modification of drainage patterns, the identification of subsurface permafrost features ahead of events can play an important part in the planning process to avoid future problems. Similarly, post-construction techniques have been adequate to maintain thermal stability (Dufour *et al.*, 1988; LaFlèche *et al.*, 1987). A long-term monitoring program could be of benefit in documenting terrain impacts for models of global climate change. The FOL sites are a good location to carry out such work on a regular basis, since the initial documentation has begun, they are well spread across the Arctic, and access is excellent.

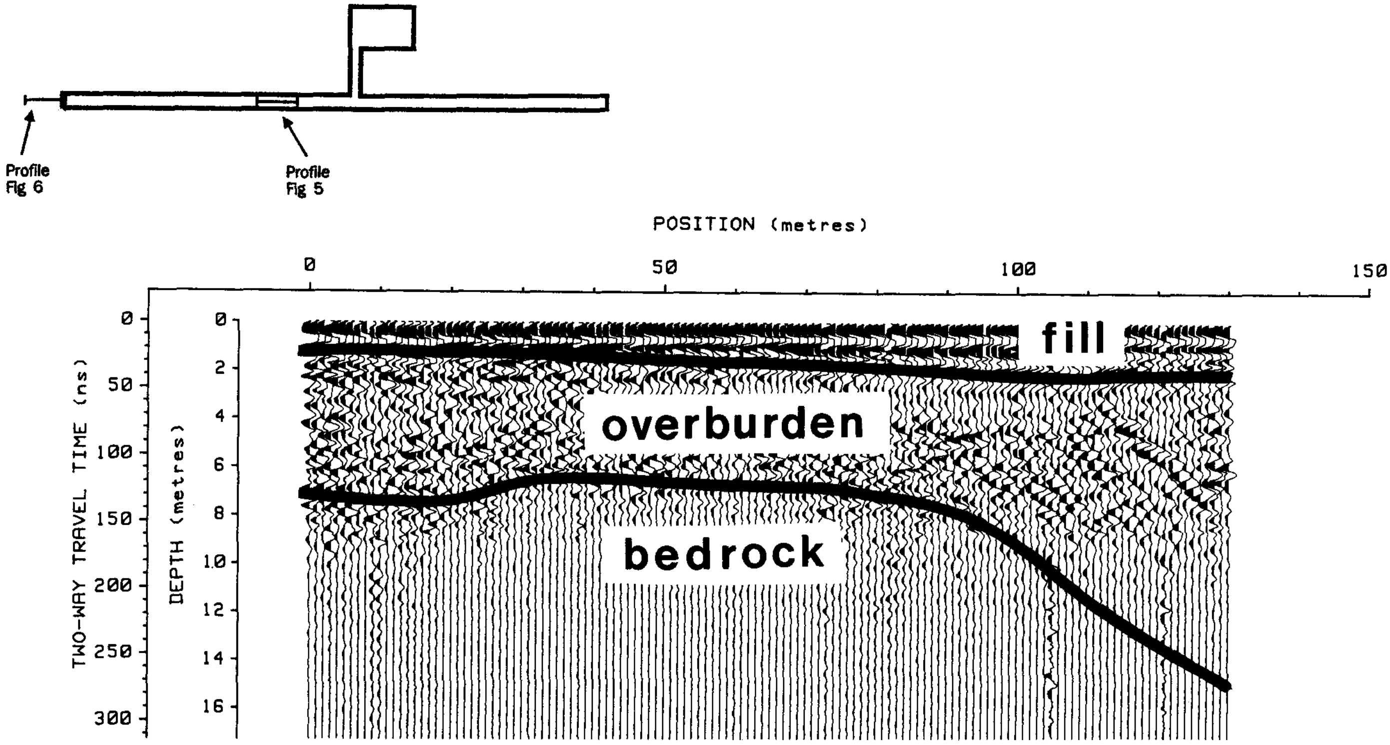

FIG. 5A. Rankin Inlet airport schematic with spring runway profile.

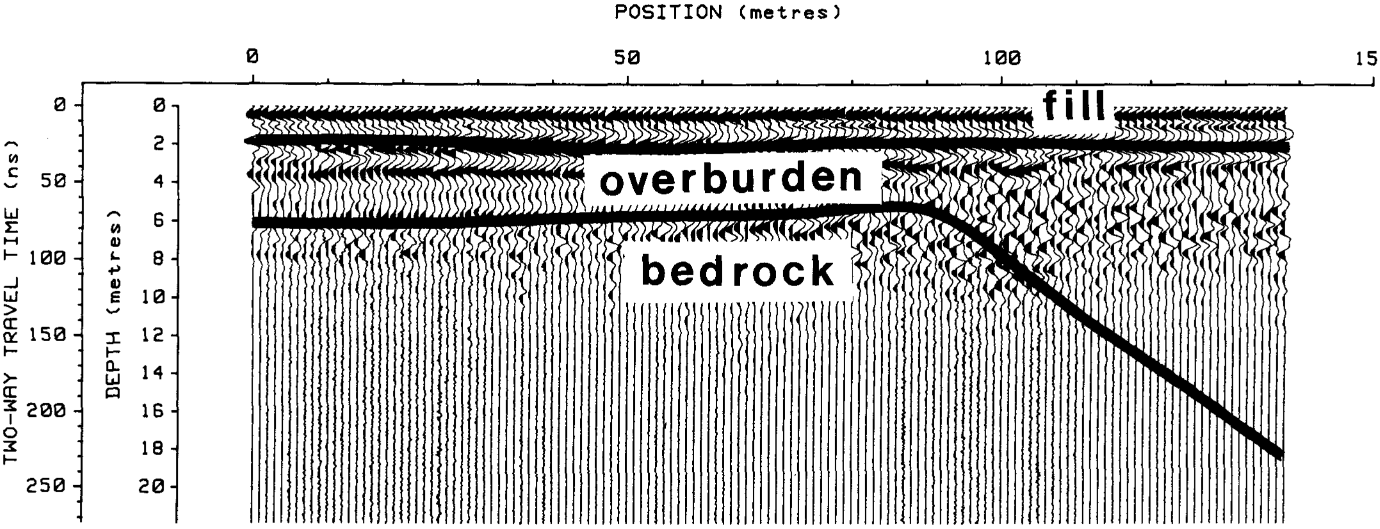

FIG. 5B. Rankin Inlet airport, fall runway profile.

CONCLUSIONS

1. Ground-penetrating radar produces better results in well-drained, coarse material than in fine-grained material. This is because the dielectric properties of granular materials produce less attenuation of the VHF signal.

2. Thick snow cover can provide less than ideal conditions for a ground-penetrating radar survey because of the multiple reflections it can produce in the recorded radar signal. It has been found that little energy penetrates through to the underlying material.

3. On long profiles, a number of CMPs are required to provide reliable depth measurements. Variability in surficial deposits will change the velocity of the radar signal and result in depth uncertainty over distance.

4. In this project, the clearest profiles required minimum amounts of data processing to reveal significant detail. In most cases, only a small amount of gain was applied. Larger gain tended to amplify the high-frequency noise contained in a given trace. This suggests that highly processed data is not always of maximum benefit in ground-penetrating radar analyses, and in fact, field interpretations from such studies can provide useful immediate results.

5. During the course of the present study, ground-penetrating radar technology was found useful to detect frost table

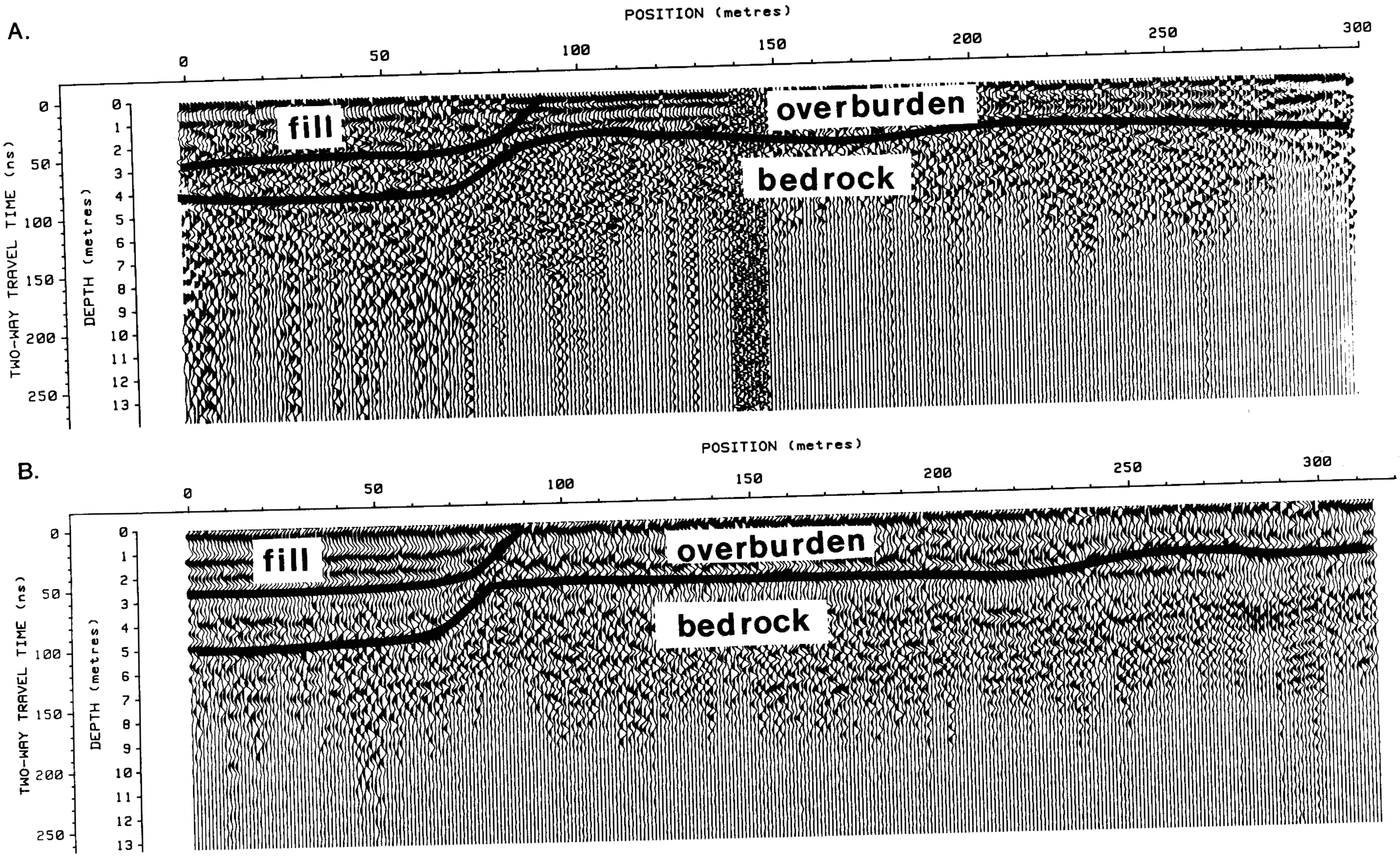

FIG. 6. A) Rankin Inlet airport, spring runway FOL extension profile. B) Rankin Inlet airport, fall runway FOL extension profile. For profile locations see schematic on Figure 5.

TABLE 1. Ground-penetrating radar–derived stratigraphy

Location	Spring	Fall
Inuvik	0-0.5 m: snow >0.5 m: surficial material with massive ice	0-1.5 m: runway fill 0-2 m: active layer 1.5-8 m: surficial material with massive ice >8 m: bedrock
Inuvik taxiway	Nil	0-2 m: active layer 0-3 m: fill 3-5 m: peat/ice >5 m: till
Rankin Inlet runway	0-2 m: runway fill 2-7 m: surficial material >7 m: bedrock	0-4.5 m: sand/gravel interface
Rankin Inlet runway extension	0-0.5 m: snow (off runway) 0.5-2.5 m: tapered runway fill/surficial material interface >2.5-4.5 m: bedrock (hummocky)	0-1 m: active layer 0-2.5 m: tapered runway fill/surficial material interface >2.5-5 m: bedrock (hummocky)

TABLE 2. Calculated velocities at field sites

Inuvik	Spring, on runway	0.08 m·ns^{-1}
	Spring, on terrain	0.11 m·ns^{-1}
	Fall, on terrain	0.08 m·ns^{-1}
Rankin Inlet	Spring, on runway	0.16 m·ns^{-1}
	Spring, on terrain	0.10 m·ns^{-1}
	Fall, on runway	0.16 m·ns^{-1}
	Fall, on terrain	0.09 m·ns^{-1}

(depth of thaw), thickness of construction fill, depth of surficial material (i.e., contact with bedrock) and a certain amount of interior detail, such as general stratigraphy and frozen versus unfrozen ground.

6. The ground-penetrating radar study proved effective in delimiting massive ground ice bodies situated within the middle to upper range of the unit's resolution.

7. The depth of penetration of the Pulse EKKO III in this study was 8 m on average, with reliable information on occasion being obtained to a depth of 11 m.

ACKNOWLEDGEMENTS

The authors would like to thank several individuals and organizations for their help with this study. Mr. V. Allen, of the Geological Survey of Canada, generously aided with field work, data processing and discussion. Mr. M. Bosch, from the Inuvik Research Laboratory of the Scientific Institute of the N.W.T., aided in the field. Airport managers at Inuvik and Rankin Inlet, Messrs. J. Logan, P.W. Tremblay and P. Kaludjak, and their staffs provided access to the various study sites. Field support was also provided by the Inuvik Research Laboratory and Polar Continental Shelf Project of Energy Mines and Resources. Thurber Consultants Ltd. of Calgary provided geotechnical information and discussion. Funding was provided by the Vice Chief of the Defence Staff, Department of National Defence, the Geological Survey of Canada, Energy Mines and Resources, and the Panel for Energy Research and Development (PERD).

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