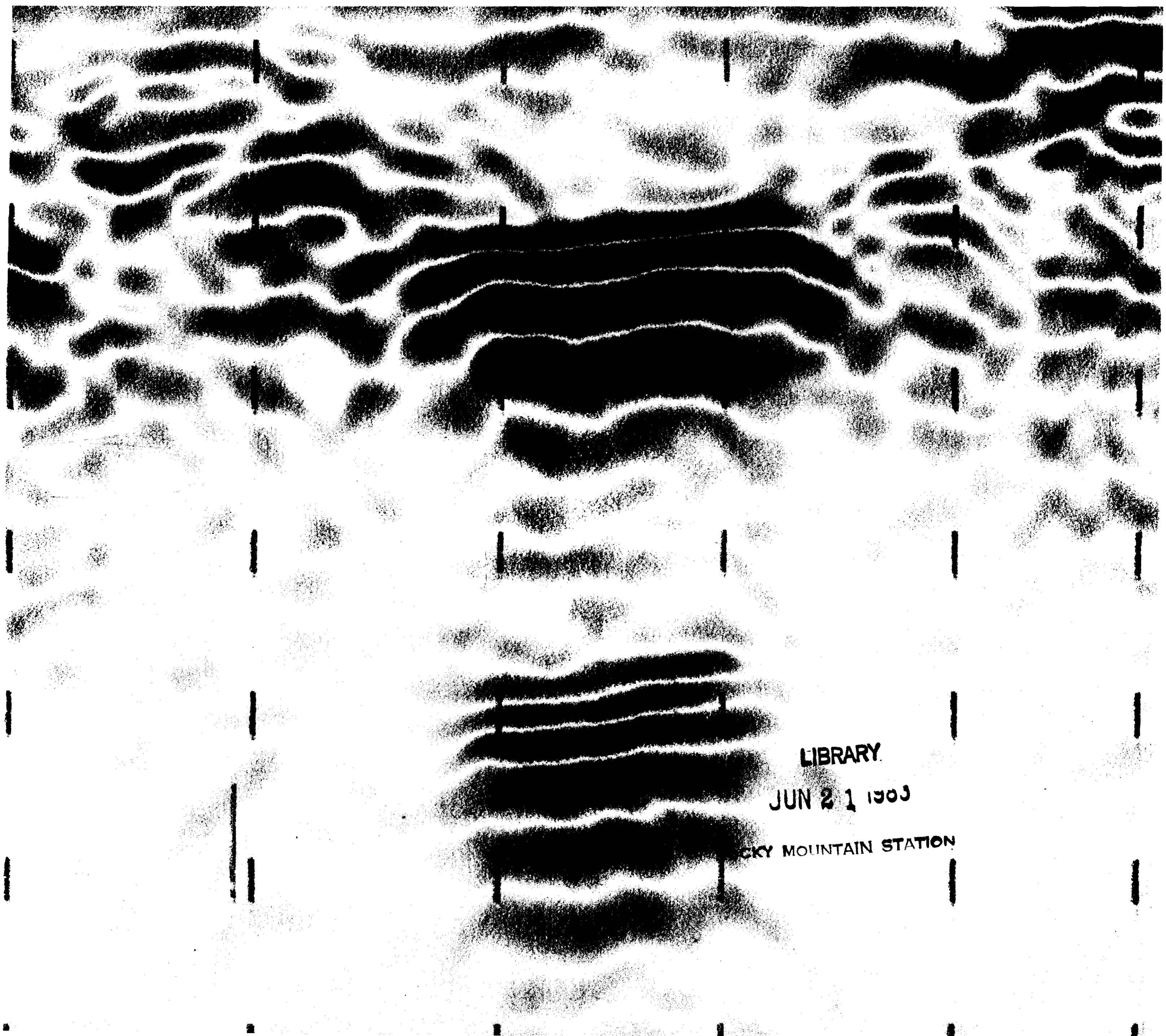
CRREL REPORT 83-11

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Radar profiling of buried reflectors and the groundwater table



CRREL Report 83-11

April 1983

Radar profiling of buried reflectors and the groundwater table

P.V. Sellmann, S.A. Arcone and A.J. Delaney

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CRREL Report 83-11	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) RADAR PROFILING OF BURIED REFLECTORS AND THE GROUNDWATER TABLE		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) P.V. Sellmann, S.A. Arcone and A.J. Delaney		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DA Project 4A762730AT42 Task D, Work Unit 011
11. CONTROLLING OFFICE NAME AND ADDRESS Office of the Chief of Engineers Washington, D.C. 20314		12. REPORT DATE April 1983 13. NUMBER OF PAGES 16
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Alaska; Cold regions; Frozen soils; Ground water; Radar; Radar penetration (soils); Radar reflectors; Soils; Water supplies		

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Investigations of ground radar performance over thawed and seasonally frozen silts, and sands and gravels containing artificial and natural reflectors were carried out in Alaska. The radar emitted 5-10 ns pulses, the center frequency of which was approximately 150 MHz. The artificial reflectors were metal sheets and discs and the natural reflectors were the groundwater table and interfaces between frozen and thawed material. The water table was profiled at three sites where the subsurface material was coarse-grained alluvium. Dielectric constants of 16 to 18 were measured for the thawed silts, 6 to 7 for the frozen silts and 3 to 9 for the sands and gravels. Signal penetration in the thawed high moisture content silts may be achieved only by use of a lower frequency radar, whereas in the sands and gravels greater depths may be detected with more sophisticated signal processing.

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

PREFACE

This report was prepared by P.V. Sellmann, Geologist, Geotechnical Research Branch, Experimental Engineering Division; Dr. S.A. Arcone, Geophysicist and A.J. Delaney, Physical Science Technician, both of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by DA Project 4A762730AT42, *Design, Construction and Operations Technology for Cold Regions;* Task D, *Cold Regions Base Support: Design and Construction;* Work Unit 011, *Electromagnetic Geophysical Methods for Rapid Subsurface Exploration.*

This report was technically reviewed by S.F. Ackley of CRREL and K.G. Neave, a consulting geophysicist from Echo Bay, Ontario, Canada.

RADAR PROFILING OF BURIED REFLECTORS AND THE GROUNDWATER TABLE

P.V. Sellmann, S.A. Arcone and A.J. Delaney

INTRODUCTION

The location and development of water resources in arctic regions is a continual problem, in part because groundwater sources are not usually available. In the subarctic, groundwater is a significant source; consequently, information on its distribution and on the properties of water-bearing horizons is required. Groundwater investigations commonly depend on costly drilling to acquire such information as the depth, slope and seasonal variation of the groundwater table. As an alternative, geophysical investigations can sometimes save both time and money in obtaining this information.

A recent survey of the literature on geophysical investigations in permafrost regions by Arcone et al. (1979) showed how various electromagnetic geophysical systems can be used to detect thaw zones and unfrozen near-surface water sources. This review covered the use of both low frequency (i.e. less than 1 MHz) and high frequency methods. In the high frequency category, a few examples covered the use of radar for detecting fresh water beneath a frozen river channel (Annan and Davis 1977) and beneath the ice cover of a deeply frozen lake (Kovacs 1978). However, no information was available regarding the use of radar for arctic and subarctic groundwater investigations.

For this report we specifically investigated the use of radar for profiling the groundwater table at several sites in interior Alaska. In addition, we used radar to determine the dielectric properties of some surficial materials commonly found in this region to help interpret the radar profiles and predict the ability of radar to penetrate these materials.

OBJECTIVE AND APPROACH

The objective of this study was to determine the response of radar to a groundwater table. The important variables were depth to the water table and properties of the overlying material. The radar system parameters, including pulse waveform, duration and transmitted power, were kept constant for all studies. Signal processing above what the system provided included some simple low pass filtering to enhance the quality of the graphic display.

Study sites

The field sites selected for the groundwater study were on alluvial deposits near Fairbanks, Alaska, and on coarse-grained outwash north of the Alaska Range near Donnelly Dome, where a deep water table had been observed. Background information was available from these areas that could be used for control. The surficial geology and water table observations for the Fairbanks area have been discussed by Péwé and Bell (1976), Nelson (1978) and Feulner (1961). Similar information for the Donnelly Dome site was previously discussed by Church et al. (1965) and Péwé and Holmes (1964). The dielectric properties of materials we anticipated encountering were studied with the use of metallic reflectors buried in an alluvial sand and gravel near Hanover, New Hampshire, and in silt near Fairbanks, Alaska, that was thawed and later frozen. Dielectric permittivity values for these materials acquired by Arcone and Delaney (1982), who used the wide-angle reflection and refraction (WARR) technique employing radar, were also used for data interpretation.

Radar equipment

The radar system was manufactured by the GSSI Company of Hudson, New Hampshire, and has been extensively described elsewhere (Davis et al. 1976, Annan and Davis 1976). The system we used consisted of a Model 4000 mainframe, Model 700P control unit and Model 3105 transmit-receive antenna. The two antennas are resistively loaded bowtie-type dipoles separated about 30 cm and located in one housing. The transmit antenna emits an oscillating pulse of several nanoseconds duration at a pulse repetition rate of about 50 kHz. The system displays an audio frequency facsimile of the radar returns and the time scale is calibrated from the period of a supplied oscillator to an accuracy of approximately ± 3%.

To profile with the radar, the antenna is towed over the ground and the echo returns are displayed graphically on electrochemically treated paper. The graphic record is a parallel series of amplitude vs time (A-scope) displays in which graphic darkness is proportional to the intensity of the return signal and the vertical axis is round trip return time. The horizontal axis is distance (antenna position). Figure 1 shows an idealized radar return and the corresponding translation into a graphic record should that return be unchanged over a short profiling distance. Because several peaks are contained in one pulse or "event," the graphic display of a pulse lasts considerably longer than one period of the pulse center frequency. Consequently, closely spaced returns may appear as one long, continuous oscillation on the graphic. Although the radar will transmit a pulse that has a center frequency of about 300 MHz into free space, the ground loads the antenna sufficiently

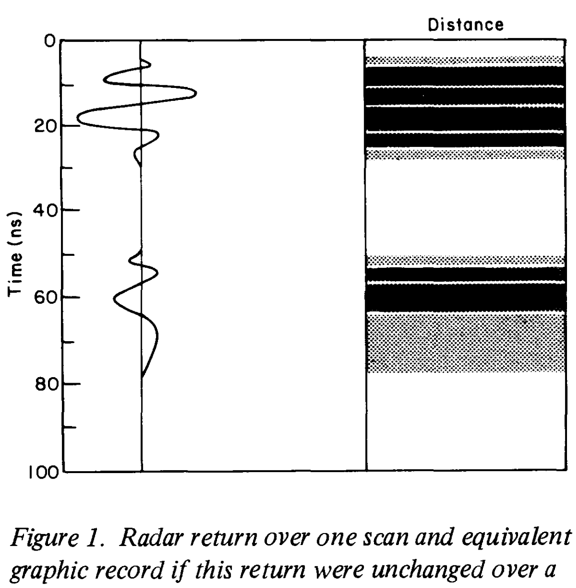


Figure 1. Radar return over one scan and equivalent graphic record if this return were unchanged over a series of scans. A "start of scan pulse" (not shown) initiates a system sweep of the echoes.

to reduce this to about 150 MHz. Increased gain is supplied to the later returns. The estimated performance figure is about 60 to 70 dB.

BURIED REFLECTORS

Sand and gravel site

This site was situated on part of a large esker deposited in the Connecticut River Valley near Hanover, New Hampshire. Four 1.2- x 2.4-m (4- x 8-ft) metallic reflectors were buried at various depths. Three of these were placed horizontally and one was placed on an incline. The horizontal reflectors were buried under the local sand and gravel to depths of 1.0, 1.8 and 2.9 m, while the ends of the sloping reflector were 1.5 and 2.9 m from the surface. Although the natural bedding and structure were disturbed over the reflectors, the density should have been close to that of the undisturbed adjacent sediments since the material was compacted when it was returned to the hole. However, the moisture content was probably less because of exposure to the air during excavation.

An example of the radar returns from the horizontal reflectors is shown in Figure 2. These returns allowed computation of the dielectric constant for both disturbed and undisturbed material. Values for the disturbed sediments were calculated from travel times measured directly above the reflectors using

$$\epsilon = \left(\frac{ct}{2d}\right)^2 \qquad (1)$$

where c is free space velocity of light, t is round trip time of return and d is the depth of the reflector. Undisturbed values were calculated from the diffractions (flat-topped hyperbolas of Fig. 2) off the edges of the reflectors. In this case ϵ is computed from the formula

$$\epsilon = \left(\frac{c}{m}\right)^2 \qquad (2)$$

where m is the distance/time slope of the linear portion of the hyperbola. This procedure is valid because the holes were just large enough to accept the reflectors, thereby providing a path through undisturbed material when the antenna was moved away from the reflectors. This was particularly true of the hole width that was surveyed on the eastwest transects; it provided the least disturbance for the edge diffractions.

The dielectric data for the three reflectors are compiled in Table 1. Values for the disturbed material are consistently lower than those computed for the undisturbed material on the east-west transects; this is most likely due to the drying effect of excavation.

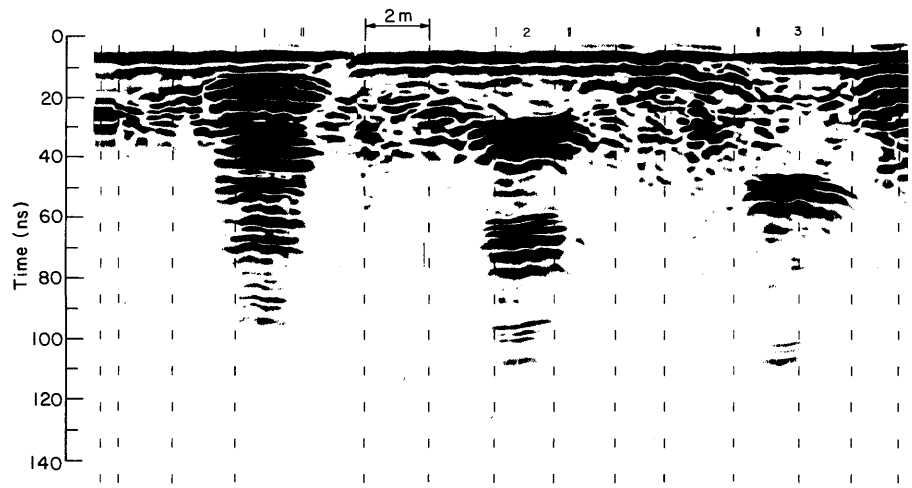


Figure 2. Radar profiles of 1.2- x 2.4-m reflectors buried in alluvial gravel. The reflectors range in depth from 1 m at no. 1 to 2.9 m at no. 3.

Table 1. Dielectric constant data from reflectors buried near Hanover, New Hampshire.

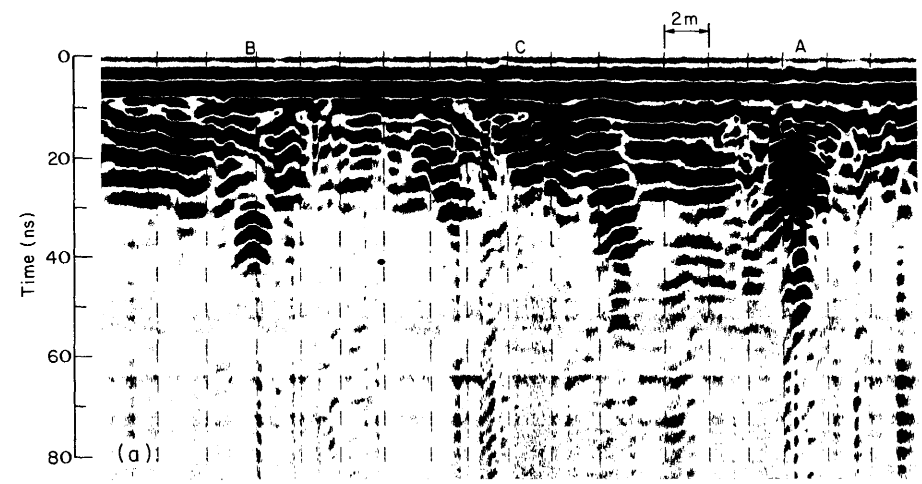
	Vertical distance (m)	*Horizontal distance from edge (m)*	*Direct distance to edge (m)*	*Travel time (ns)*	*Dielectric constant*	*Average dielectric constants*
		Shallow 1.2- x 2.4-m reflector				
	1.00	0.75	1.24	17.5	4.9	
N-S transect*	1.00	0.30	1.03	15.0	5.3	5.5
	1.00	0.52	1.12	18.0	6.3	
Above	1.00	-	-	13.9	4.9	5.0
reflector	1.00	-	-	14.0	5.0	
	1.00	0.90	0.90	24.0	7.8	
E-W transect†	1.00	0.44	0.44	19.5	7.9	7.6
	1.00	0.75	0.75	21.5	7.3	
		Mid-depth 1.2- x 2.4-m reflector				
N-S transect	1.8	1.23	2.21	34.5	5.8	5.9
	1.8	0.60	1.93	30.5	5.9	
Above	1.8	-	-	28.9	6.0	6.0
reflector	1.8	-	-	29.2	5.9	
E-W transect	1.8	0.50	1.89	31.0	6.8	6.8
		Deep 1.2- x 2.4-m reflector				
N-S transect	2.9	1.89	3.40	55.0	6.1	6.1
Above	2.9	-	-	48.3	6.5	6.6
reflector	2.9	-	-	48.6	6.6	
	2.9	3.25	4.35	85.0	8.8	
E-W transect	2.9	1.15	3.15	58.5	8.0	8.2
	2.9	1.55	3.28	60.0	7.8	

*N-S transects correspond to the 2.4-m dimension of the reflectors.
†E-W transects correspond to the 1.2-m dimension of the reflectors.

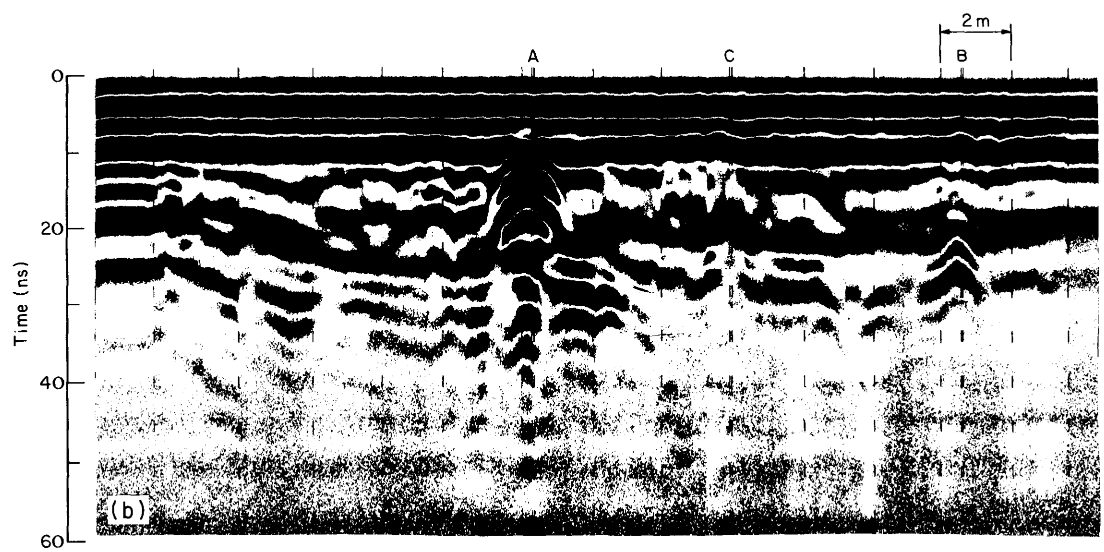
The average dielectric constant values above the reflectors and along both transects are also given in Table 1. For the sloping reflector, the disturbed average was 6.1 compared with 7.0 for the adjacent undisturbed material. The large contrast of amplitude with background noise and the clear presence of multiple reflections on the records (noted in Fig. 2) indicated a low dielectric loss with probable penetration to well over 6 m. The permittivity of dry sand has been measured at 2.5 to 3.0 (Hoekstra and Delaney 1974), which indicates the influence of soil moisture at this site. Based on these studies a dielectric constant ranging between 5.0 and 8.0 was to be expected for unfrozen alluvial sand and gravel.

Silt site

This site was located at CRREL's original Alaskan Field Station north of Fairbanks, Alaska, on Farmer's Loop Road. It was previously used for permafrost degradation studies by Linnell (1973) and was selected by us because 1) one area provided a fairly thick thawed silt section where permafrost had melted to a depth of at least 7.0 m because of removal of the vegetation and organic cover, 2) the electrical properties of the fine-grained material would provide an excellent contrast with those of the sand and gravel previously studied, and 3) its electrical properties were expected to be similar to those of the active layer in major segments of Alaska's permafrost terrain as well



a. September 1980.



b. April 1981.

Figure 3. Radar profiles over three buried reflectors in moist silt at the Alaska Field Station. The ground surface was frozen when profile b was made.

Table 2. Dielectric constant data from Alaska reflectors.

			Thawed surface layer (Sept)		Frozen surface layer (April)	
Reflector	Reflector depth (m)	Material	Travel time (ns)	Dielectric constant	Travel time (ns)	Dielectric constant
A	0.60	Silt	16.5	17.6	9.5	6.3
B	1.10	Silt	28.2	15.5	18.5	6.9
C	1.83	Silt*	62.0†	26.4	49.5	17.0

*Near saturation.
†Estimated.

as those in poorly drained sites that have fine-grained soils and no permafrost. The material ranged from silt to organic silt. The area was previously examined with other geophysical methods that indicated the silt was electrically homogeneous with a d.c. resistivity of about 40 ohm-m when thawed (Arcone et al. 1978).

Three circular metalic reflecting plates were installed horizontally in 0.7-m diameter drill holes at depths of 0.6, 1.1 and 1.8 m. Installation at a greater depth was limited by the high moisture content of the sediments which caused the hole walls to be unstable. The horizontal position of the reflectors are labeled A, B and C in Figures 3a and b, which show the radar profiles made in September 1980 and April 1981 respectively. The dark bands along the top of each profile are the reflections from the ground surface. No other uniform horizontal reflection is seen in the September profile because the ground is completely thawed to a depth greater than the penetration capability of the radar. Definite hyperbolic returns are visible from reflectors A and B, and a marginal return is evident from reflector C.

Table 2 shows the dielectric constant values calculated for the thawed silt from the time delays of the reflector echoes. The average is 16.5 as calculated from the leading edge of the arrival. The use of this reference point gives the correct value for the real part of the relative permittivity for this kind of material (Arcone 1981), which exhibits relaxations in the GHz range. The d.c. resistivity value of 40 ohm-m is equivalent to an imaginary relative permittivity of 3.0 at 150 MHz and causes almost 50 dB of attenuation over the round trip distance of 3.6 m for reflector C. If this attenuation is added to the losses suffered from normal beam spreading, the total signal loss is over 60 dB, which is approximately the estimated performance figure of the radar without considering losses due to the finite size of the reflector. This can explain the lack of strong returns from reflector C in the September survey.

The April profile in Figure 3b also shows strong responses only from reflectors A and B. This is due to the energy lost on reflection from the interface between the seasonally frozen surface layer and the thawed silt beneath. The reflection from this interface is the dark band running across the record at 18-19 ns delay and coinciding with the return from reflector B. A dielectric constant of 6.9 was calculated for this frozen layer from the known reflector depth (Table 2). Since the average dielectric constant of the thawed silt was calculated to be about 16.5, and the resistivity of the frozen silt is well over several hundred ohm-m, the absolute value of the complex reflection coefficient R^* of the freeze/thaw interface can then be estimated from the formula

$$R^* = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}^*}{\sqrt{\epsilon_1} \quad \sqrt{\epsilon_2}^*} \tag{3}$$

where ϵ_1 and ϵ_2* are the relative dielectric permittivities of the frozen and thawed materials respectively. Substituting for these values gives us

$$R^* = \frac{\sqrt{6.9} - \sqrt{16.5 - j3.0}}{\sqrt{6.9} + \sqrt{16.5 - j3.0}} \tag{4}$$

assuming no major contributions to the imaginary part at VHF from relaxation processes. The absolute value of R^* is then 0.32 which corresponds to approximately 13 dB of loss upon reflection. This loss, when added to an additional loss of about 20 dB in the thawed silt and about 12 dB due to beam spreading, gives an estimated total propagation loss of at least 45 dB. Additional losses due to the finite size of the target would then allow the total loss to be comparable to the performance figure of the radar and explain why the return from reflector C was so weak in the April survey.

GROUNDWATER INVESTIGATIONS

The above investigations led us to conclude that penetration beyond about 1 to 2 m in high moisture content thawed silt was not possible and also highly unlikely if freeze/thaw interfaces occur. The higher near-freezing temperatures and associated unfrozen water in the perennially frozen silt in the Fairbanks area could bring signal losses fairly near those observed for temperatures above freezing, and could make radar observations below 2 to 3 m difficult in this material. Therefore, because of these penetration problems, we decided to concentrate only on sites containing sand and gravel. There is also the added advantage that the water table would form a more detectable sharp transition in electrical properties in these coarse-grained sediments.

Sites 1 and 2 at Fort Wainwright

Two sites on coarse-grained alluvial material deposited by the Chena River were chosen at Fort Wainwright. The material was mapped as Chena Alluvium by Péwé et al. (1976), a deposit that is generally free of permafrost. The top of the static water table was reported to be at about 3 m, but it depends on the local topography (Péwé 1975, Péwé and Bell 1976, Nelson 1978). This general location seemed ideal since the depth to the water table was certainly within the detection capability of the equipment. The sites were profiled in late April before surface thaw had begun.

Site 1 was adjacent to the Chena River. The surface vegetation had been removed but no additional site modification was apparent. The radar profile of this location is shown in Figure 4. The record contains two distinct reflection horizons. The upper horizon A is thought to correspond with changes in material type within the alluvium, particularly since it lacks lateral continuity. Arcone and Delaney (1982) have calculated a dielectric constant of 4.8 for this cold, icy gravel, which would put horizon A at a depth of approximately 2.6 m. The reflections constituting horizon B continue across the entire record at a uniform delay, are less distinct, and have a lower frequency content then the overlying layer. These differences suggest a more widespread and dielectrically dispersive type of material for the sediment below the second horizon. Our choice was that this is the water table, which was estimated to be at about the 5.1 m depth by measurement of the elevation above the nearby Chena River. The time delay of horizon B relative to A corresponds to a dielectric constant of about 3.0 for the remaining 2.5 m between the two horizons. This is a typical value for a dry sand or gravel (Hoekstra and Delaney 1974).

Site 2, also at Fort Wainwright, was also selected because of the shallow depth to the groundwater table. It was located near the edge of a gravel pit on the southeast corner of the Fort. All surface vegetation has been removed from the site and part of the area was deeply excavated, creating a small pond. We assumed the elevation of the pond surface to be the position of the groundwater table in the adjacent terrain, about 1.85 m below the surface along which a profile was run on 25 Arpil 1981.

The profile in Figure 5 was run along the gravelly surface near the pond edge. The first series of dark bands are reflections from the ground surface immediately below the antennas. Only one significant and continuous reflector occurs below these surface

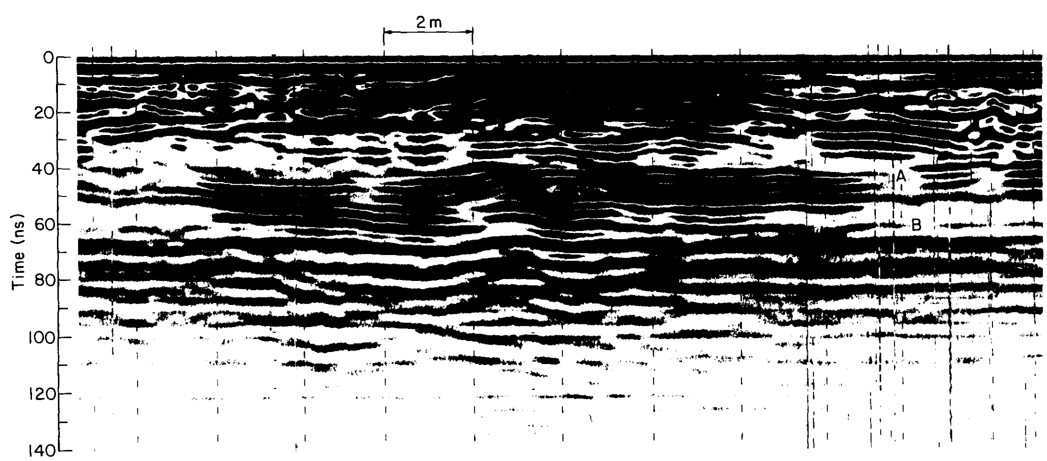


Figure 4. Two natural reflectors in thawed alluvium at site 1, Fort Wainwright, near the Chena River. The first at horizon A is thought to be caused by a change in material types. Horizon B correlates with the position of the groundwater table at a depth of about 5.1 m.

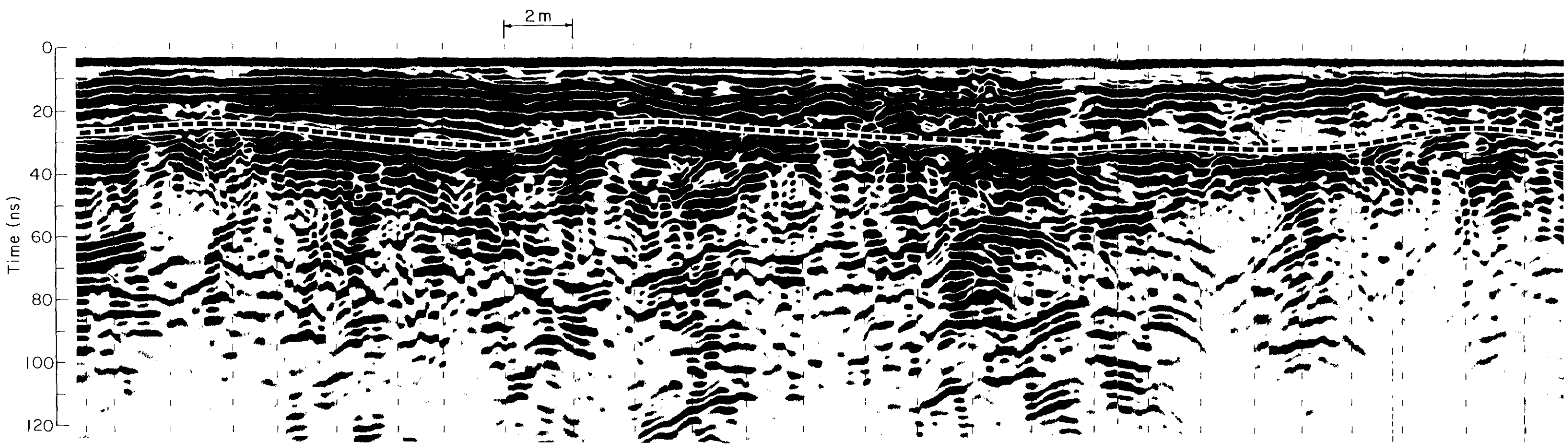


Figure 5. Radar profile of the gravel pit at site 2, Fort Wainwright. The shallow reflector at the approximately 1.85-m depth is shown by a dashed line and corresponds to the projected depth of the groundwater table in this coarse-grained alluvium.

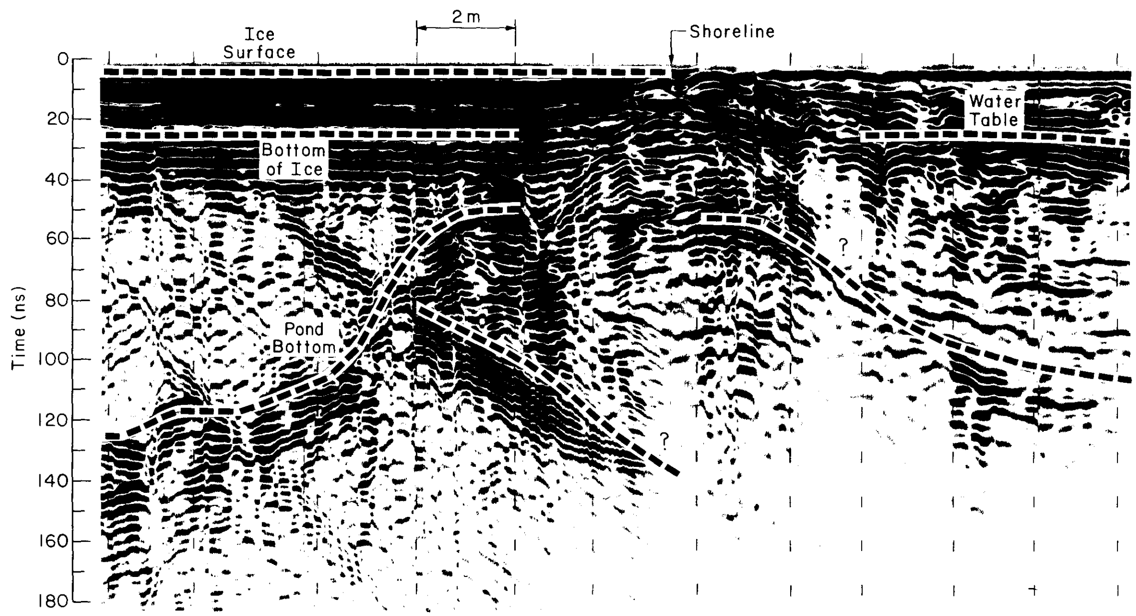


Figure 6. Radar profile of the shoreline transition at site 2, Fort Wainwright, Alaska.

reflections and it shows only minor variations in its two-way travel times, which range from 22 to 28 ns. Assuming the water table to be uniform at 1.85 m, we found that these travel times would give a range for the dielectric constant of 3.2 to 5.2, values that closely agree with those calculated for site 1.

The profile in Figure 6 started on the ice surface near the center of the pond and then traversed the bank to intersect the previous profile at right angles. The pond segment is seen on the left and contains reflections from the ice cover and pond bottom. The return from the ice bottom is delayed about 20 ns. The ice cover was extremely decomposed, consisting of candle ice with a hard surface layer only a few cm thick. Dielectric constant determinations for the ice cover were not possible due to difficulties in measuring the thickness of the deteriorated ice. The central part of Figure 6 shows the transition from the ice cover to frozen sediments. This is complicated because the radar was towed up the sloping bank for several meters thereby changing the radiation angle for this segment of the profile. At the extreme right, a horizontal reflector at about 23 ns is probably the assumed water table horizon seen in Figure 5.

Site 3 at Donnelly Dome

This area is a glacial outwash plain consisting primarily of stratified sand and gravel located near Fort Greely, Alaska. The location was selected for study because Church et al. (1965) and Péwé and Holmes (1964) reported a water table in drill holes at the 14.9-m depth and a perched water table at a depth of 7.3 m. The north end of our study area was located near one of these drill holes. The profile shown in Figure 7 was part of a 1-km profile run along a temporary runway surface. Construction of this runway did not significantly modify the natural ground conditions.

The profile shows several localized returns within the first 60 ns and then a continuous reflector with a slight slope, ranging between 110 and 130 ns. The two-way travel time to the reflector ranged from 110 ns at the north end to 168 ns on the southern end of the profile (the total profile is not shown). We obtained a dielectric constant of 5.5 for the materials in the upper 2 to 3 m at this site by WARR methods (Arcone and Delaney 1982). This value places the reflector at a depth of 7.1 m on the north end and 10.8 m at the south end. The calculated depth at the north end of the line agrees with the observed depth of 7.3 m for the perched water table in this area. The radar profile suggests that the water table or impermeable horizon supporting it is continuous and has a gentle slope of about 0.2° (relative to the surface) to the north. This slope is in the logical direction since further to the north at the edge of the outwash the groundwater table surfaces in springs (Church et al. 1965). This slope is also suggested by the data for the deeper water table obtained from drill holes to the south and the hole near the northern end of our line (Péwé and Holmes 1964, Church et al. 1965).

It is extremely unlikely that we could have observed reflectors below the perched water table because of the energy lost to the reflections from this higher water table. If the reflector in this profile had been the deeper water table, an unrealistic dielectric constant of 1.2 would have been required for these materials to justify the observed time delay.

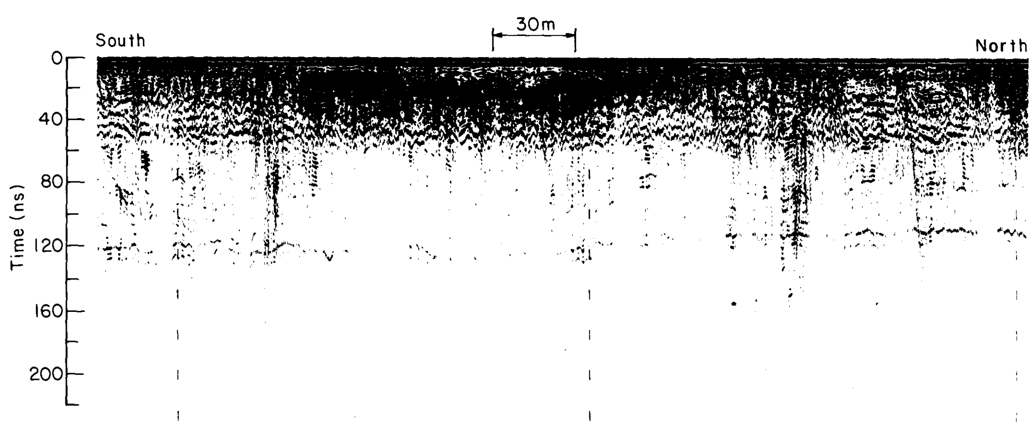


Figure 7. Deep (7 to 11 m) continuous reflector in glacial outwash at site 3, Donnelly Dome. The depth of the reflector corresponds with a perched water table observed in a drill hole.

SUMMARY AND CONCLUSIONS

This report has presented some investigations of ground radar performance over frozen and thawed silts, and sands and gravels containing artificial (metal sheets and discs) and natural (groundwater table, freeze/thaw interfaces) reflectors. Severe losses in amplitude due to absorption and interfacial reflections limited signal penetration in silts to less than 2 m. The low-loss nature of the sands and gravels in most frozen and thawed states allowed much better penetration and detection of the groundwater table, in one case, at depths between 7 and 11 m. Dielectric constants for the thawed silts were measured at about 16 to 18, 6 to 7 for the frozen silts and about 3 to 9 for the sands and gravels, some of which were also frozen.

The poor penetration of the radar signals in thawed silt or beyond freeze/thaw interfaces demonstrated the inadequacy of a 60-dB dynamic range for surveying of this kind of material with radar. However, greater penetration may have been achieved in better drained upland silt. Arcone (1981) has shown that pulse waveform degradation can be so severe in high moisture content silt that returns may be difficult to recognize even with improvements in amplification and signal-to-noise ratio. The use of higher frequencies would be influenced by absorption due to dielectric relaxation, but lower frequencies would give better penetration because skin depth becomes inversely proportional to the square root of frequency below about 30 MHz. Therefore, we conclude that areas containing thawed wet silt would only be effectively penetrated to more than 2 m at significantly lower frequencies.

The radar performed well in the sands and gravels and the results at Donnelly Dome apparently approached the limit of this system. Not only do deeper water table reflections become weaker but they also become more diffuse as evidenced by the apparent change in waveform seen at site 1 at Fort Wainwright. Ionic conductivity can make wet materials slightly dispersive in this radar frequency range of 75 to 225 MHz and so the water reflection could cause some waveform degradation. However, waveform degradation was not so severe that greater depths of penetration could not be realized by improvements in signal processing.

It was also very helpful to have an independent method for obtaining dielectric properties. In these studies we used buried reflectors and wide angle reflection and refraction (WARR) profiling. The latter method has been discussed by Arcone and Delaney (1982) and Annan and Davis (1976). If reflectors at some known depth are not available, we highly recommend the WARR method for providing necessary dielectric property data.

Currently, some radar systems are approaching 120 dB performance figures using digital noise reduction techniques. Table 3 presents some approximate ranges of depth that may be explored with such systems in a variety of materials. Although

Table 3. Expected radar performance for a variety of sedimentary materials.

*Material**		*Approximate resistivity range (ohm-m)*	*Approximate range of radar exploration depths* (m)* 50 MHz†	100 MHz	150 MHz
Glacial lake sediments— clayey soils	Thawed	10–100	1–4	1–3	<1–2
	Frozen	20–1000	2–12	1–9	1–7
Loess deposits— silty soils	Thawed	20–300	2–7	1–5	1–4
	Frozen	300–5000	7–25	5–18	4–15
Wind and stream transported material— sandy soils	Thawed	500–5000	9–25	6–18	5–15
	Frozen	1000–10000	12–34	9–25	7–20
Stream deposits and glacial outwash—alluvial sand and gravel	Thawed	500–5000	9–25	6–18	5–15
	Frozen	1000–10000	12–34	9–25	7–20
Glacial till—rocky soils with a clay fraction	Thawed	10–5000	1–25	1–18	<1–15
	Frozen	100–10000	4–34	3–25	2–20

*Based on a maximum radar performance figure of 120 dB. Calculation based on consideration of electrical properties of the soil and geometric spreading losses. Losses due to target reflection, intermediate reflections and scattering not considered.
†Frequencies refer to center of pulse spectrum.

there is a great deal of variation in the ranges given, this information should help in evaluating whether or not radar is the appropriate method for use in a given situation.

LITERATURE CITED

Annan, A.P. and J.L. Davis (1976) Impulse radar sounding in permafrost. *Radio Science,* **11**(4): 383-394.

Annan, A.P. and J.L. Davis (1977) Impulse radar applied to ice thickness measurement and fresh water bathymetry. Geological Survey of Canada, Report of Activities, Part B, Paper 77-1B.

Arcone, S.A. (1981) Distortion of model subsurface radar pulses in complex dielectrics. *Radio Science,* **16**(5): 855-864.

Arcone, S.A. and A.J. Delaney (1982) Measurement of ground dielectric properties using WARR. CRREL Report 82-6.

Arcone, S.A., P.V. Sellmann and A.J. Delaney (1978) Shallow electromagnetic geophysical investigations of permafrost. In *Proceedings, Third International Conference on Permafrost, Edmonton, Alberta,* vol. 1, pp. 501-507.

Arcone, S.A., A.J. Delaney and P.V. Sellmann (1979) Detection of arctic water supplies with geophysical techniques. CRREL Report 79-15.

Church, R.E., T.L. Péwé and M.J. Anderson (1965) Origin and environmental significance of large-scale patterned ground, Donnelly Dome area, Alaska. CRREL Research Report 159.

Davis, J.L., W.J. Scott and A.P. Annan (1976) Impulse radar experiments on permafrost near Tuktoyaktuk, N.W.T. *Canadian Journal of Earth Sciences,* **13**: 1584-1590.

Feulner, A.J. (1961) Geology and water conditions at Ladd Air Force Base, Alaska. USGS Hydrol. Data Report 13.

Hoekstra, P. and A. Delaney (1974) Dielectric properties of soils at UHF and microwave frequencies. *Journal of Geophysical Research,* **75**(11): 1699-1708.

Kovacs, A. (1978) Remote detection of water under ice-covered lakes on the North Slope of Alaska. *Arctic,* **31**(4): 448-458.

Linell, K.A. (1973) Long-term effects of vegetation cover on permafrost stability in an area of discontinuous permafrost. In *Permafrost: the North American Contribution to the Second International Conference, Yakutsk, USSR.* Washington, D.C.: National Academy of Sciences, pp. 688-693.

Nelson, G.L. (1978) Hydrologic information for land use planning, Fairbanks vicinity, Alaska. USGS Open-File Report 78-959.

Péwé, T.L. (1975) Map showing groundwater conditions in the Fairbanks D-2 SE quadrangle, Alaska. USGS Miscellaneous Field Studies Map MF-669B.

Péwé, T.L. and G.W. Holmes (1964) Geology of the Mt. Hayes D-4 Quadrangle, Alaska. USGS Miscellaneous Geologic Investigations, Map I-394.

Péwé, T.L. and J.W. Bell (1976) Map showing groundwater conditions in the Fairbanks D-2 SW quadrangle, Alaska. USGS Miscellaneous Investigations Series, Map I-829C.

Péwé, T.L., J.W. Bell, R.B. Forbes and F.R. Weber (1976) Geologic map of the Fairbanks D-2 SE quadrangle, Alaska. USGS Miscellaneous Investigations Series, Map I-942.