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Ground penetrating radar surveys along the Norman Wells Pipeline route, 1989-94: a summary of results

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Ground Penetrating Radar Surveys Along the Norman Wells Pipeline Route, 1989-1994

A Summary of Results

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submitted to:

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EXECUTIVE SUMMARY

Ground penetrating radar (GPR) surveys have been conducted along the Norman Wells pipeline route by staff of the Geological Survey of Canada annually since 1989. These surveys were conducted in an effort to monitor thaw conditions on wood chip insulated slopes and as a test of the suitability of GPR for pipeline right-of-way (ROW) mapping. Pipe temperatures were observed to increase with distance south from Norman Wells until 1992, after which new operating conditions warmed pipe temperatures at the more northerly slopes. Hence, the potential for growth or enlargement of thaw bulbs has recently increased beneath many of the wood chip slopes.

Many of the early surveys (1989-1992) were of a cursory nature. Detailed grid surveys were conducted at 10 slopes in late summer 1993. During the summer of 1994, detailed grid surveys were conducted at numerous sites throughout the thaw season, in an effort to follow the seasonal progression of thaw. Surveys were supported with ground-truthing from temperatures measured in boreholes, depth-of-thaw probing, and lithological information from boreholes where available.

A high degree of variability in depth of thaw is suggested for several slopes. For example, the slope at Bosworth Creek North appears to maintain thaw within the woodchips for the upper portions of the slope, however a zone of thaw up to 3.5 m is interpreted for the lower slope. The slope at Little Smith Creek shows thaw up to 5 or 6 m thick in both the upper and lower sections of the slope, separated by a zone about 50 m long in the middle of the slope where thaw appears to remain within the wood chips. Hot spots also appear to have promoted some differential slope thaw. Interpreted thaw characteristics for individual slopes have been summarized in Table 2.

The most intensive surveying was conducted at 13 slopes within 272 km of Norman Wells. Average slope thaw appears to 1994 to have been maintained within the woodchips north of kp 84 inclusive, yet with zones of deeper thaw such as that noted at Bosworth Creek. These slopes are likely to be most affected in the future by the new pipe operating temperatures. Average slope thaw south of kp 84 appears to be well below the base of the woodchips, again with some zones of thaw deeper than slope averages (see Figure 11). Surveying in the early years of this project (1989-1992) was mainly of a cursory nature, yet several sites show a trend of increasing thaw between 1989 and 1994 (see Figure 12).

Surveys were conducted throughout the 1994 thaw season. Due to limitations in radar resolution, the changes in thaw extent within one season are likely not detectable. Future radar surveys should be conducted near the start of the thaw season in order to take advantage of the increased radar penetration with colder ground temperatures.

Ground penetrating radar represents one of the most useful tools for non-destructive subsurface mapping of wood chip slopes. However, the need for ancillary data to support interpretations (*i.e.* ground temperatures, depth-of-thaw probing, knowledge of local geology) is of paramount importance for confident interpretations.

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INTRODUCTION

Slope instability is of major concern in permafrost regions as a warming of the ground can induce permafrost thaw and surface subsidence, differential settlement, or slope failure due to a decrease in soil strength. In 1984 and 1985, Interprovincial Pipe Line (NW) Ltd. (IPL) constructed an 869 km long buried oil pipeline from Norman Wells, N.W.T. south to Zama, Alberta (Figure 1). Electromagnetic surveys conducted prior to construction showed that frozen ground underlay approximately 75% of the terrain at the northern end of the pipeline right-of-way (ROW) and diminished to 35% or less at the southern end (Kay *et al.*, 1983). However, much of this permafrost was likely within a few degrees of 0°C, and thus would be especially susceptible to any warming. Ground warming is common on the ROW due to pipe-operating temperatures or vegetation removal during construction.

The need therefore arose for preservation of permafrost on thaw-sensitive slopes, especially in the northern portion of the route where many steep slopes are encountered at stream crossings. For this reason, 56 slopes along the pipeline route were covered with a 0.5 to 1.8 m insulating blanket of woodchips, in an effort to confine thaw to within the woodchip layer or to the previous active layer of the underlying soil (*i.e.* ~1.0 m). Woodchips were selected because of their excellent insulating capacity, local availability, ability to conform to the surface should settlement occur, and ease of placement during cold weather (Pick, 1987). Several thaw scenarios have been suggested

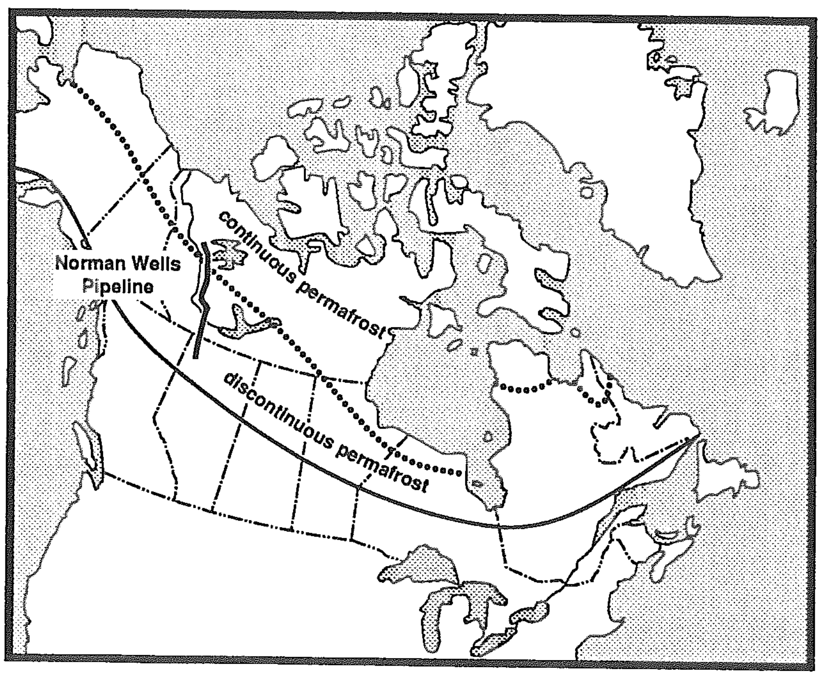


Figure 1. The Norman Wells pipeline originates in continuous permafrost at Norman Wells and ends in scattered discontinuous permafrost at Zama, Alberta, 869 km to the south

to occur at various locations along the ROW (Figure 2). Increased pipe temperatures could lead to a thaw bulb surrounding the pipe (Figure 2a), an active layer thicker than anticipated coalescing with the pipe thaw bulb (Figure 2b), and the thaw bulb around the pipe combined with settlement and/or groundwater flow resulting in a cavity in the pipe vicinity (Figure 2c).

The original geothermal design of the woodchip slopes assumed the pipe to be passive (*i.e.* operating at the same temperature as the surrounding soil (between 0°C and -2°C)). From startup in 1985 to 1993, oil was chilled to -2°C before entering the line at Norman Wells. The oil responded to thermal conditions of the surrounding terrain (cleared ROW), assuming a seasonal temperature cycle, and after the first 50 km was in fact operating at average annual temperatures above 0°C (Burgess, 1992). Average annual temperatures increased with distance south of Norman Wells (Figure 3). These warmer pipe operating temperatures than originally planned has led to the development of thaw bulbs under many of the more southerly woodchip slopes. Thaw zones around the pipe as deep as 4 m and as wide as 10 m have been confirmed with manual probing by IPL in 1990 and 1992. Some of this thaw may be due to the localized presence of "hot spots" on some slopes caused by biological activity within the woodchip layer (Figure 2d)(Burgess *et al.,* 1993).

In 1993 IPL implemented revisions to operating conditions which allow for oil temperatures to vary seasonally at the chilled input: up to a maximum of 12°C in summer and down to a minimum of -4°C in winter. These changes have resulted in several of the more northerly wood chip slopes (especially in the first 50 km of the pipeline) experiencing prolonged periods of warm pipe temperatures for the first time since 1985. Hence the potential for growth or enlargement of thaw bulbs has increased beneath many of the wood chip slopes.

As a part of the "Environmental Agreement" for the IPL Norman Wells pipeline, the federal government Departments of Indian and Northern Affairs (INAC), Natural Resources Canada (NRCan)(formerly Energy, Mines and Resources (EMR)), the National Research Council of Canada (NRC), and Agriculture Canada established a co-operative Permafrost and Terrain Research and Monitoring (PTRM) program devoted to monitoring permafrost conditions along the pipeline route. Much of the background information can be found in various government publications from INAC and the Geological Survey of Canada (GSC, a branch of NRCan)(Burgess, 1988; MacInnes *et al.,* 1989; 1990; Pilon *et al.,* 1989; Burgess and Harry, 1990; Burgess and Naufal, 1990; Burgess, 1992). Additional co-operative work has been conducted between the GSC and IPL under the Industrial Partners Program (IPP).

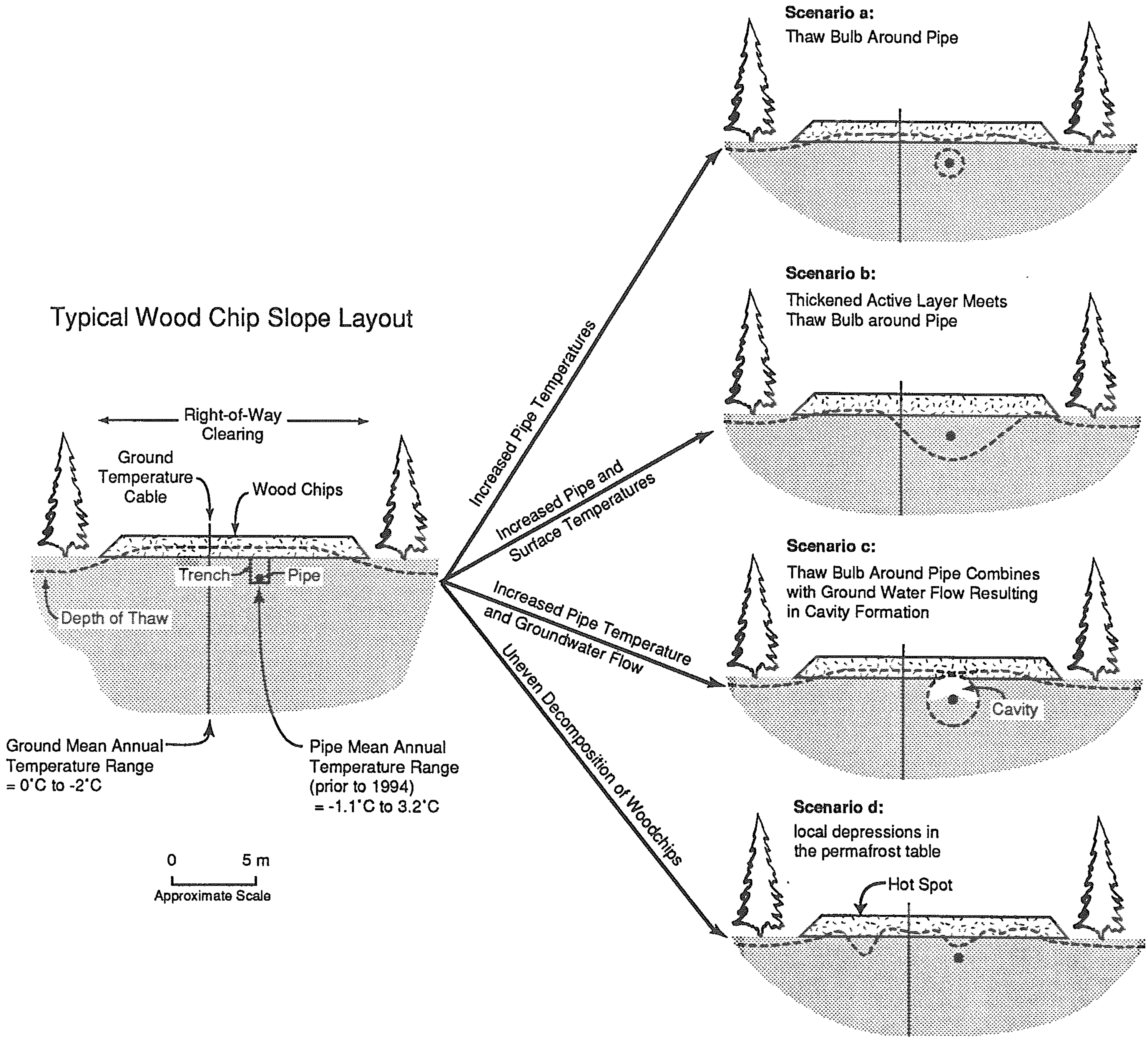


Figure 2. A schematic diagram of the layout of a typical woodchip insulated slope and four possible scenarios for permafrost thaw.

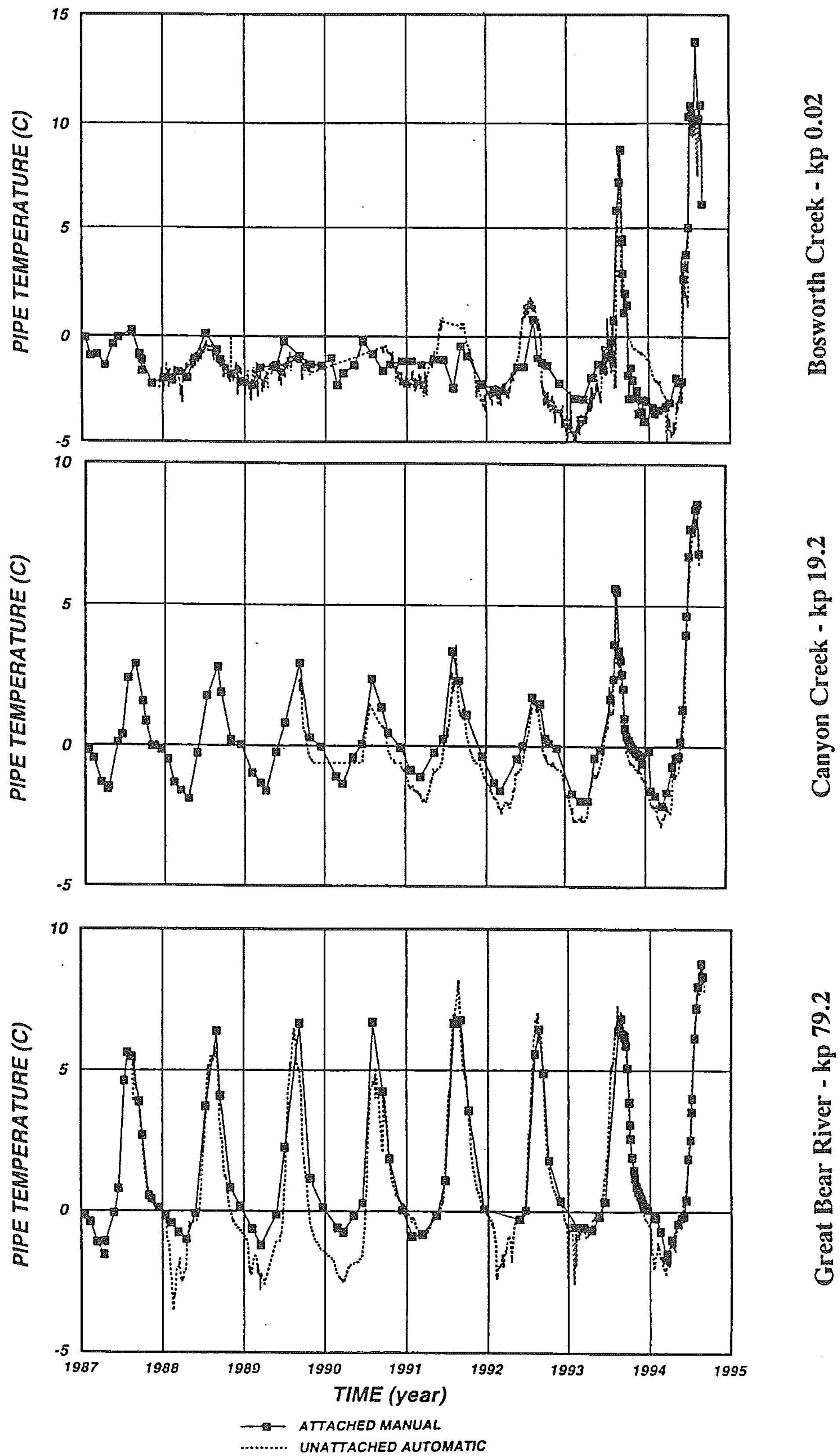


Figure 3. Pipe temperatures at northern study sites. Note increase with distance from Norman Wells until 1992. The new warmer pipe operating temperatures implemented in 1993 represent a more drastic change at more northern sites (kp 0.2 and kp 19.2) (data from PTRM study sites, M.M. Burgess, personal communication, 1995).

Initially, the thermal monitoring of these woodchip slopes was restricted to manual probing and temperatures recorded within boreholes. To augment these data, ground penetrating radar (GPR) surveys have been conducted along the northern portions of the pipeline route by researchers at the Geological Survey of Canada annually since 1989 (Moorman, 1991; 1993; 1995; Robinson and Moorman, 1995). The original intention of this survey project was to assess the ability of GPR to map permafrost conditions along the pipeline route as GPR represents relatively new technology and many of its potential applications remain unproven.

This report summarizes the major results of six years of GPR surveying along the northern portions of the pipeline route. Included are both the spatial and temporal analyses of radar surveying. The benefits and limitations of GPR surveying, as well as recommendations for future work are also discussed.

METHODS

Ground penetrating radar (GPR) surveying has been shown to be a fast, reliable and relatively inexpensive technique for non-destructive, high resolution mapping of the shallow subsurface (Davis and Annan, 1989). GPR principles are very similar to those of the reflection seismic method. The main difference is that GPR energy is electromagnetic (EM), not acoustic. With the GPR reflection technique, an energy pulse is transmitted into the ground, with a portion of this energy being reflected back to the receiver at an interface between materials (Figure 4). The remainder of the energy continues to travel downwards through the ground, with additional portions reflected at subsequent interfaces. The two-way travel time in the ground for these reflectors is measured by the GPR unit, and if the propagation velocity is known (or calculated through a CMP profile), the depth to these reflectors can be determined. Each energy pulse transmitted at a survey position is called a trace. A collection of traces from evenly spaced survey positions allows the construction of a cross-section, or profile, through the ground. For a detailed discussion of GPR principles, see Davis and Annan (1989).

The first reflection that the receiver senses is the air wave that travels through the air between the transmitter and receiver. As this first wave arrival remains constant throughout the survey and travels at high speed, it serves as a handy zero marker for the ground surface (Figure 4). The next arrival is the ground wave, traveling directly from the transmitter to the receiver through the surface skin of the ground. As the propagation velocities through ground are always slower than through the air, the ground wave will arrive slightly later than the air wave, however they often appear as one, thicker wave where ground velocities are high. The next waves to arrive will be from interfaces within the ground, arriving in order of depth (top first). In the case of very shallow structure, reflectors may be indistinguishable from the ground wave.

Following simple data processing (noise filtering and gain application), profiles are plotted with the horizontal axis representing survey position and the vertical axis representing two-way travel time for the EM energy in the ground. The propagation velocity of the electromagnetic energy in the ground can be determined from a Common Mid-Point (CMP) sounding. This technique involves collecting several traces (usually 20-30) in which the spacing between transmitter and receiver is successively increased (about a mid point) with each recorded trace. As distance from the mid-point is consistently increased, reflections from that mid-point will arrive at a later time. On a profile showing antenna separation (horizontal axis) vs. travel time (vertical axis), the inverse of the slope of the direct ground wave and the linear portion of the returns from reflectors is the propagation velocity of the EM pulse through the ground. The CMP survey often gives a value for near-surface velocity, and should be used with caution if complex stratigraphic environments are encountered. Once the velocity is known, an interpreted depth scale can be presented to accompany the travel time on the vertical axis of a cross-section.

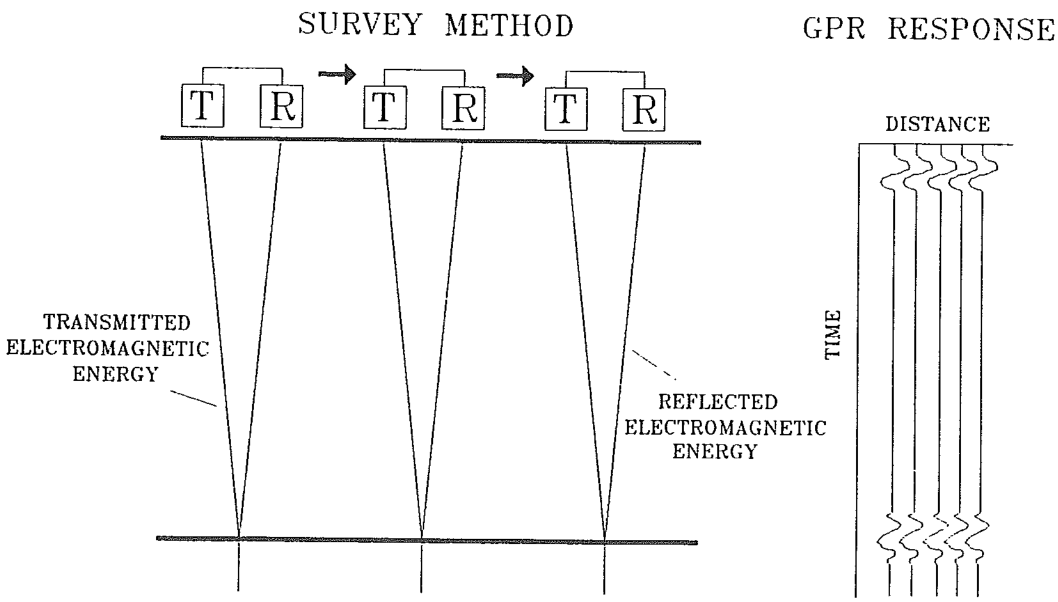


Figure 4. Ground penetrating radar configuration during profiling (T=transmitter, R=receiver).

Ground penetrating radar systems have been used for permafrost mapping for several years. GPR technology has been used to map permafrost stratigraphy (Kovacs and Morey, 1985; Dallimore and Davis, 1987), seasonal thaw (Doolittle *et al.*, 1990), massive ground ice (Dallimore and Davis, 1992; Robinson *et al.*, 1993), discontinuously frozen peatlands (Doolittle *et al.*, 1992; Kettles and Robinson, 1994), and as an aid in the monitoring of road and runway performance (LaFleche *et al.*, 1988; Judge *et al.*, 1991). Monitoring of the pipeline and wood chip slopes represents a previously untested GPR application. The complex nature of the slopes (complex stratigraphy, variable thermal structure, presence of a buried pipe, interference from cribbing and the edge of the wood chips etc.) resulted in a degree of uncertainty as to the potential success of GPR surveying. This project therefore presented a unique opportunity for assessing the suitability of GPR to such mapping.

The pulseEKKO III and IV ground penetrating radar units were used for survey data collection (Figure 5). Antennas with centre frequencies of 50, 100, and 200 MHz were used in conjunction with either a 400 or 1000 volt transmitter. The lower frequency antennas provide deep penetration, but at the expense of resolution. Higher frequency antennas yield higher resolution data, yet with a corresponding loss of penetration. At some sites, where repeat visits were possible or time was not a factor, survey lines were repeated using different antenna configurations. At other sites where there may have been time constraints, one antenna configuration was selected to optimize results.

SUMMARY OF SURVEYS CONDUCTED; 1989-1994

The results of surveys conducted to date can be found in various GSC contract or Open File reports (*1989* and *1990* results in Moorman, 1991; *1991* in Moorman, 1994; *1993* in Moorman, 1995; and *1994* results in Robinson and Moorman, 1995). Surveys conducted during the summer of 1992 were of a very cursory nature, and the results were not compiled. Table 1 lists the slopes surveyed during each field season.

Surveys conducted between 1989 and 1992 were mainly of a cursory nature, conducted in an effort to determine the applicability of GPR surveying to northern pipeline routes. These early surveys focused on shallow phenomena using higher frequency antennas. Research efforts were intensified in 1993 with the focus being on the delineation of zones of deeper thaw, yet surveying in the years 1989-1993 was conducted only at the end of the thaw season. In 1994 surveys were conducted throughout the thaw season in an effort to characterize the seasonal characteristics of thaw and the determine the optimal seasonal timing for GPR surveys.

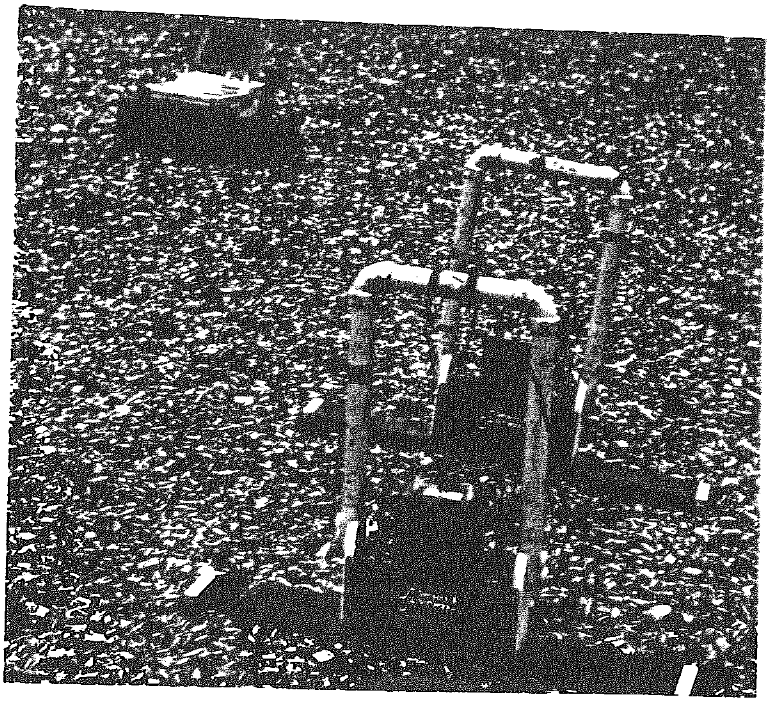


Figure 5. The pulseEKKO IV ground penetrating radar unit was used for the surveys. Transmitting and receiving antennas (100 MHz) are shown in the foreground, with the laptop computer and control unit (in backpack) in the background. The components are connected by fibre optic cables.

Table 1. Slopes surveyed and survey intensity during each field season.

Slope	Slope#, kp	1989	1990	1991	1992	1993	1994
Bosworth Ck. North	1, kp 0.3		C			G	M
Bosworth Ck. South	2, kp 0.4		C			G	M
Canyon Ck. North	3, kp 19.3		C		C	G	M
Canyon Ck. South	4, kp 19.5					G	C
Heleva Ck. N and S.	11&12, kp 25.6						C
Prohibition South	16, kp 32.2						C
Great Bear River S.	29B, kp 79.0	C	G	G	C		M
Unnamed Slope S.	31A, kp 84.0						G
Unnamed Slope N.	44, kp 133.6					G	M
Unnamed Slope S.	45, kp 133.7					G	M
Little Smith Creek S.	48B, kp 160				C	G	M
Steep Ck. North	62, kp 194.6					G	C
Unnamed Ck. North	73, kp 271.5					G	
Unnamed Ck South	74, kp 271.9						M
Ochre River South	82, kp 286.0		C	G			
Smith Creek South	99, kp 325.3		C				
Unnamed Ck. South	109, kp 351.9		C	G			
Mackenzie River S.	142, kp 529.7			G		G	G

C - *cursory survey*

G - *grid survey*

M - *multiple grid surveys throughout thaw season*

At most slope sites, two profiles were conducted parallel to the pipe down the length of the slope. A minimum of three profiles across the woodchip slopes were also conducted at each site to complete the grid pattern. Long profiles were generally conducted on both sides of the ROW, at least 2 m from the buried pipe in order to minimize interference. All cross slope profiles cross the pipe, and in these cases interference from the pipe cannot be avoided. For this reason, results in the direct vicinity of the pipe are often difficult to interpret, and may not yield any useful information. Radar traces collected near borehole instrumentation may be similarly affected. Antenna separation was 1 m for both the 100 and 200 MHz antennas, and 2 m for the 50 MHz antennas. These configurations provide reduced near-surface geometric distortion, while keeping signal saturation to a minimum. Surveys conducted between 1989-1991 used a station spacing of 1 m. To improve lateral resolution, a station spacing of 0.25 m was used for the 1993-1994 profiles, however, during some time constraints, lateral resolution was sacrificed (station spacing 0.5 m) in order to maintain adequate slope coverage.

Coarse topographic surveys were conducted along each profile, however, the GPR results have not been corrected for topography as vertical exaggeration would have to be increased to the point where surface detail would be lost. Additionally, most reflections of interest are basically parallel to the slope surface, and topographic correction would not aid in interpretation. Depth scales on the profiles are based on velocities calculated from CMP surveys (see Methods, above). In many cases, velocity will change with depth or lateral position along the profile, and as the radar plotting software can only handle a one-layer velocity structure, the depth scale should only be taken as a guide. For example, if the CMP was conducted over a well-frozen section (usually of higher velocity), then reflector depths will be overestimated in thawed sections (lower velocity), resulting in a pseudo cross-section. For this reason, depth scales are to be used as a guide only, especially in areas of complex thermal structure.

Although GPR surveying may give a good indication of ground condition, ground-truthing is required, most often from borehole stratigraphy, temperatures measured in boreholes, and active layer probing. Stratigraphic information from boreholes drilled at the time of construction is available for most slopes. Thermal data from temperature cables installed in slope boreholes was obtained during IPL's weekly line patrol for the date closest to the radar survey. At some sites, thermal data was also collected on the day of the radar survey. This data has been incorporated to help verify radar interpretations. Shallow active layer probing was also conducted at many of the sites at the time of GPR surveying.

SUMMARY OF GPR RESULTS; 1989-1994

As previously mentioned, the complete sets of radar profiles conducted along the Norman Wells pipeline route, along with some interpretations, can be found in other publications. This section of the report is concerned with summarizing these results based on permafrost trends noted at various locations along the ROW, with the variation in permafrost conditions on individual slopes, and temporal trends noted both over the extent of the monitoring project and on a seasonal basis.

SPATIAL ANALYSES

DEPTH OF THAW VARIABILITY ON INDIVIDUAL SLOPES

Temperatures measured in borehole installations can provide point-specific thermal information. However, the number of boreholes located on each slope is minimal, usually 1 or 2, and thus anomalous conditions may be overlooked. Radar surveying has shown the amount and extent of differential thaw on several slopes, where borehole temperatures could not provide such detailed results. However, where available, temperatures recorded in boreholes and depth-of-thaw probing have been used to support radar interpretations. Several examples are presented below.

At Bosworth Creek (kp 0.3-0.4) interpreted GPR profiles suggest that both the north and south slopes have shallow thaw on the insulated slope crest and in the upper slope (Figures 6 and 7). This seasonal thaw near the slope crest reaches a maximum of approximately 0.80 m, and likely freezes again each winter. A slight thickening of thaw is noted towards the middle of the north slope. A major thickening of the thaw zone is noted near the base of both slopes, to 3 or 4 m on the north slope and to at least 6 m on the south slope. This thaw pattern is confirmed by shallow probing and temperatures recorded in boreholes. The approximate lateral extent of these two thawed areas was delineated through a grid network of radar surveys (Figures 6 and 7). The zone appears to be thicker and more extensive across the ROW west of the pipe on the lower north slope, and has maximum dimensions of approximately 10 by 12 m. The deeper thawed zone on the south slope has maximum dimensions of about 12 by 12 m, and is slightly most extensive on the west (pipe) side of the ROW. A thin layer of frozen woodchips is generally present above the thaw zone until late in the summer on both slopes. Interference from the pipe, edge of the woodchips, and the cribbing at the base of the slope make some interpretations difficult on cross profiles. The cause of these thawed zones is unknown, although with these sites being so close to the Norman Wells pump station they would be very strongly influenced by warmer pipe temperatures. However, the thawed zones do not conform to the orientation of the pipe, and the fact that there appears to be minimal thaw at the top of the slope near the pipe suggests an alternate

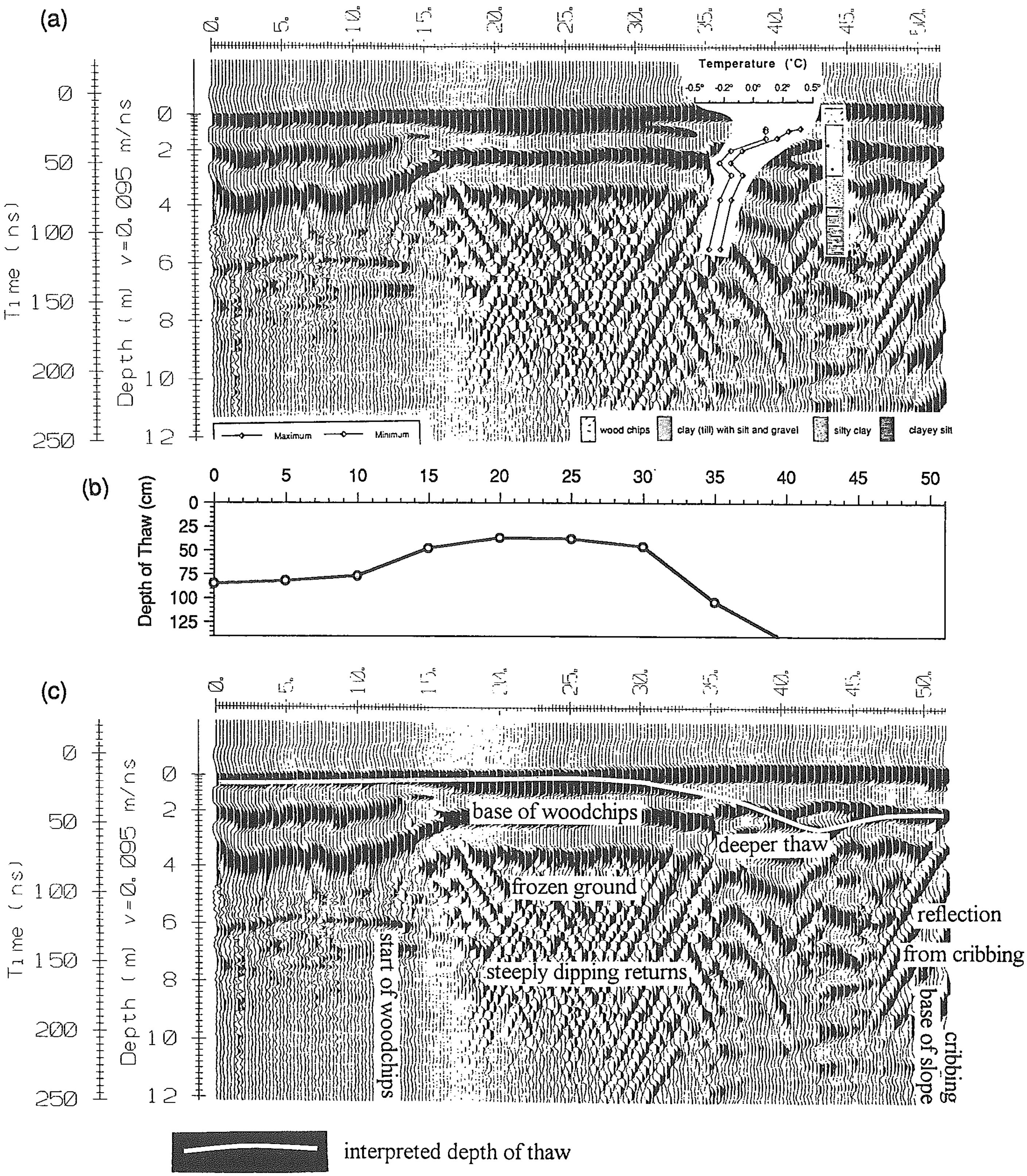


Figure 6. **(a)** Raw radar profile conducted at Bosworth Creek North on June 7, 1994 using the 50 MHz antennas with lithology and temperatures from boreholes, **(b)** depth of thaw probing along radar line, and **c)** interpreted radar profile

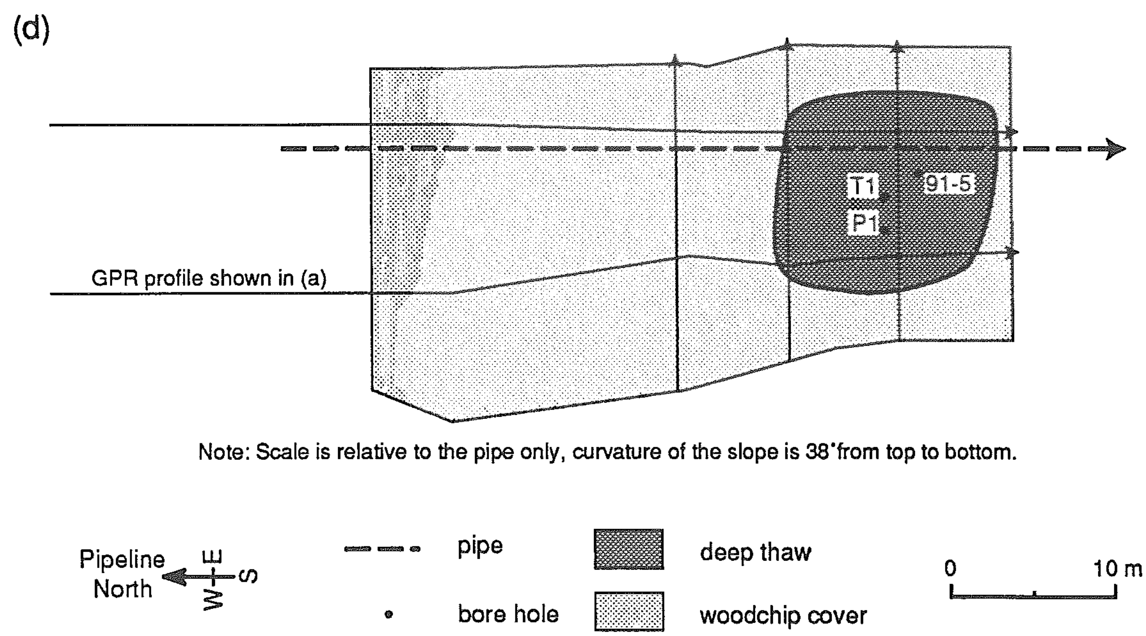


Figure 6d) Site plan showing radar survey grid and interpreted extent of deeper thawed zone at Bosworth Creek North.

source for the thaw. This pattern of deep thaw at the base of the slope is not noted at any other sites. It is possible that there is some cribbing-induced thawing at the base of the slope, as the cribbing represents a surface for the penetration of warm summer temperatures into the lower woodchips.

The hot spots noted at several slopes (Burgess *et al.*, 1993) appear to have promoted some differential slope thaw. These hot spots are caused by biological activity within the woodchips. Surveying conducted at slope 31A (kp 84) shows the increase in interpreted thaw depth in the vicinity of the mapped hot spots (Figure 8). Depth of thaw probing at the same time as GPR surveying confirmed the interpretations. Hot spots at this site were categorized as being extensive (Burgess *et al.*, 1993) and a maximum temperature within the woodchips of 18°C was noted in October 1993. Away from the hot spots, ground thaw is maintained within the woodchips. Hot spots have been noted on the ROW on at least 56% of slopes between kp 84 and 403.7, and on 0% of slopes north of the Great Bear River. It is unclear at this point how extensive hot spots may be

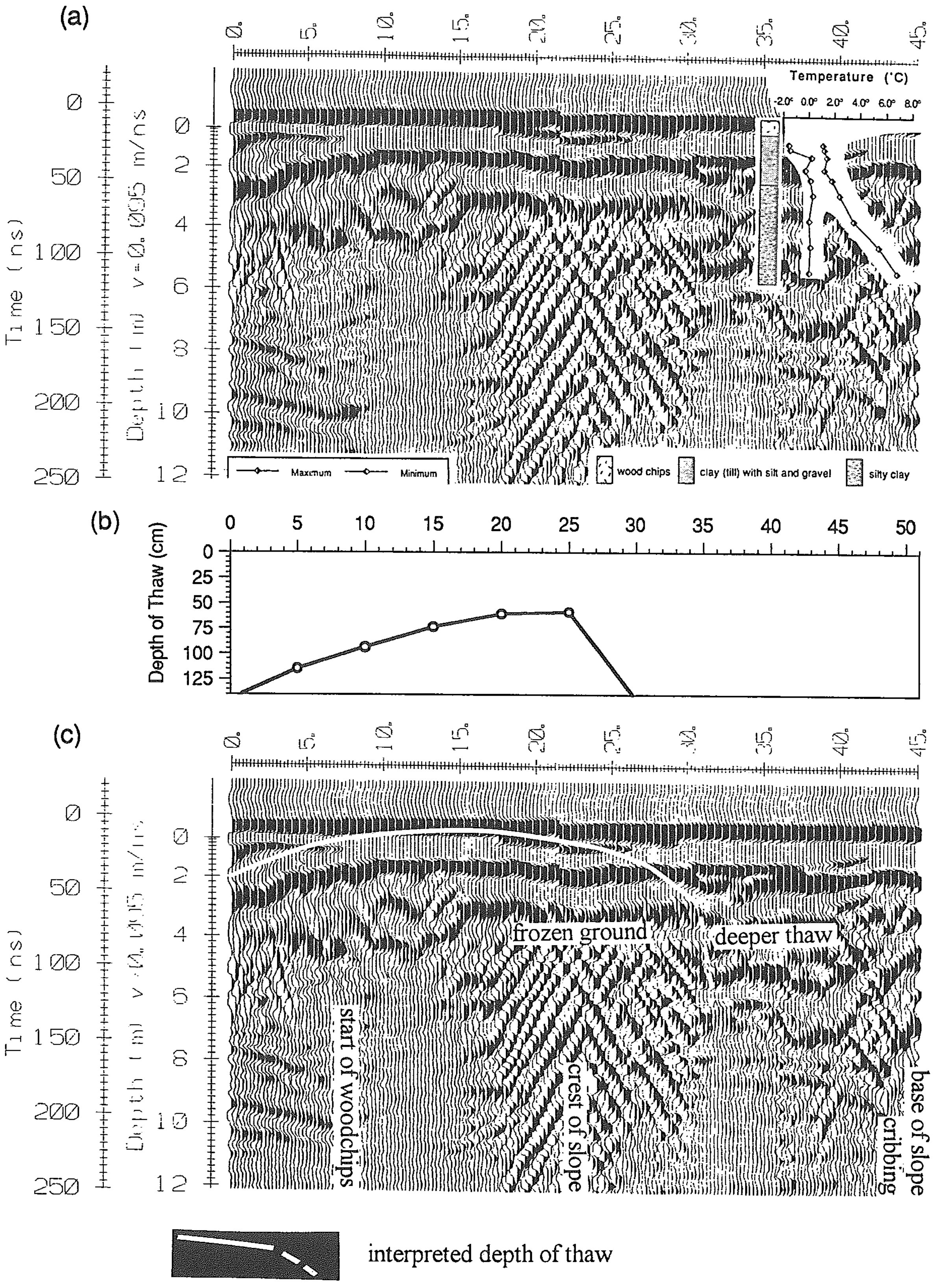


Figure 7. **(a)** Raw radar profile conducted at Bosworth Creek South on June 7, 1994 using the 50 MHz antennas with lithology and temperatures from boreholes, **(b)** depth of thaw probing along radar line, and **c)** interpreted radar profile

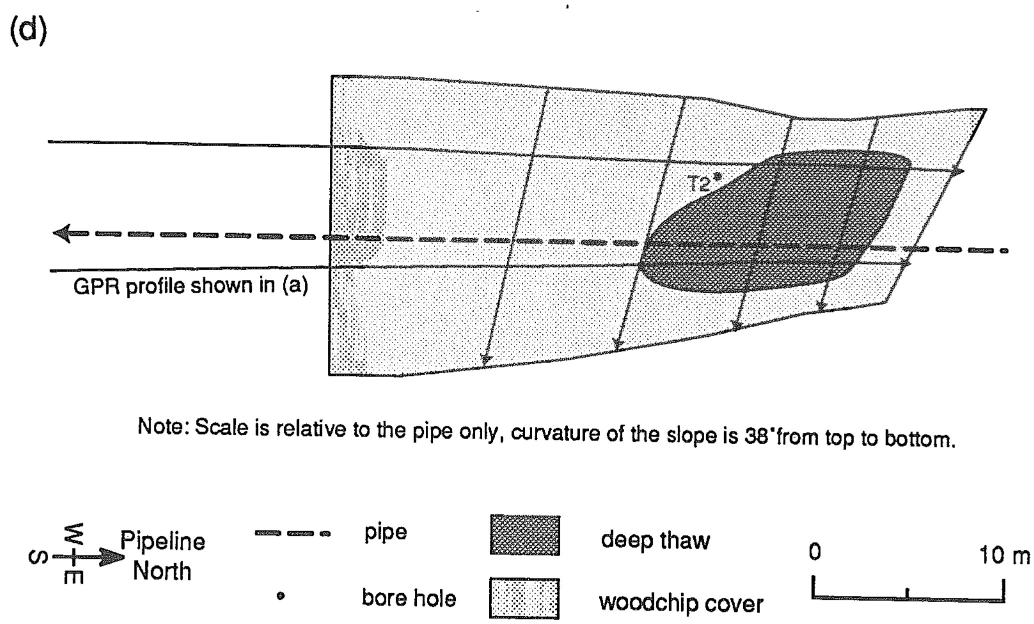


Figure 7d) Site plan showing radar survey grid and interpreted extent of deeper thawed zone at Bosworth Creek South.

on other slopes, and what influence they may be having upon thaw. However, it is evident from the surveys conducted at kp 84 that the location of hot spots coincides with deeper thaw than at other sections of the slope. It is also unclear as to the lifetime, sporadic nature and dynamics of hot spots. If they can be extensive across large portions of a given slope, or if they shift location with time, then they may represent a major contribution to the thermal degradation of the slope as a whole. The hot spots at kp 84 have been instrumented with thermal loggers in an effort to monitor the persistence and growth or decline of such features. Initial results show that the temperatures within some hot spots decrease from the centre outwards; others show, heating to be greatest at the margin, indicating perhaps a radial growth of fungal activity (Burgess et al., in press). Due to the lack of instrumentation at other sites, and the limited number of visual inspections, it is difficult to determine if hot spots extend across entire slopes, or if they shift location eventually causing some

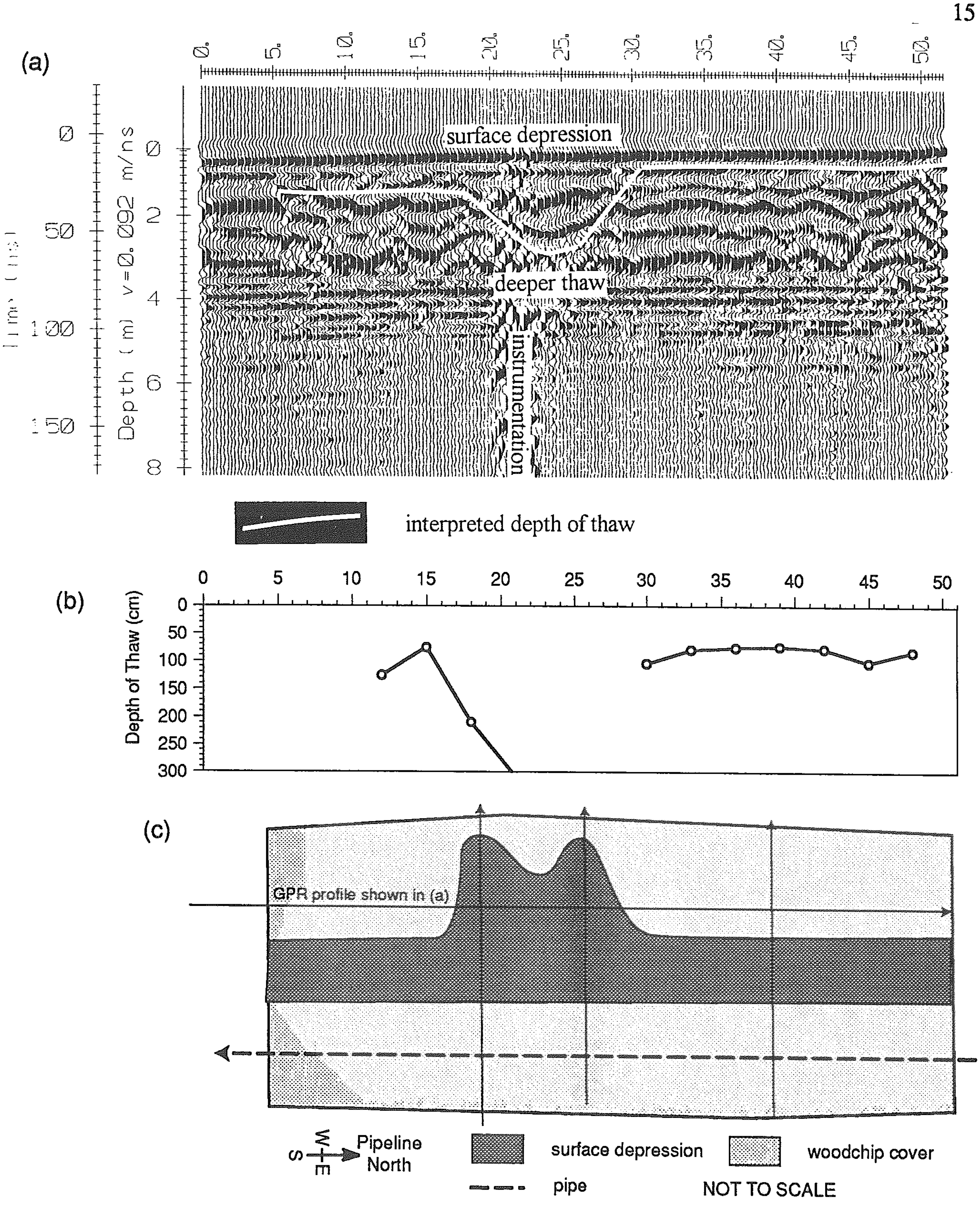


Figure 8. (a) Radar survey conducted on August 23, 1994 at Slope 31A (kp 84) showing interpreted zone of deeper thaw in the vicinity of mapped hot spots, b) depth of thaw probing along survey line, and c) mapped hot spots.

degree of thaw across major portions of the slope. This may contribute to extensive thaw observed across many of the slopes further south.

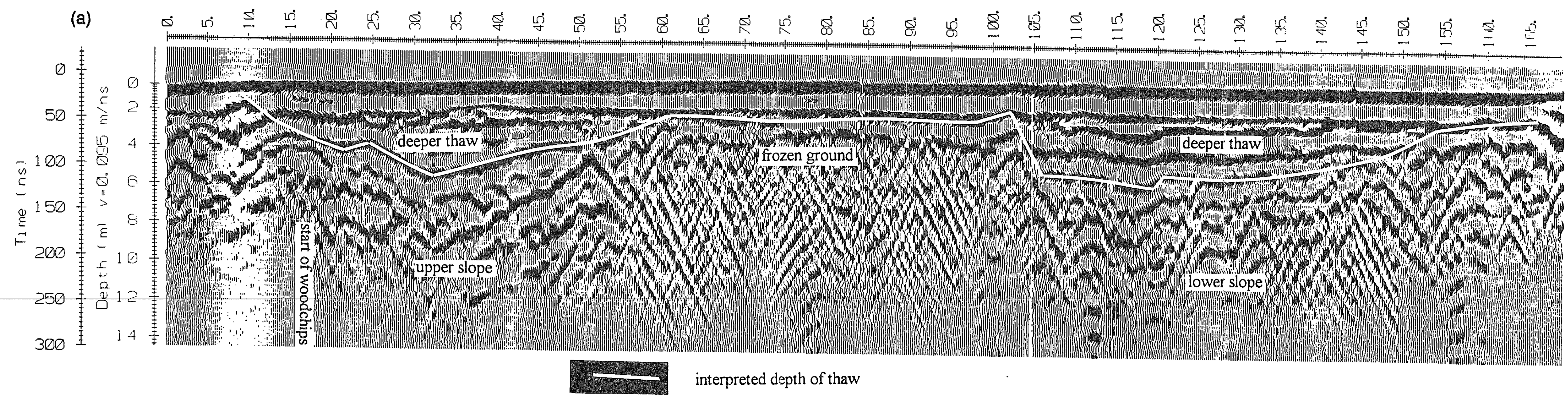
The woodchip insulated slope at Little Smith Creek (kp 160) also shows distinct variability in depth of thaw on different portions of the slope. This slope has also been targeted by the PTRM as one of the most critical slopes along the pipeline route. Interpretations of detailed GPR surveys conducted in 1993 and 1994 indicated two separate regions that were interpreted as having deep thaw (Figure 9). The upper 35 m of the woodchip slope appears to have been thawed to depths of 4 or 5 m. The next 48 m (middle portion) of the slope is interpreted as being frozen at depth, with thin active layer development on a seasonal basis. The basal 50 m of the slope is interpreted to have been thawed to depths greater than 4 m.

The cause of such complex GPR returns is not known. From the slope and pipe design, the thermal influence of the pipe (a warm pipe creating a large thaw bulb) should be consistent along the length of the slope, yet the observed GPR pattern suggests a more complex subsurface structure. This may be the result of a more complex lithological, hydrogeological or thermal environment being present than currently than currently thought. A small amount of water flows out from underneath the eastern side of the woodchips. High pore water pressures on the slope led to the installation of drainage slots in February 1994. In order to minimize interference from the pipe, most profiles were conducted parallel to, yet a few metres away from the pipe. Thus the conditions in the immediate vicinity of the pipe cannot generally be mapped, and in most cases the cross-profiles do not improve the confidence. In such cases, the GPR may be mapping the general permafrost conditions of the slope, at the expense of conditions in the immediate pipe vicinity.

Numerous slopes do not show any areas of significantly deeper thaw. Figure 10 shows the results of a radar survey at Canyon Creek North where fairly homogeneous ground conditions are interpreted by the consistent nature of the radar returns. Depth-of-thaw probing and temperature cables confirmed that the slope is frozen. The presence of steeply dipping returns, although technically a form of interference, have been strongly correlated with the presence of frozen ground, in the shallow subsurface (see explanation in *Benefits and Limitations of GPR* section).

The installation of drainage slots on slopes 44 (kp 133.6), 45 (kp 133.7), and 48B (kp 160) may have promoted (at least short term) thaw in their immediate vicinity. These slots create interference on GPR profiles (see Benefits and Limitations of GPR section), preventing the delineation of thaw within 4 or 5 m of the slots. However, shallow depth-of-thaw probing, in the first summer after their installation, showed the depth of thaw to be greater than 1.3 m within about 1.5 m of the open

(a)



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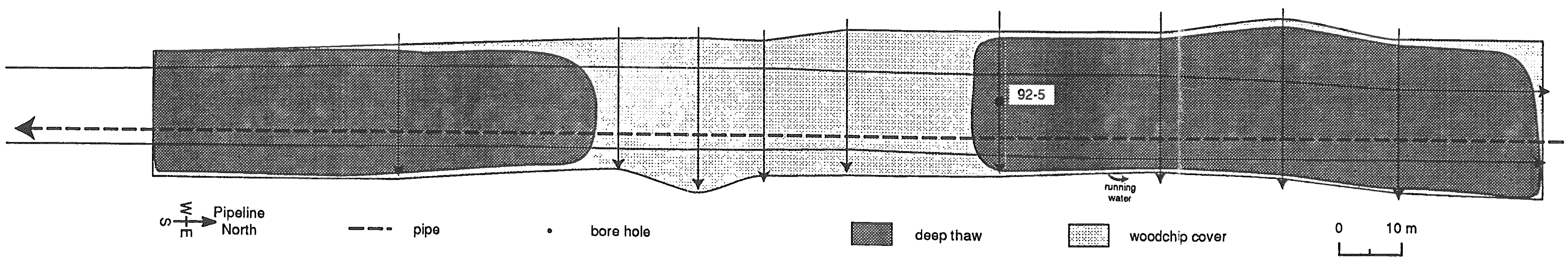


Figure 9. **(a)** 50 MHz radar survey conducted on July 6, 1994 at Little Smith Creek (Slope 48B, kp 160), showing deeper thaw beneath the upper and lower sections of the slope, and **(b)** radar survey grid map with interpreted extent of thawed zones.

NOTE:
Drainage slots were difficult to locate on this slope at the time of surveying as they had recently been backfilled. The radar signal does not seem to be adversely affected by the drainage slots on this slope (except on some cross profiles). The upper and lower zones of deeper thaw, interpreted on this and the 1993 profiles do not appear to have been influenced by the installation of the drainage slots.

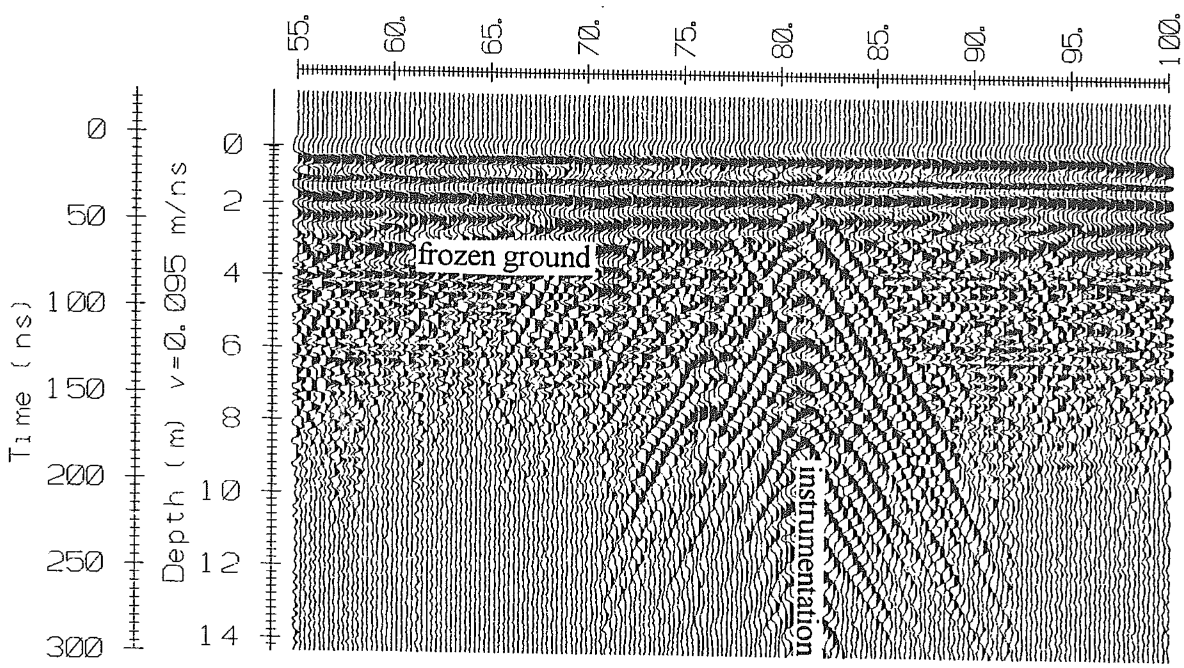


Figure 10. Radar profile (June 21, 1994, 100 MHz) from Canyon Creek North where the combination of homogeneous radar patterns, temperatures measured in boreholes, and depth-of-thaw probing allows the conclusion that the slope is well frozen.

drainage slots, whereas a few metres away seasonal frost was encountered within 0.45 m of the surface. The upper portion of the slots was filled with woodchips in July 1994.

Table 2 presents interpreted thaw patterns for the slopes surveyed between 1989-1994. A description of any noted thaw patterns is included. A degree of interpretation confidence has also been indicated, based upon the time since surveying, the amount of the slope covered during surveying, support of interpretations from shallow depth-of-thaw probing and borehole temperatures, and repeatability of reflectors from one survey to the next.

Table 2. Interpreted thermal conditions for slopes during most recent survey

Slope	Slope #, kp	Most recent survey	Interpreted thermal conditions	Confidence	Hot spots (#, size)
Bosworth Ck. North	1, kp 0.3	1994	Upper slope frozen, thawed zone to 3 or 4 m across base of slope, minor thaw possible arour pipe*	High	Not noted
Bosworth Ck. South	2, kp 0.4	1994	Upper slope frozen, thawed zone to at least 6 m across base of slope	High	Not noted
Canyon Ck. North	3, kp 19.3	1994	Appears well frozen, active layer remains within woodchips, no evidence of thaw around pipe*	High	Not noted
Canyon Ck. South	4, kp 19.5	1994	Thaw may extend below woodchips in some locations	Low[1]	Not noted
Heleva Ck. N and S.	11&12, kp 25.6	1994	Frozen but approaching 0°C, active layer appears to remain within woodchips	Moderate[2]	Not noted
Prohibition South	16, kp 32.2	1994	Appears well frozen, active layer remains within woodchips, no indication of thaw around pipe*	Moderate[2]	Not noted
Great Bear River S.	29B, kp 79.0	1994	Appears well frozen beneath seasonally thawed layer less than 1 m thick	High	Not noted
Unnamed Slope S.	31A, kp 84.0	1994	Majority of the slope appears frozen, thaw up to 2.8 m deep underlying hot spot area	High	Extensive
Unnamed Slope N.	44, kp 133.6	1994	Seasonal thaw only at slope crest, deeper thaw to 2 or 3 m below slope crest, early thaw of seasonal frost near drainage slots	Moderate[3]	Extensive
Unnamed Slope S.	45, kp 133.7	1994	Thaw to a maximum of 3 or 4 m across much of the slope, early thaw of seasonal frost near drainage slots is likely, slightly thinner thaw near slope crest	Moderate[3]	>7, 3-6 m diameter
Little Smith Creek S.	48B, kp 160	1994	Upper 35 m of the slope thawed to depths of 4 or 5 m, middle 48 m of the slope appears frozen with active layer remaining within the woodchips, basal 50 m of the slope thawed to a maximum of 4 m, slots promote early thaw of seasonal frost	High	2 minor hot spots
Steep Ck. North	62, kp 194.6	1994	Entire slope appears to be thawed to at least 5 or 6 m	Moderate[2]	Not noted
Unnamed Ck. North	73, kp 271.5	1993	Temperatures slightly below 0°C are present in the near-surface, however a freezing point depression resulting in unfrozen conditions is interpreted	Moderate[4]	Extensive
Unnamed Ck South	74, kp 271.9	1994	Slope appears to have thaw varying between approximately 1 and 2.2 m, with deeper thaw possibly attributable to hot spots	High	3 minor hot spots
Ochre River South	82, kp 286.0	1991	Thaw interpreted to be 1.5-2 m below the woodchip surface, underlain by considerable amounts of ground ice	Moderate[2]	Extensive
Smith Creek South	99, kp 325.3	1990	Thaw up to 4 m near the top of the slope, undulating thaw front averaging 2 m across the remainder of the slope	Low[2]	Not noted
Unnamed Ck. South	109, kp 351.9	1991	Thaw interpreted to be approximately 2 m	Low[1,2]	Not noted
Mackenzie River S.	142, kp 529.7	1994	Large degree of thermal variability, however much of the slope appears to be thawed to at least 3 m, freezing point depression is suspected due to the presence of fine-grained sediments	Low[4]	Not noted

Notes:

* - interference from the pipe prevents definite determination of thaw around the pipe

[1] - lack of borehole temperatures or manual probing prevents high confidence

[2] - inadequate slope coverage prevents high confidence

[3] - interference from drainage slots and lack of borehole temperatures (slope 44) prevents high confidence

[4] - freezing point depression in fine-grained soils likely causes the sediment to appear unfrozen on radar profiles, even though temperature are slightly below freezing (in these cases, the soil is not in frozen state)

SPATIAL ANALYSES

THAW VARIABILITY ALONG THE PIPELINE ROUTE

Surveys have been conducted on 18 individual slopes between Norman Wells and the Mackenzie River crossing near Fort Simpson. The most intensive surveying was conducted in 1994 at 13 slopes within 272 km of Norman Wells. Analyses of results for these slopes displays an interesting trend in depth-of-thaw in the northern portion of the pipeline route (Figure 11). Starting at Bosworth Creek (kp 0.3-0.4), both the north and south slopes show shallow thaw on the insulated slope crest and in the upper slope (Figures 6 and 7). A thickening of the thaw zone is noted near the base of the slopes, to 3 or 4 m on the north slope and to at least 6 m on the south slope. Thus, although average slope thaw is only slightly more than 1 m, deep thaw limited in extent does occur near the base of the slope resulting in the large depth-of-thaw range illustrated in Figure 11.

Slopes located between Canyon Creek North (kp 19.2)(Figure 10) and Great Bear River (kp 79.4) inclusive appear to only have shallow thaw averaging less than 1 m, thus remaining within the woodchips. The variability of thaw thickness is also minimal. The only exception appears to be the southern wood chip slope at Canyon Creek, where thaw varies between 0.30 and 1.40 m. The woodchips at this site are 0.5 m thick and only cover the bottom third of the slope.

An extensive region with deeper thaw and greater thaw variability begins at slope 31A (kp 84)(Figure 8) and continues southwards to at least kp 272. Radar interpretations from slope 31A suggests that much of the slope appears to contain thaw within the woodchips to 0.8-1.0 m depths, yet several patches of thaw up to 2.8 m appear to coincide with the known pattern of hot spots (see section *on Depth of Thaw Variability on Individual Slopes*). The average thaw for this slope is approximately 1 m thick. Average and maximum thaw depths increase south from the kp 84 site to approximately kp 195. Interpreted thaw is a maximum of 2.2 m at Slope 74 (kp 271.9). This trend is likely related to the increase in pipe temperatures south of Norman Wells. The trend may also be associated with effects such as a latitudinal effect of slightly warmer climate, a relic of pre-construction ground temperatures and permafrost conditions, or an increase in slope area affected by hot spots.

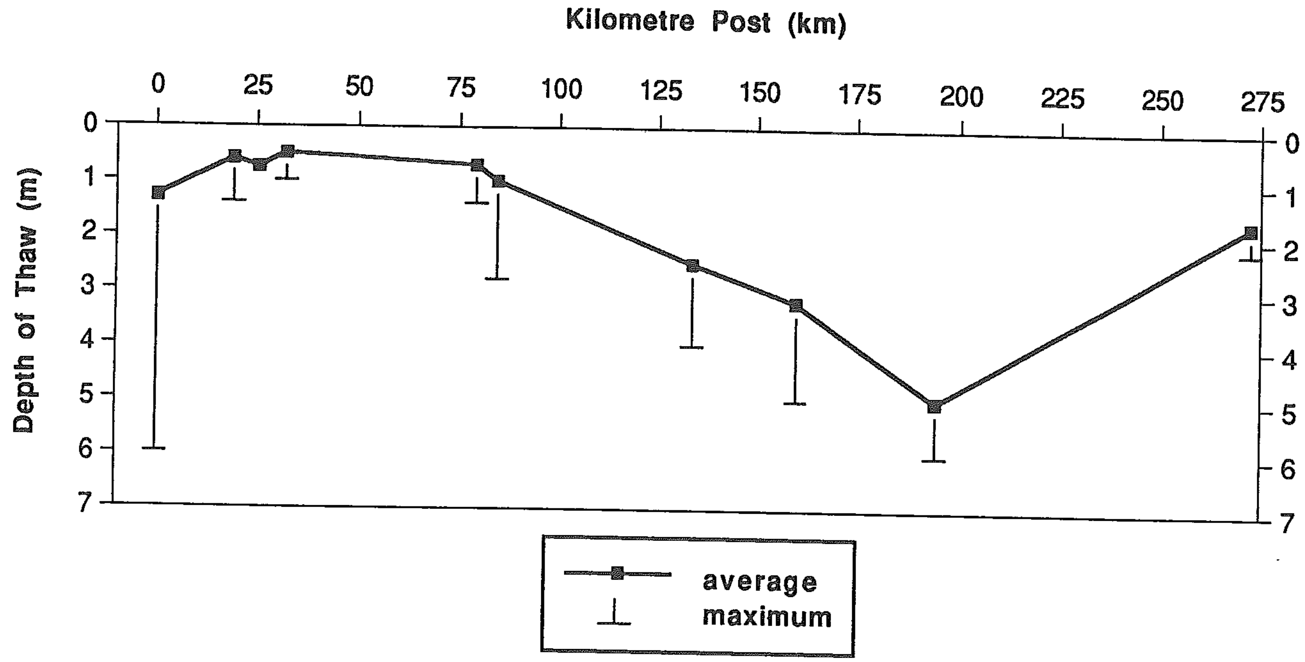


Figure 11. Average and maximum depth of thaw interpreted for 1994 radar surveys of woodchip insulated slopes.

TEMPORAL ANALYSIS

CHANGES 1989-1994

Radar profiles permitting the examination of long-term changes are available for only for a few sites. It is not known if these sites are representative of the pipeline ROW as a whole. Comparisons are possible between 1993 and 1994 for many slopes. Figure 12 shows depth-of-thaw (DOT) changes noted between 1990-1994, with the 1990 and 1992 depths based on probing alone, and the 1993 and 1994 results based upon radar results supported by probing. It should be noted that in such generalized analyses the potential for error is large, and the graph should be used for examination of trends only.

Depth-of-thaw probing at Bosworth Creek North was conducted at three locations by IPL staff in 1990. The frost table was found to be at or below the base of the woodchips at all three locations, ranging from 1 to 2 m depths. The presence of a deep thaw bulb near the base of the slope was first noted during the August 1993 radar surveys, where its interpreted thickness was up to 3 m. At this time, the thaw bulb appeared to be limited to the west side of the ROW. Temperatures measured in borehole 91-5 showed thaw to about 3.5 m in both 1993 and 1994. Cursory radar surveys conducted in 1990 did not delineate a thaw bulb, however at this time the lateral radar resolution was one-quarter that in subsequent surveys, and borehole 91-5 had not yet been installed for interpretation support. Similar results have been presented for the Bosworth Creek South slope. The presence of a thaw bulb was noted on 1993 radar surveys, however its exact thickness was difficult to determine due to changes in propagation velocity. Temperature cables T-1 and TA-7 showed deep thaw in 1993. By 1994 it appeared as though the ground at depth had warmed further (beneath thin seasonal frost), resulting in a thaw bulb interpreted to be at least 5 or 6 m thick.

Changes in the lateral extent of these thaw bulbs is difficult to map, however it appears that by 1994 the thaw bulb had extended to the east side if the ROW on the north slope. Otherwise, the lateral dimensions of the thaw bulb do not appear to have changed significantly. The presence of multiple interference on the 1993 surveys hinders interpretations at some positions of the profile. The effect of a warmer pipe operating temperatures do not appear to have been noticeable during recent radar surveying. However, delineation of thaw beneath the pipe is nearly impossible to interpret due to interference from the pipe itself. The lateral expansion of a thaw bulb may be possible to interpret if change in thickness is greater than the radar pulse width (*i.e.* about 5 ns for

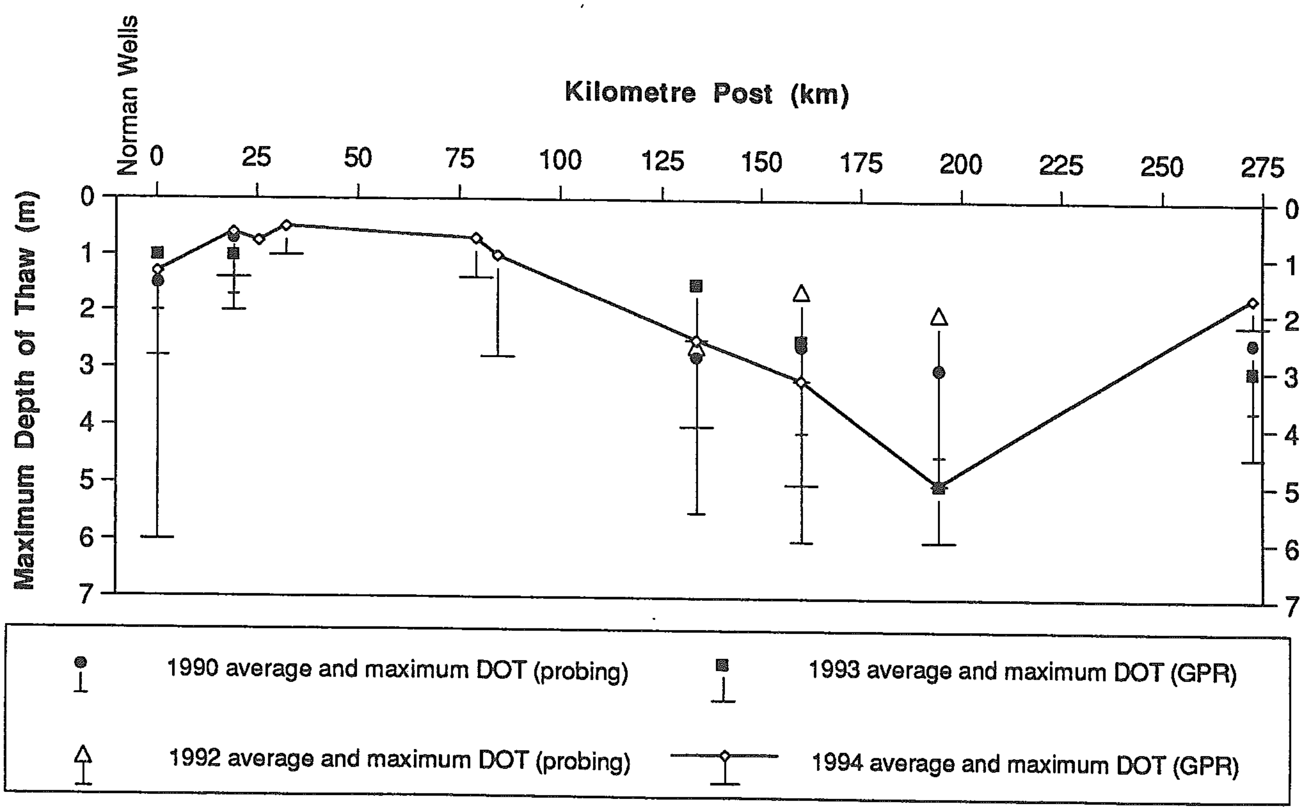


Figure 12. 1990-1994 changes in depth-of-thaw along the northern 275 km of the pipeline ROW.

100 MHz antennas; see explanation of Figure 15) and if expansion is within the lateral resolution imparted by station spacing. For example, from a 100 MHz survey that had 50 cm station spacing, a depth of thaw increase of 10 cm or greater, or a lateral expansion of 50 cm or greater should be able to be detected.

The interpreted depth of thaw appears to have increased at slopes 44 and 45 between 1993 and 1994. This could be due in part to the installation of drainage slots or the growth of a thaw bulb around the pipe, which may have increased thaw within their immediate vicinity. The lack of borehole temperature support on slope 44 prevents confident interpretation of results although probing in 1990 confirmed thaw was beneath the base of the woodchips at most locations. At slope 45 borehole temperatures at depth had been consistently hovering near 0°C for several years until late summer 1994, when measurement indicated thawed conditions to 6 m depth. Increased water flow through the drainage slots located nearby may have raised temperatures slightly in 1994, perhaps in response to sprinkler emplacement during the 1994 forest fire. Alternatively, thaw may be related to continued expansion of thaw zone surrounding the pipe and/or hot spot activity.

Radar surveying at Little Smith Creek in 1993 and 1994 delineated two zones of deep thaw beneath the base of woodchips. The extent and thickness of these two zones, located in the upper and lower slopes, does not appear to have changed appreciably between the two survey years. Unfortunately there was no radar surveying conducted in previous years, so longer-term changes cannot be noted.

Limited radar surveying at Slope 62 (kp 194.6) showed thaw consistently deeper than 1990 or 1992 probing, perhaps consistent with an expanding thaw bulb around the pipe. The radar results were supported by measurements from borehole temperature cables. It is unclear if this means thaw has increased in thickness between 1990 and 1994, or if earlier probing was subject to error (see discussion on the limitations of current thaw probing techniques).

TEMPORAL ANALYSIS

SEASONAL CHANGES, 1994

Surveys were conducted throughout the thaw season at several sites in 1994 in order to quantify changes in thaw and GPR mapping ability. The most detailed surveys were conducted at the Bosworth Creek slopes, where 4 complete grids were surveyed.

The signal loss dramatically increases towards the end of the thaw season (Figure 13), preventing the mapping of deep structure. Prior to 1994, GPR surveys had traditionally been conducted at the end of August, however the 1994 surveys show that in order to optimize results, surveying should be conducted as early in the thaw season as possible. Late season surveys are also more prone to multiple interference (or ringing) from the well developed active layer (Figure 14; Moorman, 1995). Velocity variability is also most dramatic later in the thaw season, resulting in a higher degree of uncertainty of depth interpretations.

Velocity variations across the slope are significant through the thaw season. Measured velocities on the Bosworth Creek slopes ranged from 0.097 m/ns in early June to 0.80 m/ns by the end of August. Variability is expected to be greater in areas of differential thaw, and could result in depth determination errors on the order of 10-25%. This uncertainty stresses the need for the acquisition of additional ancillary data. Most useful would be additional temperature cables and detailed depth-of-thaw probing.

The resolution of GPR surveys is such that changes in thaw extent within one thaw season may not be detectable. Figure 15a illustrates the interpreted depth of thaw progression for the thaw bulb noted at the base of the Bosworth Creek North slope. Error bars indicate the interpretation uncertainty due to radar pulse width (resolution potential). All error bars fall within the same range, suggesting that any changes in thaw depth are not within radar resolution limits at this site. Resolution is greater with higher frequency antennas (Figure 15b), yet the poor performance of higher frequency antennas during the late season precludes their use for seasonal mapping of thaw extent. Theoretically the lower frequency antennas can delineate changes on the order of 0.30 m, however the seasonal velocity changes add an extra uncertainty to depth measurements.

Thus it can be concluded that repeated surveying throughout the thaw season is not warranted. Detectable changes are more likely to be found through surveying on an annual basis. Future surveying should be conducted near the start of the thaw season.

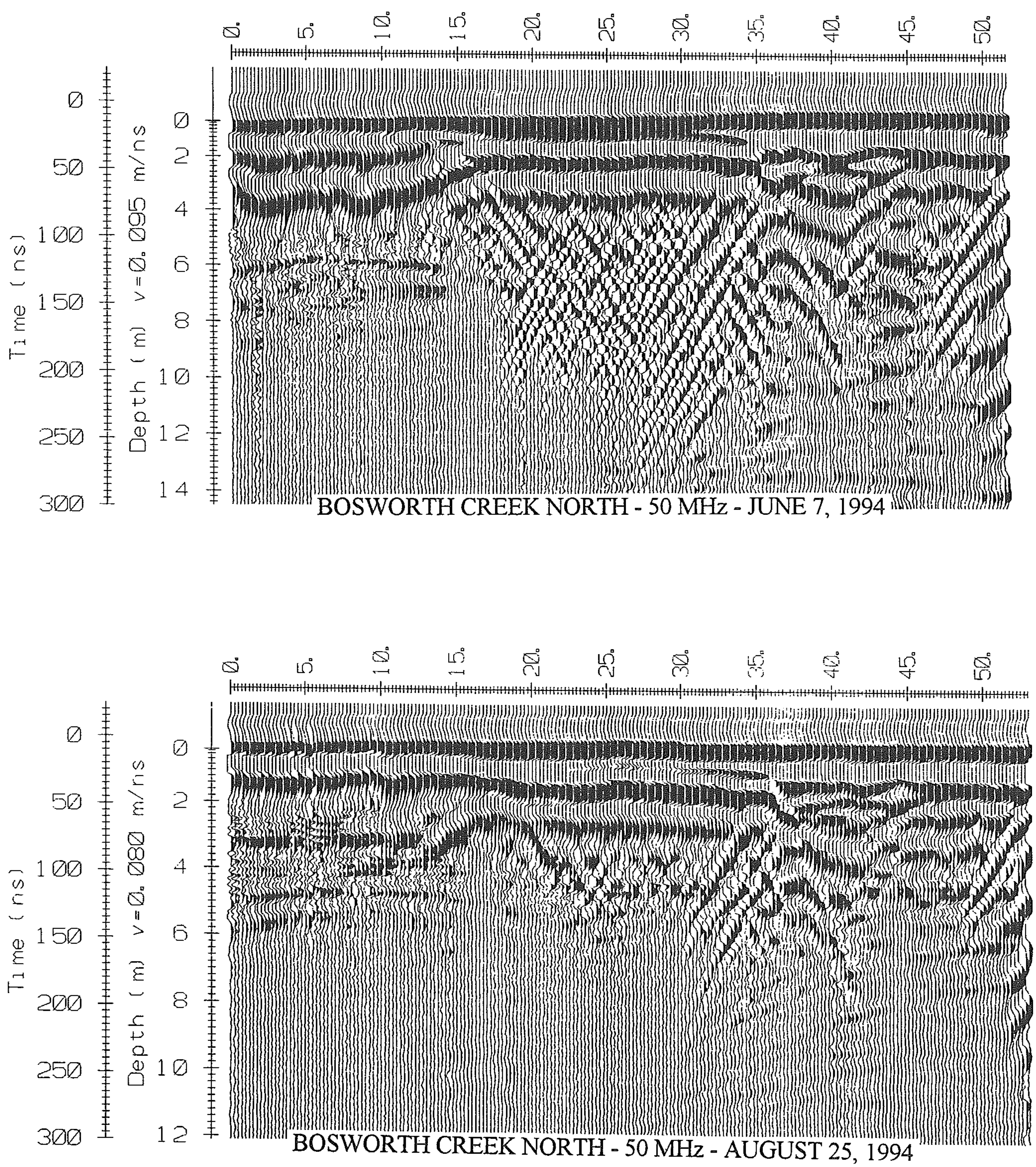


Figure 13. Signal loss is dramatic between early season (upper) and late season (lower). This suggests that subsequent radar surveys should be conducted early in the thaw season to optimize results.

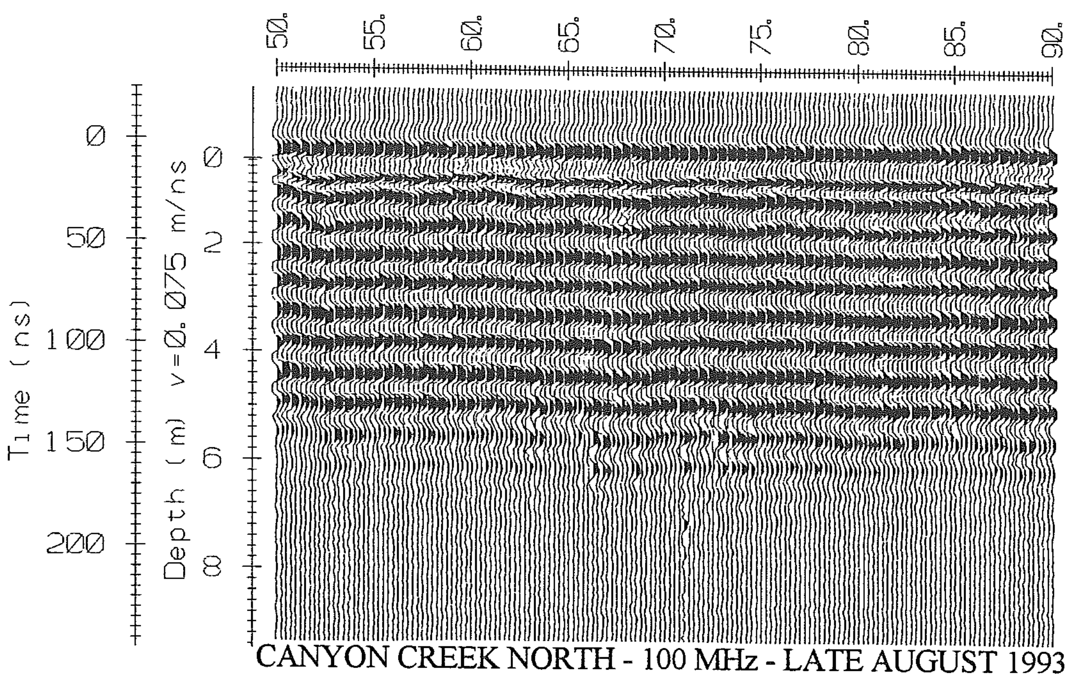
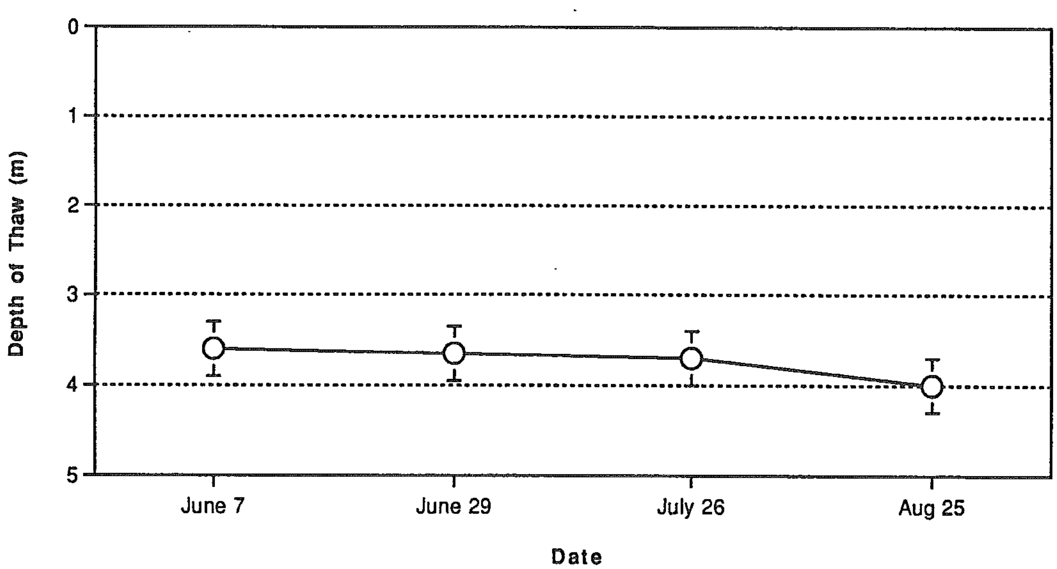


Figure 14. Multiple interference has been noted to occur during some late season surveys. This acts to overwhelm any true reflectors that may be present.

(a)



(b)

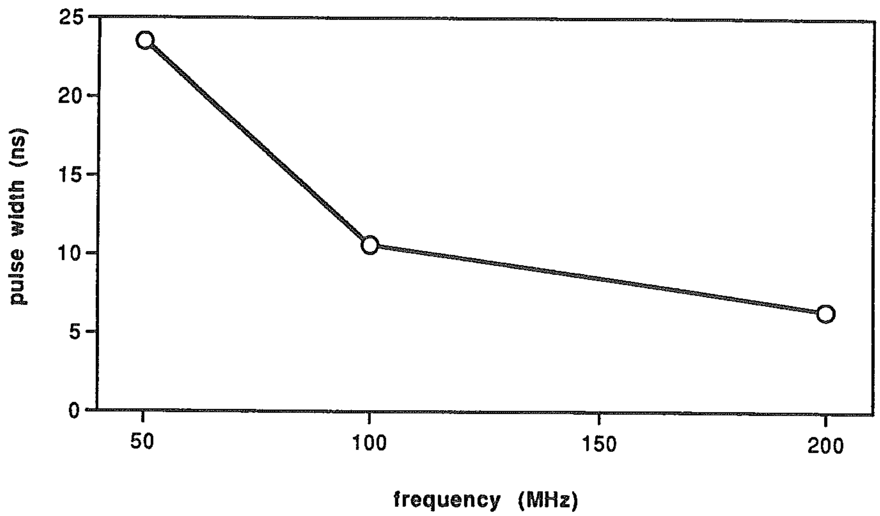


Figure 15. **(a)** Interpreted 1994 depth of thaw progression for the thaw bulb at the base of the Bosworth Creek North slope. Error bars indicate interpretation uncertainty due to radar pulse width. All error bars fall within the same range, suggesting that seasonal changes in thaw are not within radar resolution limits. **(b)** Resolution potential is greater with higher frequency antennas.

BENEFITS AND LIMITATIONS OF GPR FOR PIPELINE ROW MAPPING

Ground penetrating radar has been shown to be a very useful tool for non-destructive mapping of the shallow subsurface along the pipeline ROW. However, there are numerous limitations and uncertainties that must be kept in mind during survey operation and profile interpretation. This section will highlight conditions where GPR mapping can be extremely beneficial, as well as outline several of the critical limitations of GPR mapping under the conditions found along the pipeline route. Comparisons with other commonly used monitoring techniques will also be discussed.

BENEFITS of GPR SURVEYING

GPR surveying represents one of the most versatile choices for thaw monitoring on the pipeline ROW. GPR technology is relatively fast, inexpensive, portable, easy to operate, and one of the most reliable tools for detailed shallow subsurface mapping in permafrost environments. With an experienced radar operator and interpreter, GPR should give many clues as to the ground conditions at the time of surveying. The need for ancillary data to support interpretations (*i.e.* ground temperatures, depth-of-thaw probing, knowledge of local geology) is of paramount importance for confident interpretations.

Radar interpretation is often very subjective. However, if the researcher has a good idea of the survey objective, a geological model, and an understanding of the equipment and its limitations, much of the guess work can be removed. Research over the past 10-15 years has shown that certain geological conditions yield often predictable radar results. Being a continuous profiling technique, the pattern of radar reflections on the profile gives the interpreter clues as to the nature of material encountered at any location within the survey. Continuous line returns are expected from continuous, relatively smooth interfaces. In this study, continuous reflections would be expected from the base of the woodchips, frozen-unfrozen interfaces, and abrupt lithological contacts. Chaotic returns may be the product of thin layers or small point reflections within the ground. Some reflections may appear to be a combination of semi-continuous and chaotic, and may be caused by larger, more extensive joints, sediment, woodchip or ice lenses. Pattern recognition plays an important role in GPR interpretations. For example, the higher velocities typical of frozen material enable the entire pulse width to be reflected by an interface faster, with a higher frequency (narrower) return sensed at the receiver. Signal losses are also lower in frozen material, generally resulting in signal penetration to depths greater than those possible in most unfrozen materials. Slower propagation velocities, common in unfrozen wet materials, cause the pulse to "drag", resulting in a thicker, smeared reflector. When this knowledge is combined with the information on the nature of reflectors, a clearer picture of ground conditions emerges. For example, a frozen silt with numerous ice and clay lenses would appear as a zone of chaotic, narrow reflectors, probably with fairly deep penetration (see, for example Moorman *et al.*, 1994). Certain materials are also known to attenuate the signal more rapidly than other materials.

Mapping the contrast between frozen and unfrozen ground using GPR is often very successful due to the large contrast in electrical properties encountered. In general, radar signals are transmitted very well through frozen material, and a loss in signal or a lowering of return frequency may be interpreted as a transition to unfrozen ground. In examining thaw along the pipeline ROW, we are fortunate in that the boundary between frozen and unfrozen material is in most cases a strong reflector, and can thus be readily identified. Changes in ground ice content also result in strong reflectors. An experienced operator can conduct a detailed survey of a 150 m long woodchip slope in one day. All of these properties of GPR surveying make it the best choice for thaw mapping along the pipeline route when combined with ancillary data.

Other commonly used techniques for determining the thickness of thaw include shallow depth-of-thaw probing and the installation of temperature cables in boreholes. Both of these methods only yield information at a point, whereas GPR presents a cross-sectional profile. GPR surveying can be designed to cover the entire slope in varying degrees of detail, while temperature cables are stationary once installed. Although temperature cables generally provide accurate thermal data, results may become suspect as the lifetime of the cables is approached (see results from Bosworth Creek South cable T-1 in Robinson and Moorman (1995)). Depth-of-thaw probing is very subject to human error, and may become very inaccurate in clayey sediments.

LIMITATIONS TO GPR SURVEYING

Depth of signal penetration

The depth of electromagnetic signal penetration, and hence the effective depth of surveying, varies greatly with ground conditions. One of the most important factors affecting signal penetration is the *electrical attenuation* of the media through which the pulse is traveling. The higher the attenuation of the material, the greater the energy losses (in dB) that will be experienced by the pulse per unit distance traveled (m). Of materials encountered along the pipeline route, unfrozen clay and some fine silts have high attenuation values (up to 300 dB/m), and thus signal penetration will be limited in these materials. Materials such as ice (frozen pore water), woodchips (pores either water- or air-filled) and sand generally display much lower attenuation, and thus surveying is likely to be more successful. Results are commonly much better in frozen material compared to the same material unfrozen, especially if water content is high. Figure 16 shows two profiles through the same material (clay), where in (a) the clay is unfrozen and signal penetration is limited to only a few metres, and in (b) frozen clay allows signal penetration to over 5 m. Refer to Davis and Annan (1989) for a detailed list of the attenuation to be expected from various geologic materials.

GPR Surveying in Clayey Material

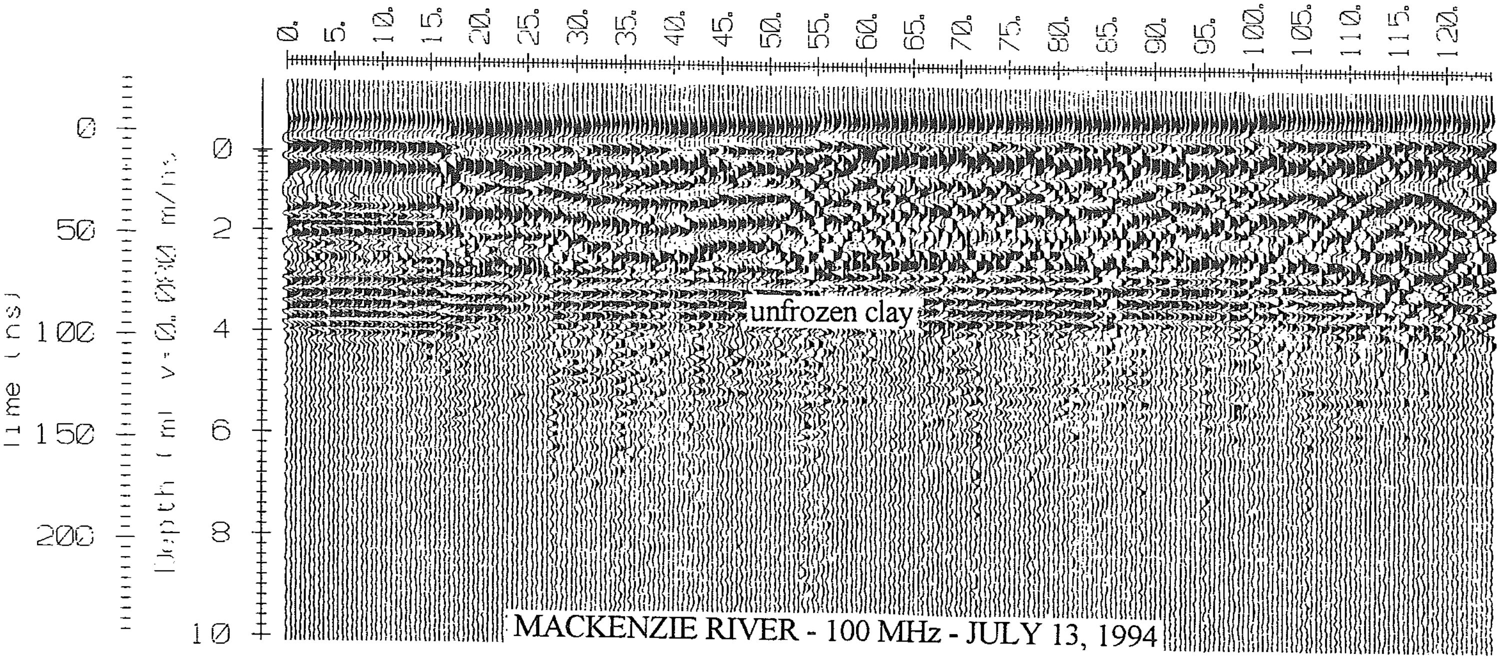
As briefly discussed above, the presence of clay presents unique problems to GPR surveying. In addition to often limiting signal penetration, the unique physical properties of clay must also be taken into account during radar interpretation. In some cases, a reflector may not be present where one should be expected based on a known transition in the ground. This commonly occurs in clay if the transition between unfrozen and frozen conditions (called the *frozen fringe*) is not a sharp boundary in the ground. This *frozen fringe* may represent a gradual change from

unfrozen to frozen conditions; a gradual boundary that might not be detected by the radar unit, or if it is detected it will be of very low frequency (smeared) and may not be identifiable. Appreciable amounts of unfrozen water may be present within clay at temperatures slightly below zero. Radar is influenced by the phase change more than the temperature change, and thus a frozen-unfrozen contact interpreted from the radar may not correspond exactly with temperature readings. In these cases, without support from borehole temperatures it may be impossible to pinpoint the change in ground conditions. The exact characteristics of the ground will be difficult to determine, even with ground truthing.

Reliability of Reflector Depth Determinations

Depths interpreted from CMP surveys are one of the most common potential sources of error, especially under heterogeneous ground conditions. The radar unit records only the energy travel time, and any interpreted depths are based on an assumed travel velocity. The velocity of electromagnetic energy travel through the ground is a function of the material, water content, and temperature (frozen Vs, unfrozen). In general, velocities are higher if the material is frozen or if it is dry compared to the same material when unfrozen or saturated. CMP surveying derives either a velocity value for the uppermost ground surface (upper 0.50 m approx.) or an integrated value of velocities to greater depths. Thus if a layered structure is present within the ground, with each

(a)



(b)

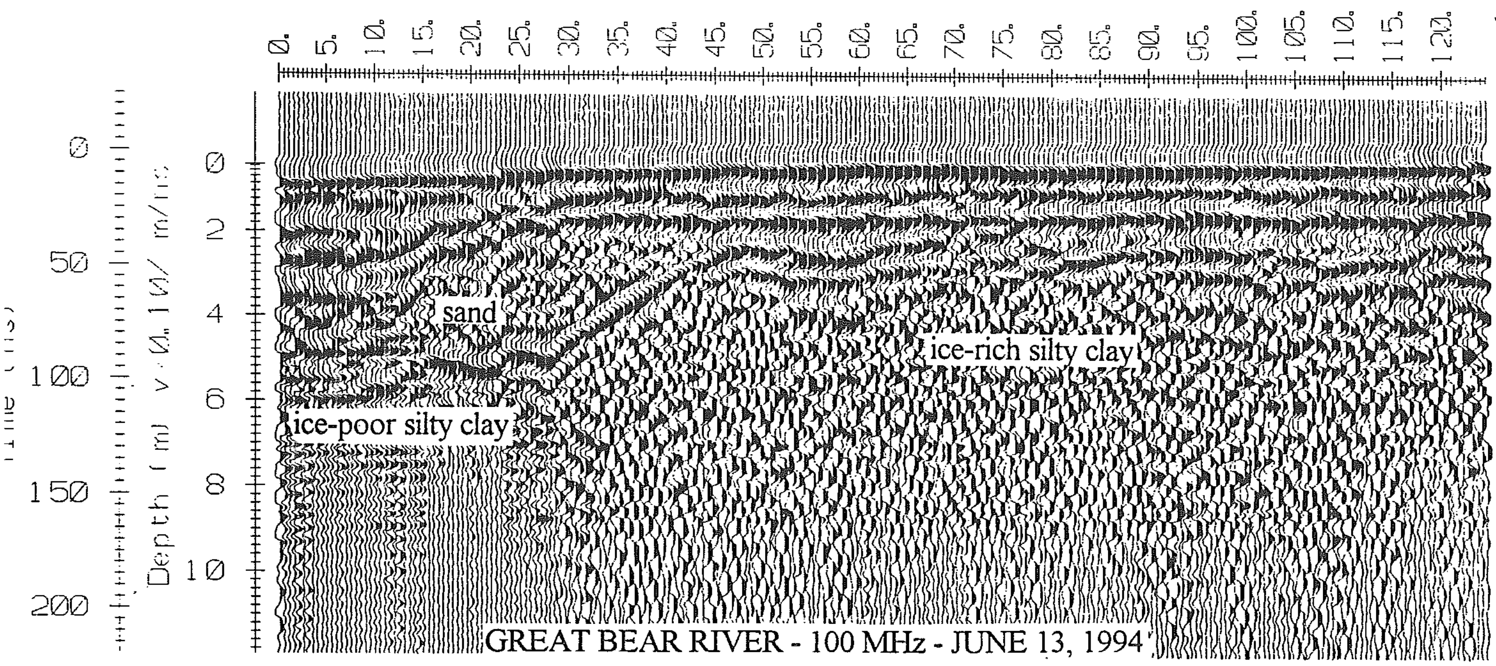


Figure 16. Radar survey conducted in unfrozen clay (**a**) shows limited signal penetration compared to (**b**) frozen clay.

layer exhibiting different velocities, the potential for error in depth determination is great. If the CMP survey only managed to derive a velocity value for the near surface, the error potential is also large, as near-surface ground conditions are rarely a good surrogate for deeper conditions.

Figure 17 shows some potential scenarios for depth determination error. In all cases, the velocity calculated at the surface was assumed to be representative of the entire column. In (a), depth determinations will be relatively accurate as there is little velocity change with depth. In (b), the presence of a 1 m thick talik (velocity = 0.07 m/ns) beneath 2 m of frozen material (velocity 0.16 and 0.15 m/ns) distorts the radar profile, such that the talik appears to be over 2 m thick. Although the presence of a talik could be detected using GPR, its true thickness would be difficult to determine without ancillary data (such as borehole temperatures). Scenario (c) presents the most common conditions found in surveying along the pipeline ROW. Surveying conducted during the summer will encounter a layer of unfrozen woodchips, which will commonly yield a velocity of 0.075 m/ns. However, applying this value to the entire column will result in underestimated depths for subsequent reflectors if the underlying material is frozen. Similarly in (d), the thickness of an air pocket would be underestimated (and perhaps even overlooked) due to its very high velocity (0.3 m/ns). Thus, if a layered ground structure is suspected, depth determinations should be viewed as only being a guide, and not as absolute depths. In such cases, the presented profiles are pseudo-cross sections. With the incorporation of ancillary data such as known thickness of geologic units, borehole temperatures, or depth-of-thaw probing, it is possible to improve the reliability of depth determinations.

Radar Interference Along the ROW

There are numerous sources of interference encountered on the woodchip slopes that may hamper GPR surveying. These range from interference from buried objects (*i.e.* pipe, borehole installations, drainage slots), multiple reflections as a results of ground conditions, or steeply dipping returns on frozen portions of some woodchip slopes. Large nearby objects such as a building, helicopter, or overhead wire can also cause interference, but are generally not a problem on the ROW.

Interference from Buried Objects

Figure 18a is a schematic diagram showing potential interference sources on cross-slope radar profiles. The GPR unit does not transmit a focused beam, instead there is a "side-looking" component to the returns. Very strong reflection sources such as the pipe or drainage slots are

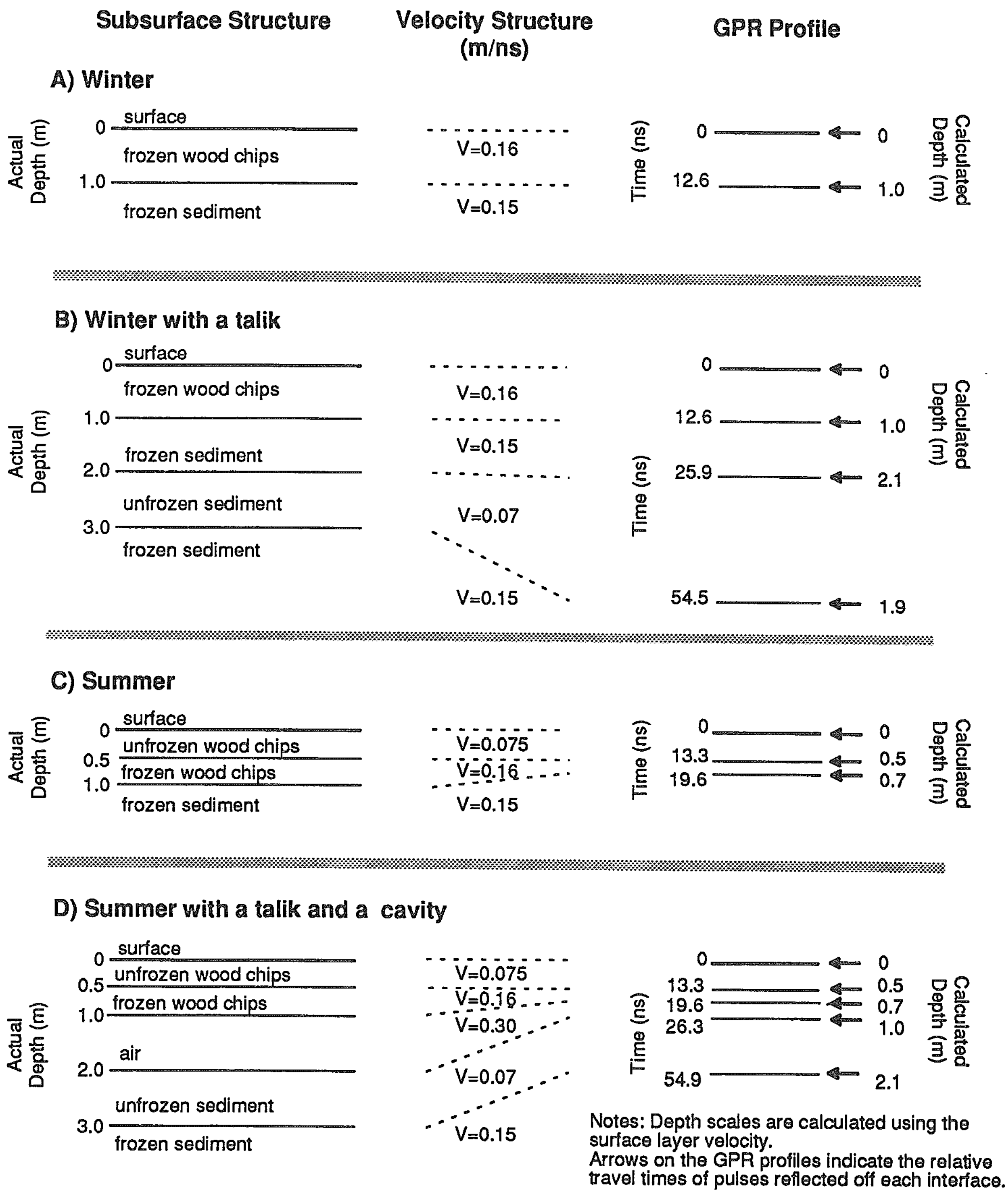
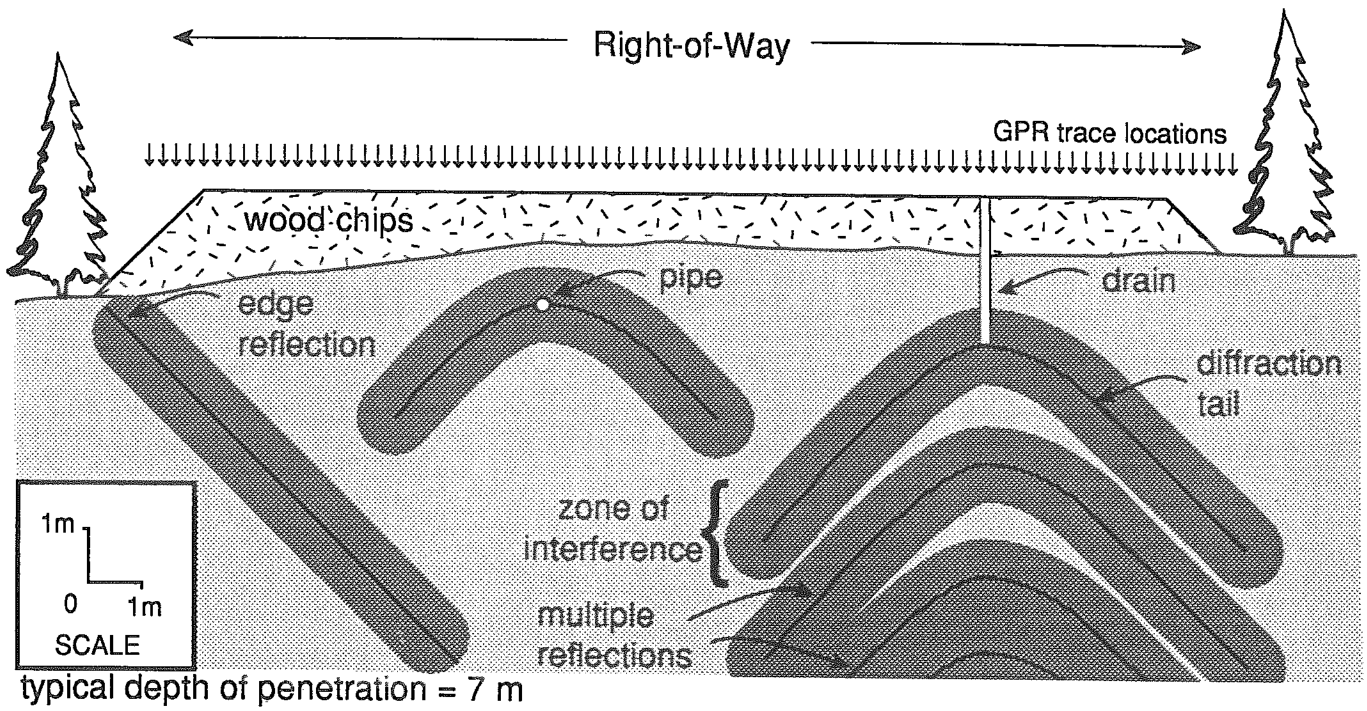


Figure 17. Potential scenarios for depth determination error based upon velocity variability. See text for discussion.

(a)



(b)

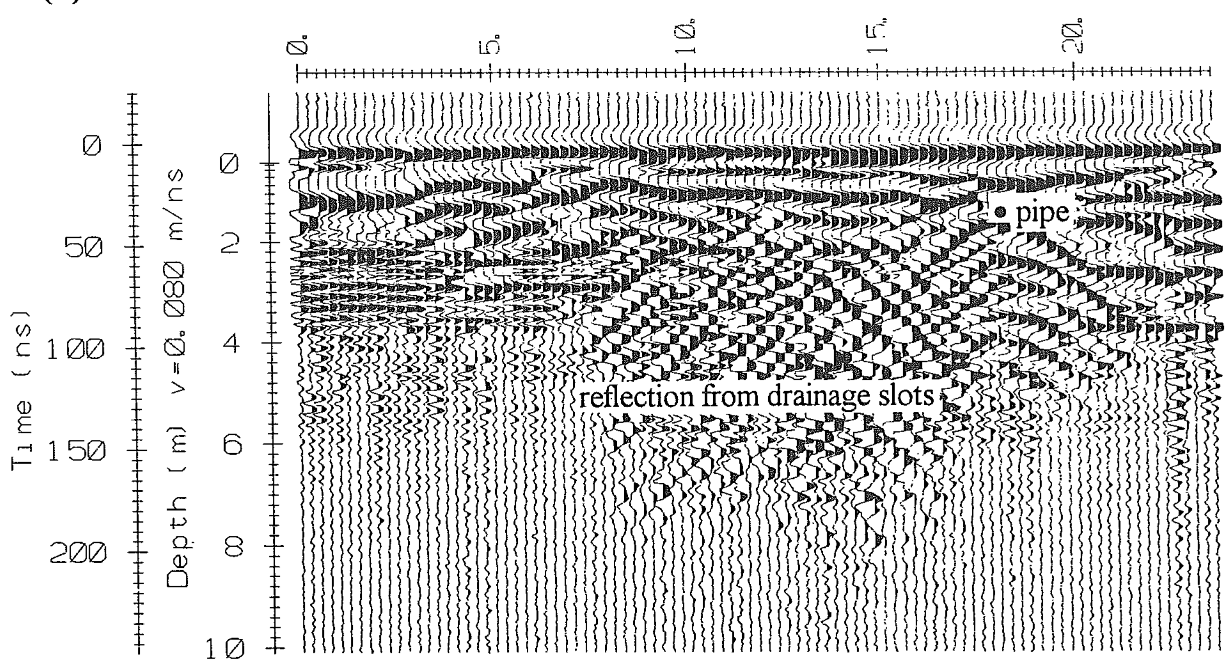


Figure 18. **(a)** Schematic diagram illustrating potential interference sources on cross-slope radar profiles. **(b)** Cross-slope radar profile from Slope 44 showing interference from both the drainage slots and pipe.

detected on the profile prior to, during, and following survey passage over that feature. This results in a hyperbolic interference pattern that obscures other information. The buried pipe itself will often result in a hyperbolic reflection, or in some cases excess interference, and may make the interpretation of thaw depth very difficult in the immediate vicinity of the pipe.

However, anomalous conditions immediately above the pipe may be detectable as the returns will arrive before those from pipe interference. The PVC tubing component of borehole installations can also cause similar interference. One arm of a hyperbolic interference pattern is often noted as the cribbing at the base of slope or a side-bank on the woodchip slope is approached. The effect of such interference can be seen on ROW profile in Figure 18b. Long profiles are conducted parallel to the pipe or drainage ditches and are not as strongly affected by such interference.

Multiples

Under some conditions multiple reflections may be received from a single source. Multiples are found to occur where there are two sharp boundaries surrounding a very good radar wave propagator. A large proportion of the pulse of energy is reflected at each interface, thus the signal reverberates back between the two interfaces. The numerous returns received at the surface indicate discrete reflections from the same source arriving at seemingly increasing times. Although they appear to be from depth, the source is shallow and the reflectors often serve to obscure any meaningful reflectors. Multiples can be identified by the cyclic appearance of near-identical reflectors (Figure 14), often with a common time interval separating the waves. Multiples are also commonly noted if the active layer thickness corresponds closely to the wavelength being propagated. This has been noted during late season surveys on the pipeline route in 1993, when the active layer was in the order of 1 m thick. The contact between a thick, saturated active layer and underlying frozen ground presents a huge electrical contrast that produces multiples. Often using a different frequency antenna may prevent multiples, but then the operator is forced to accept the penetration and resolution characteristics of those antennas.

Steeply dipping returns on frozen woodchip slopes

At several sites (most notably Bosworth Creek North, Bosworth Creek South, Canyon Creek North, Great Bear River, and Little Smith Creek South), a series of returns, dipping steeply both up- and downslope (similar in appearance to diffraction patterns but often without an obvious hyperbolic crest), are noted underlying the upper flat-lying reflections on profiles run parallel to the pipe (Figures 6a and 7a). These returns show velocities of about 0.1 m/ns indicating that they are produced within the ground. These returns obscure all other reflections present in that section of the slope, but their presence is usually correlated to the presence of a shallow depth of thaw. Thus, although radar surveys across frozen ground do not always display this pattern, where it is observed it can be said with some confidence that the ground beneath is frozen. This pattern was not observed in the 1993 surveys, likely due to decreased signal penetration in the late season associated with the increased depth of thaw. Preliminary modeling of these patterns suggest that they could be produced by a series of air-filled cracks near the woodchip-mineral soil interface. As this pattern is most notable on surveys conducted parallel to the pipe, this would imply that the survey is continually approaching, passing over, and moving away from cracks running perpendicular to the pipe. No such cracks were ever visible at the woodchip surface, and any tension cracks noted on the slopes were found to be roughly parallel to the pipe, the result of tension in the cross-slope direction. Steeply dipping reflectors such as these would be expected on cross-profiles at sites where the drainage slots were installed in 1994. Although some dipping interference patterns was noted from the slots, it was in no case as prominent or regular as those described above, suggesting that whatever is causing the dipping returns represents a large contrast in electrical properties of the ground. It should be stressed that although modeling of the radar results show they could have been caused by cracks at the base of frozen woodchips, this remains unproven.

Limits of Radar Resolution

Ground penetrating radar surveys are subject to detection limits, based upon the size of objects, the antenna configuration used, and the contrast in electrical properties between the object and the surrounding material. In general, extensive flat-lying reflectors (such as most geologic strata) will be detected, yet small point-source reflectors may be overlooked. In many cases, small boulders will be detected as small "blips", but the source of the blip cannot be determined without ground truthing. In theory, higher frequency antennas (such as the 100 MHz antennas) are capable of higher resolution, but often the background noise is also greater, resulting in many reflectors being "lost" in the deluge of returns.

Lateral radar resolution is most strongly affected by the spacing of traces. Early radar surveys on the pipeline ROW (*i.e.* 1989-1991) utilized a 1 m spacing between traces. In an effort to improve lateral resolution, station spacing in subsequent surveys was reduced to 0.25 m, resulting in a four times increase in resolution (Figure 19). Although surveys now require more time, the results show a greater continuity amongst reflectors, and the higher resolution makes detailed

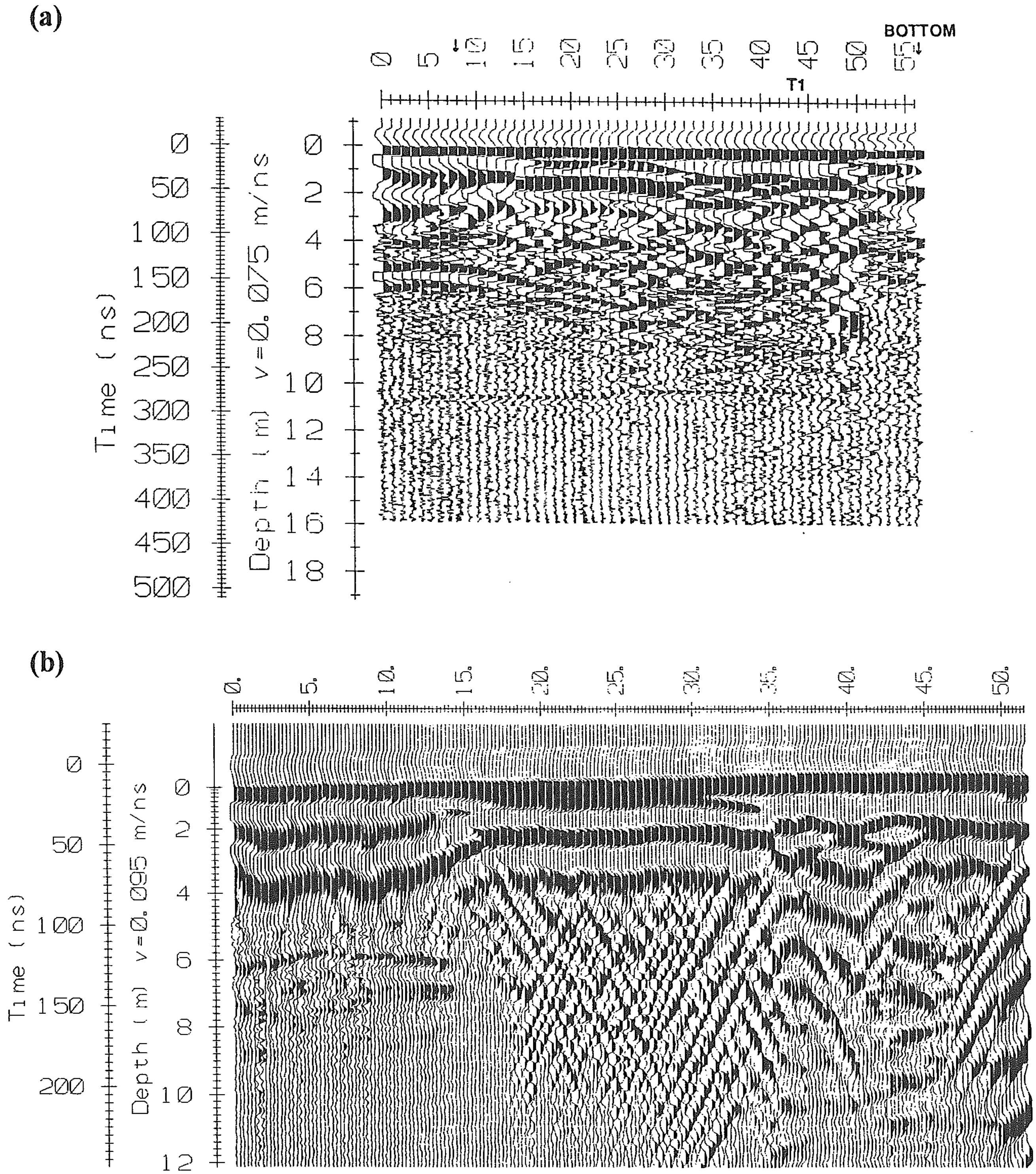


Figure 19. (a) Surveys conducted 1989-1992 were generally of low (1 m) lateral resolution. This 50 MHz example is from Bosworth Creek North, late summer 1990. (b) Subsequent surveys utilized a 0.25 m station spacing, resulting in much improved lateral resolution. This 50 MHz example is from Bosworth Creek North, June 1994.

interpretation much simpler. A station spacing of any finer than 0.25 m would not likely provide additional resolution to warrant the added time commitment.

Lateral resolution becomes somewhat of a problem on cross-slope profiles. In order for the operator to make accurate interpretations, a fairly lengthy stretch of reliable data is required in order to trace reflectors or establish reflector patterns. Unfortunately, cross-slope profiles are most susceptible to interference (see *Radar Interference Along the ROW* section above), and are by their nature relatively short profiles, often making it impossible to establish the identity of reflectors or reflector patterns. Thus the usefulness of detailed cross-slope profiles must be questioned.

Cavities

The presence of cavities underneath the woodchip slope was noted at Great Bear Crossing in 1991. However this was only delineated on the radar profile after ground inspections discovered the cavity. On the radar profile a cavity would not be displayed as a major event, mainly because high radar velocities through the air would drastically underestimate its size. Thus, the delineation of cavity extent is possible through radar profiling, but only after its presence has been confirmed through alternative means.

The Need For Ancillary Data

Radar surveying alone may give the interpreter an indication as to ground conditions, but the incorporation of ancillary data is required in order to improve confidence. Along the pipeline route ancillary data takes the form of temperatures recorded in boreholes, depth-of-thaw probing, and underlying geology from borehole logging or ditchwall logs. As the primary aim of ROW radar surveying is to delineate frozen vs. unfrozen ground, temperatures recorded in boreholes and probing are the most important forms of supporting data. Unfortunately, the majority of slopes surveyed contain only one or two temperature cables, and any early season probing (the best time to conduct GPR surveys) will be hampered by the remnants of seasonal frost.

In order to overcome the lack of ancillary data on some slopes, it would be beneficial to install several new thermistor strings. IPL has stated that they would like to decrease the frequency of manual measurements on the slopes. This may be possible, but only if the degree of confidence in GPR results could be improved through new installations. Another possibility to increase the quality of ancillary data would be to improve the manual means of depth-of-thaw probing. The development of a small-bore drill might be more useful than push-type probes.

SUGGESTIONS FOR FUTURE WORK

Surveying has been conducted annually since 1989, and has resulted in a large volume of data. This data has been summarized in various reports and much valuable information has been obtained. From this knowledge, it is now possible to outline the potential future focus of GPR monitoring of woodchip insulated slopes.

Several slopes should be targeted as priorities for the most detailed future work;

1) **Bosworth Creek North and South** - The presence of thaw bulbs at the base of both slopes has been noted during radar surveying. Detailed GPR surveys should be conducted in the future to monitor changes in extent. Additionally, these sites are close to the Norman Wells pumping station, and may be heavily influenced by modified pipe operating temperatures.

2) **Canyon Creek North** - Although the most recent surveying seems to indicate that the slope is relatively well frozen, the proximity to Norman Wells suggests that the slope may be influenced in the future by modified pipe temperatures.

3) **Slopes 44 and 45** - Deep thaw has been noted on both of these slopes and the effect of newly installed drainage slots remains unproven (although pore pressures have been reduced). The drainage slots cause considerable radar interference on cross-slope profiles, yet down slope profiles are relatively unaffected. These slopes are also on IPL's critical slope list.

4) **Little Smith Creek** - Extensive thaw noted beneath the upper and lower slope warrants further surveying. Additionally, the 1994 fire burned much of the region just to the west of the ROW, and may cause future slope instability.

5) **Slope 55 (kp 182)** - Although this slope has never included in any survey campaign, the effects of the 1994 fire may include future slope instability. It is important to establish baseline conditions (such as ground ice content) as soon as possible following the fire, and to continue monitoring for several years.

Slopes of lesser survey priority include Great Bear Crossing, Slope 31A (kp 84), and Slope 74 (kp 271.9). Unfortunately, the geological conditions at both slopes 62 (predominantly unfrozen clay) and 142 (complex thermal regime and unfrozen clay) are such that GPR surveying has not been very successful. Future surveys are not likely to give any better results. These slopes are on IPL's critical slope list as of November 1994.

Repeated monitoring through the thaw season is likely not warranted. The series of surveys conducted in June-August 1994 proved that the early summer is the best time to conduct radar surveys. Signal penetration is greatest prior to the development of a thick active layer. Resolution loss is such that any seasonal changes in the size of thaw bulbs may not be detectable with any confidence. As thaw bulbs are expected to continue to change through the winter (*i.e.* they don't refreeze), any changes would be best detected in subsequent annual or biannual surveys.

At several of the sites where future changes are expected, it would be prudent to survey on an annual basis for the next few years. The sites close to Norman Wells are included in the recommendation for annual surveying due to potential impacts from warmer pipe temperatures. Sites where drainage slots have been recently installed should also be surveyed annually until the impacts have been established. Should the impacts prove to be minimal, it would possible to conduct subsequent surveys biannually.

If surveys were to be conducted at regular intervals (annual or biannual), it would be necessary to establish regular survey grids on the slopes. This could be as simple as installing semi-permanent markers denoting the start and end of each survey line. In order to obtain accurate comparisons between surveys, it is important to re-survey along the exact same lines. Cross-slope profiles are in many cases of limited use, and perhaps should be conducted in detail only if time permits. However, several cross profiles should always be conducted at each slope to confirm pipe location and in an effort to map conditions surrounding the pipe itself. A consistency in survey parameters and processing should also be established.

One of the most important requirements for the continued success of GPR surveying is the acquisition of additional ancillary data. To improve the success of future surveys, it is recommended that several new temperature cables be installed on critical slopes. A new method of depth-of-thaw probing needs to be developed to make data more accurate and easier to collect. IPL has indicated that they would like to reduce the frequency of temperature cable readings. GPR surveying suggests that this frequency reduction may be feasible, but only if additional temperature cables were installed on critical slopes to improve GPR interpretations. Thus, it is an increase in spatial resolution that is required, to be collected possibly at the expense of temporal resolution.

CONCLUSIONS

A high degree of variability in depth of thaw is suggested for several slopes. For example, the slope at Bosworth Creek North appears to maintain thaw within the woodchips for the upper portions of the slope, however a zone of thaw up to 3.5 m is interpreted for the lower slope. A similar pattern was noted at the Bosworth Creek South slope. The slope at Little Smith Creek shows thaw up to 5 or 6 m thick in both the upper and lower sections of the slope, separated by a zone about 50 m long in the middle of the slope where thaw appears to remain within the wood chips. Hot spots also appear to have promoted some differential slope thaw. Interpreted thaw characteristics for individual slopes have been summarized in Table 2.

The most intensive surveying was conducted at 13 slopes within 272 km of Norman Wells. Average slope thaw appears to be maintained within the woodchips north of kp 84 inclusive, yet with zones of deeper thaw such as those noted at Bosworth Creek. Average slope thaw south of kp 84 appears to be well below the base of the woodchips, again with some zones of thaw deeper than slope averages (see Figure 11). Surveying in the early years of this project (1989-1992) was mainly of a cursory nature, yet several sites show a trend of increasing thaw between 1989 and 1994 (see Figure 12).

Surveys were conducted throughout the 1994 thaw season. Due to limitations in radar resolution, the changes in thaw extent within one season are likely not detectable. Future radar surveys should be conducted near the start of the thaw season in order to take advantage of the increased radar penetration with colder ground temperatures.

Pipe temperatures were observed to increase with distance south from Norman Wells until 1992, after which new operating conditions warmed pipe temperatures at the more northerly slopes. Hence, the potential for growth or enlargement of thaw bulbs has recently increased beneath many of the wood chip slopes. The more northerly slopes are likely to be most affected in the future by the new pipe operating temperatures.

Several slopes have been targeted as priorities for the most detailed future work. At the Bosworth Creek North and South slopes the annual monitoring of thaw bulbs at the base of the slopes should be conducted. The most northerly slopes (Bosworth and Canyon Creeks) are likely to be most influenced by modified pipe temperatures, and thus warrant future monitoring. Deep thaw has been noted at both slopes 44 and 45, and the effect of the newly installed drainage slots remains unproven. Extensive thaw noted beneath the slope at Little Smith Creek warrants further surveying. Although slope 55 (kp 182) has never been included in any survey campaign, the effects of the 1994 fire may include future slope instability, and thus there is the need to establish baseline conditions and to continue monitoring for several years.

Ground penetrating radar represents one of the most useful tools for non-destructive subsurface mapping of wood chip slopes. However, the need for ancillary data to support interpretations (*i.e.* ground temperatures, depth-of-thaw probing, knowledge of local geology) is of paramount importance for confident interpretations. It is suggested that several new temperature cables be installed on the critical slopes.

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