Winter Short-Pulse Radar Studies on the Tanana River, Alaska

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ABSTRACT. Subsurface profiles were obtained during airborne and surface short-pulse radar surveys along a winter roadway over the Tanana River near Fairbanks, Alaska. The roadway crossed ice-covered channels and intervening frozen channel bars. The airborne profiles were intended for ice thickness profiling but also revealed sporadic reflections from a deeper horizon beneath the bars. Later profiling from the surface recorded these deeper reflecting horizons in detail, and they were found to correspond with the base of seasonal frost, measured in drill holes. The sediments immediately beneath the frozen material were saturated and represented the top of a seasonally variable groundwater table confined and controlled by frost penetration. The profiles made from the surface also revealed reflections from the bottom of the ice and the channel bottom. However, no significant reflections were observed beneath the channel bottom; reflections from sloping horizons above and below the base of the frost in the bar may indicate alluvial bedding patterns in these deposits. Eleven holes were drilled along the roadway to determine ice thickness, water depth, frost depth and the depth to the river ice-alluvium contact. Wide-angle reflection and refraction soundings were also made to determine electrical properties of materials and to verify our depth interpretations from echo times. These observations indicate that the airborne technique provides an effective method of locating unfrozen channels and measuring the depth of frost penetration beneath bars. The surface surveys revealed additional data on sedimentary structure.

Key words: short-pulse radar, airborne surveys, dielectric permittivity, groundwater, alluvial-bedding patterns, ice thickness, Tanana River, Fairbanks, Alaska

RÉSUMÉ. Au cours de relevés aériens et terrestres effectués à l'aide d'un radar à impulsions courtes, on a obtenu des profils du dessous de la surface le long d'une route d'hiver sur la rivière Tanana, près de Fairbanks en Alaska. La route traversait des chenaux couverts de glace et des bancs gelés apparaissant à certains intervalles dans le chenal. Les profils aériens devaient donner le profil de l'épaisseur de la glace, mais ils ont aussi révélé des réflections sporadiques venant d'un horizon plus profond sous les bancs. Les profils obtenus par la suite à partir de la surface ont révélé en détail ces horizons de réflection plus profonds, et on a trouvé qu'ils correspondaient à la base du gel saisonnier, mesurée dans des trous de forage. Les sédiments venant tout de suite sous les matériaux gelés étaient saturés et représentaient la partie supérieure d'une nappe phréatique variant avec les saisons, délimitée et contrôlée par la pénétration du gel. Les profils obtenus à partir de la surface ont aussi révélé des réflections depuis la partie inférieure de la glace et le fond du chenal, mais on n'a observé aucune réflection significative venant de dessous le fond du chenal; des réflections d'horizons inclinés au-dessus et au-dessous de la base du gel dans le banc indiquent peut-être certains agencements de couches alluviales dans ces dépôts. On a foré onze trous le long de la route pour déterminer l'épaisseur de la glace, la profondeur de l'eau, la profondeur du gel et la profondeur du contact entre la glace de rivière et les alluvions. On a aussi effectué des échographies de réflection et de réfraction grand-angle pour déterminer les propriétés électriques des matériaux et pour vérifier nos interprétations de la profondeur à partir du temps d'écho. Ces observations montrent que la technique de relevés aériens représente une méthode efficace pour localiser les chenaux non gelés et pour mesurer la profondeur de la pénétration du gel sous les bancs. Les relevés effectués à partir de la surface ont permis d'obtenir des données supplémentaires sur la structure sédimentaire.

Mots clés: radar à impulsions courtes, relevés aériens, constante diélectrique, eau souterraine, agencement des couches alluviales, épaisseur de la glace, rivière Tanana, Fairbanks, Alaska

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INTRODUCTION

Under some circumstances, radar surveying using short pulses in the very high frequency (VHF) and ultra high frequency (UHF) bands is a viable method for shallow subsurface exploration. Given a relatively smooth surface of low reflectivity, airborne transmitted radar signals in the 50-1000 MHz band can penetrate on the order of metres into frozen sediments and on the order of kilometres into glacial ice. One application of interest in the Arctic and Subarctic is locating winter water supplies because of the scarcity of surface and ground water. During the winter, water may be found beneath thick seasonal frost and in isolated pockets beneath ice-covered streams and lakes, most of which freeze to the bottom. This report discusses a survey that utilizes radar's ability to measure ice thickness and provides data on its capability to locate channels and measure the thickness of deep seasonal frost over saturated sediments in an alluvial setting common to the Arctic and Subarctic.

Previous investigations using radar in the Arctic and Subarctic have included studies of active layer characteristics (Arcone *et al.*, 1982), general permafrost distribution and detection of associated massive ice (Bertram *et al.*, 1972;

Annan and Davis, 1976, 1977b; Kovacs and Morey, 1979, 1985; Pilon *et al.*, 1985; Haley, 1988) and sea, lake and river ice thickness (Campbell and Orange, 1974; Kovacs, 1978 a,b; Arcone and Delaney, 1987; Annan and Davis, 1977a, 1978; Kovacs and Morey, 1985; Delaney and Arcone, 1988). The electrical properties of ice-rich silt and frozen alluvium that determine wave speed at short-pulse radar frequencies have been discussed by Arcone and Delaney (1988, 1989). In this paper, we discuss the use of both airborne and ground radar over a braided stream with its many channels and intervening bars. The data on frost depth are interesting, as they were collected in April 1989 after an extended cold period.

In our river ice studies (e.g., Arcone and Delaney, 1987) and in much of our unpublished data, reflections from deep interfaces appear throughout airborne radar traverses over channel bars and in areas where the river ice is frozen to the bed. These reflections have been seen in surveys conducted on the Tanana and Yukon rivers in interior Alaska and on several rivers in northern Alaska. An airborne survey of a series of ice bridges and channel bars recorded in 1988 revealed numerous sporadic reflections from a horizon within the sediments. These reflections were present in areas where the river was frozen to the bed and could be followed beneath

exposed bars and islands. Limited drilling in 1988 suggested that these sporadic reflections represented the interface between the base of seasonal frost and the top of the unfrozen alluvium. The reflections could be interpreted as the depth to a potential water supply and may be of value for arctic and subarctic operations, particularly when river flow in channels becomes isolated or ceases because the ice cover freezes to the bed (Arcone *et al.*, 1989).

This paper discusses these 1988 airborne radar reflections, along with the results of the more detailed profiling from the surface and further drilling during the 1989 winter. The surface profiling allowed greater penetration of the radar signals and better correlation with results of drilling. This profile extended across one channel of the Tanana River and 60 m onto an adjacent channel bar. Additionally, wide angle reflection and refraction (WARR) soundings were made to determine electrical properties of materials and to verify our depth interpretation computed from the echo times.

<div style="text-align:center">METHODS</div>

Site Description

The study area crosses the main channel of the Tanana River south of Fairbanks, Alaska, and is shown in Figure 1. It is part of a winter route extending across Goose Island from South Cushman Street to the Bonnifield Trail and is constructed annually by the U.S. Army Sixth Infantry Division (L). The study line is actually a roadway over three frozen channels and intervening channel bars. The surface of the bars was approximately 1.0 m above the ice surface in the channels. The ice is thickened over the channels by
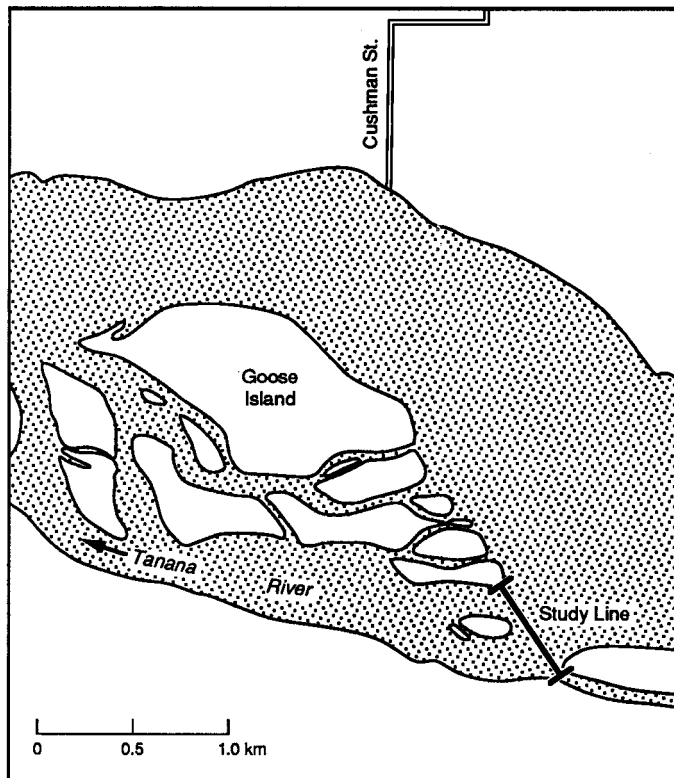

FIG. 1. Location map showing the Tanana River near Fairbanks, Alaska. The ice bridges extend from the southern tip of Goose Island to the Bonnifield Trail south of the river.

artificial surface flooding to provide an adequate ice cover for heavy equipment and to extend the period of use, both early and late into the season. Holes were augered through the frozen sand and gravel to the saturated unfrozen sediment below. The grain size of the sediments was extremely variable, as would be expected for alluvial deposits. The sediments included clean sands, sandy silts, and sandy gravels, with the gravelly horizons containing pebbles up to 7-10 cm in diameter. Ice thickness and water depth were determined at seven locations along the ice bridge roadway to establish where the ice was in contact with the river bottom.

Radar

The system used for these investigations consisted of a short-pulse radar control unit and data recorder coupled to a 500 MHz bi-static transducer. The control unit triggers pulses at a pulse repetition frequency (PRF) of 51.2 kHz. The received UHF signals are sampled and converted to an audio frequency facsimile for display and simultaneous recording on digital magnetic tape. The reconstructed signal can be displayed over a selected calibrated time range window. Variable time range gain may be applied to the audio scan to suppress the higher amplitude early returns and enhance the lower amplitude later returns (see Morey, 1974, Annan and Davis, 1976, or Arcone and Delaney, 1987, for more complete operating descriptions).

For the airborne survey, the radar control unit was mounted in a Bell 206B aircraft, with the transducer suspended from supports attached to the right-side cargo rack (Fig. 2). The survey altitude was 3-5 m and air speed was approximately 5 m·s^{-1}. In air, the frequency spectrum of the radiated pulse is centered near 500 MHz. For the surface profile the transducer was pulled at a slow walk along the ice surface. An insulated box protected the control unit and tape recorder from low temperatures and blowing snow. The closeness of the antennas to the ground (2-3 cm) in these studies caused an impedance loading that centralized the frequency spectrum to between 300 and 400 MHz.

Interpretation of Graphic Records

Interpretation of short-pulse radar records is dependent upon knowledge of the electrical properties of the subsurface

FIG. 2. Radar transducer on mounting bracket attached to a Bell 206B aircraft.

that determine the propagation speed, v, of radiowaves. Knowledge of v then allows echo return time to be translated into geologic depth. For low loss materials, v depends on the real part K' of the complex relative dielectric permittivity K* of the material such that

$$V = \frac{C}{\sqrt{K'}} \qquad (1)$$

where c = 3 × 10⁻¹⁰ cm·s⁻¹, the speed of electromagnetic waves in free space. The quantity K* = K'-jK″, where K' and K″ are the real and imaginary parts respectively and j = $\sqrt{-1}$. A low loss material is one for which the wave amplitude attenuation rate is low and is generally characterized by K″/K' <0.01.

Three materials were encountered in this survey: water (assumed to be at 0°C), ice and frozen alluvium. A K' of 88 was used for water at 0°C; however, water has such a high attenuation factor for radiowaves in our frequency band that propagation is severely limited. Figure 3 (after Arcone and Daly, 1989) shows the attenuation rate as a function of frequency for water at 0°C. At a frequency of 500 MHz, 1 m (2 m round trip) of relatively "clean" water of 100 ohm-m resistivity will attenuate wave amplitude by 48 dB. The value of K' = 3.2 for ice is well known (e.g., Glen and Paren, 1975). Dielectric permittivity values for some alluvial sediments at −0.4°C were recently measured by Arcone and Delaney (1989) and generally ranged from 4.8 to 5.7 for material near the Chena River in Fairbanks with very low values of K″.
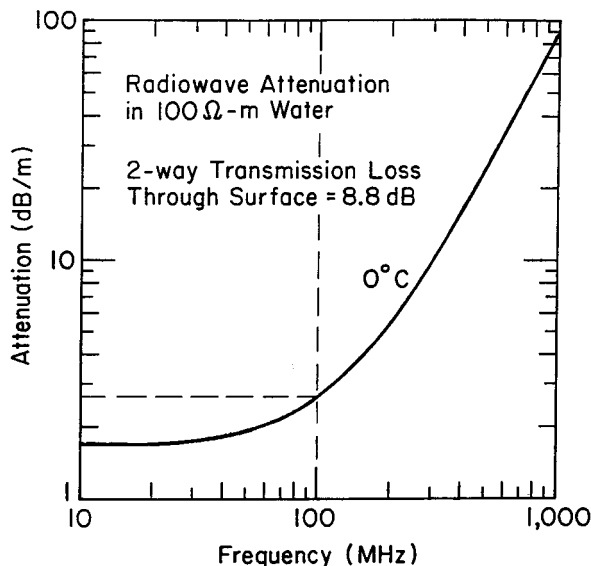
FIG. 3. Attenuation rate of radiowaves in fresh water as a function of frequency at a conductivity of 0.01 S/m (100 ohm-m).

A typical radar graphic record is shown in Figure 4. The formation of the dark bands results from the composite of many scans. An equivalent waveform is shown to the left. The first event is the direct coupling (so labeled) between transmit and receive antennas, which are spaced about 15 cm apart in this antenna housing. The second event, labeled "subsurface reflector," is the pulse reflected from the top of the ice surface. This event occurs at a depth d (cm) such that

$$d = \frac{ct}{2\sqrt{K'}} \qquad (2)$$

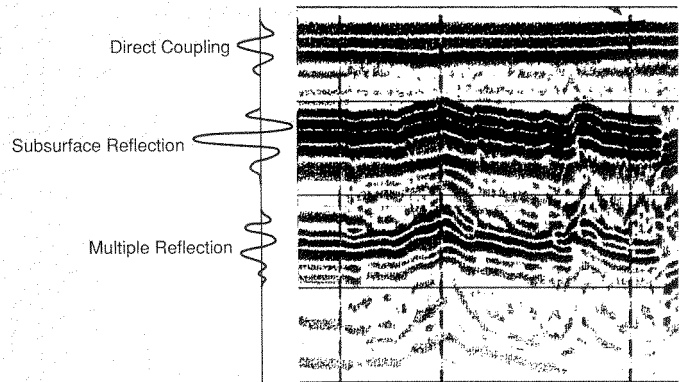where t is the time in nanoseconds measured between the

FIG. 4. Segment of a typical radar graphic record resulting from the composite of many scans.

visual onset of the direct coupling and that of the reflector and c = 30 cm/ns. The factor of two accounts for the round-trip propagation time. A vertical depth scale on the record is then obtained for the material between different horizons from the material electrical properties and radar time range selected.

Drilling

A mobile track-mounted drill rig was used to auger 15 cm diameter holes along the study line. The base of the frost layer was marked when resistance to drilling dropped suddenly and when, upon removal of the auger, water flowed into the hole. In several cases the hole was terminated just before the frozen layer was penetrated. When the remaining thin frozen layer was broken with a steel probe rod, water flowed immediately into the hole (as happened in all cases). Holes were logged by collecting cuttings off the auger flight, and three samples from each hole were oven-dried to obtain an average gravimetric moisture content. Frost had penetrated well below the level to which the ground water would rise (piezometric surface). After allowing sufficient time for stabilization, the depth to the top of the water was measured in each hole. Since the channel bar is completely surrounded by flowing water, the elevation of the piezometric surface should be uniform across the island and was used as datum to determine relative elevation of the ground surface and frost depth.

RESULTS AND DISCUSSION

Airborne Survey

In 1988, three airborne radar profiles spaced 50 m apart were surveyed across the river (one is shown in Fig. 5). The vertical event marks on Figure 5 delineate the limits of the ice bridges. Helicopter speed was variable; therefore, the 100 m distance scale shown on the horizontal axis of Figure 5 for the segment studied on the ground is approximate. Ice bridge 1 was 71 m long, 2 was 138 m long, and 3 was 52 m long. The vertical scale is time in nanoseconds, which translates into 1.38 m/division in air and 0.78 m/division in ice. The wavy character of the reflections across the record was caused by fluctuations in helicopter altitude. The ground survey was placed to correspond with the center line airborne survey over the roadway shown in Figure 5.
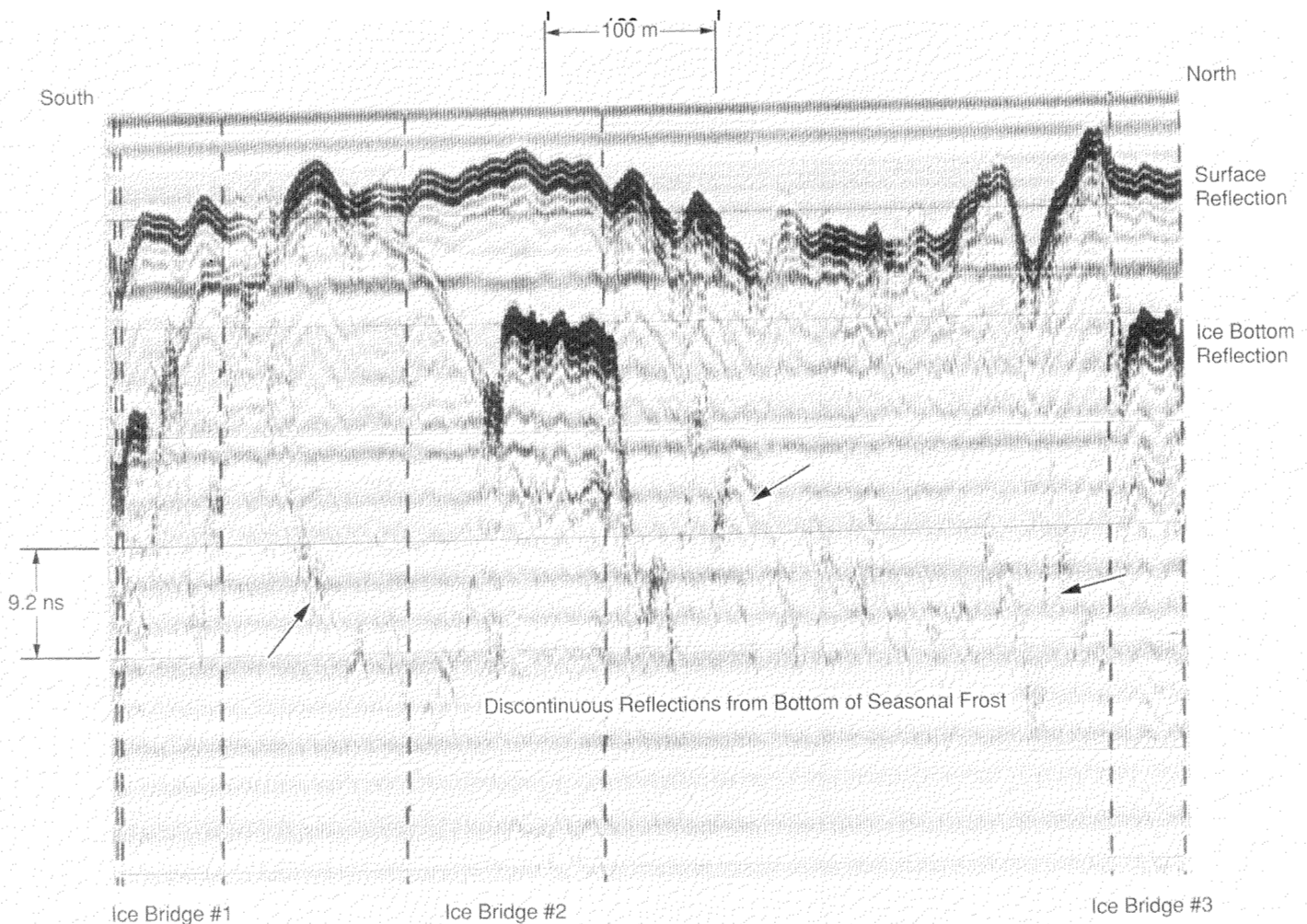
Region of Surface Profile Taken in 1989

FIG. 5. The airborne profile of the entire river cross section recorded in 1988. The first band of reflections is from the ice surface. Below are very strong (dark) reflections indicating water beneath the three ice bridges and fainter reflections where ice is frozen to the bed. Between ice bridges 2 and 3, a discontinuous band of faint reflectors (20-30 ns) occurs below the surface reflection, which is the object of the study. The 100 m segment profiled on the ice surface in 1989 is indicated at the northern margin of ice bridge 2.

The first reflections in Figure 5 are from the ground surface. The later and more intense reflections seen along the ice-bridge sections are from the ice/water transition. At the north side of bridge 1 and the south side of bridge 2, the intensity suddenly abates and the reflections migrate to the surface. This is the zone where ice is in contact with the river bed. Of interest are the faint, discontinuous reflections seen within the channel bars and occurring 20-35 ns after the surface reflection. The record suggests that these reflections represent a continuation of the water/ice interface, which implies that they represent the depth of the seasonal frost (frozen alluvium/saturated sediments). This groundwater may be below the piezometric surface because of frost penetration into the aquifer. Frost penetration measured in a few drill holes ranged from 1.1 to 2.1 m along the same segment of ice bridge roadway studied in 1989.

Surface Radar Profile

The 100 m surface profile recorded in 1989 is shown in Figure 6. The profile has three different subsurface segments:

segment 1, an artificially thickened ice sheet over an actively flowing channel (0-30 m); segment 2, a short transition section where thick ice is frozen to the bed (30-33 m); and segment 3, a channel bar (33-100 m) where thin ice (10-20 cm) overlies frozen sand and gravel and unfrozen material at depth. Snow removal from the roadway and extremely low winter temperatures accounted for unusually deep frost penetration (3.1-3.8 m) measured on 5 April 1989.

Depths to the reflecting horizons were interpreted from the vertical time scale and the material electrical properties were calculated from the echo times and the WARR soundings discussed later. These interpretations were then compared with direct observations from the drill holes.

Segment 1 — Sheet ice over water (0-30 m): Three distinct reflections can be seen in this segment (Fig. 6). Immediately beneath the direct coupling (i.e., the surface) are reflections from the ice/water interface. These reflections arrive 5-13 ns after the direct coupling, which, given the dielectric permittivity for fresh water ice of 3.2, corresponds to an ice thickness of 0.42-1.08 m. The measured ice thickness ranged from 0.40 to 1.20 m at seven locations between 20 and 30 m.
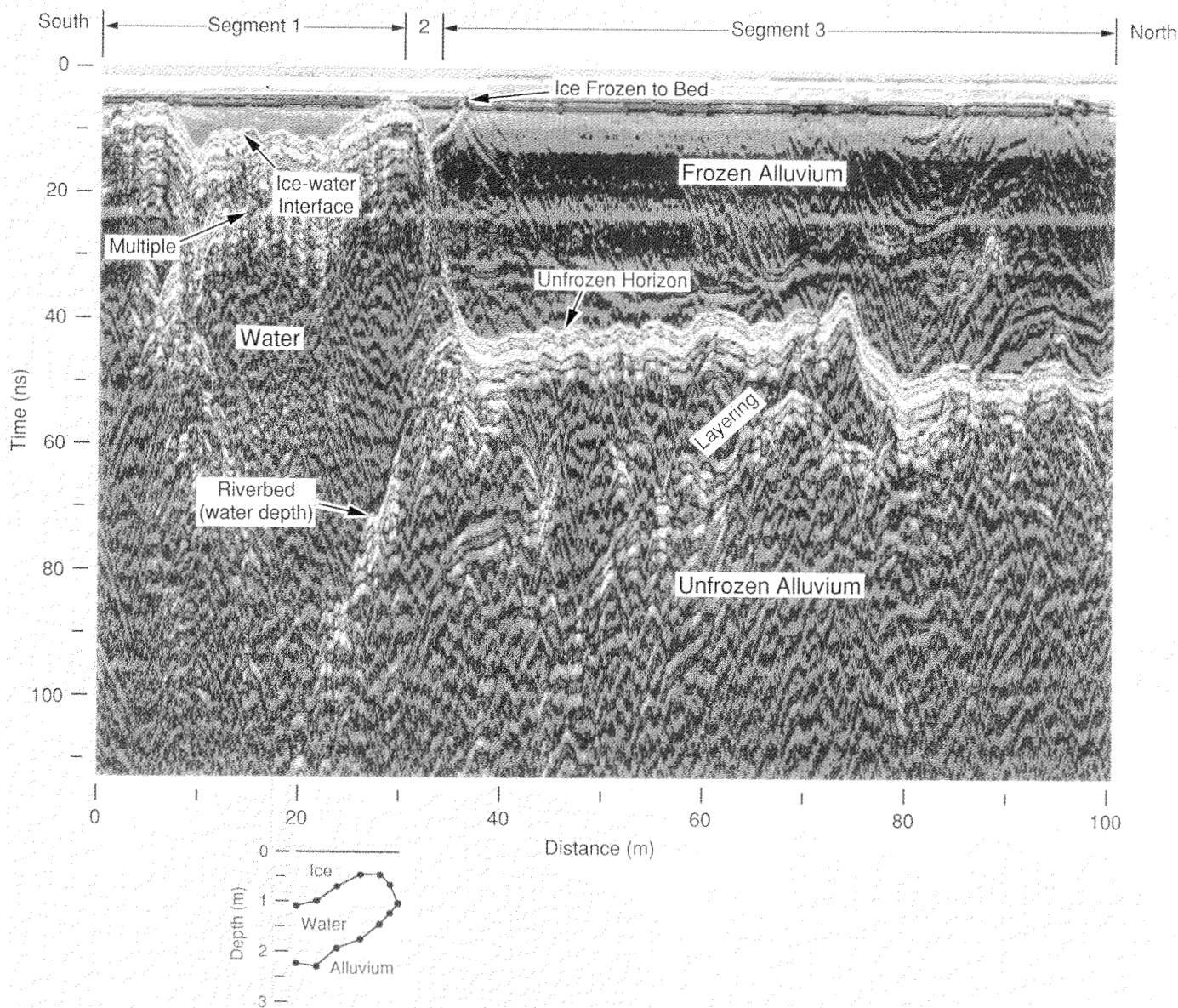
FIG. 6. The 100 m long surface radar profile recorded in April 1989. The profile traverses an ice-covered channel, a segment where ice is frozen to the river bed, and a channel bar segment where thin ice and frozen alluvium overlie a depressed water table. Horizontal distance is in metres, with vertical event marks located every 10 m.

Immediately below and paralleling the ice bottom is a multiple reflection resulting from a strong signal bounce between the ice/air interface and the ice/water interface. A third major reflection occurs between 20 and 27 m, with an arrival time of 56-75 ns after the ice/water interface. This time delay corresponds to a water depth range of 0.90-1.20 m using the value $K' = 88$ for fresh water at 0°C. A profile of measured water depth and ice thickness shown directly below reveals water depth to range from 0.90 to 1.30 m. A round-trip distance of 2.6 m provides at least 42 dB of attenuation in cold water at the radar center frequency of 400 MHz (Fig. 3). This loss does not include interface transmission and reflection losses (at least 18 dB) and geometric spreading losses, all of which explains why reflections from the stream bed disappear rapidly.

Segment 2 — Transition (30-33 m): At 30 m, 1.2 m of ice was frozen to the river bed and at 33 m the ice thickness

thinned to less than 0.10 m. This transition is seen on the radar record by the faint reflections occurring from 3 to 12 ns beneath the direct coupling. The absence of strong reflectors in this short segment of the record may be attributed to the lack of contrast in dielectric permittivity between the ice and frozen alluvium and to the nature of the slope of the reflecting horizons. The radar record suggests a very steep and scoured slope along the transition from the ice/water interface to the water/alluvium interface. Simple wave migration (Robinson, 1983) allows us to interpret this discontinuous time-distance horizon to have an average slope of about 30°. If this slope were more than 45°, no returns would appear, since the radar signals would be reflected away from the direction of the receiving antenna.

Segment 3 — Channel bar: From 33 to 100 m a strong continuous reflection occurs between 34 and 48 ns. These time delays are interpreted as depths ranging from 2.7 to 3.4 m

using the value K' = 4.7, which was determined independently using the WARR method (discussed below). The actual frost depths ranged from 3.1 to 3.8 m at four locations as measured by auguring through the frozen gravel to the unfrozen alluvium. The piezometric surface in the channel bar was 3.0-3.25 m above the transition from frozen to unfrozen alluvium. Therefore, this strong reflection must be the base of the seasonal frost and, in this case, the top of the seasonally confined groundwater aquifer.

Between 40 and 80 m, fainter continuous reflections occur beneath the continuous frost line reflections. This horizon slopes down toward the active channel and is probably associated with a change in material type rather than a change in moisture content. Between stations 80 and 90 m, two distinct reflections with a hyperbolic shape can be seen that may originate from large, anomalous features, such as buried trees. Several other horizons are apparent between 33 and 100 m, although they are much weaker than the continuous reflections from the frost line. These reflections occur both above and below the frozen/unfrozen interface and are shown again, in greater detail, in an enlarged section of the radar record from 50 to 70 m (Fig. 7). Apparent is a series of sloping (south-north) reflections that occur at wave-migrated angles between 12 and 30°. The direction and slope of these reflectors seem to indicate individual layers within the alluvial sediments deposited as the channels of the Tanana River migrated across the flood plain. The source of the reflections within the layers is not known, but it is thought to be associated with the changes in grain size. These migrated angles are only approximate, since the slope also depends on the direction of the radar profile relative to the strike of the bedding, which is unknown.

Electrical Properties from WARR Profiles

This technique is similar to a seismic refraction survey. Separate receive and transmit antennas on the ground surface are continually separated and the travel times of refractions and reflections from interfaces are recorded. The time/distance slopes of the events are converted to a velocity and then a single dielectric permittivity value for the profile. The technique as applied to short-pulse radar has been discussed by Annan and Davis (1976) and Arcone (1984).

Three wide angle reflection and refraction (WARR) profiles, using transverse horizontal polarization, were made between 50-60 and 60-70 m to verify our computation of dielectric permittivity from the drilling results. Between 50 and 60 m, WARR profiles were run in two directions to compensate for possible sloping reflectors. The WARR profile recorded between stations 50 to 61 m (Fig. 8) has the significant events identified. The faint air wave is direct propagation above the surface at a velocity of 30 cm·ns^{-1}. The ground waves identified for this and all of the WARR profiles correspond to a refraction beneath the surface with a velocity of 14 cm·ns^{-1}, or K' = 4.7. The several other reflections seen in the WARR profile are from deeper horizons and merge with the ground wave beyond about 10 m.

The K' value of 4.7 computed from the WARR profiles is very close to the 4.8-5.7 range measured for frozen alluvium using cross-borehole propagation (Arcone and Delaney, 1989). The cross-borehole measurements were made at 100 MHz in perennially frozen alluvium near the Chena River on Ft. Wainwright. The Chena River site is located approximately 8 km NE of Goose Island. Materials at both sites are mapped as flood plain alluvium by Pewe (1958) and had
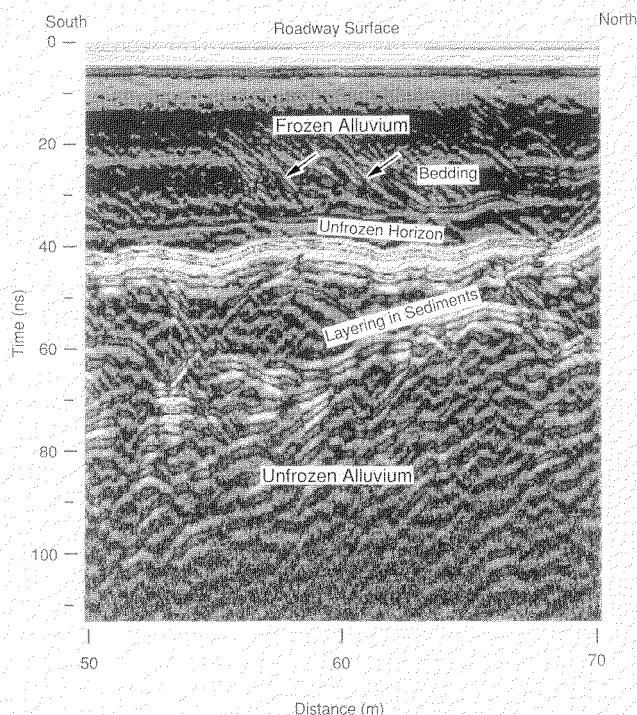
FIG. 7. An enlarged section of the radar profile shown in Figure 6 between 50 and 70 m, showing the detail of weaker reflections originating from both above and below the top of unfrozen material.
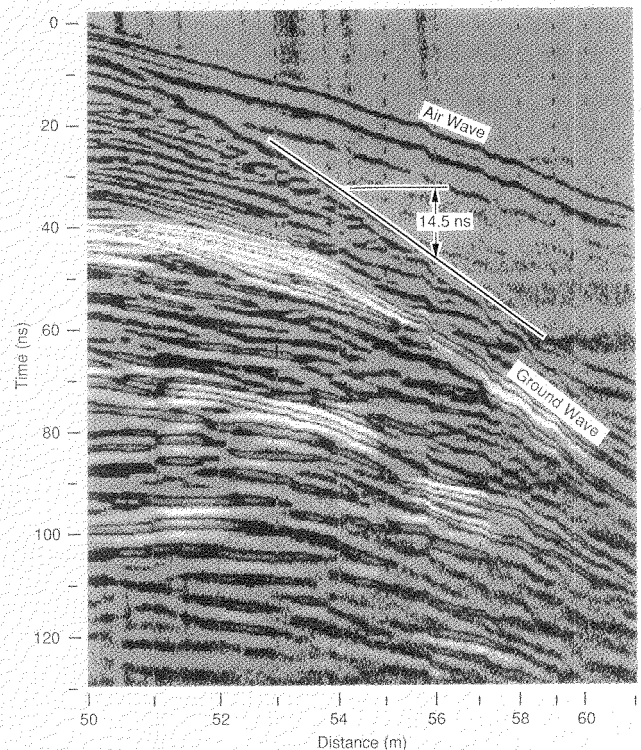
FIG. 8. A WARR profile used to calculate the dielectric permittivity of the frozen alluvium.

similar coarse-grained sediments, based on our drilling observations. Dielectric K' values obtained from the two-way pulse travel times measured on Figure 6 and the measured depth to the unfrozen horizon range from 3.3 to 4.5. These are slightly lower than the WARR value and may reflect inaccuracies in measuring the depth to the exact reflecting horizon, but they are most likely attributable to local variations in moisture content along the study line. The gravimetric moisture content of samples obtained from the borings ranged from 2.8 to 14.2%. The moisture content of samples from the Chena River study ranged from 10 to 40%, which can explain why permittivity values there were higher. Changes in moisture content at subfreezing temperatures can still affect the dielectric permittivity because some moisture remains in a state of unfrozen adsorption on the silt particles in the alluvium (Arcone and Delaney, 1989). The total range of dielectric permittivity (3.1-5.7) for both sites is small for a material with such a wide variation in grain size.

CONCLUSIONS

These investigations show that airborne radar surveys are capable of detecting open channels beneath an ice cover and measuring depth of frost beneath bars in a braided river. Frozen river sand and gravel is an excellent radar propagation medium and horizons should be detectable to 10-12 m depth. Thus, the airborne technique may be an effective way to determine the position of significant anomalies, such as local thaw zones. The surface profile confirmed the unfrozen horizon detected by the airborne survey and revealed structure within the frozen alluvium. Reflections from the the stream bed were seen when water depth beneath the ice was less than 1.3 m.

The low dielectric permittivity values measured for these gravels suggest that detecting frost depth when the underlying unfrozen material is not saturated could be difficult, since little contrast may exist between the permittivity of frozen and unfrozen material. However, despite the very probable lack of dielectric contrast, there are reflections that apparently originate at the interface between ice and frozen alluvium (Fig. 5) and from alluvial layering above the base of the frost (Fig. 7).

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