GEOLOGICAL SURVEY OF CANADA

OPEN FILE 3070

Ground penetrating radar surveys along the Norman Wells pipeline route, summer 1994

Part 1 – Site descriptions and radar interpretations

Part 2 – Radar profiles

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1995

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GROUND PENETRATING RADAR SURVEYS ALONG THE NORMAN WELLS PIPELINE ROUTE, SUMMER 1994

Part 1
Site descriptions and Radar Interpretations

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October, 1994

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SUMMARY

Ground pentrating radar surveys were conducted on 15 woodchip insulated slopes along the Norman Wells pipeline route from June to August 1994. When combined with temperatures recorded in boreholes and shallow depth-of-thaw probing, the patterns of thaw on the slope can often be determined. Several slopes displayed very complex thermal (and hence radar) structure (in some places caused by interference from drainage slots or the buried pipe), and thus thaw patterns were indeterminate for all sites. An extensive forest fire in 1994 affected the pipeline route between approximately kp 135 and 200. The terrain around several slopes was burned, and further monitoring of the effects of this fire upon the slopes is warranted.

A site-by-site summary outlining thaw patterns and preliminary results is as follows;

Bosworth Creek North (kp 0.3)

The majority of the slope appears to exhibit shallow thaw remaining within the woodchip cover. This thaw reaches a maximum thickness of about 0.80 m. Seasonal thaw thickens from the top towards the middle of the slope. The bottom portion of the slope is underlain by a deeper thawed zone (not a seasonal phenomena) of up to 3 or 4 m. This zone, as supported by borehole thermal measurements and probing, appears thicker and more extensive across the western side of the lower slope. The extent of this thaw zone does not appear to change in size appreciably through the summer. A thin layer of frozen woodchips is generally present above the thaw zone until late in the summer. As the ground beneath this frozen layer continues to warm through the summer, lateral heat transfer may be occurring. Minor additional thaw may be present in the vicinity of the pipe.

Bosworth Creek South (kp 0.4)

Similarly to Bosworth Creek North, this site shows a shallow seasonal thaw (active layer) across much of the upper slope. A steep drop-off in frost table was noted in the vicinity of slope instrumentation near the base of the slope; instrumentation which suggests permafrost is absent. Thus, deeper thaw (to depths of at least 6 m) is interpreted for the lower slope. The thaw zone in this case appears to be slightly more extensive on the eastern side of the slope. The dimensions of the thawed zone do not appear to have changed through the thaw season, even though deep temperatures at the instrument site do increase. It is suggested that this zone (and the one at Bosworth Creek North) will not re-freeze over the winter, and thus the potential for long-term thaw zone expansion continues through the winter. A thin layer of frozen woodchips is generally present above the thaw zone until late in the summer. Additional thaw in the vicinity of the pipe is not evident from the radar profiles.

Canyon Creek North (kp 19.2)

The Canyon Creek North site does not appear to have any zone of thaw extending beneath the

woodchips. Seasonal active layer thaw was found to be a maximum of 0.67 m. Additional thaw in the vicinity of the pipe is not evident from the radar surveys.

Canyon Creek South (kp 19.4)

Conditions are difficult to confirm without borehole thermal data, however it appears as if the slope may be frozen beneath the seasonally active layer, which is known to extend from as little as 0.30 m to greater than 1.4 m in some areas by late August. Above the woodhip insulated portion of the slope, the upper sediments appear to be unfrozen. This implies that thaw is below the woodchips in some areas. Tension cracks parallel to the pipe were noted by September 1994, however no indication of these cracks are seen in the June surveys.

Helava Creek North and South (kp 25.7)

These slopes appear to be well frozen beneath the shallow active layer, without any indications of thaw extending beneath the woodchips. Limited "depth-of-thaw" probing showed an active layer consistently between 0.65 and 0.78 m on both slopes. Temperatures measured within the sediments beneath the woodchips are all between 0 and -0.7°C, indicating that the sediments may have large unfrozen water contents. This may explain the relatively shallow depth of penetration (<4m) for the radar signal. Cross profiles also suggest homogeneous conditions across the slopes, with no indication of additional thaw in the vicinity of the pipe.

Prohibition Creek North (kp 32.4)

GPR surveying shows fairly homogeneous conditions of thin seasonal thaw across the entire slope, with no indications of any zones of deeper thaw. The deeper signal penetration between the 20-60 m survey positions is likely due to the colder ground temperatures (compare with Heleva Ck. results where the ground is 2-3 degrees warmer) or higher ground ice content. The cross profile, conducted near the base of the slope, does not show any indications of anomalous conditions near the pipe.

Great Bear River (kp 79.4)

Both the radar results and thermal measurements in boreholes suggest that this slope is well frozen beneath a seasonally active zone consisting of the upper portions of the woodchip layer. There are no indications of anomalous conditions on this slope, nor are there any indications of additional thaw in the vicinity of the pipe. It should be stressed that the pipe may mask any indications of local thaw were it present. Cavity development (remediated by IPL) was noted on previous surveys; there is no indication of the presence of cavities in 1994. A steeply dipping reflector at the crest of the slope may represent an old slope failure plane (observed to a depth of 18-19 m), and it is continuous with evidence of an old failure plane on either side of the ROW.

Slope 31A (kp 84)

A large depression parallel to the pipe on the west side of the slope is underlain by thaw up to about 2.8 m, portions of which correspond to previously observed hotspots. This depression extends the entire length of the slope, and is up to 8 m wide. Thaw at the edge of the depression, and away from the area of the depression in general ranged from 0.76 to 1.27 m thick on August 23.

Slope 44 (kp 133.6)

Active layer thaw above the crest of the slope remains within the woodchips at 0.72-0.86 m depth. Deeper thaw appears to coincide with the drainage slots on the June 23 surveys. This thaw, beneath a layer of seasonal frost is interpreted to extend to 2 or 3 metres. The thermal conditions are unclear between the drainage slots due to radar interference from the slots themselves while surveying in the cross-slope direction. This interpretation remains speculative as there are no temperature cables installed on this slope.

Slope 45 (kp 133.7)

It is difficult to make firm conclusions due to interference from the drainage slots. However, it appears as if thaw may be present to a maximum of 3 or 4 metres beneath a seasonal frost layer. These conditions appear to be similar across the slope, with the exception of slightly less thaw above the slope crest. Similar to Slope 44, thaw appears to have been promoted in the immediate vicinity of the drainage slots, perhaps due to water input during fire prevention or water channelling.

Little Smith Creek (slope 48B, kp 160)

Two separate regions of deep thaw are interpreted for this slope. The upper 35 m of the woodchip insulated slope appears to be underlain by thaw to depths of 4 or 5 m. The next 48 m 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 again thawed to a maximum depth of about 4 m. Although there is a seasonal frost layer across the entire slope, it was not resolved on the GPR surveys.

Steep Creek (Slope 62, kp 194.6)

It is interpreted that the entire portion of the slope surveyed is thawed to at least 5 or 6 m. This is shown by the loss of signal due to high conductivity of unfrozen clay. Surveys were conducted in late August, and there was no trace of any seasonal frost remaining.

Slope 74 (kp 271.9)

Thaw across this slope appears to vary between approximately 1 and 2.2 m. The deeper thaw occurs in a small area near the base of the slope. These observations are supported by thermal measurements.

Mackenzie Crossing (Slope 142, kp 529.7)

The results of the GPR surveys are very inconclusive for this slope. This is in part due to the large degree of thermal variability on the slope, the lack of any reflector indicating thaw, and the variability of woodchip cover. Being underlain by clayey material, it is possible that the frozen fringe is wide and freezing point depression causes soil with temperatures slightly below 0°C to contain little or no ice (*i.e.* lacking reflectors). Signal penetration was limited to 6 or 7 m using the 50 MHz antennas. However, much of the slope appears to have radar characteristics associated with unfrozen material to at least 3 m depth. New tension cracks were noted in late summer 1994.

INTRODUCTION

Slope stability 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 a buried pipeline from Norman Wells, N.W.T. south to Zama, Alberta. Much of the Norman Wells pipeline route is underlain by permafrost within a few degrees of 0°C, and thus may be thermally unstable. Ground warming is common on the Right-of-Way due to pipe operating temperatures or vegetation removal during construction, and therefore the need arose for preservation of permafrost on thaw-sensitive slopes. For this reason, 56 slopes along the pipeline route were covered with a 0.5 to 1.8 m insulating blanket of woodchips. Warmer pipe operating temperatures (up to 12°C in 1994) than originally planned has led to the development of thaw bulbs under many of the woodchip 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. Much of the background information can be found in various government publications from INAC and the Geological Survey of Canada (a branch of NRCan)(Burgess, 1988; MacInnes et al., 1989a; 1989b; 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 in under the Industrial Partners Program (IPP), from which came partial funding for this project.

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 staff of the Geological Survey of Canada (GSC) annually since 1989 (Moorman, 1991; 1993; 1994). These surveys have traditionally been conducted near the end of the thaw season in late August or early September to survey the maximum amount of thaw. However, many of these surveys have been plagued by multiple reflectors and noise generated within the thick active layer (Moorman, 1994). In order to avoid this, and to monitor the seasonal progression of thaw, 1994 surveys were planned to span the majority of the thaw season, from early June to late August. Although most sites surveyed have in situ temperature cables, GPR can be used to gain continuous two- and three-dimensional lithological and thermal information, using the temperature cables to provide points of ground truth.

This report represents a summary of surveys conducted during the 1994 field project, along with a preliminary interpretation of results, with some initial profile annotation. In addition to surveys on woodchip insulated slopes, several survey sites were established on flat ground near Norman Wells, to examine conditions surrounding the pipe in an area most likely to be affected by new pipe operating temperatures. These surveys will be included in a second report, with more detailed interpretations and comparisons with GPR surveys from previous years. This second report is expected to be submitted for publication as a GSC Open File Report in early 1995.

METHODS

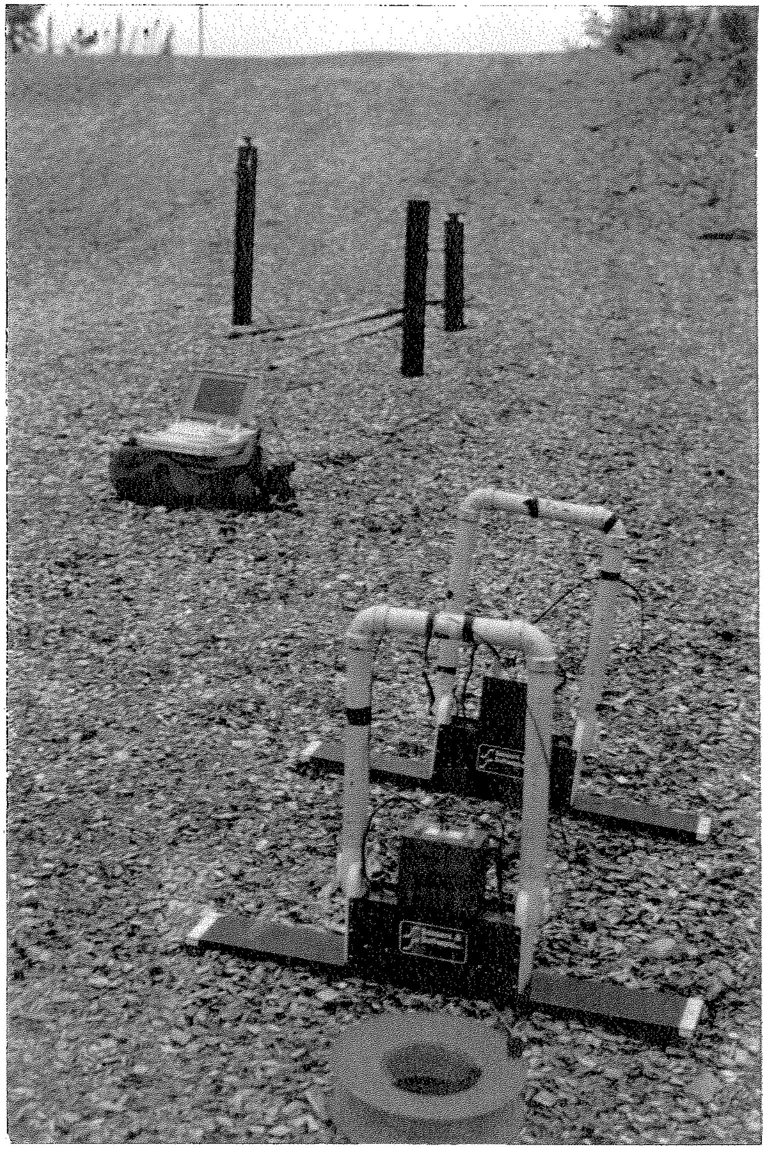
The pulseEKKO IV ground penetrating radar unit was used for survey data collection. Antennas with centre frequencies of 50, 100, and 200 MHz were used in conjunction with a 400 volt transmitter. The lower frequency antennas provide deep penetration, but at the expense of resolution. Higher frequency 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. A station spacing of 0.25m was planned for the profiles, however, during some time constraints, lateral resolution was sacrificed (station spacing 0.5m) in order to maintain adequate slope coverage. Antenna separation was 1m for both the 100 and 200 MHz antennas, and 2m for the 50 MHz antennas. These configurations provide reduced near-surface geometric distortion, while keeping signal saturation to a minimum.

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. Long profiles were generally conducted 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.

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 Techniques, below). In most 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). In some cases this can be accounted for with two separate depth scales.

Data editing and processing consisted only of that available through the pulseEKKO software. Radar traces collected in error have been removed. To smooth out high-frequency noise, minor temporal filtering was applied. Due to energy losses as the signal travels deeper, the relative strength of later returns was amplified by applying an automatic gain control function.

Thermal data from 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.



PulseEKKO ground penetrating radar unit used for these surveys

RADAR INTERPRETATION TECHNIQUES

Ground penetrating radar principles are very similar to those of the reflection seismic method. The main difference is that GPR energy is electromagnetic, not acoustic. With the GPR 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. The remainder of the energy continues to travel downwards through the ground, with additional portions reflected at subsequent interfaces. The 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.

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. The next arrival is the ground wave, travelling 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. They arrive in order of depth (top first). In the case of very shallow structure, reflectors may be indistinguishable from the ground wave.

Geometric distortion, caused by antenna separation, must be accounted for during profile interpretation. The greater the antenna separation (2m when using 50 MHz antennas), the greater the near-surface distortion due to the sub-vertical energy path. With this in mind, the returns from the near surface (upper 2-3 m) are presented with a slightly compressed depth scale.

The pattern of reflections on the profile gives the interpreter clues as to the nature of material encountered in 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. Hyperbolic reflections are produced when the survey approaches, passes over, and continues past a small body which has considerably different electrical properties than the surrounding material. The pipe would cause this type of reflection in this study. Boulders and slope instrumentation may also be the source of hyperbolic reflections (see for example, the hyperbolic reflections from the Canyon Creek North surveys). A steeply dipping (45° when corrected for vertical exaggeration), straight reflection would result from the survey approaching the cribbing at the base of the slope. Chaotic returns may be the product of thin layers or small point reflections within the ground. In this study, these may be from joints in bedrock, sediment or ice lensing, or small cobbles. 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. 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.

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 (actually refraction patterns), dipping steeply both up- and downslope (often without an obvious hyperbolic crest and overlain by flat reflections), are noted underlying the upper flat-lying reflections on 50 MHz profiles. If these reflections were from an above-ground source, the slope should be equal to the velocity of light (0.3 m/ns). However, these returns show velocities much lower (about 0.1 m/ns) indicating that they are produced within the ground. This pattern was not present in the 1993 surveys, likely due to decreased signal penetration in the late season. The 100 MHz surveys display a more chaotic appearance, typical of ice lenses within frozen sediment or jointed bedrock. A couple of possibilities exist for the origin of these reflectors. If topographic correction were applied to these profiles, the reflectors dipping upslope would become relatively flat-lying, and those dipping downslope would become even steeper. It is possible that these reflectors represent fracturing in the shale bedrock common beneath these slopes. If this were the case, then the good penetration depth would imply that the bedrock remains frozen. Similar reflectors noted in previous surveys have been attributed to tension cracking within the woodchips (Moorman, personal communication, 1994). However, 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. Additionally, the dipping returns noted at Bosworth Creek are present on the portion of the woodchips above the slope, seemingly ruling out both dipping bedrock and tension cracking (due to woodchip movement) as their source. 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 was noted from the slots, it was in no case as prominent and regular as those described above, suggesting that whatever is causing the dipping reflectors represents a large contrast in electrical properties of the ground. At several sites, it appears that supports from cribbing at the sides of the slope may extend beneath the slope, and would have the effect of being a hyperbolic reflector at depth. However, the side cribbing is of limited extent at most sites, and appears to be absent from Canyon Creek, Great Bear River, and Little Smith Creek. IPL personnel have informed me that, to their knowledge, no extensive network of cribbing supports exist beneath the woodchips (if it did, the vertical drainage slots could never have been water drilled). However caused, these reflections obscure any other reflections that may be present. There is one redeeming conclusion that can be reached based on the presence of steeply dipping reflections. At every site where these reflections are present, that section of the slope is frozen to at least the depth of the reflection origin, based on probing and borehole temperatures. 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 at least to about 2-3 m.

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. For instance, radar propagation velocities are often high (.09-.16 m/ns) in frozen material with a fairly high ice content. The higher velocities 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. For instance, penetration in clay may be limited to a few metres, perhaps more if the clay is well frozen. Appreciable amounts of unfrozen water may be present within clay at temperatures slightly below zero. Radar responds to the phase change, not the temperature change, and thus a frozen-unfrozen contact interpreted from the radar may not correspond exactly with temperature readings. Additionally within clay, 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.

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 slope of the reflectors (other than the air wave) will representing velocity. The CMP survey often gives a value for near-surface velocity, and should be used with caution if complex stratigraphic environments are encountered.

RESULTS

The results of the GPR surveys are discussed on a site by site basis, with the actual profiles presented in Part II of this report. A complete list of all slope sites surveyed during this project is included in Table 1. Site results and interpretations are arranged on a north to south basis. Borehole stratigraphy and thermal information was extracted from Hardy Associates (1978) Ltd. "Norman Wells to Zama Pipeline IPL Instrumentation Program" reports, as well as Pilon et al. (1989), Burgess and Naufal (1990) and information supplied by Margo Burgess (GSC). Temperature readings taken in 1994 are from IPL and personal readings on the day of GPR surveying. Where possible, comparisons are made with GPR results obtained previously and reported by Moorman (1991; 1993; 1994).

Maps of each survey site are presented, showing the position of radar lines as well as boreholes and major slope features. All long profiles progress downslope, and the numbering of cross profiles starts from the bottom of the slope. Some of the features encountered along each profile (i.e. boreholes, pipe) are indicated on the profiles, as are preliminary reflector interpretations. To avoid repetition, several sites are presented with detailed interpretation, and others are only discussed briefly, particularly those where results do not indicate anomalous slope conditions. More detailed interpretation and profile annotation is expected as a component of the second report.

Table 1 - Summary of GPR surveys conducted between June 2 and August 30, 1994.

SLOPE	**SURVEY DATES 1994**	**ANTENNAS**	**RESULTS on PG.#**
Bosworth Creek North Slope 1 - kp 0.3	June 2 June 7 June 16 June 29 July 26 August 25	100 MHz 50 MHz 200 MHz 50 MHz 100 MHz 50 MHz	9
Bosworth Creek South Slope 2 - kp 0.4	June 3 June 7 June 16 June 29 July 26 August 25	100 MHz 50 MHz 200 MHz 100 MHz 100 MHz 50 MHz	14
Canyon Creek North Slope 3 - kp 19.3	June 8 June 21 August 5 August 8	100 MHz* 100 MHz* 50 MHz 100 MHz	18
Canyon Creek South Slope 4 - kp 19.5	June 21	100 MHz*	20
Heleva Creek N and S Slopes 11 & 12 - kp 25.6	July 25	100 MHz*	22
Prohibition Creek South Slope 16 - kp 32.2	July 25	100 MHz*	24
Great Bear River South Slope 29B - kp 79	June 9 June 13 June 13 August 29 August 29	50 MHz 200 MHz 100 MHz* 100 MHz* 50 MHz*	26

Unnamed Slope Slope 31A - kp 84.0	August 23	100 MHz	30
Unnamed Slope North Slope 44 - kp 133.6	June 23 August 15	100 MHz 100 MHz	31
Unnamed Slope South Slope 45 - kp 133.7	June 20 August 15	100 MHz 100 MHz	34
Little Smith Creek Slope 48B - kp 160	July 6 July 7 August 18	50 MHz 100 MHz 100 MHz	37
Steep Creek North Slope 62 - kp 194.6	August 28	50 MHz	40
Unnamed Creek South Slope 74 - kp 271.9	July 15 August 27	100 MHz 50 MHz	41
Mackenzie River South Slope 142 - kp 529.7	July 12 July 13	50 MHz 100 MHz	43

* - incomplete slope coverage

Bosworth Creek North (kp 0.3)

The Bosworth Creek slopes were chosen due to their proximity to the start of the pipeline, the presence of ice-rich material, and ease of access. These slopes are also likely to be the most influenced by new pipe operating temperatures. Bosworth Creek is also the water supply for Norman Wells, and hence there are concerns about siltation associated with any slope failure.

Site Description

Bosworth Creek North is the first slope that the pipeline crosses, only 350 m from the Norman Wells pump station. The woodchip insulation covers an area about 42 m long by 17 m wide. The slope itself is about 30 m long, with an average slope of 16° facing southeast. The woodchip insulation was originally placed on the slope to a thickness of 1.1 and 0.95 m, although this has likely settled slightly. A 1 m high crib is located at the base of the slope to restrain the downslope movement of the woodchips.

Geologic Setting

Borehole information consists of a single borehole located in the centre of the ROW about 12 m upslope from the cribbing. This borehole (T-1) shows 1 m of woodchips underlain by 2 m of clay till, with about 10% ice content. The till is in turn underlain by 1.2 m of silty clay and traces of weathered shale, and fractured clay shale to borehole completion at 6 m. Examination of bedrock outcrops on the banks of Bosworth Creek show this shale to be heavily fractured.

Thermal History

Three temperature cables are installed on this slope. Two are in borehole T-1 (cables T-3 and TA-11) and one in a 1991 borehole 91-5. On June 16th, T-1 showed a thawed zone between 1.0 and 1.75 m underlying the remains of winter 1993-94 freezeback between 0.50 and 1.0 m. Seven metres downslope, readings in 91-5 showed a thaw bulb to almost 3 metres. By July 26, the remaining seasonal frost in T-1 had thinned slightly, but the deeper thaw zone had not thickened appreciably. Thaw in 91-5 had increased to about 3.5 m by July 26. On August 25, a thin frozen zone remained in T-1 just above 1 m depth, and the thawed zone below was now as deep as 2 m, below which the ground remained frozen. Thaw in 91-5 deepened to almost 4 m.

IPL personnel probed this slope in 1990, and found late-season thaw to be at or below the base of woodchips, ranging from 1 to 2 m depth.

Thus, the thermal data shows that, although the two boreholes are only a few metres apart, a complex thermal structure exists, with deeper thaw closer to the base of the slope. Moorman (1991) indicates that the ground immediately beneath the woodchips has experienced a range in temperatures of 15°C since monitoring began.

GPR Survey Results

Due to ease of access, the Bosworth Creek slopes have been the most intensively surveyed. Complete slope surveys (two long profiles and three cross profiles) were conducted with the 50 MHz (June 7), 100 MHz (June 2), and 200 MHz (June 16) antenna configurations. The 50 MHz surveys were repeated on June 29 and August 25, and 100 MHz surveys on July 26.

Early season results

Early June GPR surveys provide a great deal of information as to the thermal condition of the slope. The 100 MHz surveys show up to four fairly continuous flat-lying reflectors in the mid-slope, perhaps reflecting portions of the complex sequence of (from the surface down) active layer, seasonal frost remnant (coinciding somewhat with the base of woodchips), thawed zone (??), clay (frozen or unfrozen (??)) and into perennially frozen shale. The presence of a thawed zone beneath the seasonal frost is possible upslope of T-1 based on the number of reflectors present, however this is difficult to prove or disprove without thermal data from this section of the slope. However, the greater depth of penetration in this section would lead one to believe that a thick talik in the clay is not present. Frozen fringes within clay are generally gradational, and hence may not result in a distinct reflector.

Beneath the flat-lying reflectors lies a series of steeply dipping reflectors appearing between the 18 and 35 m survey positions on Long Profile 1 and 20 and 45 m on Long Profile 2 (50 MHz). This pattern was not present in the 1993 surveys, likely due to decreased signal penetration in the late season. These reflectors are of unknown origin, but are strongly correlated with the presence of frozen material in the upper subsurface (see discussion in the Radar Interpretation Techniques section). The 100 MHz surveys display a more chaotic appearance, typical of ice lenses within frozen sediment or jointed bedrock.

The reflector potentially representing the base of thaw (based on travel-time calculations) is seen to separate from the ground wave and deepen around 30 m (50 MHz, Long Profile 1). Towards the base of the slope (the lower 3-14 m), reflectors representing the base of thaw dip dramatically to 3 or 4 metres. Refractions typical of frozen material elsewhere on the slope are not present here, further suggesting a change in ground properties. Temperatures recorded in boreholes T-1 and 91-5 support this observation, as do radar surveys from 1993 (Moorman, 1994). Thaw may be shallower and closer to the base of the slope on the east side of the ROW. The radar returns from beneath this thaw bulb are attenuated, suggesting that much of the radar signal cannot penetrate through the thawed zone. The reflector representing the base of the woodchips drops through this section, indicating a lower propagation velocity. Although CMP surveys suggest velocities to be 0.95 to 0.1 m/ns, the complex thermal structure forces a large degree of depth uncertainty upon the depths presented in these surveys. Cross profiles confirm that the thaw bulb appears to be restricted to the lower slope, with thaw being more extensive on the west side of the ROW (see cross profile 2).

The same radar patterns indicating a thawed zone are noticed on the 50 MHz surveys, although they are more simplified due to the loss in resolution. These surveys seem to indicate that the deepest thaw may occur beneath the 40 m position on Long Profile 1. The 50 MHz also show radar energy penetrating up to 11 m depths.

It seems possible from cross profiles 1 and 2 (lower slope) that there may be additional thaw in the vicinity of the pipe, although it is difficult to confirm due to interference from the pipe itself. The 50 MHz cross profiles 1 and 2 show a reflection dipping towards the pipe on both sides of the pipe, potentially representing thaw.

The 200 MHz surveys contain useful information only in the upper 2 or 3 metres, and consist of reverberations below that. However, the zone of deeper thaw at the base of the slope is also noticeable in these surveys.

Mid-season results

In order to monitor the seasonal progression of thaw on this slope, repeat surveys were conducted mid-season (June 29 (50 MHz) and July 26 (100 MHz)). Near-surface propagation velocities decreased to 0.90 and 0.80 m/ns on these survey dates respectively. Most CMP surveys indicate near-surface velocities, which change the most over the thaw season due to moisture content of the near-surface, and may result in inaccurate depth interpretations, especially in areas of complex thermal stratigraphy.

Due to the complexity of velocities encountered on this slope, it is very difficult to determine if the thawed zone has changed in extent. Based on signal two-way travel time (as opposed to depth from an assumed velocity), it is quite likely that thaw has increased slightly in thickness by July 26 (as supported by temperatures in 91-5). Additonally, from both the long and cross profiles, the thaw bulb does not appear to have changed in lateral size.

The steeply dipping pattern found in the frozen sediments underneath the upper slope is less noticible in the July 29 surveys, suggesting that the attenuation may be becoming greater in the thickening active layer (consistently 0.38-0.50 m based on manual probing, 0.65 m in TA-11). The reflector representing the thaw front is expected to arrive with or just after the ground wave and just before the woodchip base reflector. This is best seen on the 50 MHz surveys, where the thaw thickens towards the base of the slope, peeling away from the ground wave by the 30 m position on Long Profile 1 (June 29). The July 26 surveys (100 MHz) show a more clear definition of flat-lying reflectors in the near surface (compared to the early season), likely representing the development of the active layer, with constant thickness over the upper slope, thickening towards the base of the slope. This was confirmed through manual probing.
The base of seasonal thaw on the ROW above the woodchip slope is deeper (up to 90 cm based on probing) than the majority of the slope (consistently 38-50 cm). This is also evident on the radar record, keeping in mind that the velocities above the woodchips will be much lower than the scale presented.

The degree of thaw in the vicinity of the pipe can be inferred on the cross profiles from the nature of the ground wave and reflector from the base of the woodchips. The character of these reflectors do not appear to have changed appreciably from the early season surveys, perhaps suggesting that a large degree of thawing above the pipe is not presently a seasonal phenomena.

Late season results

The 50 MHz surveys were repeated on August 25, and showed a propagation velocity of 0.080 m/ns. Thaw probing indicated frost at depths of 0.50-0.72 m above the slope crest, 0.85-0.90 m on the upper slope, and >1.35 m in the vicinity of the instrumentation. Long Profile 1 shows an additional reflection starting at about the 26 m position, likely representing this trend towards deeper thaw near the base of the slope.

Thaw at the base of the slope does not appear to have extended laterally, and appears to have thickened only slightly, as suggested by thermal measurements. Borehole T-1 shows the upper thawed active layer, underlain by the remnants of winter freezeback, in turn underlain by a thawed zone down to 2 m (August 25). The thermal readings from borehole T-1 (cables T-3 and TA-11) are problematic. Readings show that, although some seasonal frost remains, the thaw bulb beneath is warming. Thermodynamically, this implies heat is being introduced to the thaw bulb from the sides, perhaps through moisture flow or from the pipe. This pattern is also seen on several other slopes and will be discussed in the appropriate sections. It is possible that this thawed zone beneath the seasonal frost extends upslope underneath the woodchips. The number of flat-lying radar reflectors present could suggest this, and it appears that the inferred base of thaw in the lower slope is continuous with a reflector in the upslope direction. Without confirmation from borehole temperatures, this remains speculative. Manual frost probing would of course be stopped by the upper frozen layer. Late in the season, the remaining thin seasonal frost was easily punched through during manual probing. Cross profiles do not indicate any increase in extent of the inferred thaw above the pipe.

The dipping pattern noted in previous surveys is much weaker in the late season, likely due to signal attenuation in the thickening active layer.

<u>Comparisons with previous GPR surveys</u>

Surveys conducted at Bosworth Creek in 1989 and 1990 (Moorman, 1991) were of limited horizontal resolution; 1 m step size compared to 0.25m during 1994. However, indications of a thaw bulb do exist in this data, yet it is difficult to determine its dimensions due to the poor resolution.

During late summer 1993, the 100 and 200 MHz antenna surveys were plagued with reverberations and multiples that rendered high resolution mapping near impossible. This was likely due to the thicker, more saturated active layer. Amongst the reverberations however, the

1993 surveys delineated the thaw bulb near the base of the slope. Moorman (1994) does not suggest that the thaw bulb extends to the east side of the pipe. From the results of this study, it appears that there may be deep (2-3 m) thaw of limited extent at the base of the slope on the eastern side. Otherwise, the dimensions of this thaw bulb do not appear to have changed significantly over this period. GPR results from 1994 show that both the 50 and 100 MHz antenna configurations were not affected by reverberations at any time during the thaw season. The reason for the reverberations in 1993 is not known, but it may be caused by active layer thaw to depths similar to GPR operational wavelengths.

Site Summary

The majority of the slope appears to exhibit shallow thaw remaining within the woodchip cover. This thaw reaches a maximum thickness of about 0.80 m. Seasonal thaw thickens from the top towards the middle of the slope. The bottom portion of the slope is underlain by a deeper thawed zone (not a seasonal phenomena) of up to 3 or 4 m. This zone, as supported by borehole thermal measurements and probing, appears thicker and more extensive across the western side of the lower slope. The extent of this thaw zone does not appear to change in size appreciably through the summer. A thin layer of frozen woodchips is generally present above the thaw zone until late in the summer. As the ground beneath this frozen layer continues to warm through the summer, lateral heat transfer may be occurring. Minor additional thaw may be present in the vicinity of the pipe.

Bosworth Creek South (kp 0.4)

Site Description

Bosworth Creek South is the second slope that the pipeline crosses, 420 m from the Norman Wells pump station. The woodchip insulation covers an area about 45 m long by 13-19 m wide. The slope itself is less than 30 m long, with an average slope of 14° facing northwest. The woodchip insulation was originally placed on the slope to a thickness of 1.1 m, although this has likely settled slightly. A 1 m high crib is located at the base of the slope to restrain the downslope movement of the woodchips. Cribbing is also present along much of the west side of the slope.

Geologic Setting

One borehole is located on the slope, 12 m up from the base of the slope (at 42 m of Long Profile 1), and one about 25 m above the top of the slope. Similar to the north side of Bosworth Creek, the woodchips (1.1 m thick) are underlain by clay till to 2.9 m, with clay till containing weathered shale fragments to the borehole base at 6.3 m. The borehole above the slope shows a similar thickness of till (without a woodchip cover), however competent shale bedrock was reported below 3.3 m.

Thermal History

The temperature cable located above the slope (T-2) shows temperatures above freezing down to 5 m by late July. Seasonal frost remained at the time of the June 16 and 29 readings. The temperature cables located in the slope borehole (TA-7 and T-1) indicate thaw of permafrost beyond the base of the cables at 6.1 m, with seasonal frost only occurring within the lower woodchips. Thin seasonal frost remained on August 25, underlain by a warming thaw bulb.

GPR Survey Results

Complete slope surveys were conducted with the 50 MHz (June 7), 100 MHz (June 3), and 200 MHz (June 16) antenna configurations. The 100 MHz surveys were repeated on June 29 and July 26, and the 50 MHz on August 25.

Early season results

The Bosworth Creek South surveys show patterns similar to those seen at Bosworth Creek North. Deeper thaw above the woodchip slope is shown on the radar record (above the woodchips, thermistor T-2 shows thaw to 1.5 m) as a zone of shallower signal penetration, smeared (thicker) reflectors, but with some bedrock structure visible at depth on the 50 MHz surveys.

Similar to the patterns noticed at the Bosworth North slope, there appears to be deeper thaw at the base of the slope, with a reflector following topography at about 7 m depth. This reflector is not likely to be the base of thaw, as the temperature measured at 6.1 m depth was +3.9°C. Thermistor cables indicate no permafrost down to at least 6.1m (T-1), yet with thin seasonal frost remaining between 55 cm and the base of the woodchips. As temperatures are observed to increase with depth, it is unlikely that permafrost exists at depths greater than the temperature cable. The thawed zone, extending uphill from the base of the slope for 15 m, appears to be present across the bottom of the slope, but is best illustrated on Long Profile 2 (50 MHz, June 7) as there is no interference from slope installations. Interference from a thermistor installation is clearly seen centred about 41 m of Long Profile 1. The upper slope contains the same dipping reflectors described at Bosworth Creek North, and can be correlated with the presence of permafrost, at least within the shallow subsurface. These dipping reflectors are most prevalent on the west side of the slope, between the 16 and 34 m survey positions. Due to the deep signal penetration, it appears as if the upper slope remains frozen, perhaps with a small talik at the base of the woodchips. However, there are no temperature cables installed on this portion of the slope to prove or disprove this.

Cross profiles do not indicate any anomalous conditions in the vicinity of the pipe. Interference from the pipe itself extends approximately 6-7 m on either side of the pipe, and refractions from the steep woodchips banks are also noted. The cross profiles confirm the zone of deeper thaw at the base of the slope, and on Cross Profile 2 (July 26) perhaps indicate deeper thaw on the west side of the lower slope.

The 200 MHz surveys, conducted on June 16, were plagued by multiple reflections below about 2.5 m depth. Multiples such as this are frequency dependent, and thus the 200 MHz antennas were not used for subsequent surveys.

Again, the warming of the thaw bulb beneath seasonal frost is problematic, and potentially represents warming of the thaw bulb from a source other than surface temperatures, perhaps the pipe.

Mid-season results

In order to monitor the seasonal progression of thaw on this slope, repeat surveys were conducted on June 29 and July 26, both at 100 MHz frequencies. Near-surface propagation velocities had decreased to between 0.75 and 0.80 m/ns on these survey dates. Most CMP surveys indicate near-surface velocities, which change the most over the thaw season due to moisture content of the near-surface, and may result in inaccurate depth interpretations, especially in areas of complex thermal stratigraphy.

By the end of July, the seasonal thaw measured in borehole T-2 (thermistor cable TA-7) has almost completely melted, resulting in one fewer near-surface reflector. Temperatures at depth (thermistor string T-1) are generally 1.5-2°C warmer than in mid-June.

Similar to Bosworth Creek North, signal penetration on this slope decreases with thaw progression in the near-surface. The dipping structure becomes less distinct as the season progresses. Thaw at the base of the slope is also not as distinct, due to both the decreased penetration and the frequency used in the later surveys (100 MHz). Although temperatures measured in the borehole have increased, the thaw zone does not appear to have increased appreciably in lateral extent by the end of July.

Late season surveys

The thinning of seasonal frost allowed the penetration of a manual probe by the end of August. By this method it was confirmed that deep thaw (>1.3 m) was present in the vicinity of the boreholes. Just above the boreholes, manual probing encountered frost at depths of 0.76-0.80 m, with the upper slope showing thaw to 0.62 m.

Away from the inferred thaw zone at the base of the slope, cross profiles do not indicate any additional thaw around the pipe.

Depth penetration is again decreased in comparison to surveys conducted earlier in the season. This is due to increased signal absorption in the deepening active layer.

The dimensions of the thaw zone at the base of the slope do not appear to have increased over the summer, even though temperatures at depth have increased. It is suggested that this zone will not re-freeze over the winter, and thus the potential for thaw zone expansion continues through the winter. It may be easiest to detect expansion on an interannual basis, as seasonal variations may be more limited to the near-surface.

Comparisons with previous GPR surveys

Surveys conducted at Bosworth Creek in 1989 and 1990 (Moorman, 1991) were of limited horizontal resolution; 1 m step size compared to 0.25m during 1994. Indications of a thaw bulb do not exist in the 1989-90 data, yet thermal measurements indicate that it also existed at this time. It was likely not delineated due to decreased signal penetration and poor lateral survey resolution. Surveys conducted in late August 1993 (Moorman, 1994) show signs of a thaw zone near the base of the slope, of roughly the same size as interpreted here. Again, Moorman (1994) suggested that the upper slope contains only thin seasonal thaw.

Site Summary

Similarly to Bosworth Creek North, this site shows a shallow seasonal thaw (active layer) across much of the upper slope. A steep drop-off in frost table was noted in the vicinity of slope instrumentation near the base of the slope; instrumentation which suggests permafrost is absent. Thus, deeper thaw (to depths of at least 6 m) is interpreted for the lower slope. The thaw zone in this case appears to be slightly more extensive on the eastern side of the slope. The dimensions of the thawed zone do not appear to have changed through the thaw season, even though deep temperatures at the instrument site do increase. It is suggested that this zone (and the one at Bosworth Creek North) will not re-freeze over the winter, and thus the potential for long-term thaw zone expansion continues through the winter. A thin layer of frozen woodchips is generally present above the thaw zone until late in the summer. Additional thaw in the vicinity of the pipe is not evident from the radar profiles.

Canyon Creek North (kp 19.2)

This slope was selected due to its proximity to Norman Wells and ease of access. It is also likely to be influenced by new pipe operating temperatures. Localized surface disturbances on this slope have been noticed in the past, although the majority of the slope does not appear to be thawing. This site is also a joint PTRM-IPL monitoring site.

Site Description

Canyon Creek is located 19.2 km from the start of the pipeline. The north woodchip slope is about 142 m long and 22 m wide, with an average slope of 12° facing southeast. A 1 m thick woodchip blanket was initially placed on the slope, but this has likely settled to 0.85 m.

Geologic Setting

Two PTRM thermal fences are located in the vicinity of the slope, one being 200 m above the top of the slope (84-2A, 4 boreholes) and one on the slope, 55 m below the top of the woodchips (84-2B, 4 boreholes). The boreholes above the slope indicate 9 m of silty clay and clayey silt, underlain by silty shale bedrock to at least 20 m. Ice contents are low, with the shale possibly being unfrozen at the time of drilling. On the slope, clay till and silty clay is thinner (to about 2.2 m below woodchip surface), with shale bedrock (unfrozen below 4.5 m at the time of drilling) to at least 21.5 m. Excess ice content within the silty clay is about 5%, and the upper shale about 3%.

Thermal History and Depth of Thaw Probing

Although the bedrock was logged as unfrozen below 4.5 m at the time of drilling, all boreholes on the slope show frozen temperatures below the active layer (about 60-80 cm thick by early August) to depths up to 20 m. IPL personnel made a total of 9 thaw depth of thaw probings on 3 cross sections in 1990. They found that thaw tended to be greatest near the pipe (up to 1.5 m). At other locations seasonal thaw remained within the woodchips. Probing conducted in 1994 showed seasonal thaw did not extend deeper than 0.67 m at any location on the slope. The majority of the slope contained thaw between 0.43 and 0.56 m at the beginning of August.

GPR Survey Results

GPR surveys were conducted at this site on June 8 (100 MHz, lower 2/3 of the slope), June 20 (100 MHz, Long Profile 2 only), August 5 (50 MHz, whole slope), and August 8 (100 MHz, whole slope).

Early season surveys

All of the woodchip slope is underlain by the steeply dipping reflectors described previously, and strongly correlated with the presence of frozen ground in the shallow subsurface. The depth of active layer thaw is not indicated on the GPR profiles due to its shallow depth.

Late season surveys

The pattern indicating frozen conditions is again present, although muted due to increased signal absorption in the thickening active layer. Again, the depth of active layer thaw is not indicated on the GPR profiles due to its shallow depth. There is no indication of additional thaw in the vicinity of the pipe.

Comparison with previous surveys

Moorman (1994) conducted late-season surveys across the same slope, and also concluded that the seasonal thaw was shallow, without any indications of any deeper thaw. The 1993 surveys were affected by multiple interference; a condition that did not affect the 1994 surveys.

Site summary

The Canyon Creek North site does not appear to have any zone of thaw extending beneath the woodchips. Seasonal active layer thaw was found to be a maximum of 0.67 m. Additional thaw in the vicinity of the pipe is not evident from the radar surveys.

Canyon Creek South (kp 19.4)

This slope was selected due to its proximity to Norman Wells and ease of access. This slope is also likely to be influenced by new pipe operating temperatures. Relatively little background information exist for this slope, and for this reason only cursory surveys were conducted here.

Site Description

The woodchips cover is limited to the lower portion of the slope, covering approximatley 45 by 22 m. The woodchip portion of the slope has an average slope of about 14°. The slope is only covered with woodchips 0.5 m thick. The pipe runs approximately down the centre of the ROW.

Geologic Setting

Although no boreholes exist for the woodchip insulated portion of the slope, thermal fence 84-2C is located less than 100 metres upslope. These boreholes show about 6.5 m of clayey silt overlying siltstone (shale bedrock??), which occurs to depths of at least 20 m.

Thermal History and Depth of Thaw Probing

No temperature data exists for the woodchip slope, so thermal data has been taken from 84-2C. The active layer on the uninsulated ROW appears to be up to 7 m thick (little or no latent heat effects), while off the ROW, seasonal thaw penetrated about 2 m. As permafrost thaw extends into the bedrock, further permafrost degradation would likely have little effect on slope morphology. Recent ground temperature measurements indicate about 2 m of sesasonal frost underlain by 5 m of supra permafrost talik. At the time of the GPR surveys (June 21), the seasonal frost had thawed in the upper 0.60 m near the thermal fence, and 0.35-0.43 m on the woodchip slope. IPL personnel found thaw to range between 0.6 and 1.7 m during 1990 thaw probing. Moorman (1994) found thaw depths varying between 0.35 and >1.4 m.

GPR Survey Results

Surveying suggested that the slope may be frozen beneath the active layer (only 0.35-0.43 m on June 21), however without confirmation from thermal measurements, this is very difficult to confirm. Deeper thaw may be present beneath the seasonal frost, although probing would be stopped by the first frozen layer. The criss-cross pattern typical of frozen conditions at some other slopes is not observed here (this does not indicate the absence of permafrost), yet signal penetration remains fairly deep. Tension cracks parallel to the pipe were noted by September 1994, however no indication of these are seen in the June surveys. Above the woodhip insulated portion of the slope, the upper sediments appear to be unfrozen.

Comparison with previous GPR surveys

Moorman (1994), surveying in late August 1993, noted the possible presence of a zone of slightly thicker thaw near the base of the slope. 1994 survey results do not show this, however without verification from borehole data, all interpretations are very difficult to confirm.

Site Summary

Conditions are difficult to confirm without borehole thermal data, however it appears as if the slope may be frozen beneath the seasonally active layer, which is known to extend from as little as 0.30 m to greater than 1.4 m in some areas by late August. Above the woodhip insulated portion of the slope, the upper sediments appear to be unfrozen. This implies that thaw is below the woodchips in some areas. Tension cracks parallel to the pipe were noted by September 1994, however no indication of these cracks are seen in the June surveys.

Heleva Creek (kp 25.7)

In an effort to characterize and provide background data for several slopes close to Norman Wells (most likely to be affected by new operating temperatures), cursory surveys were conducted on July 25 at Heleva Creek North and South slopes using the 100 MHz antenna configuration.

Site Description

Heleva Creek is located 25.77 km from the start of the pipeline. The north slope has woodchip insulation with approximate dimensions of 88 x 18m. The south slope has woodchips covering about the same area. The south slope averages 14° (max. 17°) while the north slope averages 16.5° (max. 20°). Woodchips were placed on the north slope to a thickness of 1 m, and between 0.45 and 0.75 m on the south slope.

Geologic Setting

The north slope, with 6 boreholes, shows silty clay till (with some gravel) greater than 5 metres thick overlying clay shale bedrock. The clay till is thinner above the slope. Gravel, up to 1.8 m thick immediately underlies the woodchips on the south slope and is in turn underlain by clay till (to 3 or 4 m depth) and clay shale bedrock.

Thermal History

Thermistor strings installed on the Heleva North slope (TA-9, T-19, and T-5) all show temperatures slightly below freezing, with the exception of a shallow (30 cm) active layer on July 25. One thermistor string above the woodchip slope (T-8) shows active layer development of almost 3.0 m. Frozen conditions are also found on the south slope (thermistor strings T-17, TA-10, T-14, and TA-6), however with an active layer in the woodchips reaching 60 cm on mid-slope, and 80 cm on the lower slope.

GPR Survey Results

The base of the woodchips is easily identified on long profiles at both north and south slopes, although on the south slope it appears deeper than the suggested maximum thickness of 0.75 m. This could be due to inaccurate near-surface velocities (measured as 0.95 m/ns on the north slope). There do not appear to be any areas of anomalous conditions on either slope. Borehole temperatures measured within the clay are all between 0 and -0.7°C, indicating that the clay may have high unfrozen water contents. This may explain the relatively shallow depth of penetration for the radar signal.

Cross profiles also suggest homogeneous conditions across the slopes, with no indication of additional thaw in the vicinity of the pipe. Cross profiles were affected by refractions from the steep banks of the woodchips, and from the pipe itself.

Comparison with previous GPR surveys

No previous surveys have been conducted at these sites.

Site Summary

These slopes appear to be well frozen beneath the shallow active layer, without any indications of thaw extending beneath the woodchips. Limited "depth-of-thaw" probing showed an active layer consistently between 0.65 and 0.78 m on both slopes. Temperatures measured within the sediments beneath the woodchips are all between 0 and -0.7°C, indicating that the sediments may have large unfrozen water contents. This may explain the relatively shallow depth of penetration (<4m) for the radar signal. Cross profiles also suggest homogeneous conditions across the slopes, with no indication of additional thaw in the vicinity of the pipe.

Prohibition Creek South (kp 32.4)

In an effort to characterize and provide background data for several slopes close to Norman Wells (most likely to be affected by new operating temperatures), cursory surveys were conducted on July 25 at Prohibition Creek, south slope.

Site Description

The woodchip insulation, 1.0 to 1.5 m thick, covers an area of approximately 174 x 19 m. The slope averages 14°, with a maximum slope of 20°.

Geologic Setting

A veneer of silty clay till directly underlies the woodchips. The till thickness at the top of the slope is 1.8 m, thickening downslope to 2.4 m in borehole T-1. Beneath the till lies another silty clay, with some weathered shale fragments, down to at least 7 m. Mudstone bedrock was encountered at 7 m in a borehole near the base of the slope.

Thermal History

Temperatures recorded in boreholes T-1 (thermistor strings TA-1 and T-4) and T-2 (TA-4 and T-23) show a thin active layer (less than 30 cm) overlying well frozen material. Maximum-minimum temperature envelopes show that this slope historically has shallow active layer development.

GPR Survey Results

Equipment problems (faulty fibre optic cables) plague the mid-slope portion of the survey, between about the 75-144 m positions. However, the GPR survey shows fairly homogeneous conditions of thin seasonal thaw across the entire slope, with no indications of any deep thaw. The deeper signal penetration between 20-60 m positions is likely due to the colder ground temperatures (compare with Heleva Ck. results where the ground is 2-3 degrees warmer). The cross profile, run near the base of the slope, does not show any indications of anomalous conditions near the pipe. It should be stressed again that the pipe itself creates anomalous signals, which may mask signals indicating changes in the sediment.

Comparison with previous GPR surveys

No previous surveys have been conducted at this site.

Site summary

GPR surveying shows fairly homogeneous conditions of thin seasonal thaw across the entire slope, with no indications of any zones of deeper thaw. The deeper signal penetration between the 20-60 m survey positions is likely due to the colder ground temperatures (compare with Heleva Ck. results where the ground is 2-3 degrees warmer) or higher ground ice content. The cross profile, conducted near the base of the slope, does not show any indications of anomalous conditions near the pipe.

Great Bear River South (kp 79.4)

The Great Bear River site was selected for study due to the large amount of background information compiled, mainly from two PTRM thermal fences, IPL slope instrumentation, boreholes (lithology and thermal data), and previous GPR surveys. This slope is also representative of northeast facing slopes in ice-rich permafrost. Numerous slope failures have been noted in the area by Savigny and Morgenstern (1986). Cavity development in the pipe trench was discovered during 1991 radar surveying, and although this was remediated by IPL, slope conditions may still be of concern.

Site Description

This site is located approximately 79.4 km from Norman Wells, on the south bank of the Great Bear River. The woodchip slope (1.1 m thick following construction) is 146 m long, with an elevation change of almost 25 m (average slope is 11°). This site has numerous locations with uneven woodchip surfaces, ditchline settlement, and tension cracks.

Geologic Setting

Borehole logs are available from two PTRM thermal fences, one at the top of the slope (EMR/INAC site 84-3B) and one approximately 60 m north of the base of the slope (84-3A). Additional borehole logs from slope instrumentation boreholes are available from Hardy Associates reports.

Boreholes drilled at the top of the woodchip slope show 4 to 5 m of silty sand overlying silty clay which extends to almost 20 m depth. This sand cap thins downslope (1.8m thick at T-1), and is absent by about 2/3 of the way down the slope. Towards the bottom of the slope, fairly ice-rich clay and peat layers are noted in borehole 81-S22A. Boreholes drilled for thermal fence 84-3A show ice-rich silt in the upper few metres, underlain by silty clay. The clay underlying the slope contained an average 10-20% excess ice, although it reached up to 40% in places. The ice content of the sand ranged from only pore ice up to 10% excess ice, with an average of about 5% excess ice. A layer of ice up to 1 m thick was noted in boreholes at the base of the slope. It appears from differential settlement of the ROW that the majority of this ice has now melted-out and the ground is beginning to stabilize again.

Thermal History

Data is available from EMR/INAC thermal fences located at the top and bottom of the slope, as well as IPL thermistor cables on the woodchip slope. Pilon et al. (1989) estimate that permafrost thickness is approximately 50 m in the area.

Borehole temperature data at the time of the GPR surveys (June 9 and 13th) from the slope shows consistent frozen temperatures to at least 6 m depth beneath a thin (0.30-0.35m) active layer. Thermal readings from the thermal fences above and below the slope show thicker active layers on the ROW (1.0-1.4 m), with generally frozen conditions below that. The connector for cable T-2 contained water during the summer, and thus did not provided accurate readings. Thermal fence temperatures off the ROW are 1 to 2°C colder. Late season temperatures from previous years show active layer development on the slope to slightly less than 1 m (Moorman, 1993). Previous surveys at the thermal fences indicates that the active layer often thickens to 2 m above and below the slope.

GPR Survey Results

Surveys were conducted with the 50, 100 and 200 MHz antennas in early June covering the entire slope. Subsequent 50 and 100 MHz suveys were conducted in late August at the slope crest, in order to identify a possible failure plane noted on the early season surveys.

Early season surveys

Surveys were conducted using the 50, 100, and 200 MHz antennas on June 9 and 13. 50 MHz surveys were conducted along one long profile down the travel side (west) of the slope, roughly centred between the pipe and the edge of the ROW. Additionally, 5 cross profiles were conducted across various points on the slope. The 200 MHz surveys were conducted along the same lines, although this survey was extended to 30m past thermal fence 84-3A at the base of the slope. Eight cross profiles were conducted with the 200 MHz antennas. Due to time constraints, only the long profile down the west side of the woodchip slope was conducted with the 100 MHz antennas. Velocities determined from CMP surveys were 0.107 m/ns.

The 50 MHz survey results show coarse structure beneath the slope (all surveys start 19m above the woodchips). The sand at the top of the slope is characterised by several continuous, relatively flat-lying reflectors. Due to the thicker active layer and high water table (30 cm below ground surface) upslope from the woodchip insulation (resulting in slower propagation velocities), the depth scale is in error for this section. However, the active layer and water table are too shallow to appear on the radar record using this antenna configuration. The sand capping the slope appears to pinch out or be very thin by about the 40 m position.

Due to the high near-surface velocities over the woodchips, the ground wave appears to be incorporated into the bottom of the air wave. By the 22 m position, the woodchip layer is thick enough to be detected by the radar as the reflector immediately below the air wave. This reflector remains at a constant depth and with a consistent character down the slope, suggesting homogeneous conditions without thaw bulbs, such as those noted at Bosworth Creek. Beneath the woodchips, the deep penetration, strong signal return, and distinctive radar pattern (see discussion in Radar Interpretation Techniques section) suggests the slope remains frozen in the near-surface (with the exception of thin seasonal thaw), as supported by borehole temperature surveys and shallow probing.

The clay underlying the slope is characterised by a semi-chaotic structure on the 100 and 200 MHz profiles. This is indicative of the ice-rich nature of the clay. Higher resolution of these antennas also shows that the sand cap extends slightly further downslope than shown on the 50 MHz profiles.

Structure within the clay underlying the slope is well mapped using radar. The 50 MHz surveys show numerous steeply dipping refraction patterns confined to the clay unit. These reflectors, of unknown origin, are correlated to the presence of frozen material in the shallow subsurface. As the higher frequency antennas are of higher resolution, the reflectors tend not to be noticed to the same degree. However, one or two significant exceptions are noted. A steeply dipping reflector is noted on all profiles starting at the 32 m position (5 m depth) and continuing for about 12 m. This reflector is truncated at the overlying sand, and may represent a steeply-dipping potential failure plane within the clay. Other similar features are noted on the 100 MHz profiles between 93-101 and 136-146 m. Slopes in the region have been characterised as failure prone (Savigny and Morgenstern, 1986).

Cross profiles are strongly influenced by hyperbolic reflectors from the pipe and the steep edges of the woodchip slope, making interpretation difficult. However, none of the cross profiles show an indication of a exceptional conditions (thaw or frost bulb) surrounding the pipe.

The 200 MHz surveys continued past the base of the slope and onto the thermokarst terrain towards 84-3A thermal fence. The contorted nature of many of the reflectors and the shallower signal penetration indicate that ice melt-out likely has occurred, and portions may remain unfrozen. This region appears to have stabilized, but the melt-out of large amounts of ice means that the original borehole stratigraphy is no longer valid. The relatively sharp reflector at depth is likely due to the increasing clay content as noted in the boreholes. The depth scale is likely inaccurate for this section due to the higher ground temperatures.

Late season surveys

Two short surveys were conducted in late August at the top of the slope. These surveys attempted to identify the steeply dipping and deeply penetrating reflector. This slope is located within the bowl of an abandoned slope failure, and this reflector potentially represents a paleo-failure plane. These surveys suggest the reflector is dipping at about 45°, and is at least 16-18 m deep, capped by overlying sand.

Comparison with previous surveys

This slope was surveyed by personel of the Geological Survey of Canada in 1990 (Moorman, 1991) and 1991 (Moorman, 1993).

The 1990 surveys were conducted with a 1 m trace step, resulting in decreased spatial resolution compared to the 1994 surveys (0.25 and 0.5 m steps). The 1990 surveys also show fairly homogeneous slope conditions. The 1991 surveys were plagued by late season reverberations from within the thick active layer, and provide useful information only in the shallow subsurface.

Cavity development has been previously shown on this slope in 1991 by Moorman et al. (1994). Such cavities may be characterised high frequency reflectors on the radar profile. Surveys conducted in 1991 were over top of the pipe, whereas the surveys conducted in 1994 were about 5 m west of the pipe. Long or cross profiles conducted in 1994 did not provide any indication of cavity development.

Site summary

Both the radar results and thermal measurements in boreholes suggest that this slope is well frozen beneath a seasonally active zone consisting of the upper portions of the woodchip layer. There are no indications of anomalous conditions on this slope, nor are there any indications of additional thaw in the vicinity of the pipe. It should be stressed that the pipe may mask any indications of local thaw were it present. Cavity development (remediated by IPL) was noted on previous surveys; there is no indication of the presence of cavities in 1994. A steeply dipping reflector at the crest of the slope may represent an old slope failure plane (observed to a depth of 18-19 m), and it is continuous with evidence of an old failure plane on either side of the ROW.

Unnamed Slope (kp 84)

Little background information about this slope is available. However, hot spot warming was noted at this site (Burgess *et al.*, 1993), and subsequently monitoring instrumentation was installed. GPR surveys at 100 and 200 MHz were conducted at this site on August 23.

Site Description

An area approximately 50 x 30 m is covered with woodchips of unknown thickness. The slope is very gradual ($<5°$), and extensive surface depressions have developed and roughly follow the patterns of hot spots.

Geologic Setting

No background information is available to the author. However, sediments brought up from depth on the bottom of the thaw probe indicate that the slope is underlain by silty clay.

Thermal History and Depth of Thaw Probing

A series of shallow temperature probes were recently installed to monitor hot spot temperatures, however the data is not presently available. Thaw probing was conducted at 3 m intervals along each radar profile on August 23. In general, thaw depths away from the surface depression ranged from 0.76 to 1.27 m. A 3 m long probe was used within the depression, and in most instances the sticky clay prevented penetration before the frost table was reached. Therefore, thaw greater than 1.7 m was noted at the edges of the depression, and one site in the middle of the depression showed thaw greater than 2.8 m.

GPR Survey Results

A depression of the thaw table coinciding with the surface depression is noted. The thaw dips to just less than 3 m at the centre of the surface depression. Thaw is interpreted to be about 1 m thick (0.76 to 1.27 m based on probing) over the rest of the slope.

The 100 MHz profile has been plotted with relative topography to emphasize thaw beneath the depression. The pipe appears to be located at the eastern edge of the depression.

Site Summary

A large depression parallel to the pipe on the west side of the slope is underlain by thaw up to about 2.8 m, portions of which correspond to previously observed hotspots. This depression extends the entire length of the slope, and is up to 8 m wide. Thaw at the edge of the depression, and away from the area of the depression in general ranged from 0.76 to 1.27 m thick on August 23.

Unamed Creek North (Slope 44, kp 133.6)

This site was surveyed as recent geotechnical studies indicated a reduced factor of safety for the slope. Additionally, drainage tiles were installed on the slope in February 1994, and radar surveys may give an indication as to the influence of these installations. There is no borehole information for this slope, however IPL probing in 1992 suggested thaw may have penetrated to over 5 m depth under portions of the slope. Immediately across the creek, the south slope contains ice-rich sediments, and there is every indication the sediments under this slope are ice-rich as well. Hot spot development was also noted on this slope by Burgess *et al.* (1993).

Site Description

The woodchip insulation at this site covers an area approximately 58 x 18 m, with an average slope of about 14°. Woodchip thickness is unknown, however, gullying near the west edge of the slope revealed mineral soil at about 50 cm. Other gullies (remnants of the drainage tile installations) near the centre of the slope appeared to contain at least 1 m of woodchips. Five drainage tiles were installed on this slope parallel to the pipe, starting near the slope crest and ending between 11 and 16 m from the base of the slope. At the time of the initial surveys (June 23), snowmelt water had caused additional gullying along the installations, in places up to 1.75 m deep. These gullies were backfilled with woodchips in late June.

Geologic Setting

No borehole data is available for this slope.

Thermal History and Depth of Thaw Probing

No temperature cables are installed at this site. Thaw probing by IPL in the fall of 1992 showed thaw up to 5 m below the base of woodchips in some sections. Thaw was generally greater beneath the centre of the woodchips compared to the edges or off ROW sites. The active layer overlying seasonal frost was highly variable in thickness at the time of the June 23 site visit. Within about 0.30 m of the drainage slots (not yet filled in), the seasonal frost often did not remain, yet a few metres away from the slot frost was encountered at 35-45 cm. Not filling in these slots earlier in the season allowed warmer temperatures to penetrate into sections of the slope. On the woodchip slope above the slope crest, frost was encountered consistently at 65-72 cm. Further probing was conducted on August 15, and although the slots had been filled in with woodchips, the same pattern of thaw around the slots remained. In many sections within 0.50 m of the slots frost was not encountered in the entire 1.3 m probe length. Away from the slots, thaw within the woodchips was generally 0.72-0.86 m, although there were many sections where thaw was >1.3 m. Thaw was greater than 0.90 m above the slope.

Probing by IPL personnel in 1990 found thaw extending to greater than 3.5 m. A detailed study in 1992 showed thaw being as great as 6 m near the centre of the ROW, and as little as 1 m near the ROW edge. However, spatial variability was found to be great during the 1992 study.

Based on the combined 1990, 1992, and 1994 probing results, it is believed that deep thaw is present on this slope below the slope crest, with any frost found in 1994 being the remnants of seasonal freezing.

The deep thermal influence of the new drainage tiles is unknown, although at Slope 45 it appears as though warming occurred following the use of sprinklers in fire prevention (late July-early August 1994).

GPR Survey Results

The early season surveys were conducted on June 23 using the 100 MHz antennas. The woodchip portion above the slope crest appears to be frozen based on the typical radar pattern previously discussed. This was confirmed through probing. It appears that deeper thaw is present along the portions of the slope underlain by drainage slots (see Long Profile 1). As the drainage slots are closely spaced, and are surrounded by seemingly complex thaw patterns (see above), it appears as if these slots may have contributed to deeper thaw (see interpretation for Slope 45). However, as the radar profiles were conducted between two slots (1 m apart), it is not clear if the thaw extends away from the slots. Without confirmation from thermal cables, this remains speculative. Although shallow probing encountered frost at most locations, the presence of thaw beneath this seasonal frost is suggested to depths of 2 or 3 metres.

Determination of thaw depths or the conditions around the pipe was impossible on the cross profiles due to interference from the drainage slots.

Due to time restrictions, the horizontal station spacing had to be decreased during the August 15 surveys. This resulted in poor resolution and little useful information for the late season.

Comparison with previous GPR surveys

Moorman (1994) also surveyed this slope, but again could not make firm conclusions due to the lack of subsurface verification. However, the presence of a near-surface anomaly (less than 4 m depth) in the lower slope is discussed, perhaps indicating that the thaw zone predates the drainage slot installation.

Site Summary

Active layer thaw above the crest of the slope remains within the woodchips at 0.72-0.86 m depth. Deeper thaw appears to coincide with the drainage slots on the June 23 surveys. This thaw, beneath a layer of seasonal frost is interpreted to extend to 2 or 3 metres. The thermal conditions are unclear between the drainage slots due to radar interference from the slots themselves while surveying in the cross-slope direction. This interpretation remains speculative as there are no temperature cables installed on this slope.

Unnamed Creek South (Slope 45, kp 133.7)

This site was surveyed as recent geotechnical studies indicated a reduced factor of safety for the slope. Additionally, drainage tiles had been installed on the slope in February 1994, and radar surveys may give an indication as to the influence of these installations. IPL probing in the fall of 1992 suggested thaw may have penetrated up to 4 m depth under portions of the slope. Boreholes drilled during pipeline construction indicate that the slope contains ice-rich sediments. This slope was cut back at the time of construction. Hot spot development was also noted at this site by Burgess et al. (1993).

Site Description

The woodchip insulation at this site covers an area approximately 60 x 17 m, with an average slope of about 15°. Woodchip thickness was 1.1 to 1.5 m at the time of installation. Four drainage slots were installed on this slope parallel to the pipe, starting near the slope crest and ending at least 3 m from the base of the slope. At the time of the initial surveys (June 23), snowmelt water had caused additional gullying along the installations, in places up to 1.75 m deep. These gullies were backfilled with woodchips in late June.

In cross section, the woodchips in the upper slope have a bowl shape, with a depression in the centre of the slope up to 2 m below the edges. This is partially due to the cut-back construction technique used to flatten the slope crossing.

Geologic Setting

Boreholes T-1 and 81-S29A are located about 24 and 14 m up from the base of the slope respectively, near the middle of the ROW. The upper borehole shows clayey silt to borehole completion at 6.5 m, with 30-40% ice content. The lower borehole indicates interbedded sand and clay to a depth of 9.9 m, with clay dominating in the upper few metres. Ice content in the clay reaches a maximum of 25%, but averages around 7-10%.

Thermal History and Depth of Thaw Probing

Temperature readings from the first day of radar surveys (June 20) show seasonal frost remaining between 0.35 and 1.5 m, with unfrozen ground below that to at least 6.5 m. In the vicinity of the drainage slots (not yet filled in), the seasonal frost was encountered at greater depths. Temperature measurements following the fire showed a dramatic temperature rise of about 2°C in the deeper thermistors. The upper seasonal frost remained, suggesting that this warming may be due to water seepage (from the sprinklers set up to fight the fire) through the drainage tiles (the thermistor is less than 1 m from a tile). Although the fire of late July-early August 1994 did not reach this slope, sprinklers were installed as a preventative measure.

Probing across the slope on June 20 found seasonal thaw to 0.30 to 0.44 m below the woodchip surface. The exception was in the vicinity of the drainage slots, where no frost was found within 1.3 m of the surface within 0.35 m of the slot itself. These slots were not backfilled until late June. Thaw 0.50 m from each slot was on the order of 0.53-0.65 m. Considering that some of the slots are only 1 m apart, this is a large area that has deeper thaw. Thaw depths later in the season followed the same pattern, with a frost ridge found between slots at between 0.85-1.10 m.

GPR Survey Results

The nature of the ground conditions underneath the seasonal thaw is unclear from the survey results, in places due to interference from the drainage slots. Borehole temperatures indicate thaw below seasonal frost at 1.5 m. Radar patterns do not indicate any anomalous condition (anything different from those known condition near the borehole), and thus suggest that the rest of the slope may be unfrozen to depths of 3 or 4 m. This is the same conclusion reached by Moorman (1994) and is also supported by IPL thaw probing. Refractions arms on the long profiles are caused by approaching the slots. In the area of the drainage slots, a large increase in temperature through the thaw season may be caused by the slots themselves (water from the fire prevention sprinklers as a heat source), and thus such warming would not extend across the entire slope.

Many of the profiles in the cross-slope direction are adversely affected by the drainage slots and interference from the pipe. Interpretation of cross profile 6, above the drainage slots, suggests thaw to be slightly greater than 2 m near the top of the slope.

The decreased lateral resolution on the August 15 surveys results in little useful information being obtained from them.

Comparison with previous GPR surveys

Moorman (1994) had suggested that there were 2 layers of permafrost at this site, based on past temperature surveys, implying that permafrost may be aggrading in the near-surface. This is also noted in the 1994 data, with the upper seasonal frost remaining near the end of the summer. This pattern is also noted in the thermal measurements from 1994, although it is difficult to extend this interpretation across portions of the slope away from the borehole. Borehole temperatures from 1993 surveys indicate colder ground temperatures, further indicating that ground warming in the vicinity of the borehole may have been caused by the drainage slots and water from the fire prevention efforts.

Site Summary

It is difficult to make firm conclusions due to interference from the drainage slots. However, it appears as if thaw may be present to a maximum of 3 or 4 metres beneath a seasonal frost layer. These conditions appear to be similar across the slope, with the exception of slightly less thaw above the slope crest. Similar to Slope 44, thaw appears to have been promoted in the immediate vicinity of the drainage slots, perhaps due to water input during fire prevention or water channelling.

Little Smith Creek (Slope 48b, kp 160)

This site has been targeted by PTRM as one of the most critcal slopes along the pipeline route. A depression on the east side of the slope has a history of water flowing from beneath the woodchips. The 1994 fire burned away much of the protective vegetation on the west side of the slope, in places right up to the edge of the woodchips. Slope failure was noted about 50 m west of the slope in late August 1994, a direct result of the fire. Detailed GPR surveys were conducted on July 6 (50 MHz), July 7 (100 MHz), and August 18 (100 MHz).

Site Description

Woodchip insulation covers this slope with dimensions of approximately 152 x 17 m. The slope ranges between 5 and 14°, with an average incline of about 9-10°. A large depression has developed on the east side of the slope, with water seeping out from beneath the woodchips. This water resulted in ponding at the base of the slope. Drainage tiles were installed along a 77 m stretch of the western part of the slope in February 1994, however the tiles terminated a few metres from the base of the slope. Smaller sections of the east side of the slope were slotted. Woodchips were placed to 1.4 m depth, however by 1991 these were found to have settled to 0.7 m in some locations.

Geologic Setting

All boreholes drilled on the slope encountered clay and silt to depths of 8 m beneath the woodchip surface. At the time of drilling (1992), the clay was unfrozen to just over 4 m depth. On the borehole log for 92-4 the clay is categorized as till. There is no information as to ice contents within the till.

Thermal History and Depth of Thaw Probing

Thaw probing and thermistor readings from 1992 all show thaw depths averaging 3 m beneath the base of woodchips, with the deepest thaw being in the vicinity of the pipe. Cable readings taken at the time of the radar surveys (July 6-8) show the thaw front about 2.7 m beneath the woodchip surface in borehole 92-5. By the time of the second survey on August 17, thaw had deepened to about 3.5 m. Borehole 92-3, further upslope showed frozen conditions at 2.6 m, the depth of the first sensor. This results in a complex ground thermal regime, however, it is also possible that sections of the slope are thermally unstable due to the presence of water flow at the eastern side of the slope. Detailed depth of thaw probing was not conducted on this slope in 1994.

Photograph of drainage slots at Little Smith Creek before backfilling.

GPR Survey Results

GPR results indicate a fairly complex thermal structure for this slope. Two sections of deep thaw are interpreted, one at the top of the slope and the second at the bottom of the slope. The middle portion of this slope appears to be well frozen based on the pattern of refractions observed.

The upper slope thawed zone appears to be unfrozen to depths of 4 or 5 m (Long Profile 1 - July 6). This zone extends from the upper end of the woodchips for about 35 m. A zone of interpreted frozen conditions (beneath the seasonal active layer) is present for the next 48 metres. The lower 50 metres of the slope appears to contain thaw to depths of approximately 4 m.

Surveys conducted later in the season (August 19) show the same pattern of thaw. The thickness and extent of thaw does not appear to have changed appreciably. These later surveys were of limited horizontal resolution, yet the thermal structure is still readily apparent.

The results of IPL probing in 1990 showed that thaw was greatest in the vicinity of the pipe. Although interference from the drainage slots may have masked the signal, there is no additional thaw indicated across the mid-slope section.

Comparison with previous GPR surveys

Moorman (1994) and Moorman *et al.* (1994) interpreted two frost tables across much of this slope, *i.e.* a thaw zone beneath the upper frost, underlain by permafrost at depth. This configuration is possible from the 1994 surveys, but detailed thaw probing was not conducted. Moorman *et al.* (1994) indicate the same structure of deep thaw underneath the top and bottom portions of the slope. The depths of these zones are comparable, with Moorman *et al.* suggesting a maximum thaw of 5 or 6 m at the base of the slope. That study also concluded that refraction patterns in the middle of the slope were caused by cracks in the woodchips. The discussion presented in the Radar Interpretation Techniques section now suggests that the pattern could not have been caused by cracks within the woodchips.

Site Summary

Two separate regions of deep thaw are interpreted for this slope. The upper 35 m of the woodchip insulated slope appears to be underlain by thaw to depths of 4 or 5 m. The next 48 m 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 again thawed to a maximum depth of about 4 m. Although there is a seasonal frost layer across the entire slope, it was not resolved on the GPR surveys.

Slope 62 (kp 194.6) Steep Creek

Only cursory surveys were conducted at this site due to time constraints. These surveys were conducted on August 28 using the 100 MHz antennas.

Site Description

The woodchip insulated portion of this slope is roughly 85 x 15 m, with an average slope of about 14°. A shoo-fly crosses the slope above the woodchip portion. A second area insulated with woodchips is above the shoo-fly. This section was not surveyed. The fire of 1994 burned to the edge of the woodchips in some places.

Geologic Setting

A total of 9 boreholes have been drilled on this slope. All boreholes show clay or clay till underlying the slope to at least 20 m. The majority of the slope appeared to be unfrozen at the time of drilling, and any frozen sections contained little excess ice. Woodchips were placed to thicknesses between 0.5 and 1.65 m, although this has likely settled.

Thermal History

Temperature measurements from the boreholes on the day of GPR surveying consistently showed thaw to about 6 m depth. No depth-of-thaw probing was done on this slope in 1994.

GPR Survey Results

Although only 2 long profiles were conducted on this slope, it is interpreted that the entire portion of the slope surveyed is thawed to at least 5 or 6 m. This is shown by the loss of signal due to high conductivity of unfrozen clay.

Comparisons with previous GPR surveys

Moorman (1994) surveyed this slope and also concluded that the entire slope was thawed to at least 5 m depth. Limited depth of thaw probing in 1993 confirmed the absence of frost in the upper 1.4 m late in the season.

Site Summary

It is interpreted that the entire portion of the slope surveyed is thawed to at least 5 or 6 m. This is shown by the loss of signal due to high conductivity of unfrozen clay. Surveys were conducted in late August, and there was no trace of any seasonal frost remaining.

Slope 74 (kp 271.9)

Traditionally the slope on the north side of this river crossing (Slope 73) has been surveyed (Moorman, 1994), however it was the south side that was surveyed in 1994. Surveys were conducted on July 15 (100 MHz) and August 27 (50 MHz) covering the entire slope. Thermal imagery showed an 8 m diameter hot spot mid-slope in 1988. IPL remediated this zone through removal of woodchips during the winter.

Site Description

The woodchip insulation on this slope covers approximately 189 x 20 m, with a slope averaging about 11-12°. Two depressions have developed on the surface of the woodchips, one on the east side near the top of the slope, and a larger (but shallower) one near the middle of the slope. Woodchip thickness across the slope is approximately 1.4 m. This slope is 300 m north of the PTRM Table Mountain thermal fence 85-7C.

Geologic Setting

Four boreholes were drilled on this slope prior to construction, and three following the placement of woodchips. Cores from these holes show the upper slope to be underlain by silty clay, with minor sand and occasional gravel to cobbles. Visual ice content of this clay ranged up to 35%, averaging about 10-15%. Several lenses of ice were encountered. Peat was often found as thin layers within the clay. Boreholes at the bottom of the slope encountered 1 m of clay overlying clayey silt to 4 m (pre-construction depths). Beneath the silt was a fine-grained sand to at least 10 m.

Thermal History

Thermistor T-13, installed above the woodchip slope showed thaw to just over 3 m on August 15. Two thermistors on the woodchip insulated slope, T-11 (mid-slope) and T-9 (lower slope) indicated thaw of 2.0 and 1.6 m respectively on August 15. A thermistor string installed entirely within the woodchips (near T-11) at a depth of 0.6 m displayed temperatures ranging from 9.6 to 11.7°.

GPR Survey Results

Interpreted thaw across this slope on July 15 appears to vary slightly between 1 and 2 metres. The reflector representing the depth of thaw in shallow thaw areas (about 1 m) appears to coincide with the reflector from the base of woodchips. The main zone of deeper thaw appears to be a 20 m long area near the base of the slope. These observations are supported by the temperatures measured in boreholes. Later in the season (August 27) thaw depths appear to have increased only slightly, to a maximum of perhaps 2.2 m.

Resolution of the cross profiles is poor, and little useful information can be obtained. However they do not show any indication of anomalous conditions around the pipe.

Comparisons with previous GPR surveys

No previous surveys have been conducted at this site. However, comparisons with the slope on the south side of the creek (Slope 73)

Site Summary

Thaw across this slope appears to vary between approximately 1 and 2.2 m. The deeper thaw occurs in a small area near the base of the slope. These observations are supported by thermal measurements.

Mackenzie Crossing South (Slope 142, kp 529.7)

This slope is the most southerly of those surveyed during this project, and represents the south side of the largest river crossing on the pipeline route. Surveys were concentrated on the lower portion of the slope, and were conducted on July 12 (50 MHz) and 13 (100 MHz).

Site Description

The woodchip portion of this slope is approximately 140 m long by 35 m wide, with a slope averaging 14-15°. This slope was partially cut back during construction. The thickness of woodchip insulation at the time of installation varied from 1.45 to 1.83 m, however a borehole drilled in 1991 (for piezometer 14052) found only 0.70 m of woodchips remaining. A large berm (a remnant of construction cut back) about 3 m high runs along much of the lower slope on the east side. A small depression runs parallel to the west edge of the ROW around mid-slope. Tension cracking has been noted in the past over much of this slope. IPL remedial work has corrected locations where subsidence was uneven. Remedial work across much of the slope has likely resulted in woodchip thicknesses different than those indicated on as-built specifications.

Geologic Setting

Silty clay is found beneath the woodchips across most of the slope. Coarse backfill was placed in the pipe trench during construction. One of the post-construction boreholes encountered 2 m of gravel between the woodchips and silty clay, likely representing gravel emplaced during construction. Two of the boreholes near the base of the slope (T-1 and 81-S44A) encountered gravel beneath the clay at depths of 6.4 and 3.0 m respectively. The exact thickness of woodchips across the slope is either highly variable due to remedial work or a large degree of settlement has occurred.

Thermal History and Depth of Thaw Probing

Temperature readings taken on July 13, 1994 showed greatly variable permafrost conditions across the slope. While thermistors T-22 (lower slope) and T-10 (upper slope) both showed frozen conditions beneath the woodchips, the cable in borehole 91-7 indicated thawed conditions to 3.5 m beneath the remaining seasonal frost. Thermistors within the woodchips showed thaw to almost 1 m. Thaw probing conducted at the same time encountered probe refusal at 0.67 to 0.97 m across the slope. Some of this refusal was due to the contact with clay underlying the woodchips. Moorman (1994), working at this site later in the season, found thaw in T-10, T-22, and 91-7 to reach 2.2, 5, and 6 m respectively. All of these temperature cables are within 35 m of each other, emphasizing the huge thermal variability on this slope.

GPR Survey Results

The results of the GPR surveys are very inconclusive for this slope. This is in part due to the large degree of thermal variability on the slope, the lack of any reflector indicating thaw, and the variability of woodchip cover. Being underlain by clayey material, it is possible that the frozen fringe is wide and freezing point depression causing soil with temperatures slightly below 0°C containing little or no ice. However, much of the slope appears to have radar characteristcs associated with unfrozen material to at least 3 m depth. Shallow probing was of little use at this site in supporting GPR interpretations.

Comparison with previous GPR surveys

Surveys conducted in 1993 basically yielded inconclusive results. Deep probing from 1990 showed deep thaw (up to 3.5 m), but was again highly variable.

Site Summary

The results of the GPR surveys are very inconclusive for this slope. This is in part due to the large degree of thermal variability on the slope, the lack of any reflector indicating thaw, and the variability of woodchip cover. Being underlain by clayey material, it is possible that the frozen fringe is wide and freezing point depression causes soil with temperatures slightly below 0°C to contain little or no ice (*i.e.* lacking reflectors). Signal penetration was limited to 6 or 7 m using the 50 MHz antennas. However, much of the slope appears to have radar characteristics associated with unfrozen material to at least 3 m depth. New tension cracks were noted in late summer 1994.

ACKNOWLEDGEMENTS

This project was a joint initiative of the Geological Survey of Canada (GSC) and Interprovincial Pipe Lines (IPL), funded through the Industrial Partners Project between IPL and the GSC and by IPL through employment of SDR in the summer of 1994.

We would like to thank all those people who made this study possible. Alan Judge and Margo Burgess (Geological Survey of Canada) arranged employment for SDR with IPL for the summer of 1994. They also supplied the funding to prepare this report, without which much of the data may have gone unanalyzed.

SDR would like to thank Tom Fridel and John Smith of IPL for employment for the summer of 1994 in order to conduct these surveys. This is yet another example of IPL's commitment to environmental research along their northern pipeline route. Thanks also to Colin Babkirk and Steve Malick for their hospitality at IPL in Norman Wells.

Expert field assistance was provided primarily by Jan MacDonald of Norman Wells. Others who helped out along the way include Fons Schellekens, Kenny Thereau, Fred Perriot, Jean Bisson, and Wes Hodgson. Thanks also to the patient IPL radio operators in Norman Wells.

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GROUND PENETRATING RADAR SURVEYS ALONG THE NORMAN WELLS PIPELINE ROUTE, SUMMER 1994

Part II
Radar Profiles

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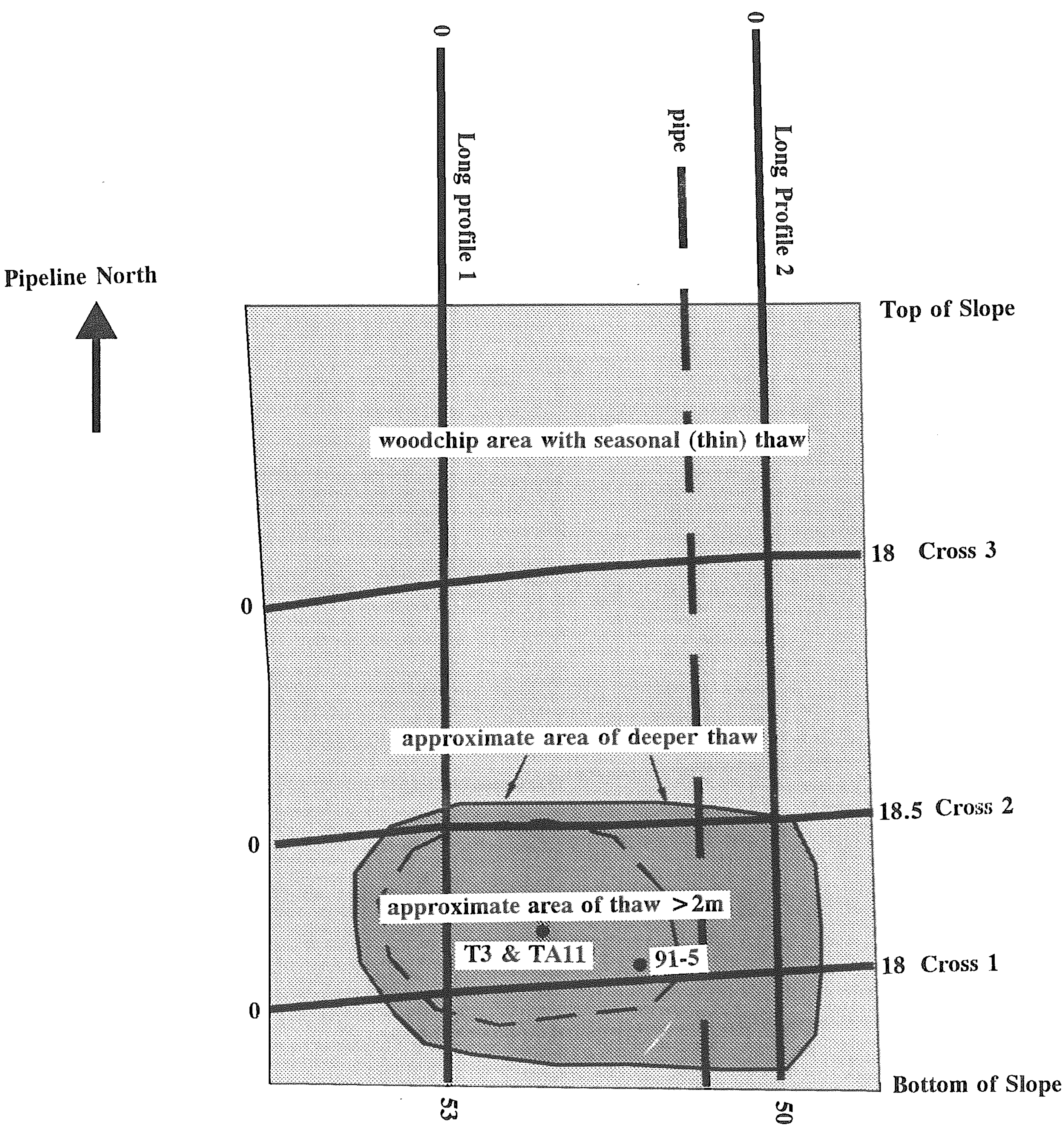
October, 1994

BOSWORTH CREEK NORTH

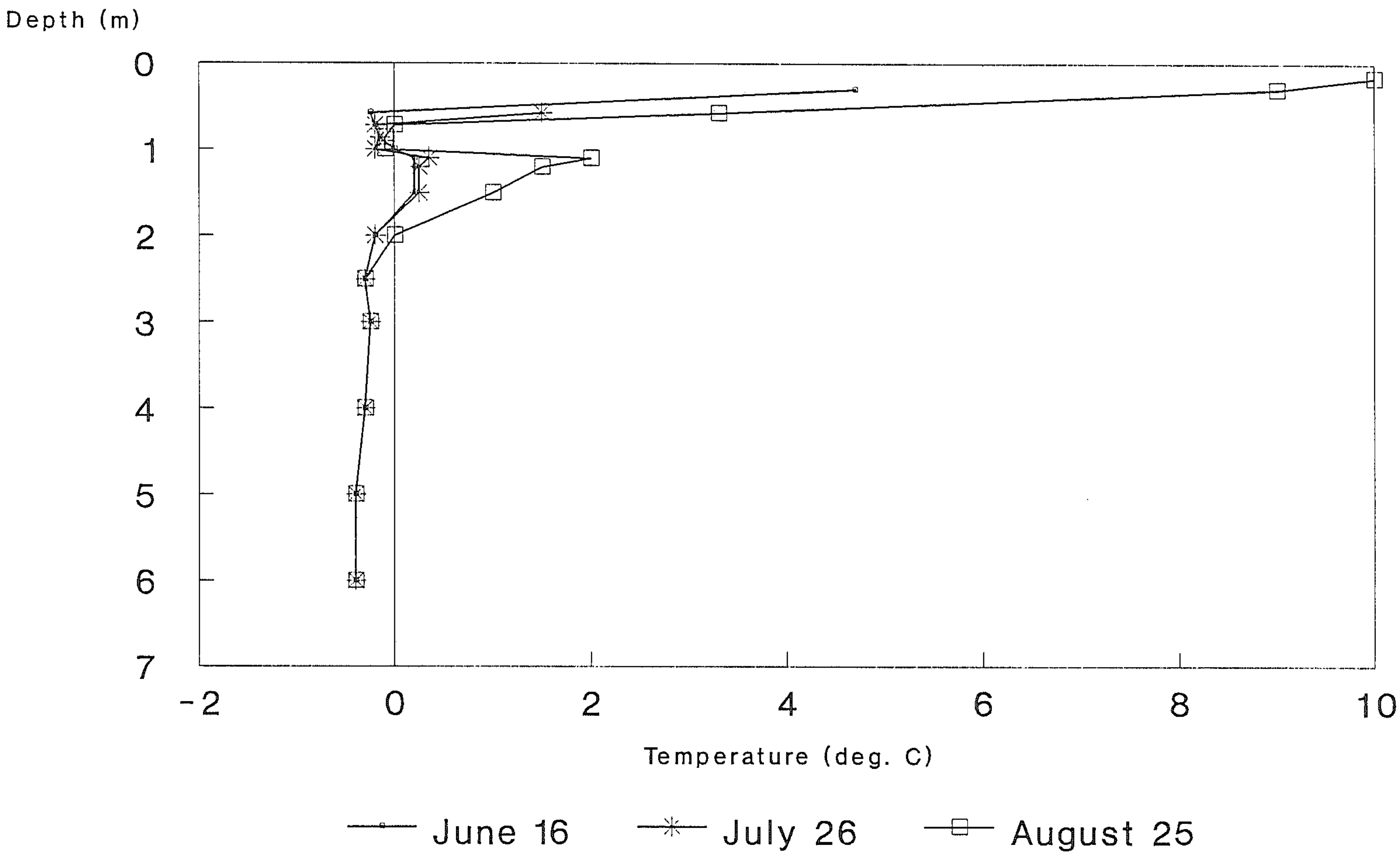
Not to Scale

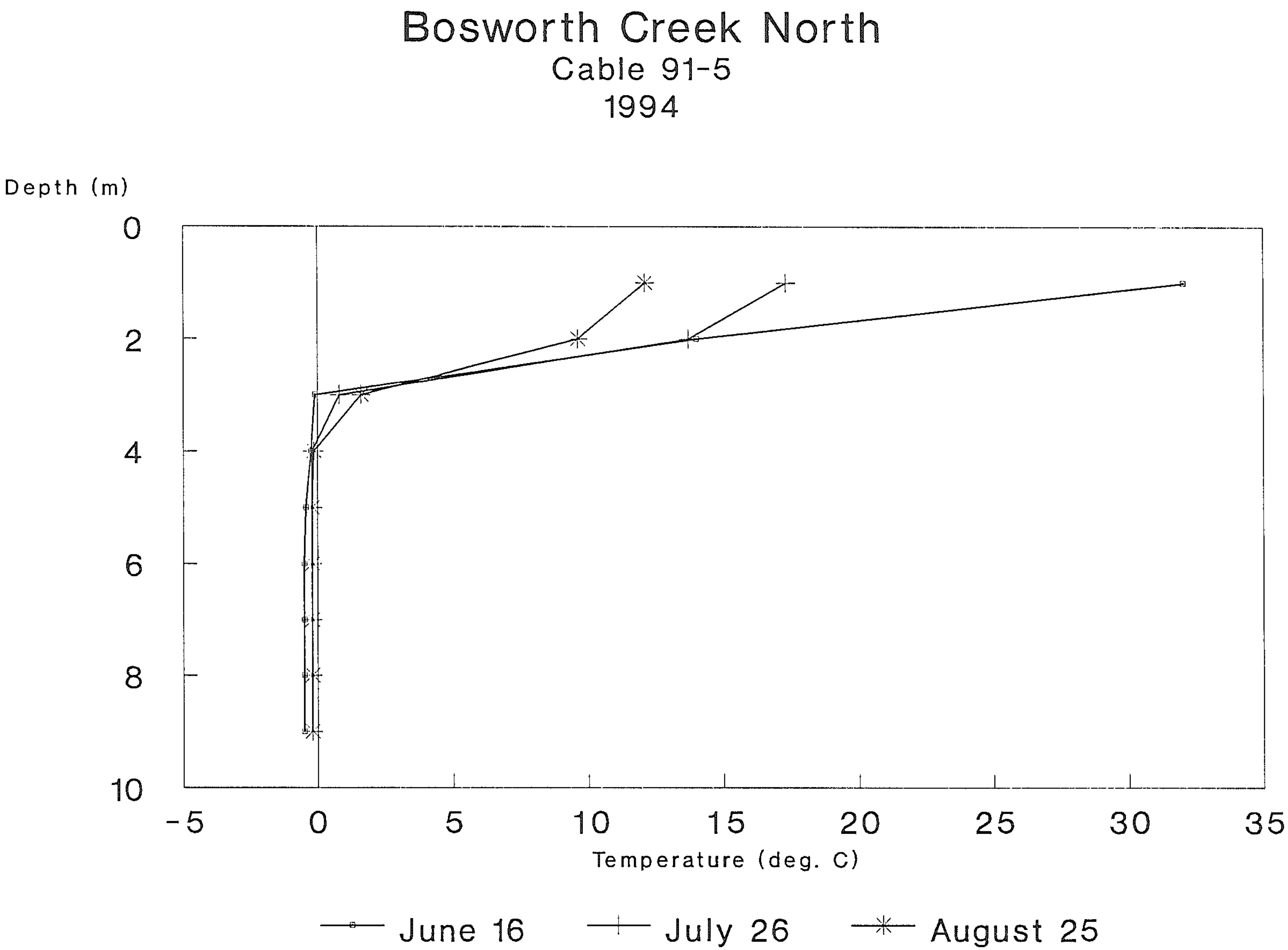


Bosworth Creek North

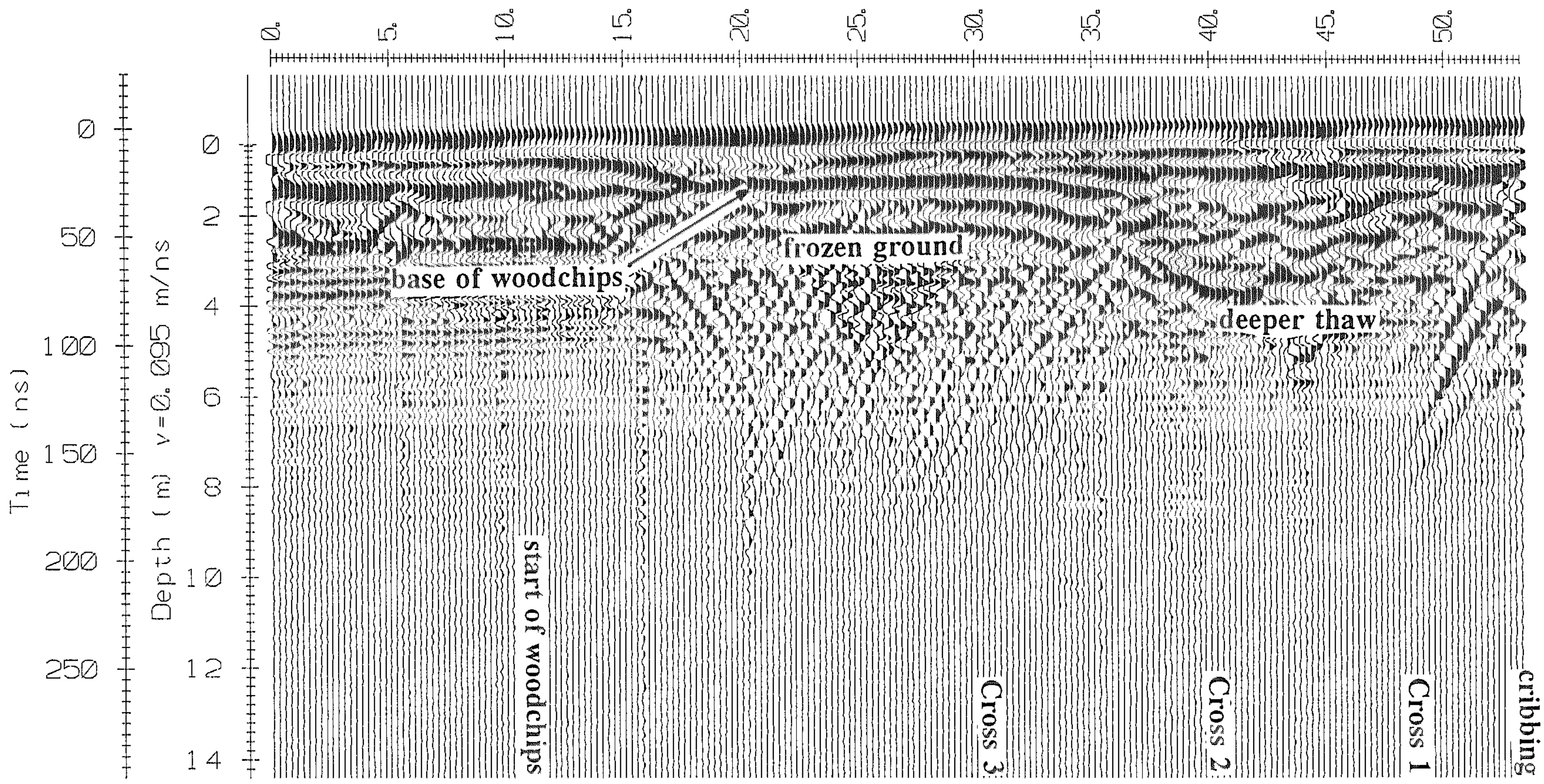
Cables T-3 and TA-11

1994

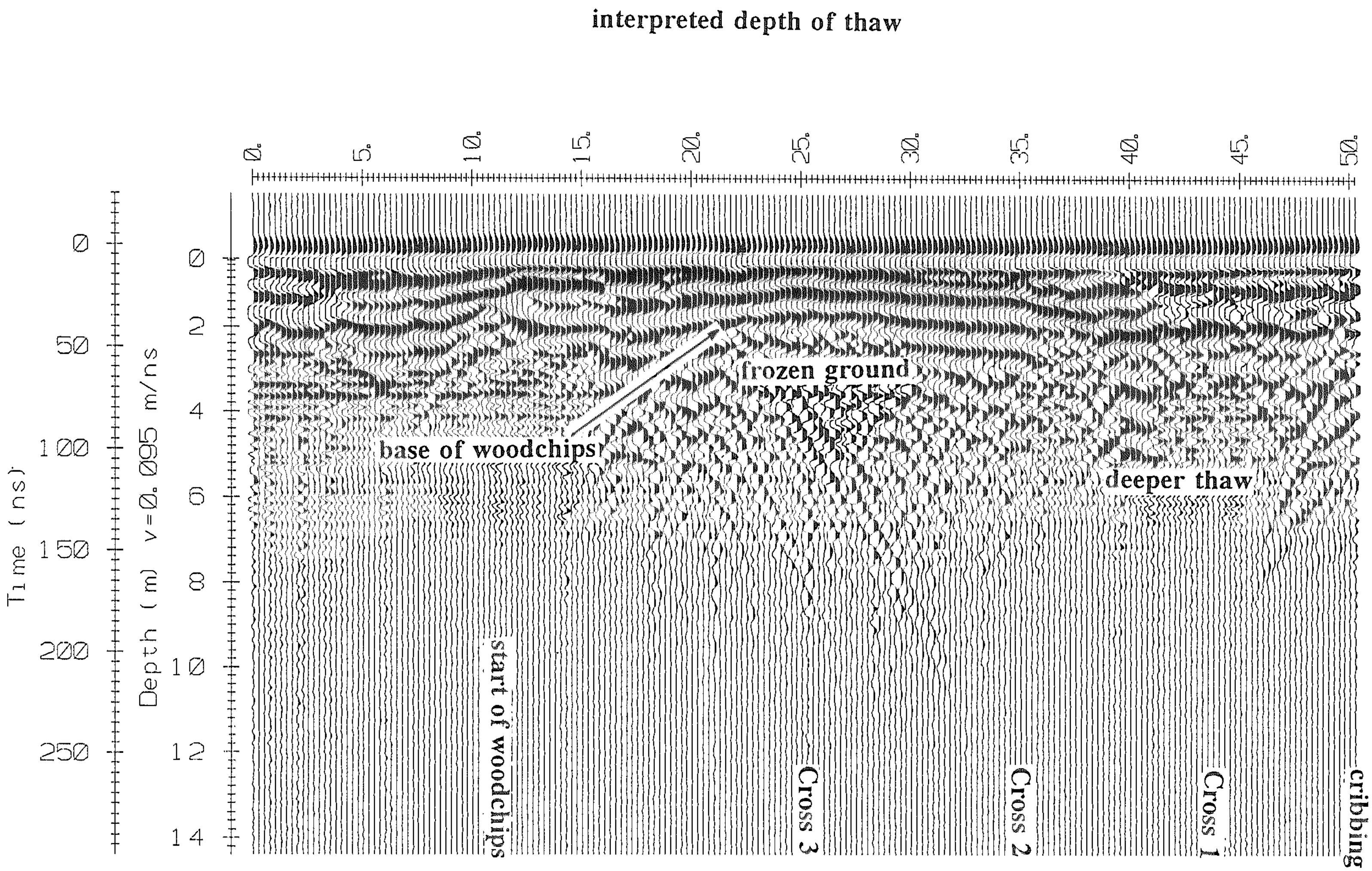



Bosworth Creek North
Cable 91-5
1994
Depth (m)
0
2
4
6
8
10
-5
0
5
10
15
20
25
30
35
Temperature (deg. C)
June 16
July 26
August 25

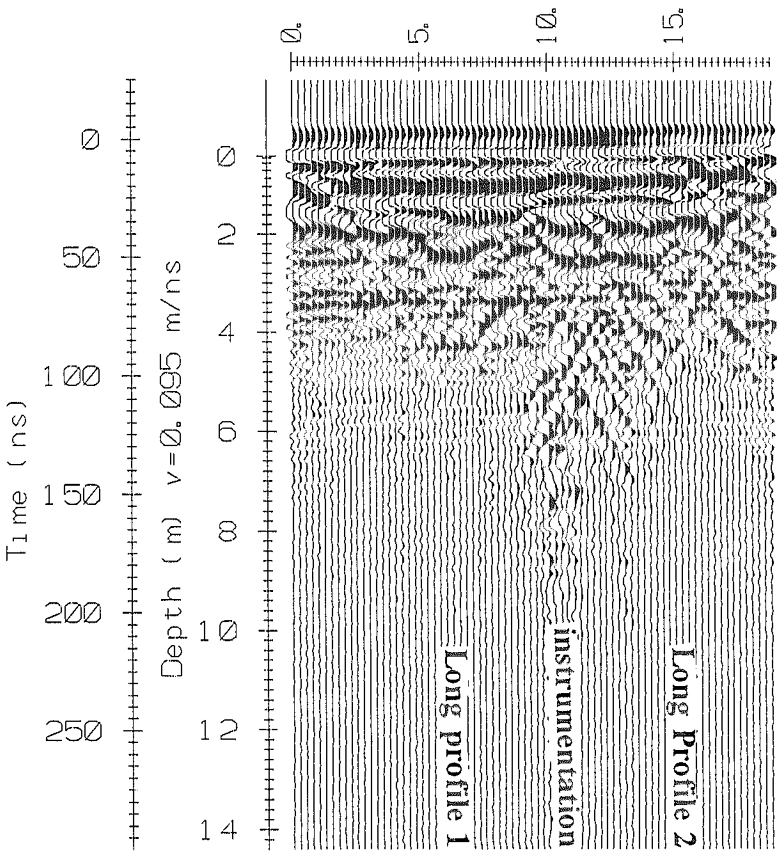
interpreted depth of thaw



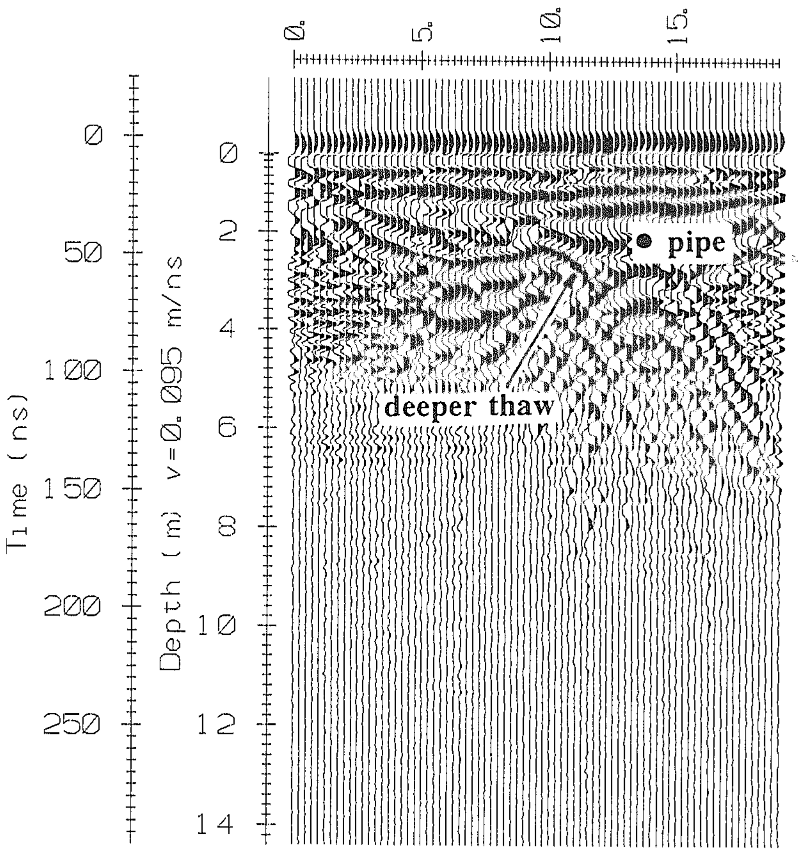
BOSWORTH CREEK NORTH - LONG PROFILE 1 - 100 MHz - JUNE 2



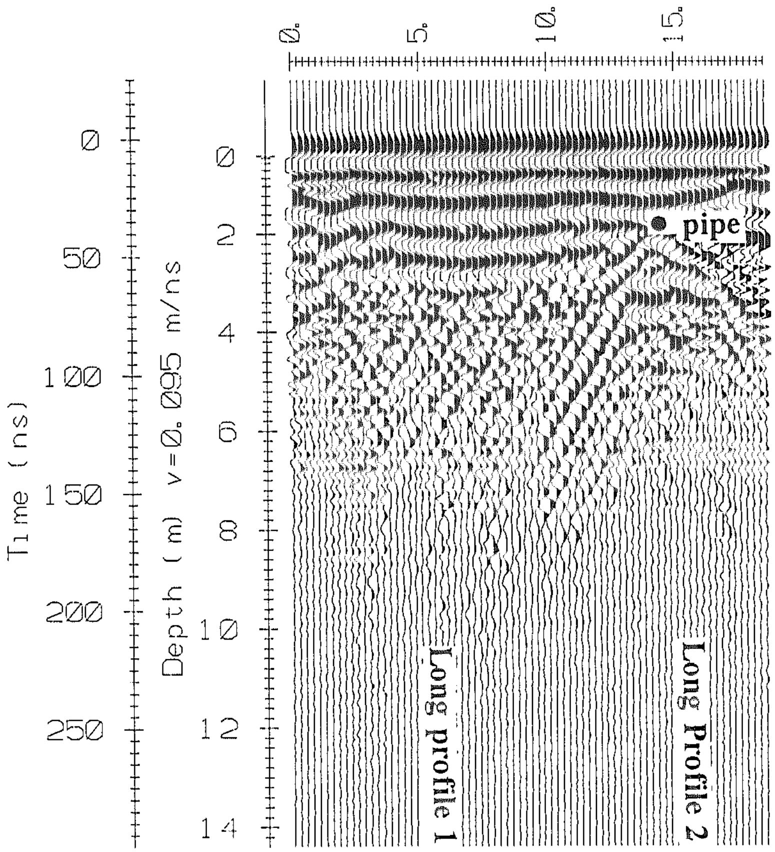
BOSWORTH CREEK NORTH - LONG PROFILE 2 - 100 MHz - JUNE 2



BOSWORTH CREEK NORTH - CROSS PROFILE 1 - 100 MHz - JUNE 2

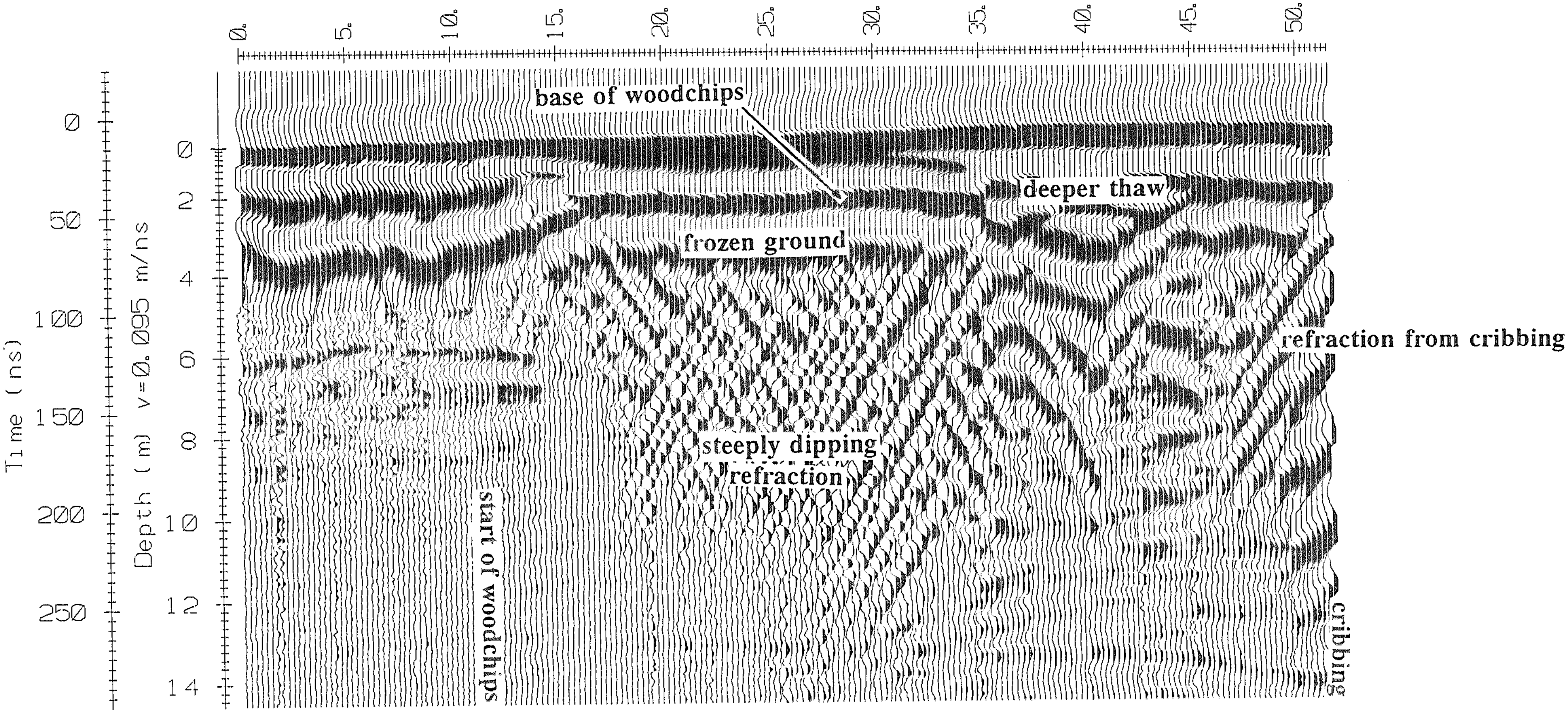


BOSWORTH CREEK NORTH - CROSS PROFILE 2 - 100 MHz - JUNE 2



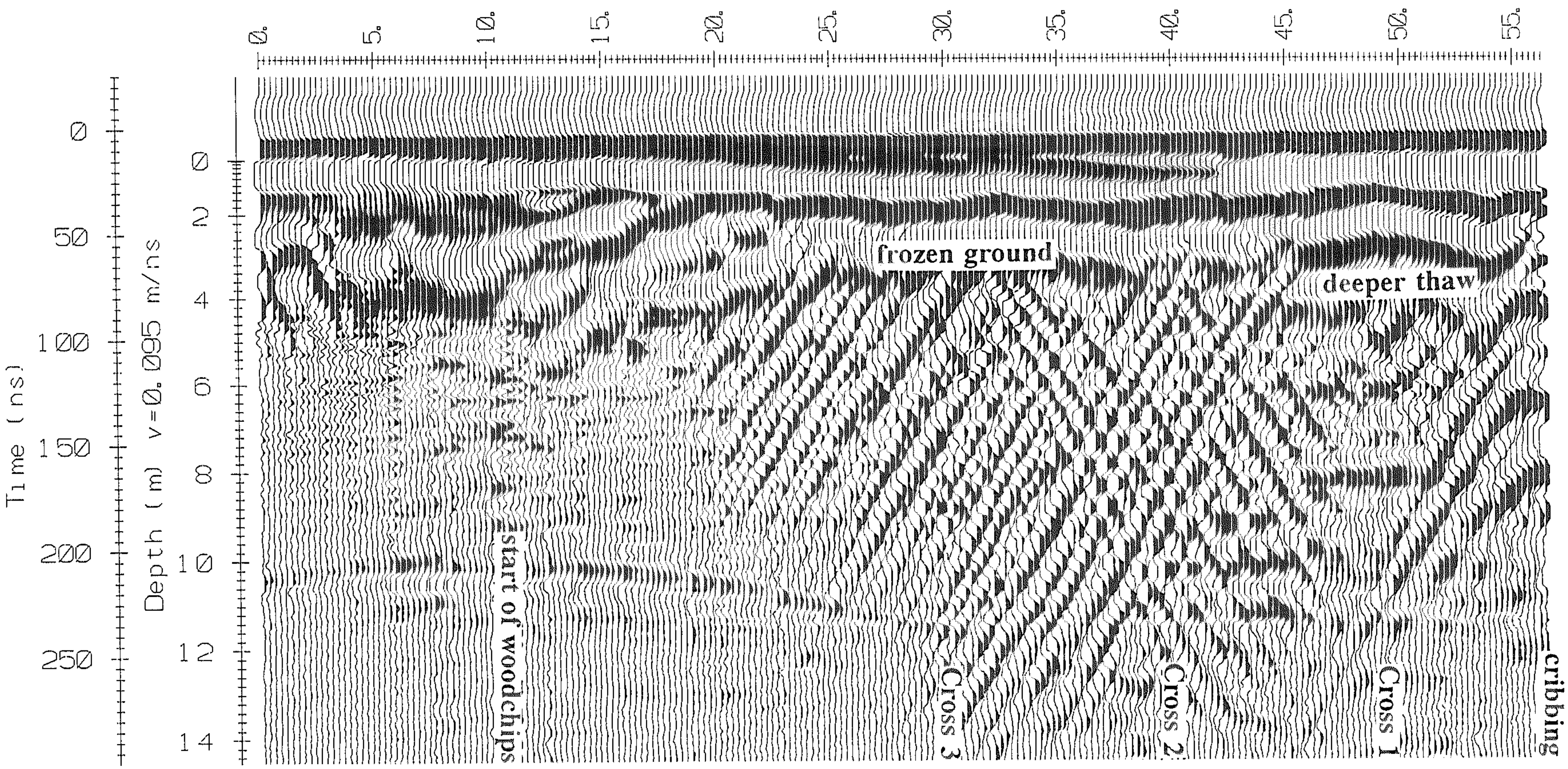
BOSWORTH CREEK NORTH - CROSS PROFILE 3 - 100 MHz - JUNE 2

interpreted depth of thaw

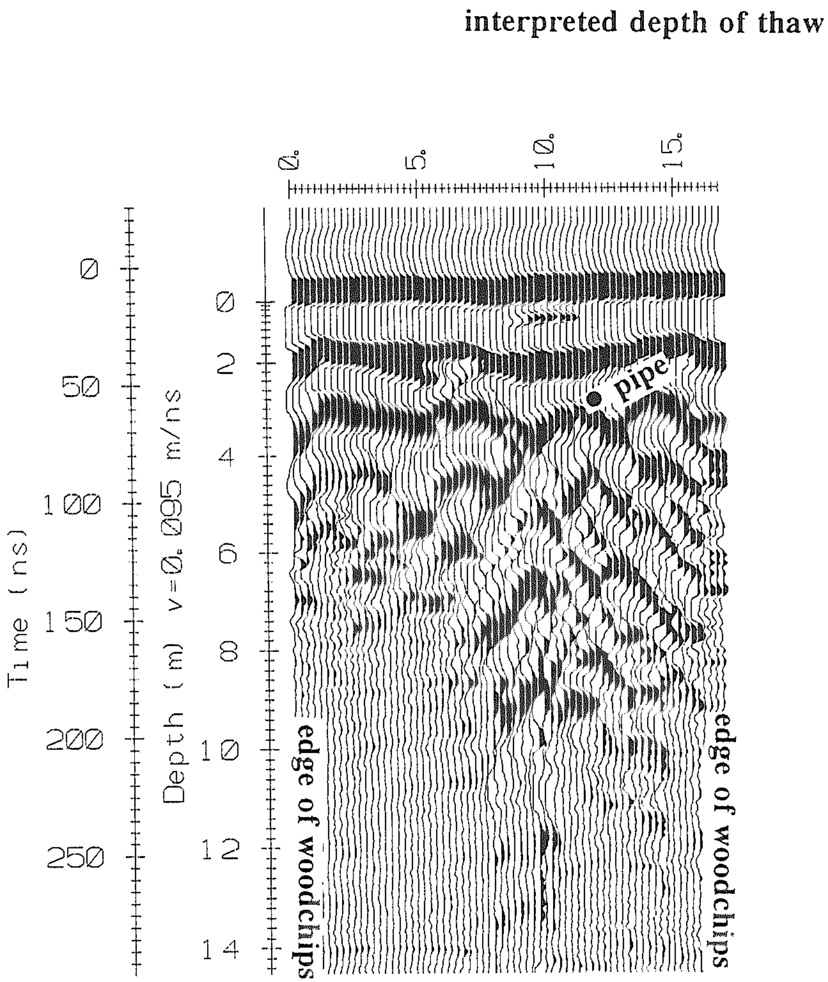


BOSWORTH CREEK NORTH - LONG PROFILE 1 - 50 MHz - JUNE 7

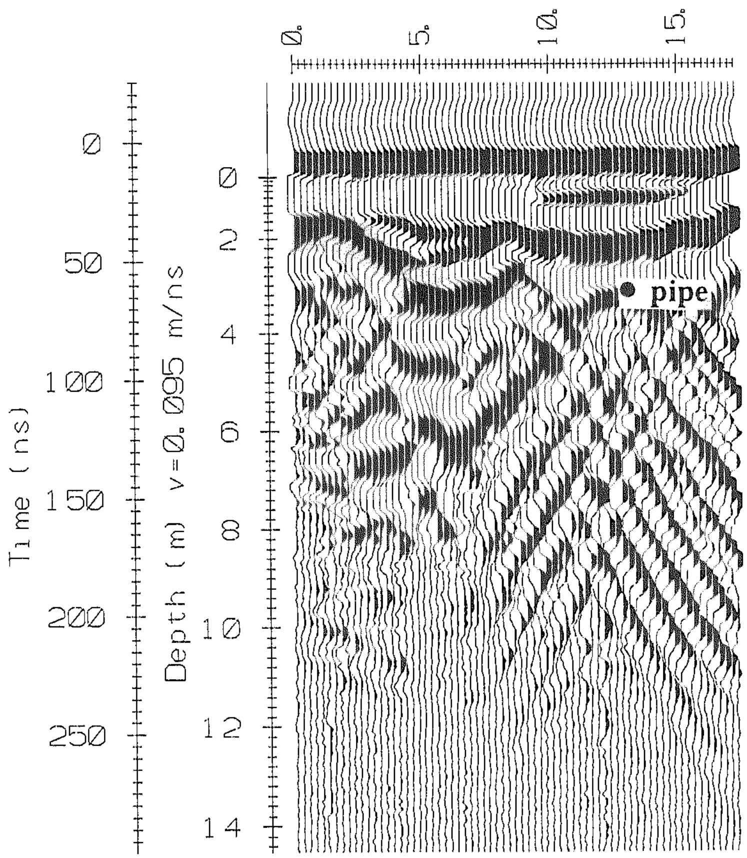
interpreted depth of thaw



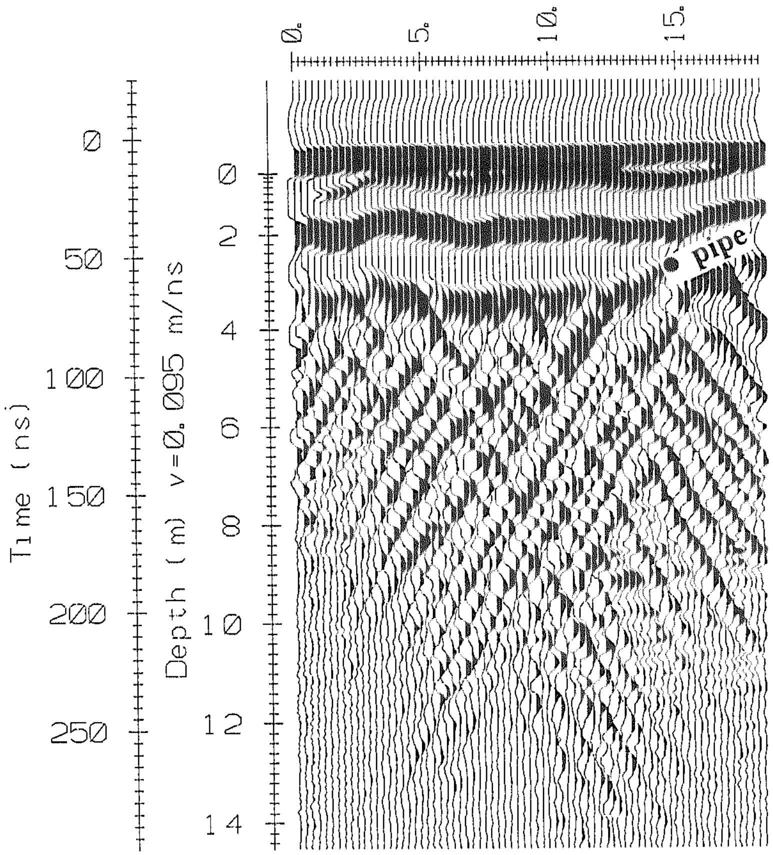
BOSWORTH CREEK NORTH - LONG PROFILE 2 - 50 MHz - JUNE 7



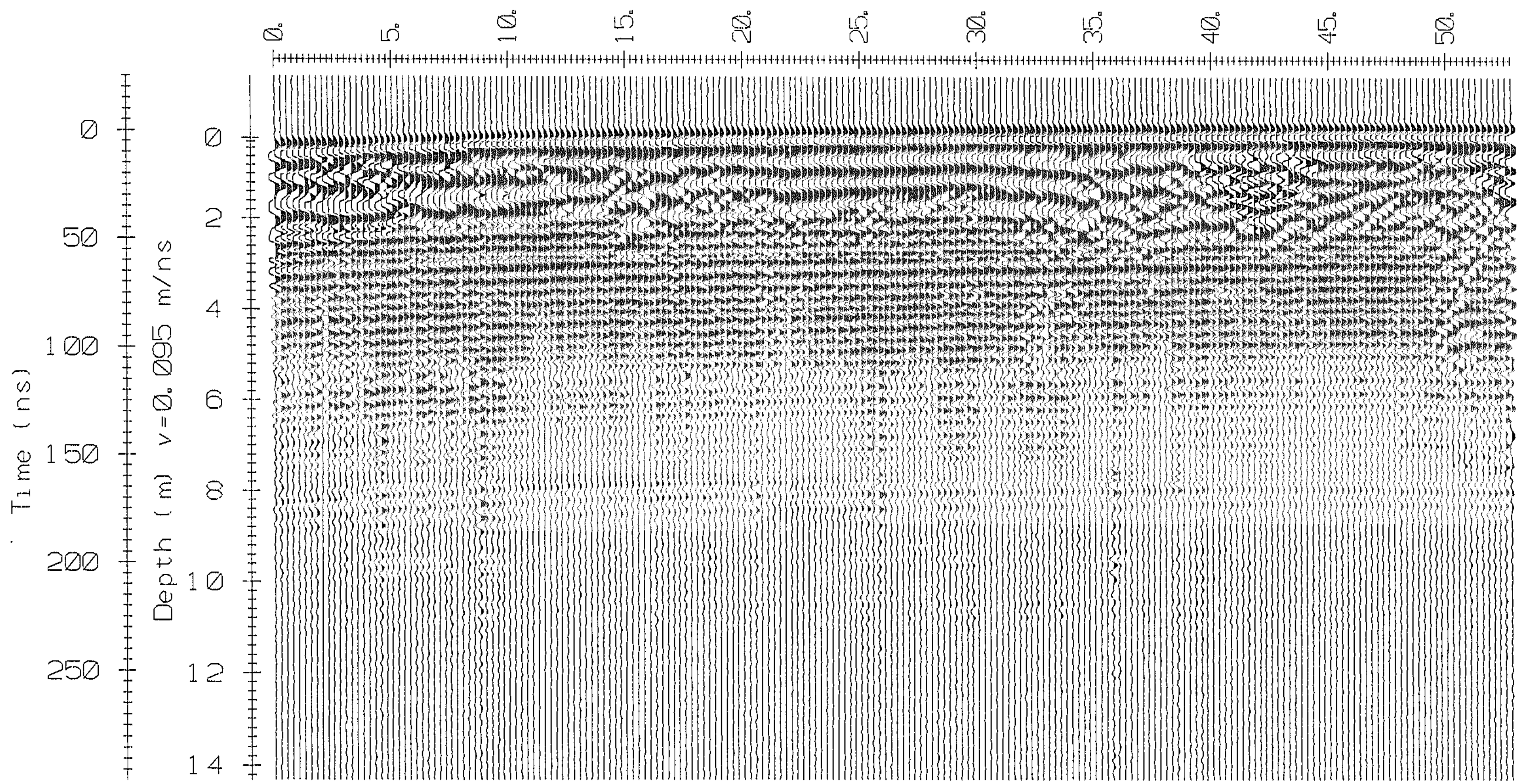
BOSWORTH CREEK NORTH - CROSS PROFILE 1 - 50 MHz - JUNE 7



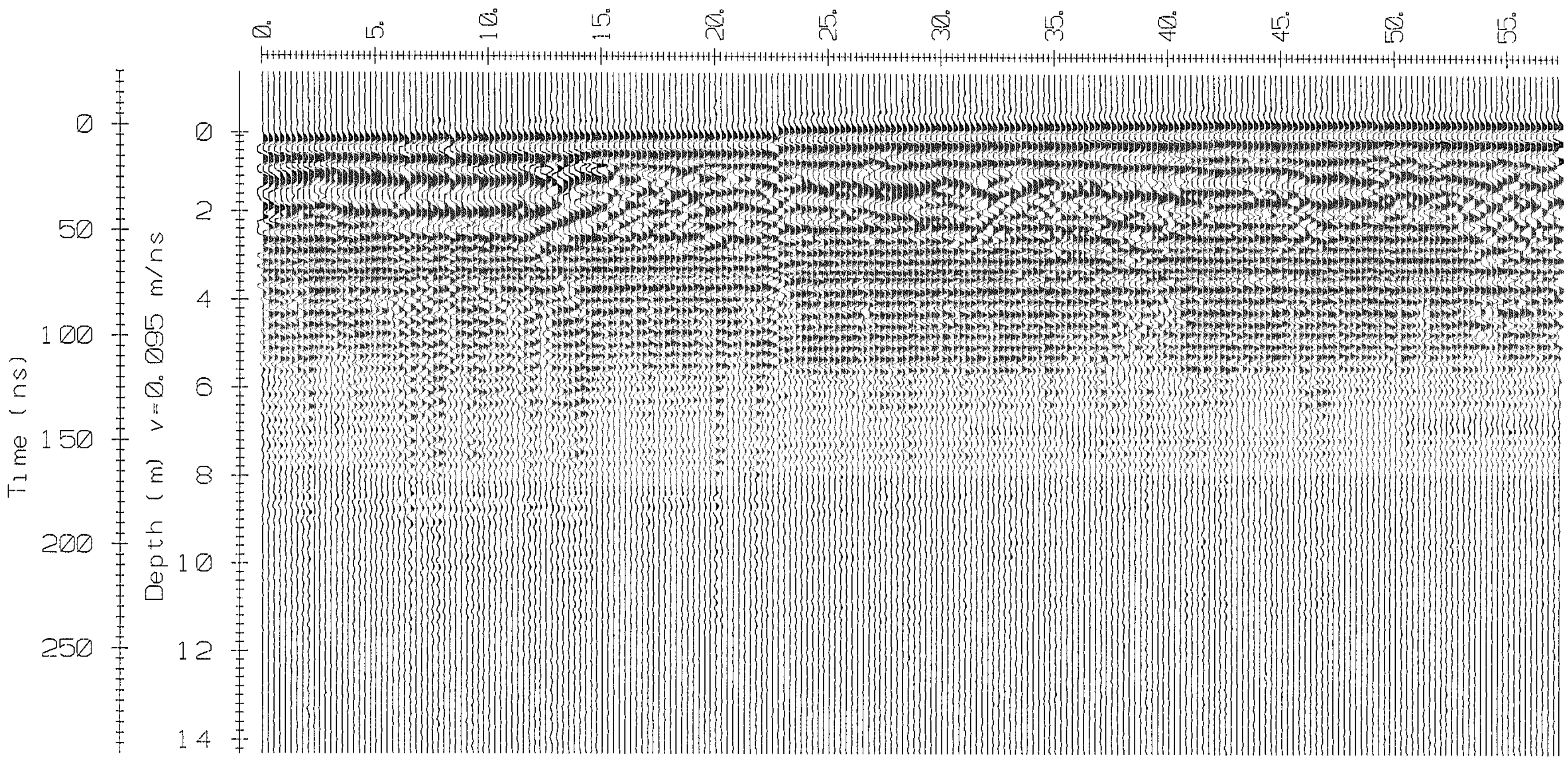
BOSWORTH CREEK NORTH - CROSS PROFILE 2 - 50 MHz - JUNE 7



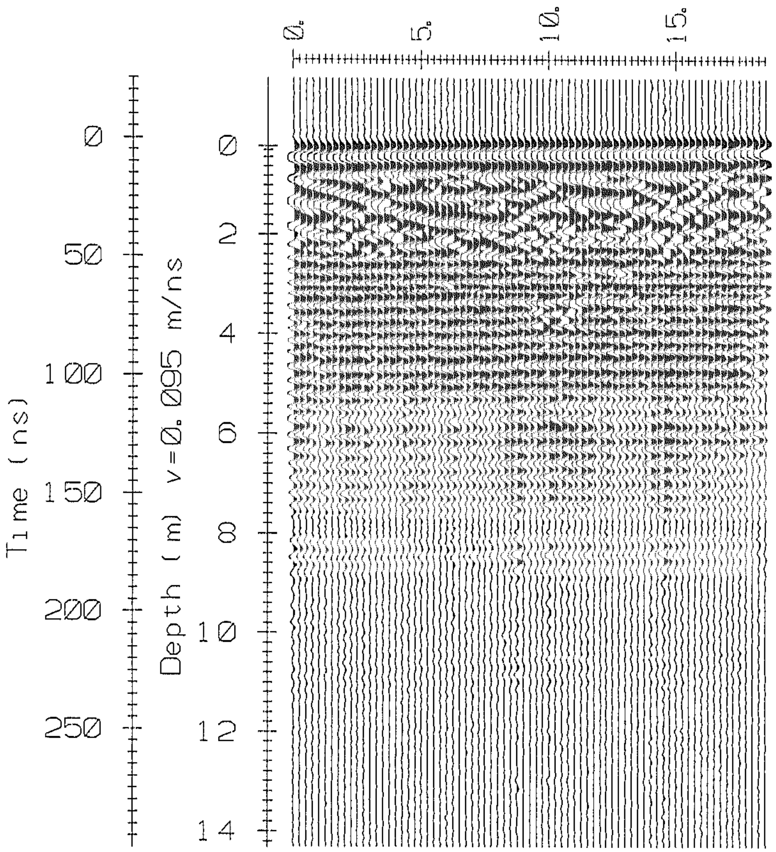
BOSWORTH CREEK NORTH - CROSS PROFILE 3 - 50 MHz - JUNE 7



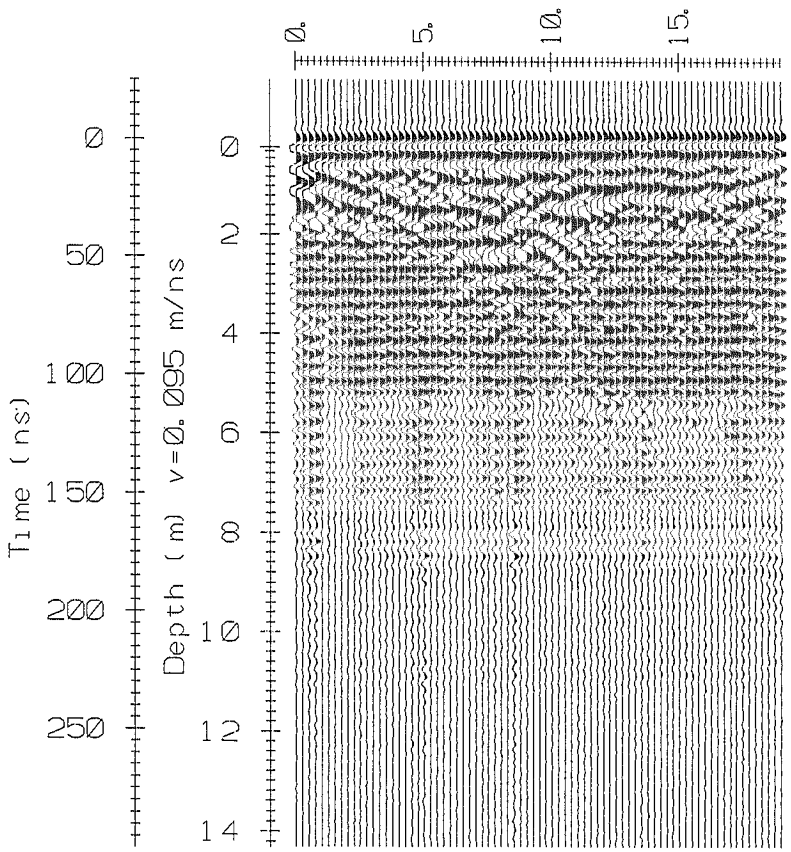
BOSWORTH CREEK NORTH - LONG PROFILE 1 - 200 MHz - JUNE 16



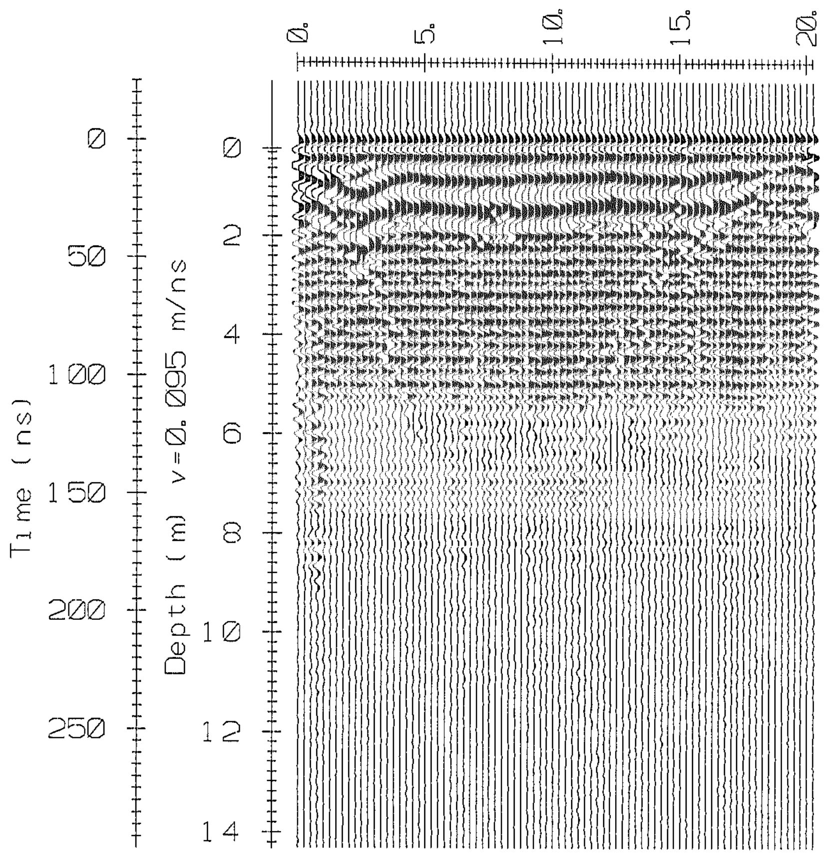
BOSWORTH CREEK NORTH - LONG PROFILE 2 - 200 MHz - JUNE 16



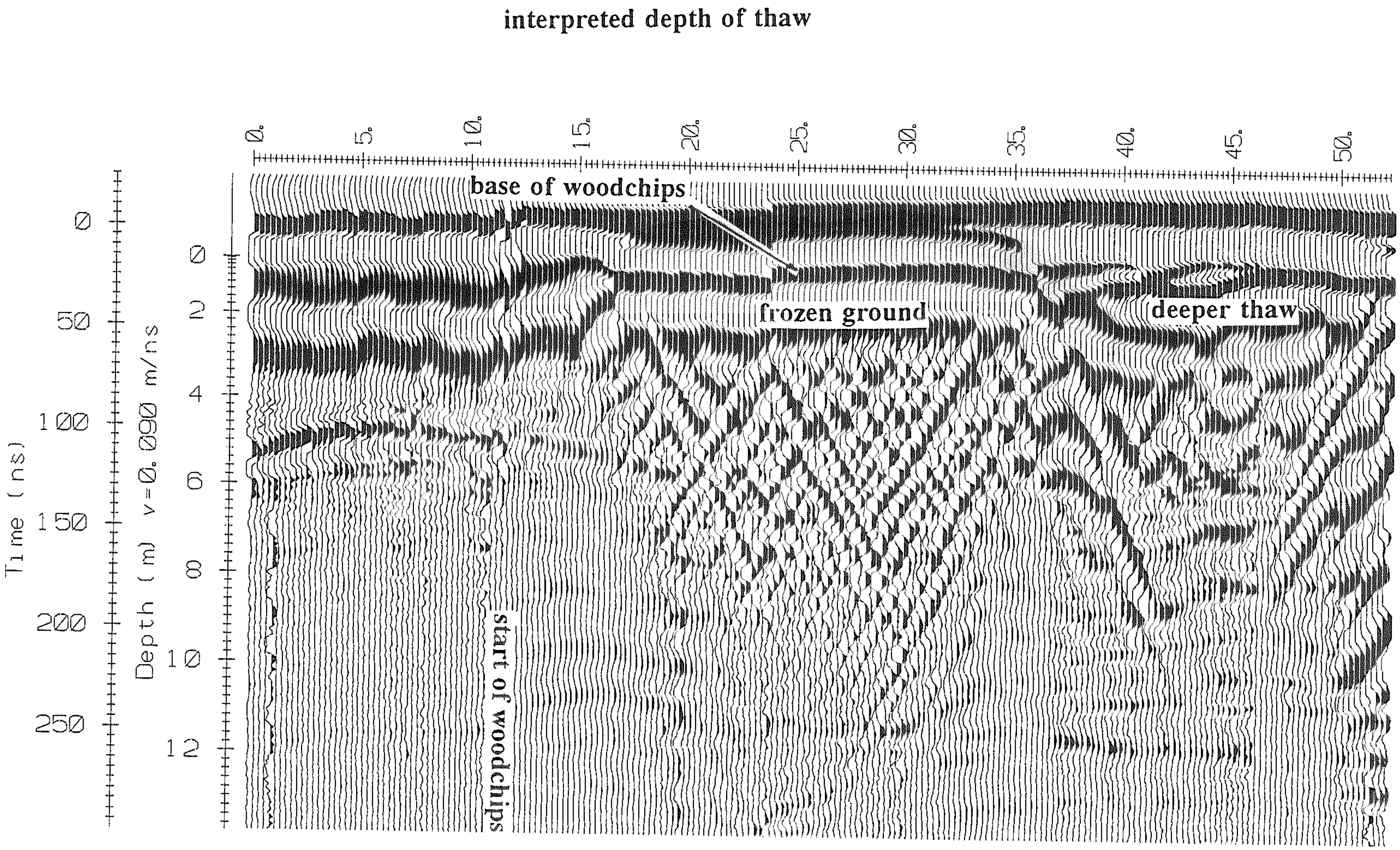
BOSWORTH CREEK NORTH - CROSS PROFILE 1 - 200 MHz - JUNE 16



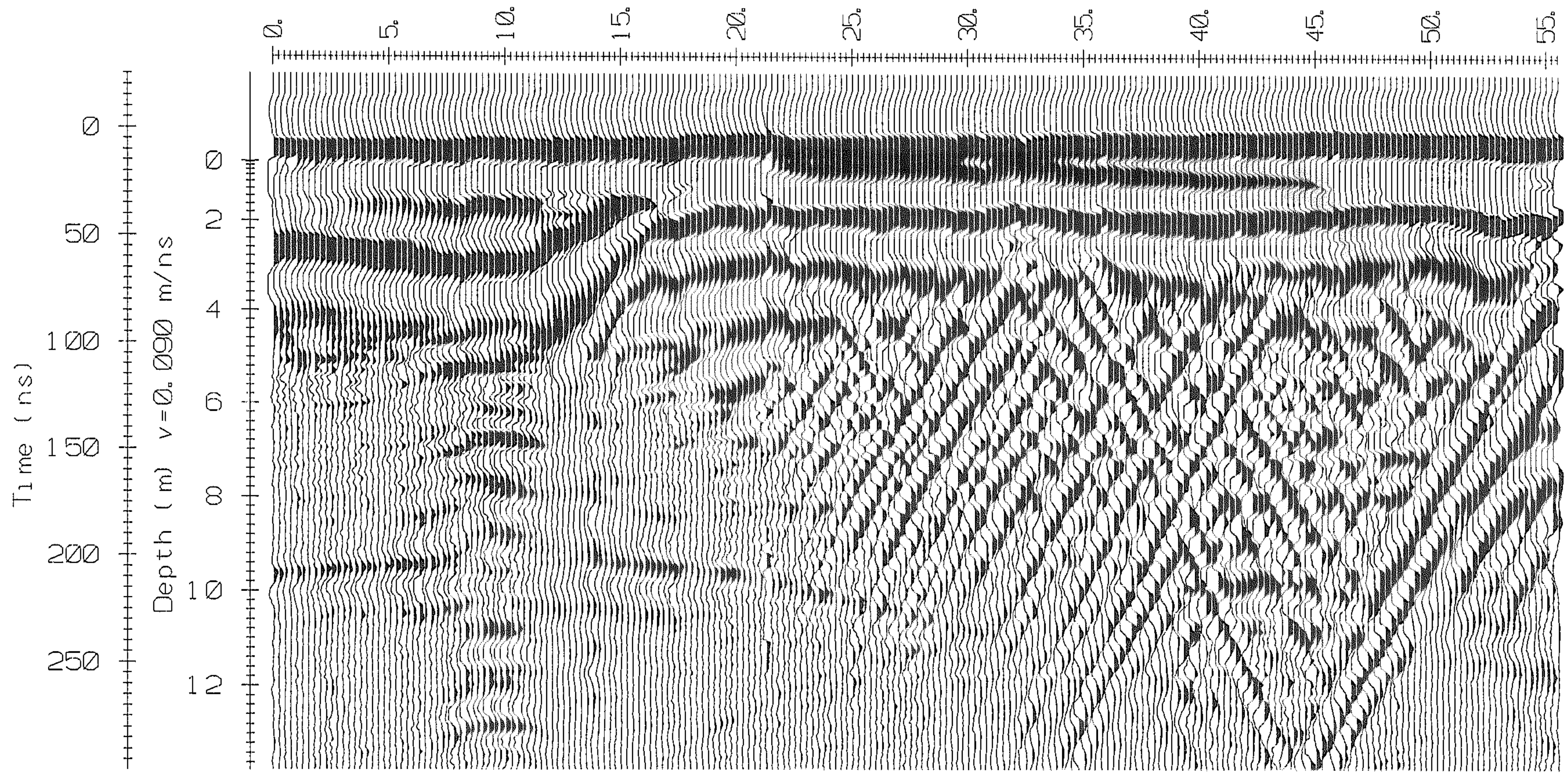
BOSWORTH CREEK NORTH - CROSS PROFILE 2 - 200 MHz - JUNE 16



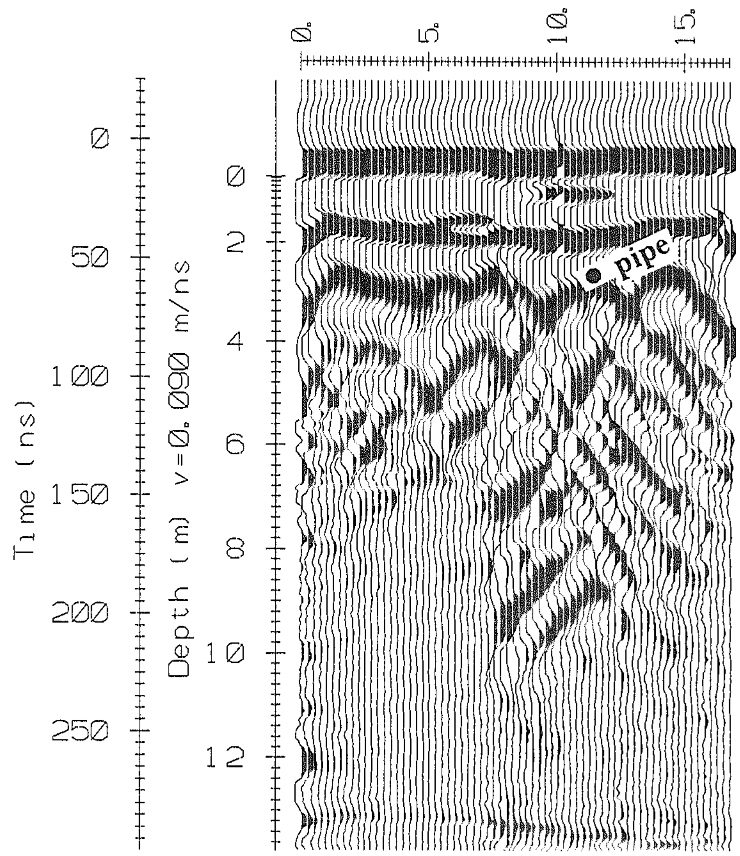
BOSWORTH CREEK NORTH - CROSS PROFILE 3 - 200 MHz - JUNE 16



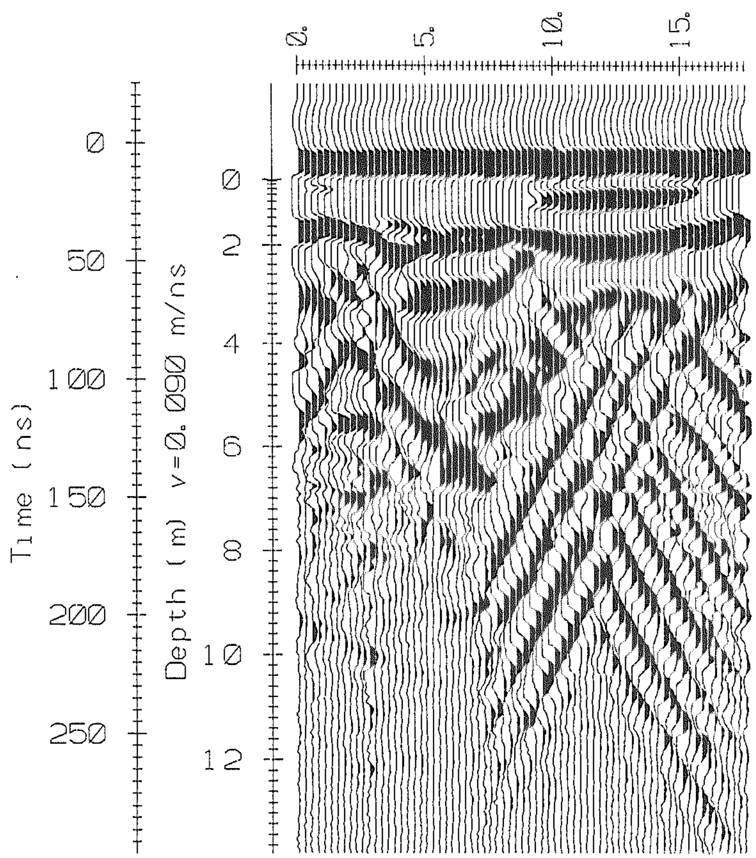
BOSWORTH CREEK NORTH - LONG PROFILE 1 - 50 MHz - JUNE 29



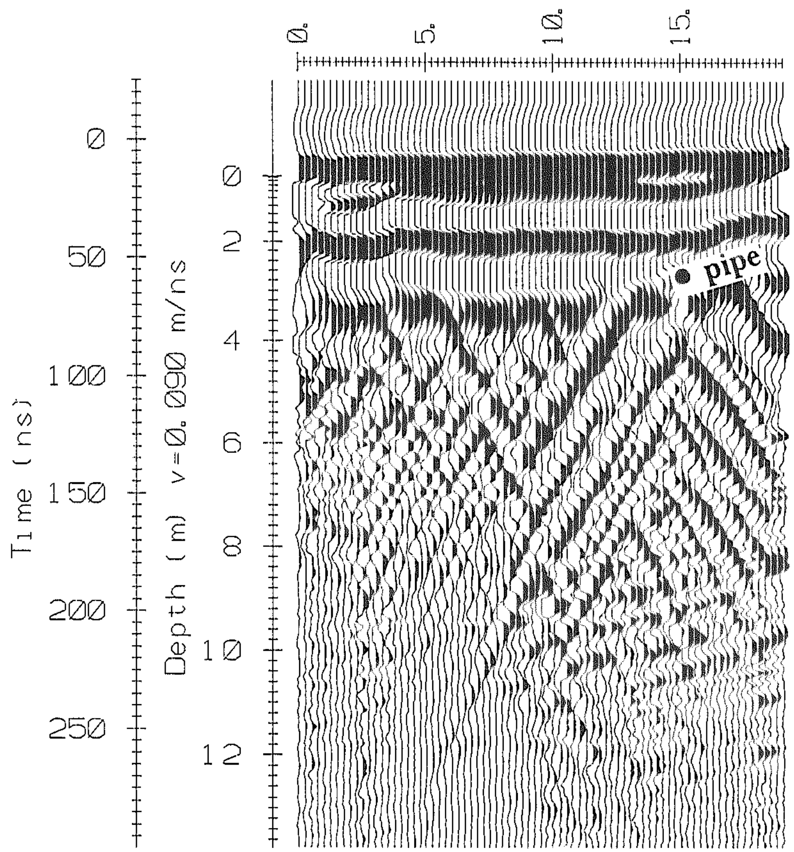
BOSWORTH CREEK NORTH - LONG PROFILE 2 - 50 MHz - JUNE 29



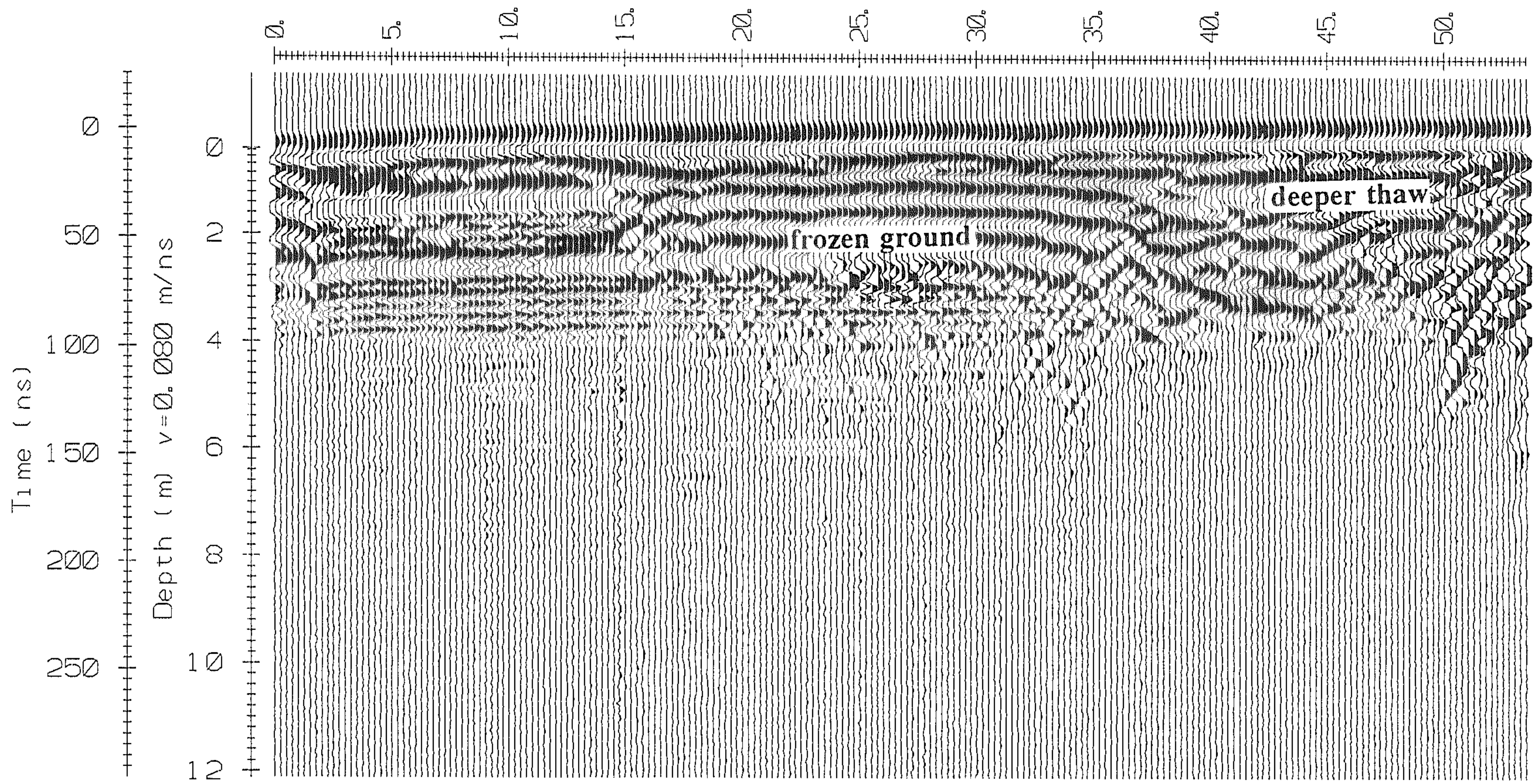
BOSWORTH CREEK NORTH - CROSS PROFILE 1 - 50 MHz - JUNE 29



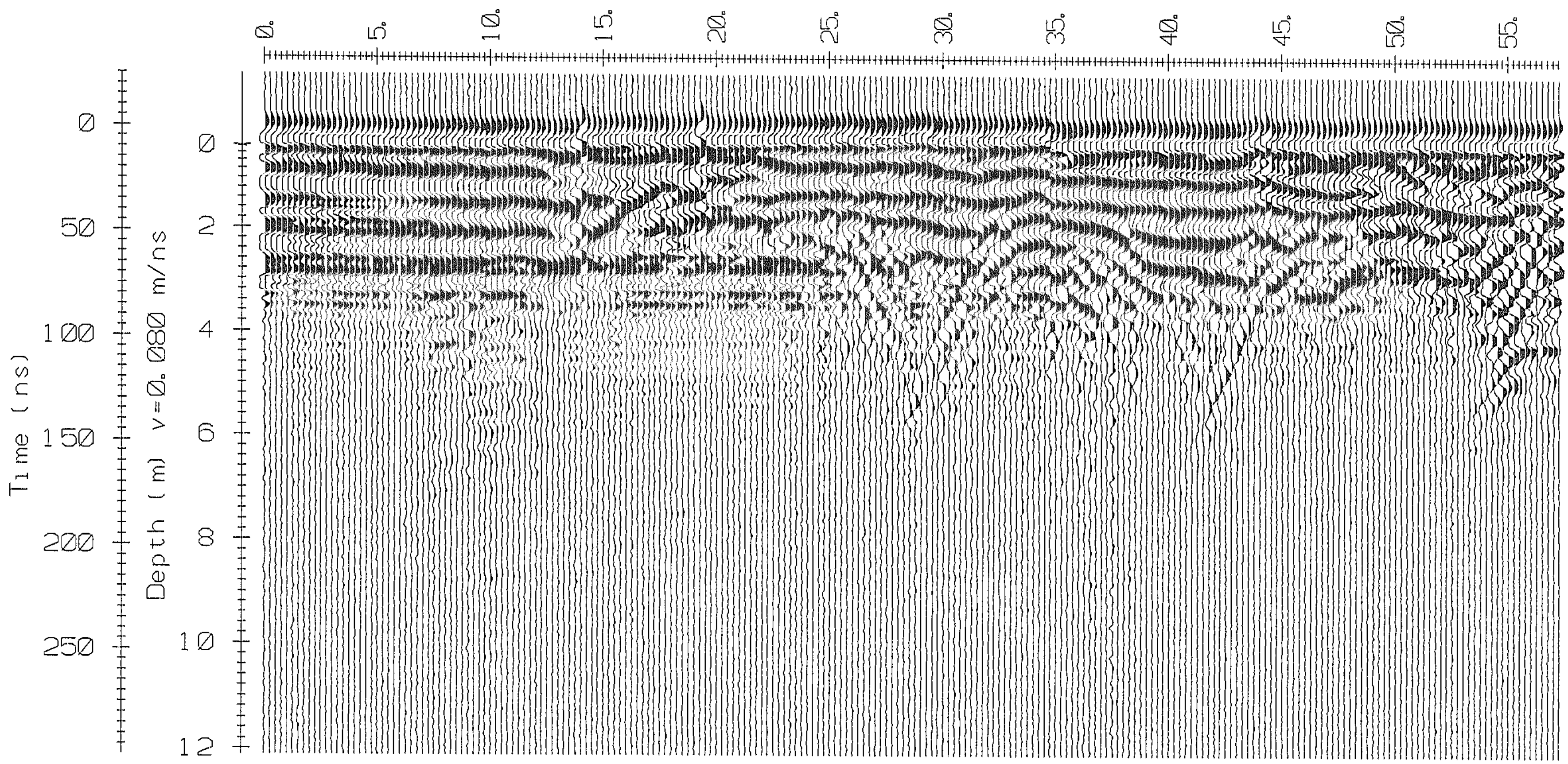
BOSWORTH CREEK NORTH - CROSS PROFILE 2 - 50 MHz - JUNE 29



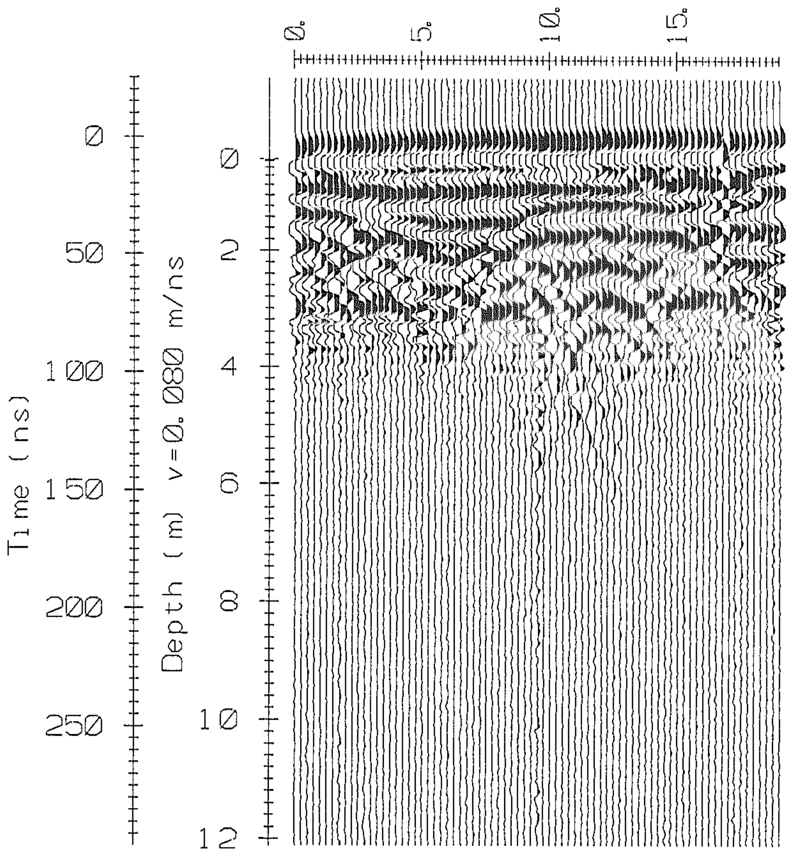
BOSWORTH CREEK NORTH - CROSS PROFILE 3 - 50 MHz - JUNE 29



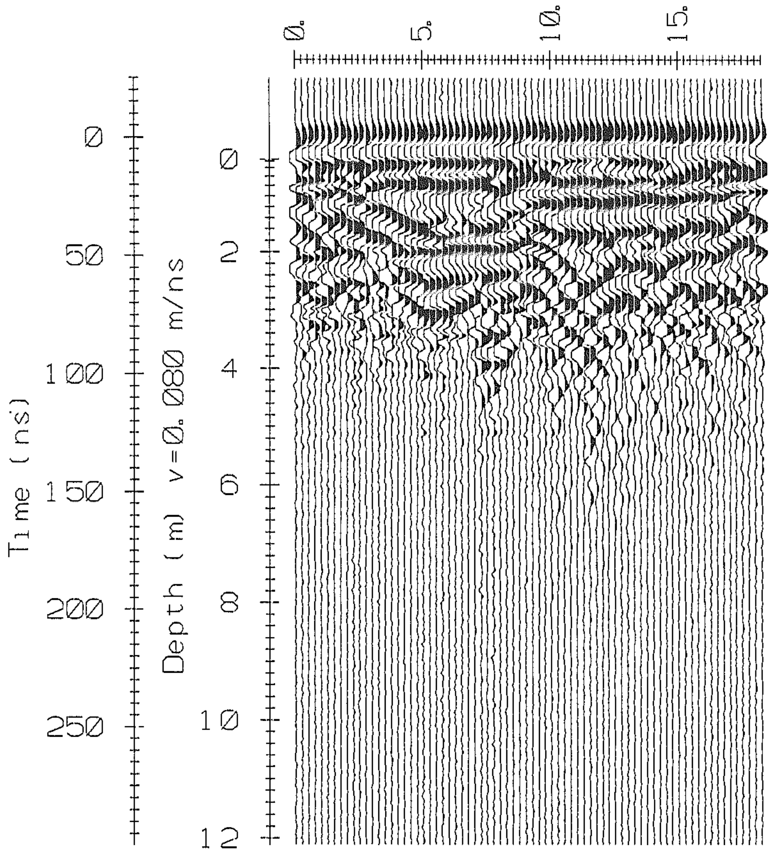
BOSWORTH CREEK NORTH - LONG PROFILE 1 - 100 MHz - JULY 26



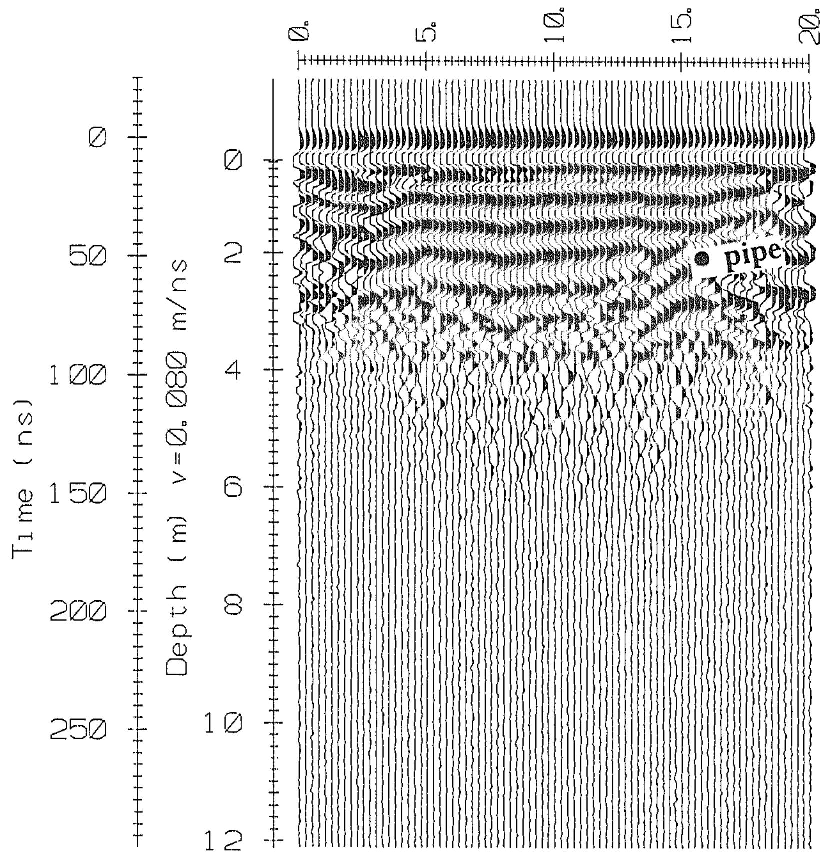
BOSWORTH CREEK NORTH - LONG PROFILE 2 - 100 MHz - JULY 26



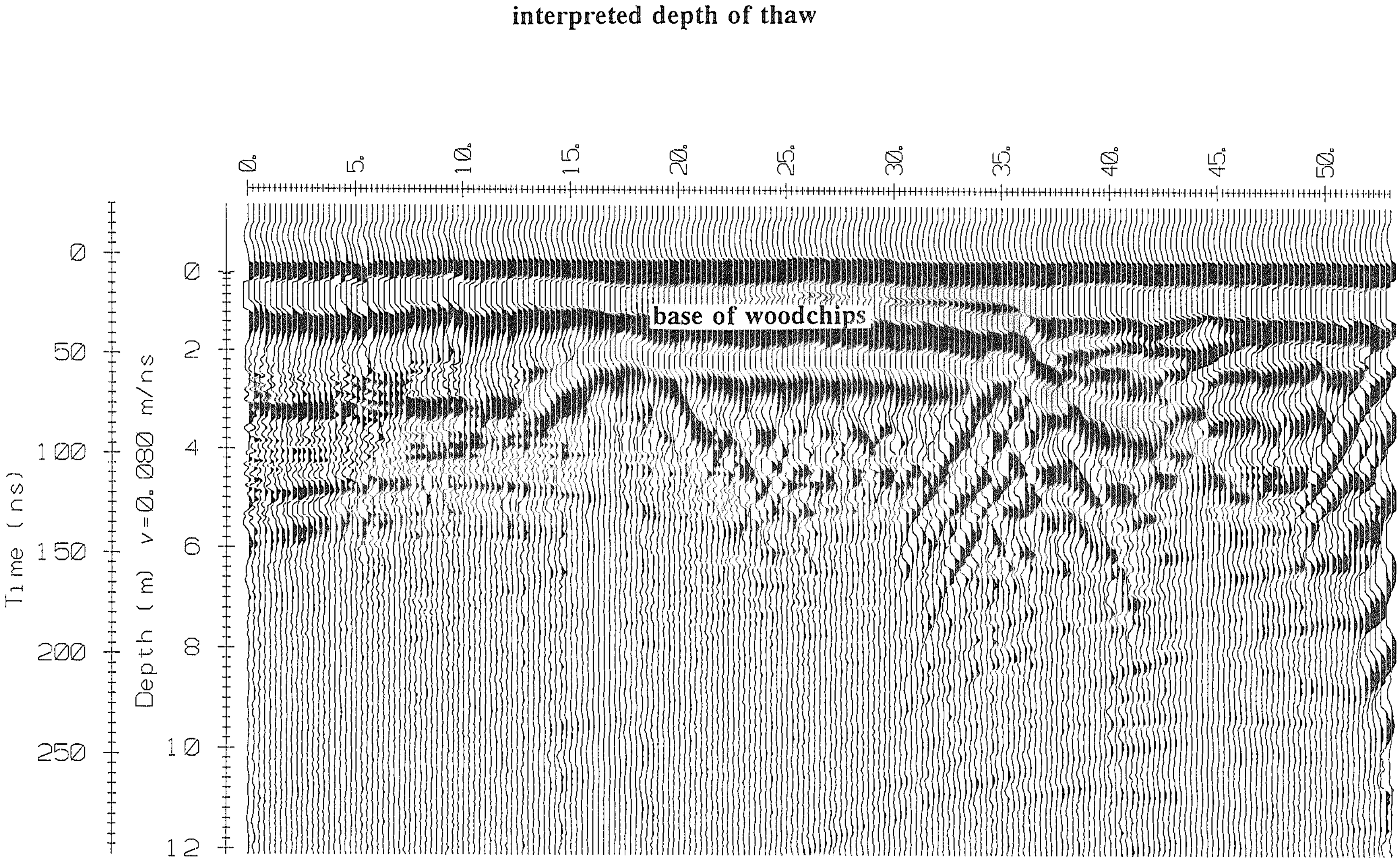
BOSWORTH CREEK NORTH - CROSS PROFILE 1 - 100 MHz - JULY 26



BOSWORTH CREEK NORTH - CROSS PROFILE 2 - 100 MHz - JULY 26

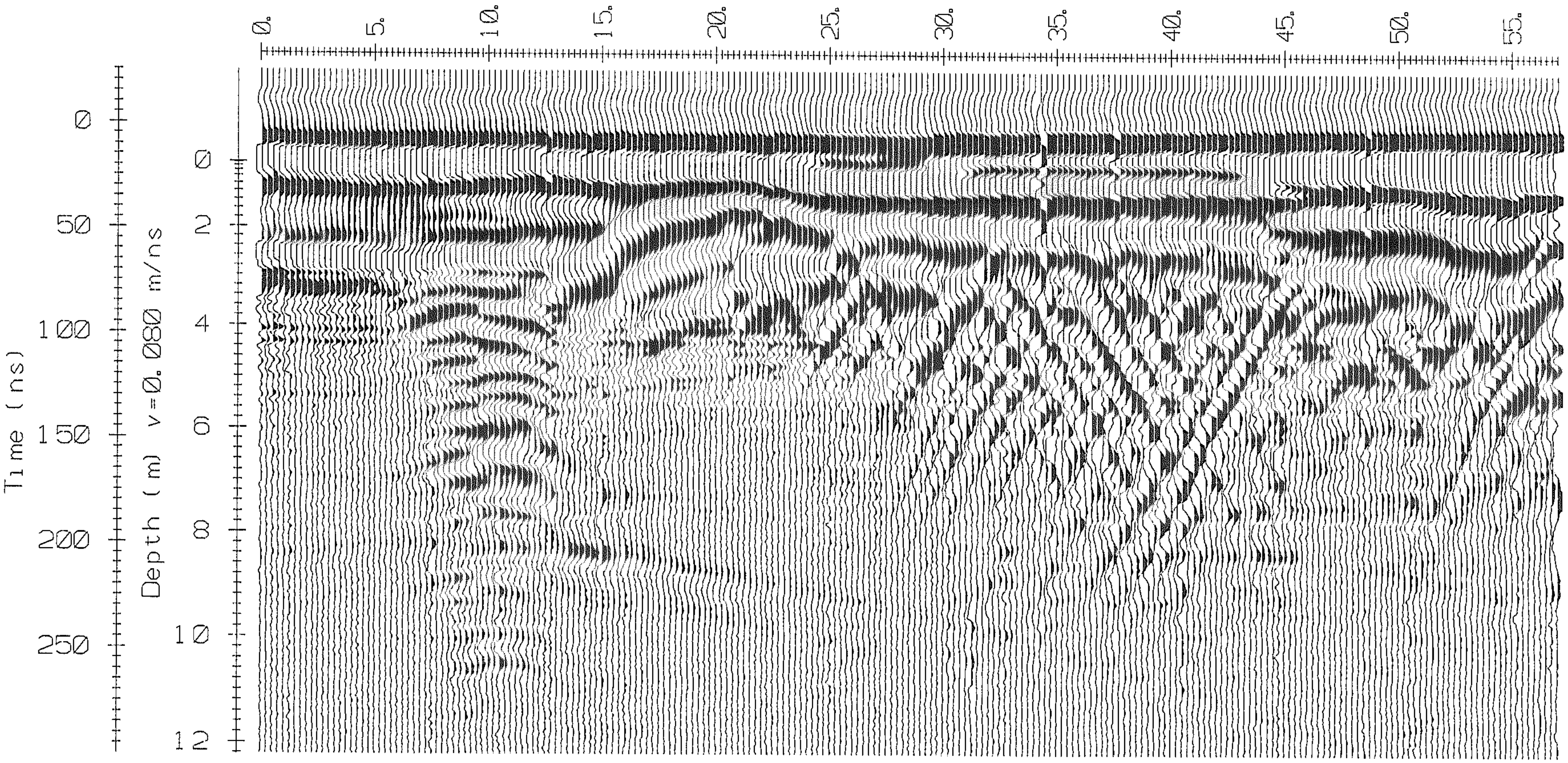


BOSWORTH CREEK NORTH - CROSS PROFILE 3 - 100 MHz - JULY 26

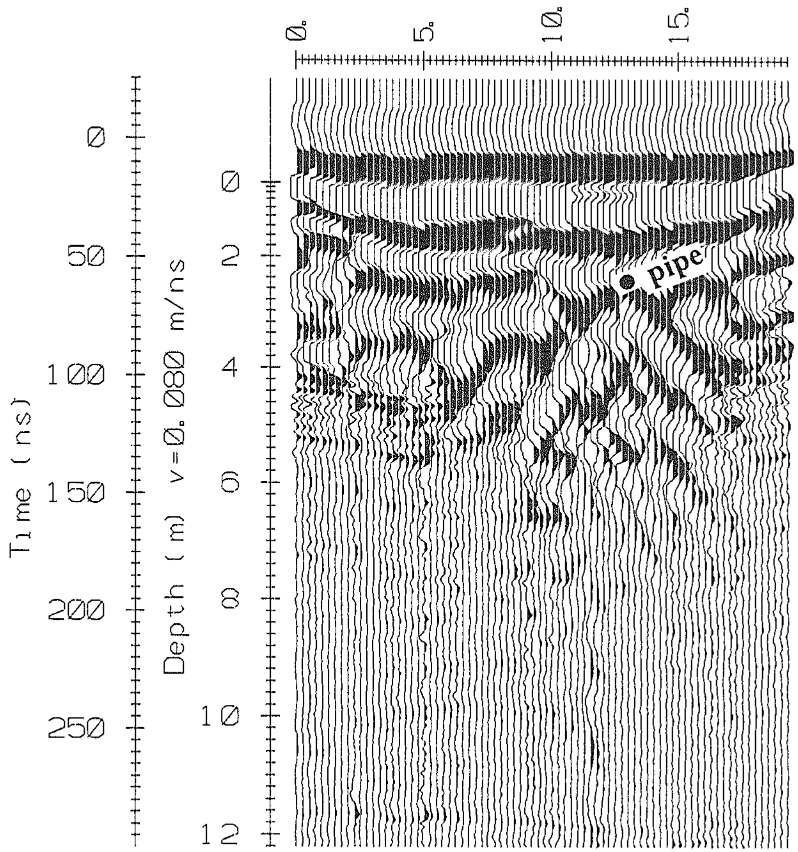


BOSWORTH CREEK NORTH - LONG PROFILE 1 - 50 MHz - AUGUST 25

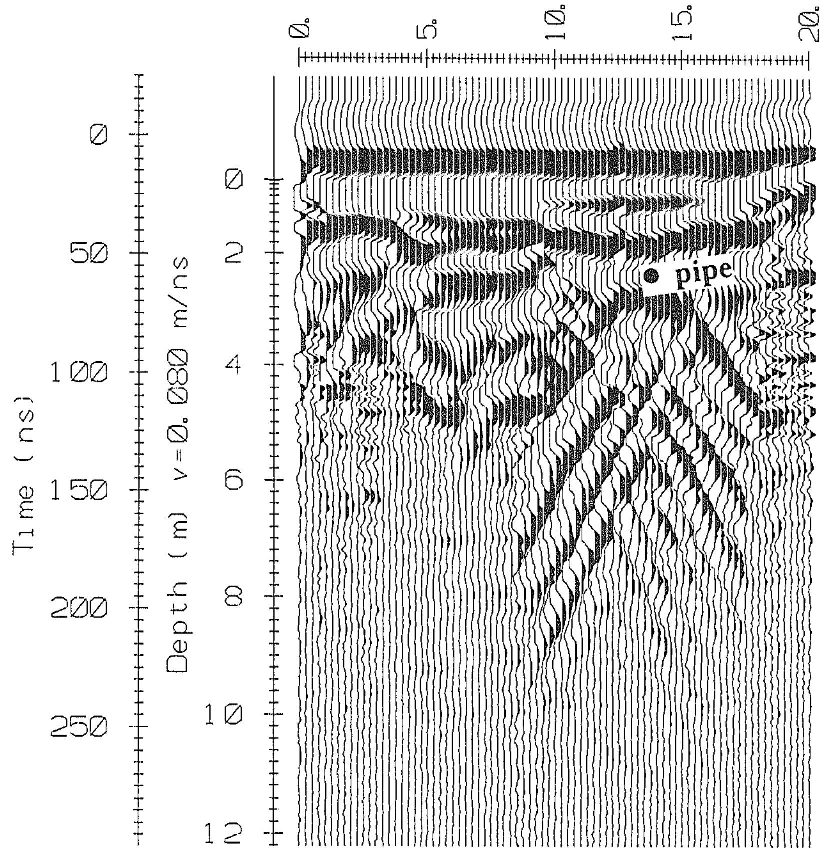
interpreted depth of thaw



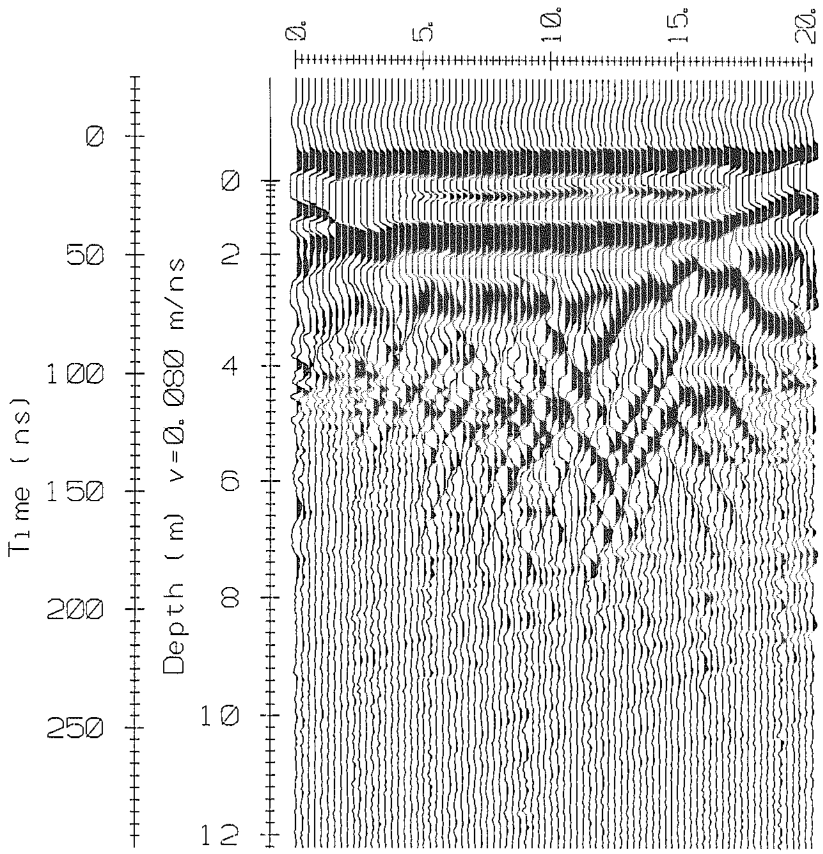
BOSWORTH CREEK NORTH - LONG PROFILE 2 - 50 MHz - AUGUST 25



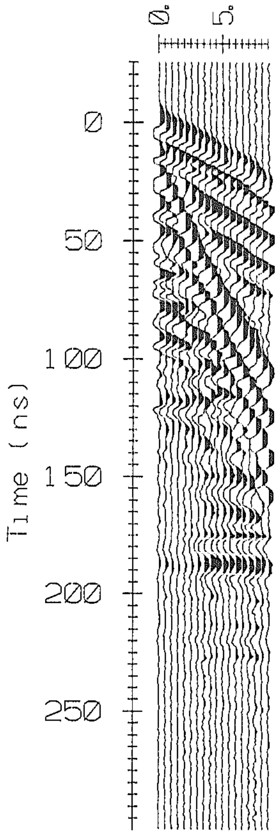
BOSWORTH CREEK NORTH - CROSS PROFILE 1 - 50 MHz - AUGUST 25



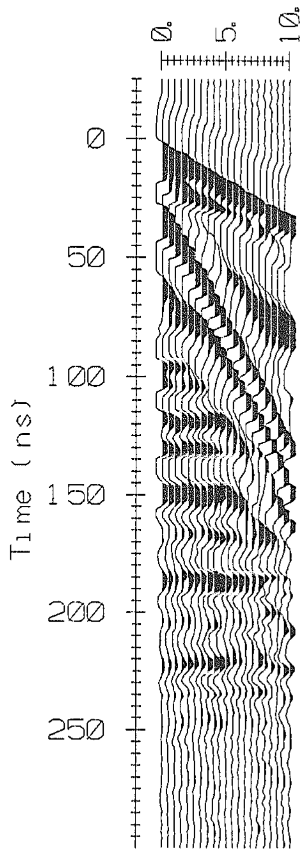
BOSWORTH CREEK NORTH - CROSS PROFILE 2 - 50 MHz - AUGUST 25



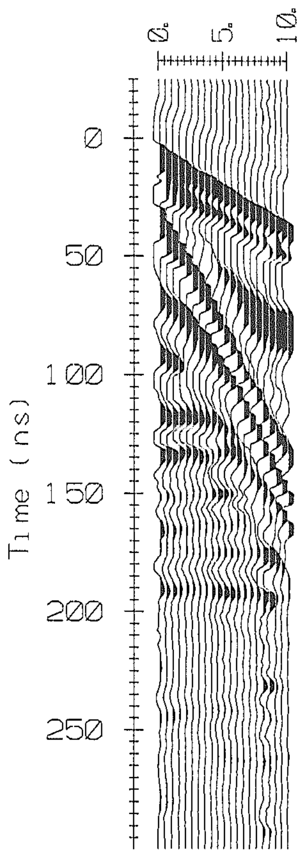
BOSWORTH CREEK NORTH - CROSS PROFILE 3 - 50 MHz - AUGUST 25



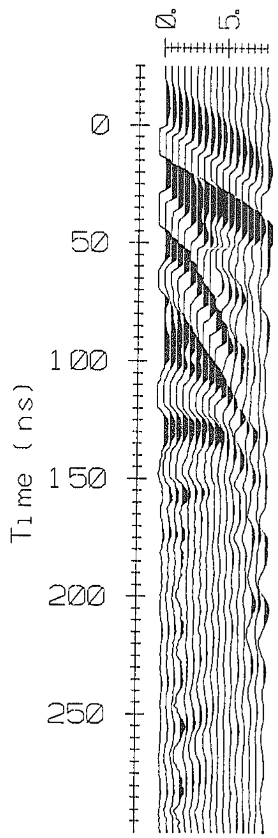
BOSWORTH CREEK NORTH - CMP - JUNE 2



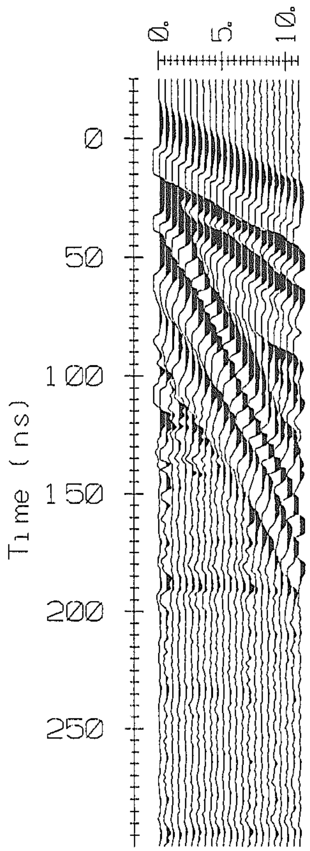
BOSWORTH CREEK NORTH - CMP - JUNE 7



BOSWORTH CREEK NORTH - CMP - JUNE 29



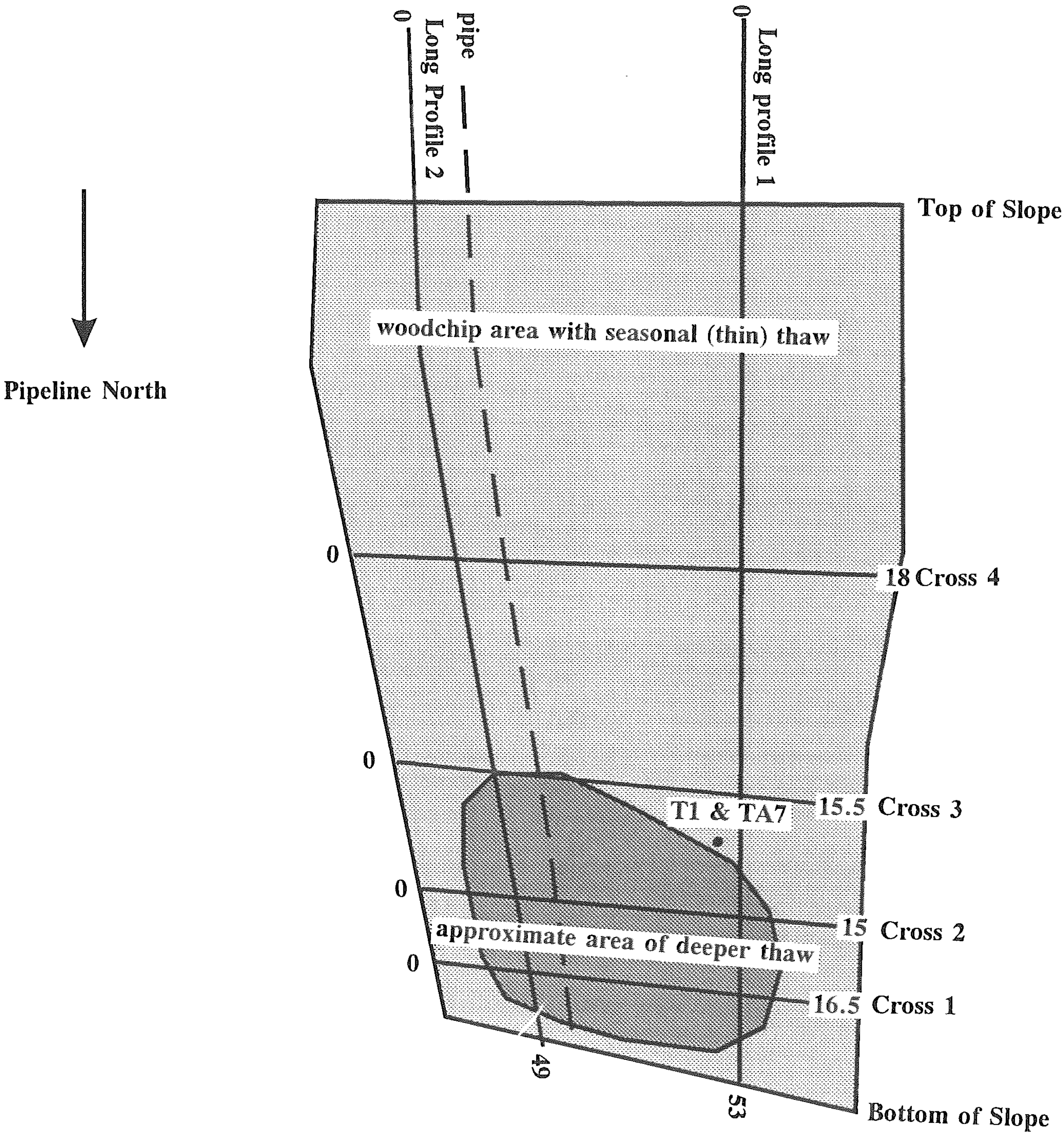
BOSWORTH CREEK NORTH - CMP - JULY 26

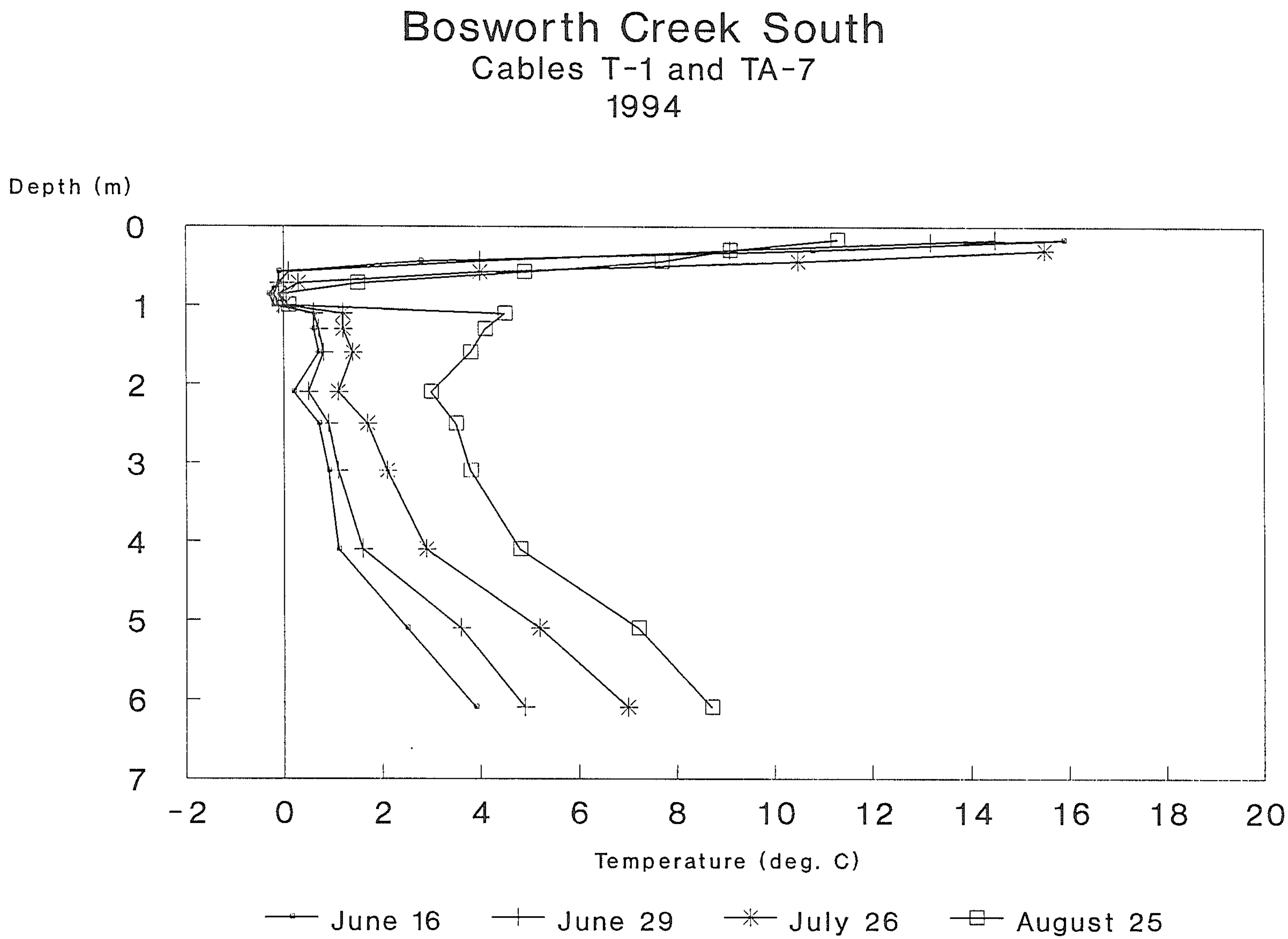


BOSWORTH CREEK NORTH - CMP - AUGUST 25

BOSWORTH CREEK SOUTH

Not to Scale

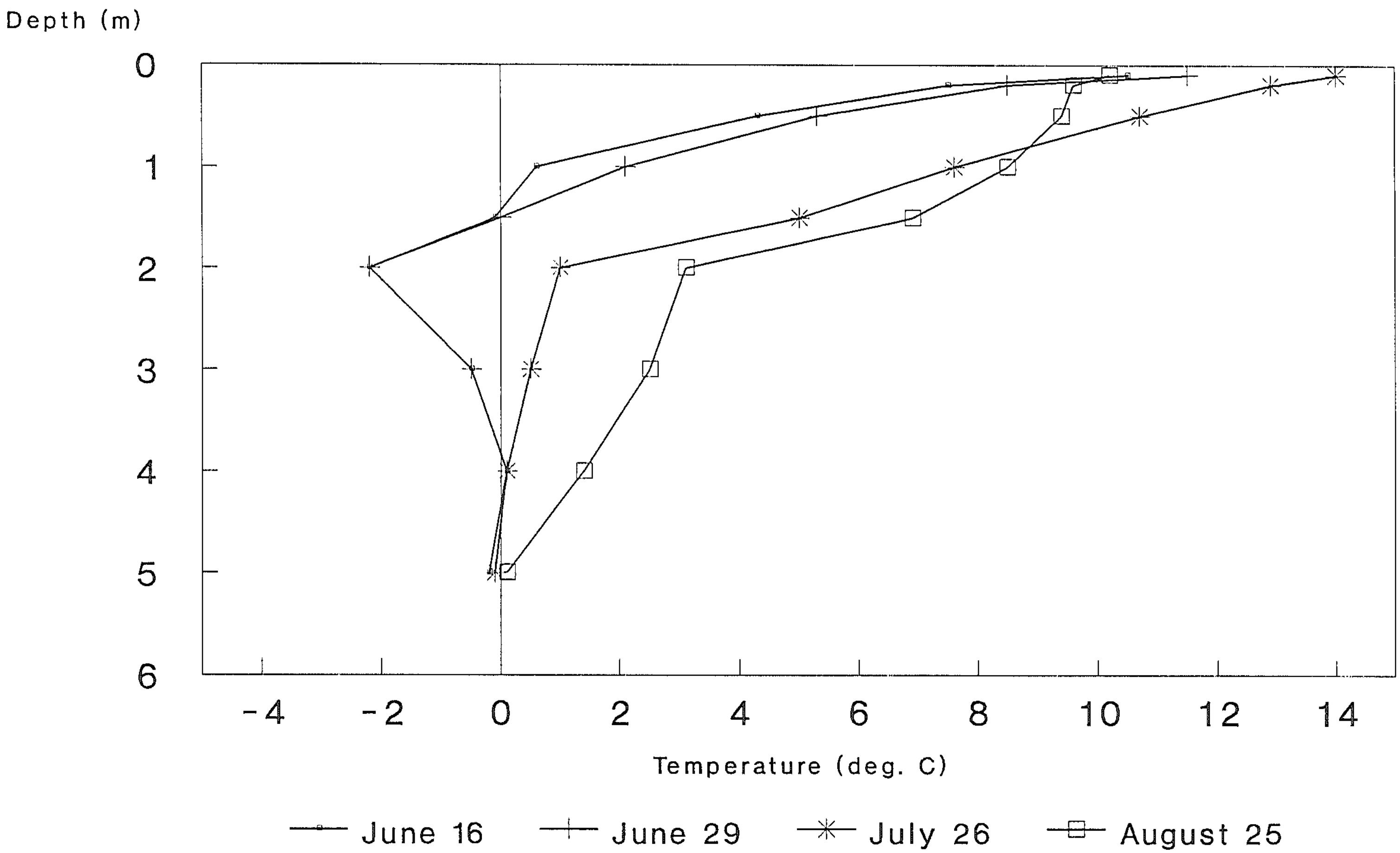



Bosworth Creek South
Cables T-1 and TA-7
1994
Depth (m)
0
1
2
3
4
5
6
7
-2
0
2
4
6
8
10
12
14
16
18
20
Temperature (deg. C)
June 16
June 29
July 26
August 25

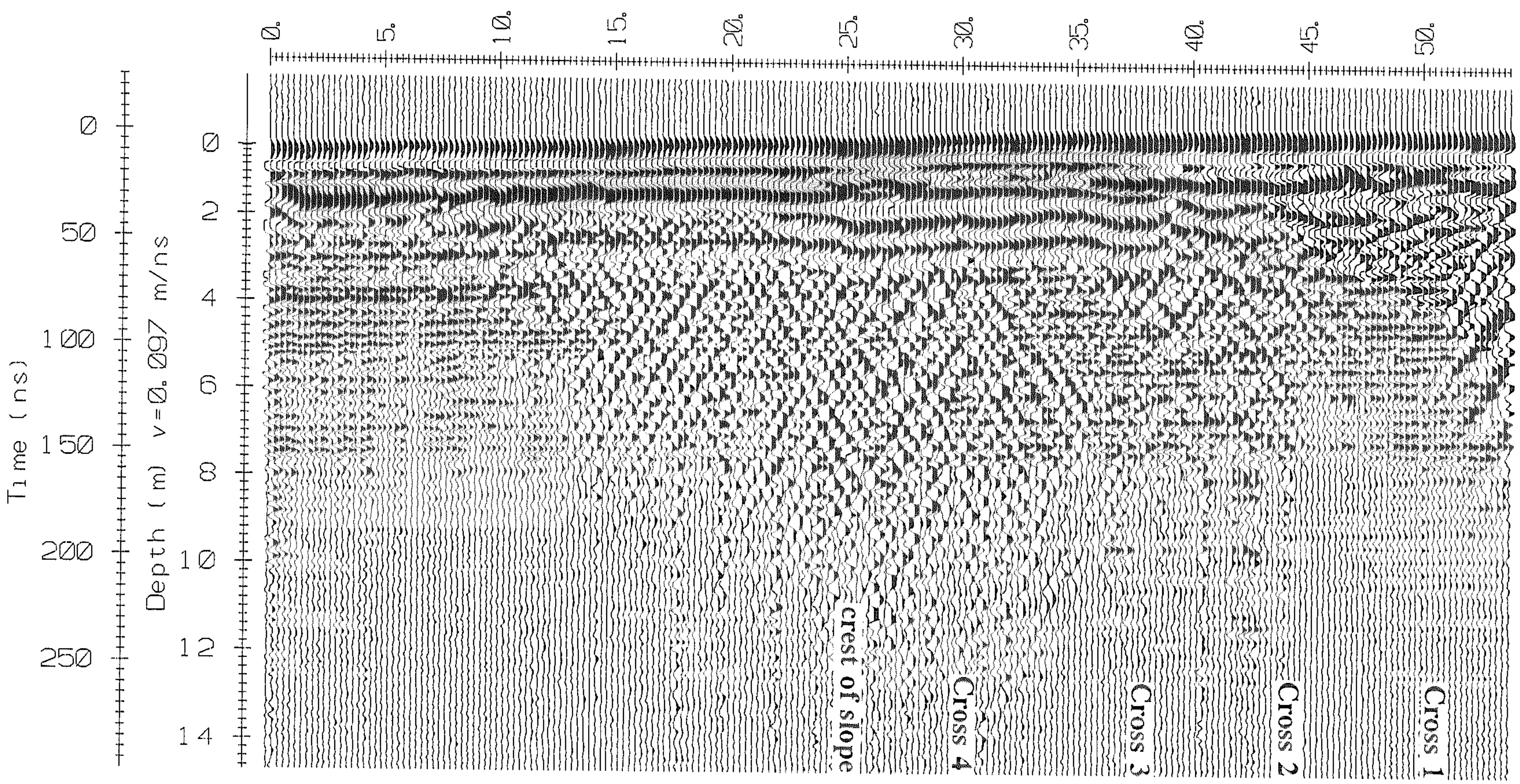
Bosworth Creek South

Cable T-2 - On ROW above slope

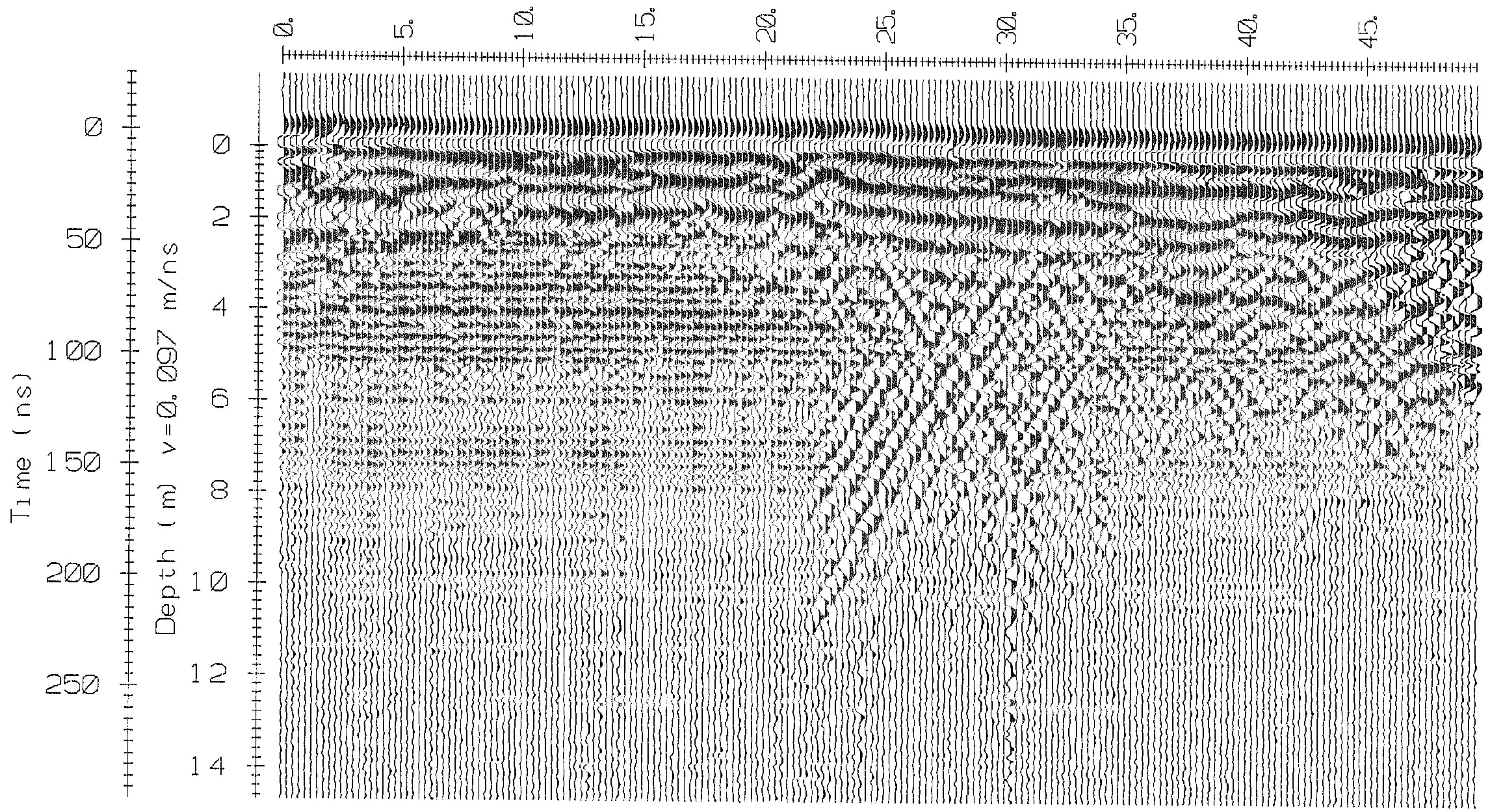
1994



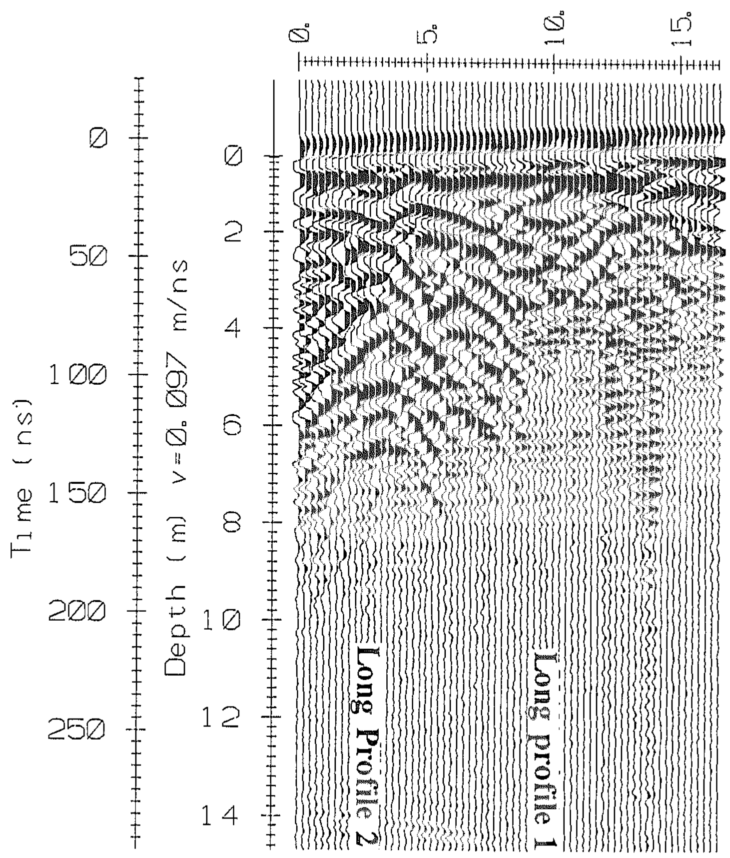
interpreted depth of thaw



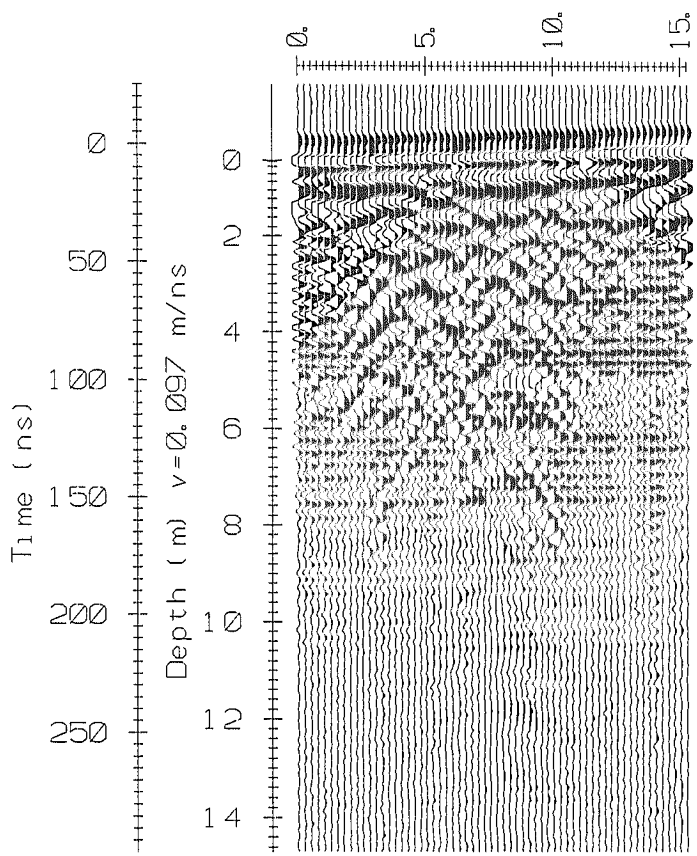
BOSWORTH CREEK SOUTH - LONG PROFILE 1 - 100 MHz - JUNE 3



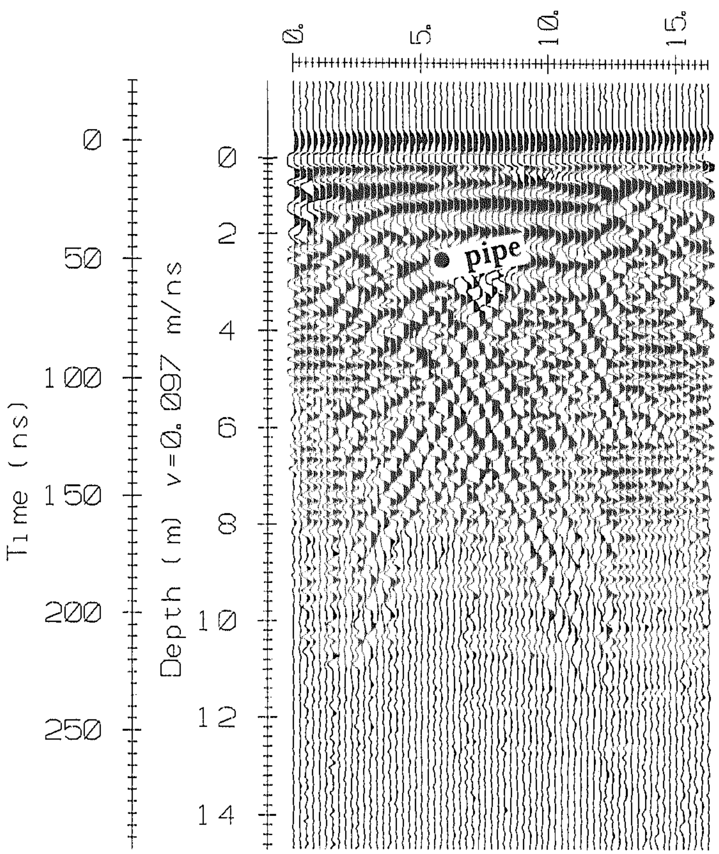
BOSWORTH CREEK SOUTH - LONG PROFILE 2 - 100 MHz - JUNE 3



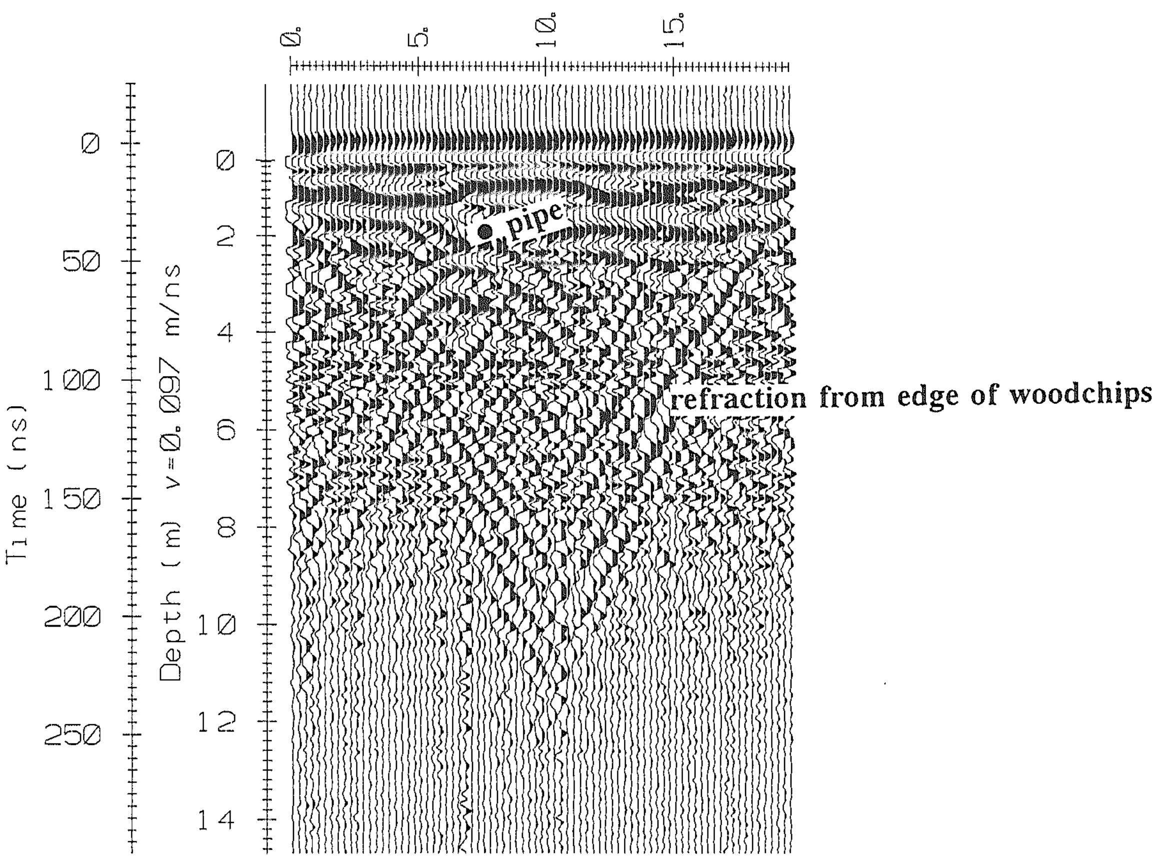
BOSWORTH CREEK SOUTH - CROSS PROFILE 1 - 100 MHz - JUNE 3



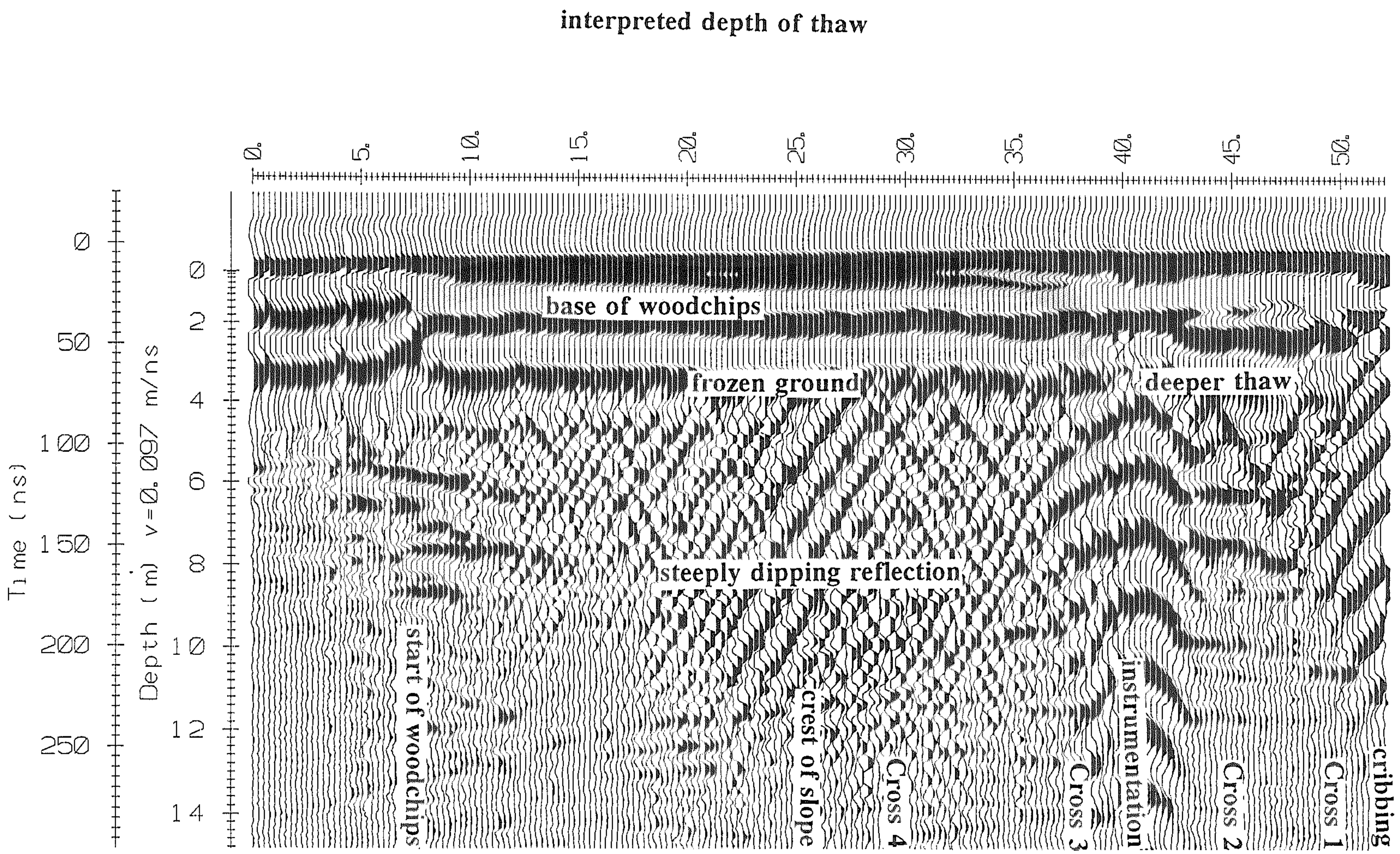
BOSWORTH CREEK SOUTH - CROSS PROFILE 2 - 100 MHz - JUNE 3



BOSWORTH CREEK SOUTH - CROSS PROFILE 3 - 100 MHz - JUNE 3

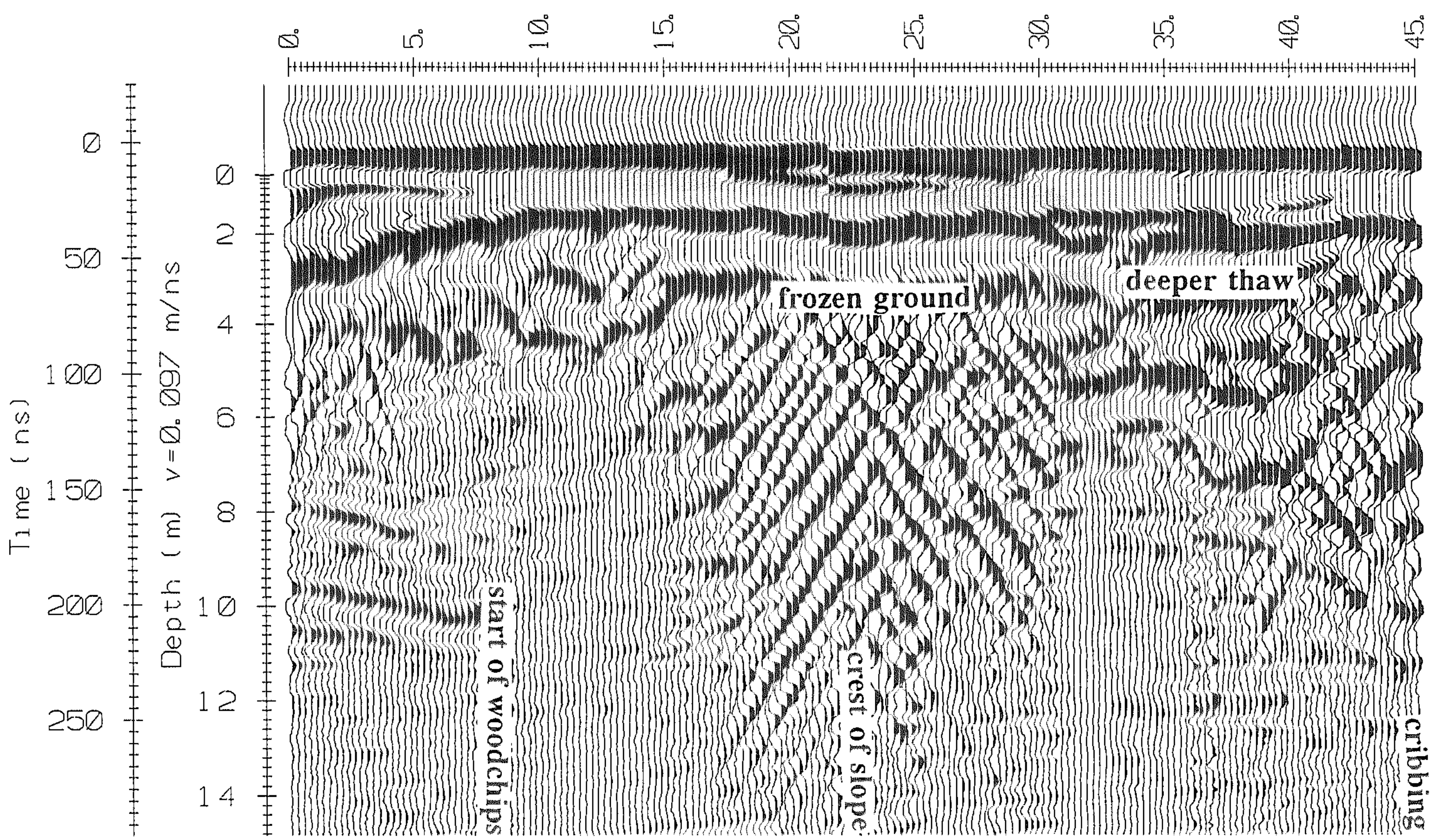


BOSWORTH CREEK SOUTH - CROSS PROFILE 4 - 100 MHz - JUNE 3

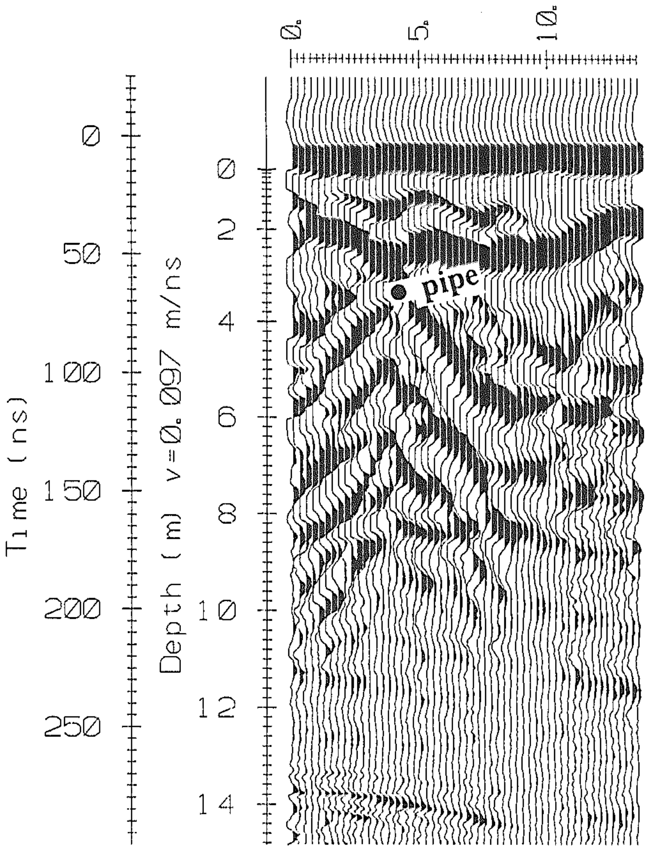


BOSWORTH CREEK SOUTH - LONG PROFILE 1 - 50 MHz - JUNE 7

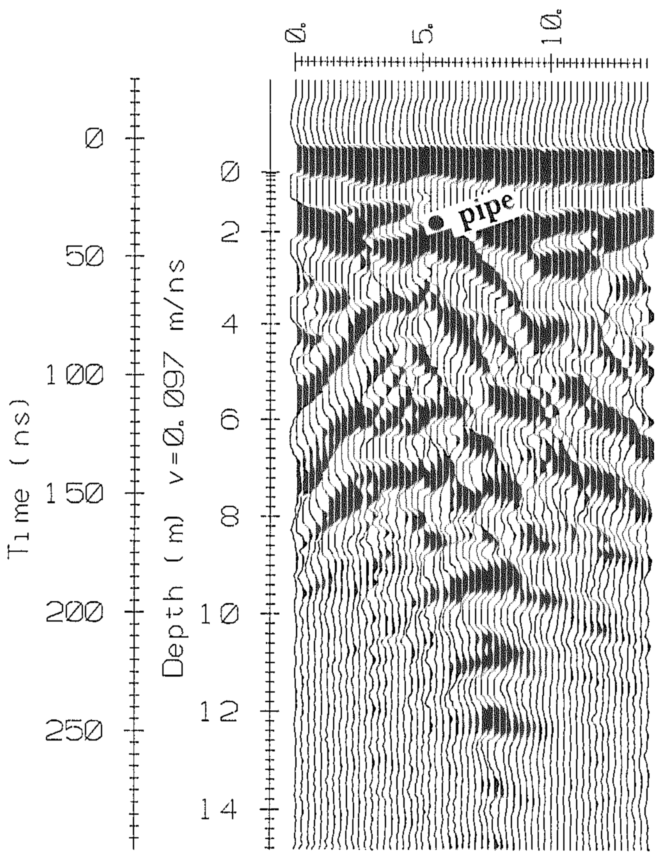
interpreted depth of thaw



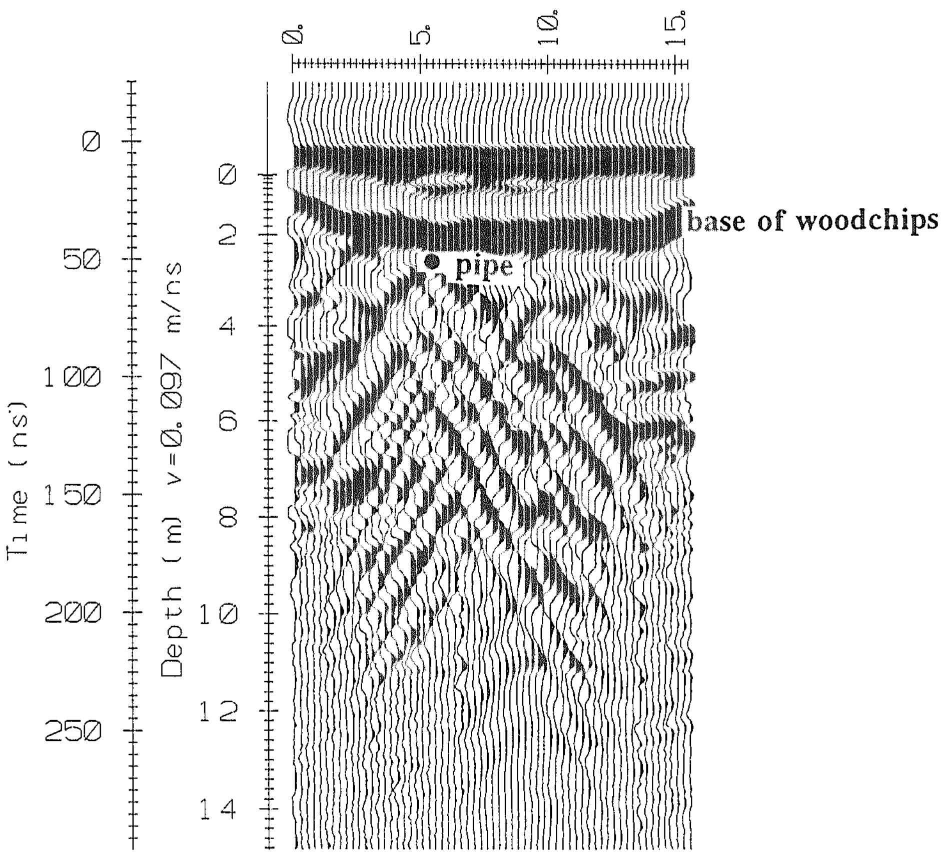
BOSWORTH CREEK SOUTH - LONG PROFILE 2 - 50 MHz - JUNE 7



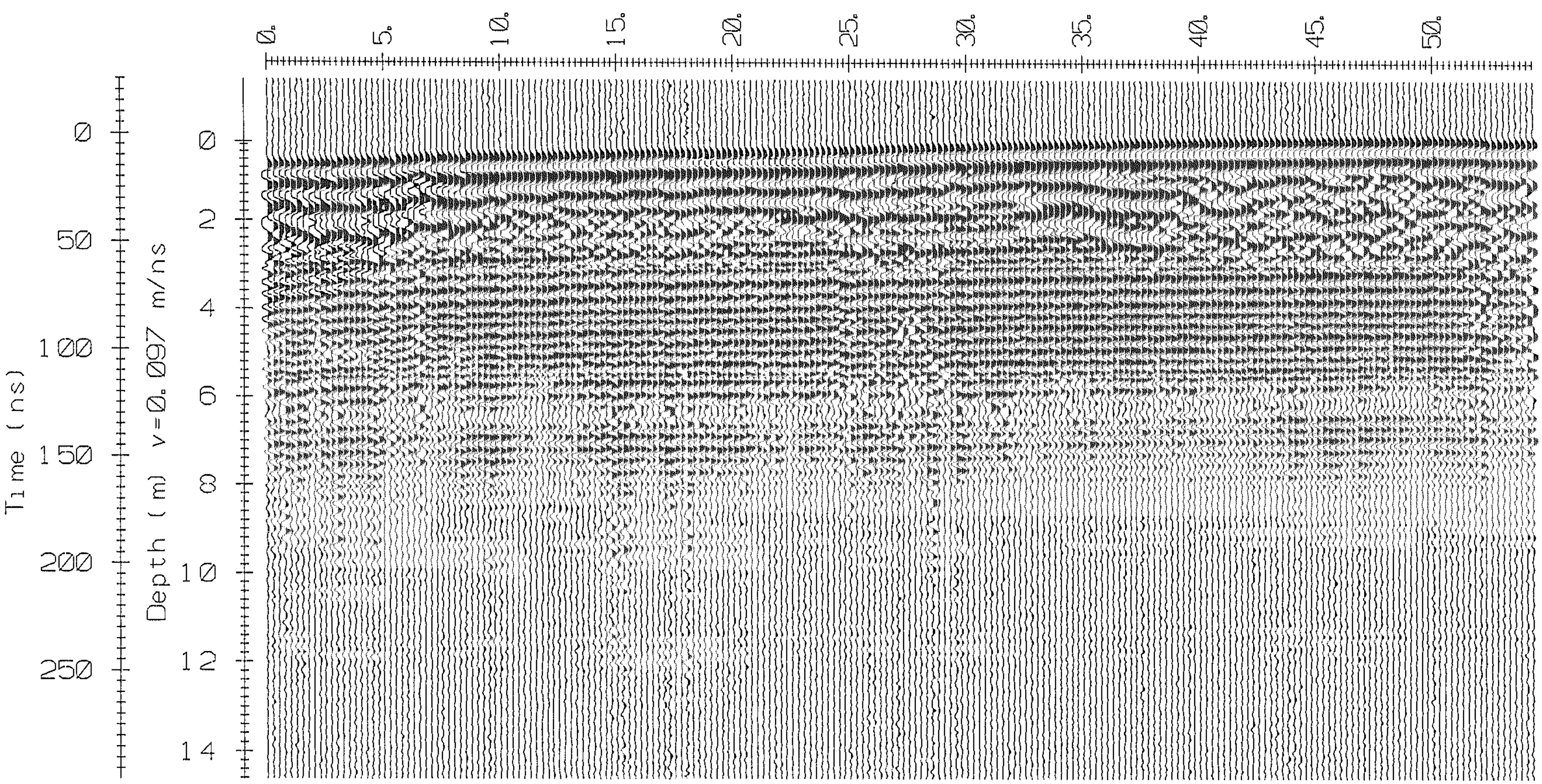
BOSWORTH CREEK SOUTH - CROSS PROFILE 1 - 50 MHz - JUNE 7



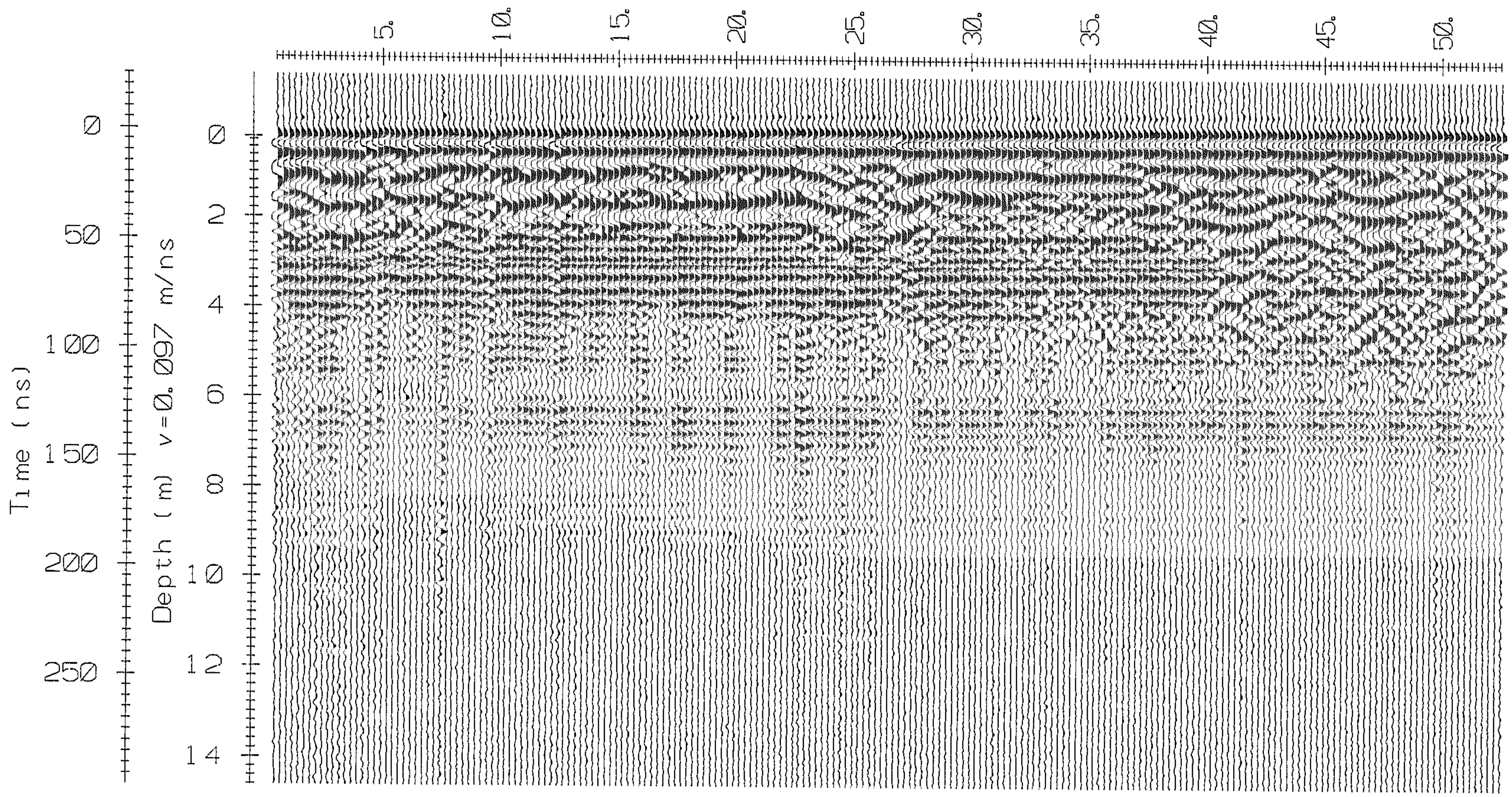
BOSWORTH CREEK SOUTH - CROSS PROFILE 2 - 50 MHz - JUNE 7



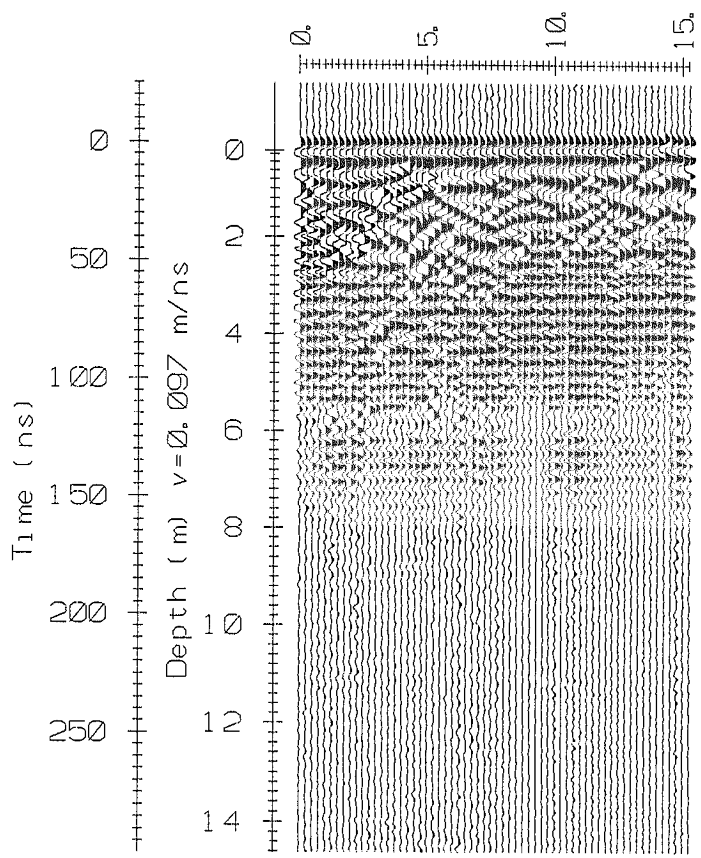
BOSWORTH CREEK SOUTH - CROSS PROFILE 3 - 50 MHz - JUNE 7



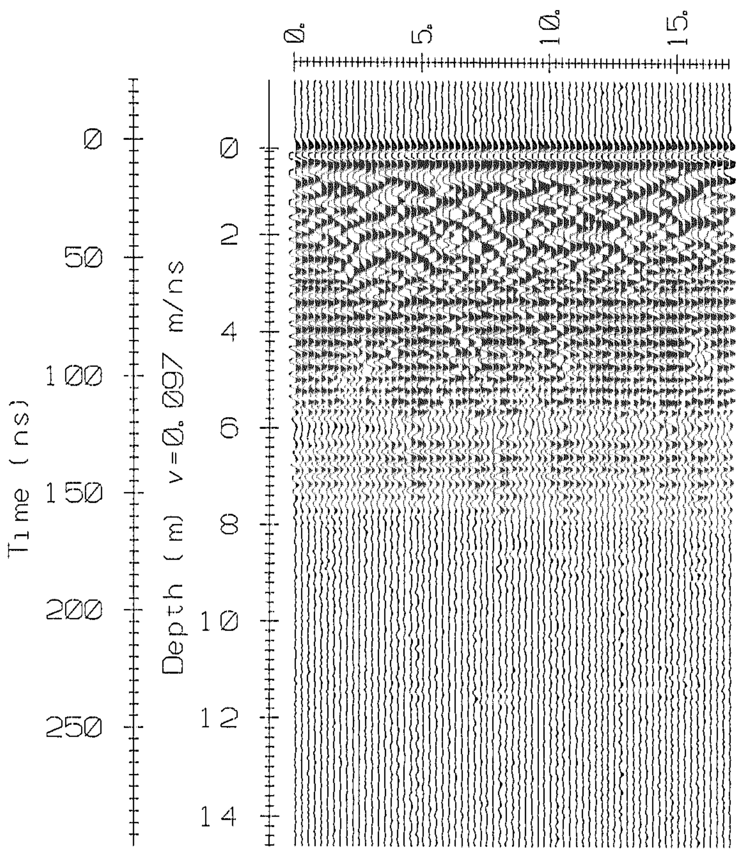
BOSWORTH CREEK SOUTH - LONG PROFILE 1 - 200 MHz - JUNE 16



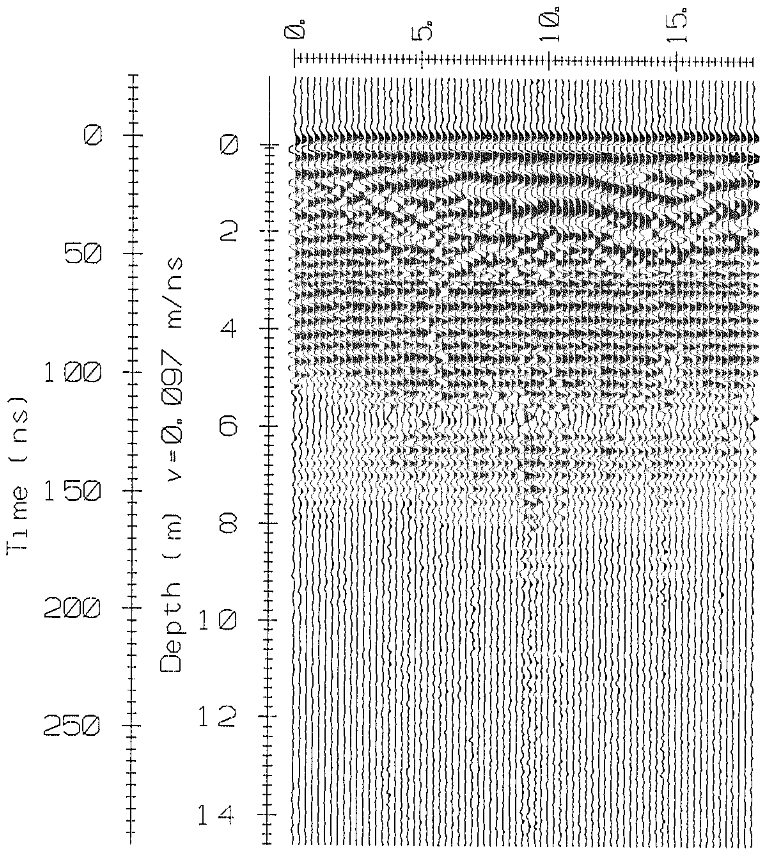
BOSWORTH CREEK SOUTH - LONG PROFILE 2 - 200 MHz - JUNE 16



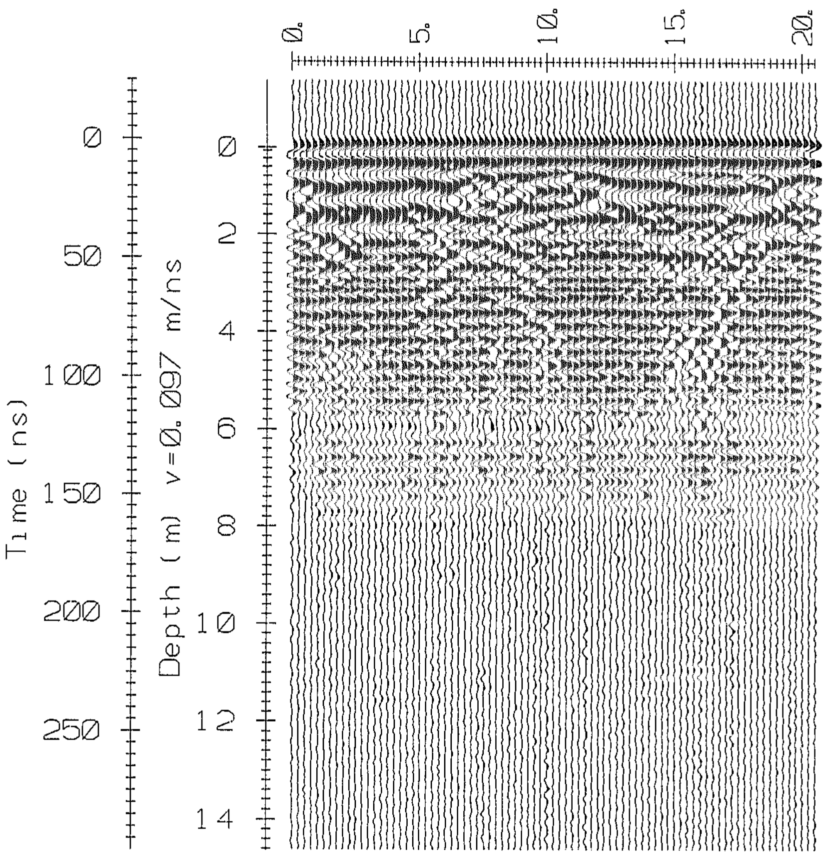
BOSWORTH CREEK SOUTH - CROSS PROFILE 1 - 200 MHz - JUNE 16



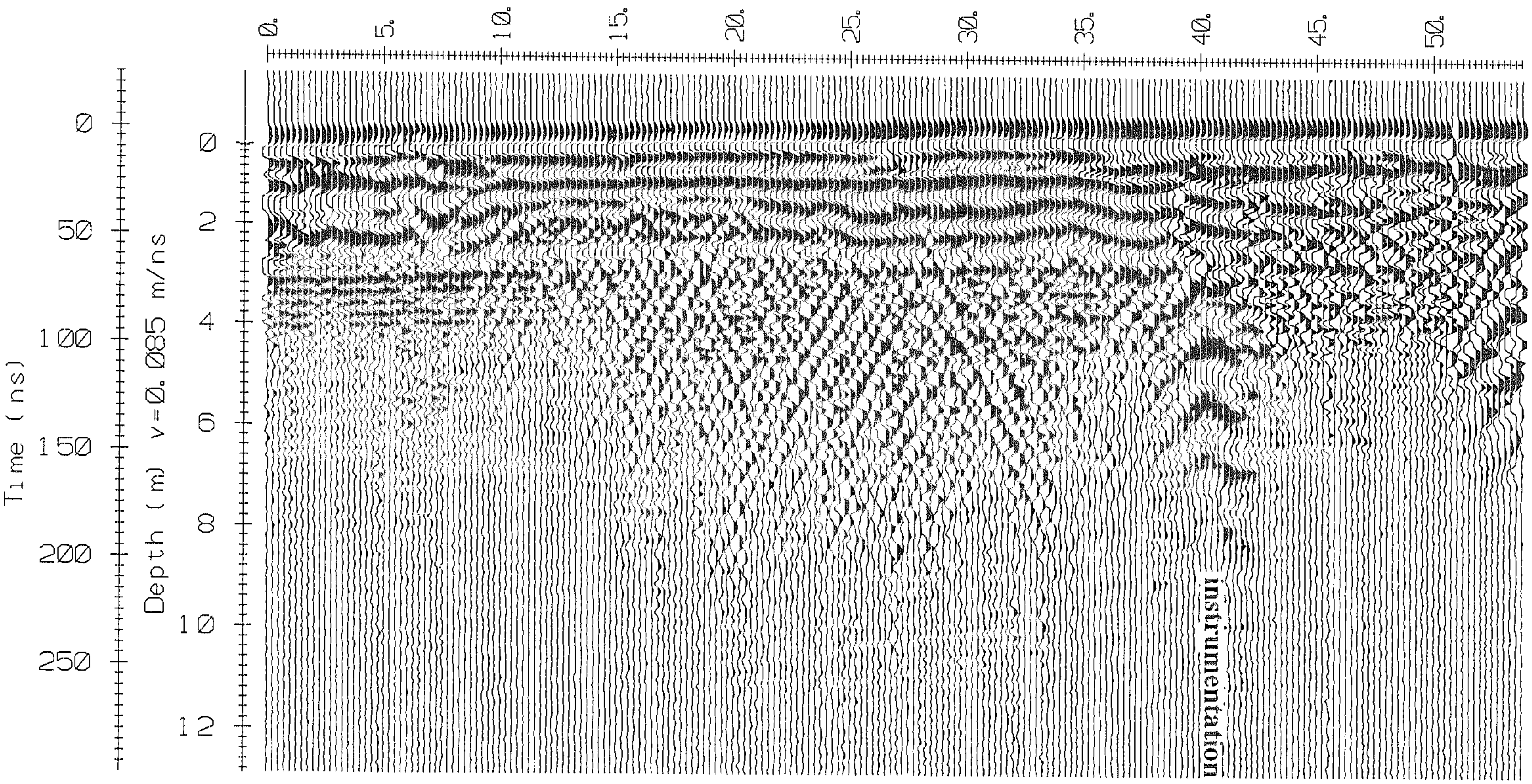
BOSWORTH CREEK SOUTH - CROSS PROFILE 2 - 200 MHz - JUNE 16



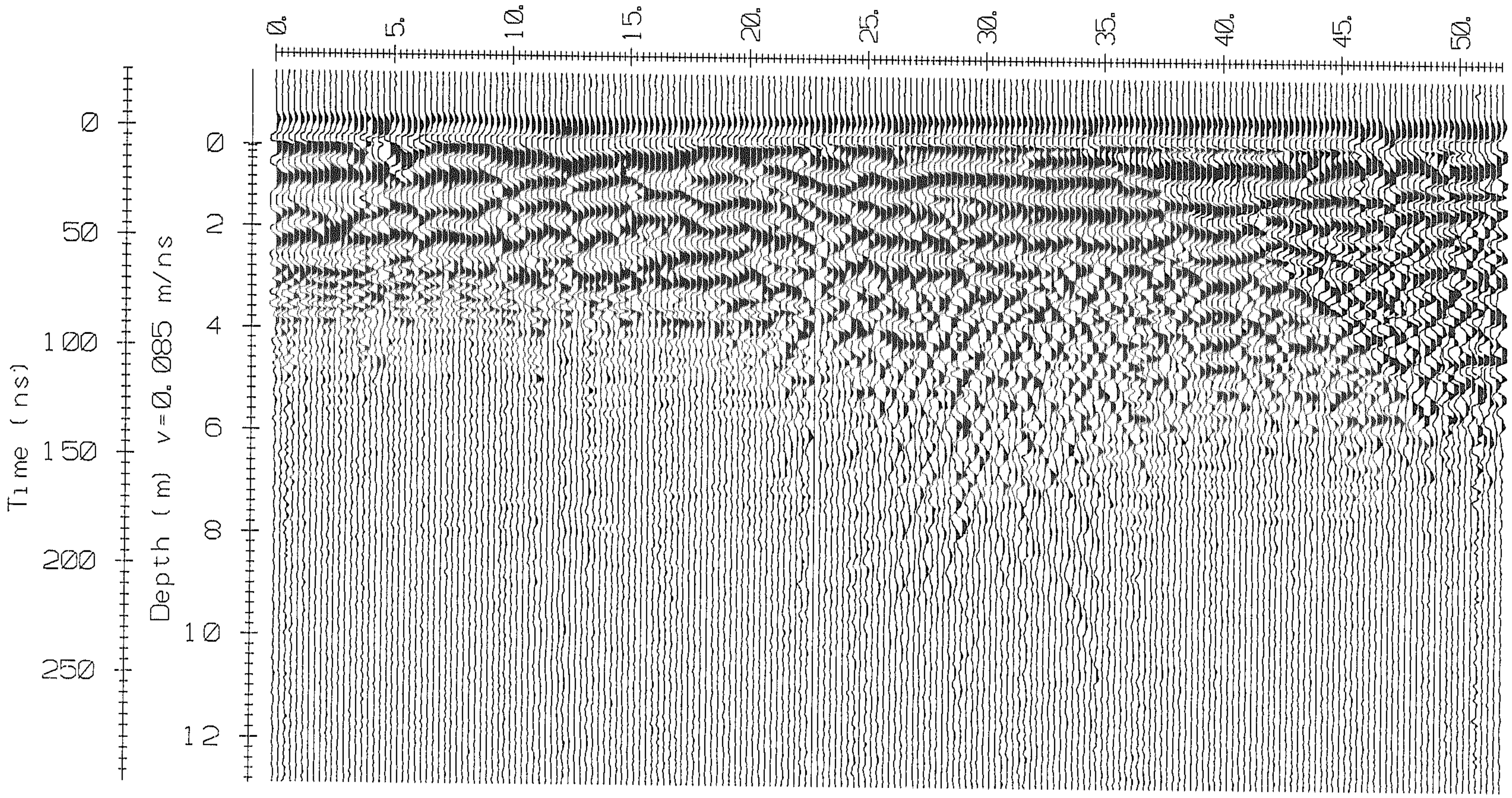
BOSWORTH CREEK SOUTH - CROSS PROFILE 3 - 200 MHz - JUNE 16



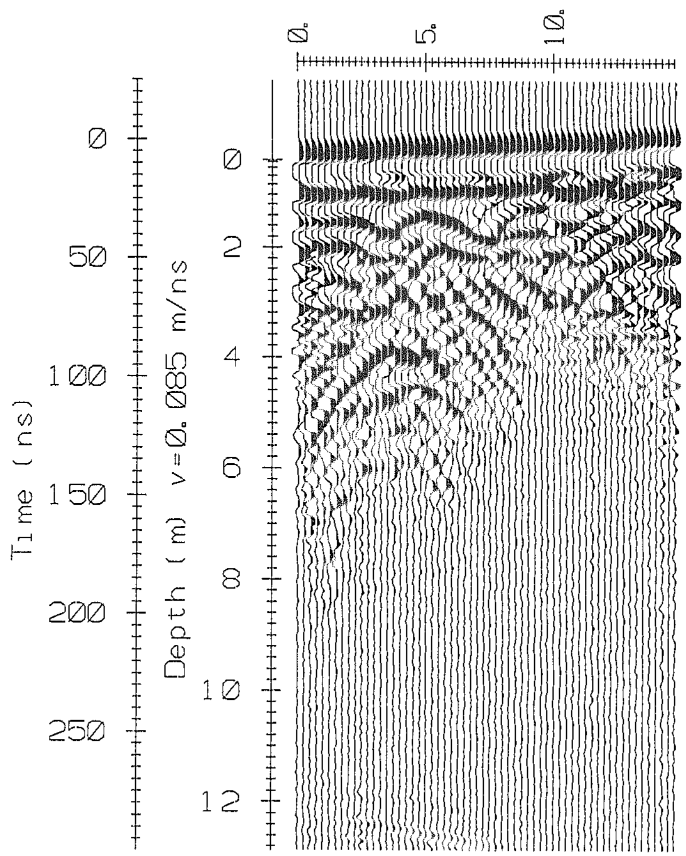
BOSWORTH CREEK SOUTH - CROSS PROFILE 4 - 200 MHz - JUNE 16



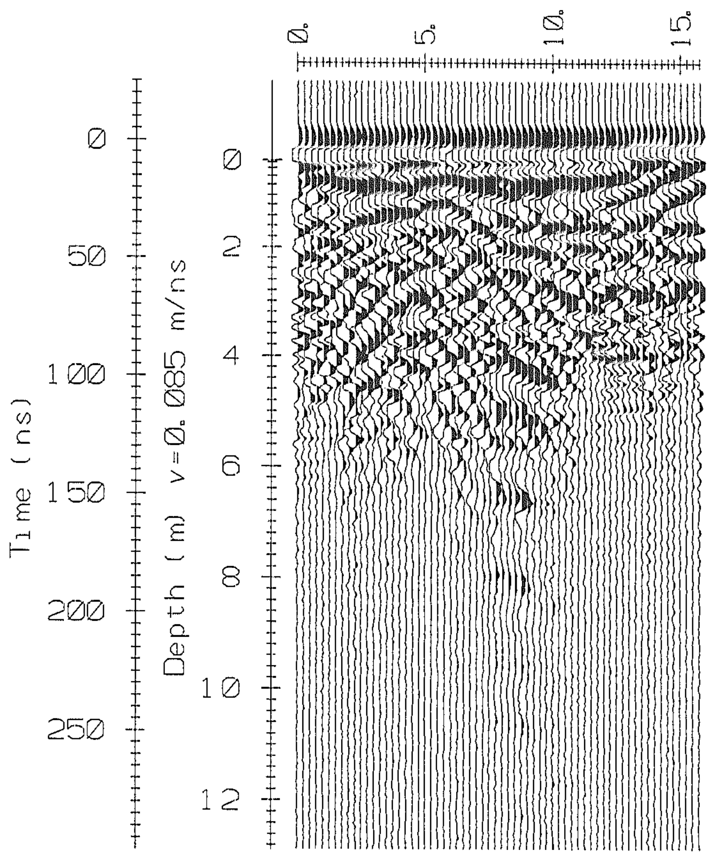
BOSWORTH CREEK SOUTH - LONG PROFILE 1 - 50 MHz - JUNE 29



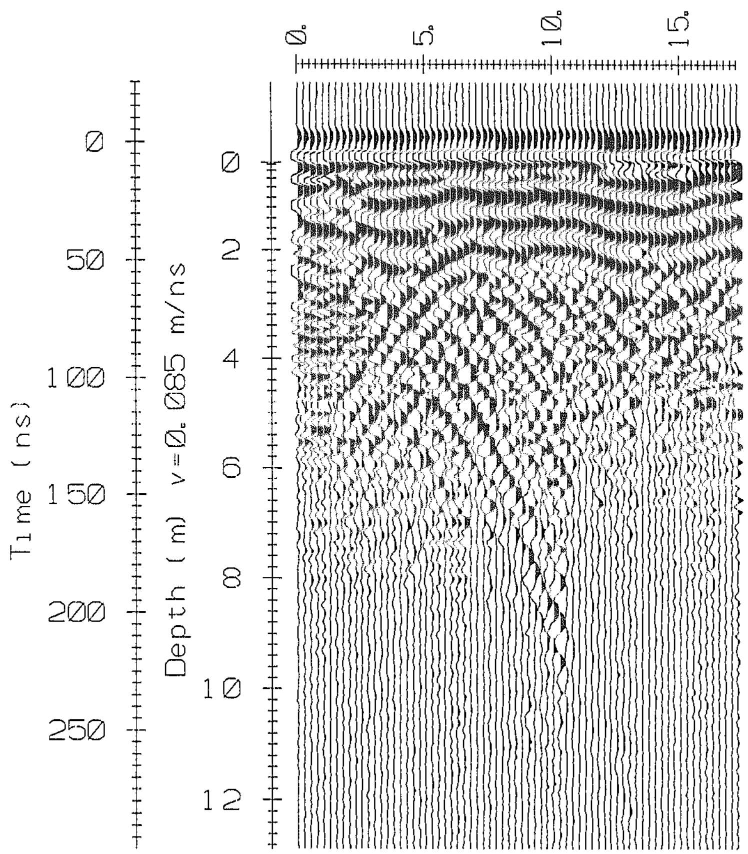
BOSWORTH CREEK SOUTH - LONG PROFILE 2 - 50 MHz - JUNE 29



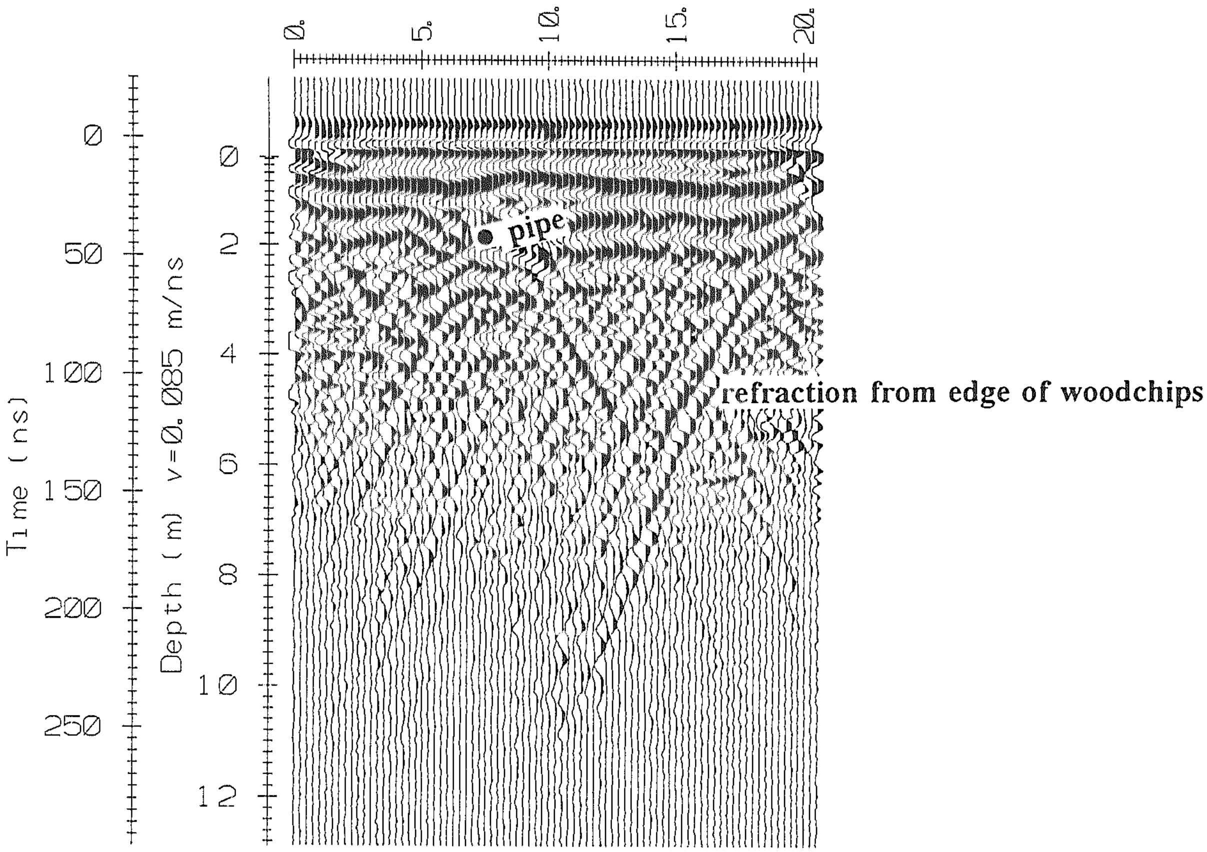
BOSWORTH CREEK SOUTH - CROSS PROFILE 1 - 50 MHz - JUNE 29



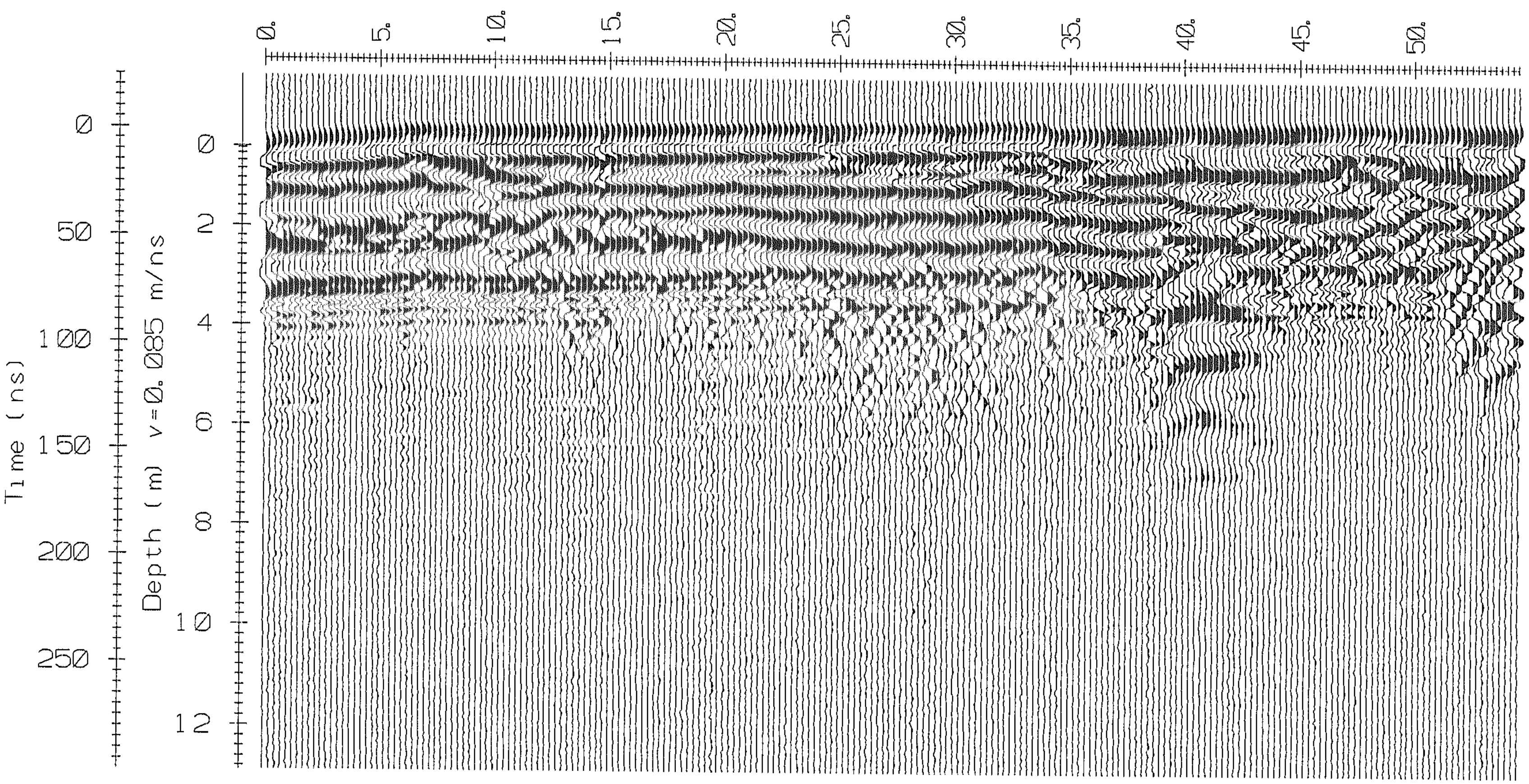
BOSWORTH CREEK SOUTH - CROSS PROFILE 2 - 50 MHz - JUNE 29



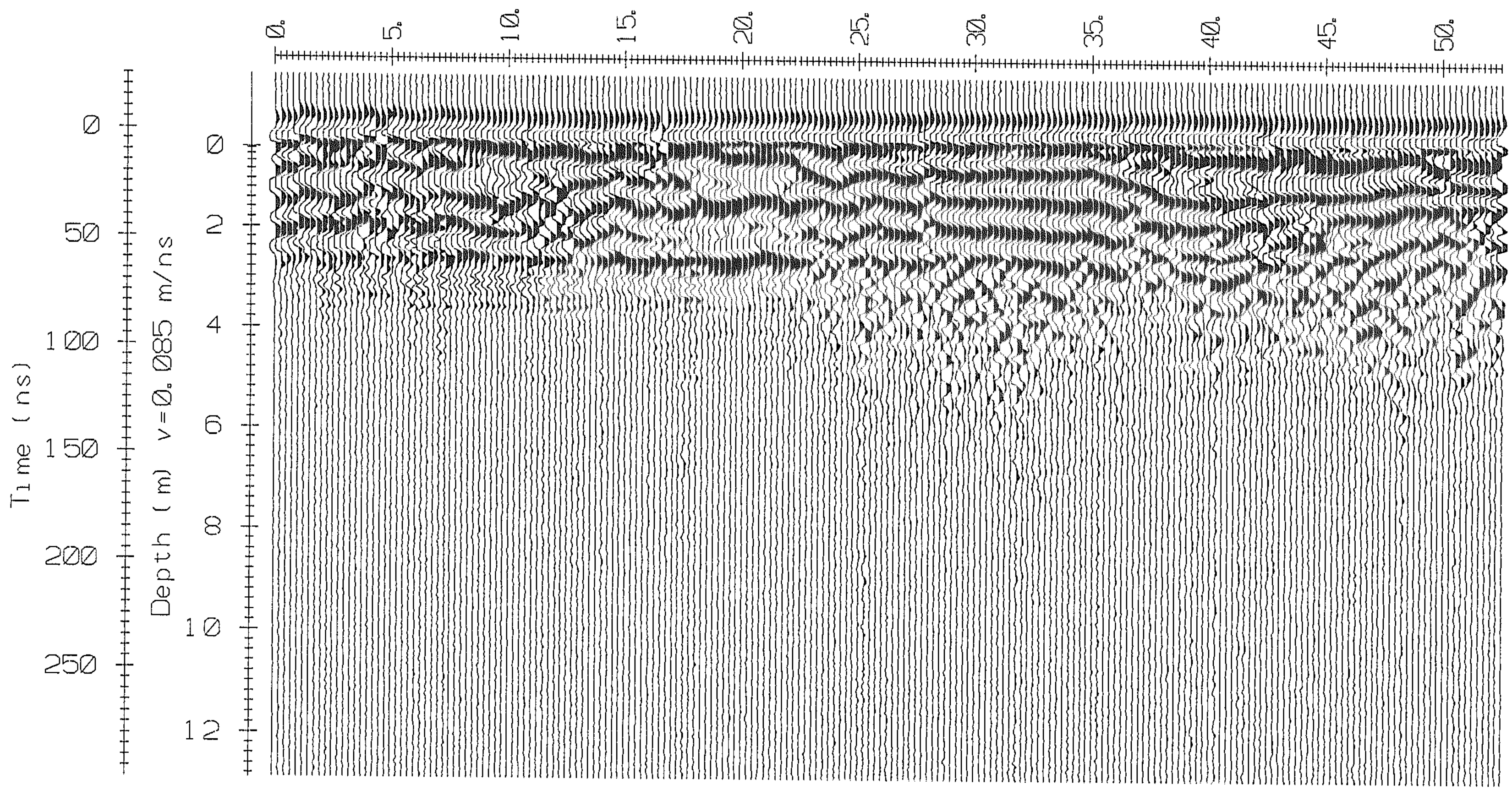
BOSWORTH CREEK SOUTH - CROSS PROFILE 3 - 50 MHz - JUNE 29



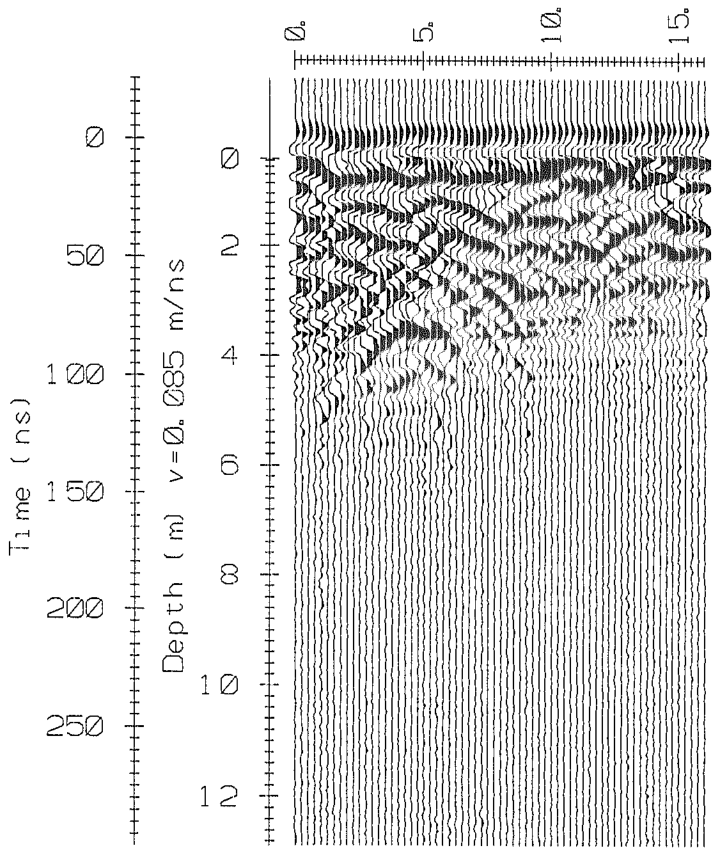
BOSWORTH CREEK SOUTH - CROSS PROFILE 4 - 50 MHz - JUNE 29



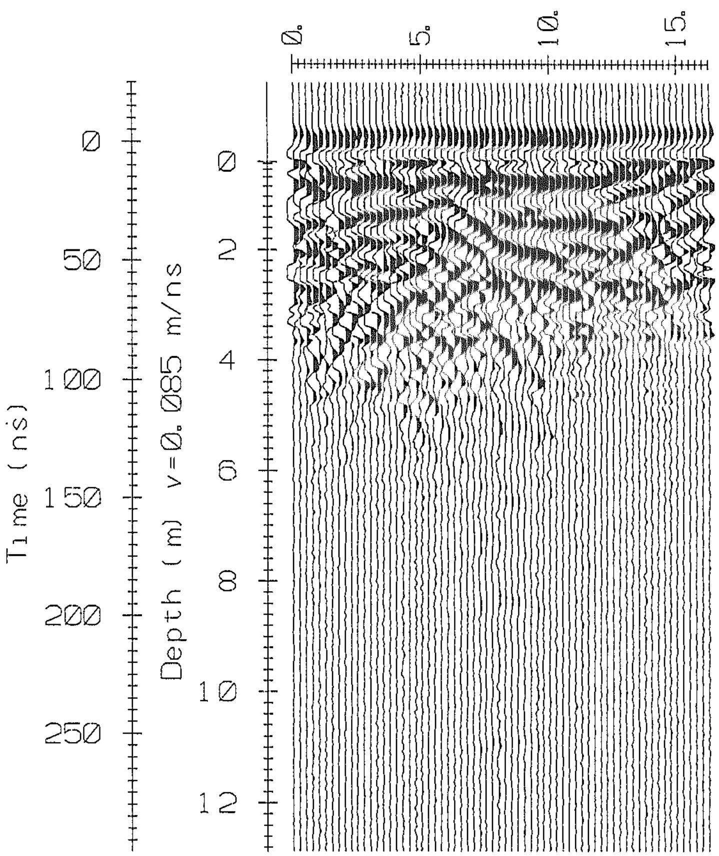
BOSWORTH CREEK SOUTH - LONG PROFILE 1 - 100 MHz - JUUL 26



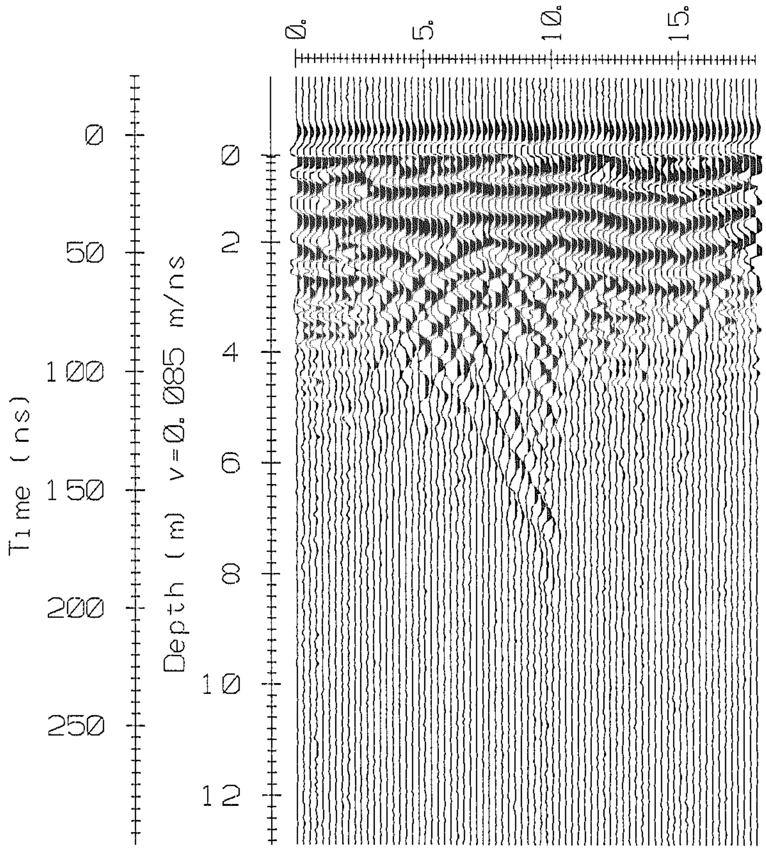
BOSWORTH CREEK SOUTH - LONG PROFILE 2 - 100 MHz - JULY 26



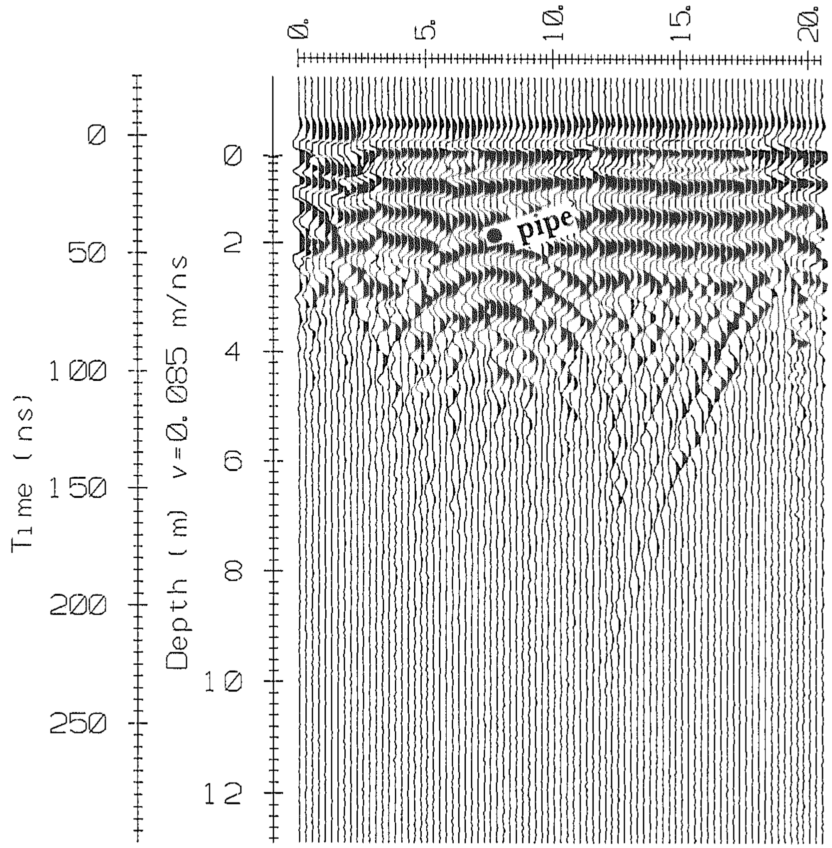
BOSWORTH CREEK SOUTH - CROSS PROFILE 1 - 100 MHz - JULY 26



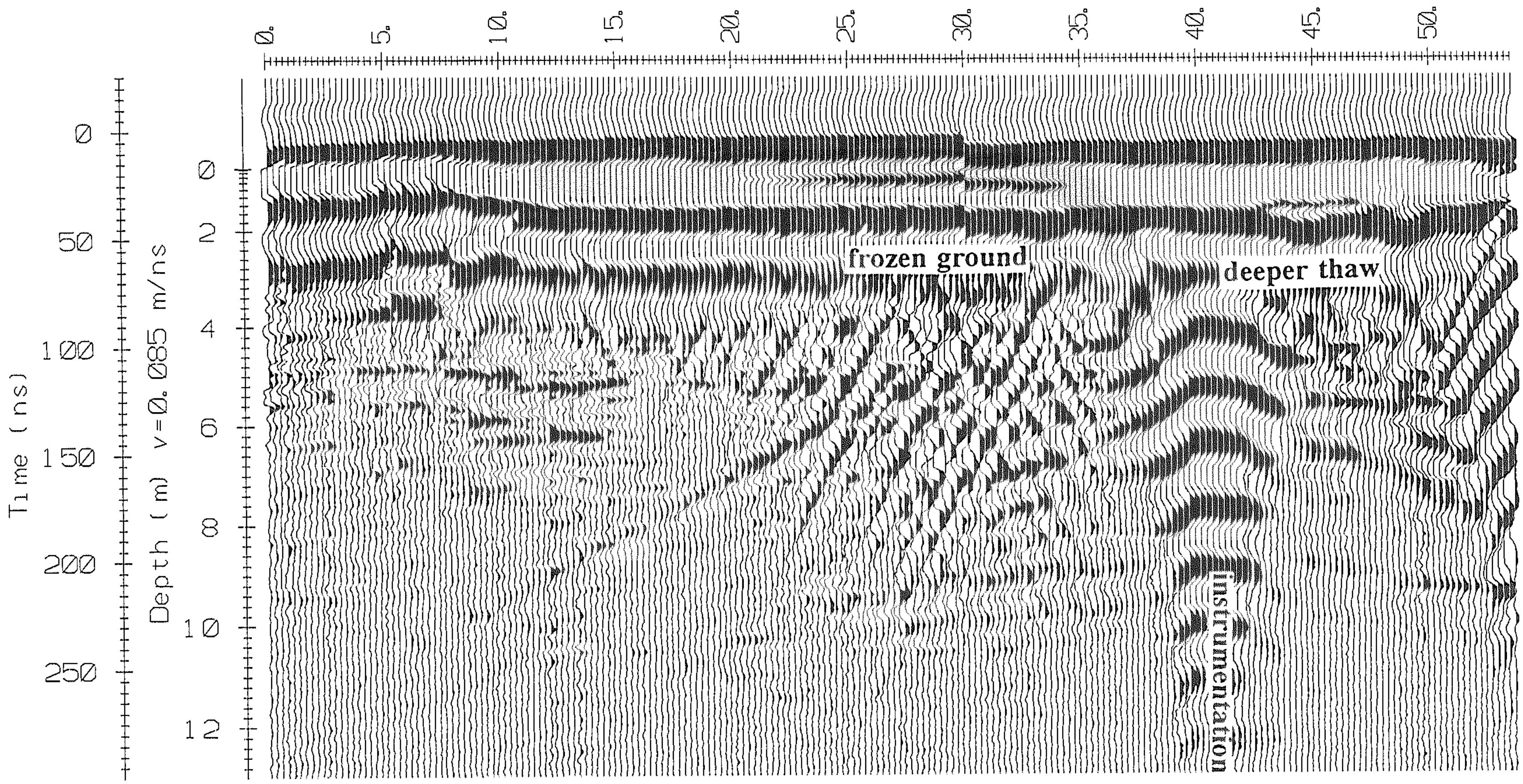
BOSWORTH CREEK SOUTH - CROSS PROFILE 2 - 100 MHz - JULY 26



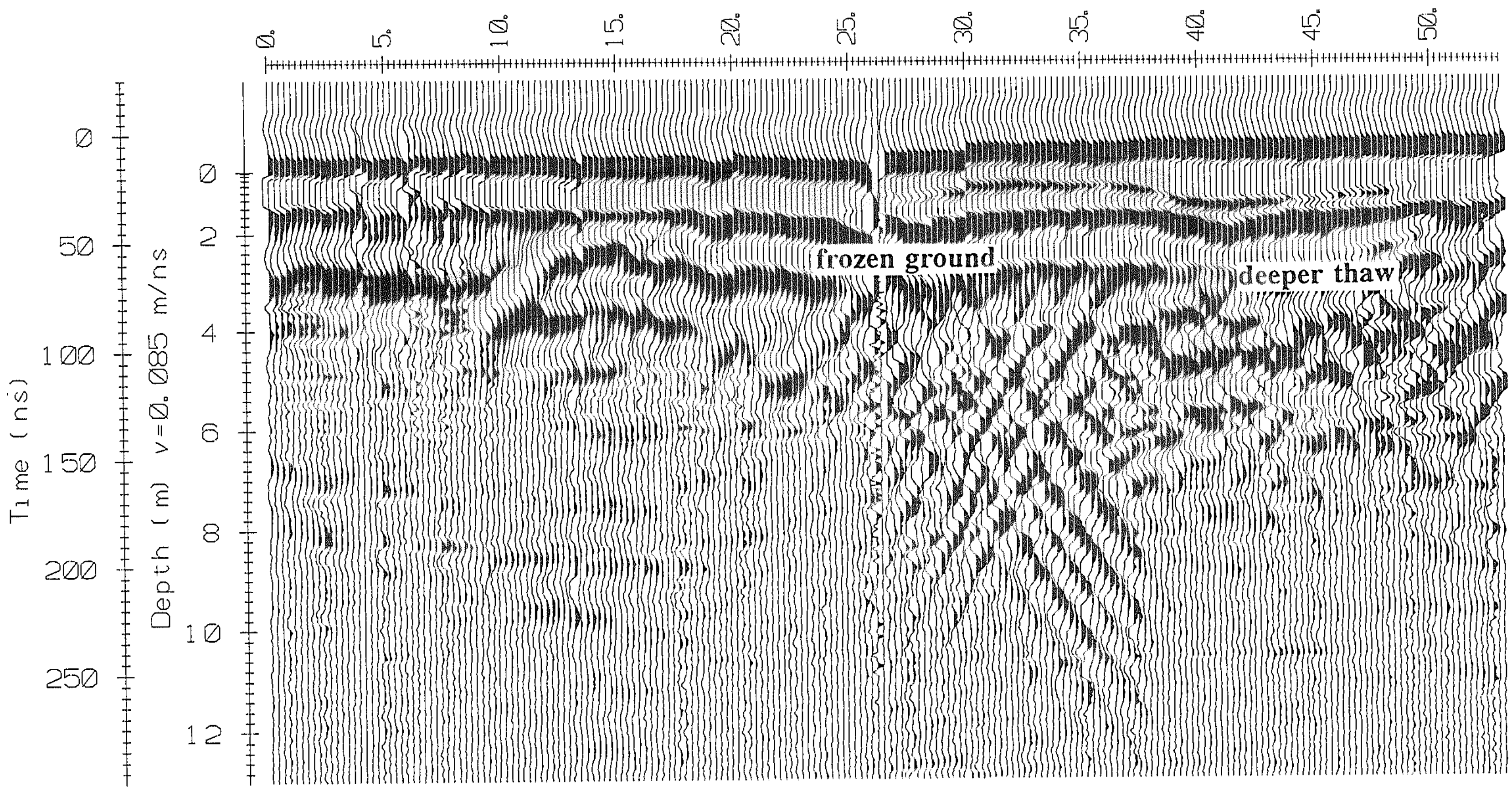
BOSWORTH CREEK SOUTH - CROSS PROFILE 3 - 100 MHz - JULY 26



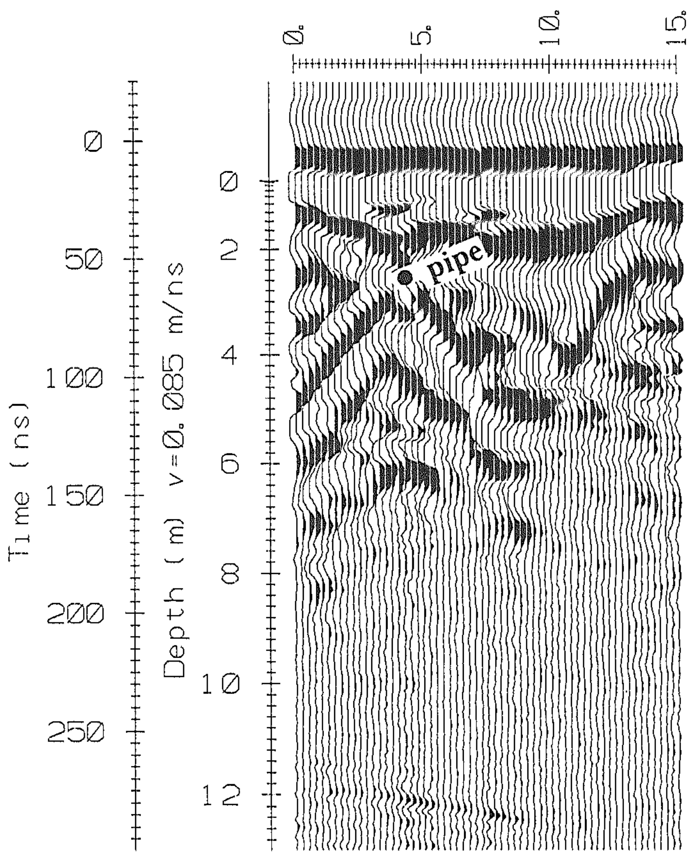
BOSWORTH CREEK SOUTH - CROSS PROFILE 4 - 100 MHz - JULY 26



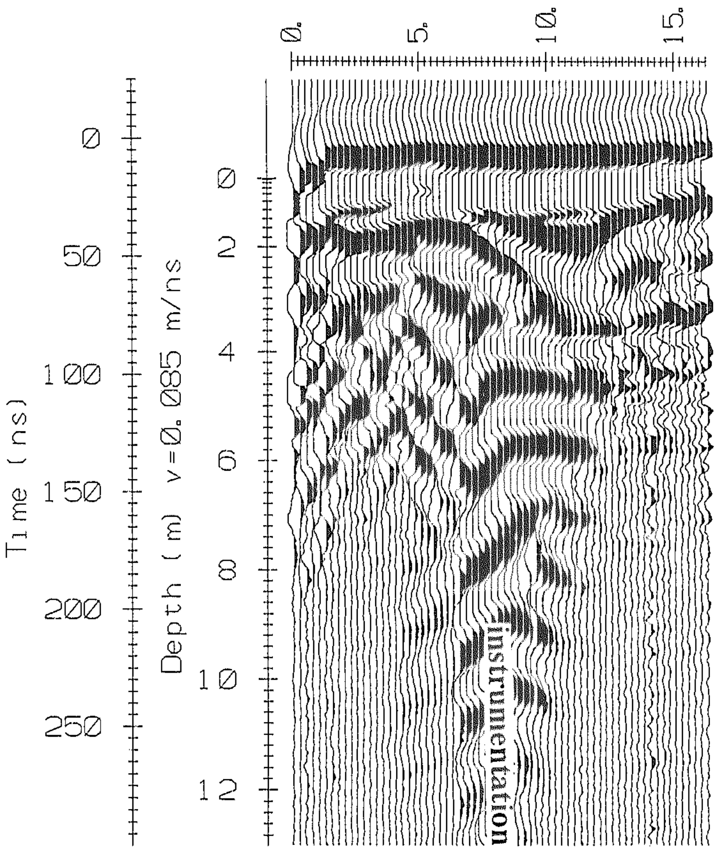
BOSWORTH CREEK SOUTH - LONG PROFILE 1 - 50 MHz - AUGUST 25



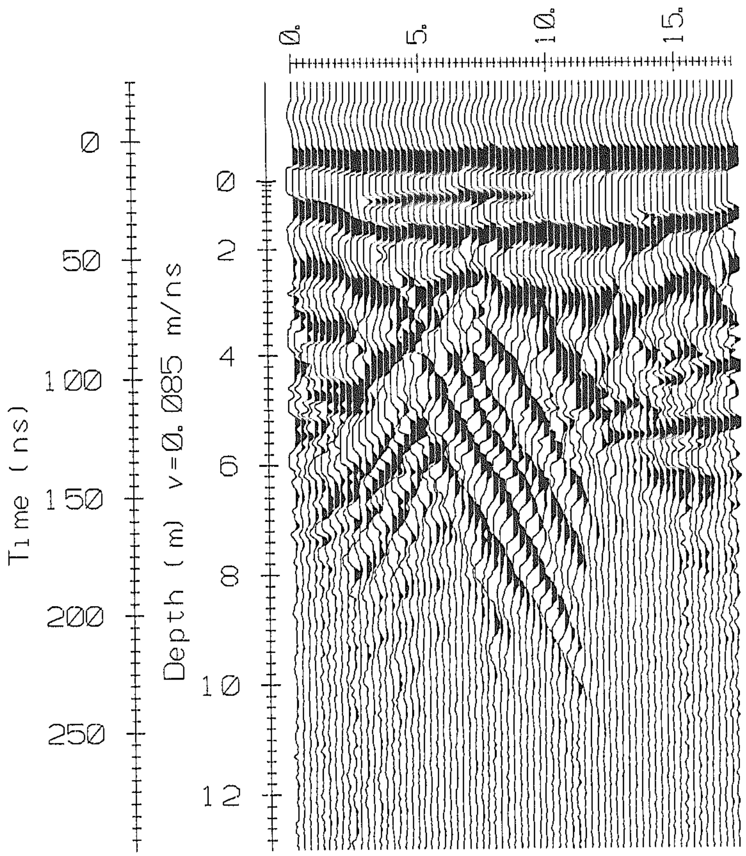
BOSWORTH CREEK SOUTH - LONG PROFILE 2 - 50 MHz - AUGUST 25



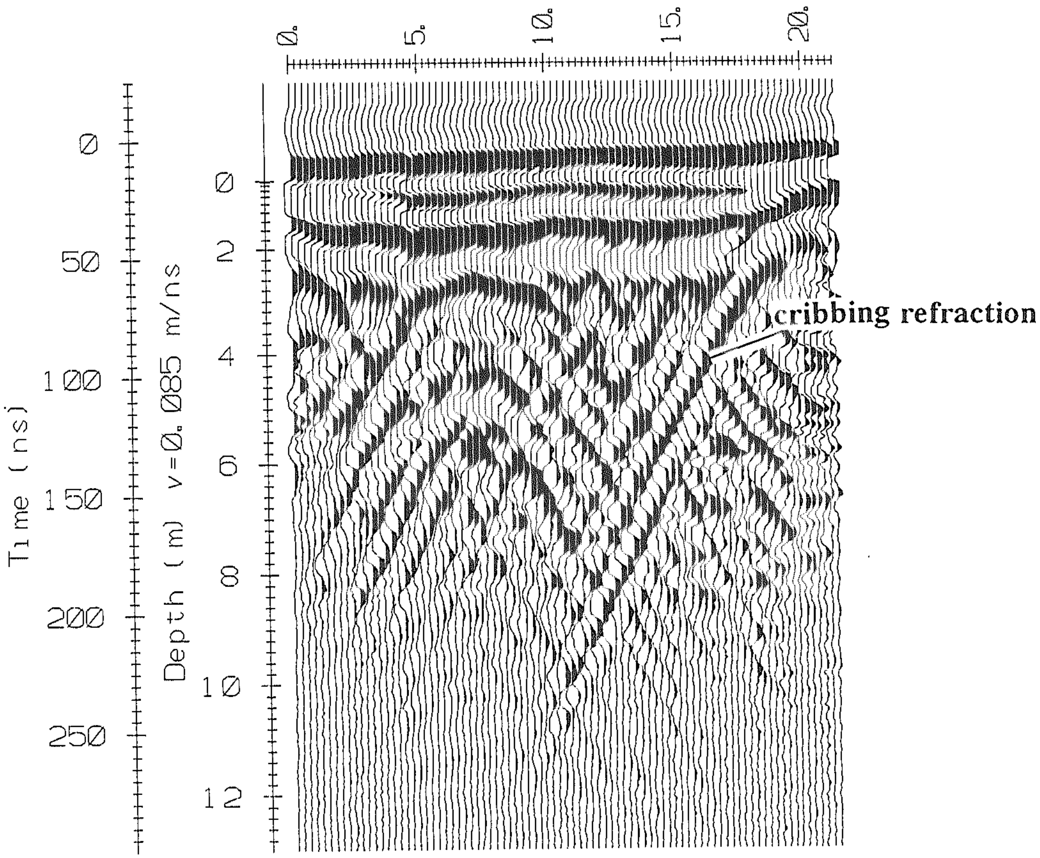
BOSWORTH CREEK SOUTH - CROSS PROFILE 1 - 50 MHz - AUGUST 25



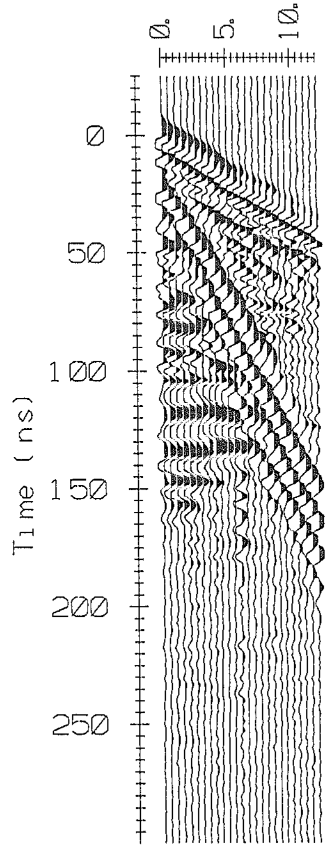
BOSWORTH CREEK SOUTH - CROSS PROFILE 2 - 50 MHz - AUGUST 25



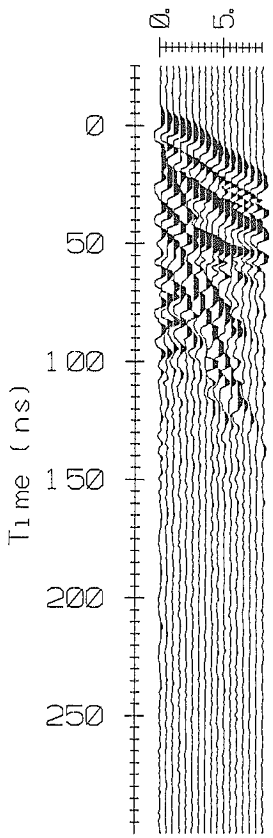
BOSWORTH CREEK SOUTH - CROSS PROFILE 3 - 50 MHz - AUGUST 25



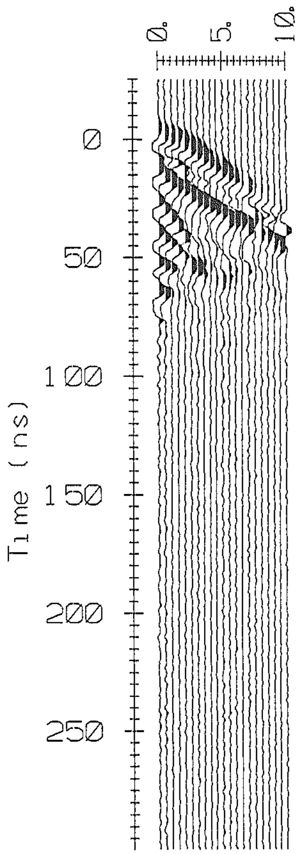
BOSWORTH CREEK SOUTH - CROSS PROFILE 4 - 50 MHz - AUGUST 25



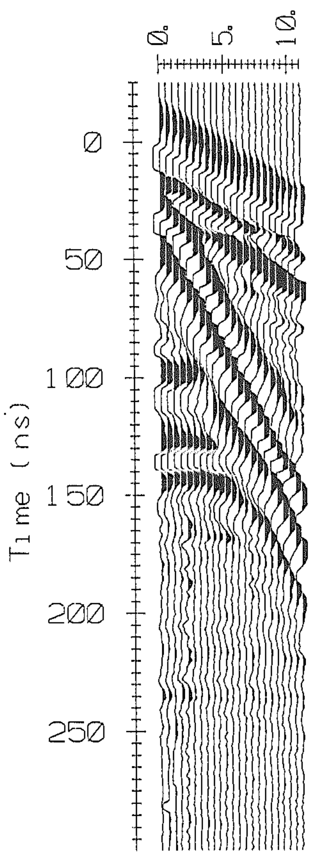
BOSWORTH CREEK SOUTH - CMP - JUNE 2



BOSWORTH CREEK SOUTH - CMP - JUNE 29



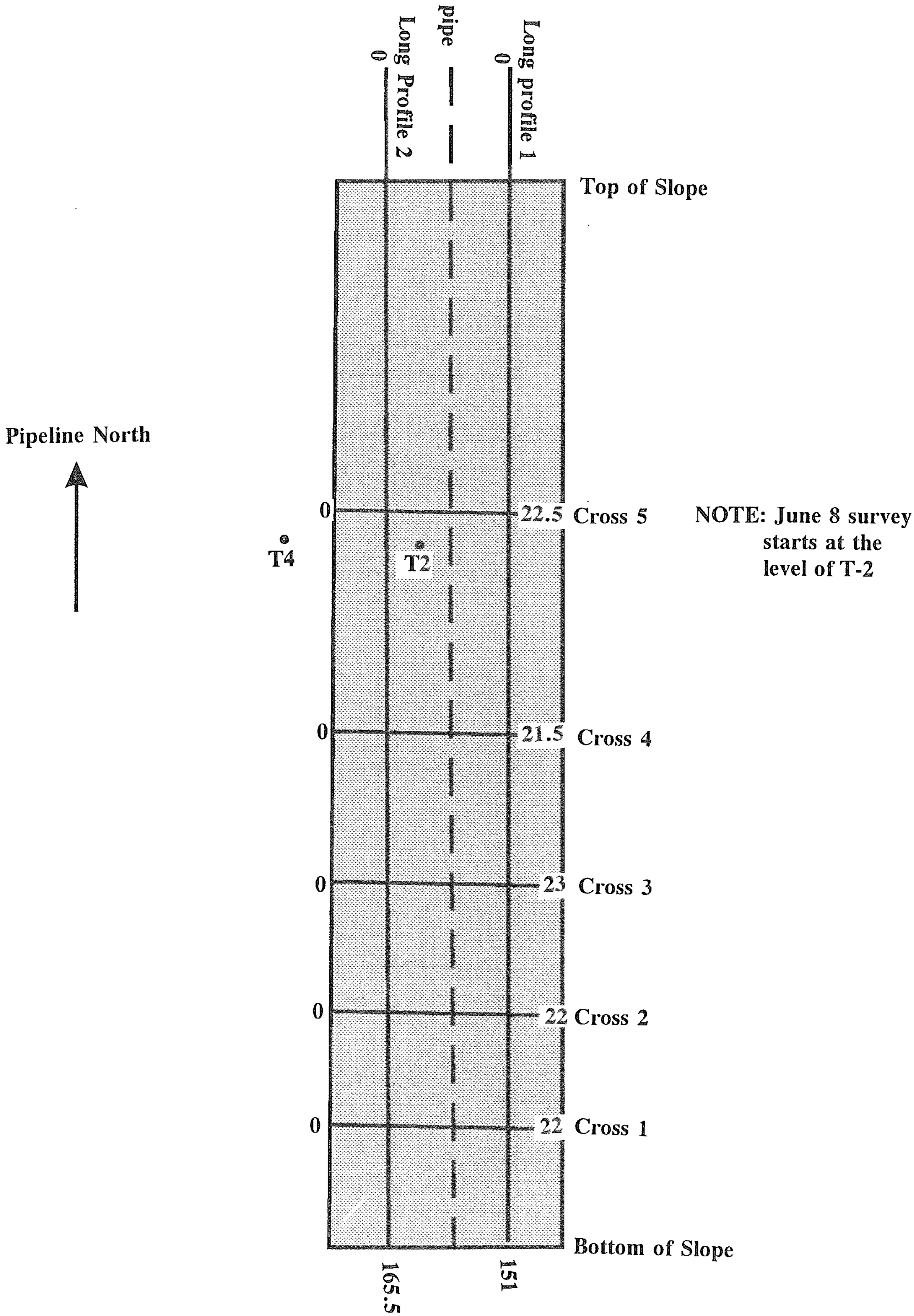
BOSWORTH CREEK SOUTH - CMP - JULY 26



BOSWORTH CREEK SOUTH - CMP - AUGUST 25

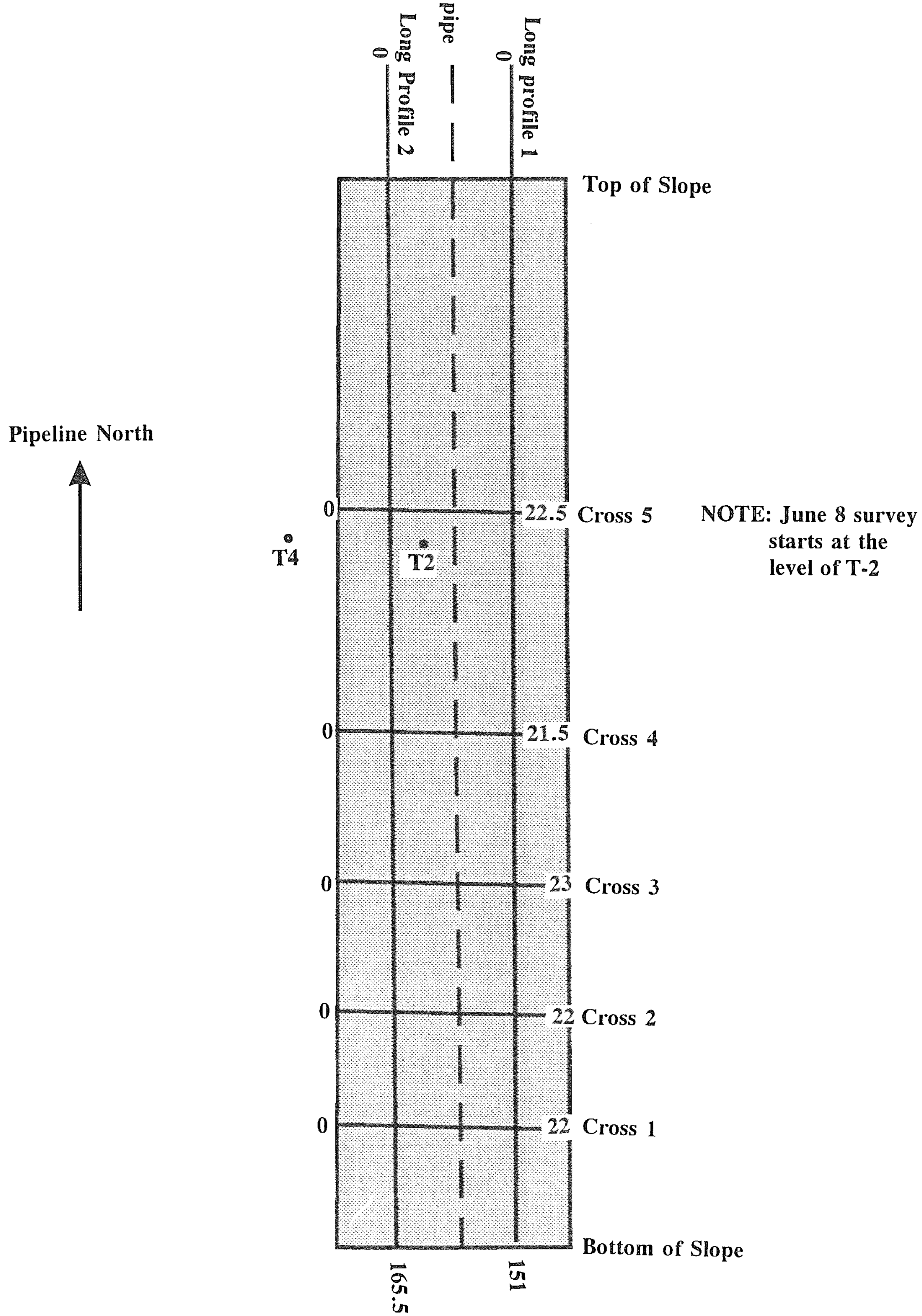
CANYON CREEK NORTH

Not to Scale

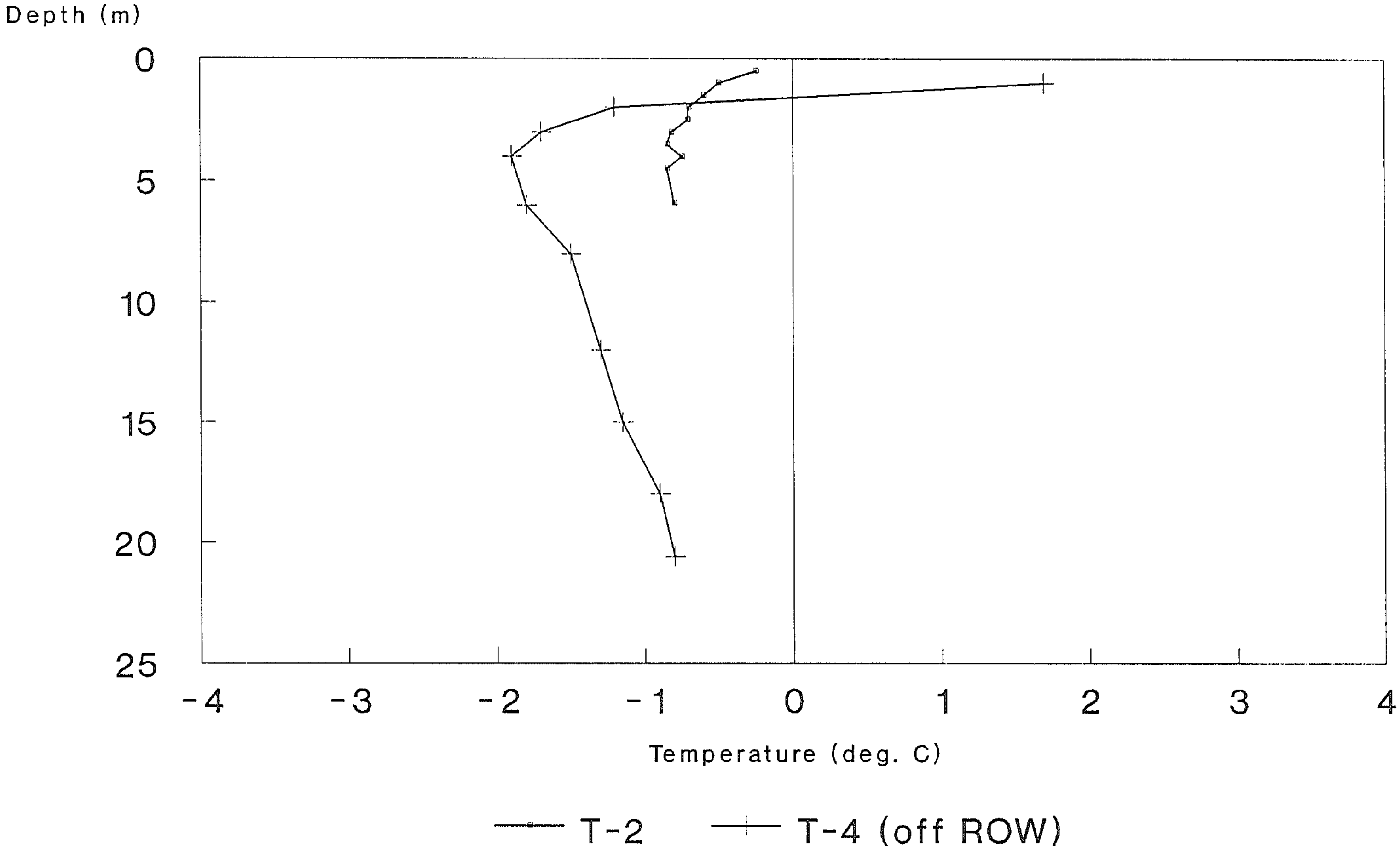


CANYON CREEK NORTH

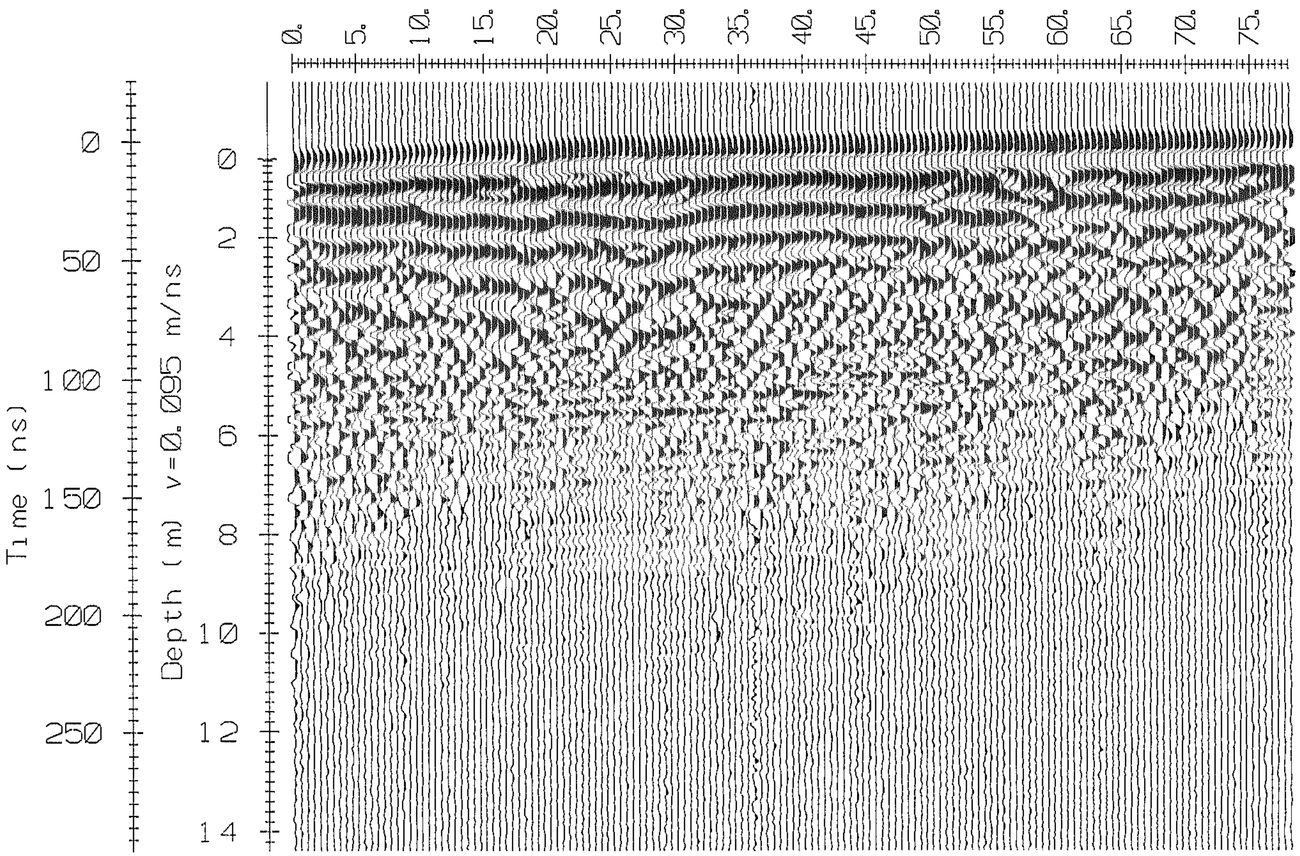
Not to Scale



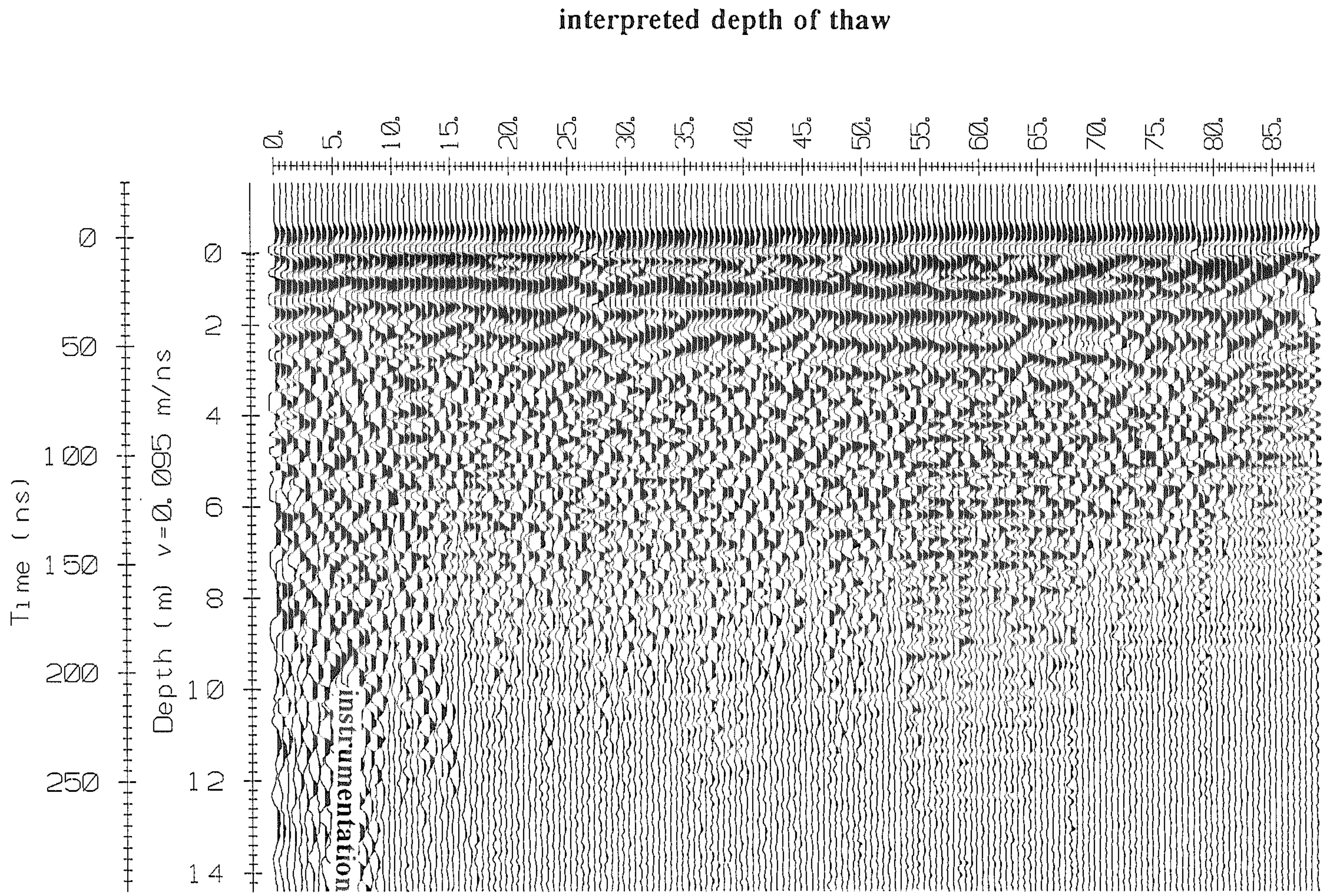
Canyon Creek North
Cables T-2 and T-4
August 5, 1994



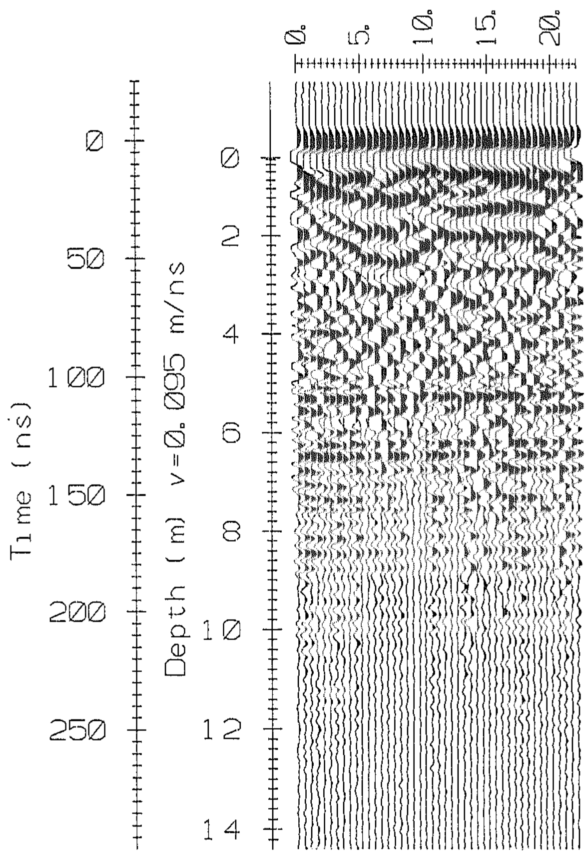
interpreted depth of thaw



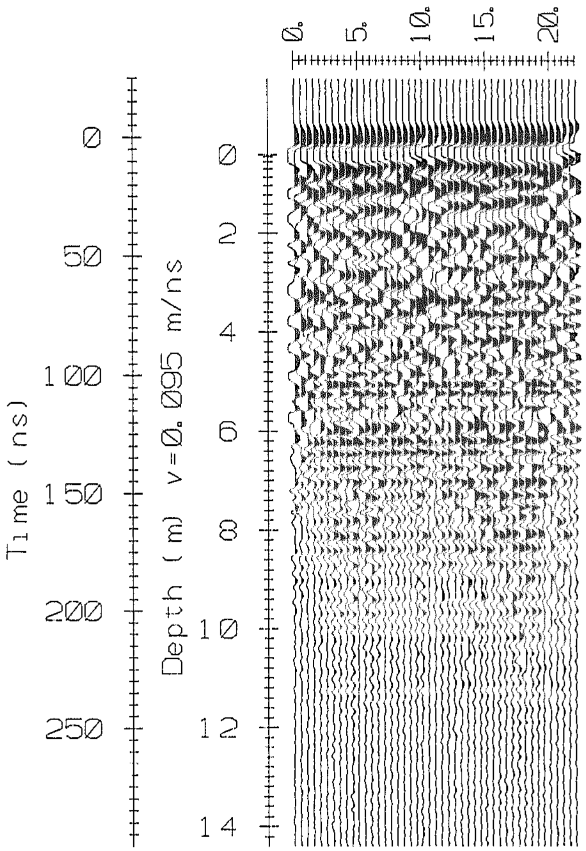
CANYON CREEK NORTH - LONG PROFILE 1 - 100 MHz - JUNE 8



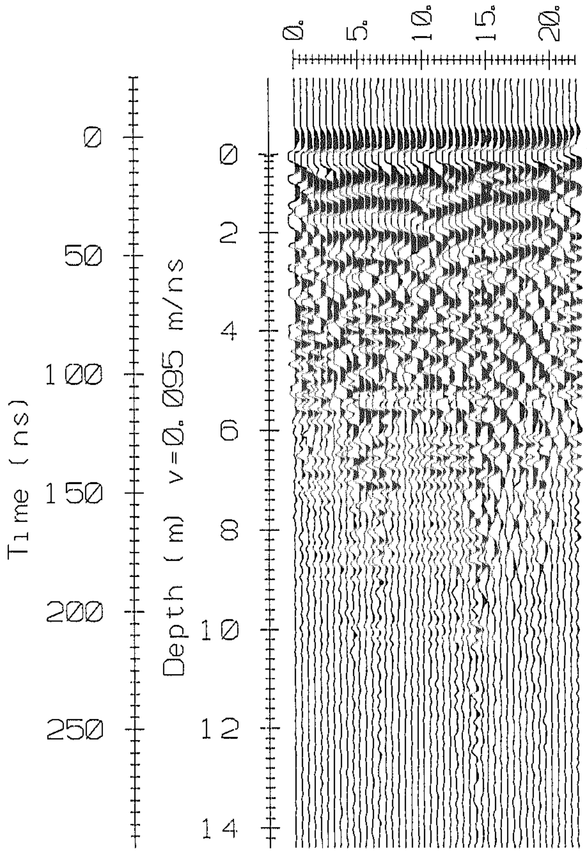
CANYON CREEK NORTH - LONG PROFILE 2 - 100 MHz - JUNE 8



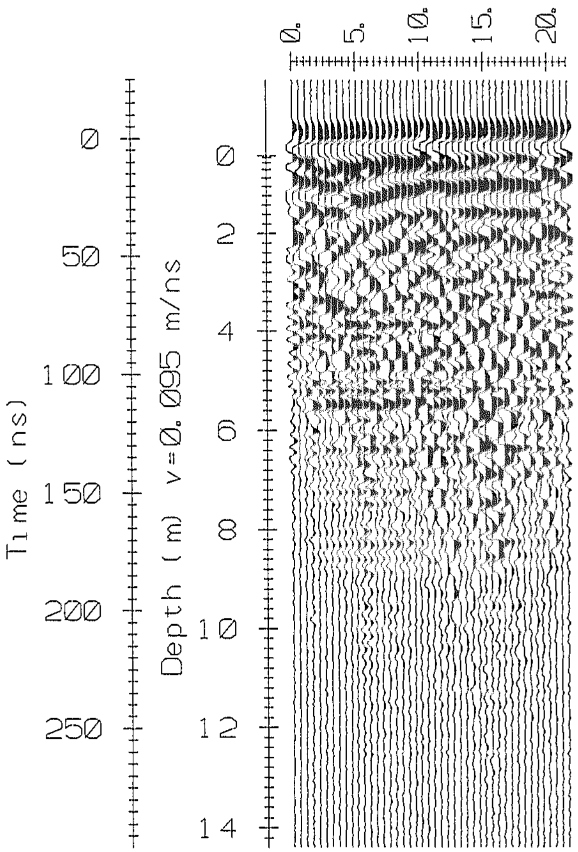
CANYON CREEK NORTH - CROSS PROFILE 1 - 100 MHz - JUNE 8



CANYON CREEK NORTH - CROSS PROFILE 2 - 100 MHz - JUNE 8

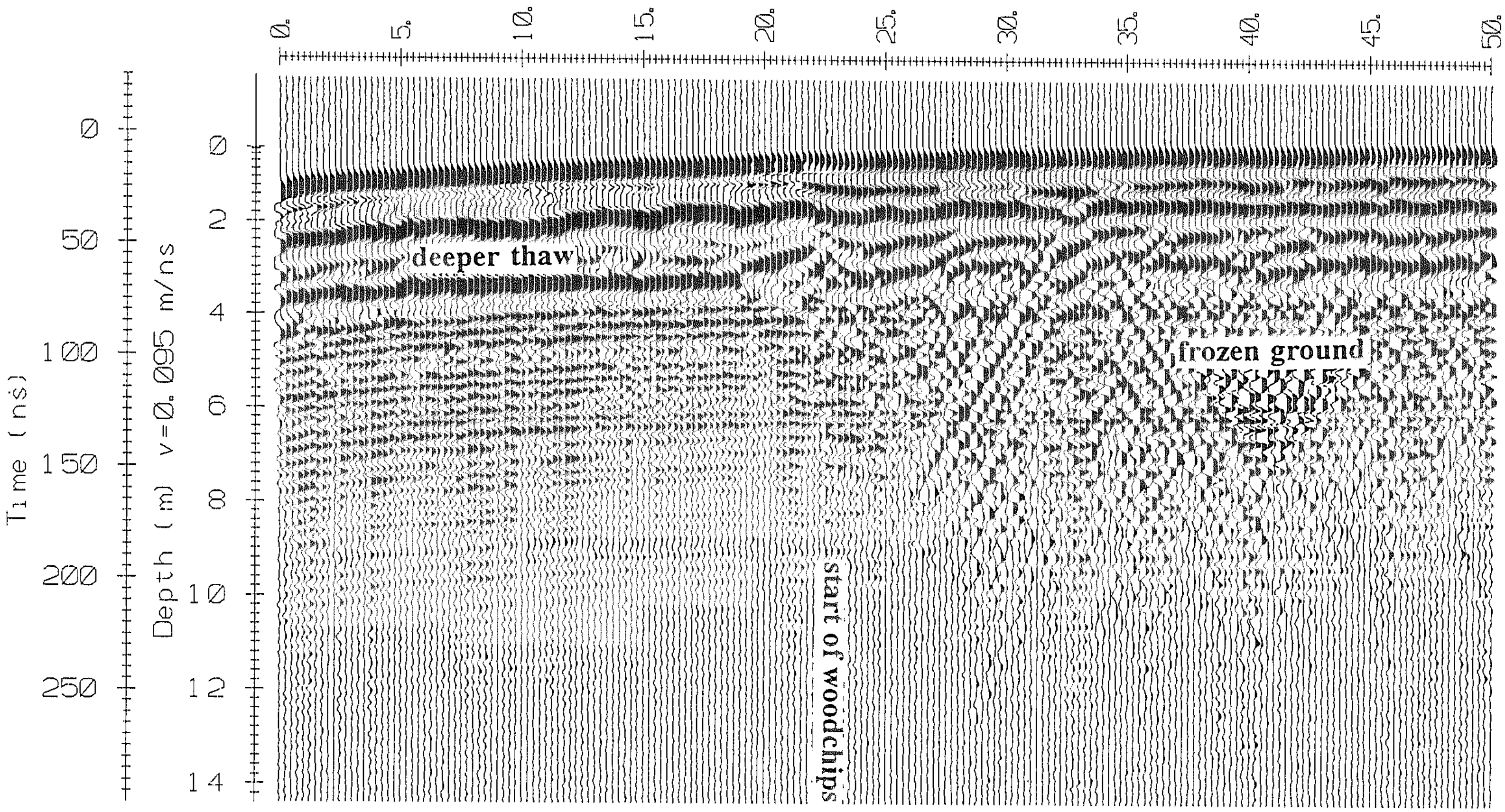


CANYON CREEK NORTH - CROSS PROFILE 3 - 100 MHz - JUNE 8

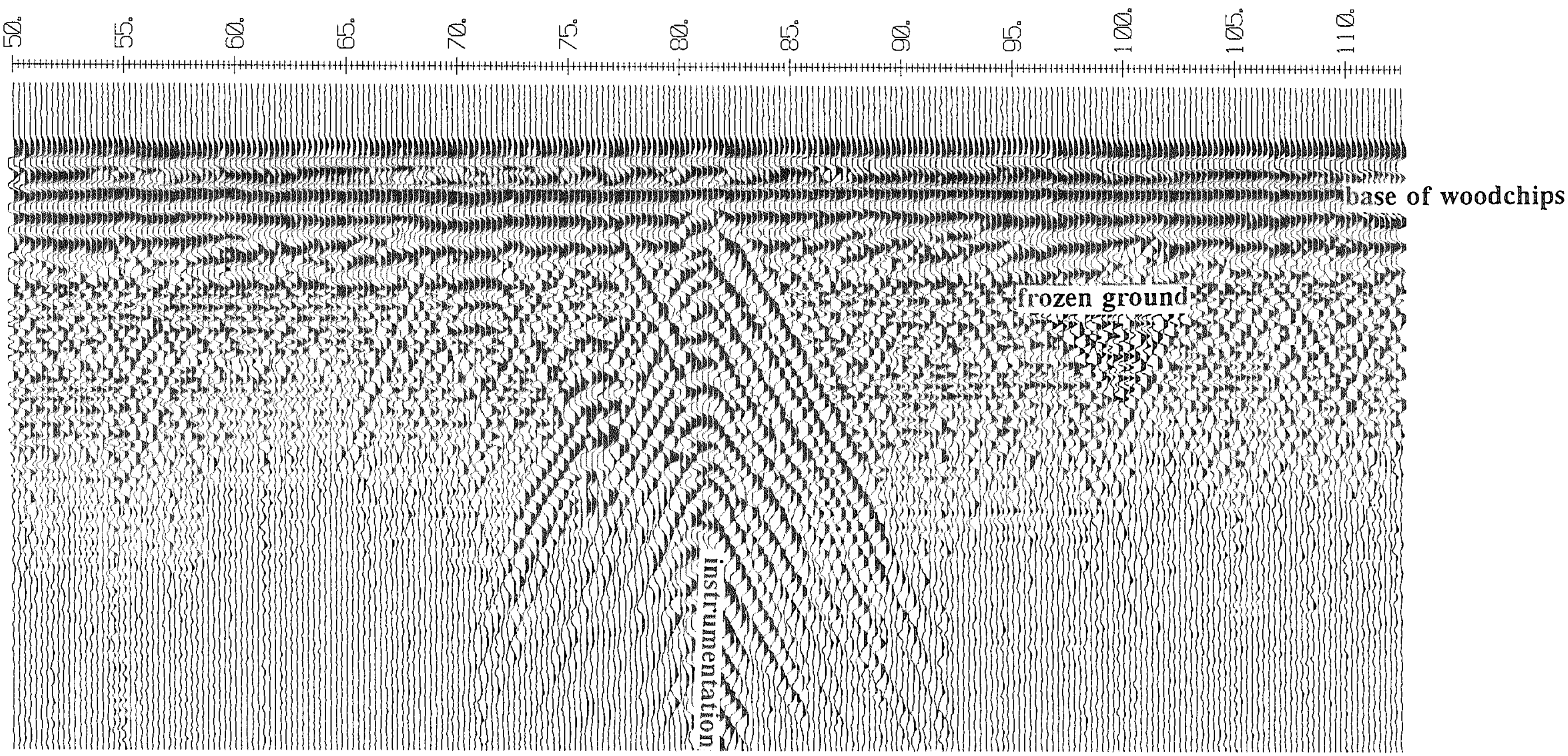


CANYON CREEK NORTH - CROSS PROFILE 4 - 100 MHz - JUNE 8

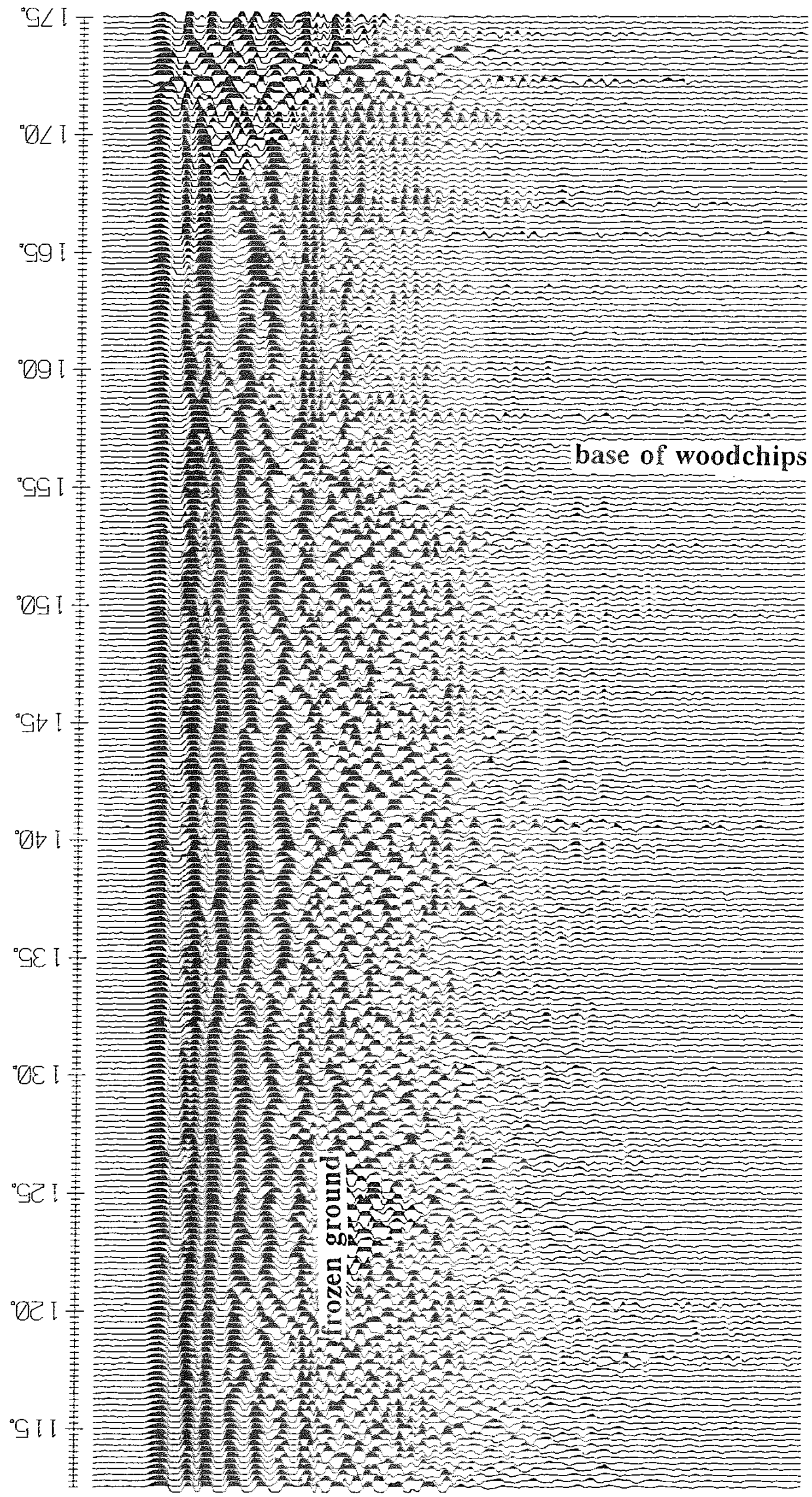
interpreted depth of thaw



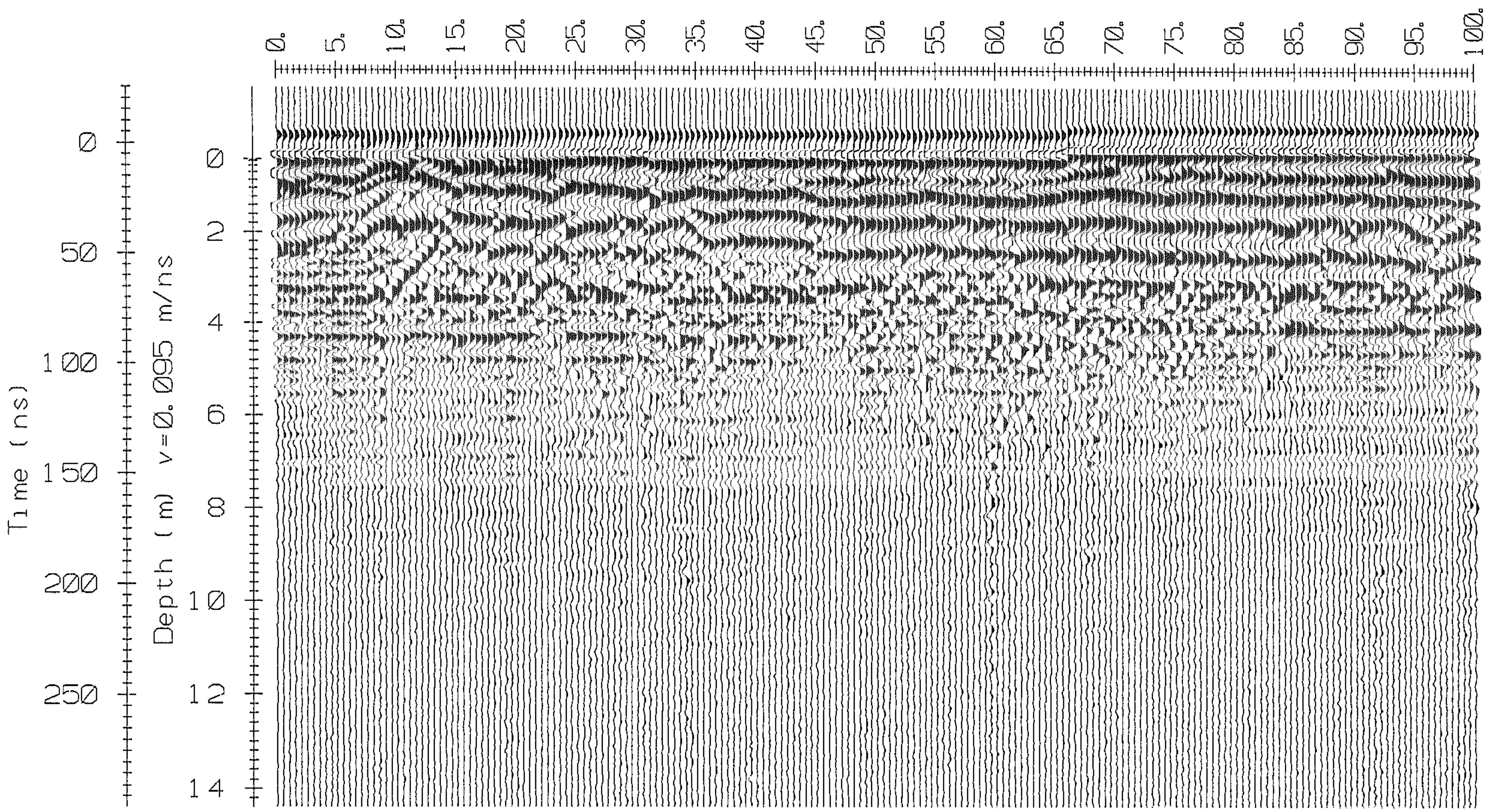
CANYON CREEK NORTH - LONG PROFILE 2 - 100 MHz - JUNE 21



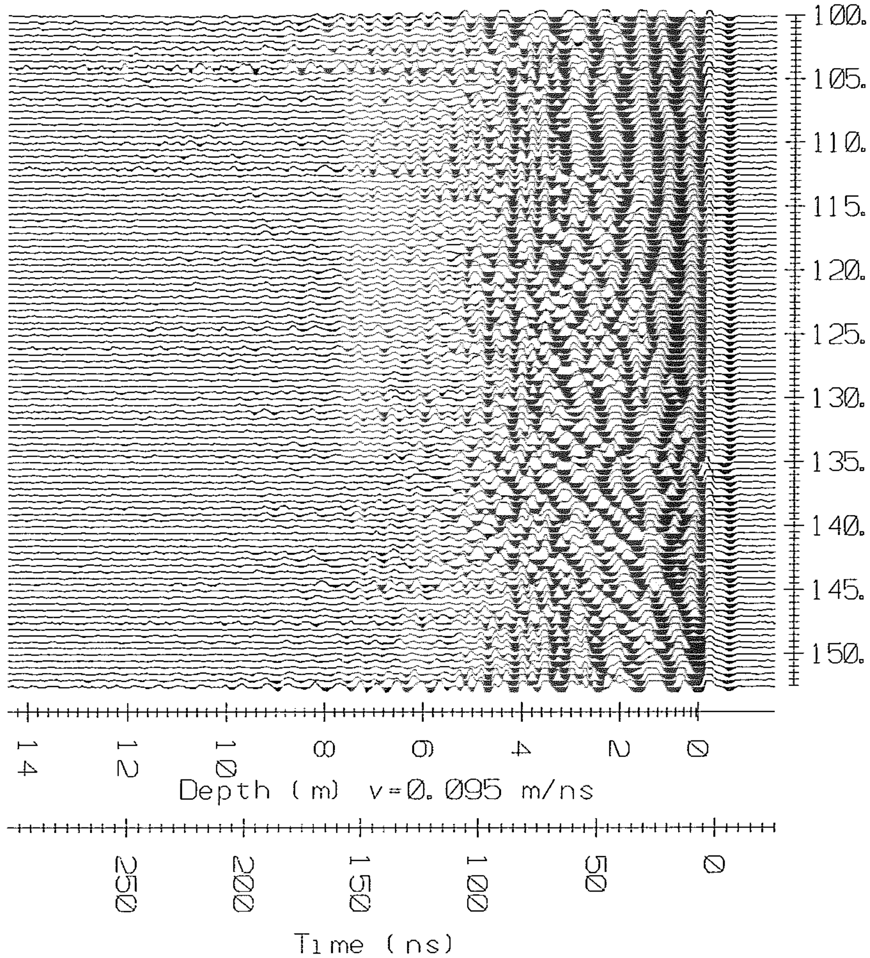
50.
55.
60.
65.
70.
75.
80.
85.
90.
95.
100.
105.
110.
base of woodchips
frozen ground
instrumentation


175.
170.
165.
160.
155.
150.
145.
140.
135.
130.
125.
120.
115.
base of woodchips
frozen ground

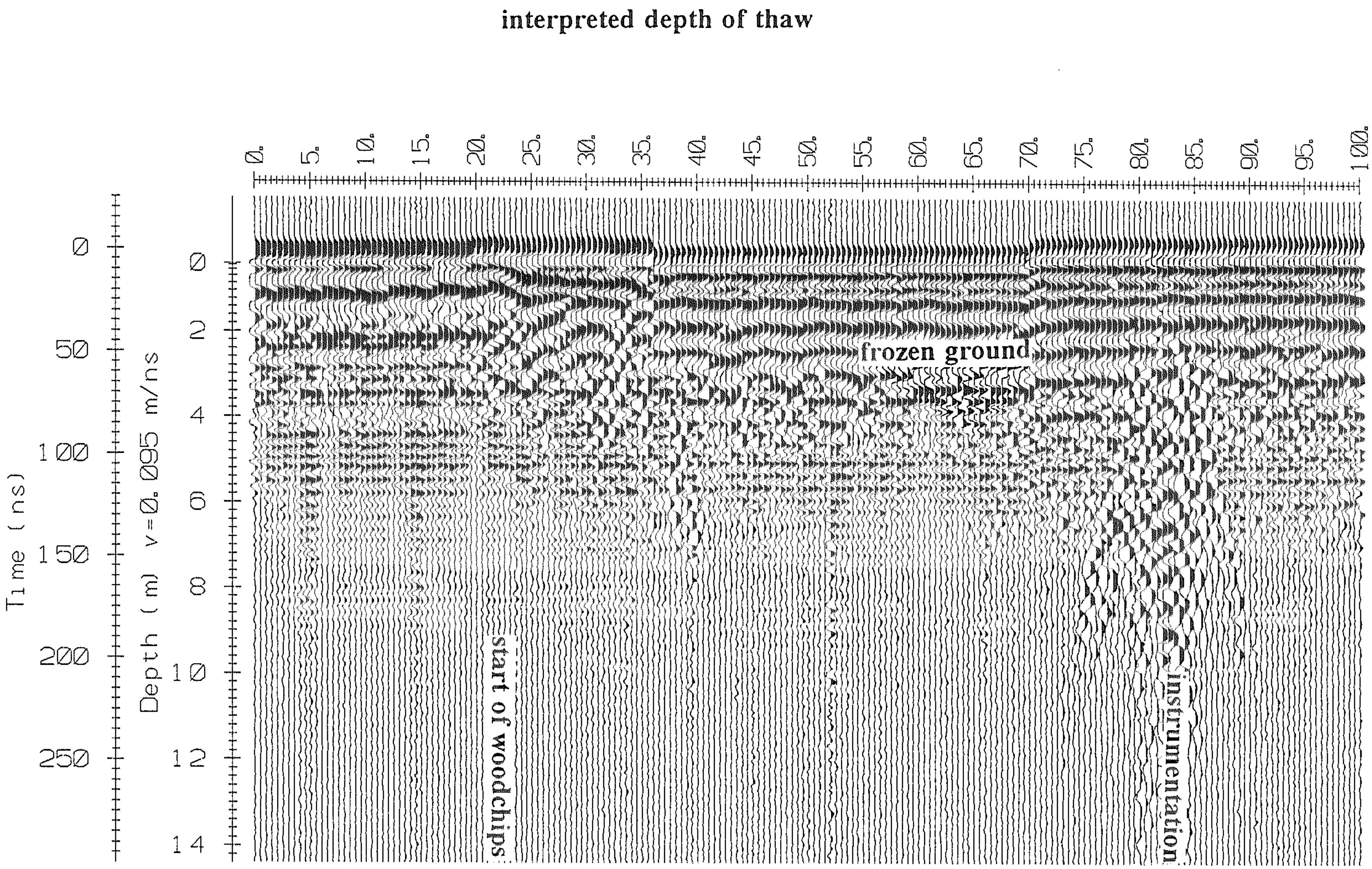
interpreted depth of thaw



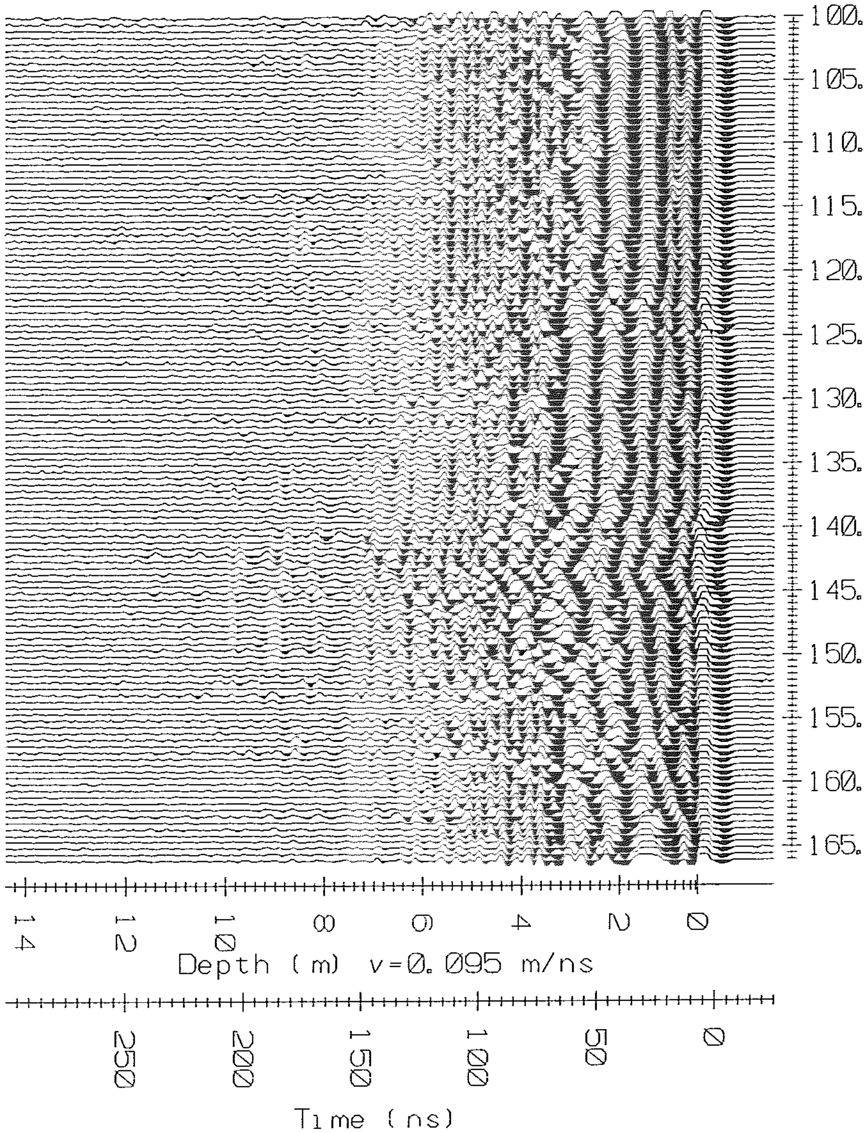
CANYON CREEK NORTH - LONG PROFILE 1 - 100 MHz - AUGUST 9

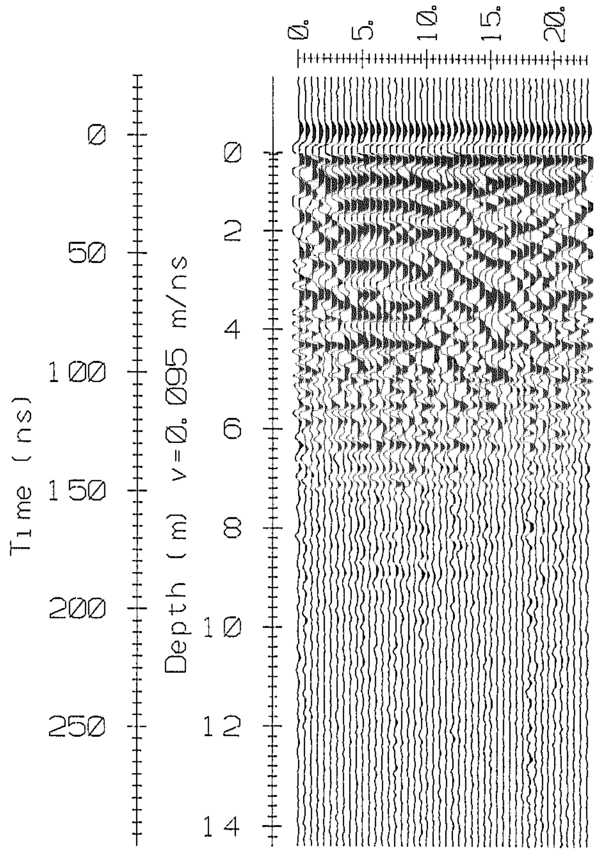


100.
105.
110.
115.
120.
125.
130.
135.
140.
145.
150.
14
12
10
8
6
4
2
0
Depth (m) v=0.095 m/ns
250
200
150
100
50
0
Time (ns)

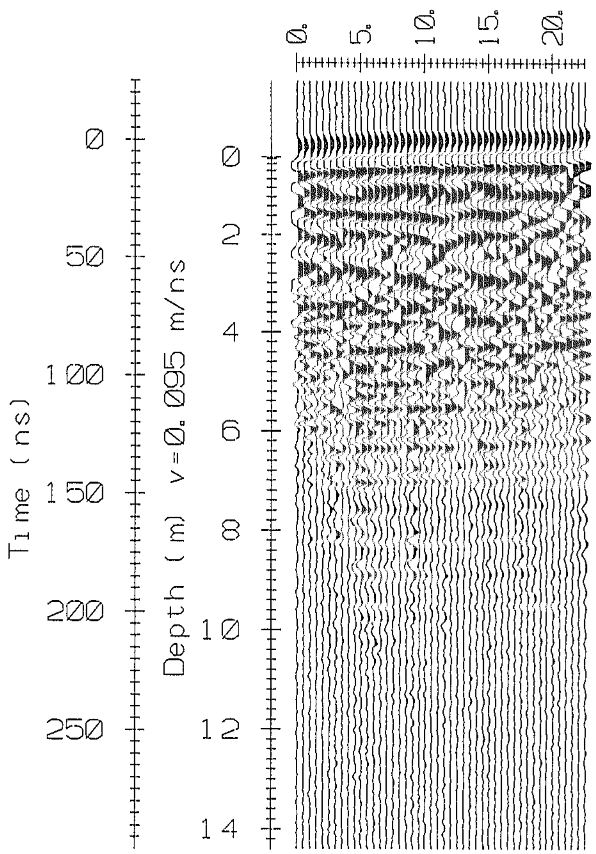


CANYON CREEK NORTH - LONG PROFILE 2 - 100 MHz - AUGUST 9

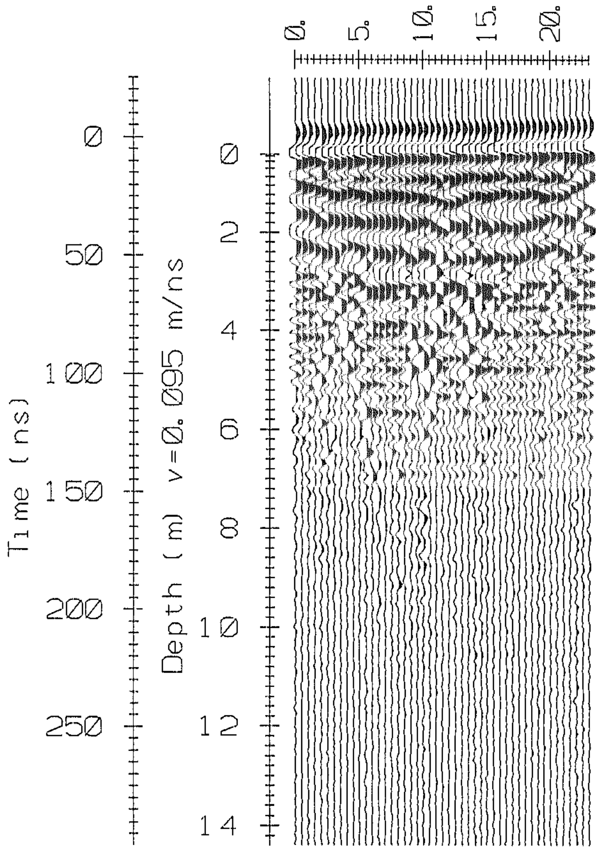

100. 105. 110. 115. 120. 125. 130. 135. 140. 145. 150. 155. 160. 165.
14 12 10 8 6 4 2 0
Depth (m) v=0.095 m/ns
250 200 150 100 50 0
Time (ns)



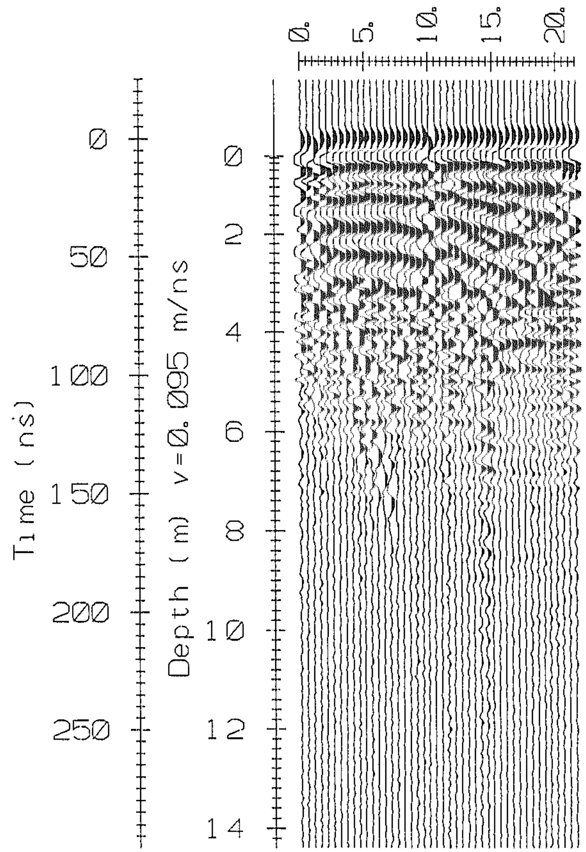
CANYON CREEK NORTH - CROSS PROFILE 1 - 100 MHz - AUGUST 9



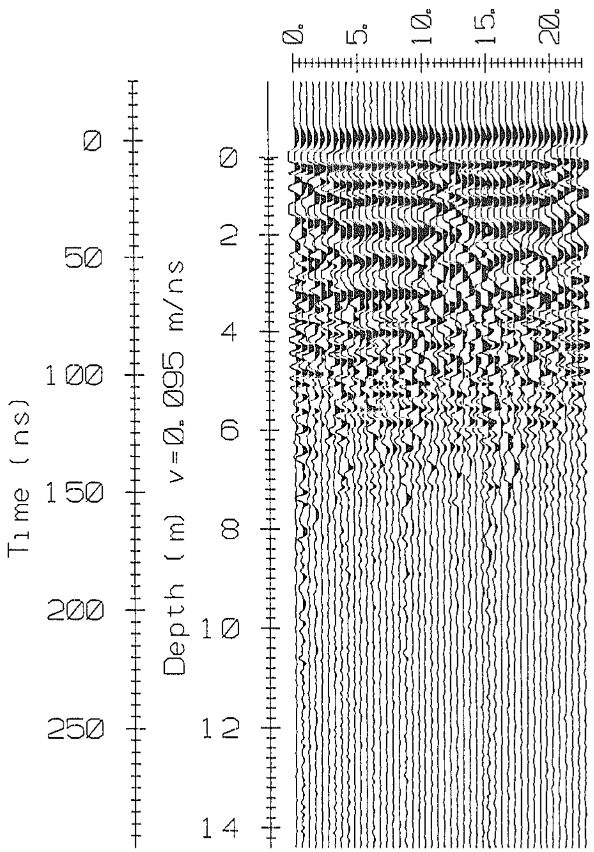
CANYON CREEK NORTH - CROSS PROFILE 2 - 100 MHz - AUGUST 9



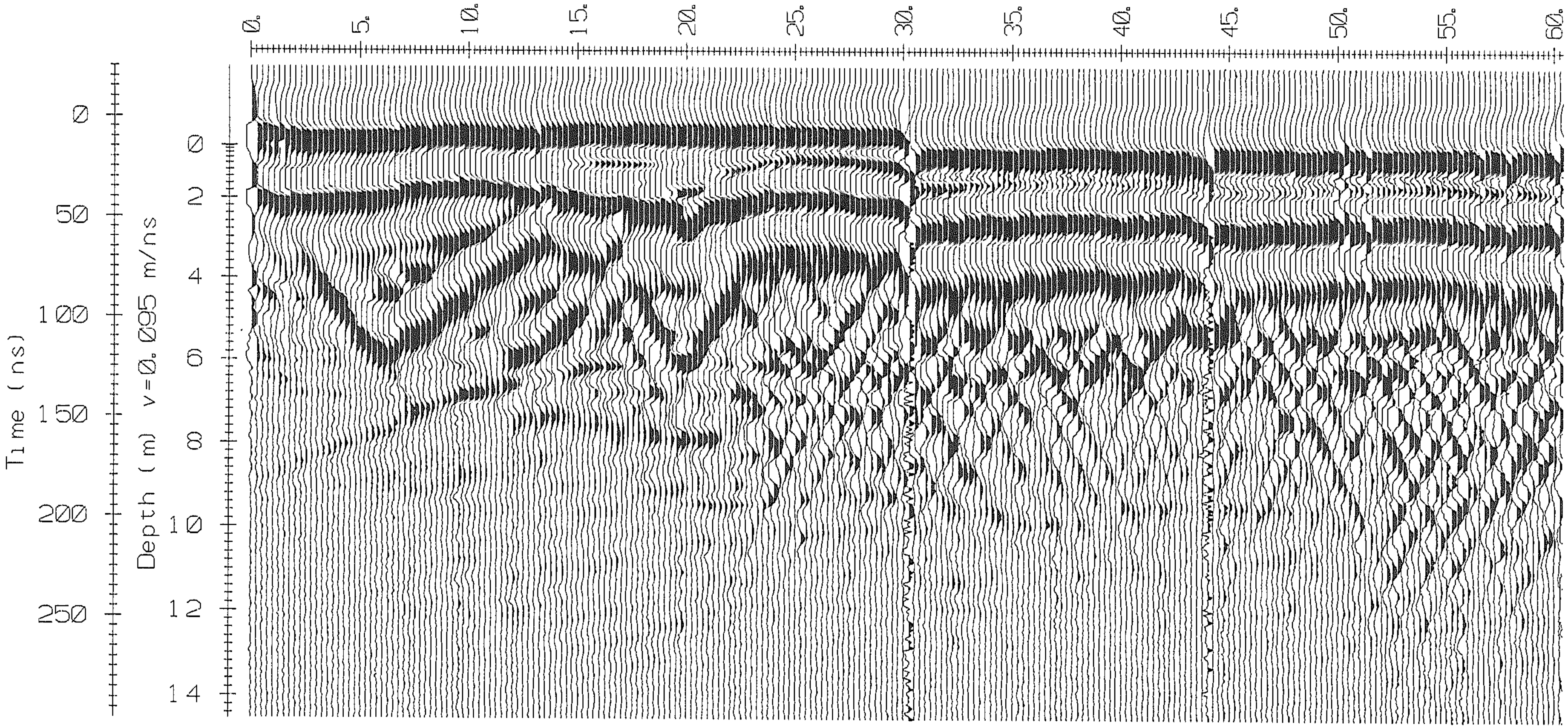
CANYON CREEK NORTH - CROSS PROFILE 3 - 100 MHz - AUGUST 9



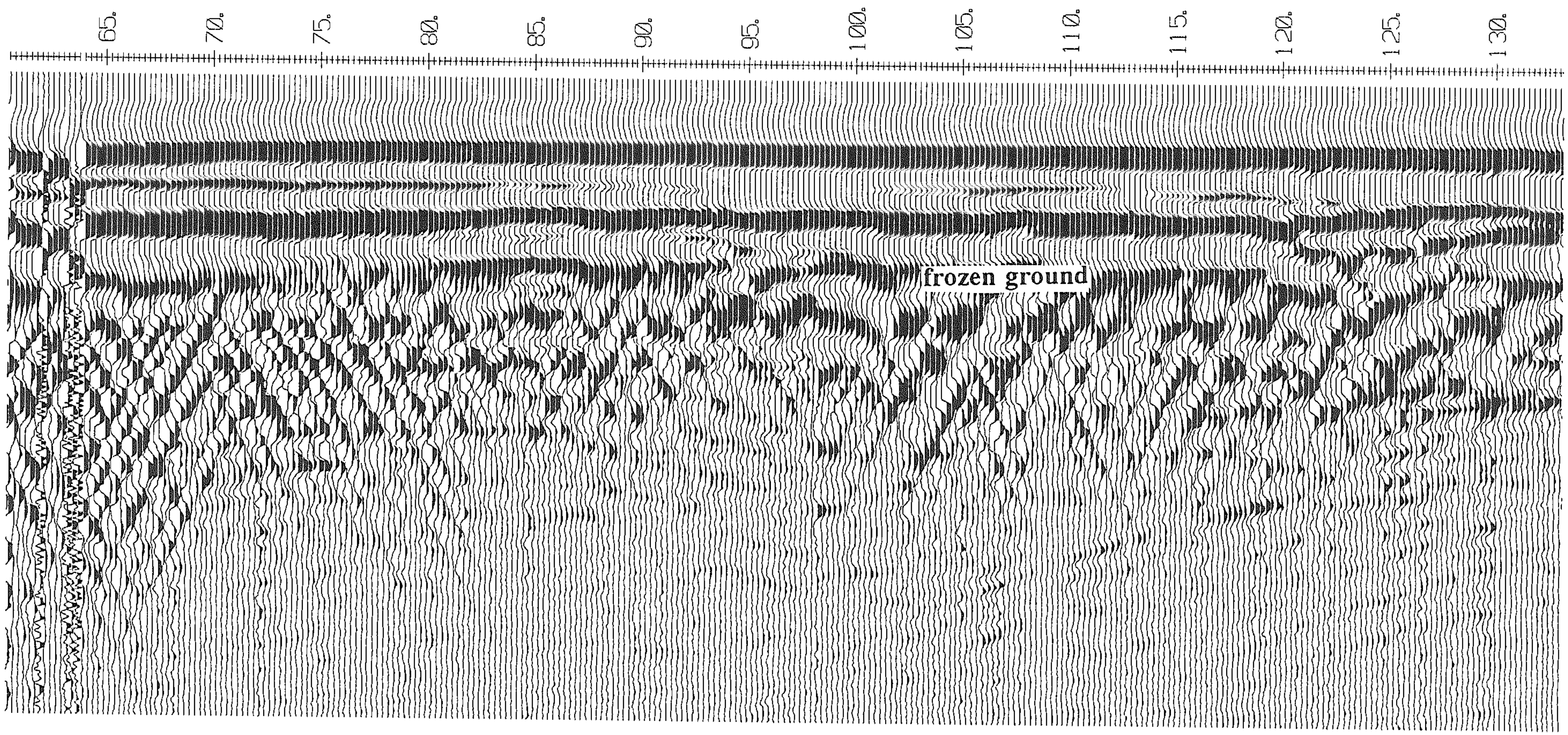
CANYON CREEK NORTH - CROSS PROFILE 4 - 100 MHz - AUGUST 9

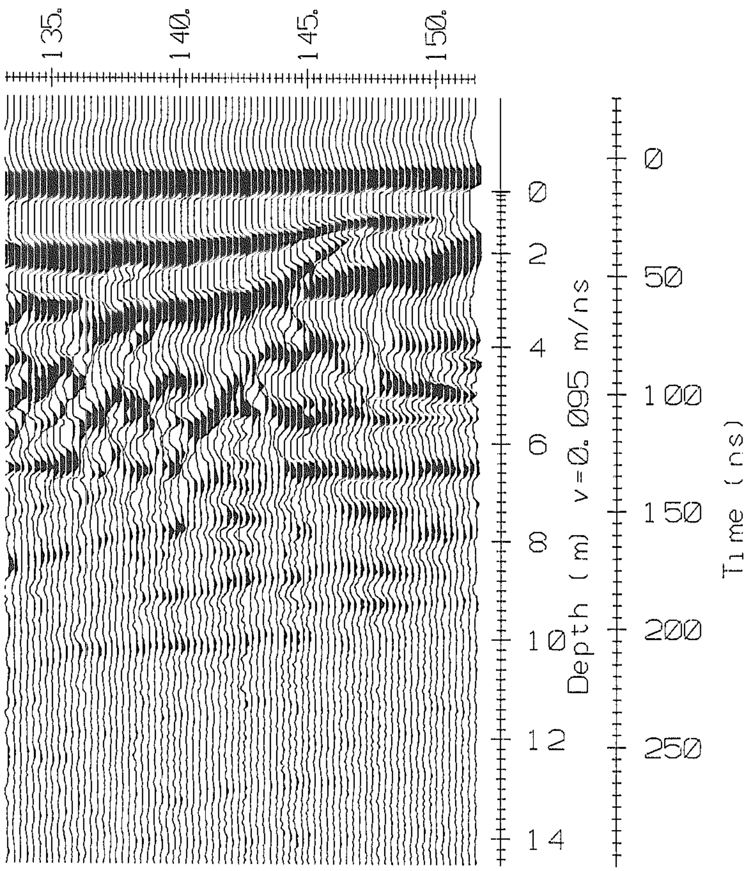


CANYON CREEK NORTH - CROSS PROFILE 5 - 100 MHz - AUGUST 9

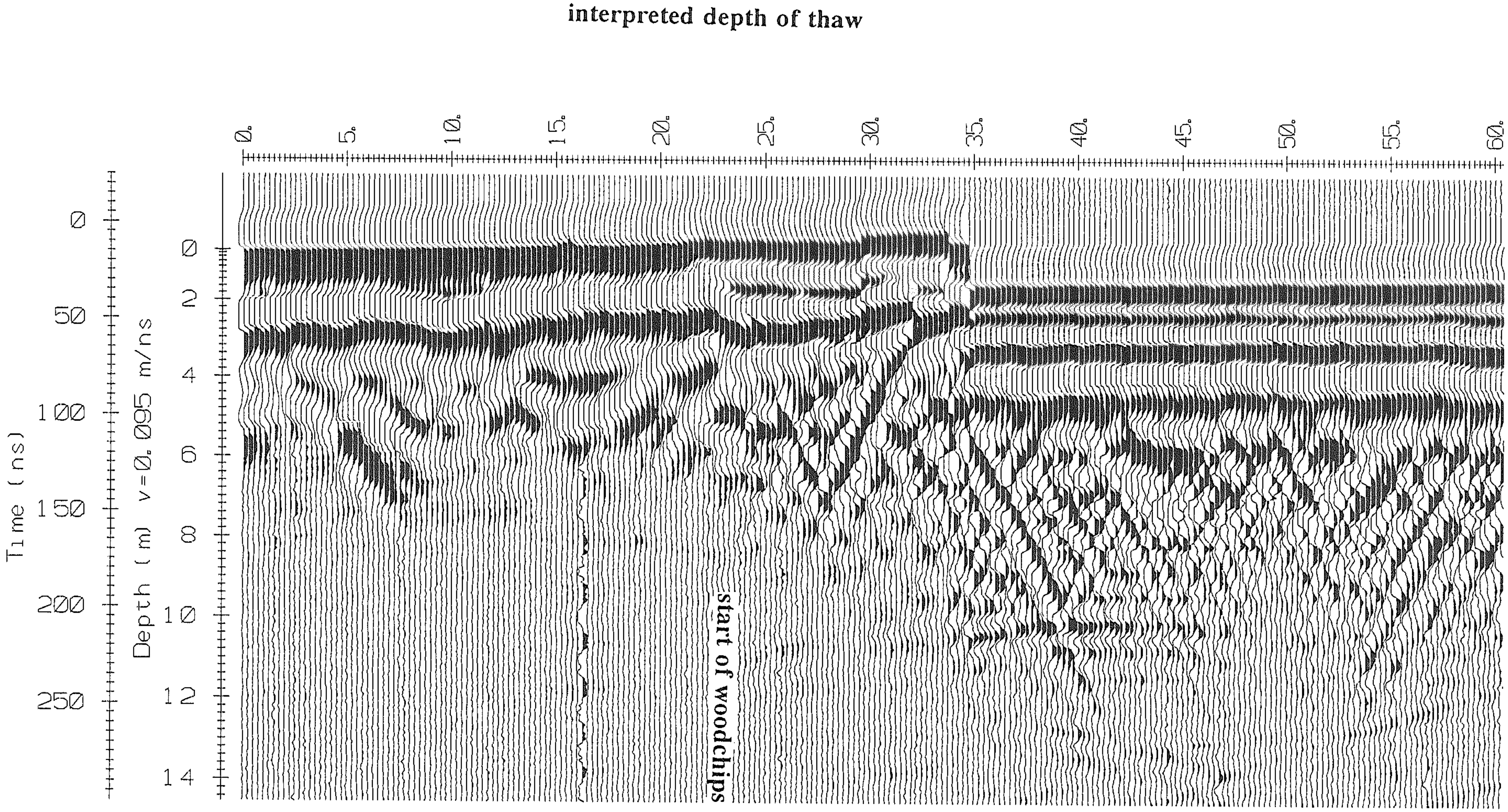


CANYON CREEK NORTH - LONG PROFILE 1 - 50 MHz - AUGUST 5

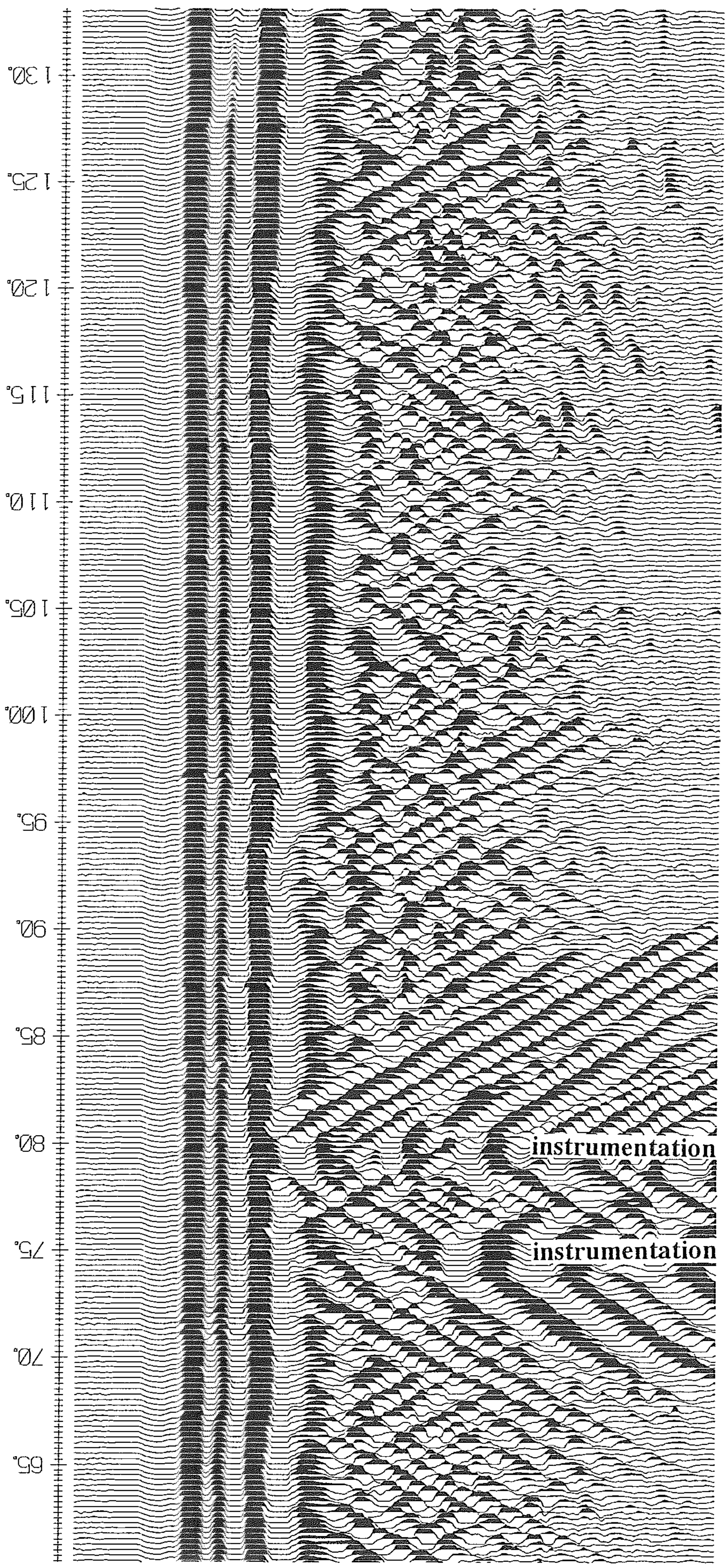

65.
70.
75.
80.
85.
90.
95.
100.
105.
110.
115.
120.
125.
130.
frozen ground

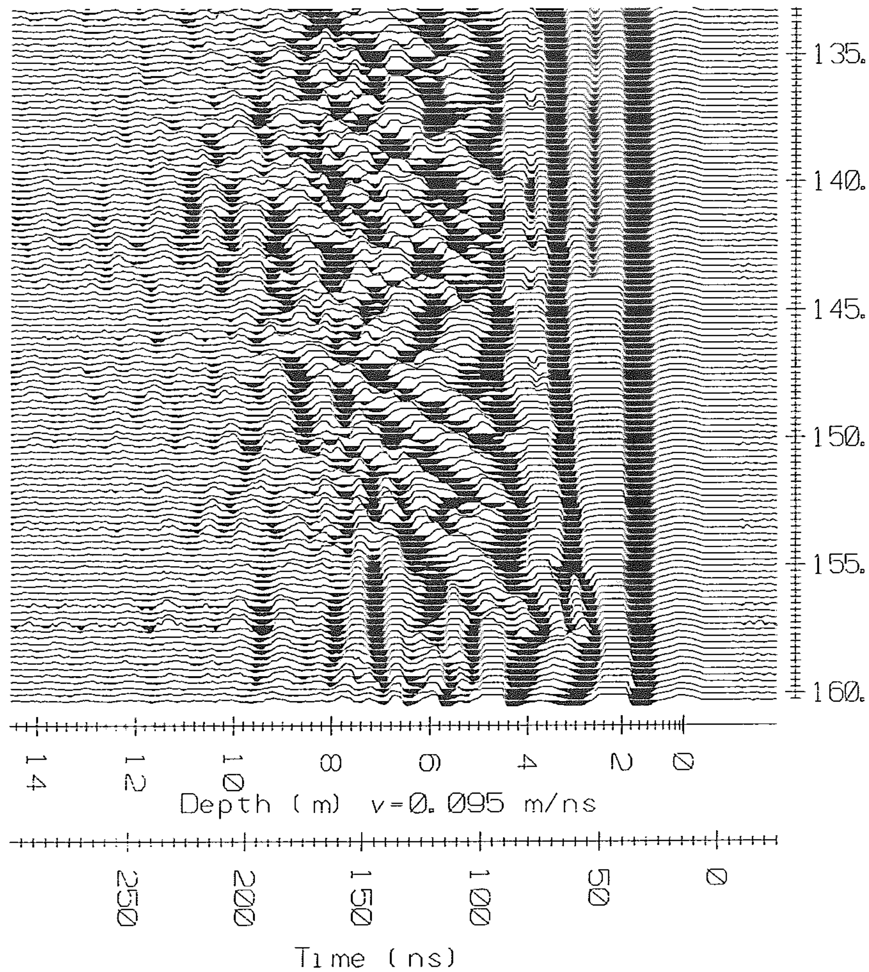


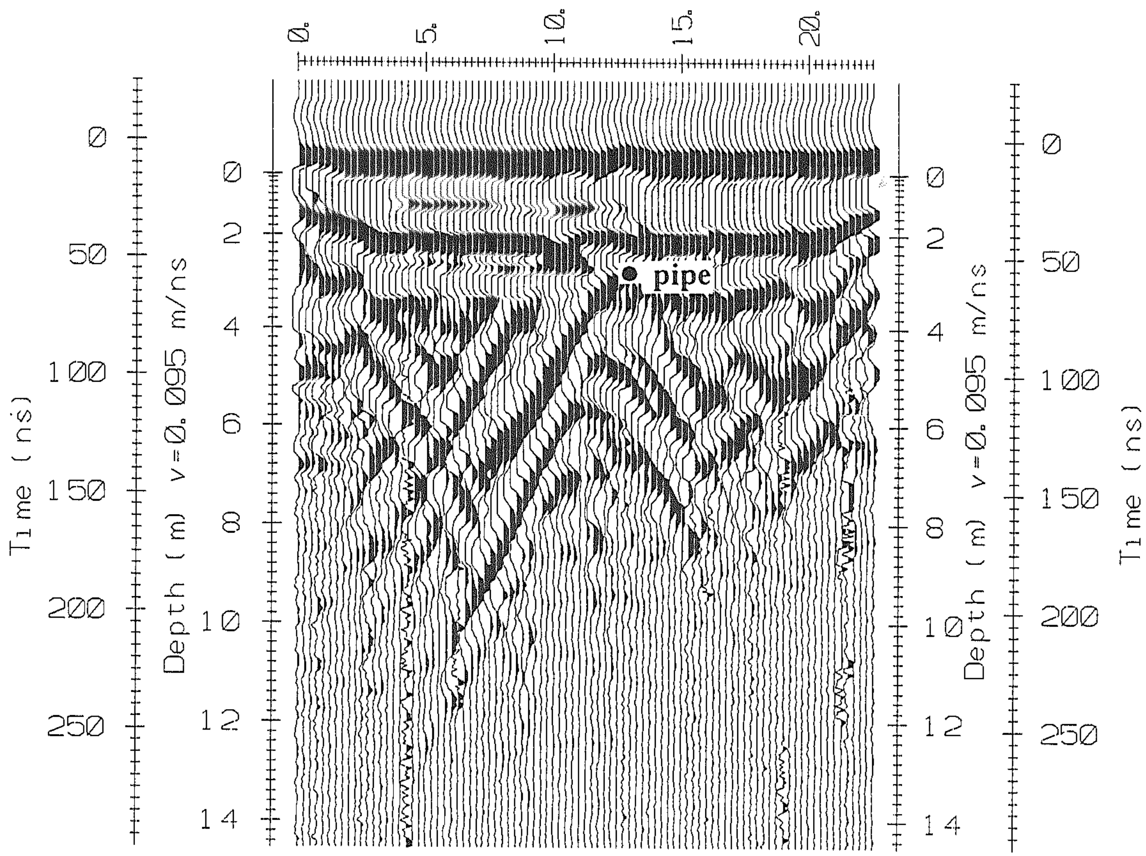
135.
140.
145.
150.
0
2
4
6
8
10
12
14
Depth (m) v=0.095 m/ns
0
50
100
150
200
250
Time (ns)



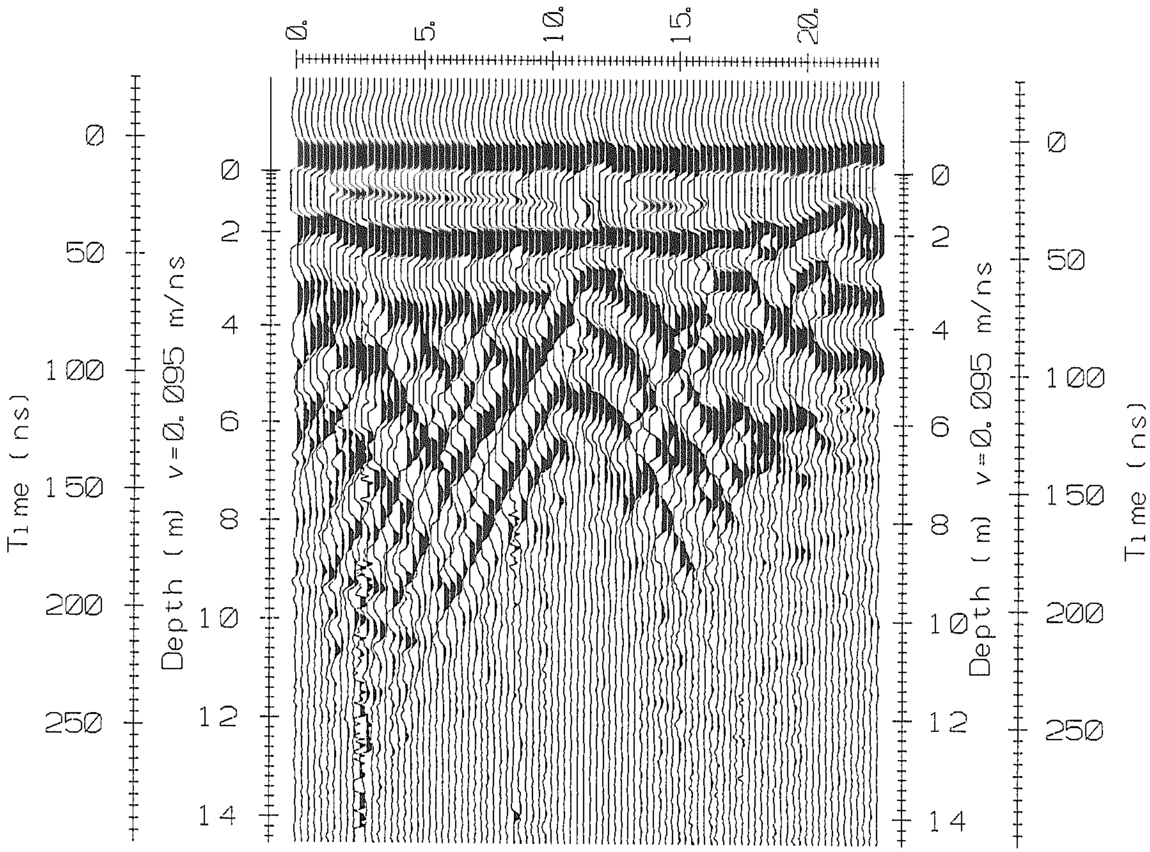
CANYON CREEK NORTH - LONG PROFILE 2 - 50 MHz - AUGUST 5


65.
70.
75.
80.
85.
90.
95.
100.
105.
110.
115.
120.
125.
130.
instrumentation
instrumentation

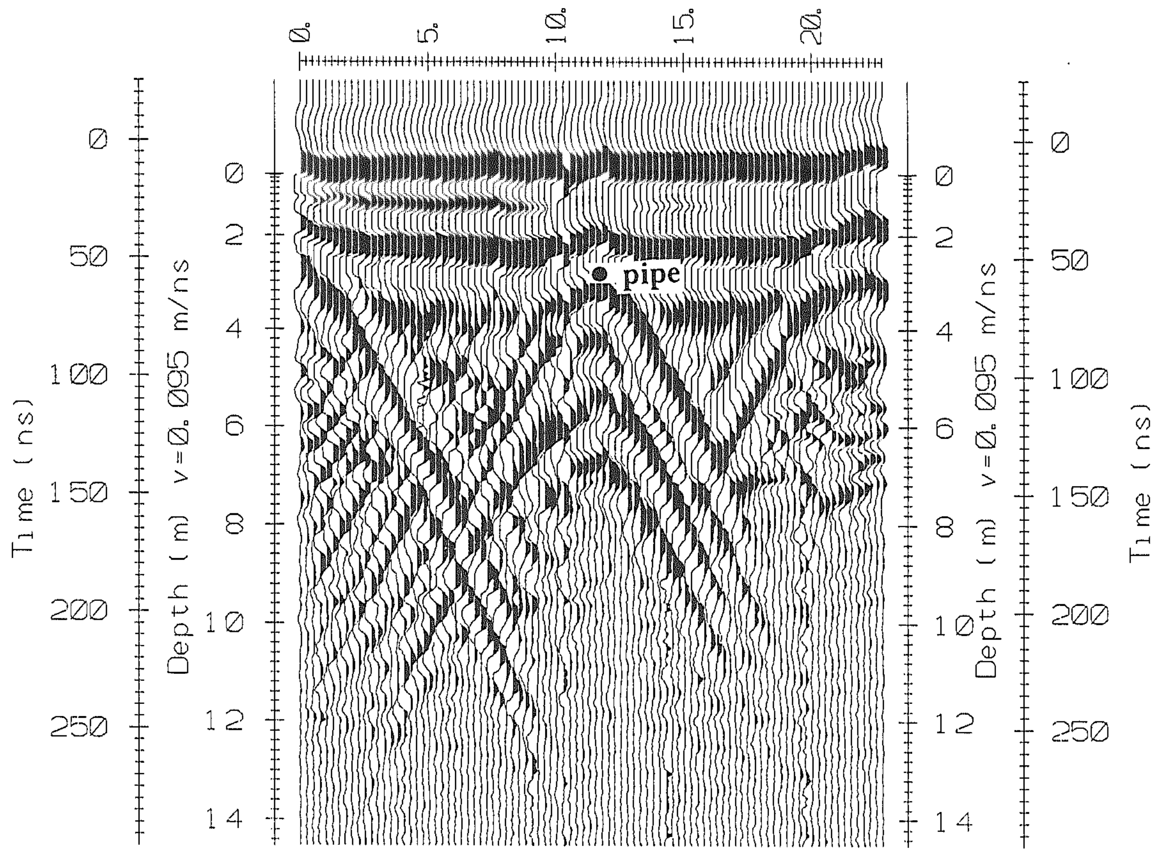

135.
140.
145.
150.
155.
160.
0
2
4
6
8
10
12
14
Depth (m) v=0.095 m/ns
0
50
100
150
200
250
Time (ns)



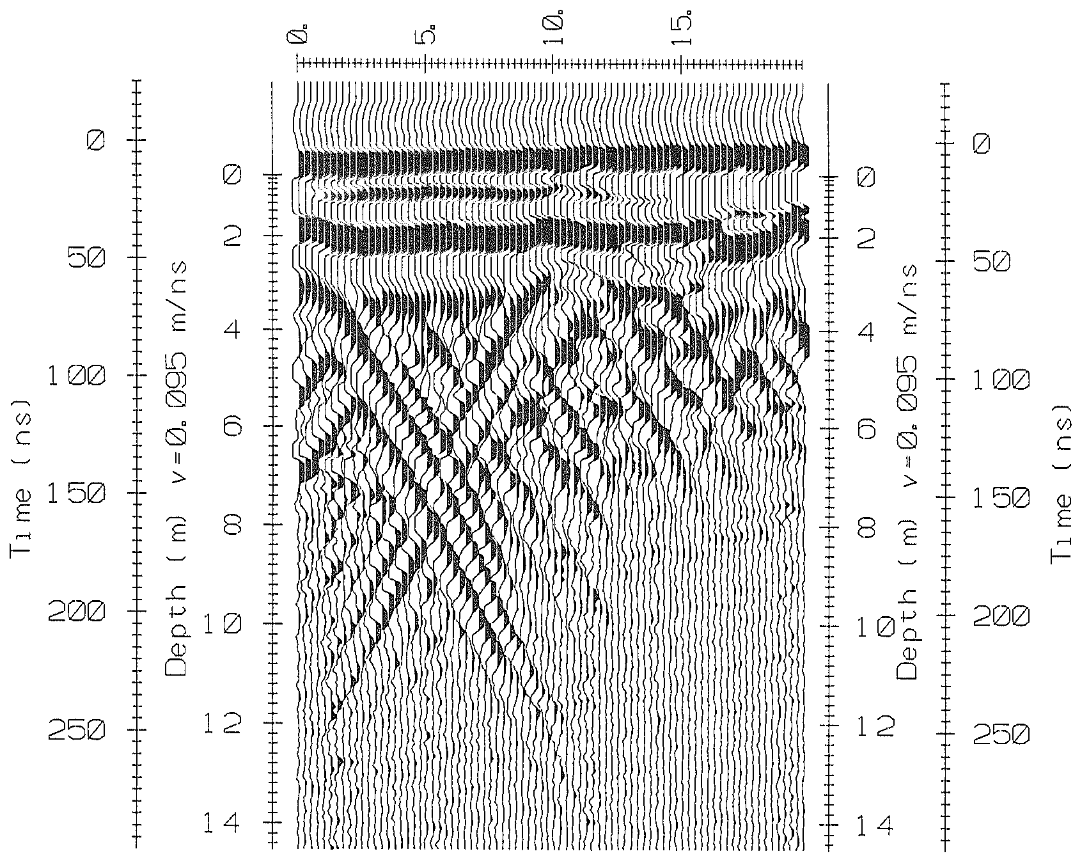
CANYON CREEK NORTH - CROSS PROFILE 1 - 50 MHz - AUGUST 5



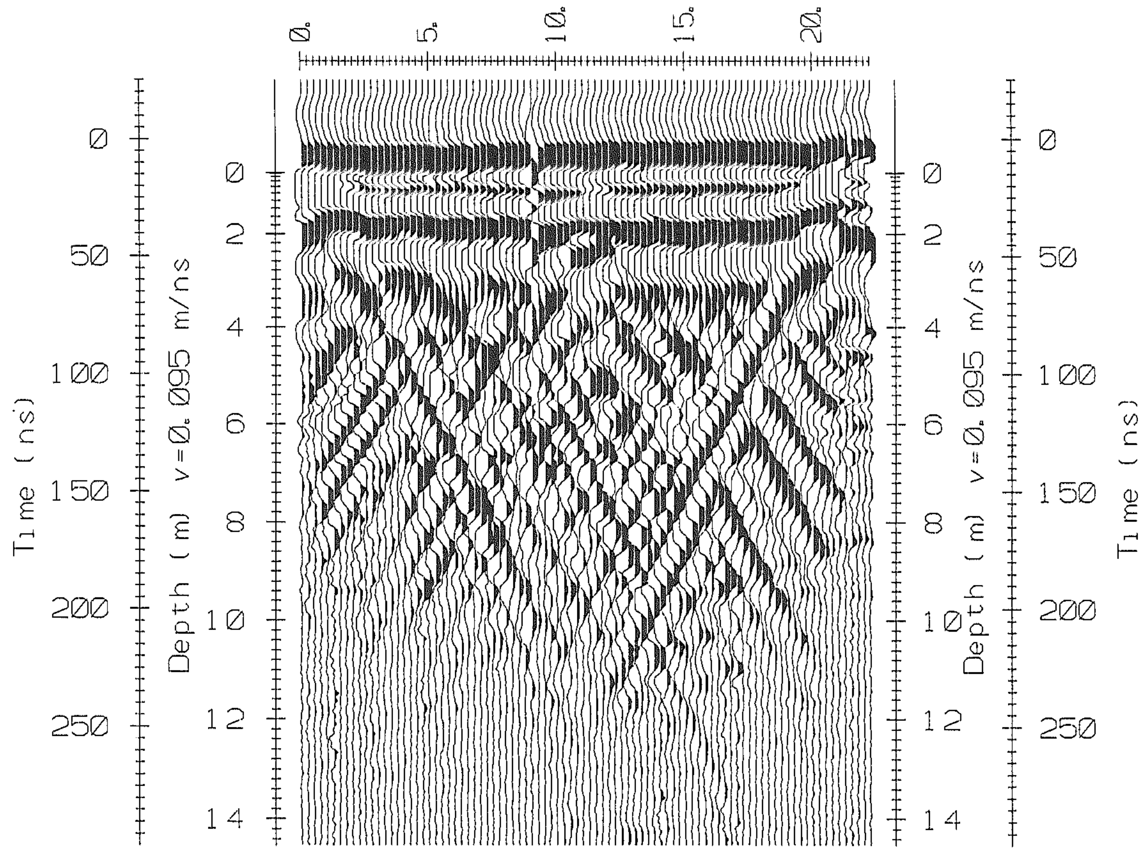
CANYON CREEK NORTH - CROSS PROFILE 2 - 50 MHz - AUGUST 5



CANYON CREEK NORTH - CROSS PROFILE 3 - 50 MHz - AUGUST 5



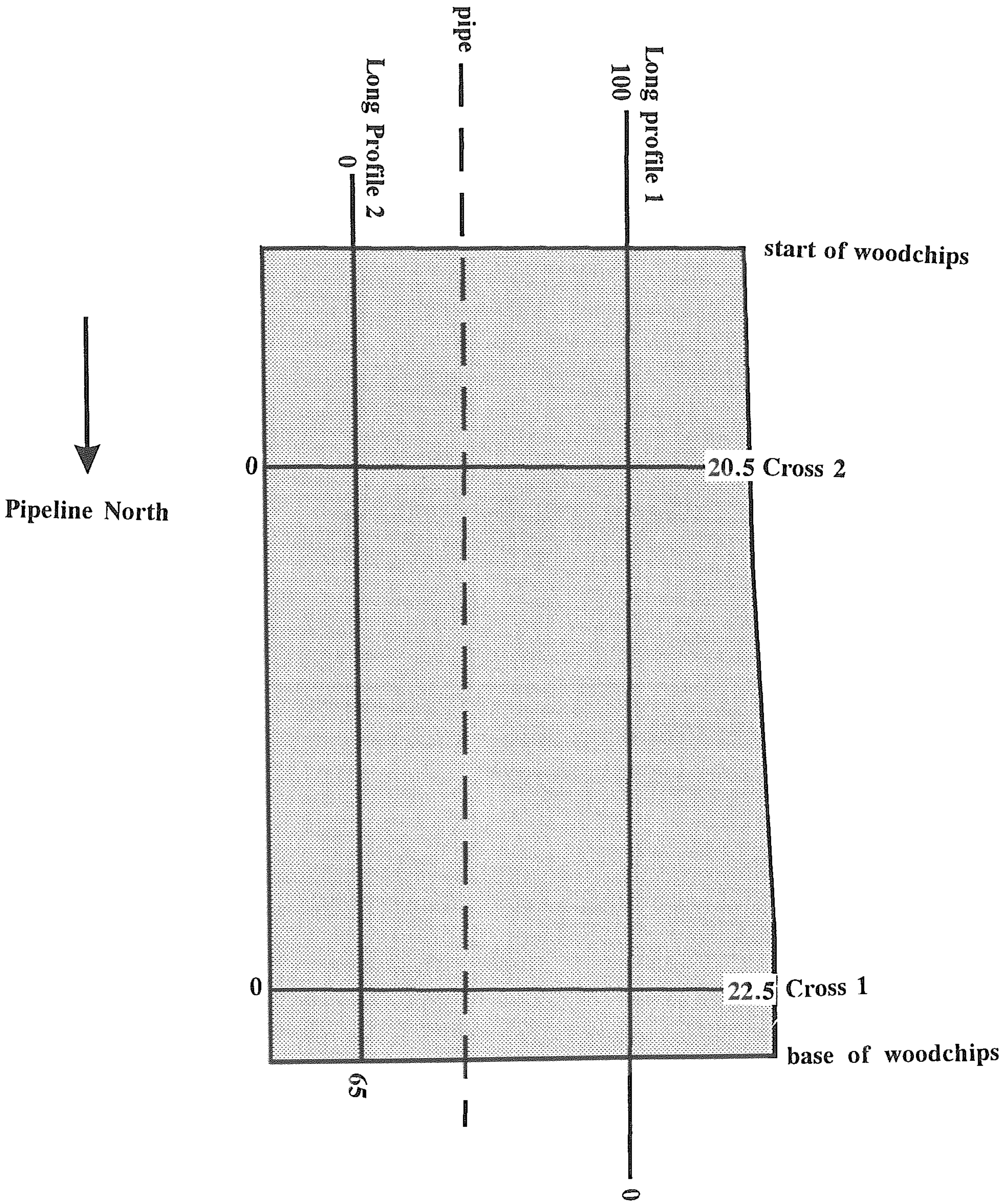
CANYON CREEK NORTH - CROSS PROFILE 4 - 50 MHz - AUGUST 5

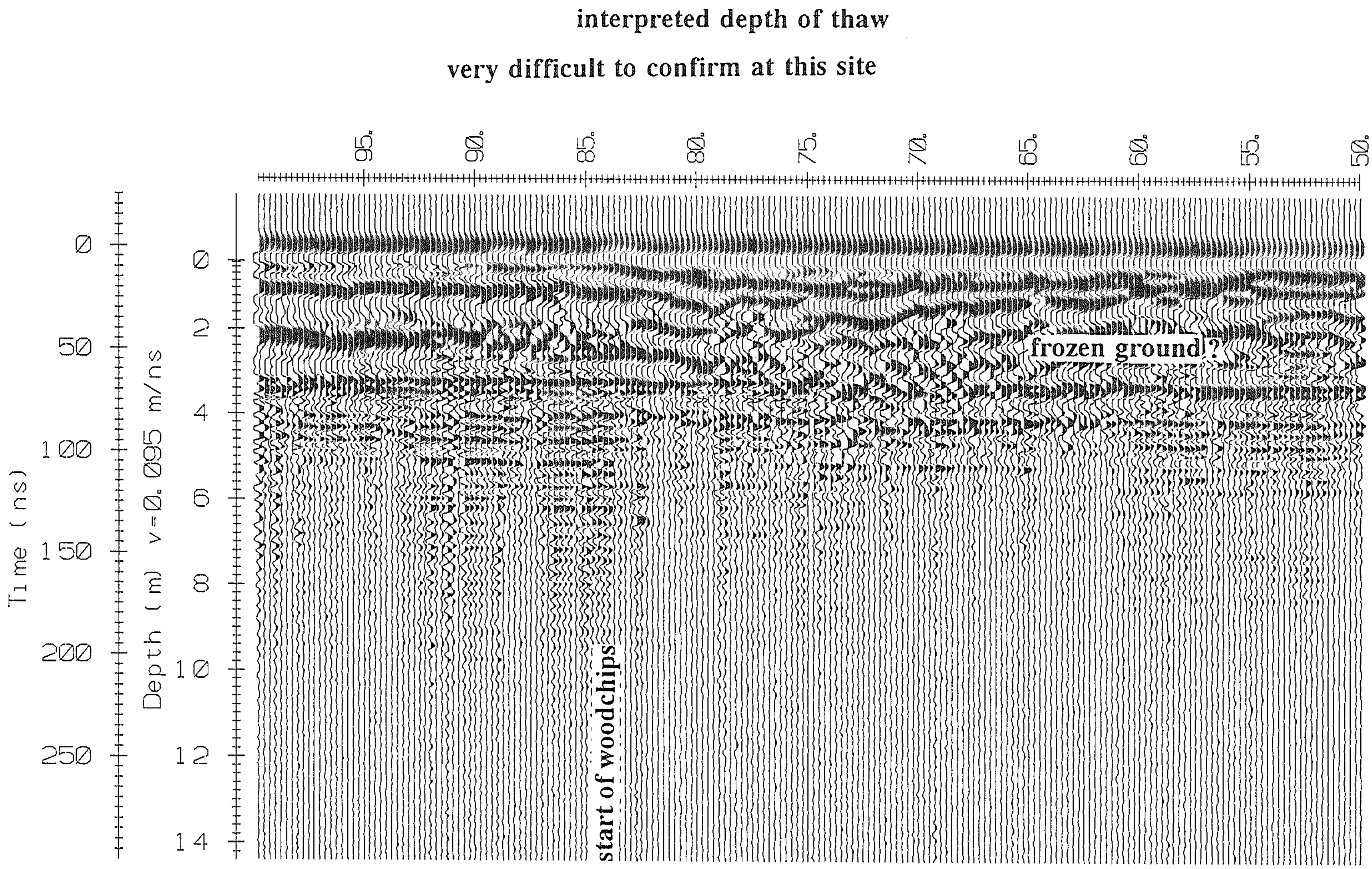


CANYON CREEK NORTH - CROSS PROFILE 5 - 50 MHz - AUGUST 5

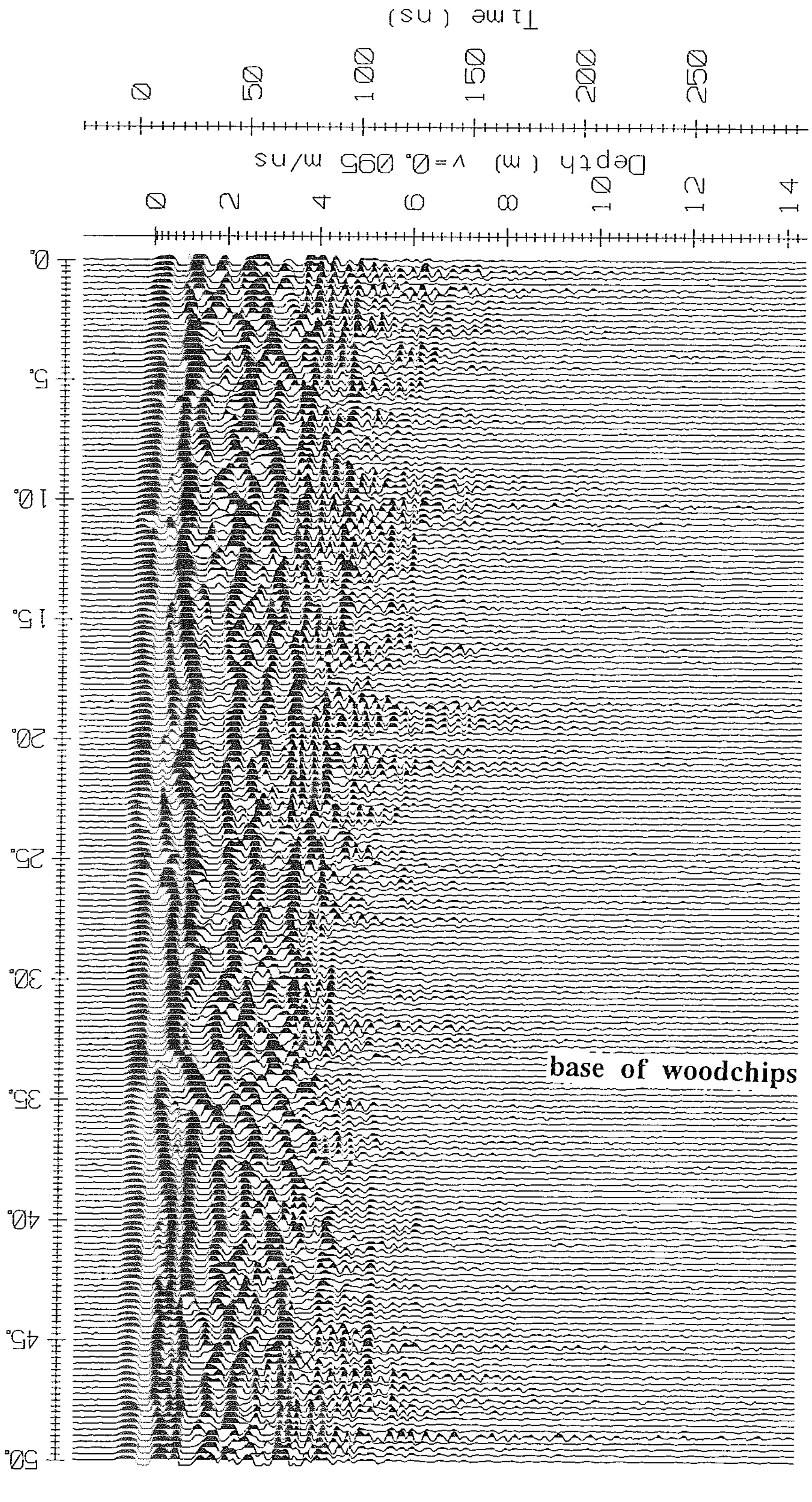
CANYON CREEK SOUTH

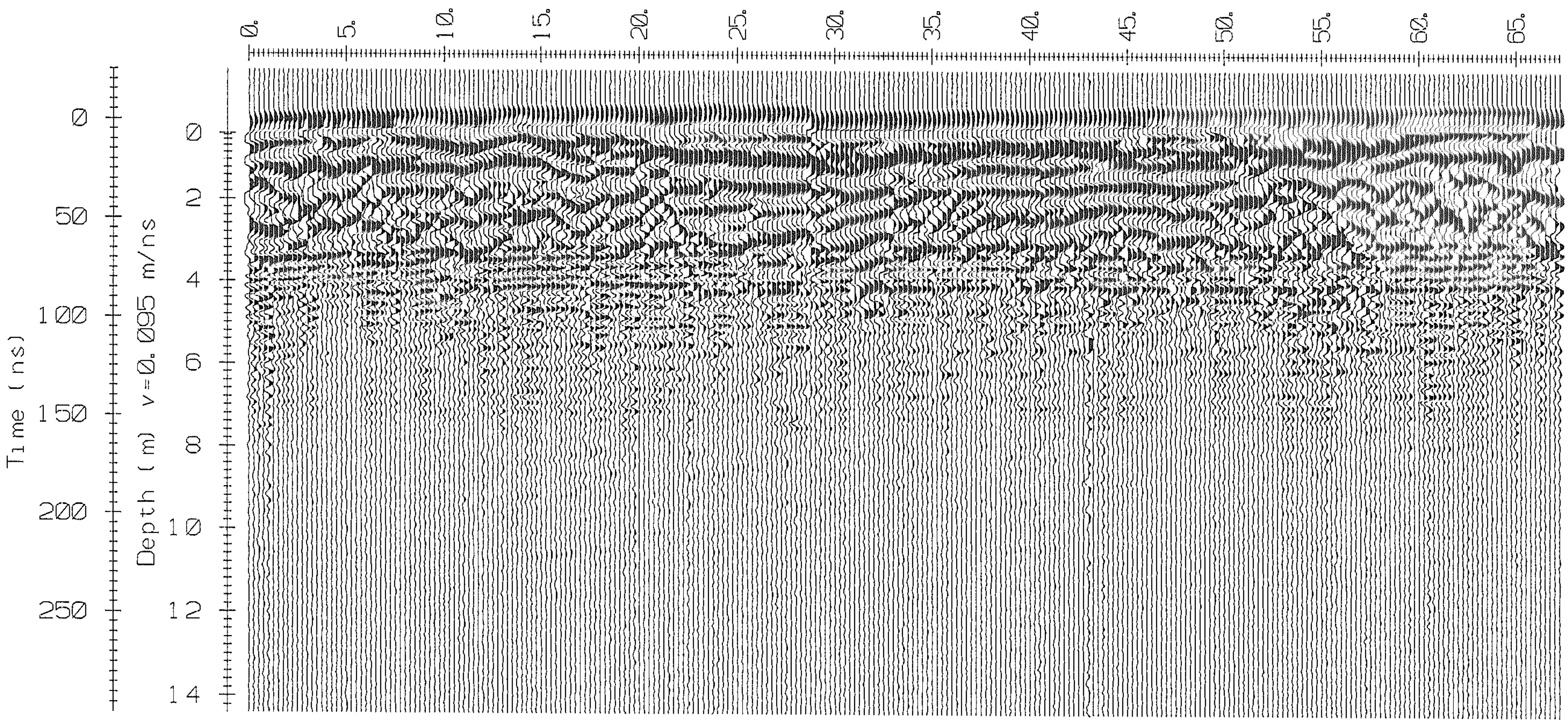
Not to Scale



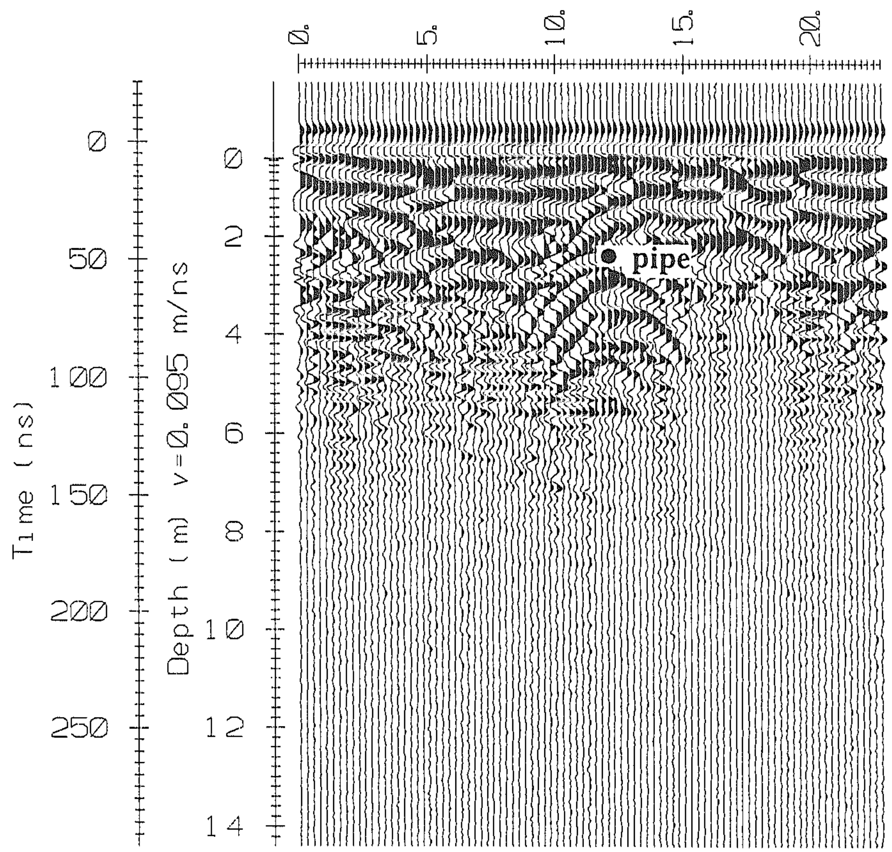


CANYON CREEK SOUTH - LONG PROFILE 1 - 100 MHz - JUNE 21

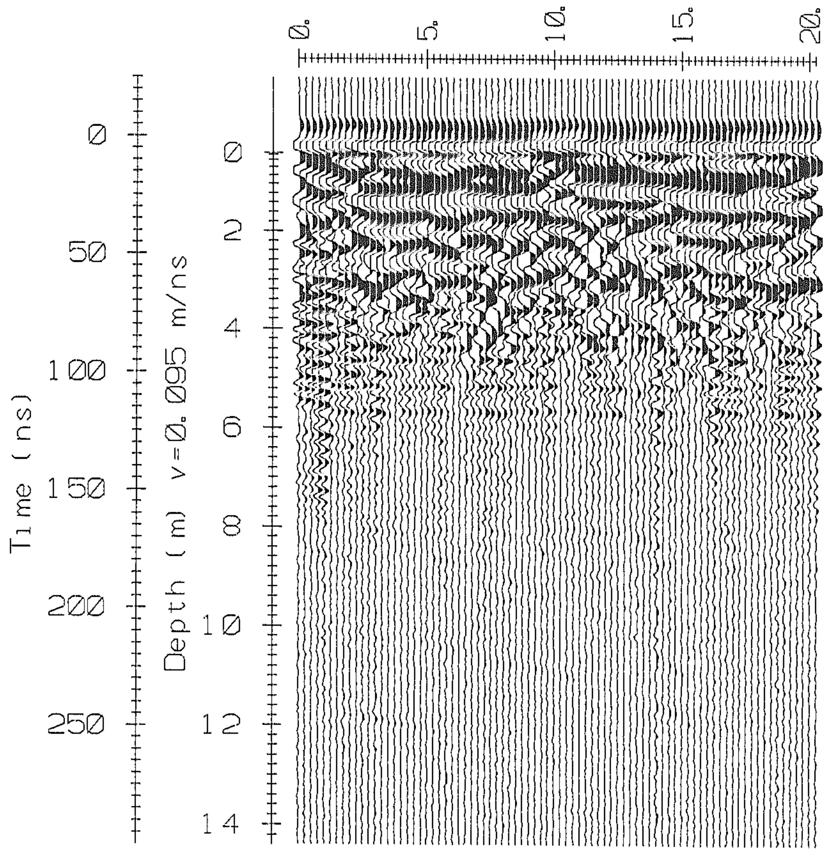

Time (ns)
Depth (m) v=0.095 m/ns
base of woodchips



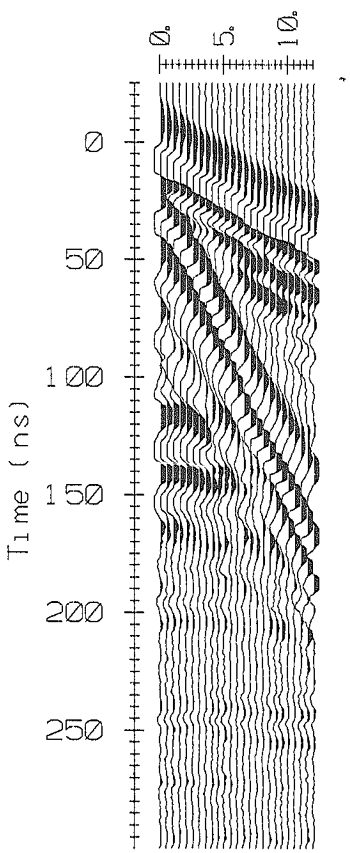
CANYON CREEK SOUTH - LONG PROFILE 2 - 100 MHz - JUNE 21



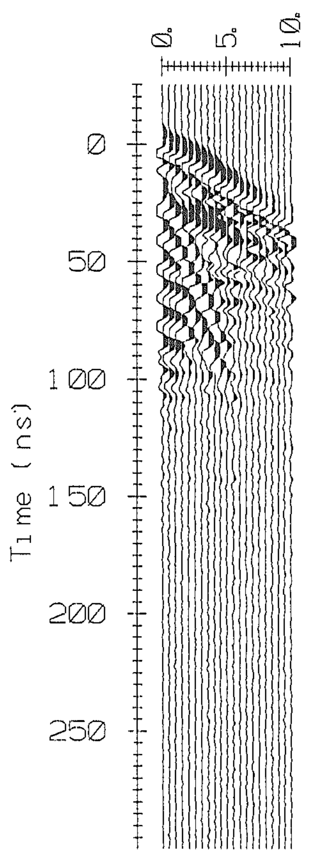
CANYON CREEK SOUTH - CROSS PROFILE 1 - 100 MHz - JUNE 21



CANYON CREEK SOUTH - CROSS PROFILE 2 - 100 MHz - JUNE 21



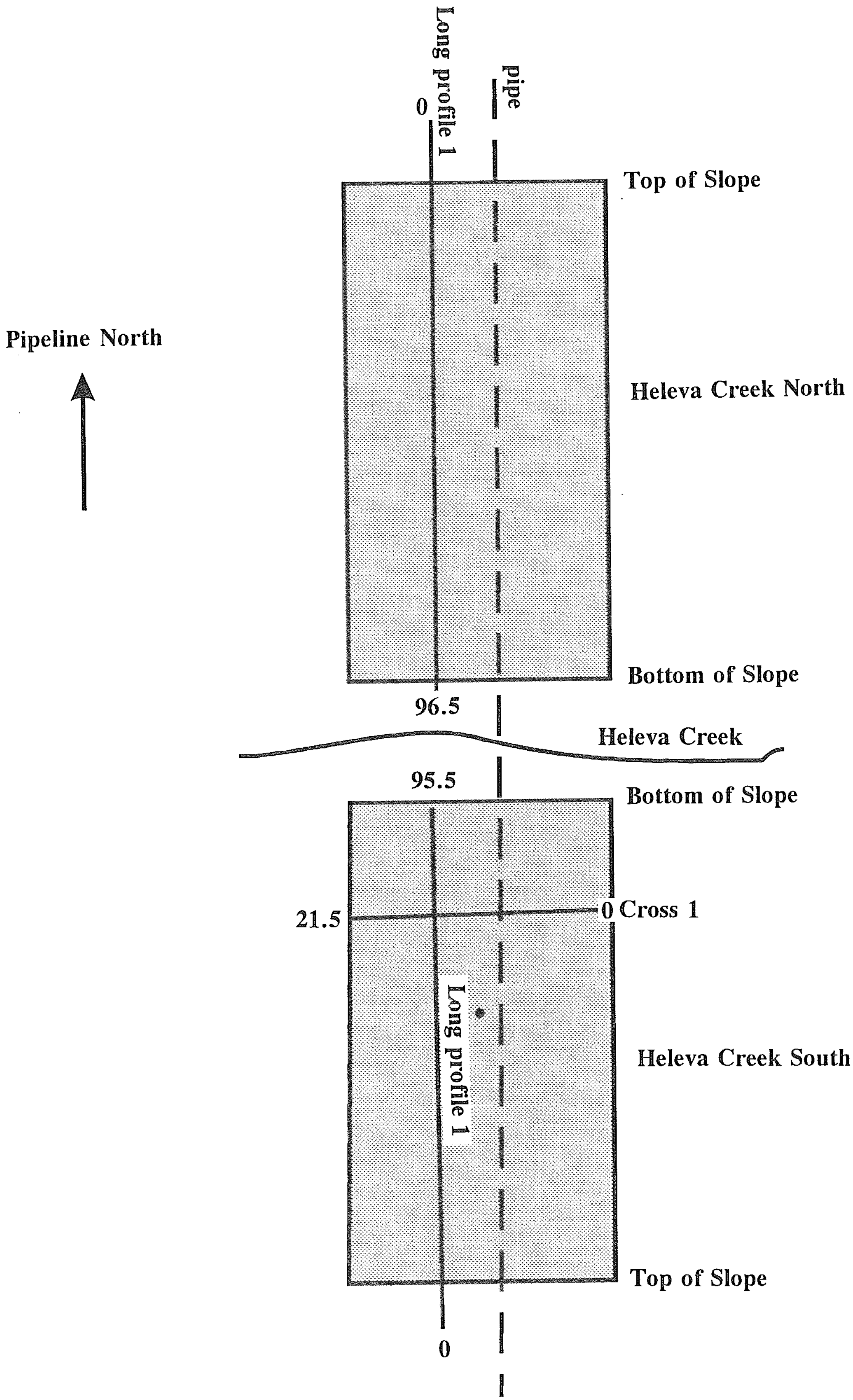
CANYON CREEK NORTH - CMP - JUNE 8

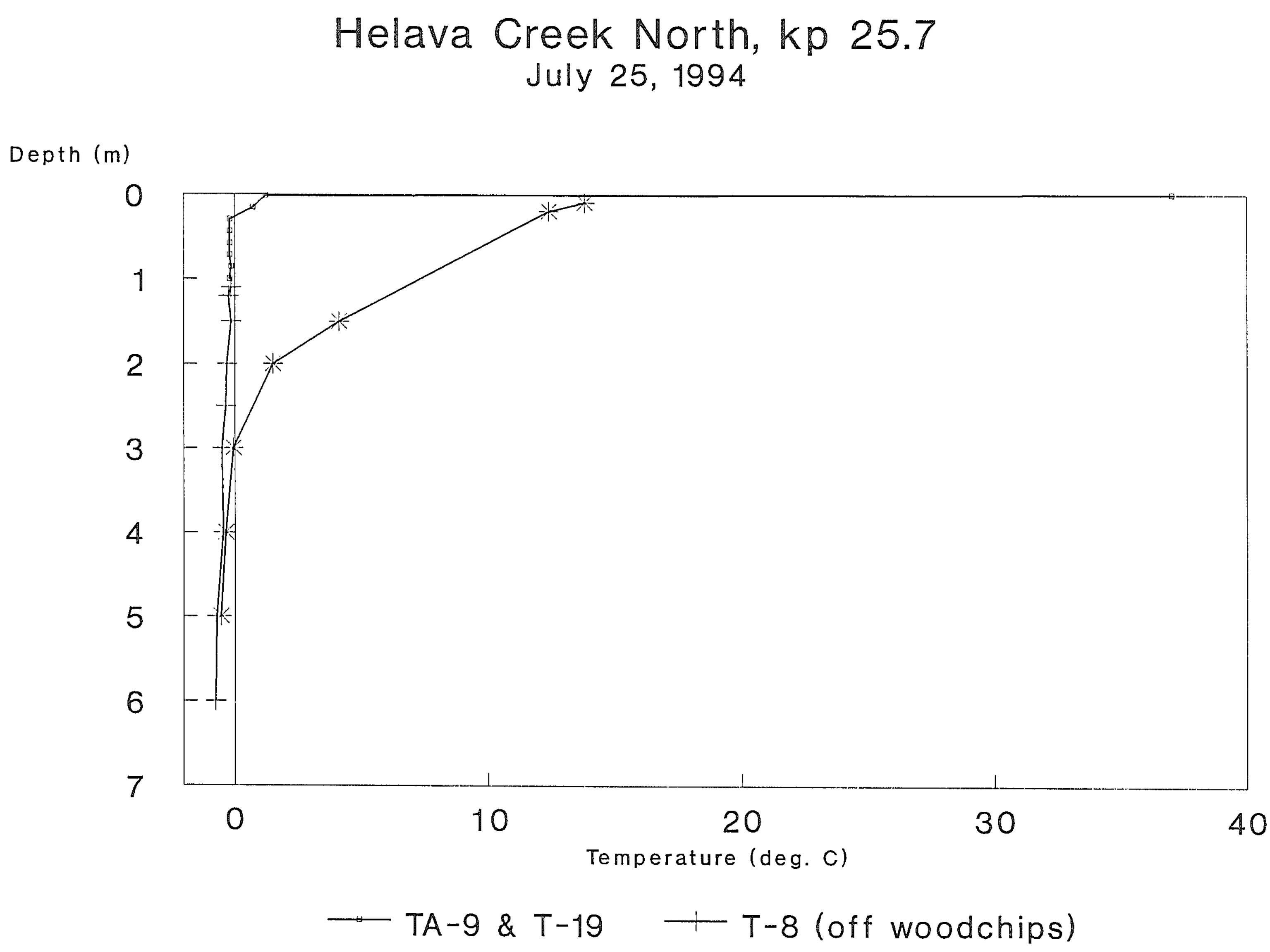


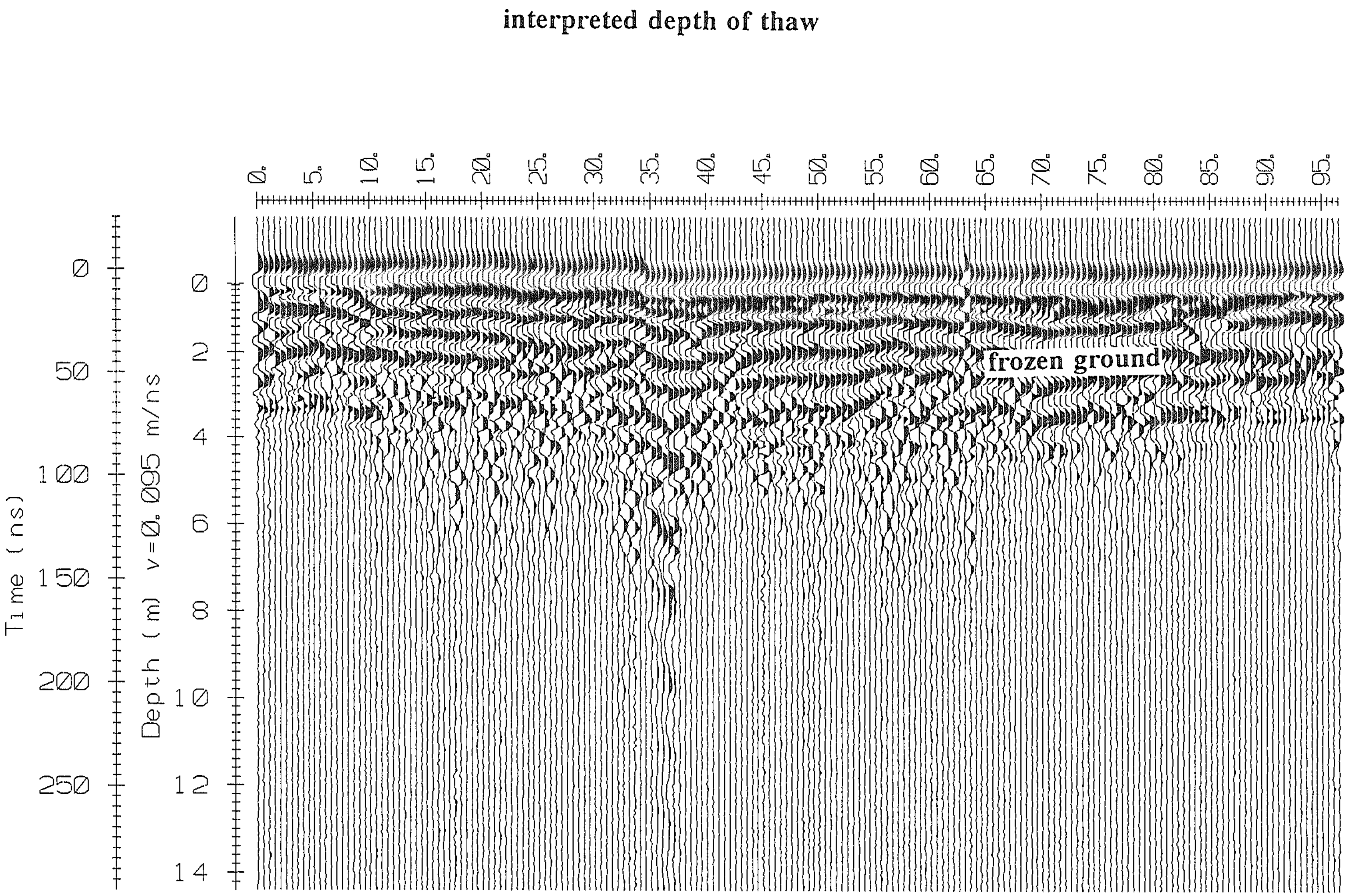
CANYON CREEK NORTH - CMP - AUGUST 5

HELEVA CREEK NORTH AND SOUTH

Not to Scale

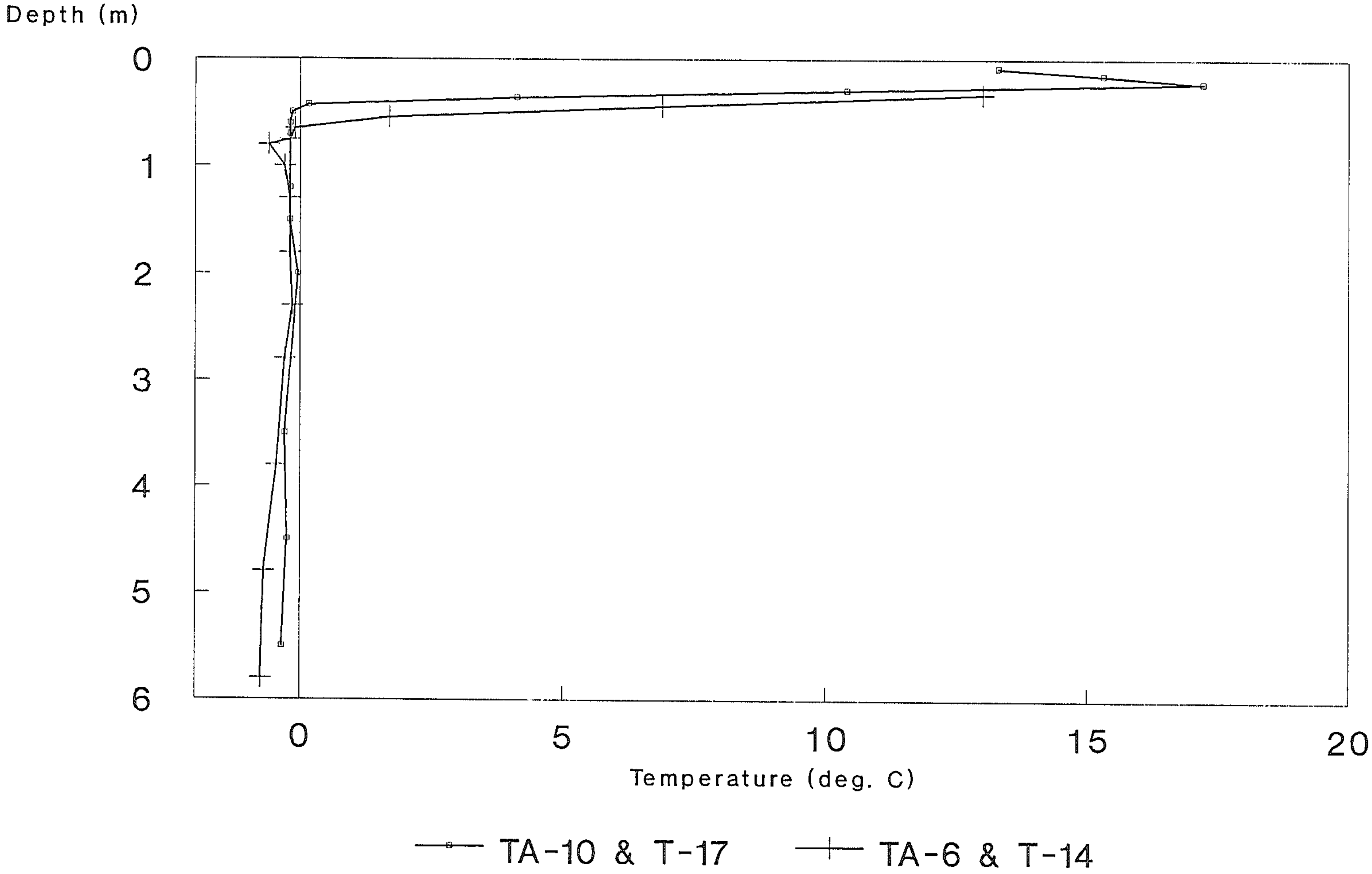



Helava Creek North, kp 25.7
July 25, 1994
Depth (m)
0
1
2
3
4
5
6
7
0
10
20
30
40
Temperature (deg. C)
TA-9 & T-19
T-8 (off woodchips)

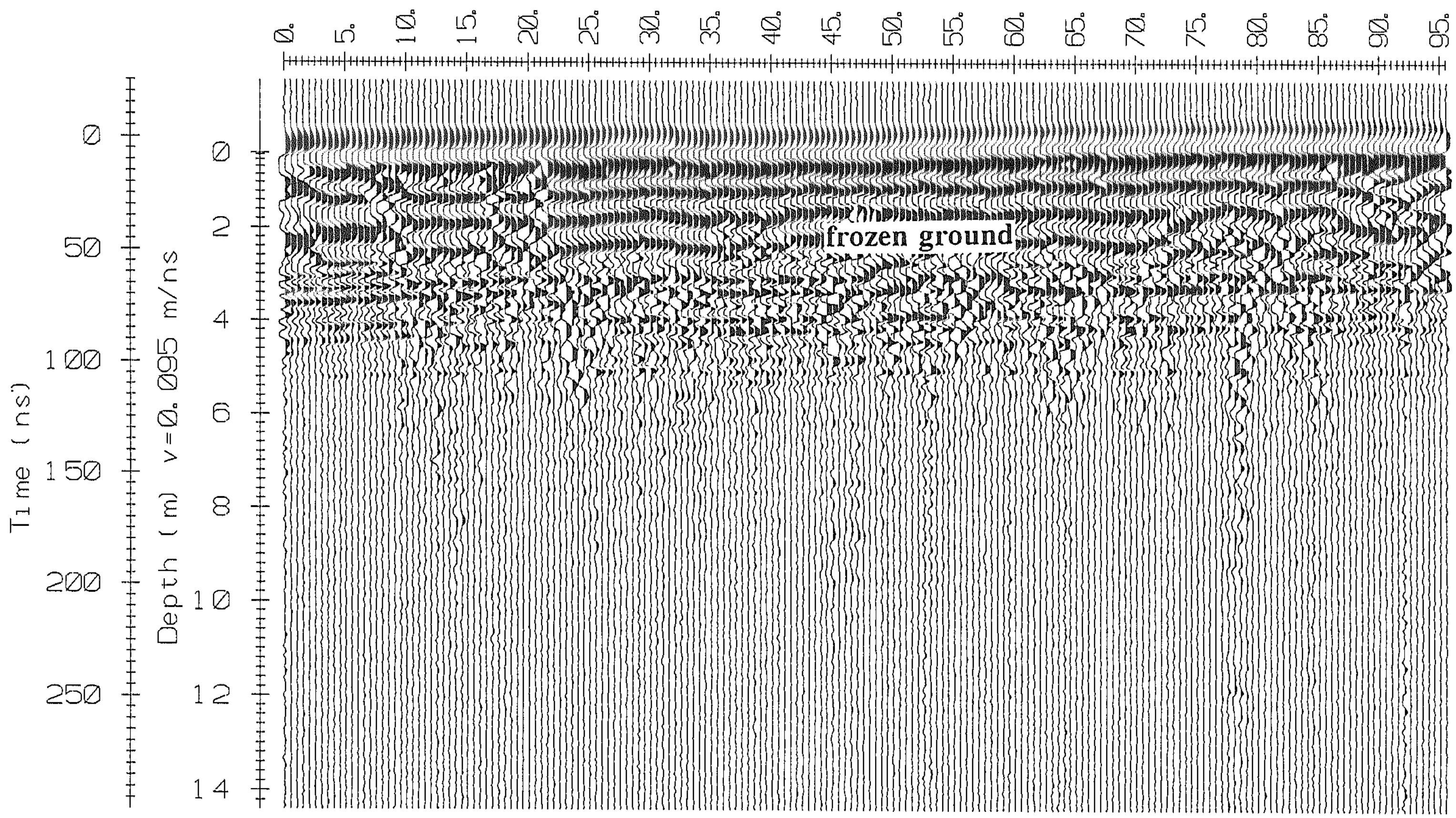


HELEVA CREEK NORTH - LONG PROFILE 1 - 100 MHz - JULY 25

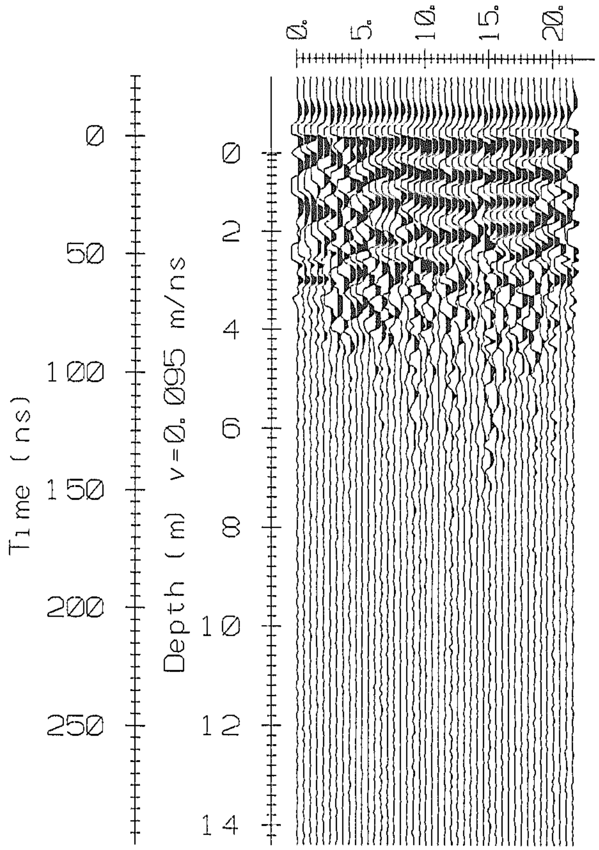
Helava Creek South, kp 25.9
July 25, 1994



interpreted depth of thaw



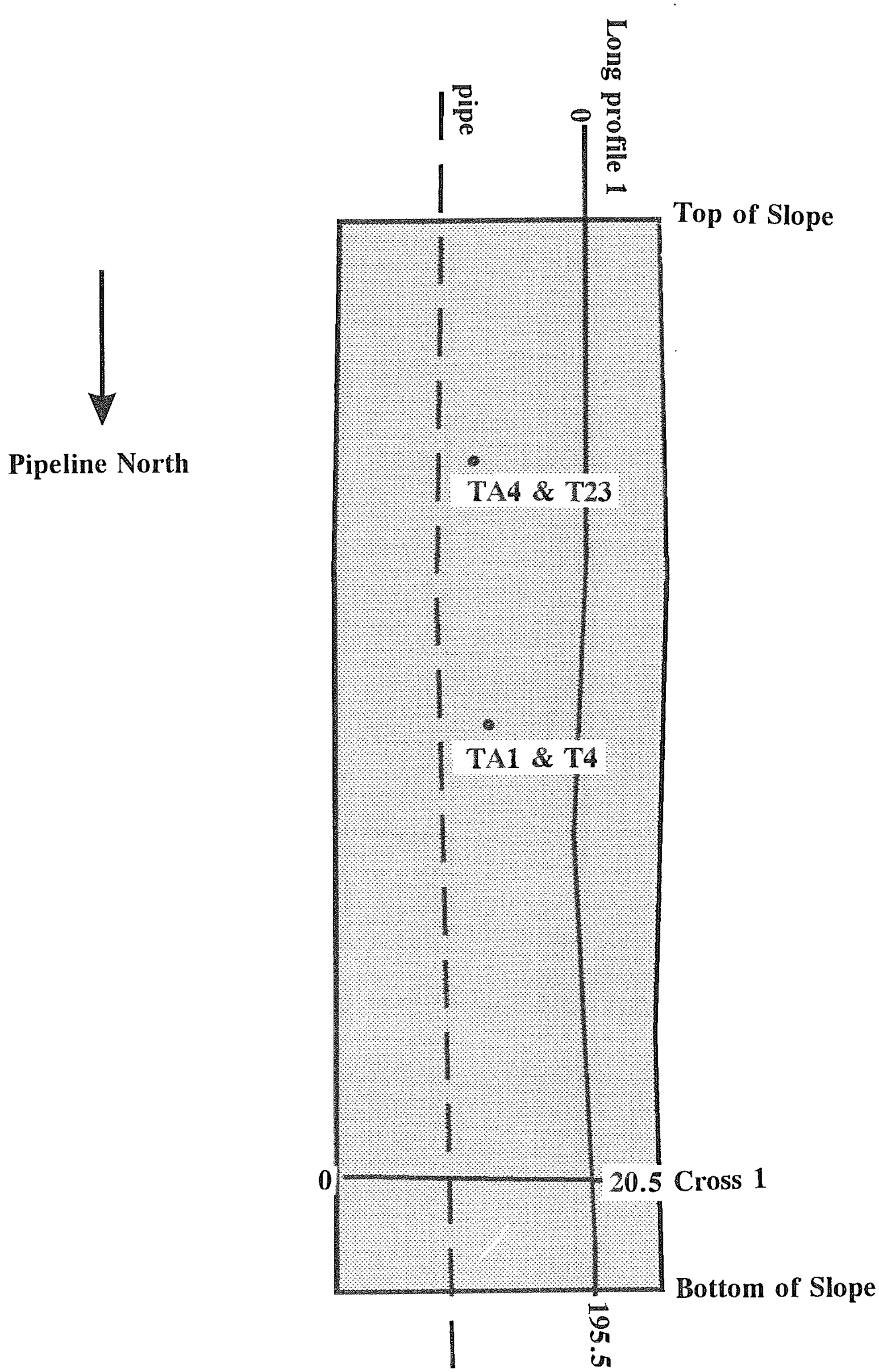
HELEVA CREEK SOUTH - LONG PROFILE 1 - 100 MHz - JULY 25

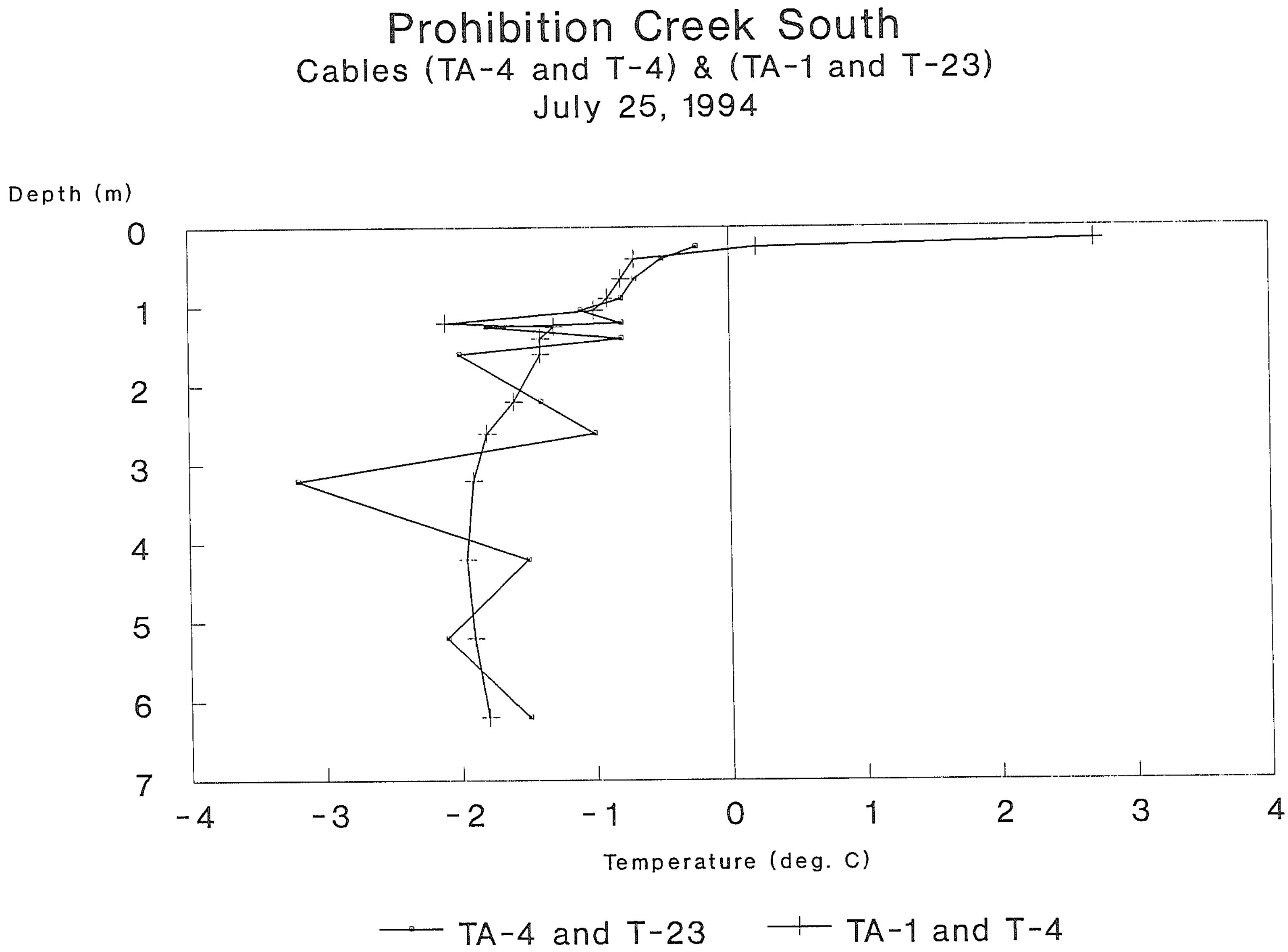


HELEVA CREEK SOUTH - CROSS PROFILE 1 - 100 MHz - JULY 25

PROHIBITION CREEK SOUTH

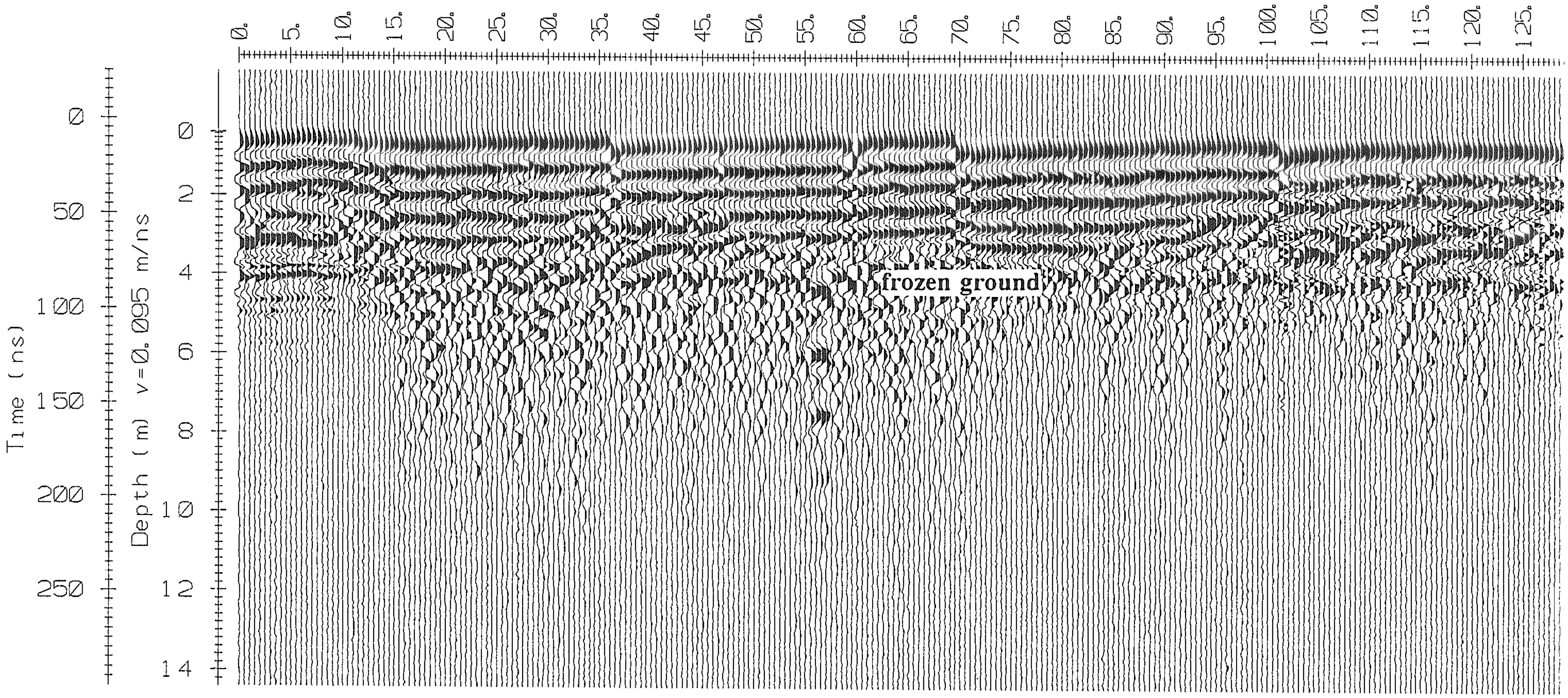
Not to Scale



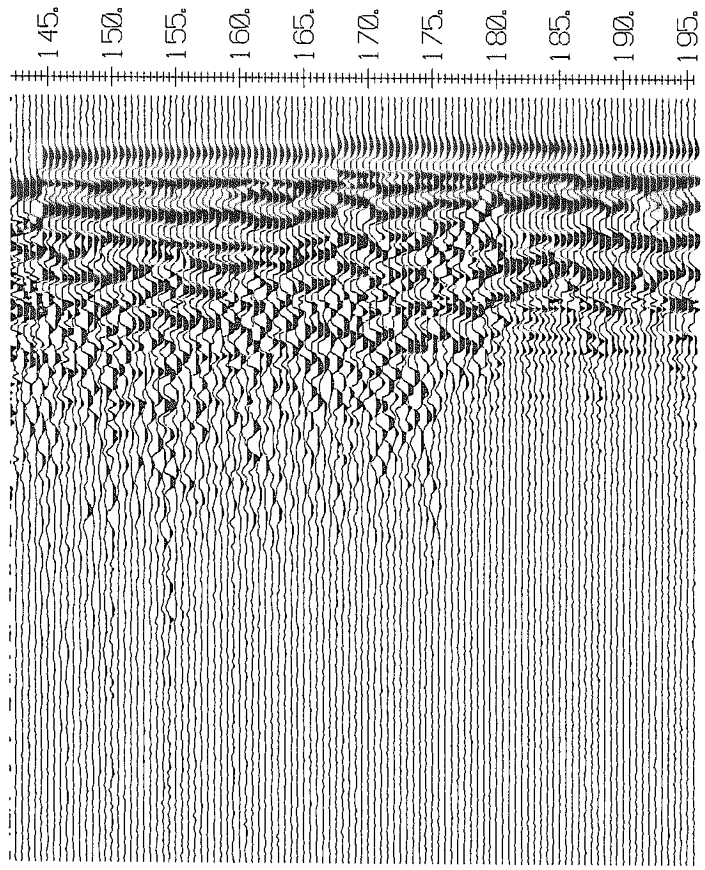


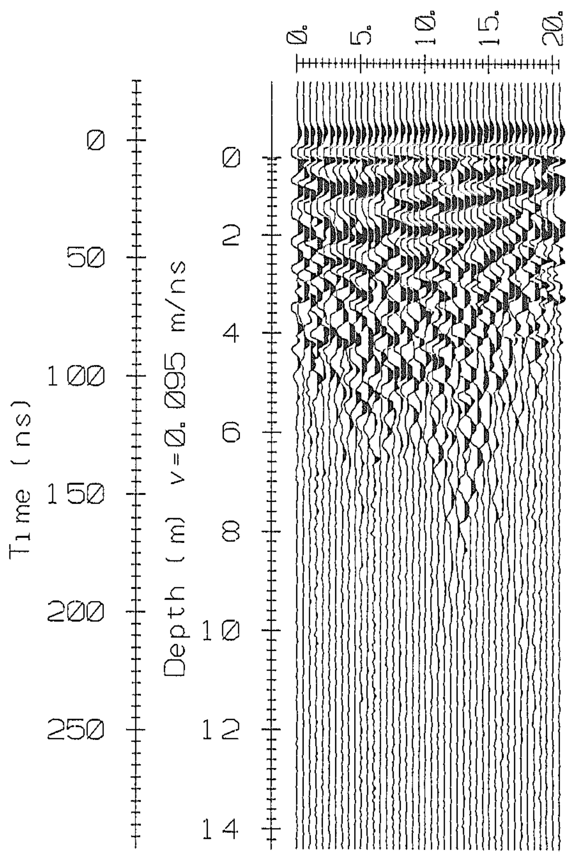
Prohibition Creek South
Cables (TA-4 and T-4) & (TA-1 and T-23)
July 25, 1994
Depth (m)
0
1
2
3
4
5
6
7
-4
-3
-2
-1
0
1
2
3
4
Temperature (deg. C)
TA-4 and T-23
TA-1 and T-4

interpreted depth of thaw

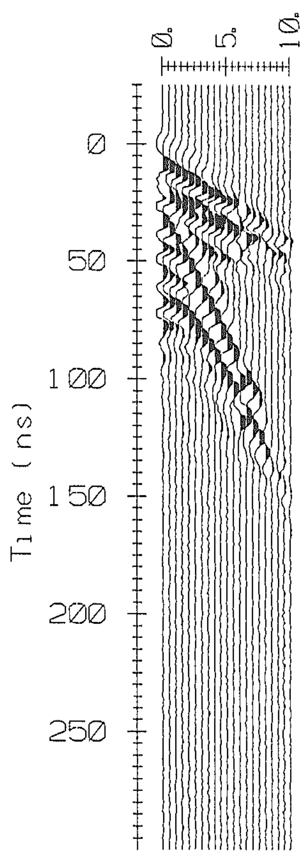


PROHIBITION CREEK - LONG PROFILE 1 - 100 MHz - JULY 25

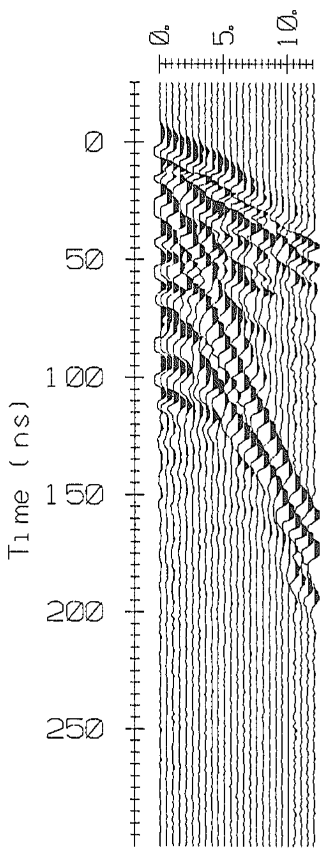

145.
150.
155.
160.
165.
170.
175.
180.
185.
190.
195.



PROHIBITION CREEK - CROSS PROFILE 1 - 100 MHz - JULY 25



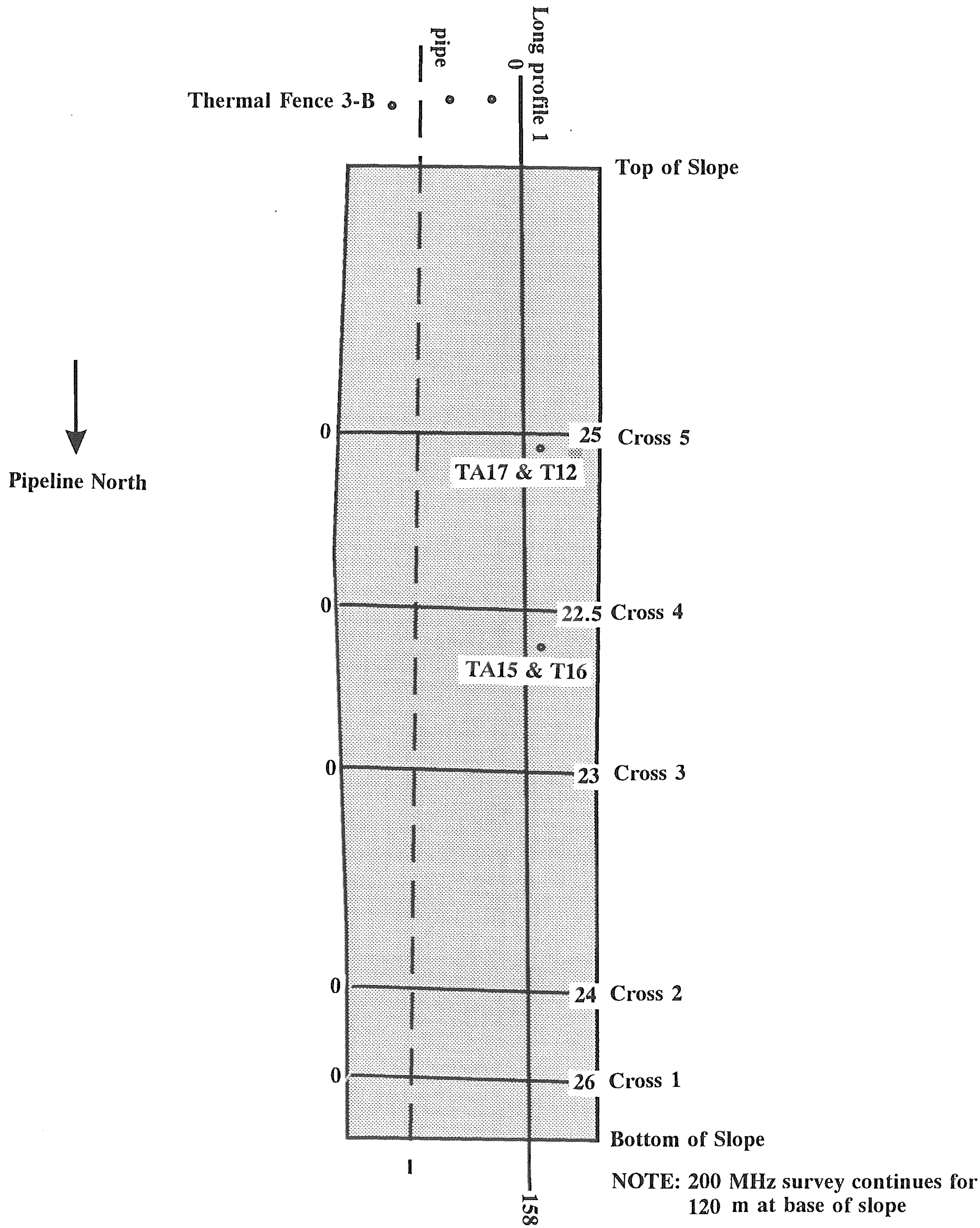
HELEVA CREEK - CMP - JULY 25



PROHIBITION CREEK - CMP - JULY 25

GREAT BEAR RIVER SOUTH

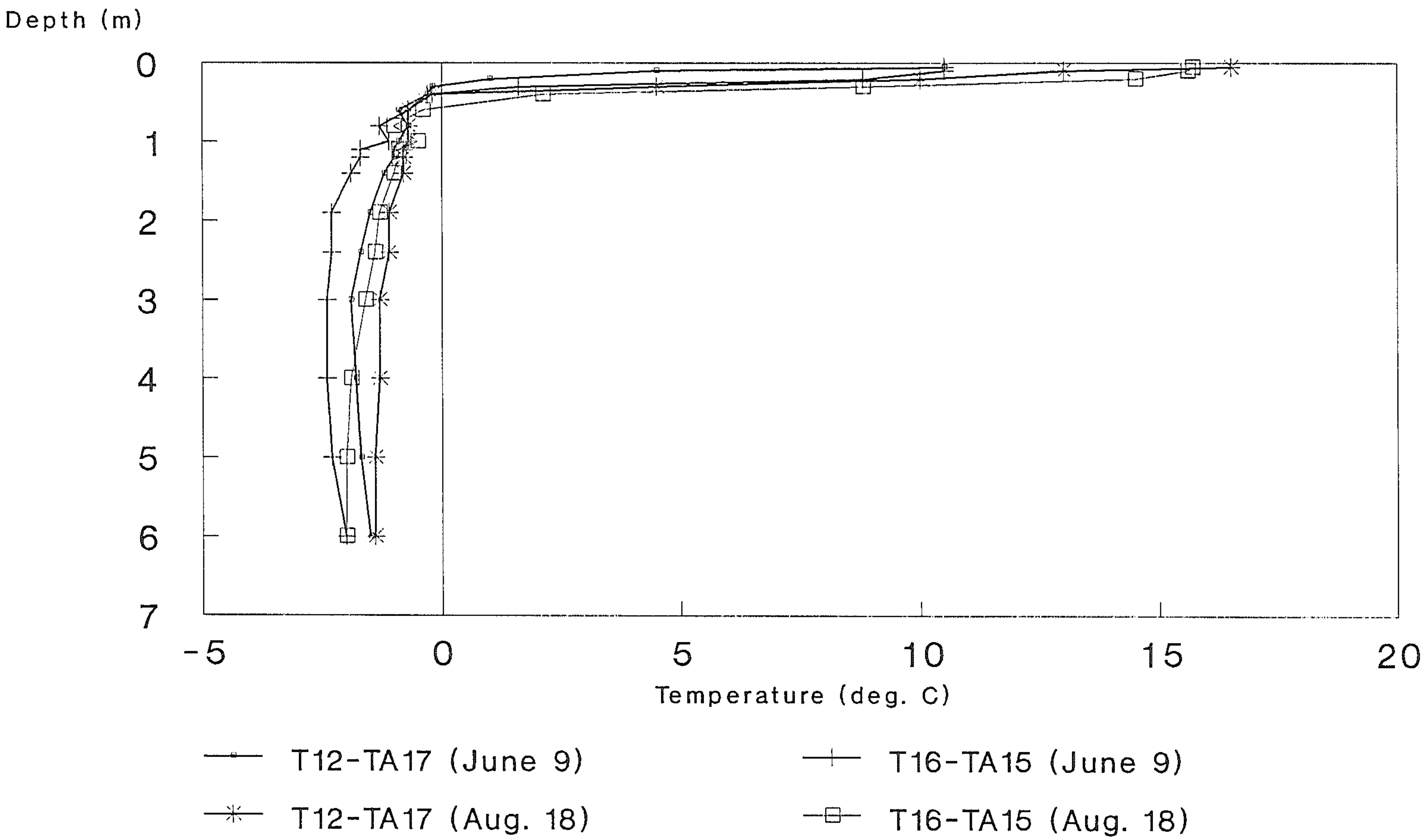
Not to Scale



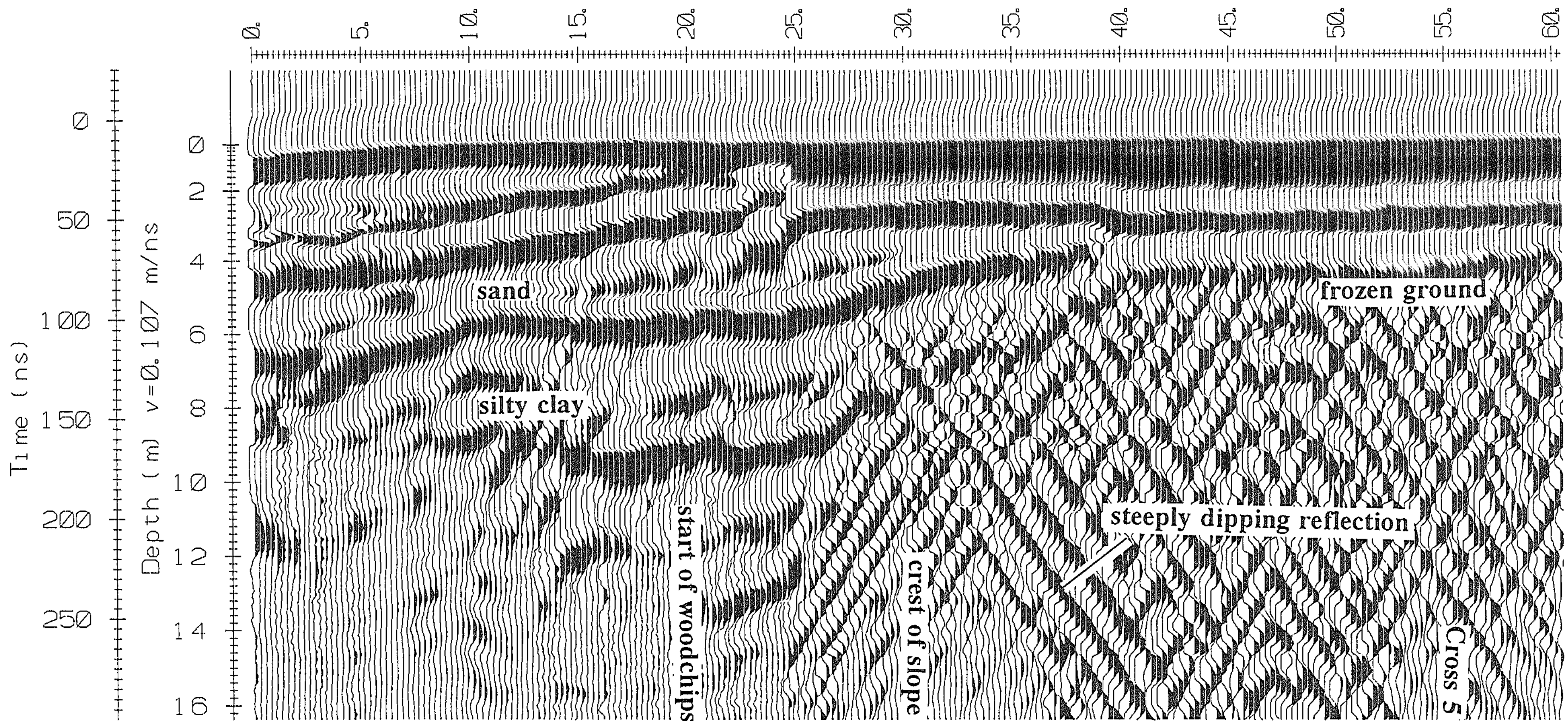
Great Bear South

Cables (T12 & TA17) & (T16 & TA15)

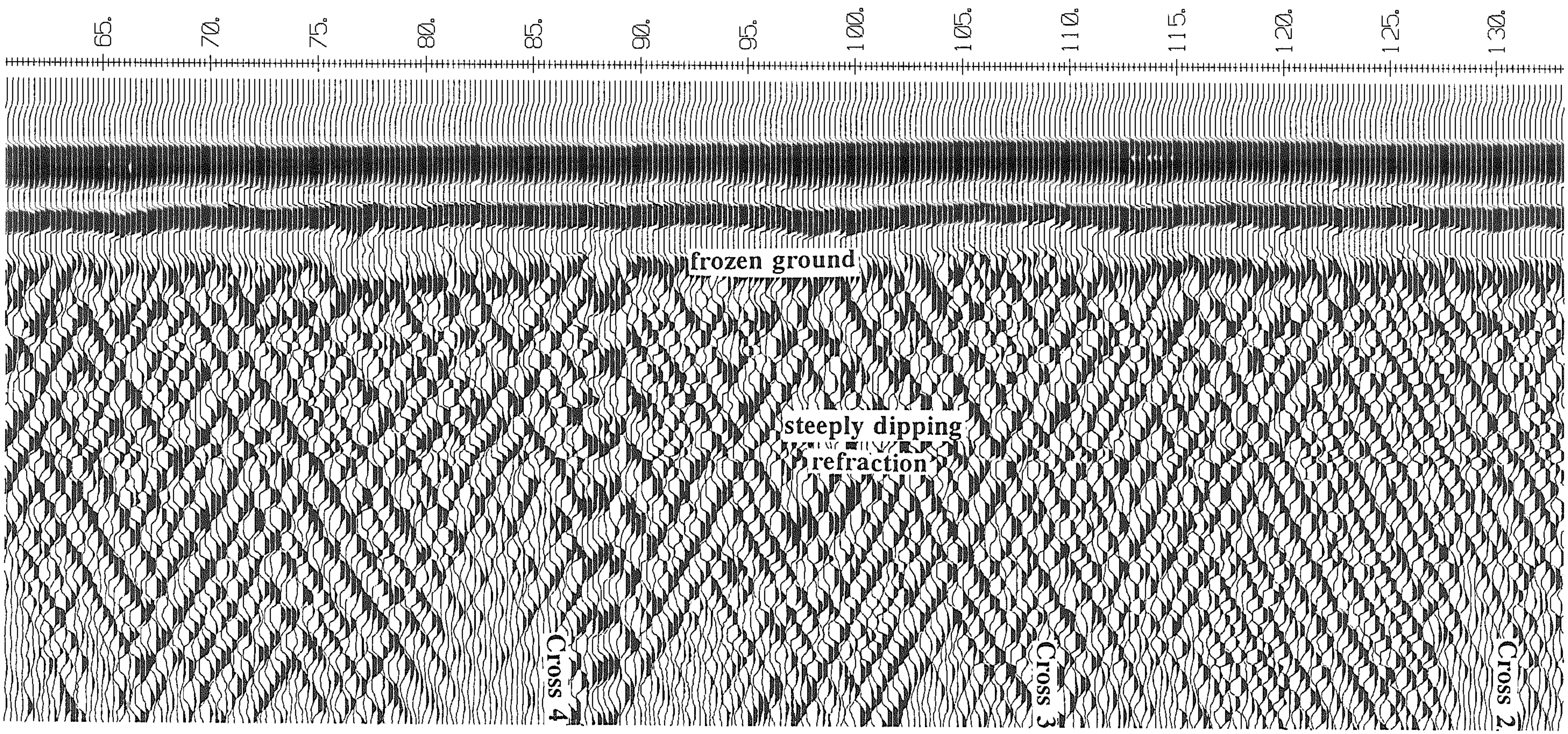
1994

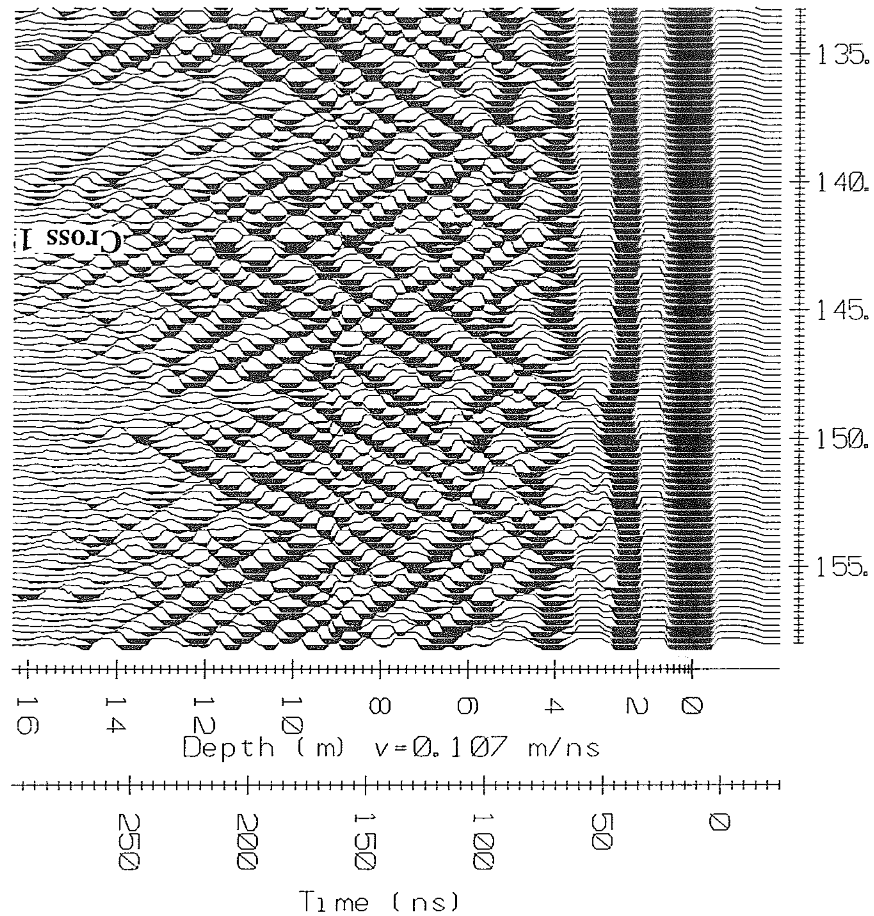


interpreted depth of thaw

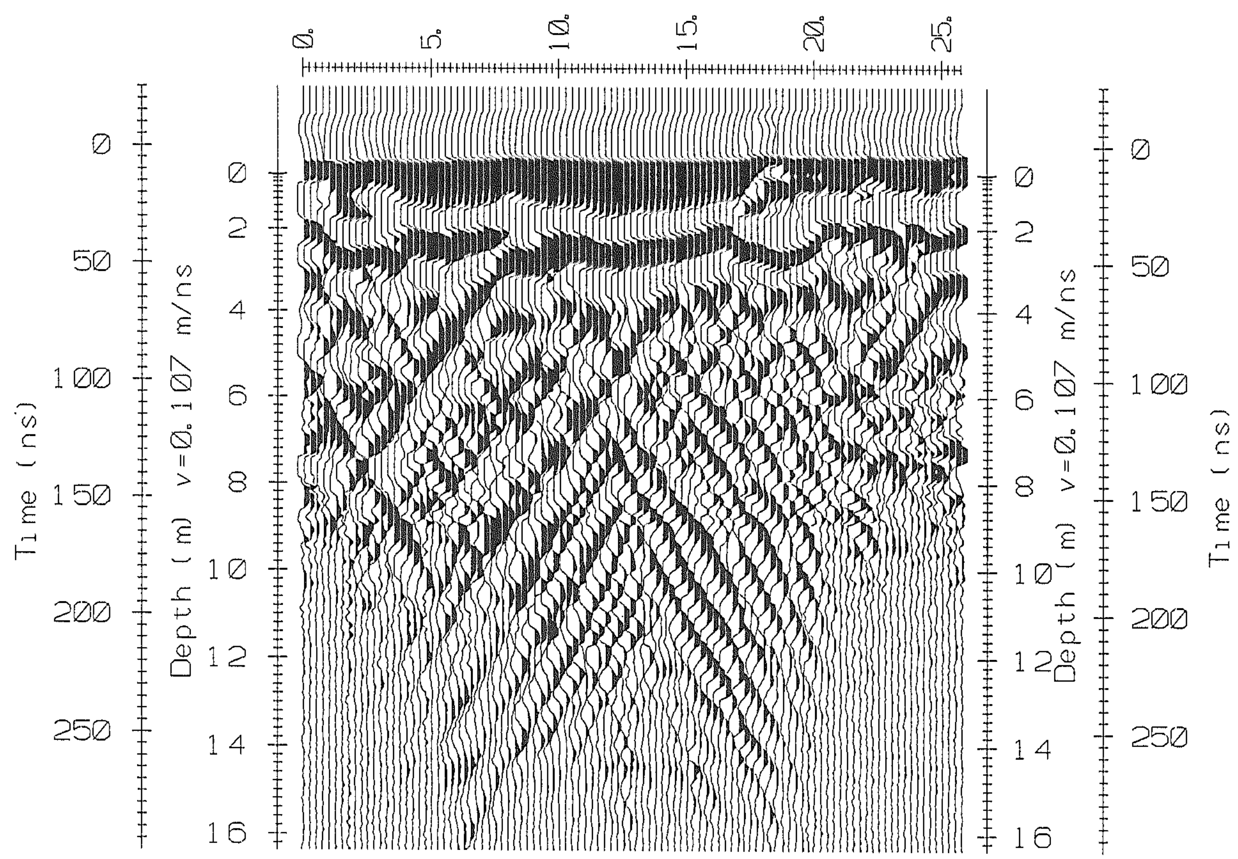


GREAT BEAR RIVER - LONG PROFILE - 50 MHz - JUNE 9

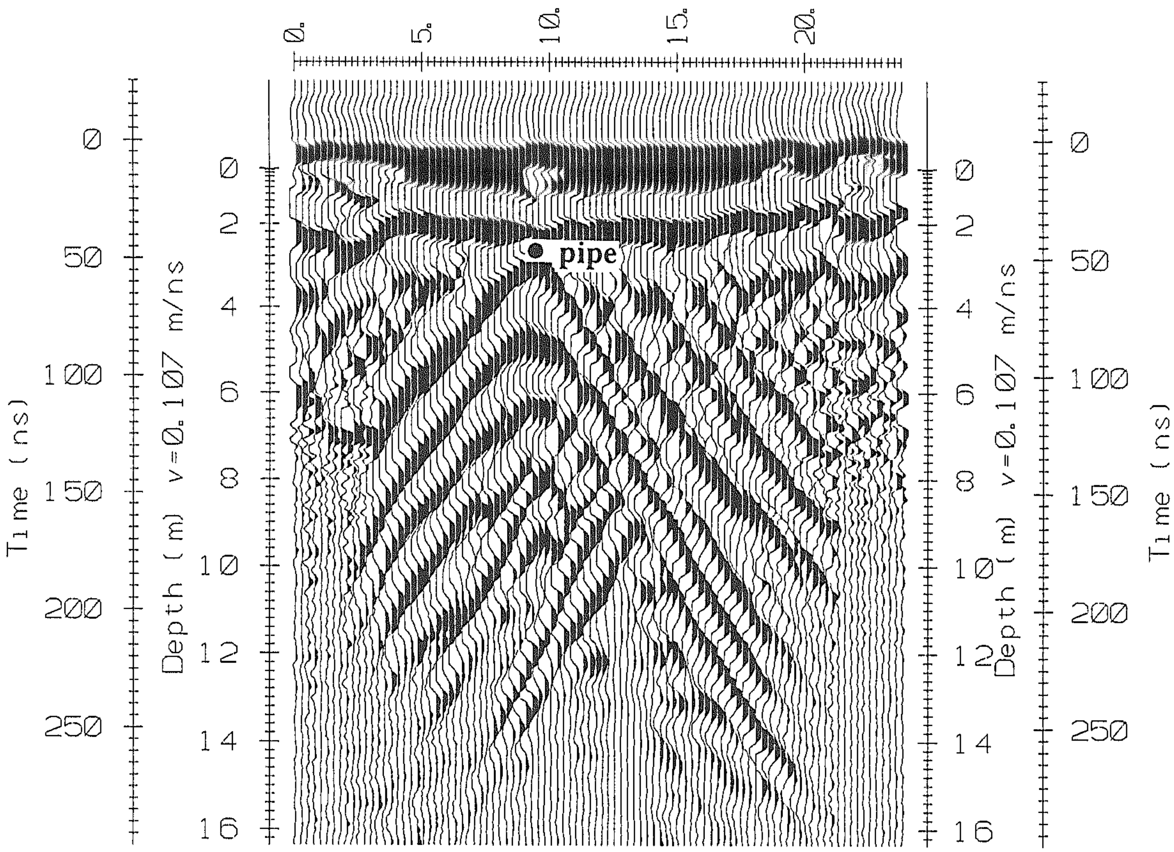

65.
70.
75.
80.
85.
90.
95.
100.
105.
110.
115.
120.
125.
130.
frozen ground
steeply dipping
refraction
Cross 4
Cross 3
Cross 2



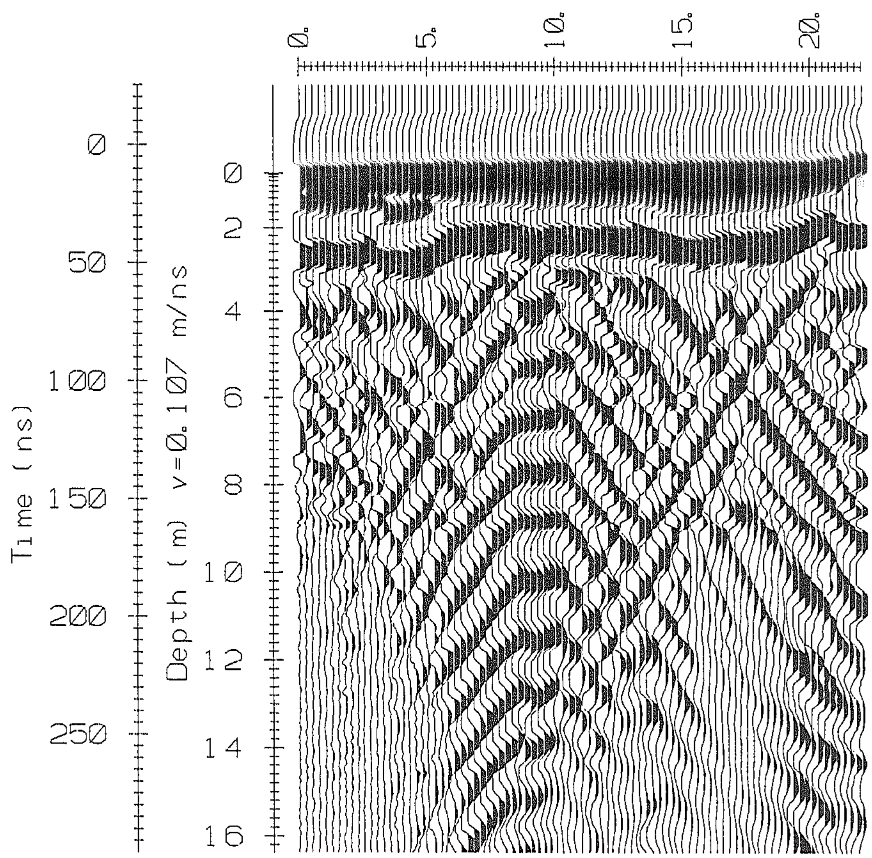
135.
140.
145.
150.
155.
Cross 1
0
2
4
6
8
10
12
14
16
Depth (m) v=0.107 m/ns
0
50
100
150
200
250
Time (ns)



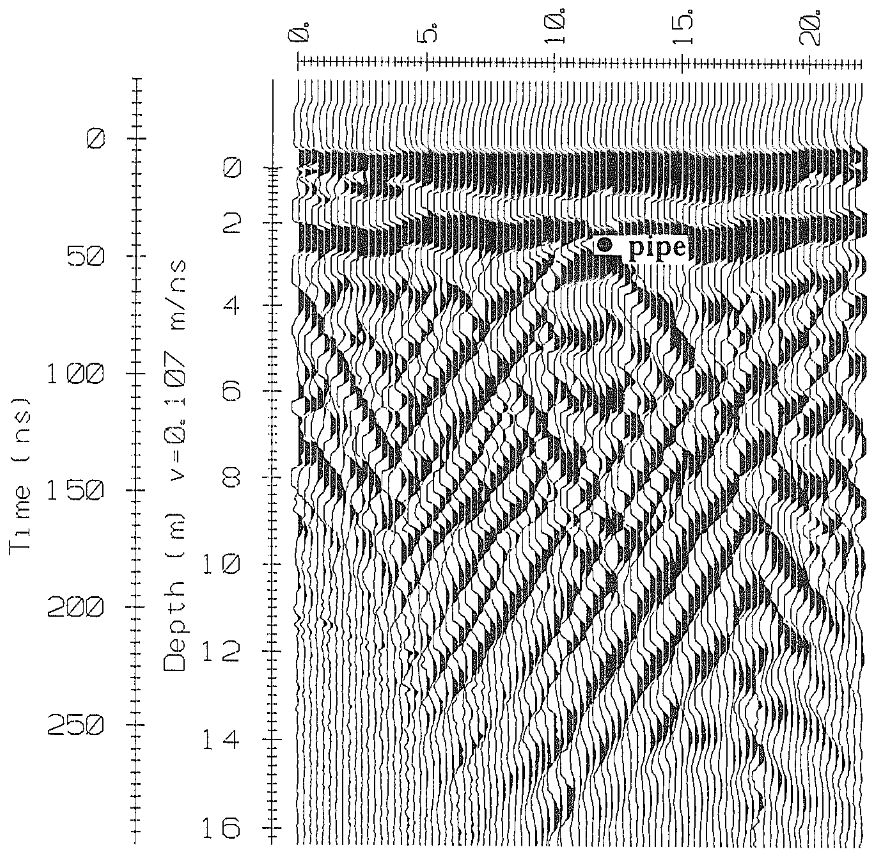
GREAT BEAR RIVER - CROSS PROFILE 1 - 50 MHz - JUNE 9



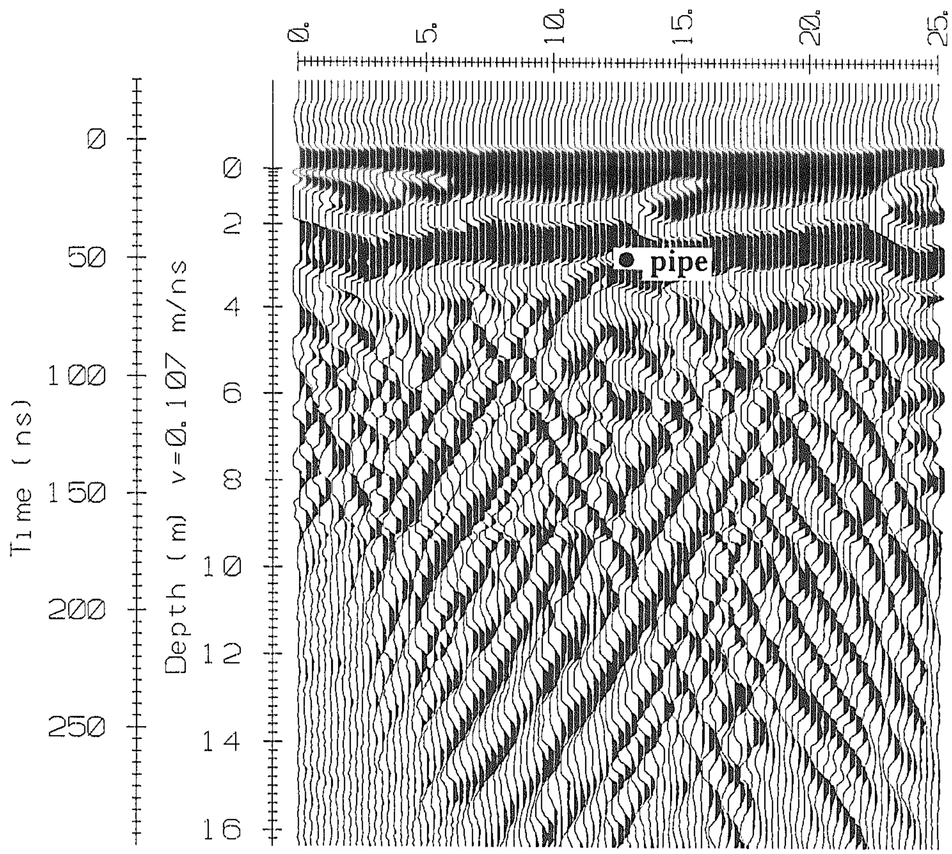
GREAT BEAR RIVER - CROSS PROFILE 2 - 50 MHz - JUNE 9



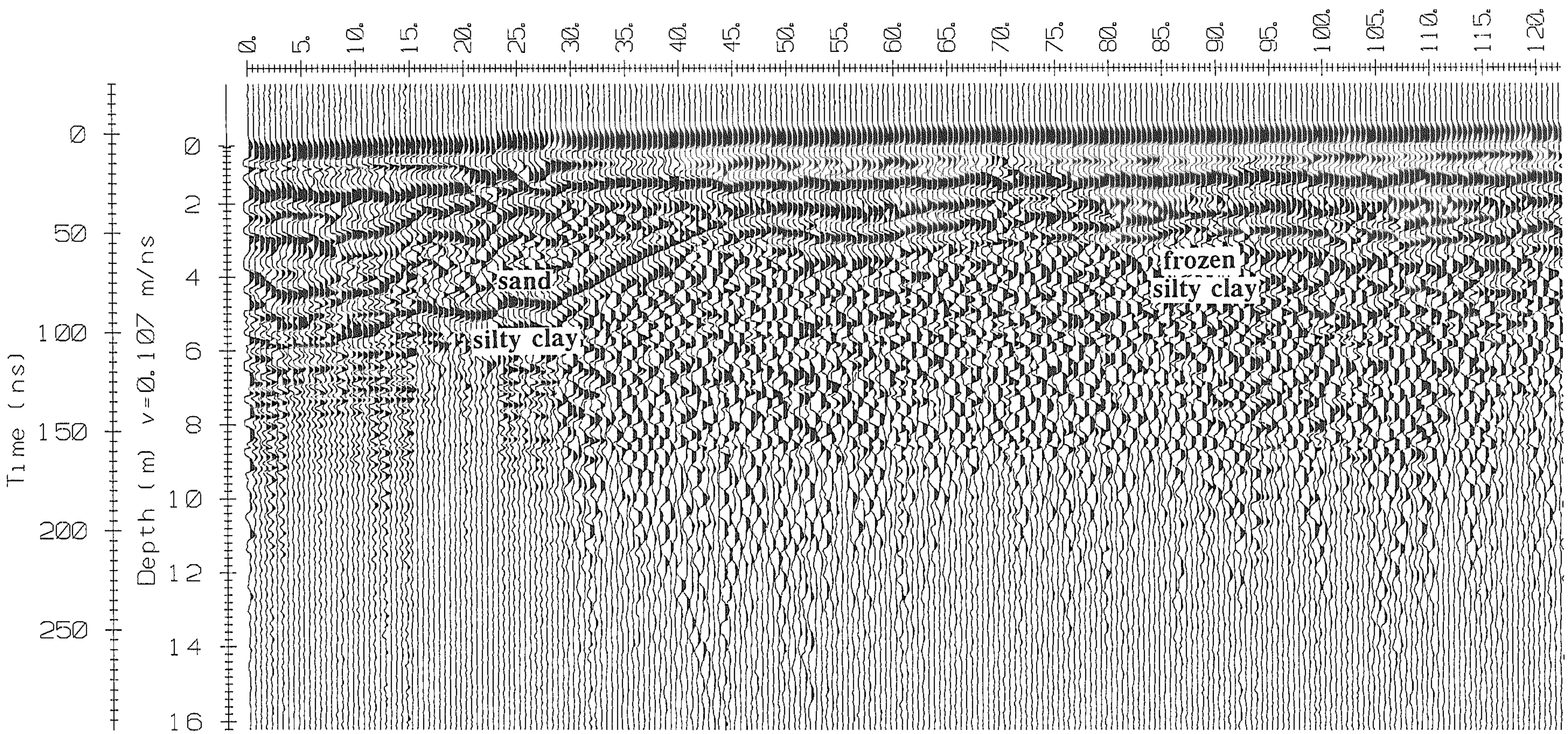
GREAT BEAR RIVER - CROSS PROFILE 3 - 50 MHz - JUNE 9



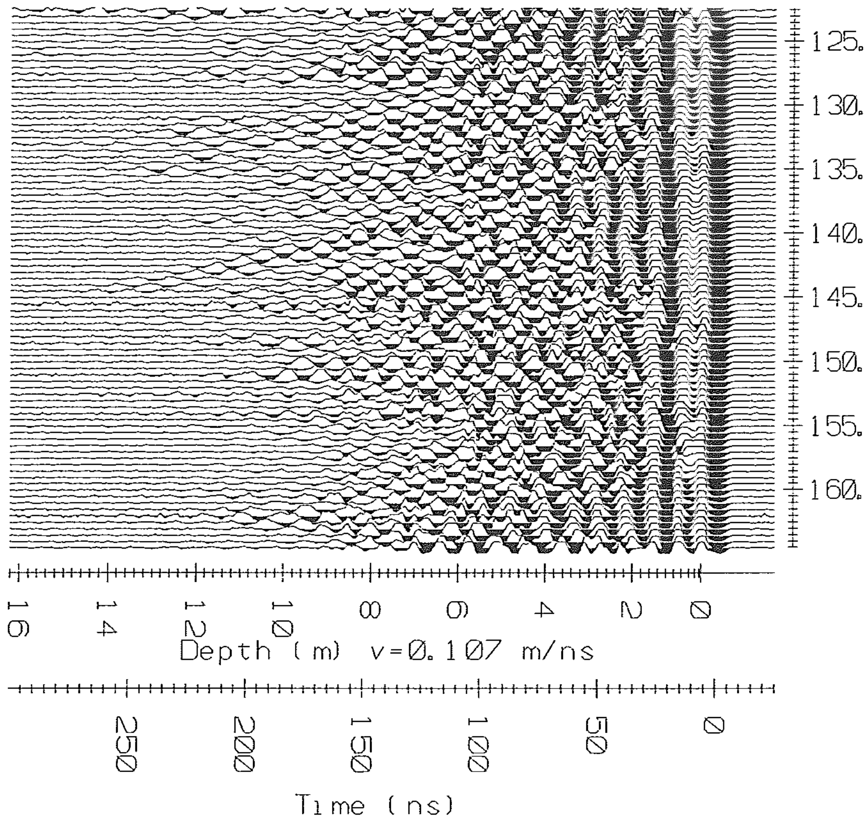
GREAT BEAR RIVER - CROSS PROFILE 4 - 50 MHz - JUNE 9



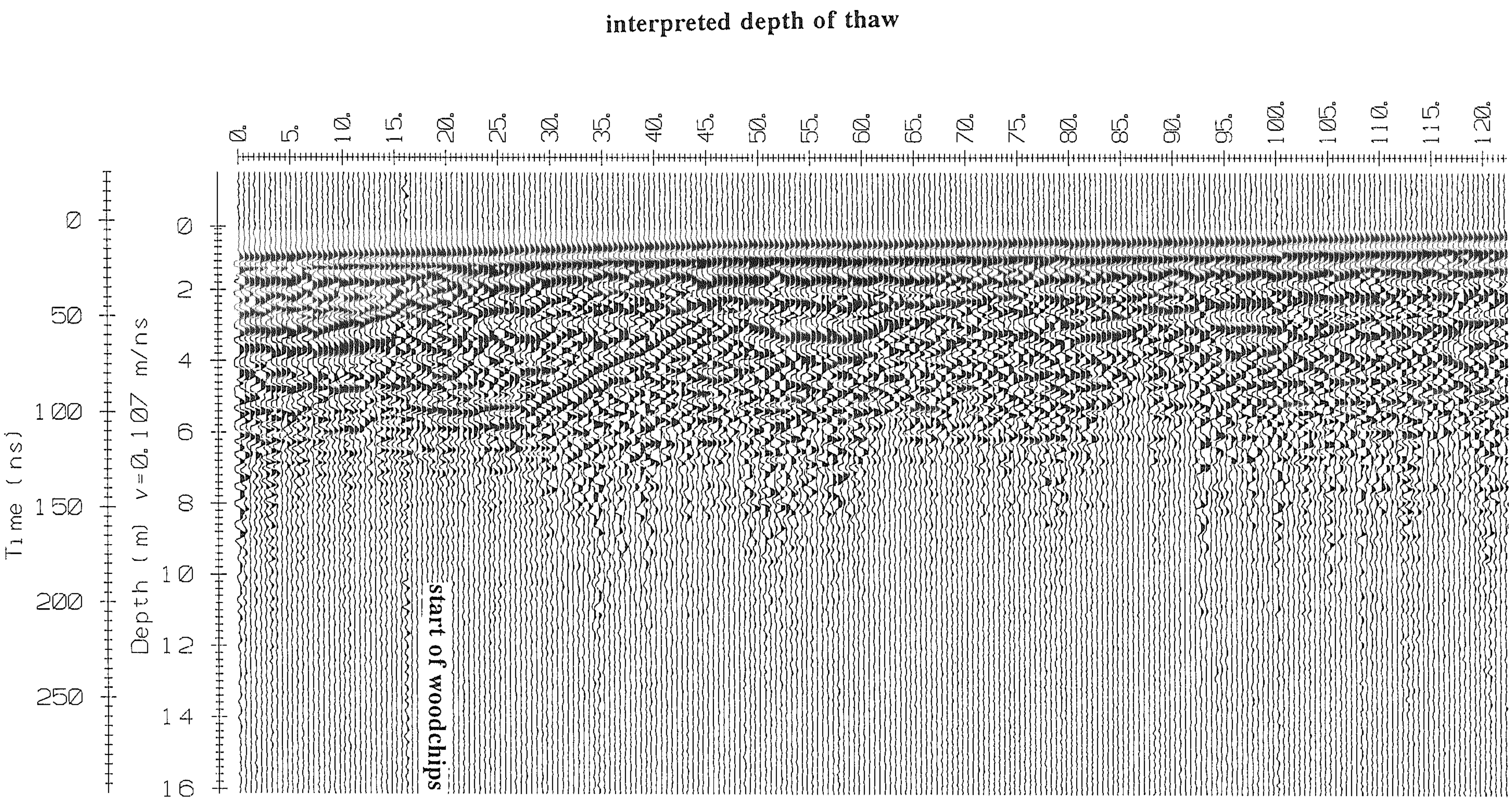
GREAT BEAR RIVER - CROSS PROFILE 5 - 50 MHz - JUNE 9



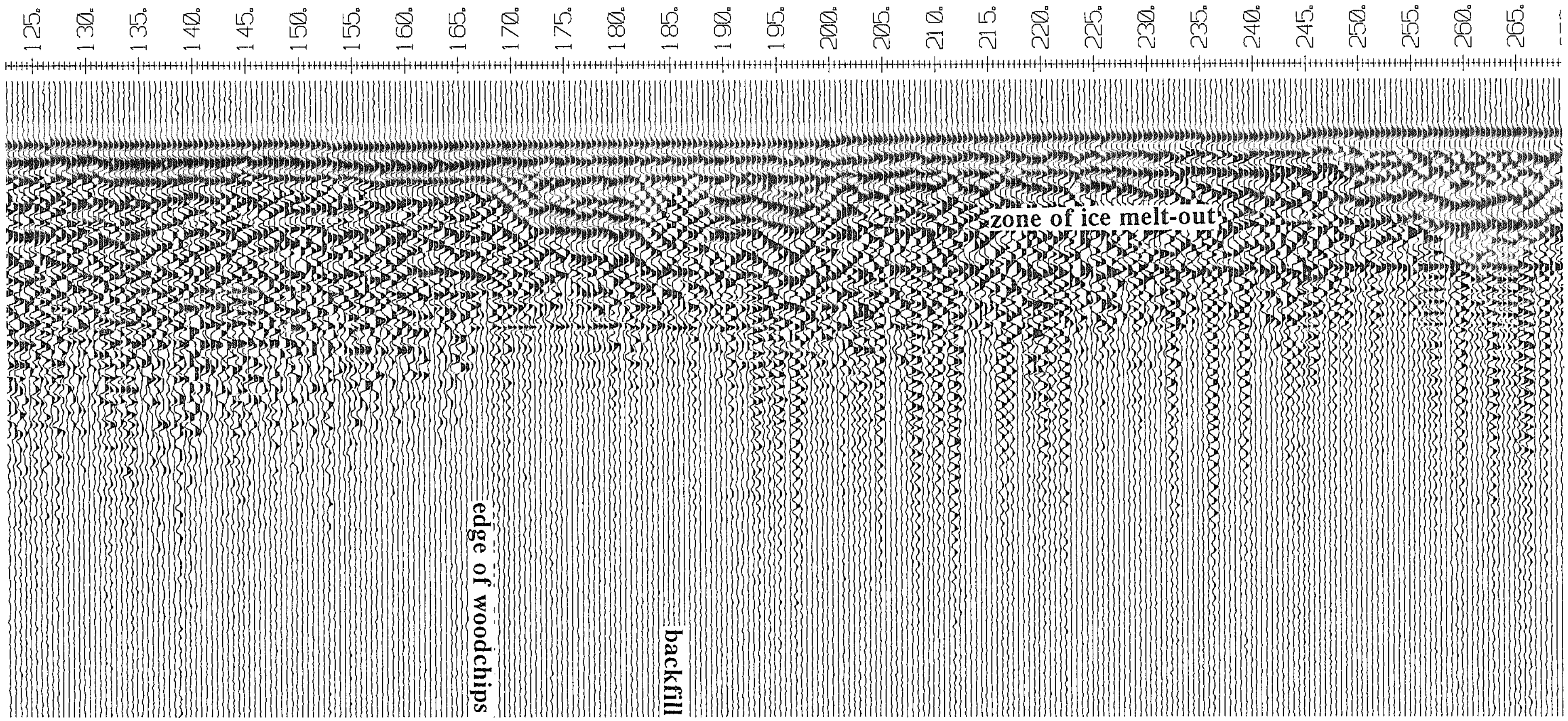
GREAT BEAR RIVER - LONG PROFILE - 100 MHz - JUNE 13



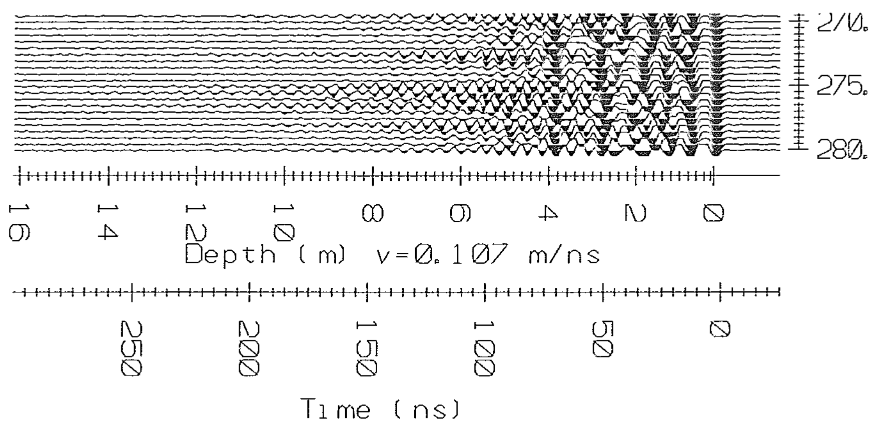
125.
130.
135.
140.
145.
150.
155.
160.
16
14
12
10
8
6
4
2
0
Depth (m) v=0.107 m/ns
250
200
150
100
50
0
Time (ns)



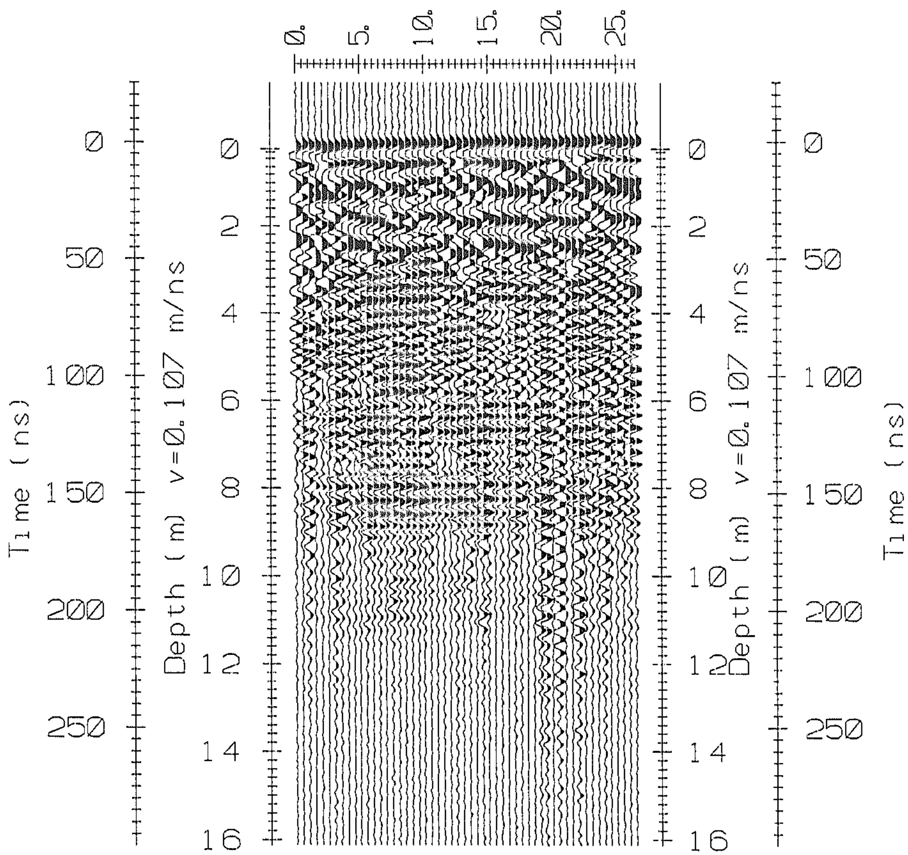
GREAT BEAR RIVER - LONG PROFILE - 200 MHz - JUNE 13



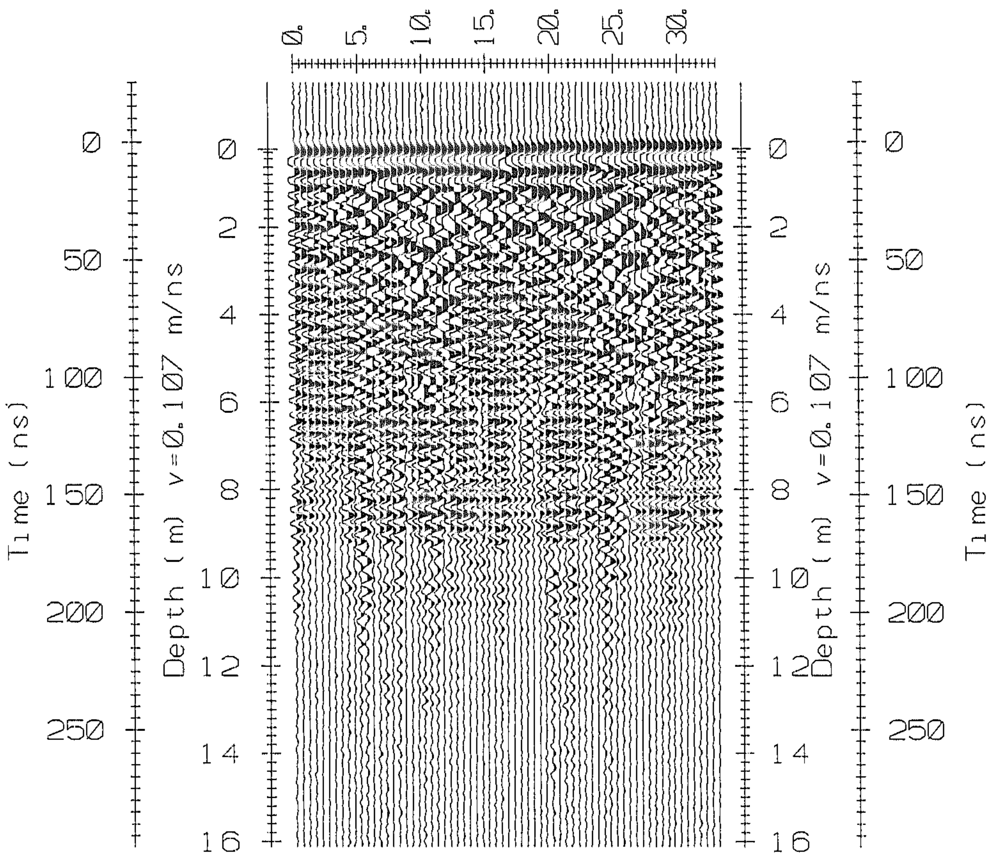
125.
130.
135.
140.
145.
150.
155.
160.
165.
170.
175.
180.
185.
190.
195.
200.
205.
210.
215.
220.
225.
230.
235.
240.
245.
250.
255.
260.
265.
zone of ice melt-out
edge of woodchips
backfill



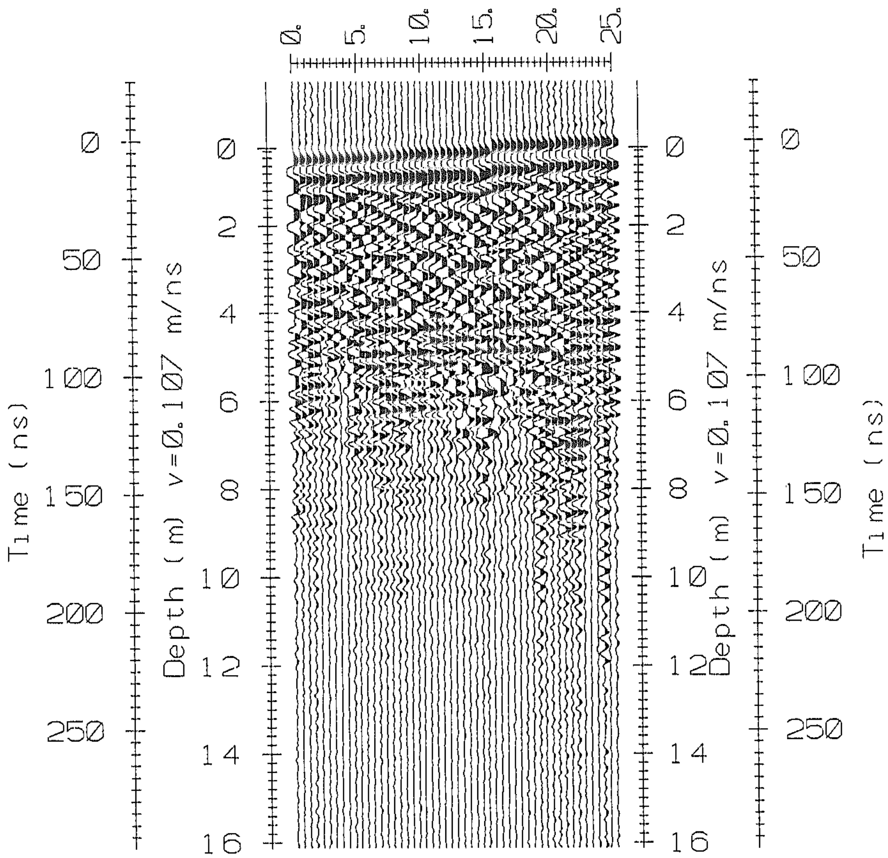
270.
275.
280.
Depth (m) v=0.107 m/ns
Time (ns)



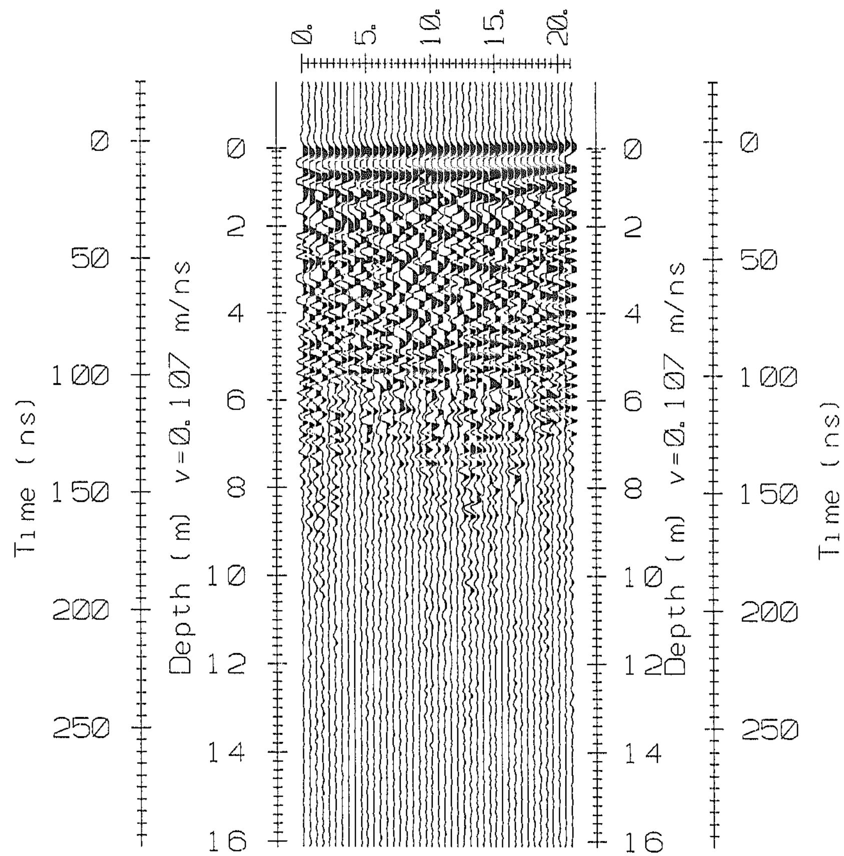
GREAT BEAR RIVER - CROSS PROFILE 1 - 200 MHz - JUNE 13



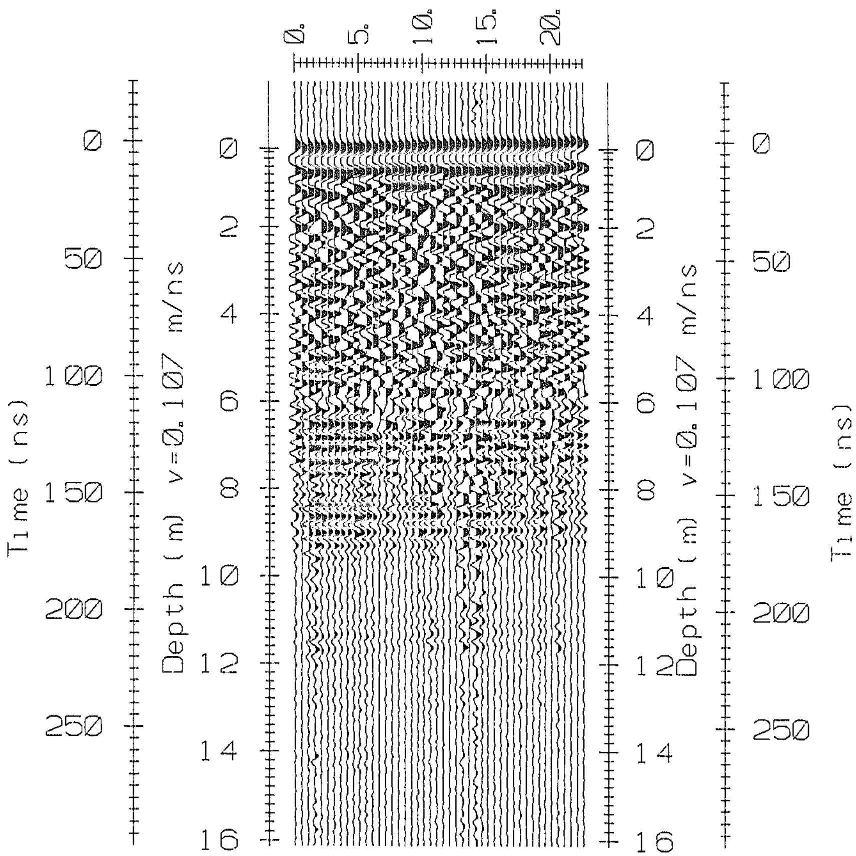
GREAT BEAR RIVER - CROSS PROFILE 2 - 200 MHz - JUNE 13



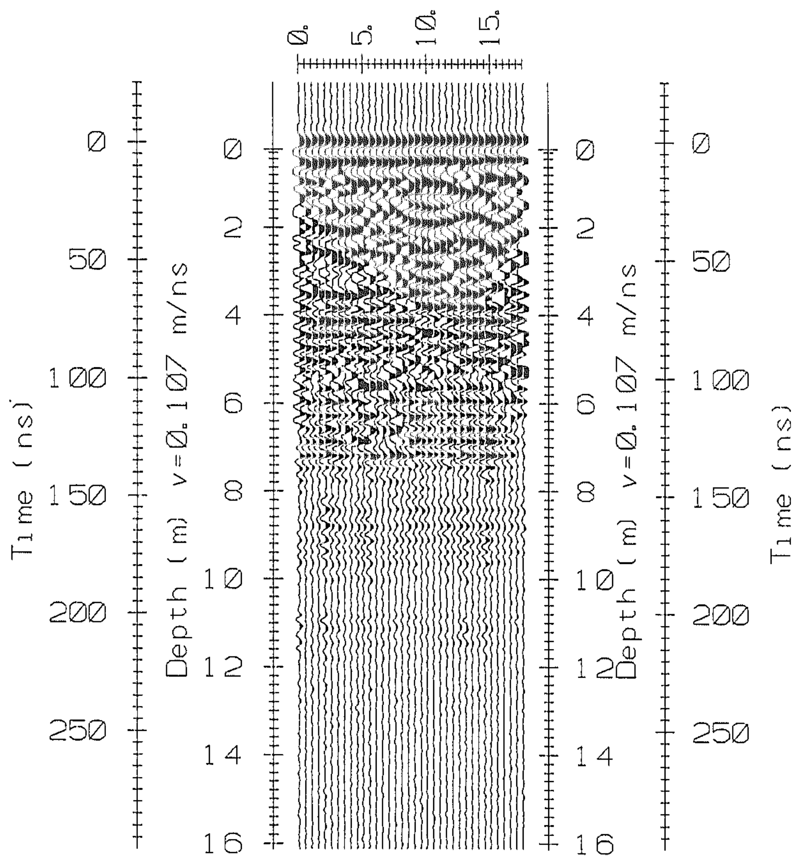
GREAT BEAR RIVER - CROSS PROFILE 3 - 200 MHz - JUNE 13



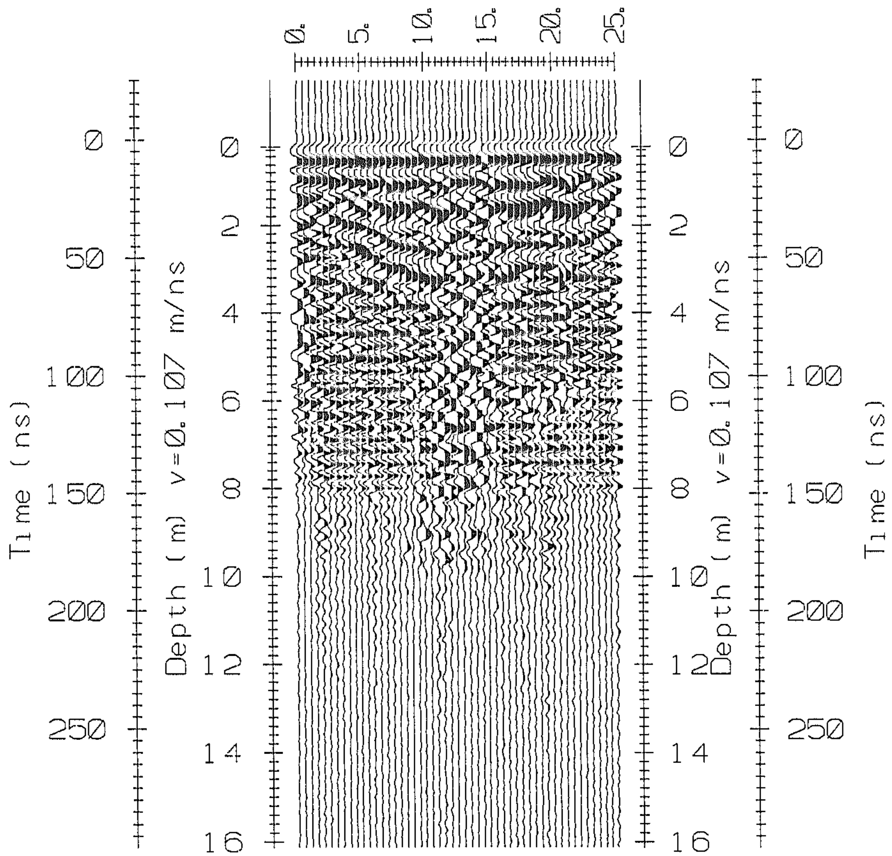
GREAT BEAR RIVER - CROSS PROFILE 4 - 200 MHz - JUNE 13



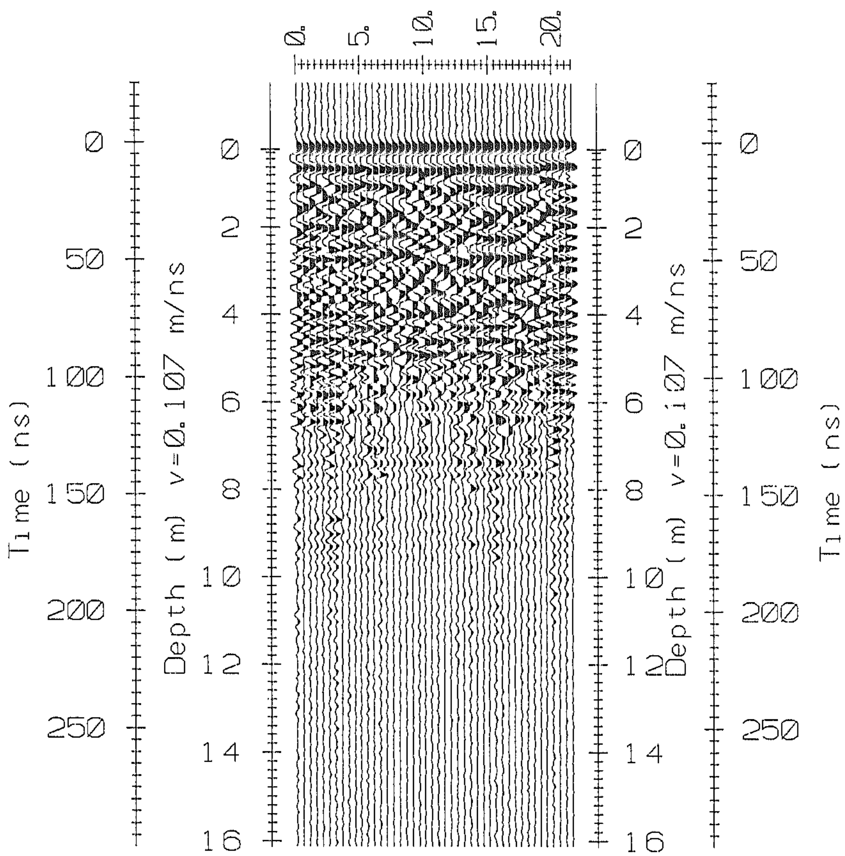
GREAT BEAR RIVER - CROSS PROFILE 5 - 200 MHz - JUNE 13



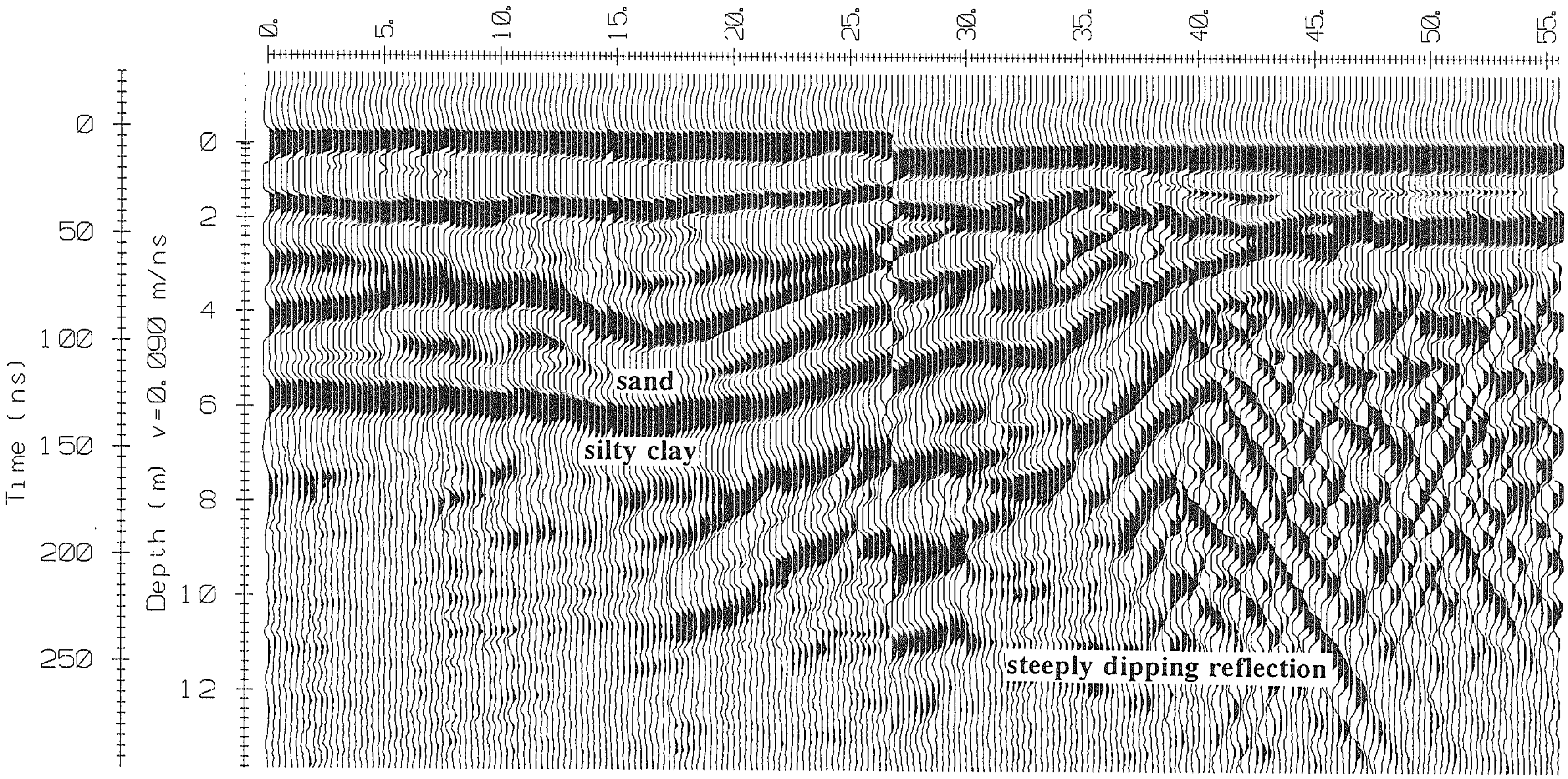
GREAT BEAR RIVER - CROSS PROFILE 6 - 200 MHz - JUNE 13



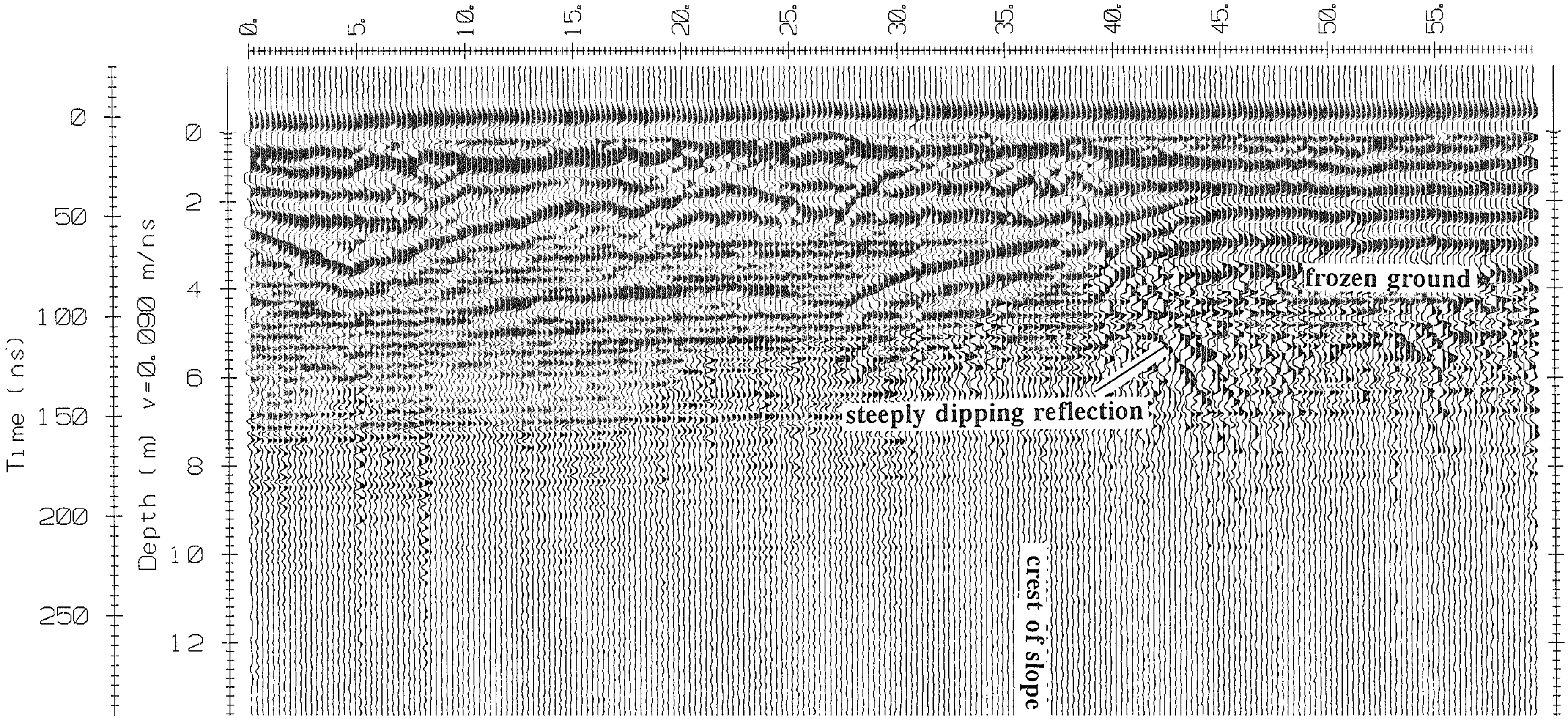
GREAT BEAR RIVER - CROSS PROFILE 7 - 200 MHz - JUNE 13



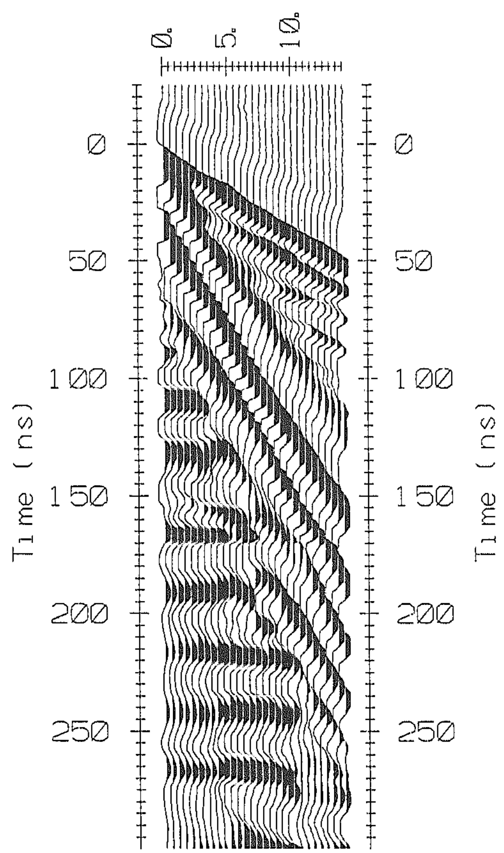
GREAT BEAR RIVER - CROSS PROFILE 8 - 200 MHz - JUNE 13



GREAT BEAR RIVER - SLOPE CREST, E SIDE - 50 MHz - AUGUST 29



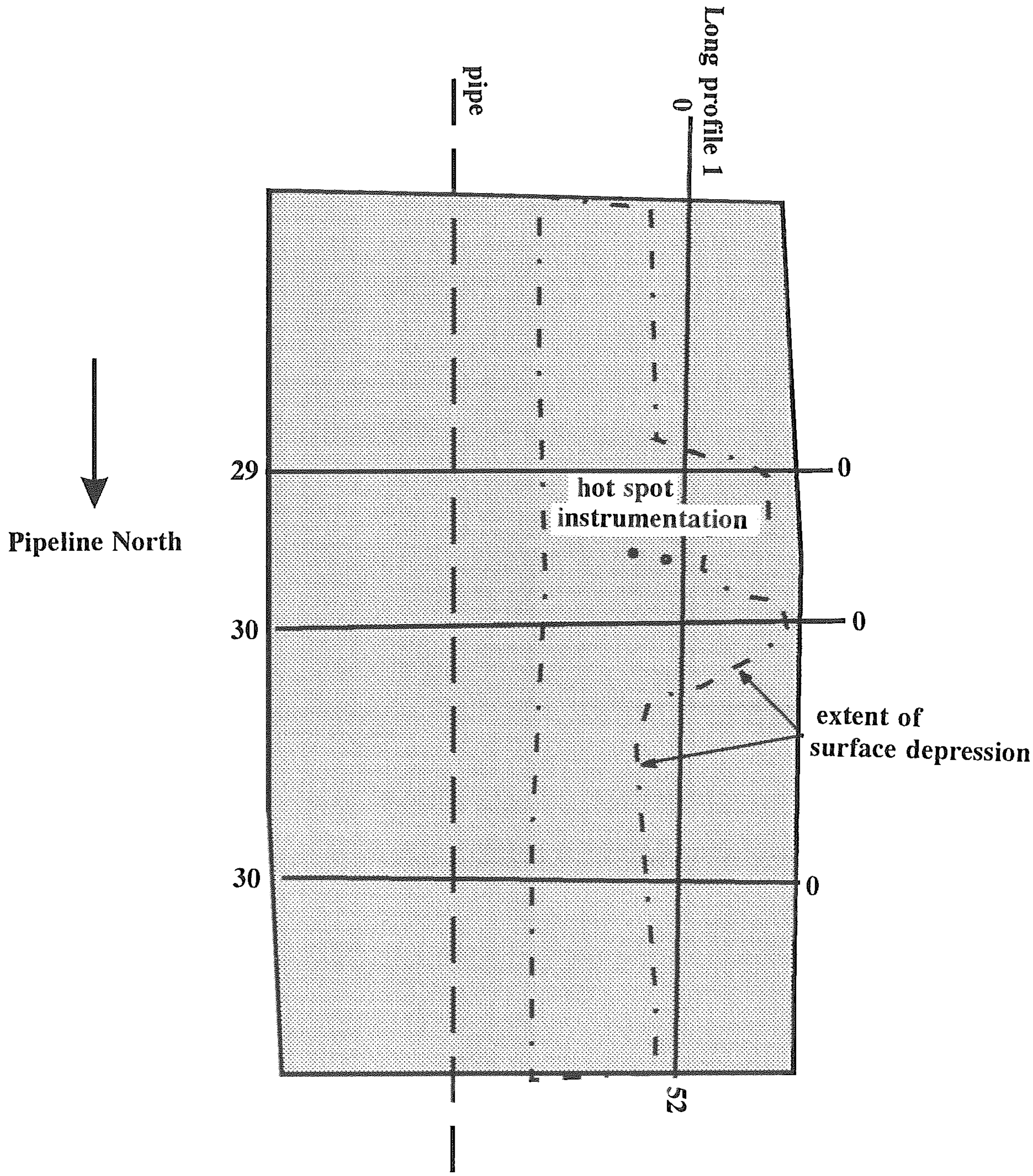
GREAT BEAR RIVER - SLOPE CREST, W SIDE - 100 MHz - AUGUST 29

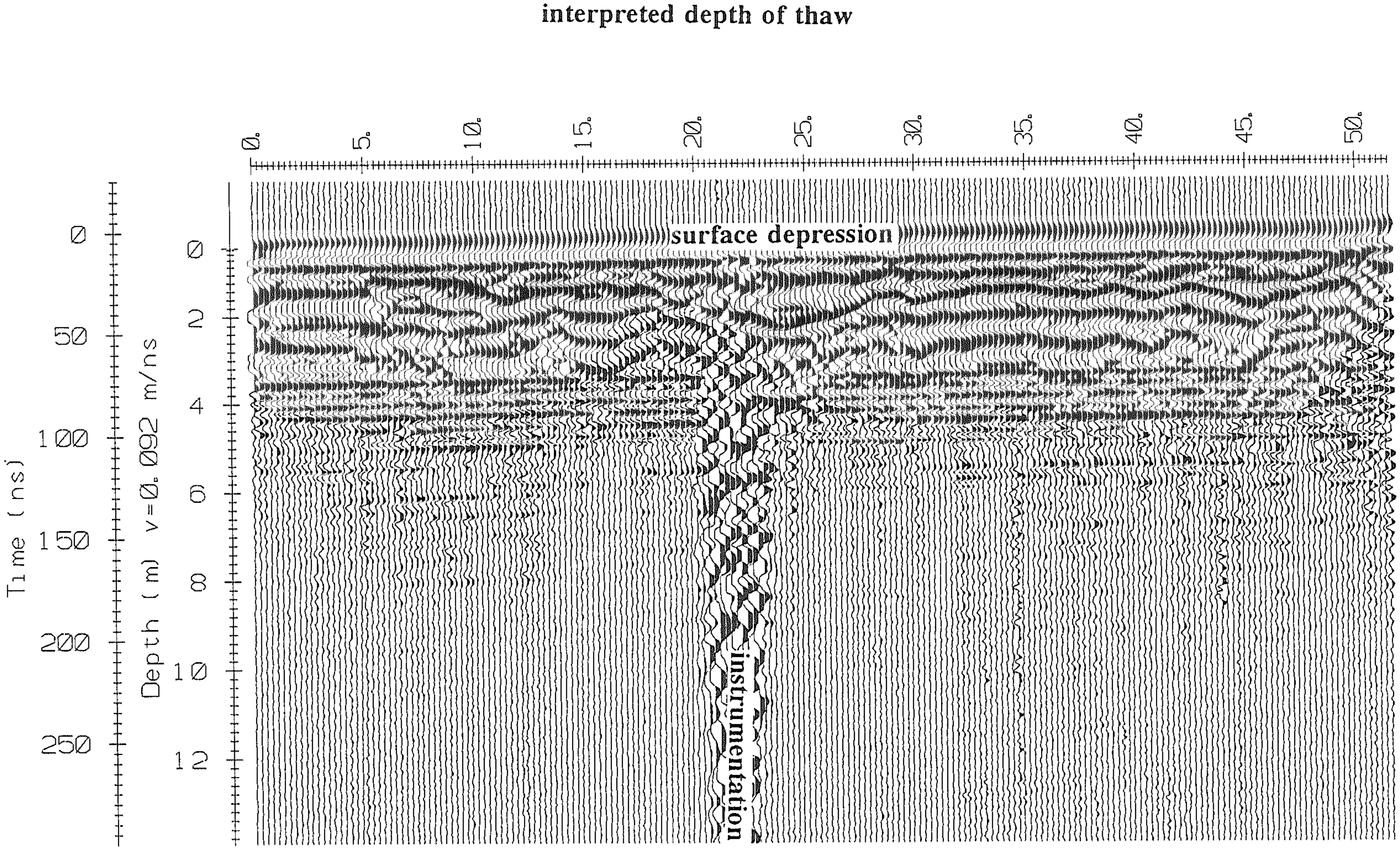


GREAT BEAR RIVER - CMP - JUNE 9

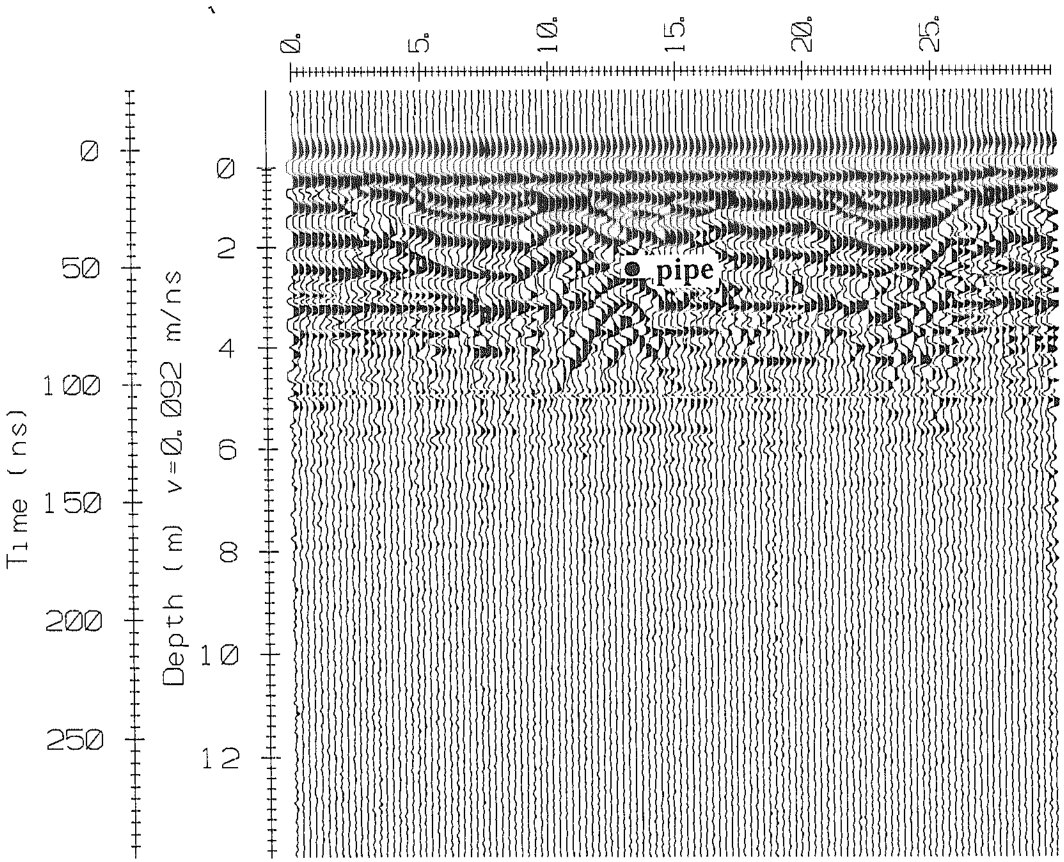
Kp 84

Not to Scale

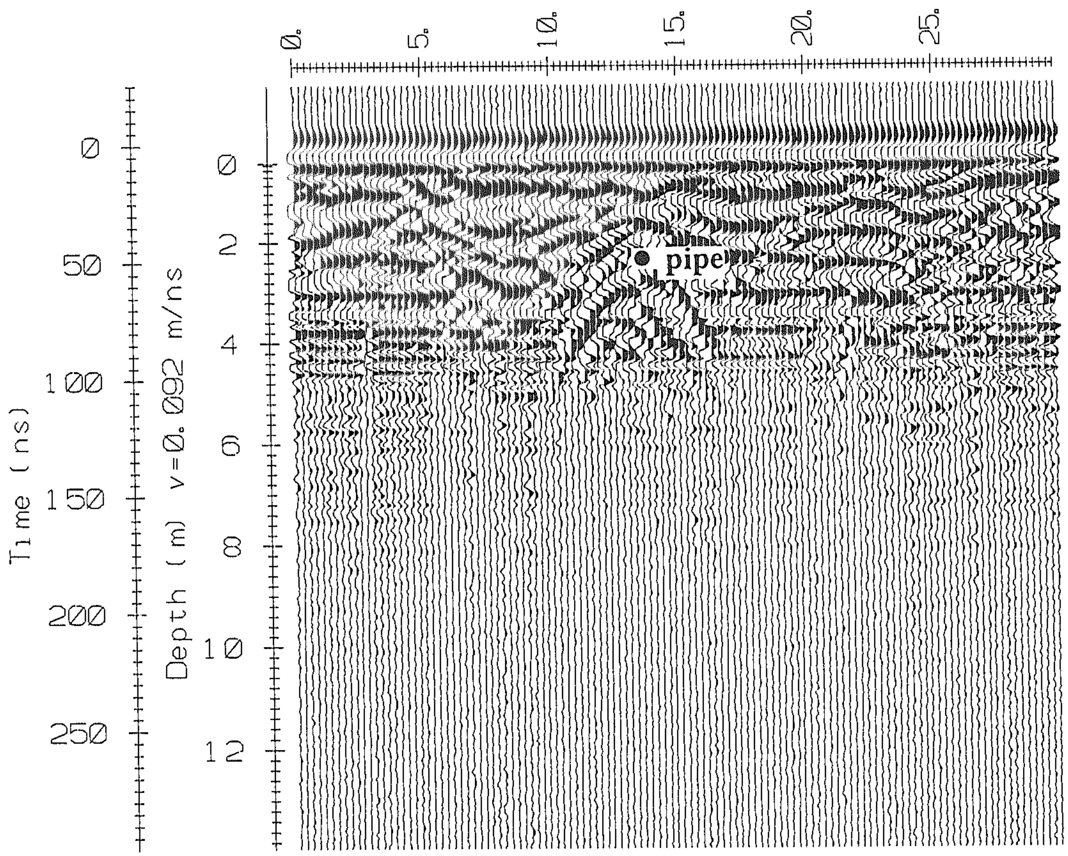




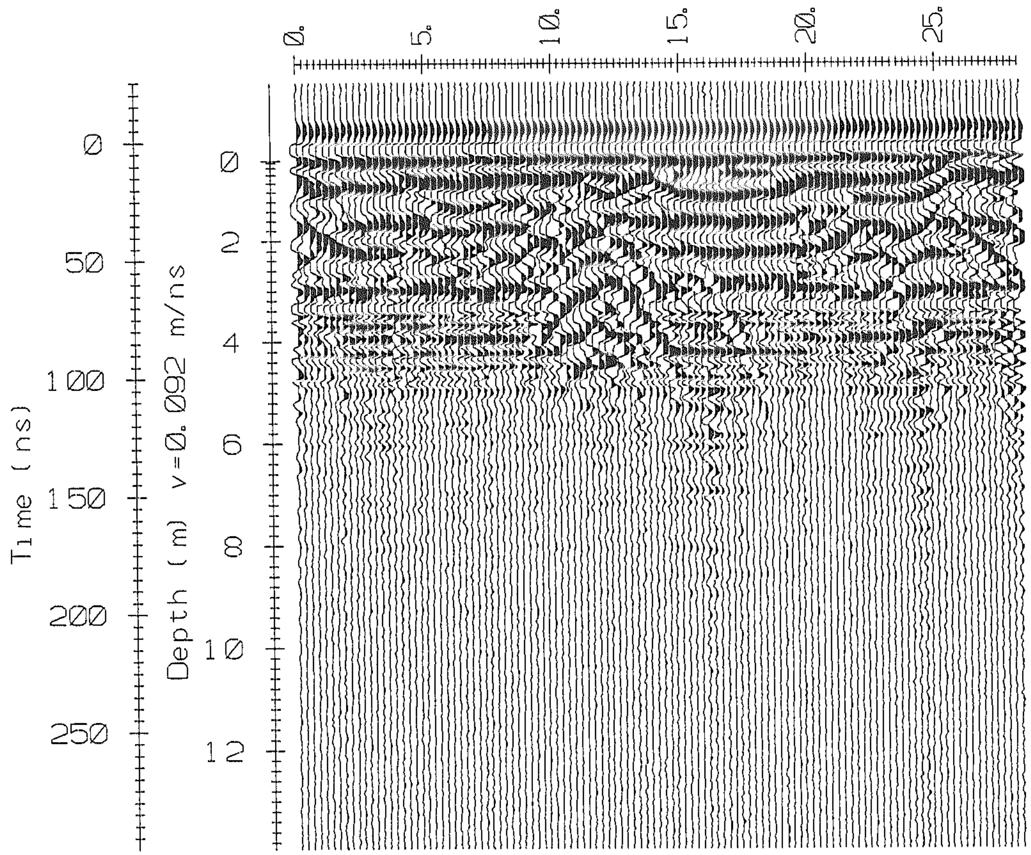
KP 84 - LONG PROFILE - 100 MHz - NO TOPO - AUGUST 23



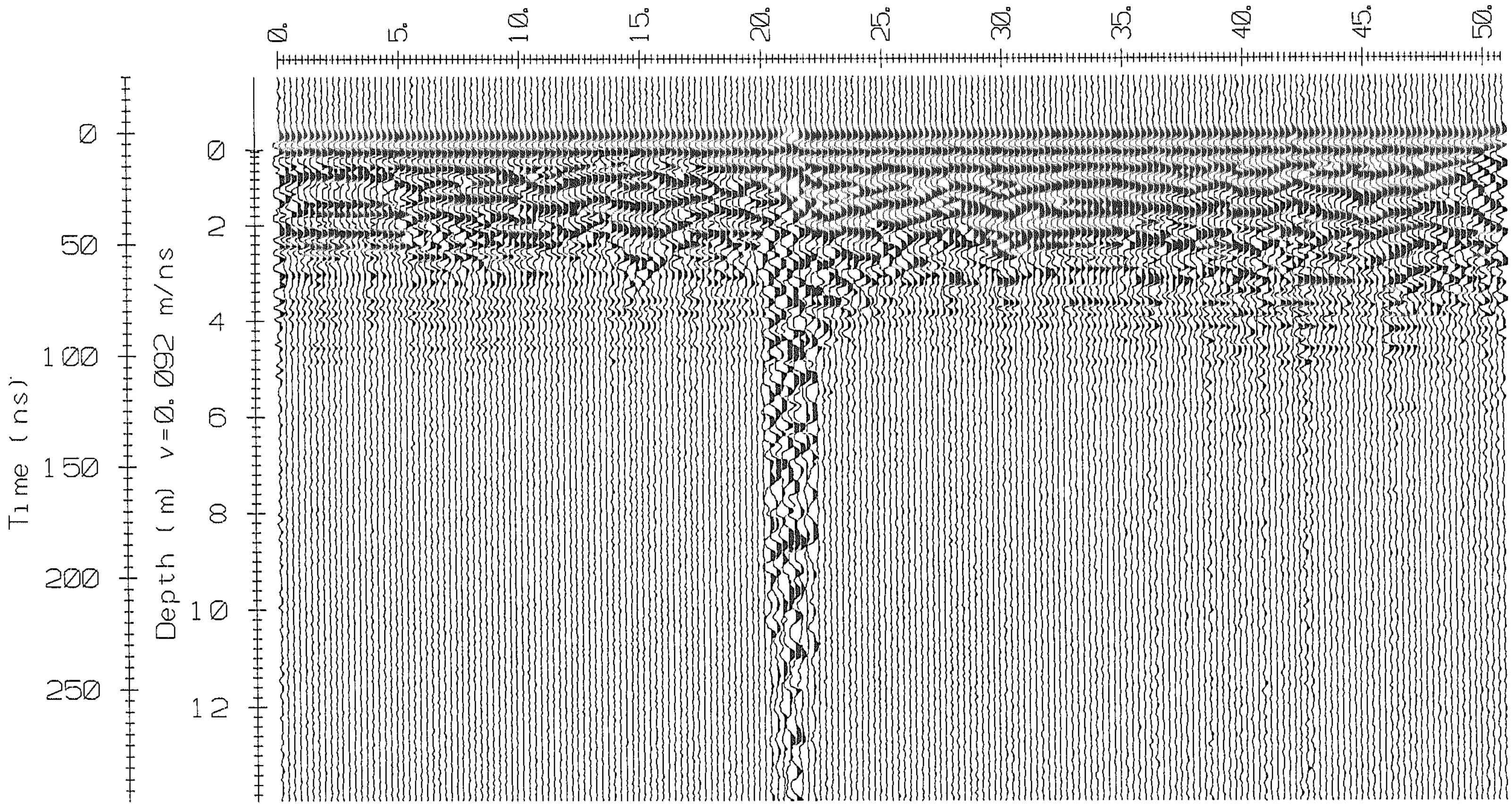
KP 84 - CROSS PROFILE 1 - 100 MHz - AUGUST 23



KP 84 - CROSS PROFILE 2 - 100 MHz - AUGUST 23

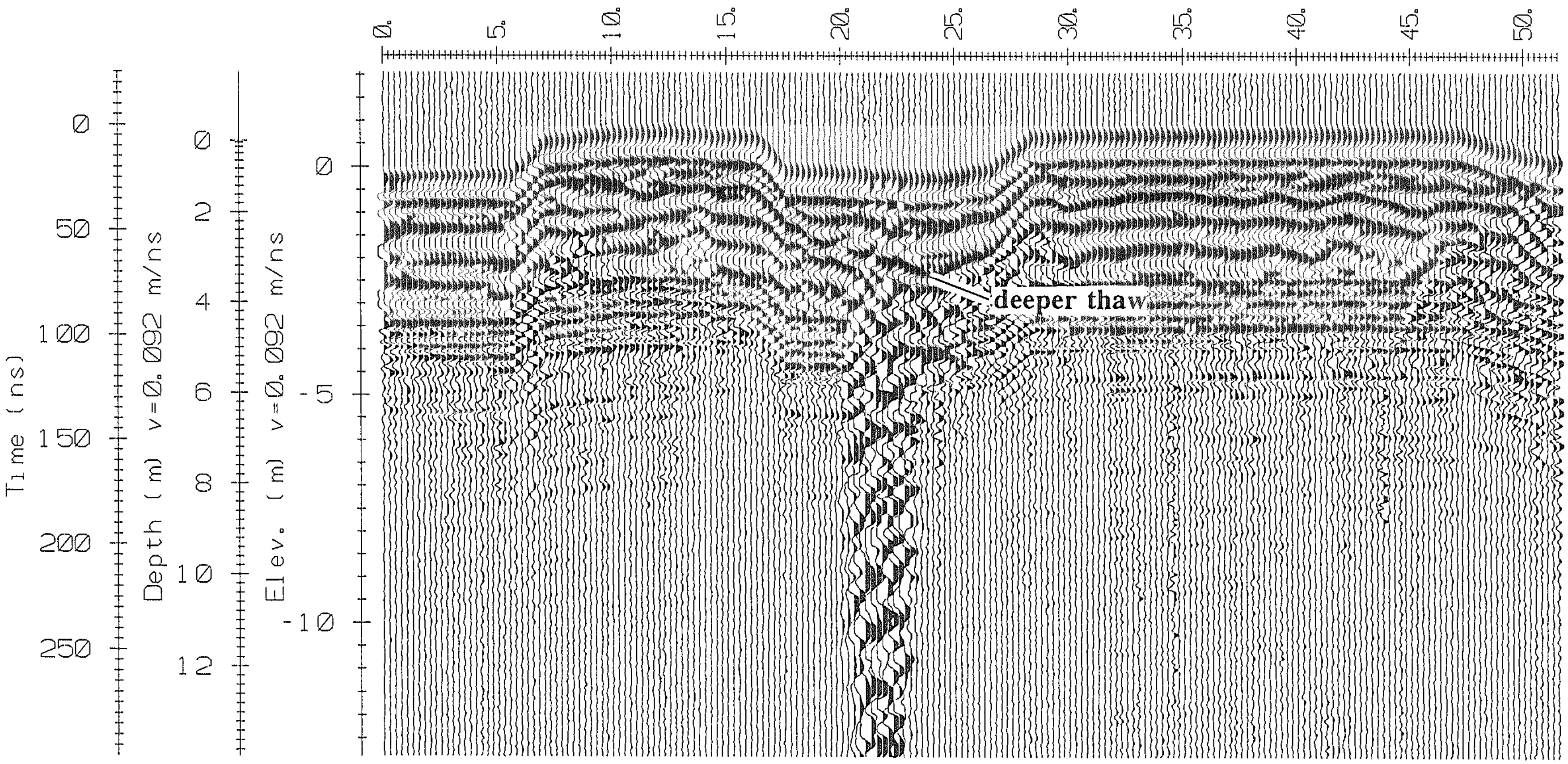


KP 84 - CROSS PROFILE 3 - 100 MHz - AUGUST 23

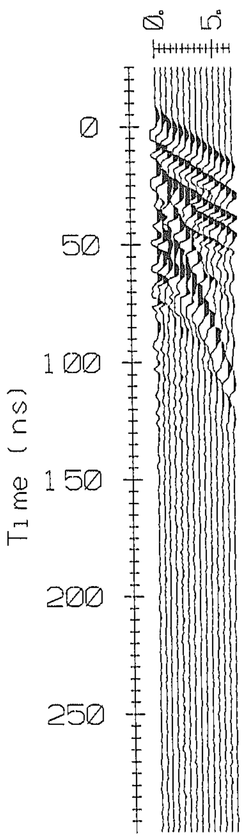


KP 84 - LONG PROFILE - 200 MHz - NO TOPO - AUGUST 23

interpreted depth of thaw



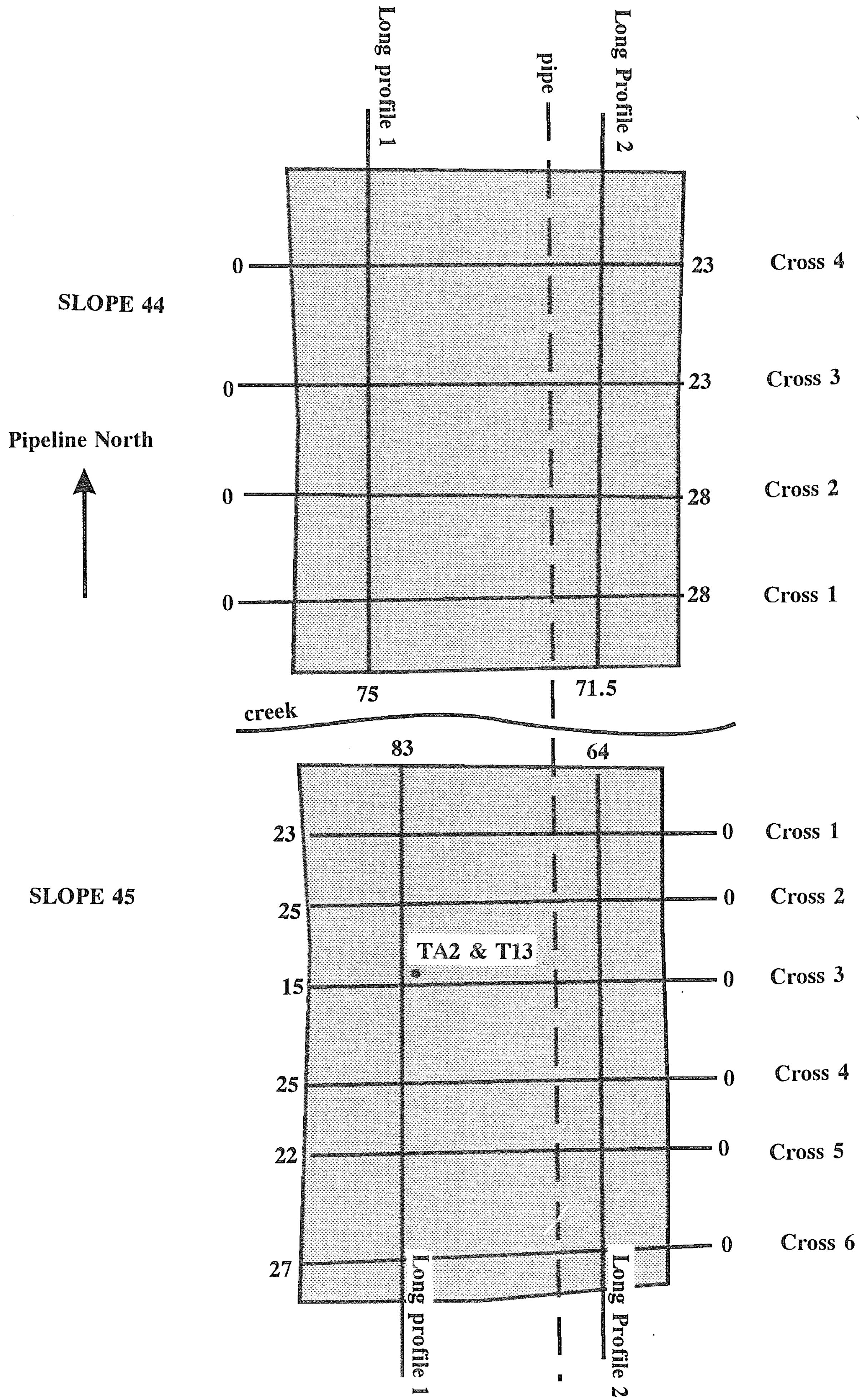
KP 84 - LONG PROFILE - 100 MHz - TOPO CORRECTED - AUGUST 23



KP 84 - CMP - AUGUST 23

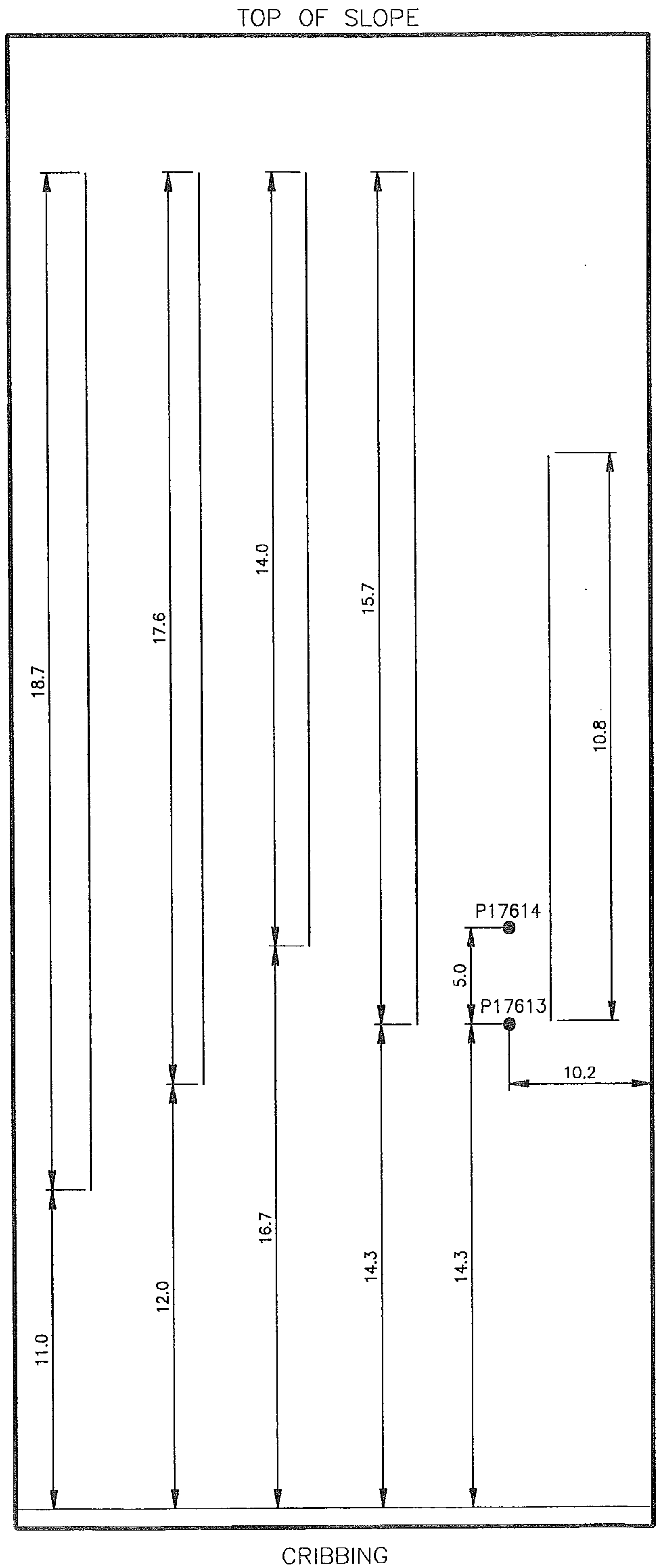
SLOPES 44 AND 45 (kp 133.6)

Not to Scale



SLOPE DRAINAGE INSTALLATION - NORMAN WELLS PIPELINE

Kp 133N, SLOPE 44, AS BUILTS FEB. 94



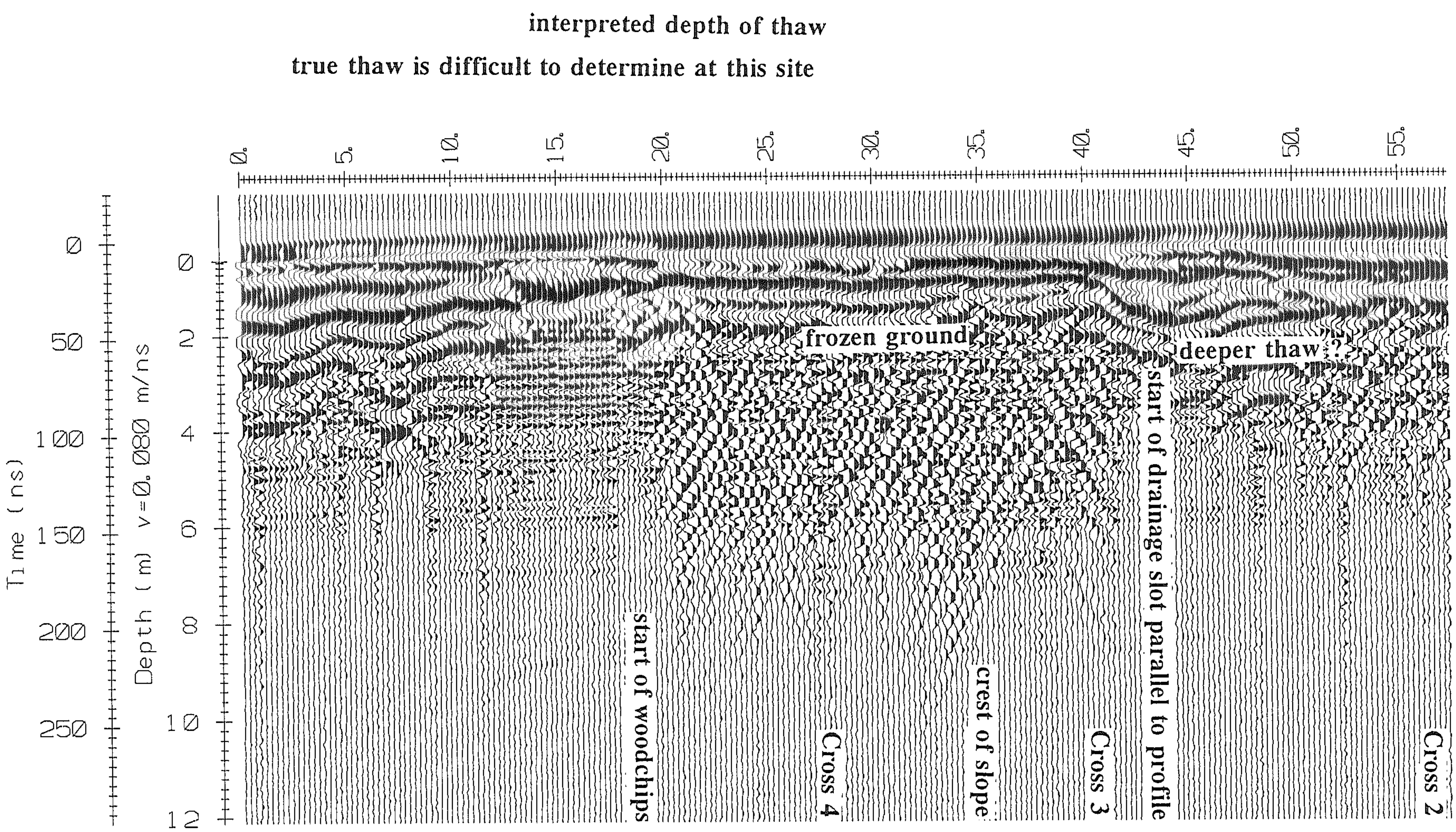
LEGEND

DRAINAGE TILE ————

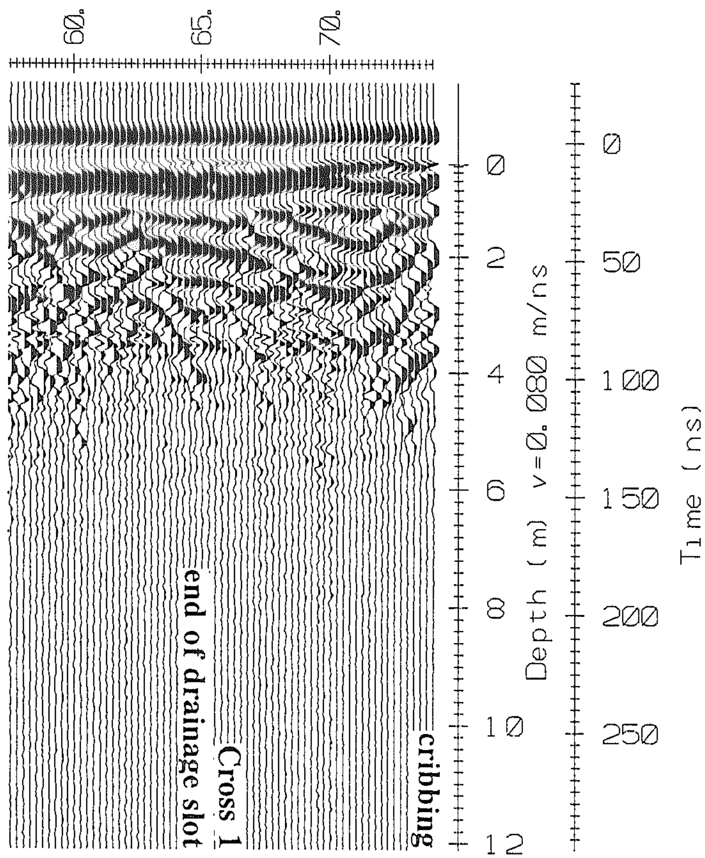
NOTE

ALL DIMENSIONS IN METERS

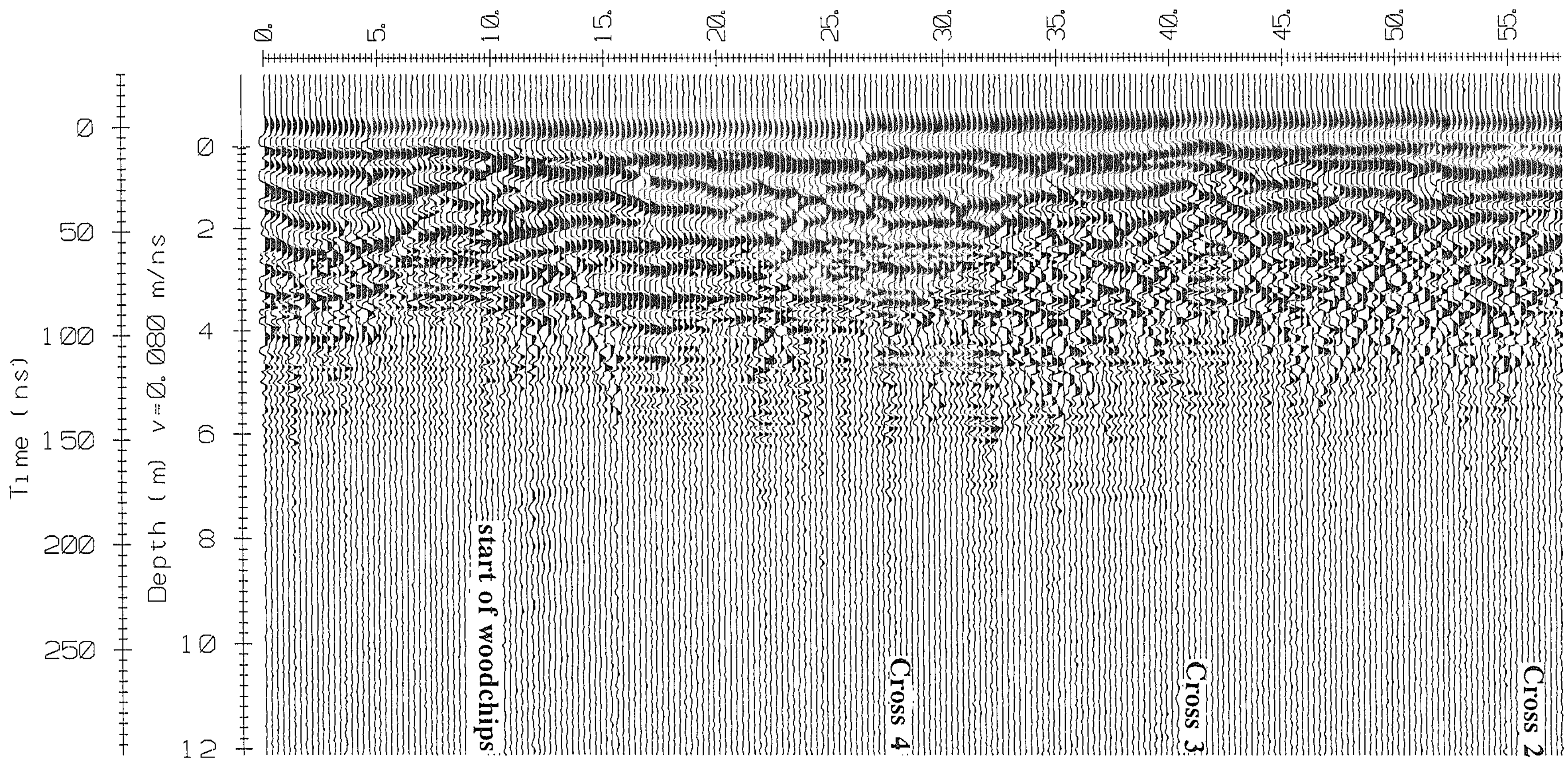
19/05/94



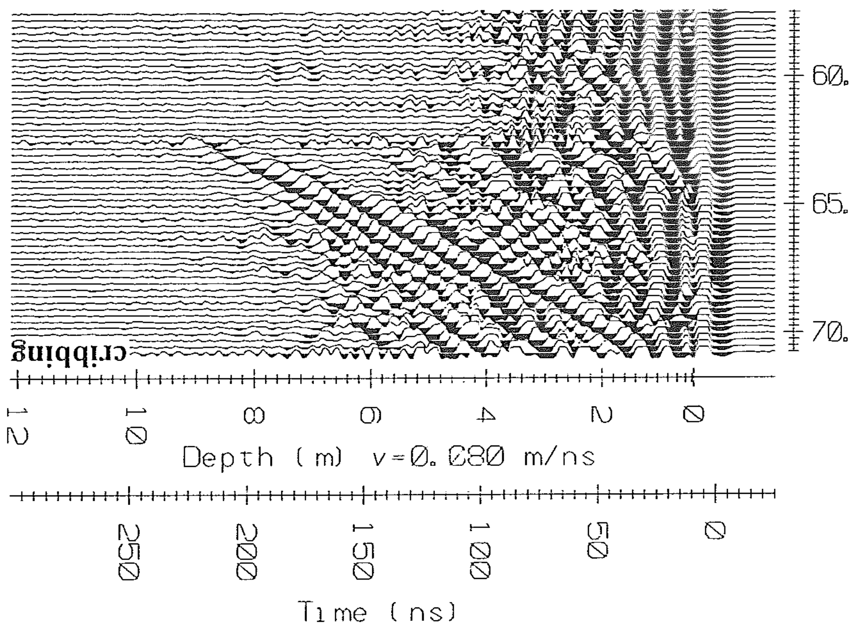
SLOPE 44 - LONG PROFILE 1 - 100 MHz - JUNE 23

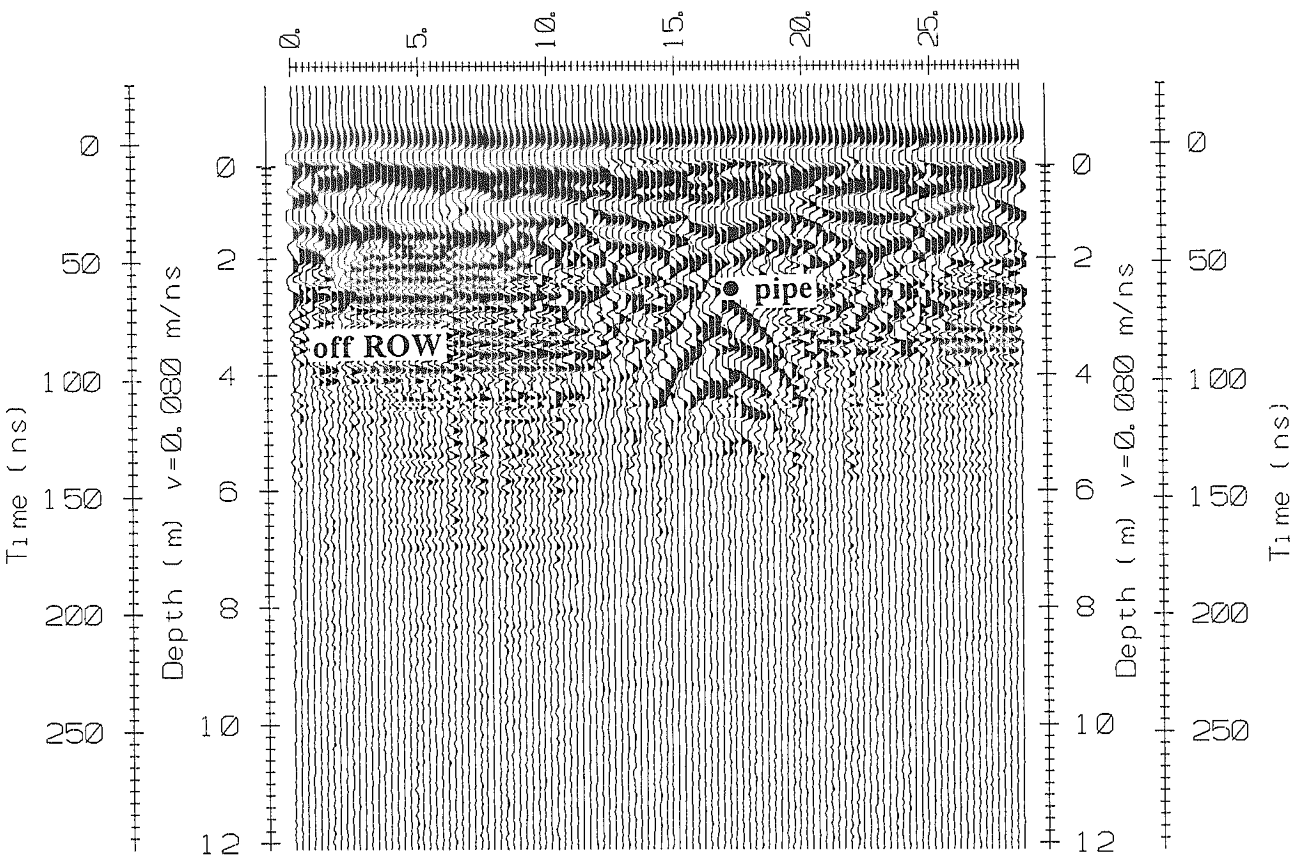

60.
65.
70.
0
2
4
6
8
10
12
Depth (m) v=0.080 m/ns
0
50
100
150
200
250
Time (ns)
cribbing
Cross 1
end of drainage slot

thaw is difficult to determine at this site

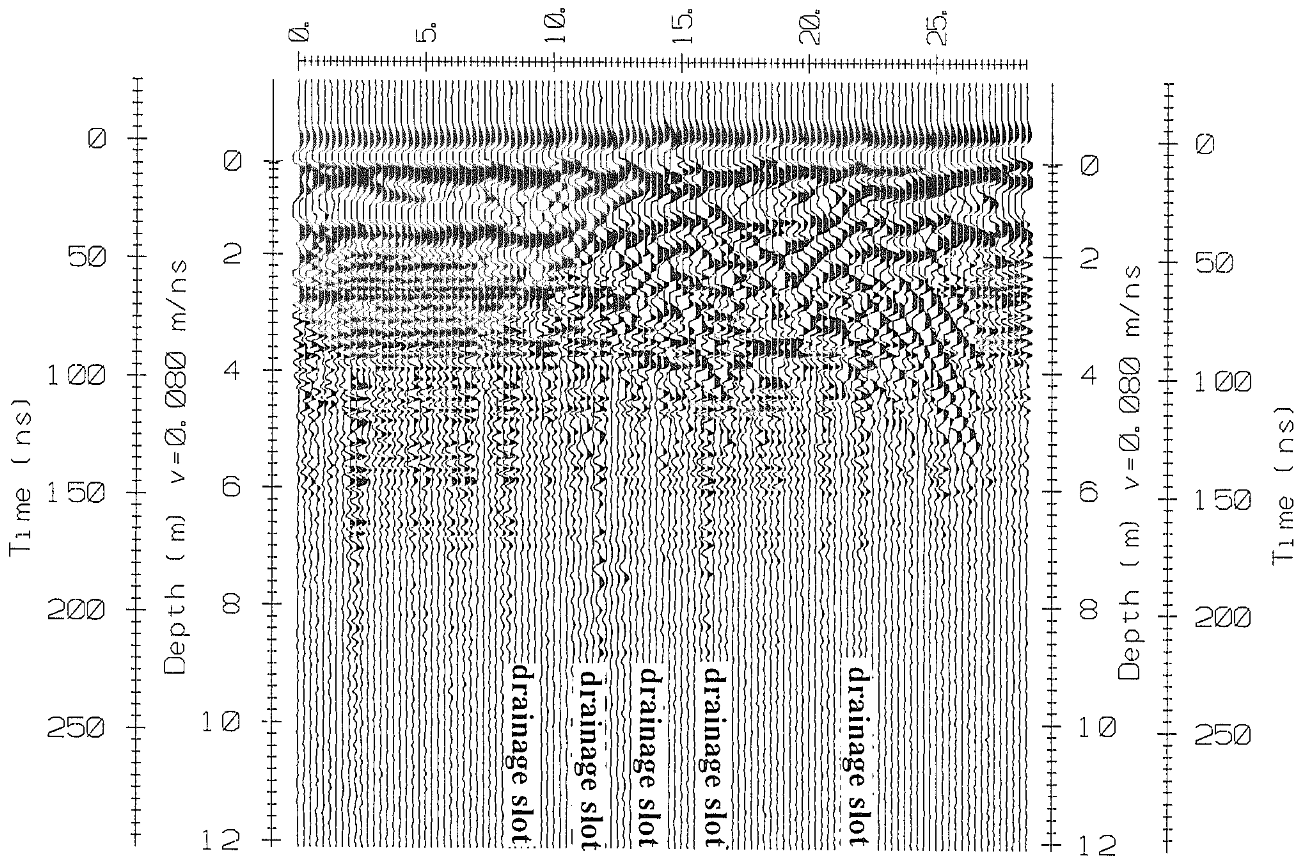


SLOPE 44 - LONG PROFILE 2 - 100 MHz - JUNE 23

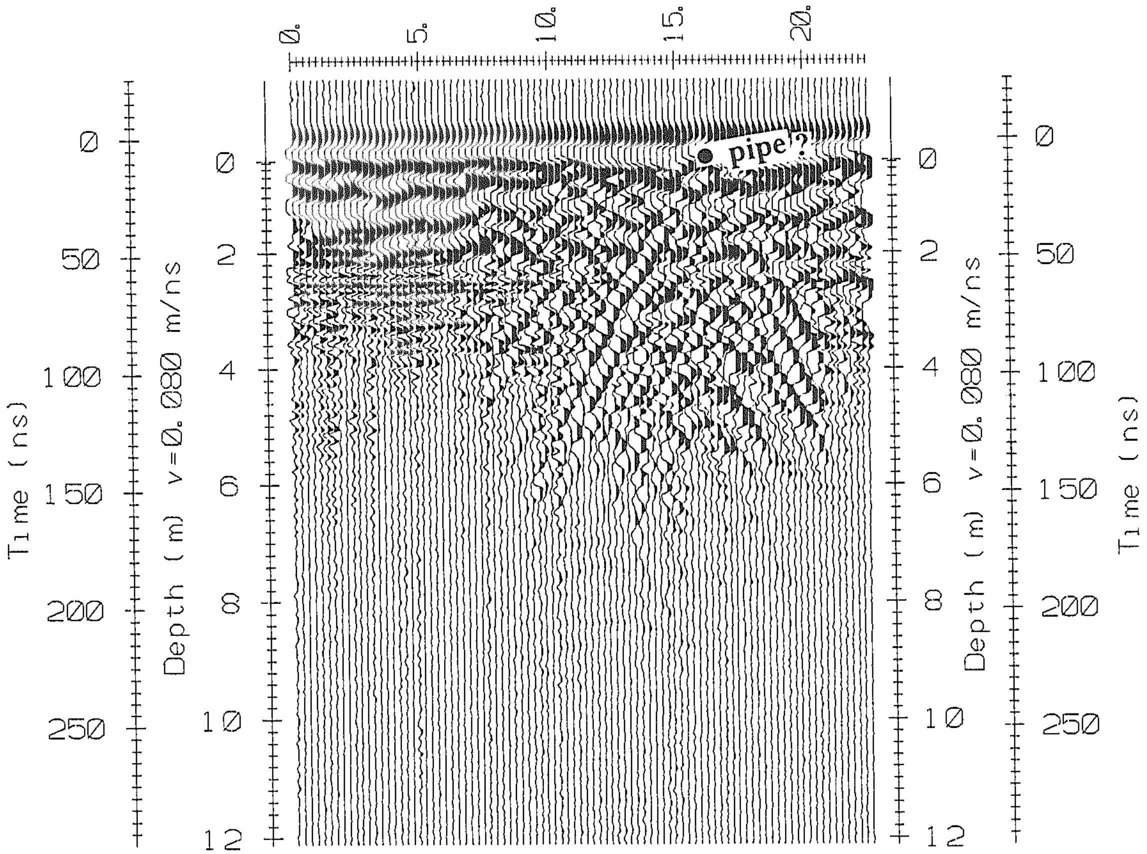

60.
65.
70.
Depth (m) v=0.080 m/ns
Time (ns)
cribbing



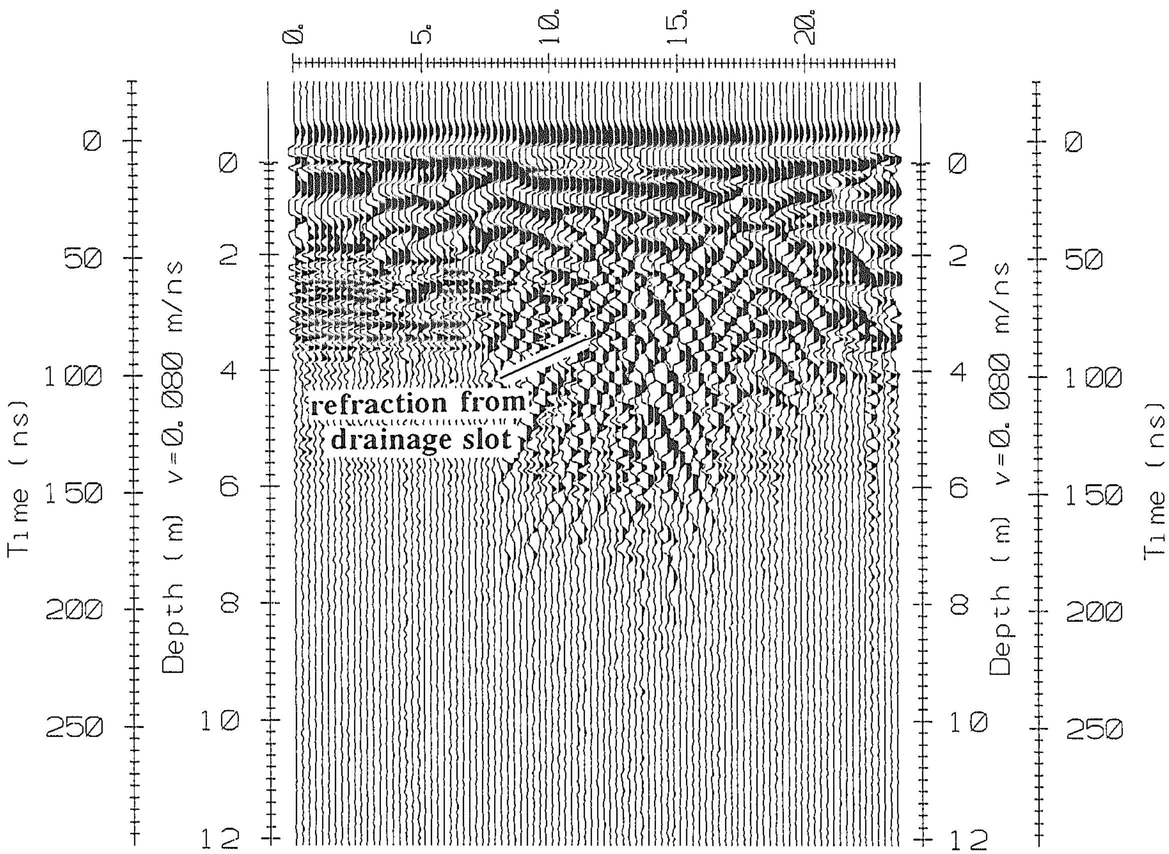
SLOPE 44 - CROSS PROFILE 1 - 100 MHz - JUNE 23



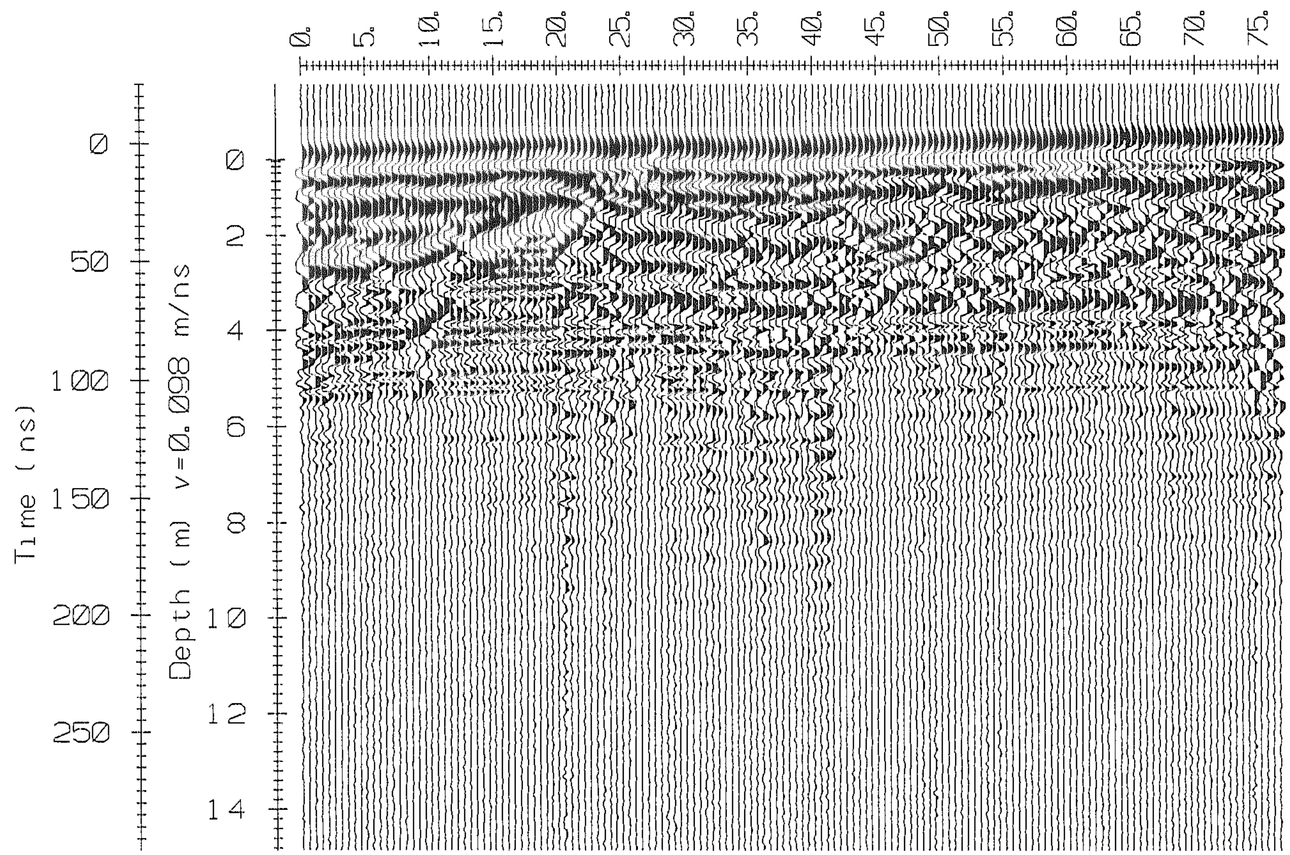
SLOPE 44 - CROSS PROFILE 2 - 100 MHz - JUNE 23



SLOPE 44 - CROSS PROFILE 3 - 100 MHz - JUNE 23

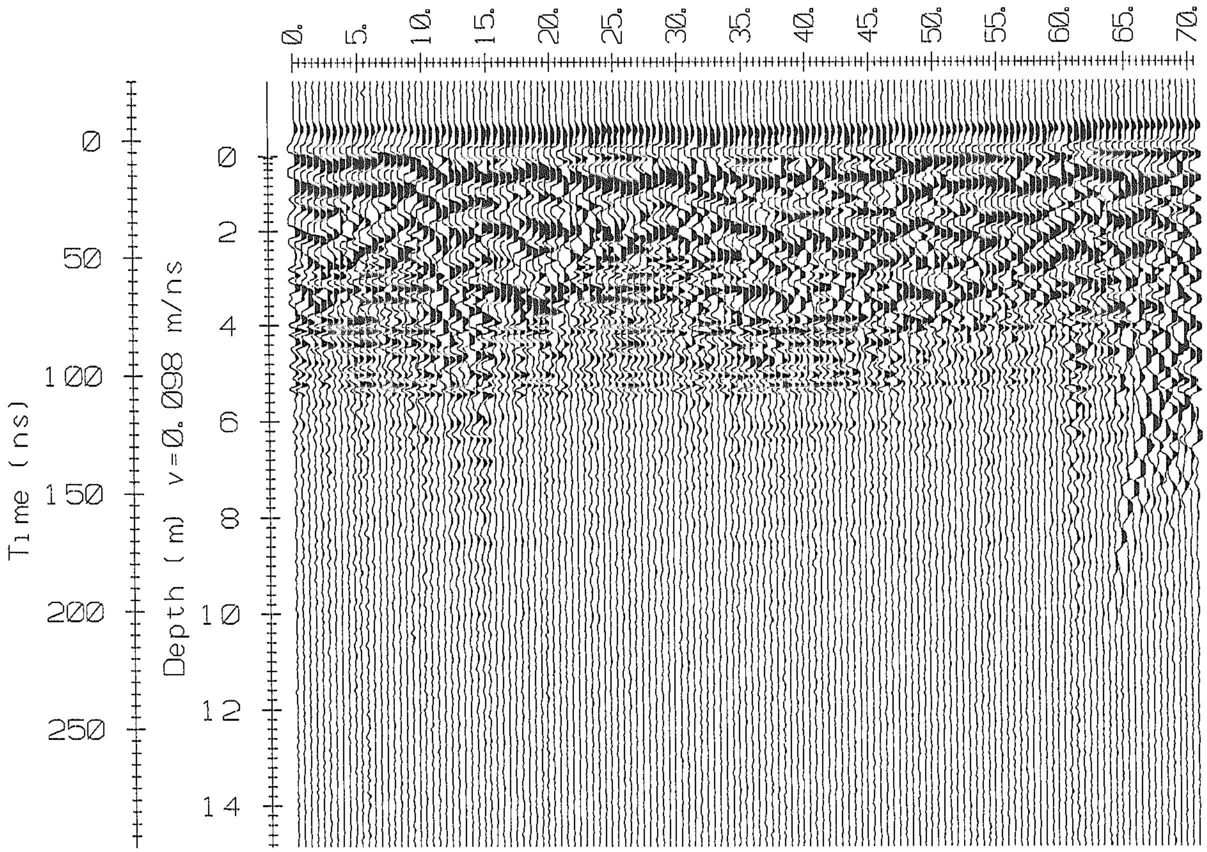


SLOPE 44 - CROSS PROFILE 4 - 100 MHz - JUNE 23

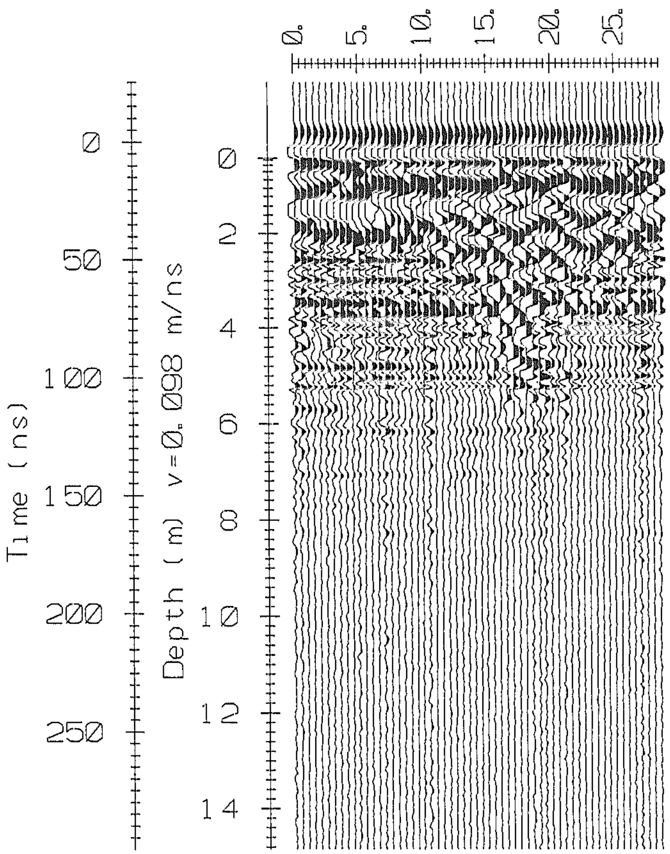


note loss of horizontal resolution with increased station spacing

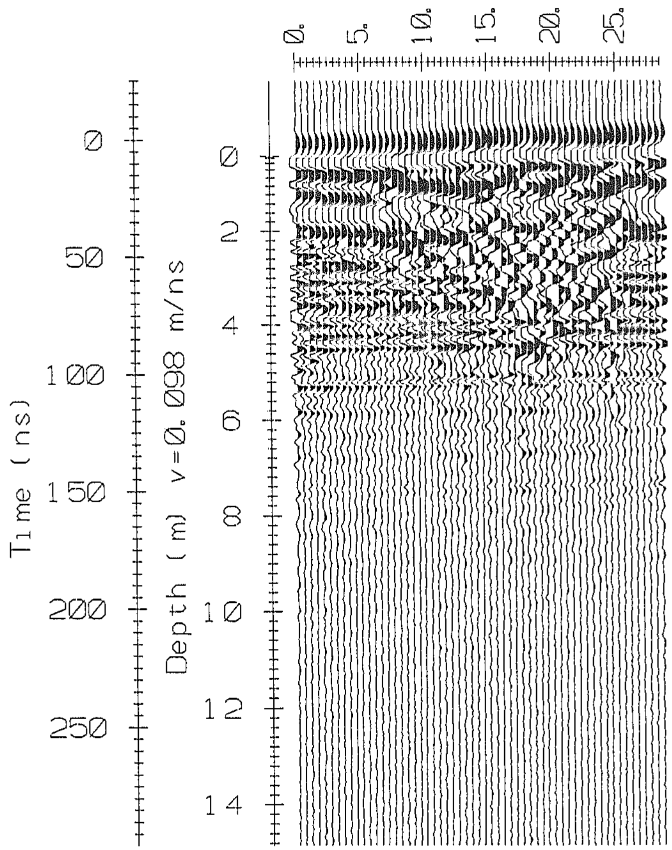
SLOPE 44 - LONG PROFILE 1 - 100 MHz - AUGUST 15



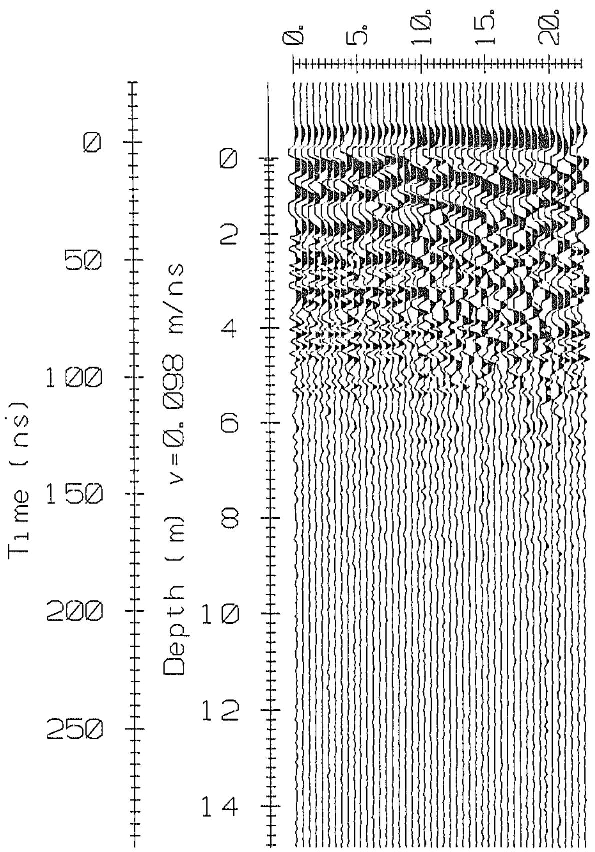
SLOPE 44 - LONG PROFILE 2 - 100 MHz - AUGUST 15



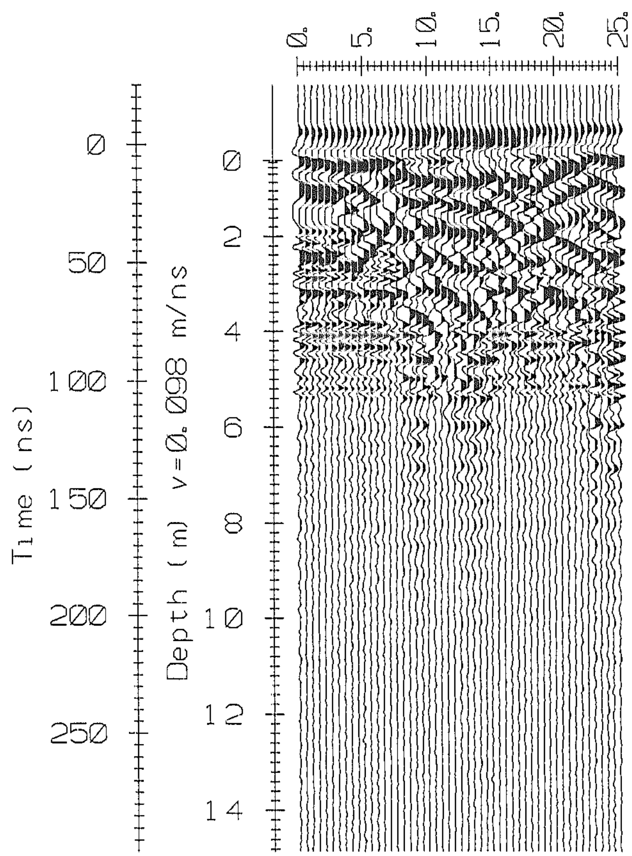
SLOPE 44 - CROSS PROFILE 1 - 100 MHz - AUGUST 15



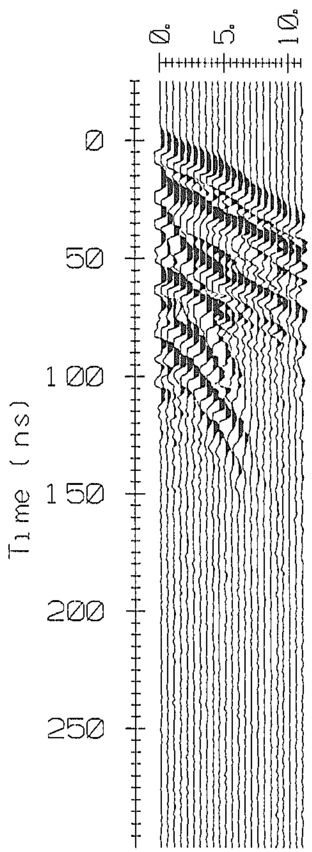
SLOPE 44 - CROSS PROFILE 2 - 100 MHz - AUGUST 15



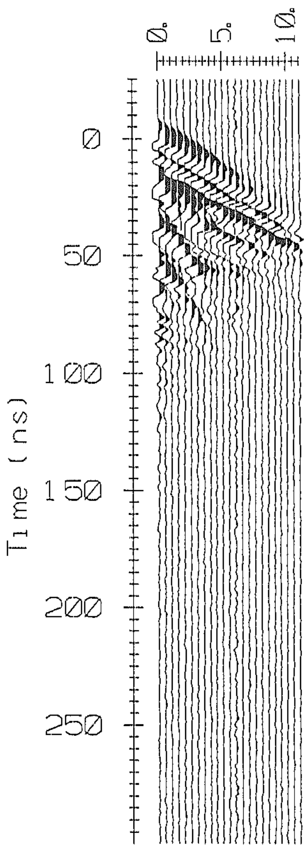
SLOPE 44 - CROSS PROFILE 3 - 100 MHz - AUGUST 15



SLOPE 44 - CROSS PROFILE 4 - 100 MHz - AUGUST 15



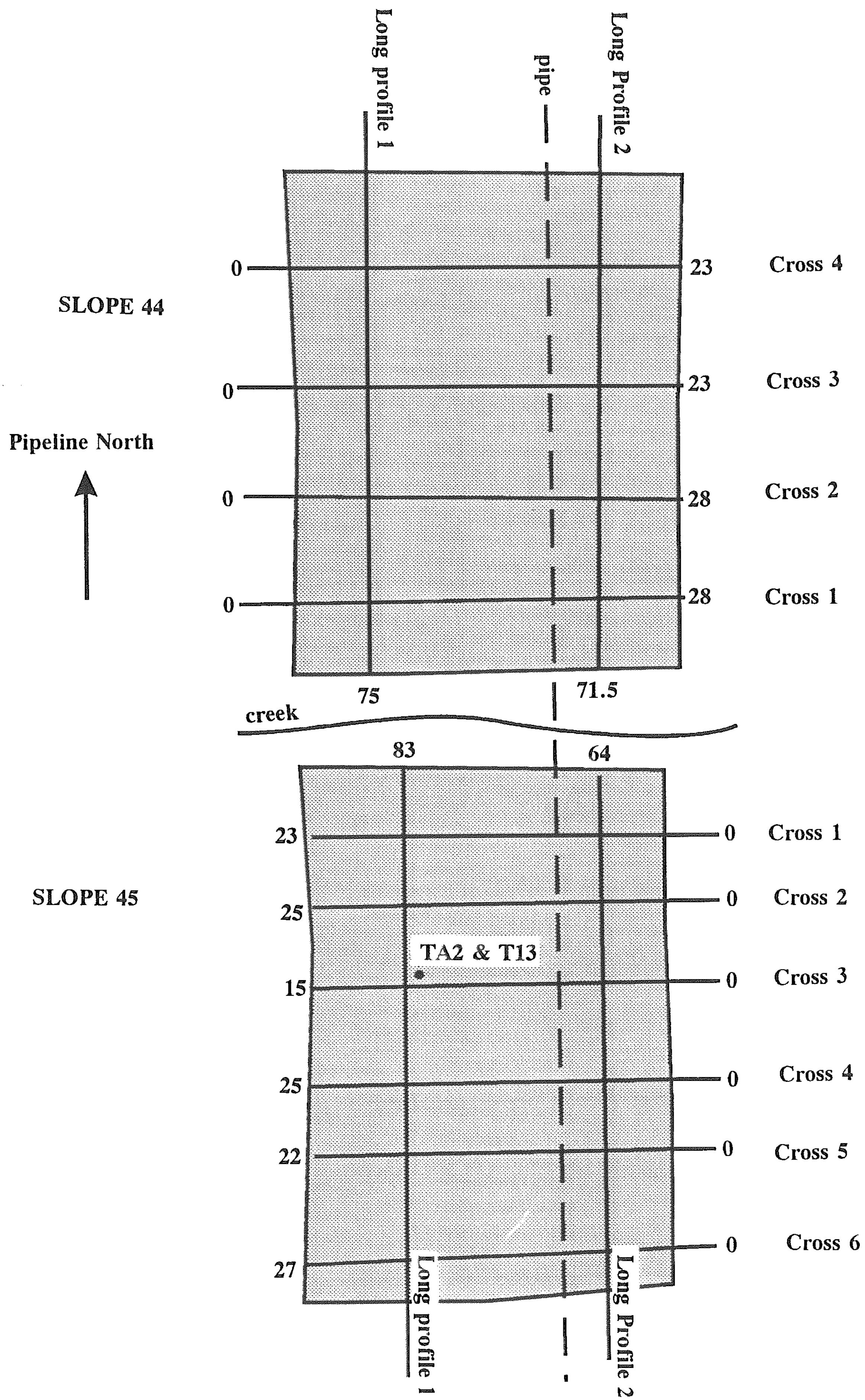
SLOPE 44 - CMP - JUNE 23



SLOPE 44 - CMP - AUGUST 15

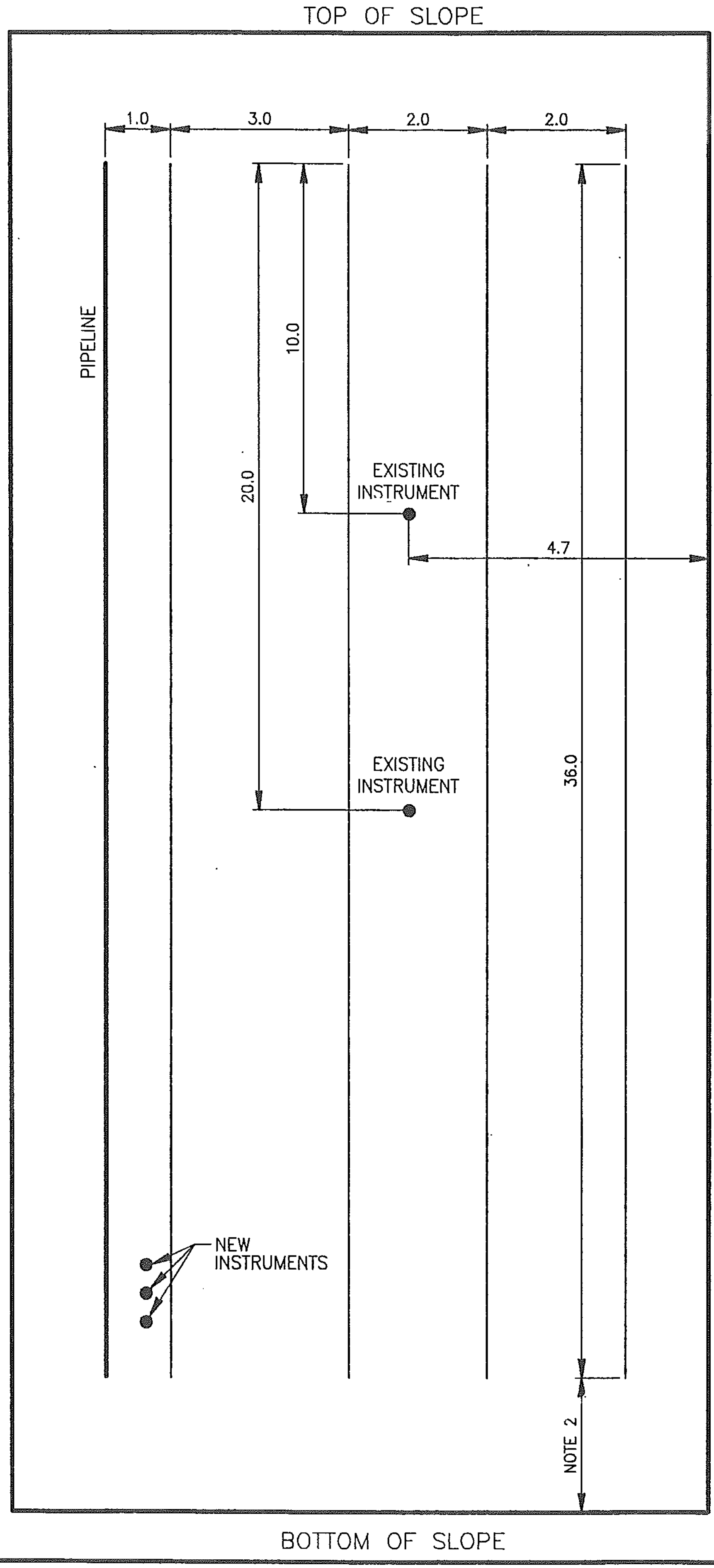
SLOPES 44 AND 45 (kp 133.6)

Not to Scale



SLOPE DRAINAGE INSTALLATION - NORMAN WELLS PIPELINE

Kp 133, SLOPE 45, AS BUILTS FEB. 94



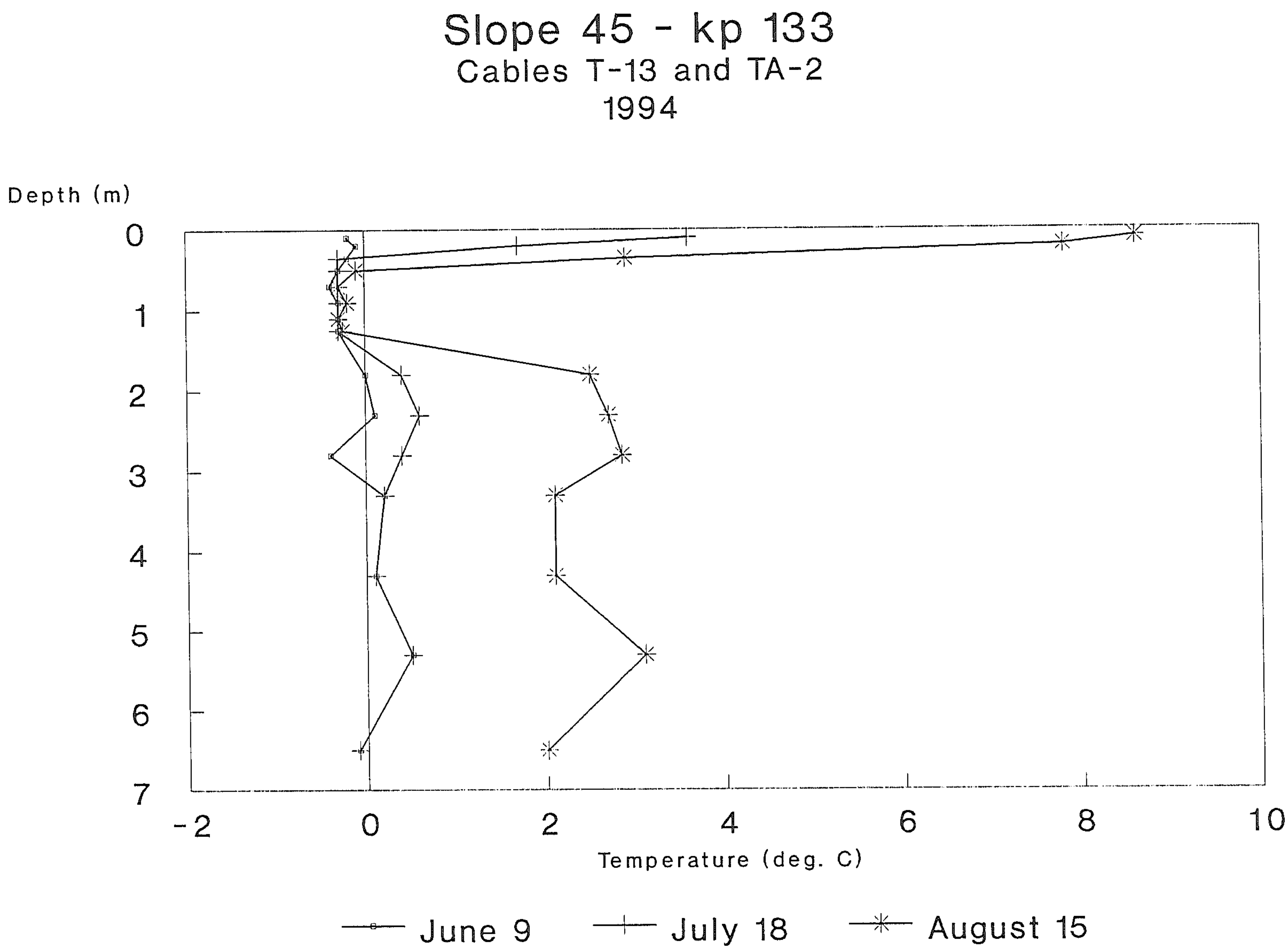
LEGEND

DRAINAGE TILE ————

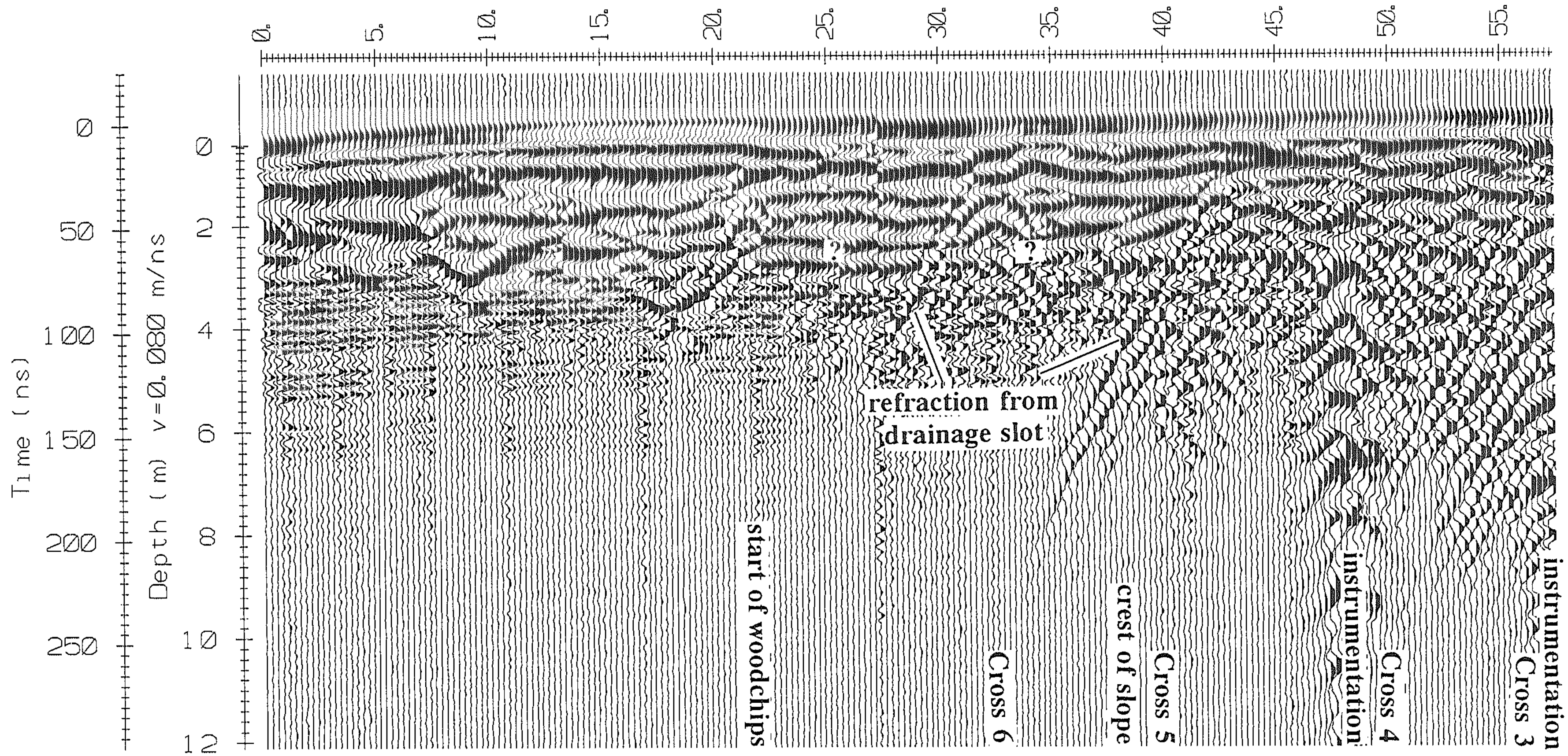
NOTES

1. ALL DIMENSIONS IN METERS
2. DRAINAGE TILES END 3 METERS FROM CRIBBING AT BOTTOM OF SLOPE

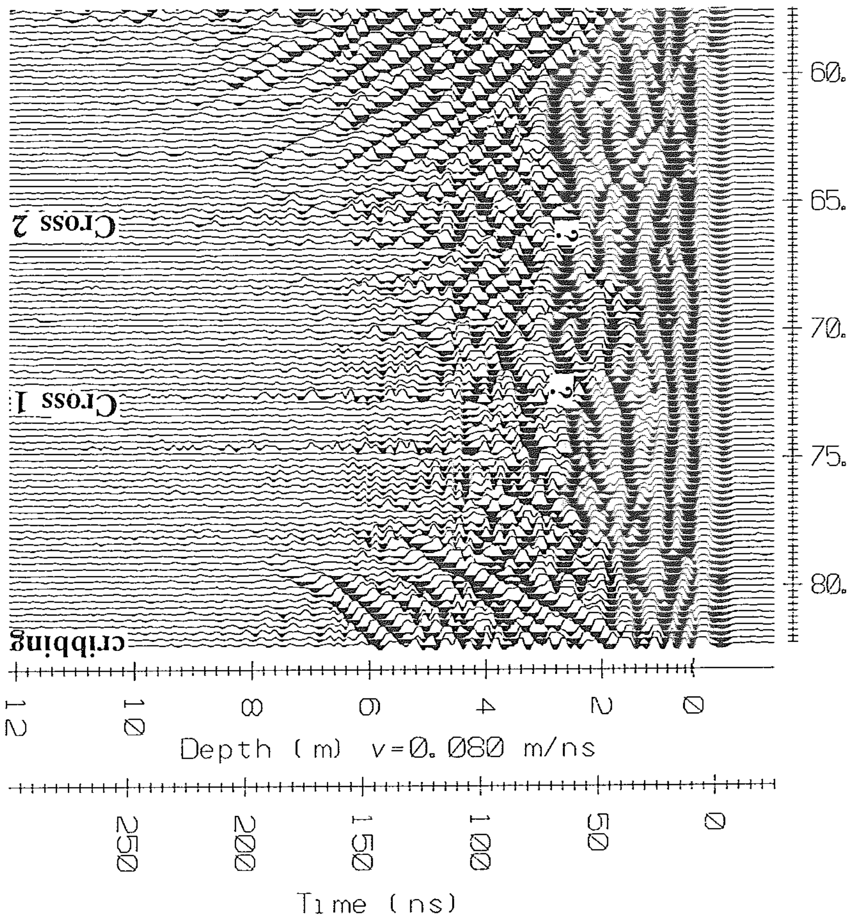
19/05/94


Slope 45 - kp 133
Cables T-13 and TA-2
1994
Depth (m)
0
1
2
3
4
5
6
7
-2
0
2
4
6
8
10
Temperature (deg. C)
June 9
July 18
August 15

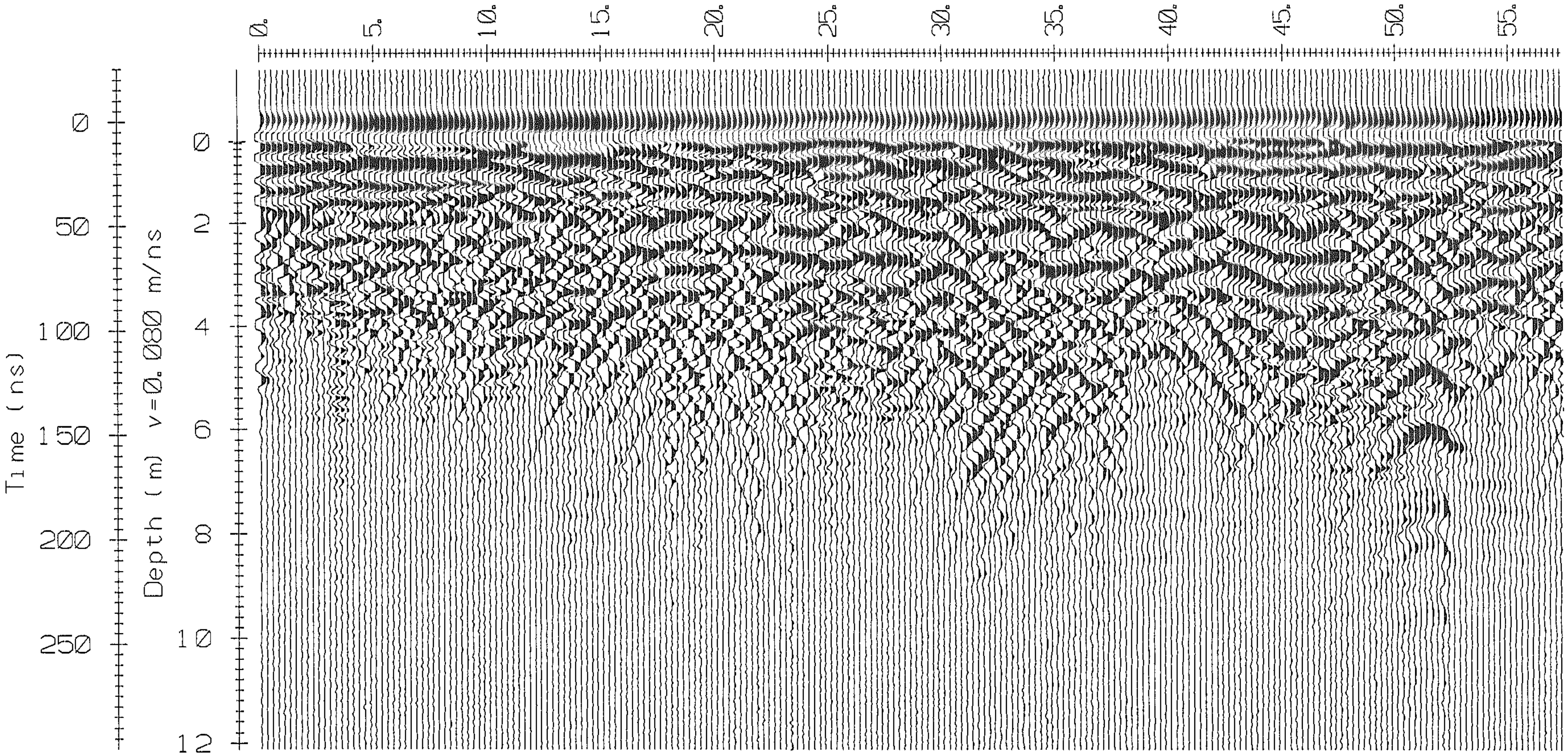
Much of this slope appears to be unfrozen, at least to depths of 3 or 4 m. Temperatures at depth increase through the summer, perhaps as a result of the drainage slots. The drainage slots themselves act to mask much of the information the radar should yield.



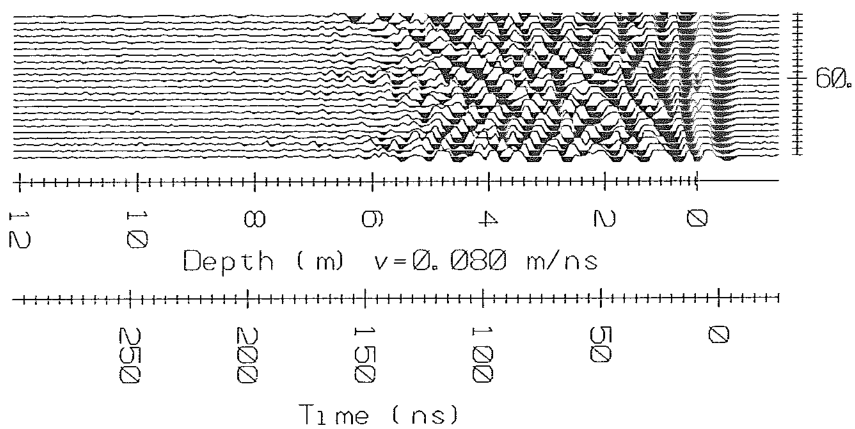
SLOPE 45 - LONG PROFILE 1 - 100 MHz - JUNE 20

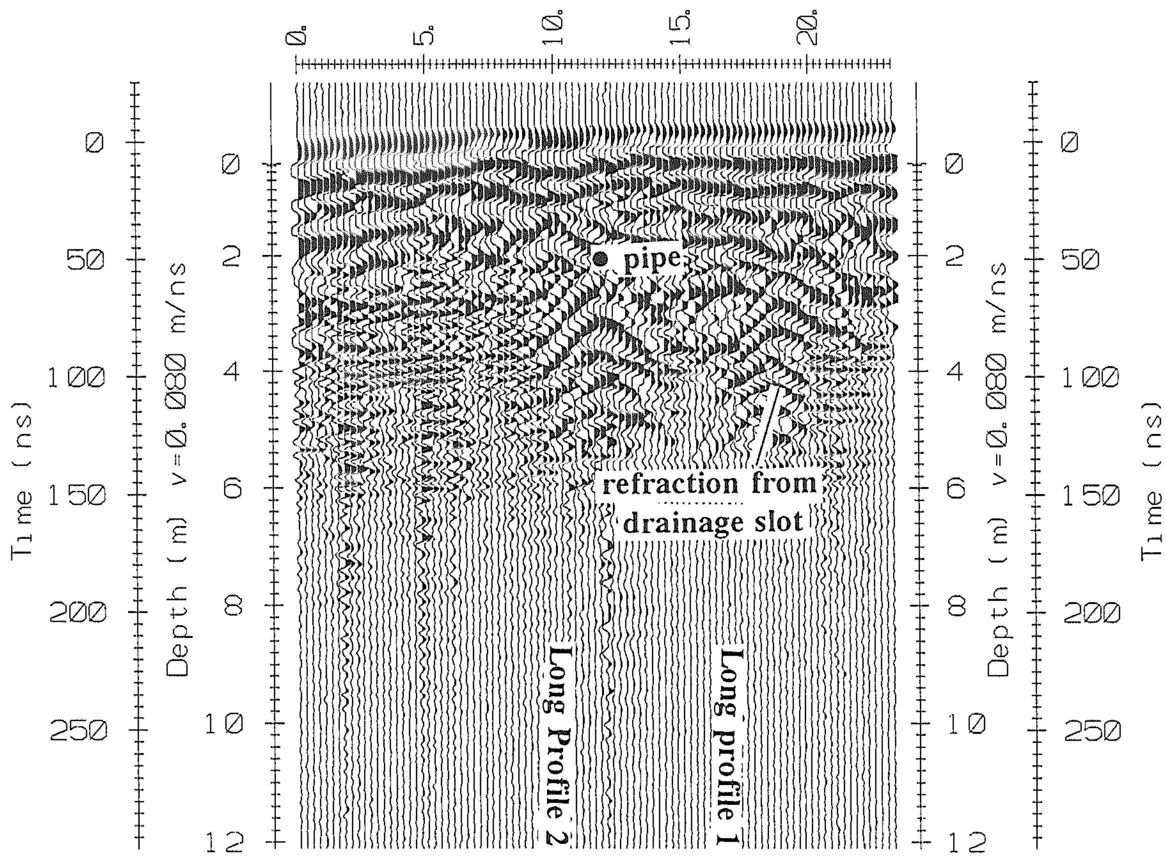


60.
65.
70.
75.
80.
Cross 2
Cross 1
cribbing
?
?
12
10
8
6
4
2
0
Depth (m) v=0.080 m/ns
250
200
150
100
50
0
Time (ns)

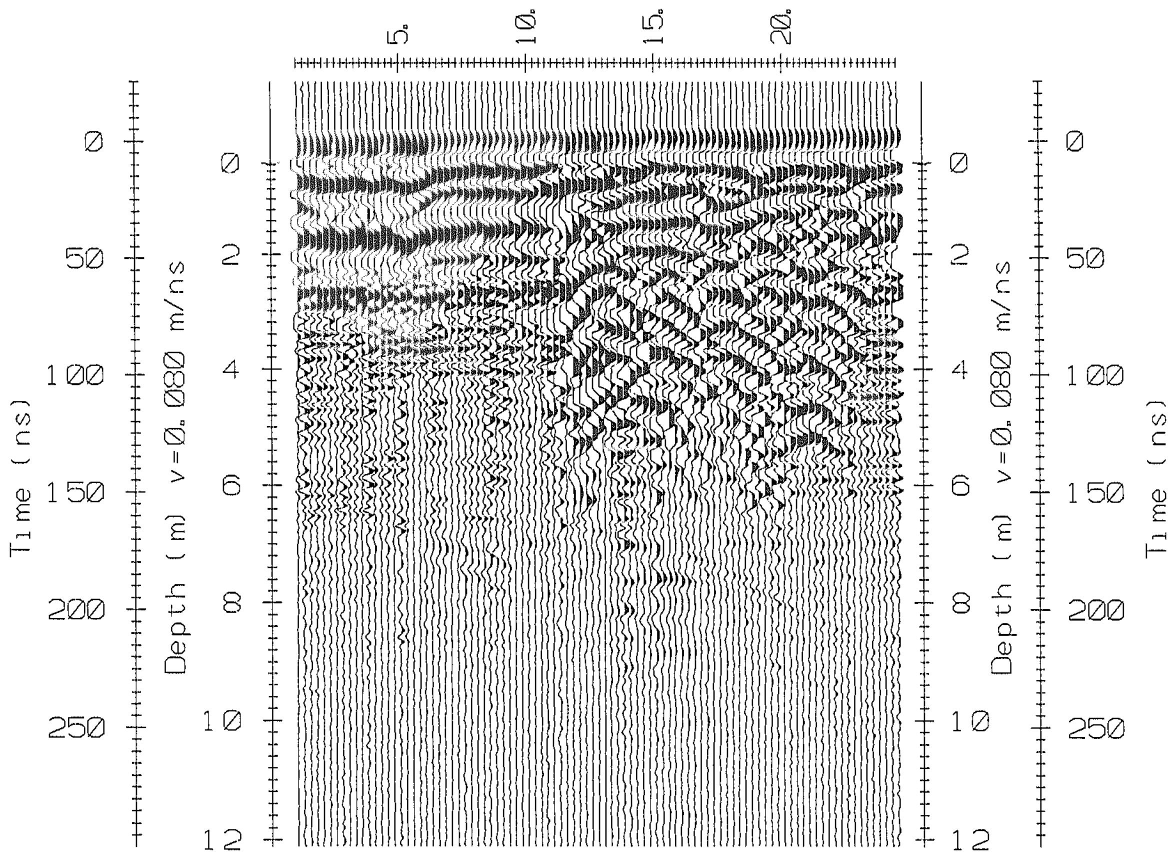


SLOPE 45 - LONG PROFILE 2 - 100 MHz - JUNE 20

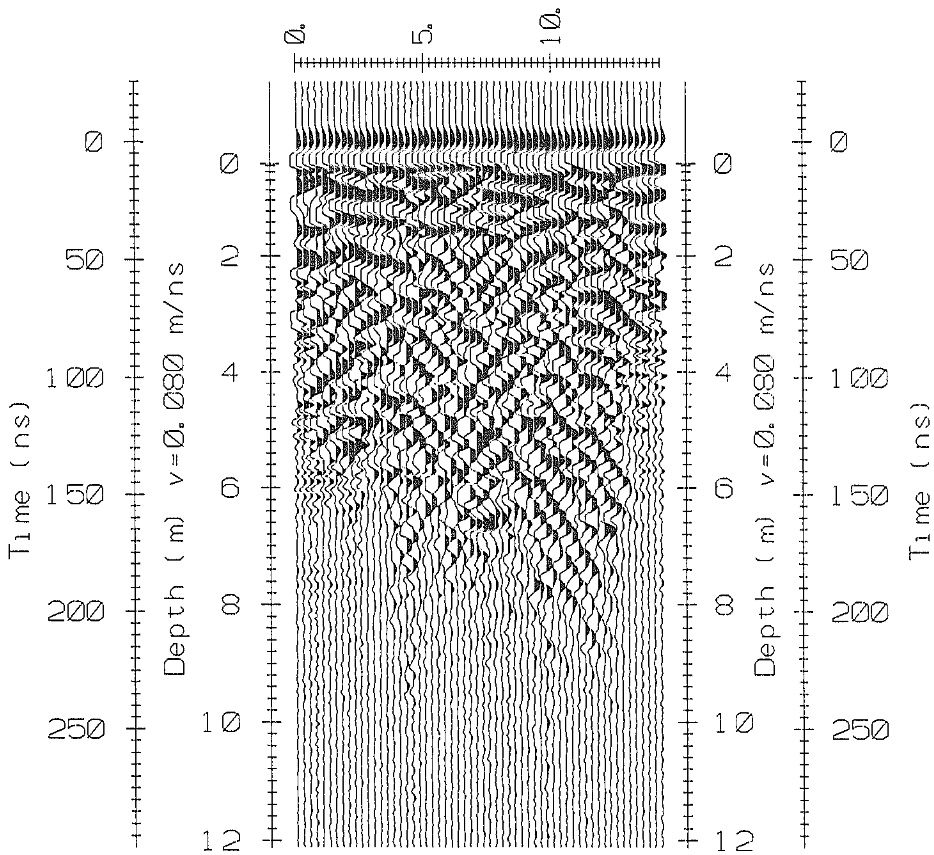

60.
12
10
8
6
4
2
0
Depth (m) v=0.080 m/ns
250
200
150
100
50
0
Time (ns)



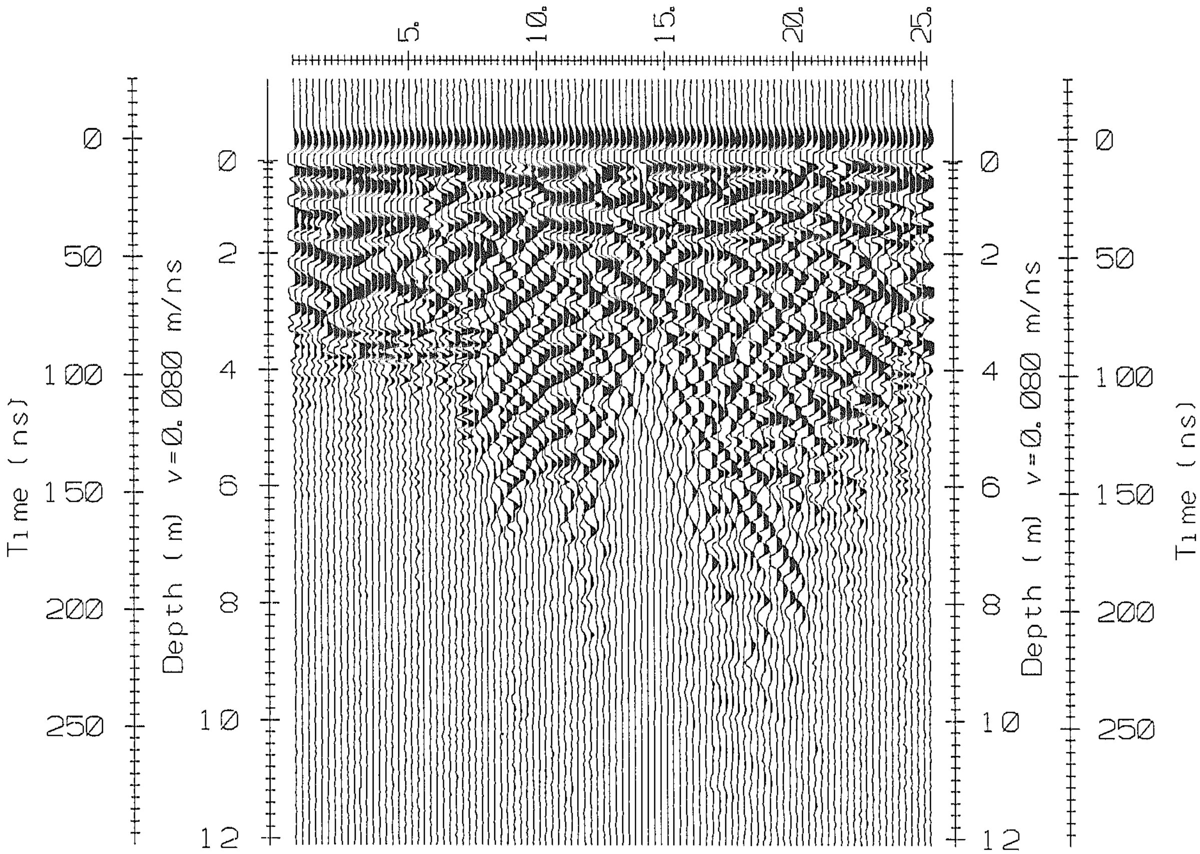
SLOPE 45 - CROSS PROFILE 1 - 100 MHz - JUNE 20



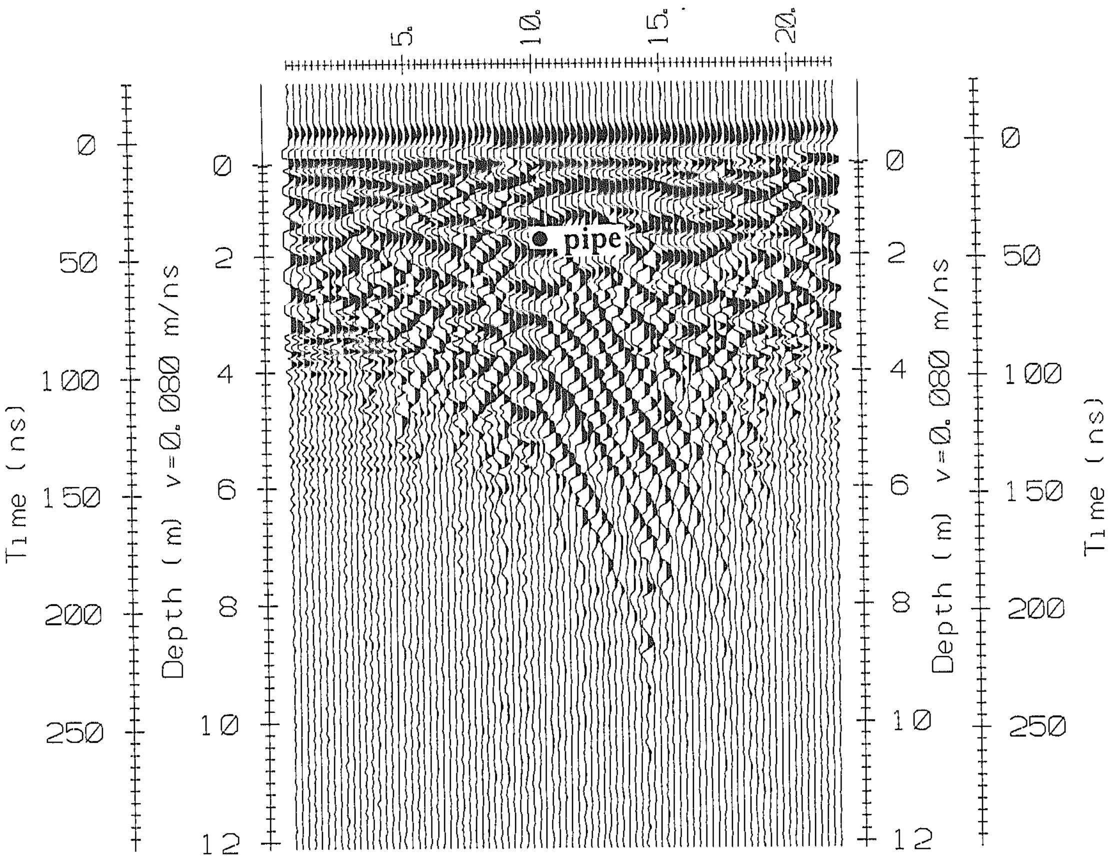
SLOPE 45 - CROSS PROFILE 2 - 100 MHz - JUNE 20



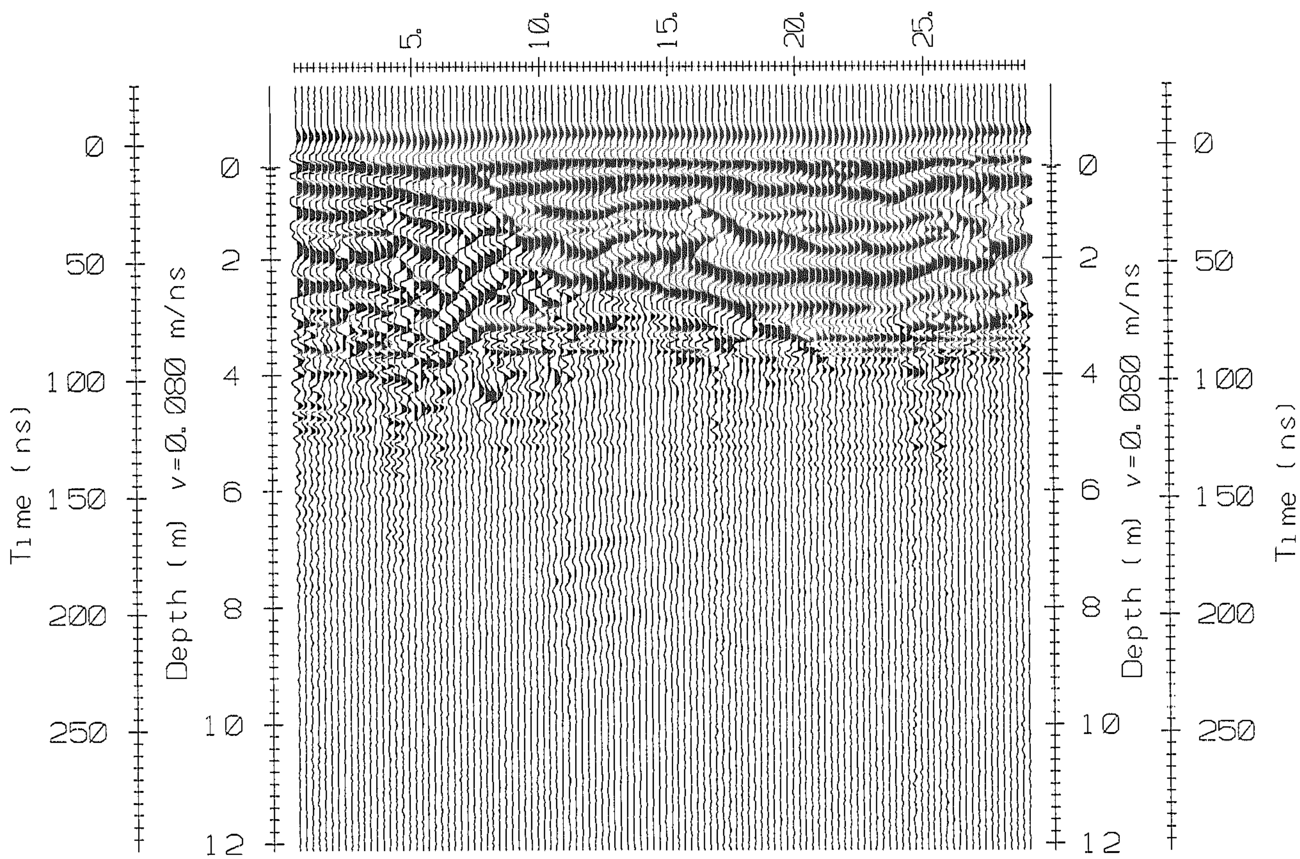
SLOPE 45 - CROSS PROFILE 3 - 100 MHz - JUNE 20



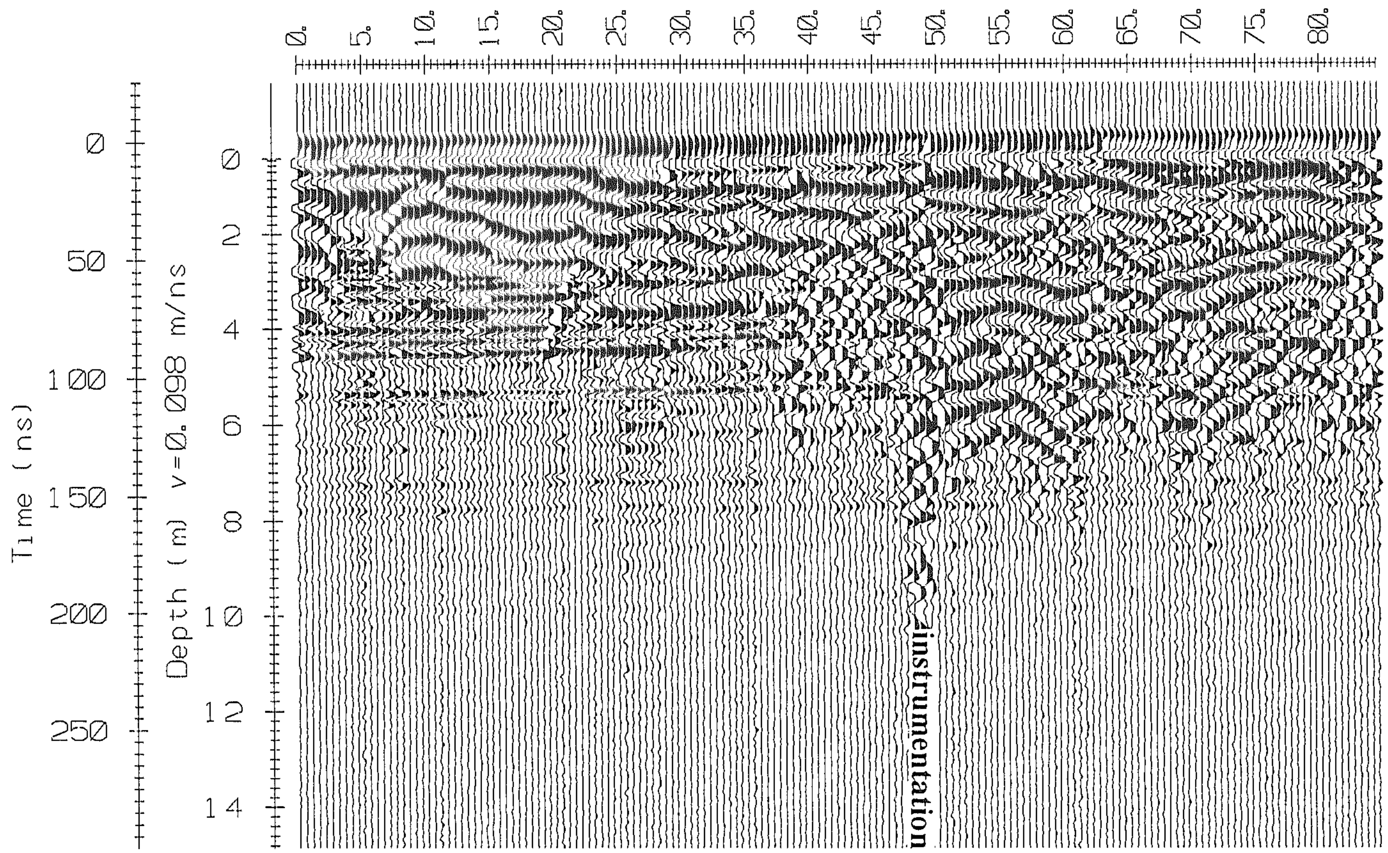
SLOPE 45 - CROSS PROFILE 4 - 100 MHz - JUNE 20



SLOPE 45 - CROSS PROFILE 5 - 100 MHz - JUNE 20

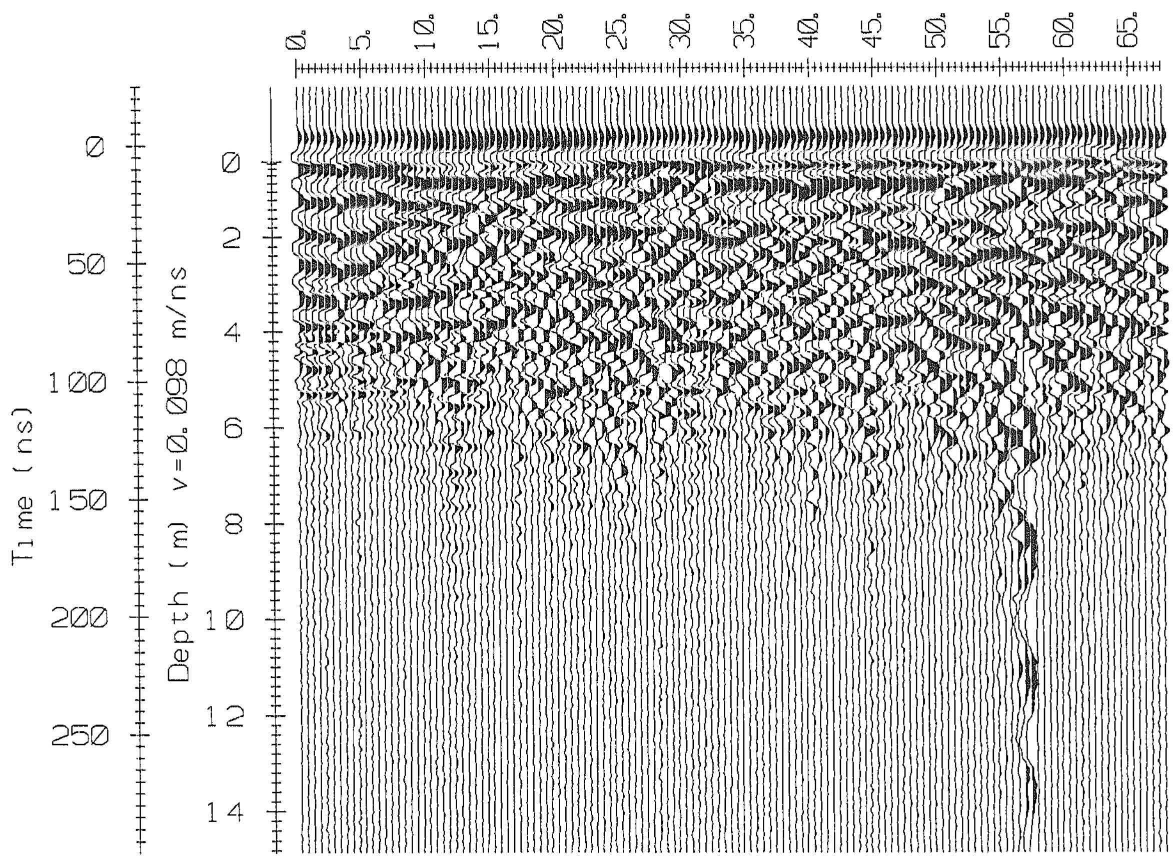


SLOPE 45 - CROSS PROFILE 6 - 100 MHz - JUNE 20

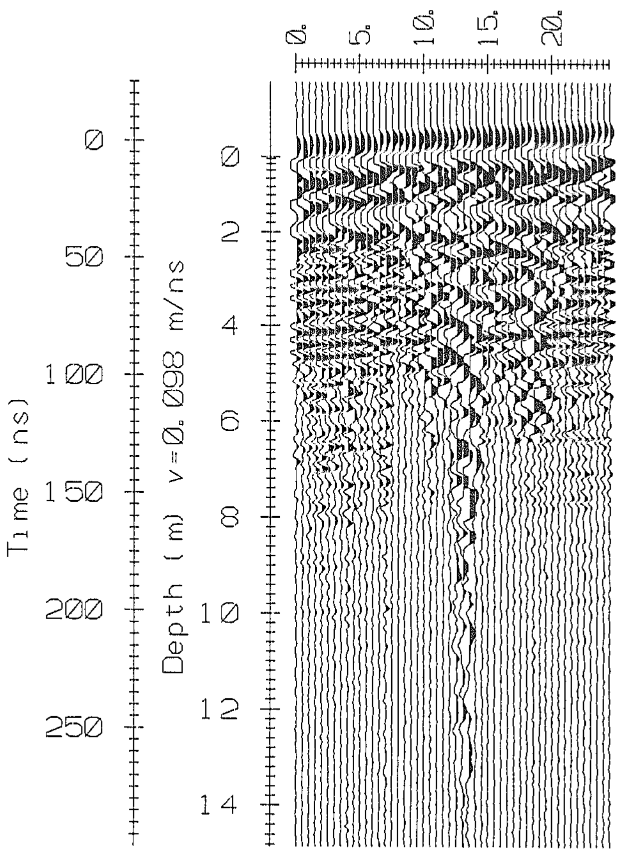


note loss of horizontal resolution
with increased station spacing

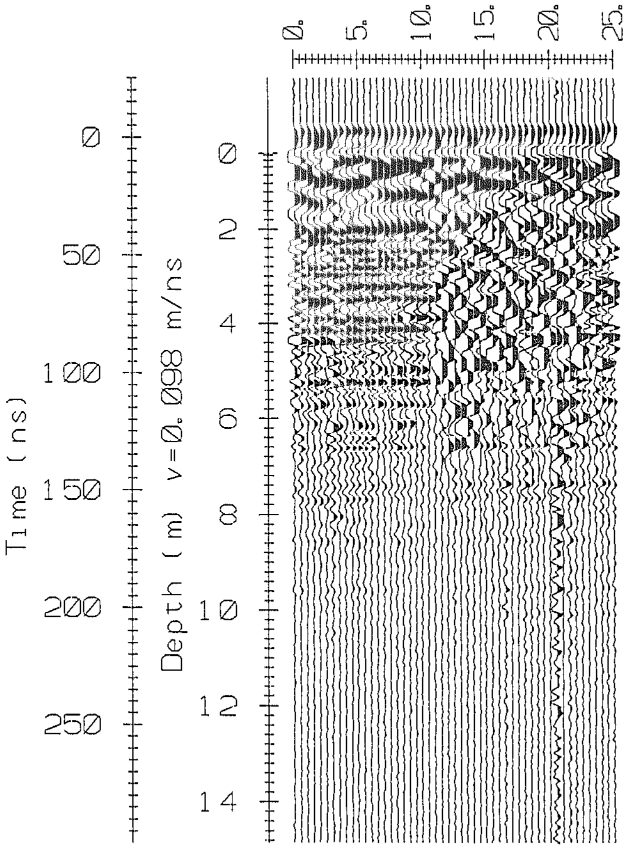
SLOPE 45 - LONG PROFILE 1 - 100 MHz - AUGUST 15



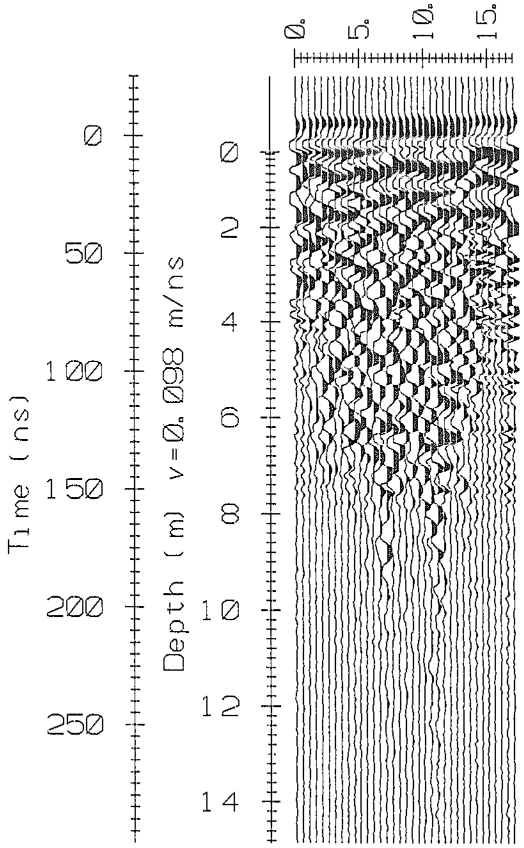
SLOPE 45 - LONG PROFILE 2 - 100 MHz - AUGUST 15



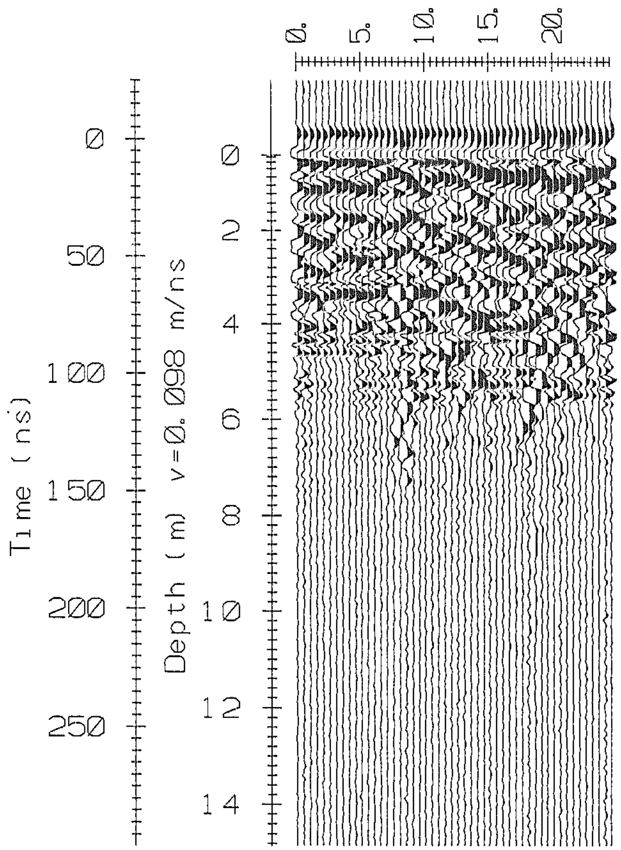
SLOPE 45 - CROSS PROFILE 1 - 100 MHz - AUGUST 15



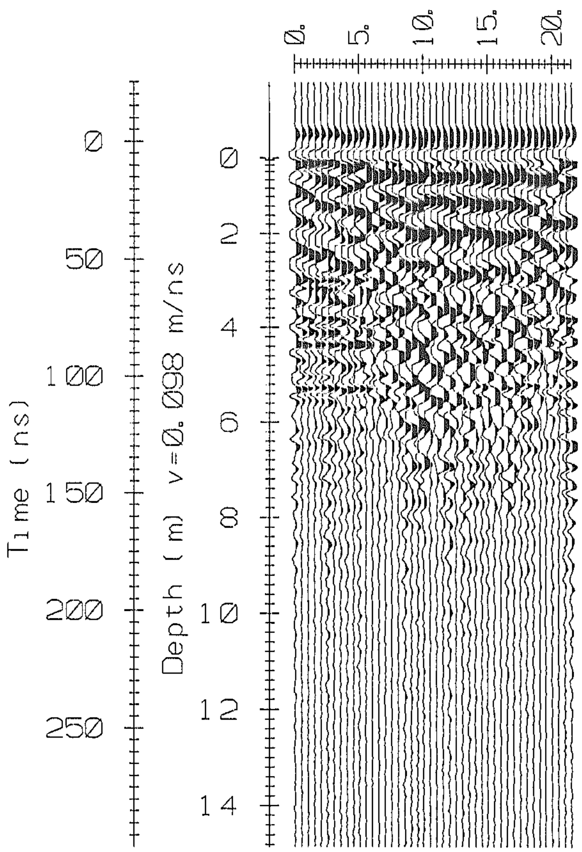
SLOPE 45 - CROSS PROFILE 2 - 100 MHz - AUGUST 15



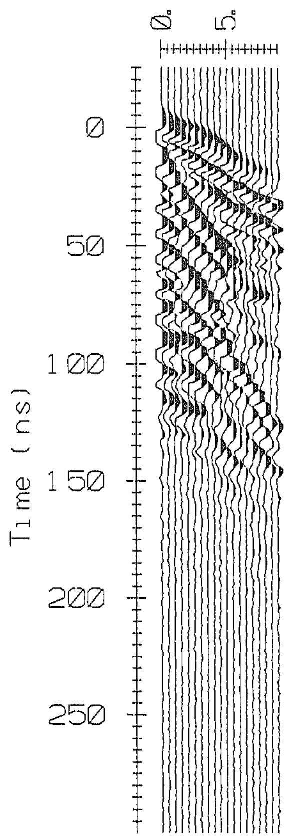
SLOPE 45 - CROSS PROFILE 3 - 100 MHz - AUGUST 15



SLOPE 45 - CROSS PROFILE 4 - 100 MHz - AUGUST 15



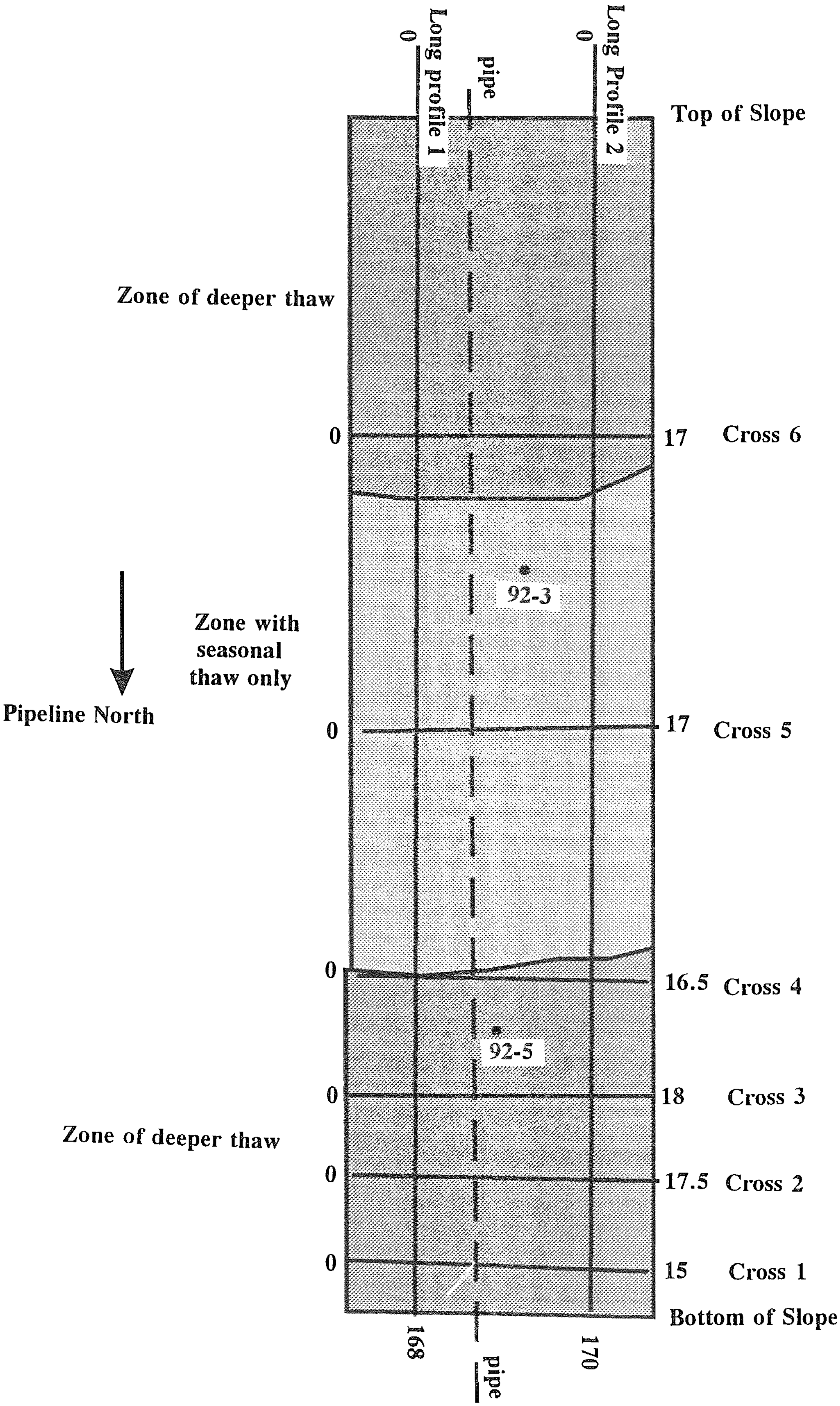
SLOPE 45 - CROSS PROFILE 5 - 100 MHz - AUGUST 15



SLOPE 45 - CMP - JUNE 20

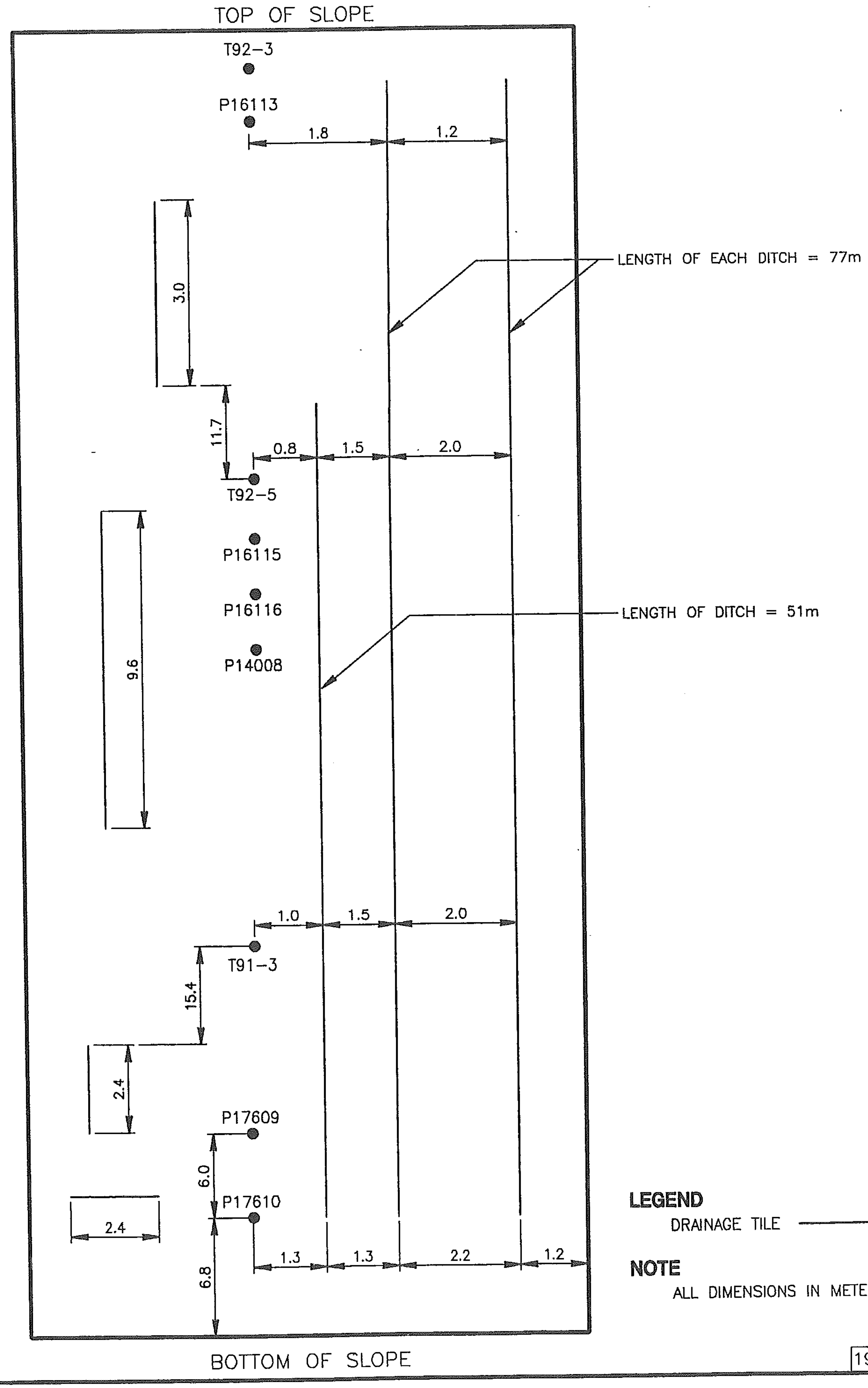
LITTLE SMITH CREEK (SLOPE 48b)

Not to Scale



SLOPE DRAINAGE INSTALLATION - NORMAN WELLS PIPELINE

Kp 160, SLOPE 48B, AS BUILTS FEB. 94



LEGEND

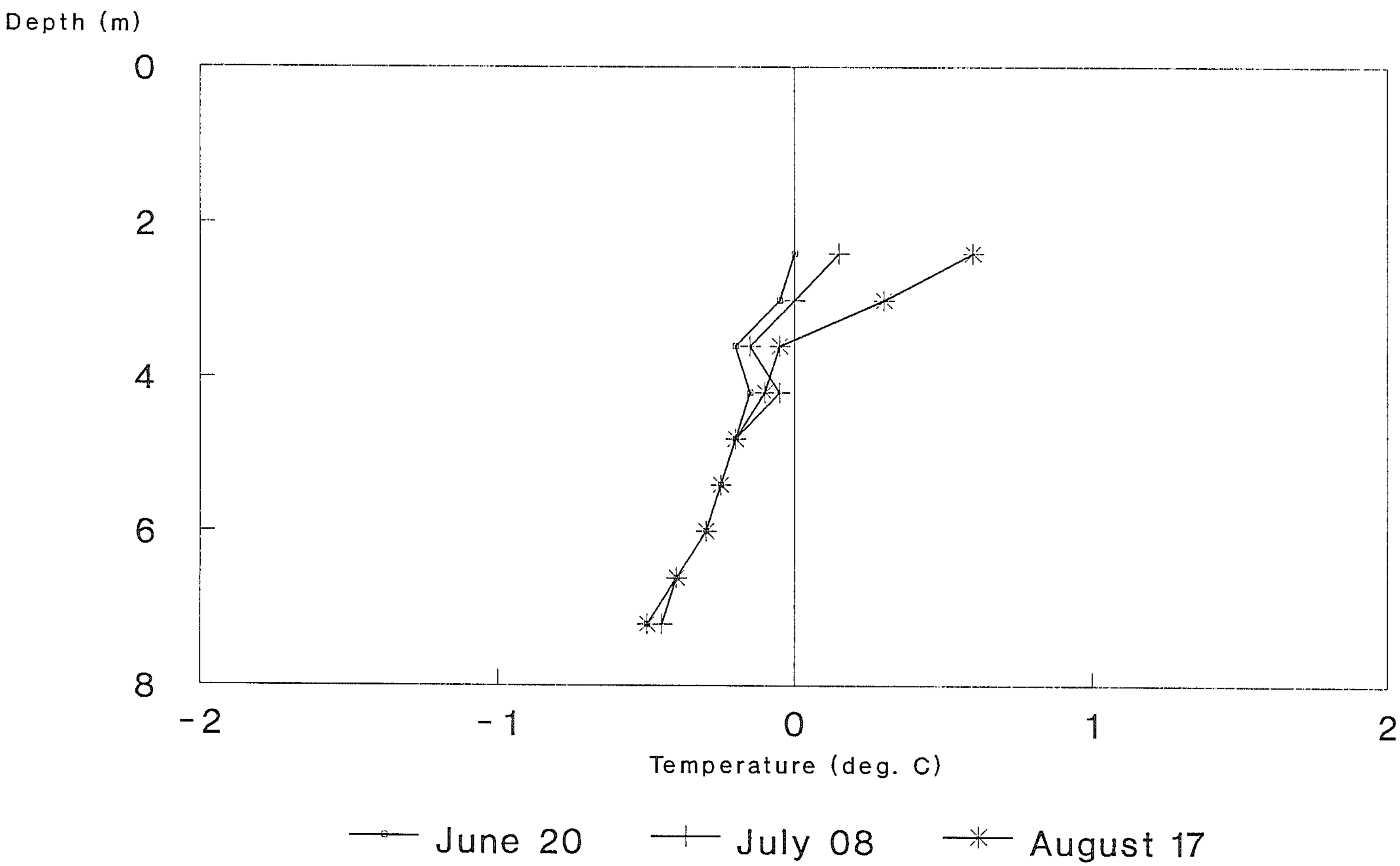
DRAINAGE TILE ————

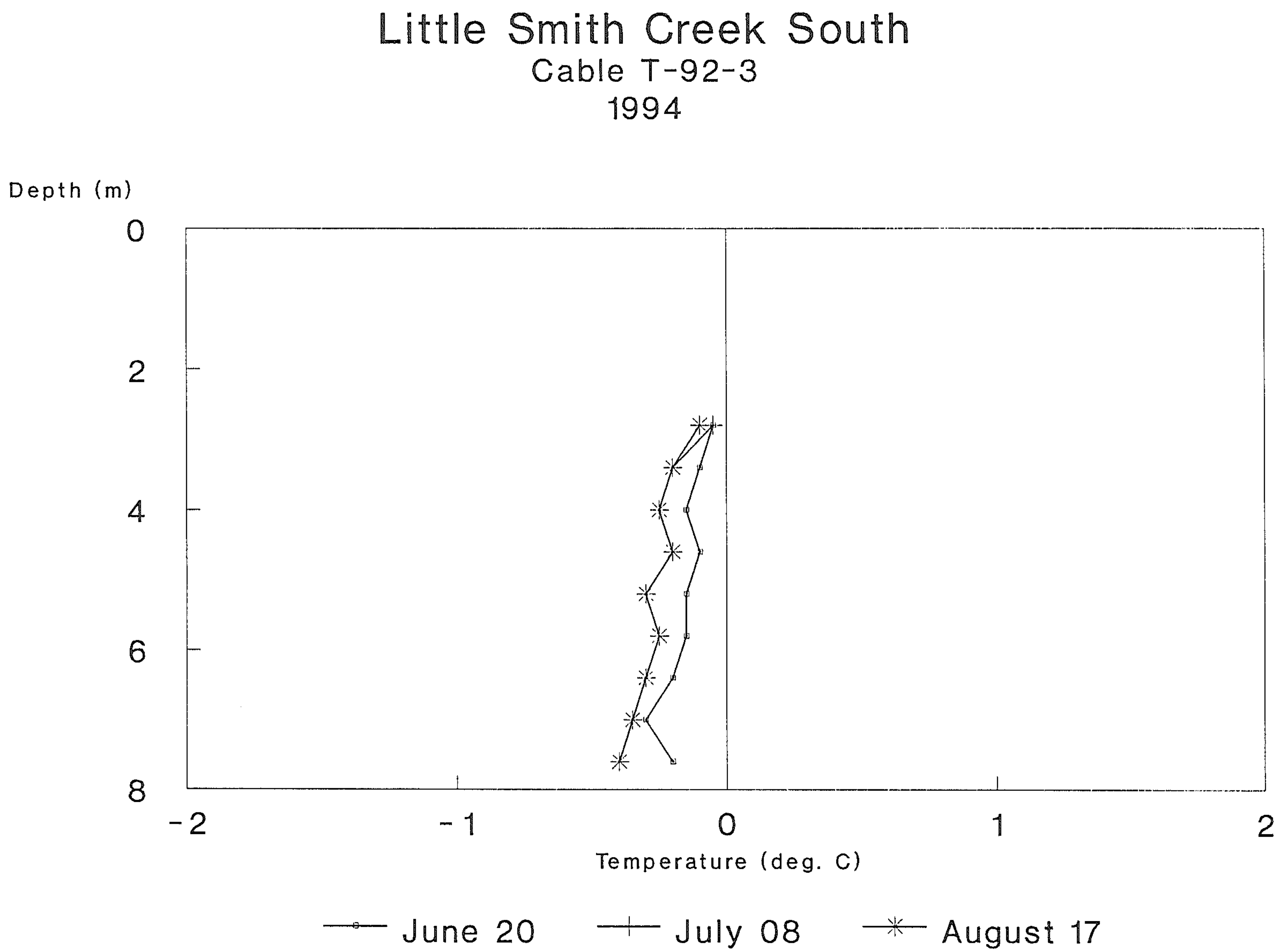
NOTE

ALL DIMENSIONS IN METERS

19/05/94

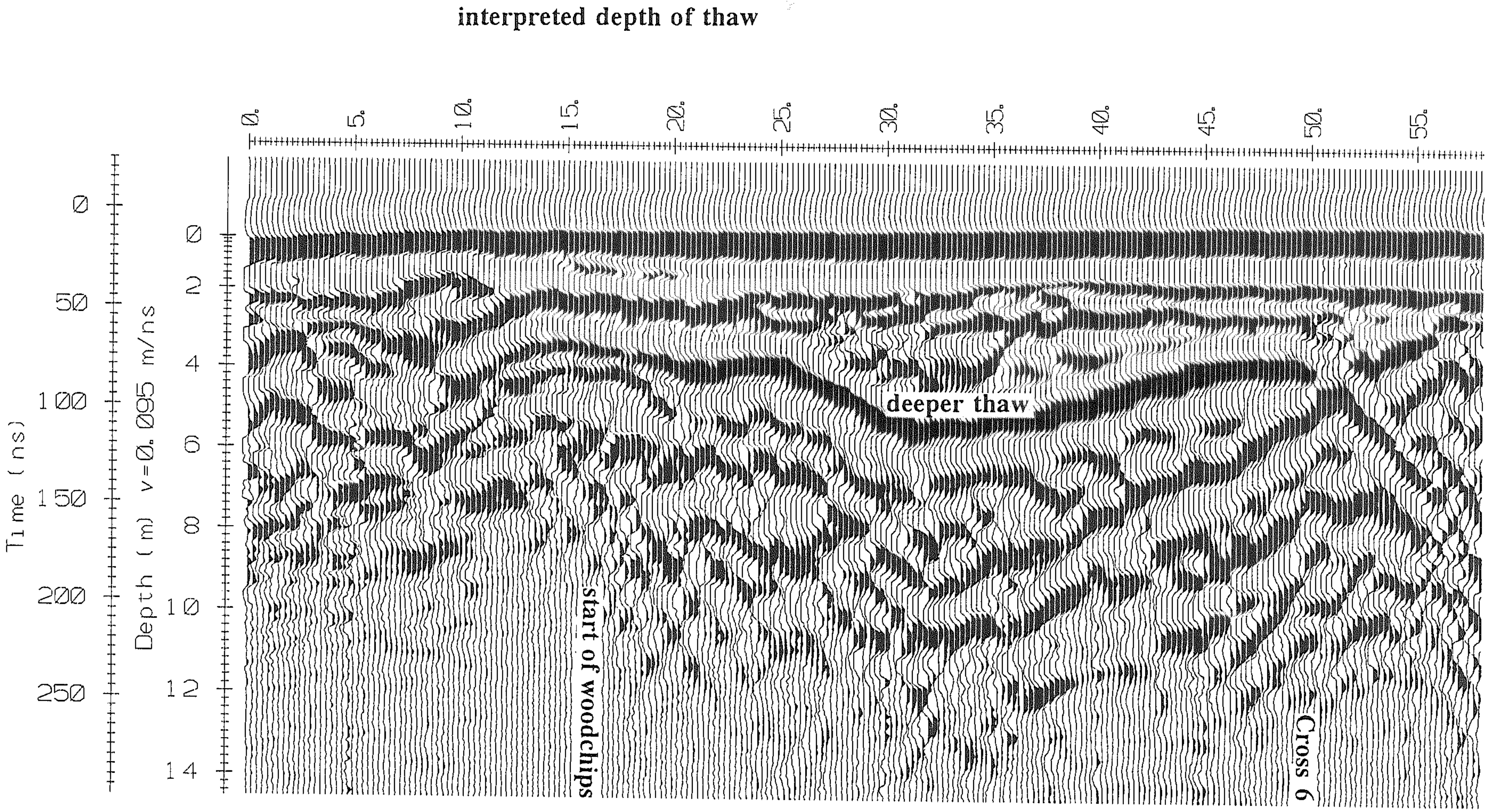
Little Smith Creek South
Cable T-92-5
1994



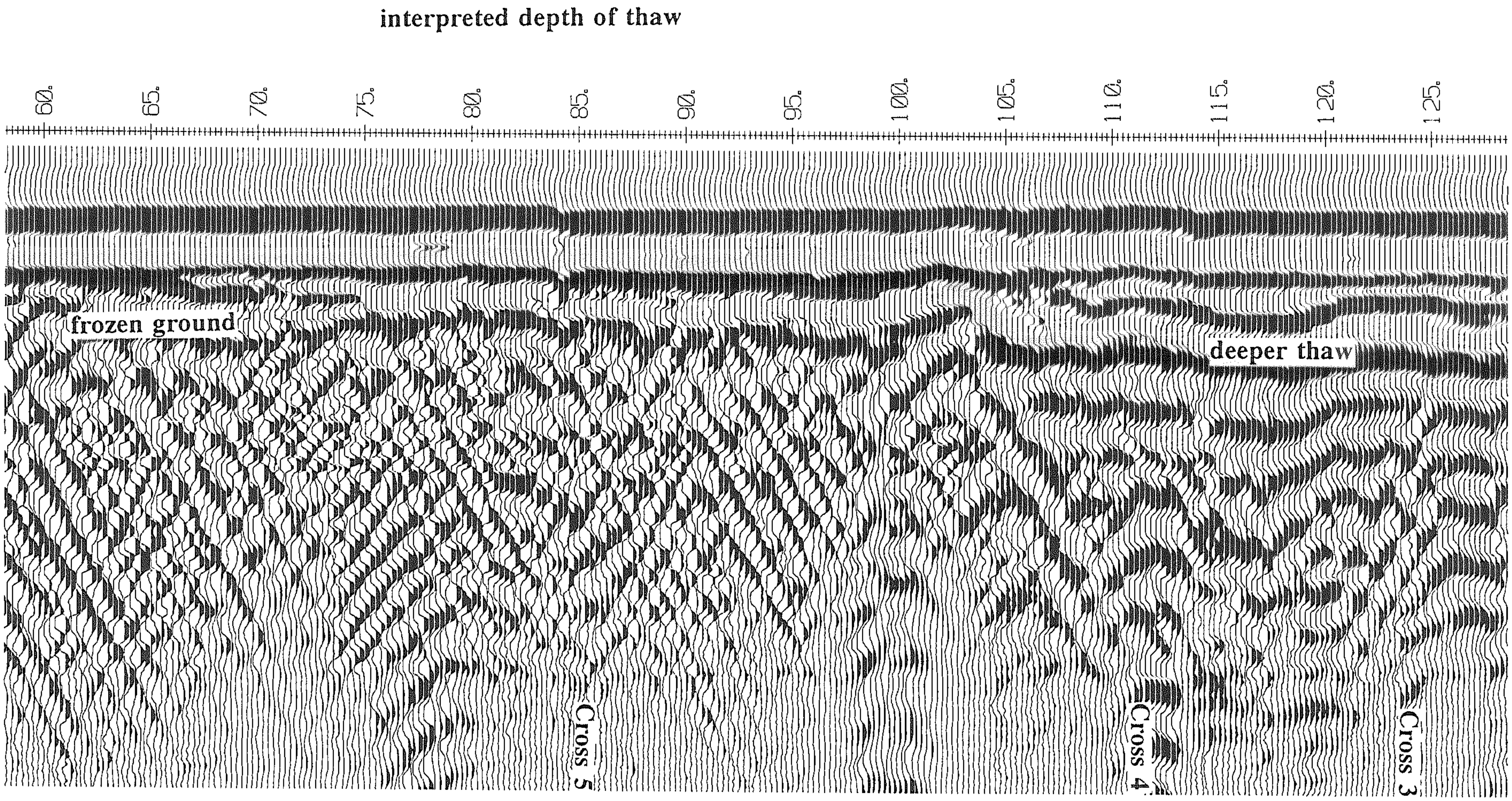


Little Smith Creek South
Cable T-92-3
1994
Depth (m)
0
2
4
6
8
-2
-1
0
1
2
Temperature (deg. C)
June 20
July 08
August 17

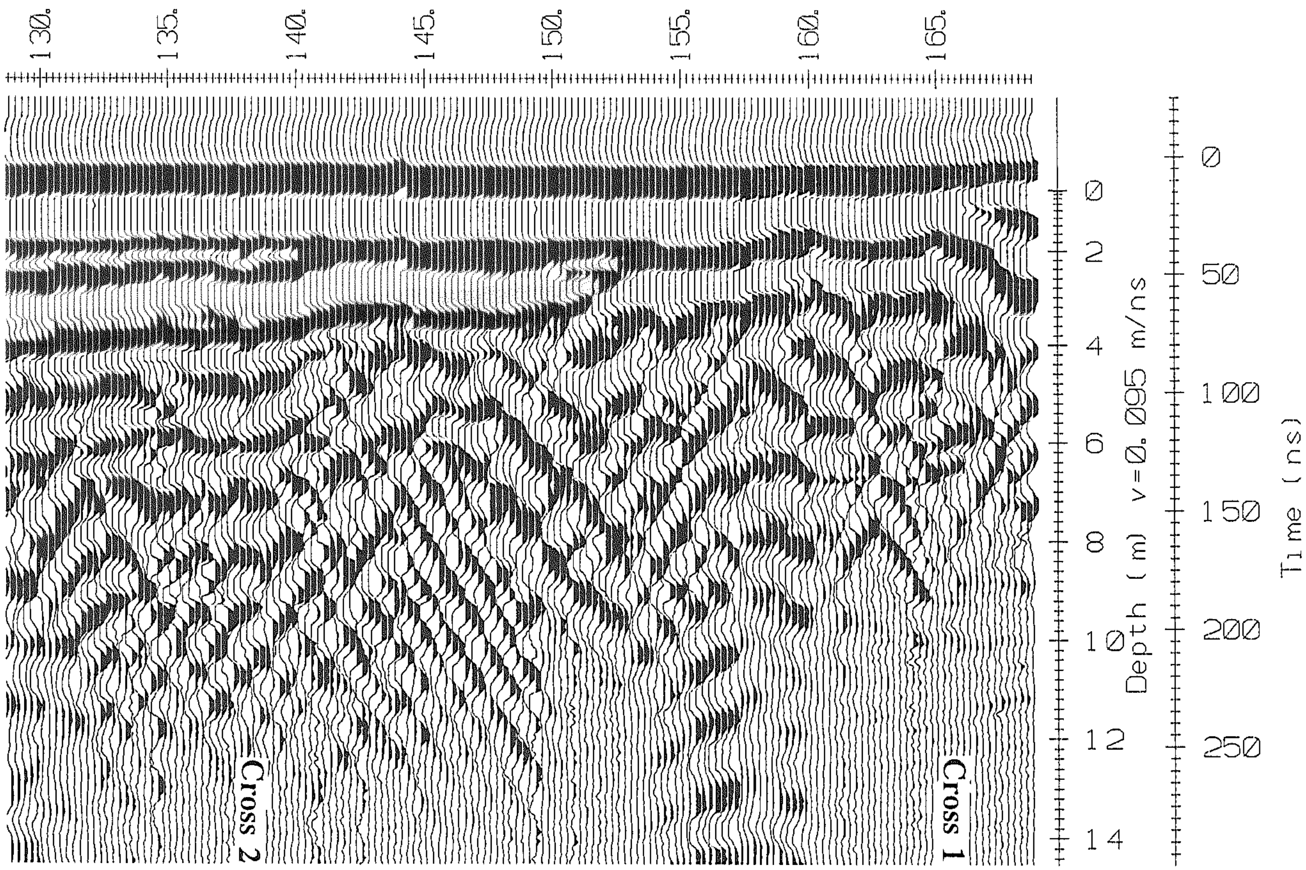
Drainage slots were difficult to locate on this slope as they had recently been backfilled. The radar signal does not seem to be adversely affected by the drainage slots on this slope (except on some cross profiles). The upper and lower zones of deeper thaw were also interpreted from the 1993 surveys,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



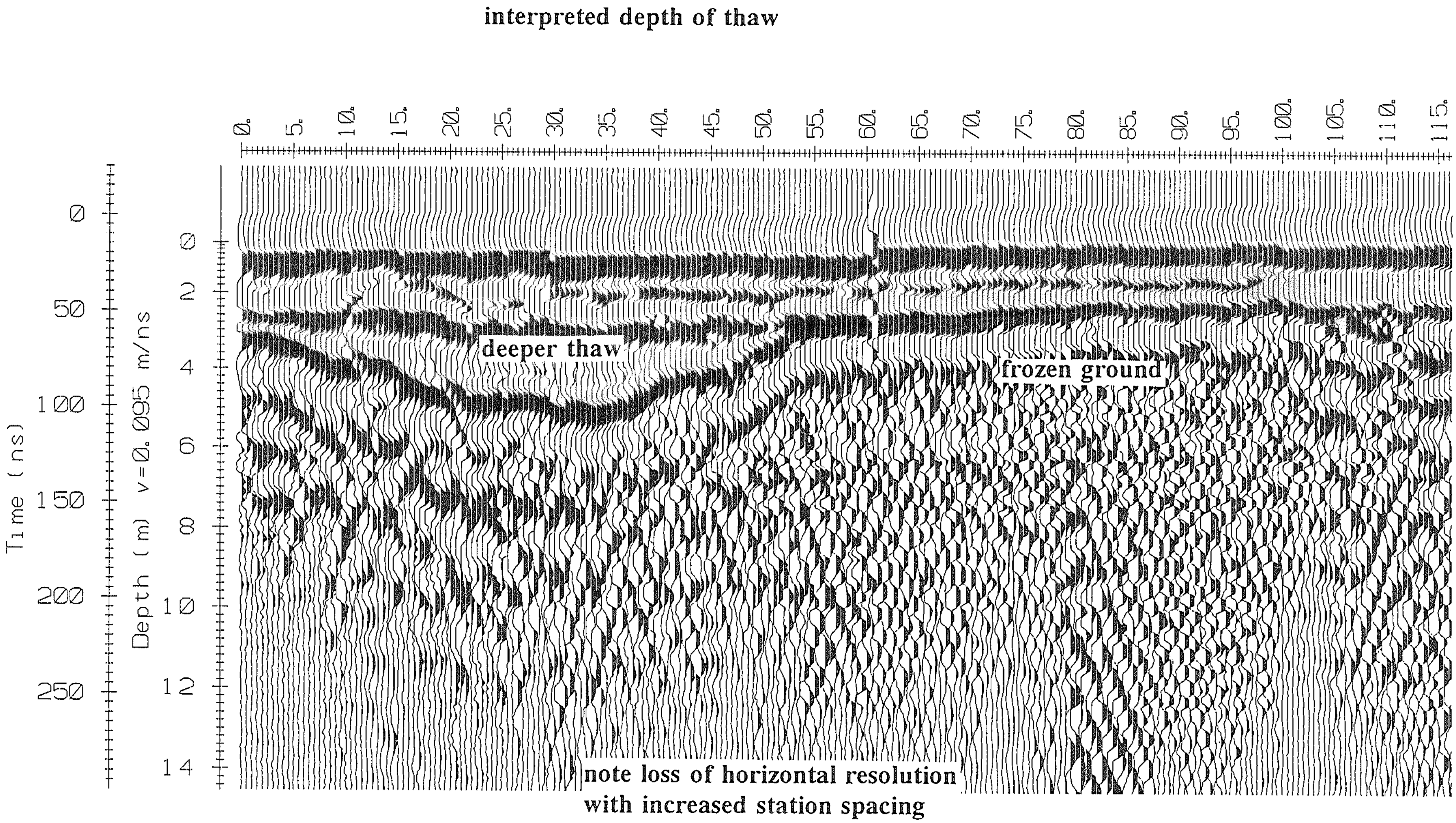
LITTLE SMITH CREEK - LONG PROFILE 1 - 50 MHz - JULY 6



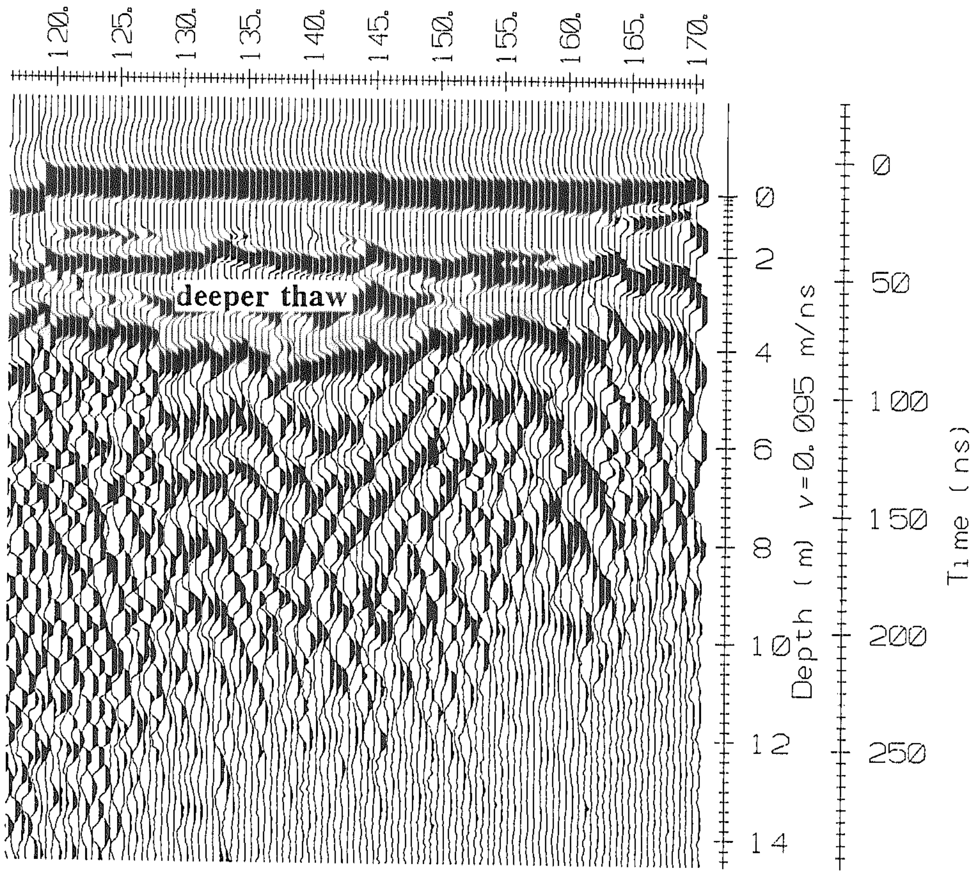
interpreted depth of thaw
60.
65.
70.
75.
80.
85.
90.
95.
100.
105.
110.
115.
120.
125.
frozen ground
deeper thaw
Cross 5
Cross 4
Cross 3



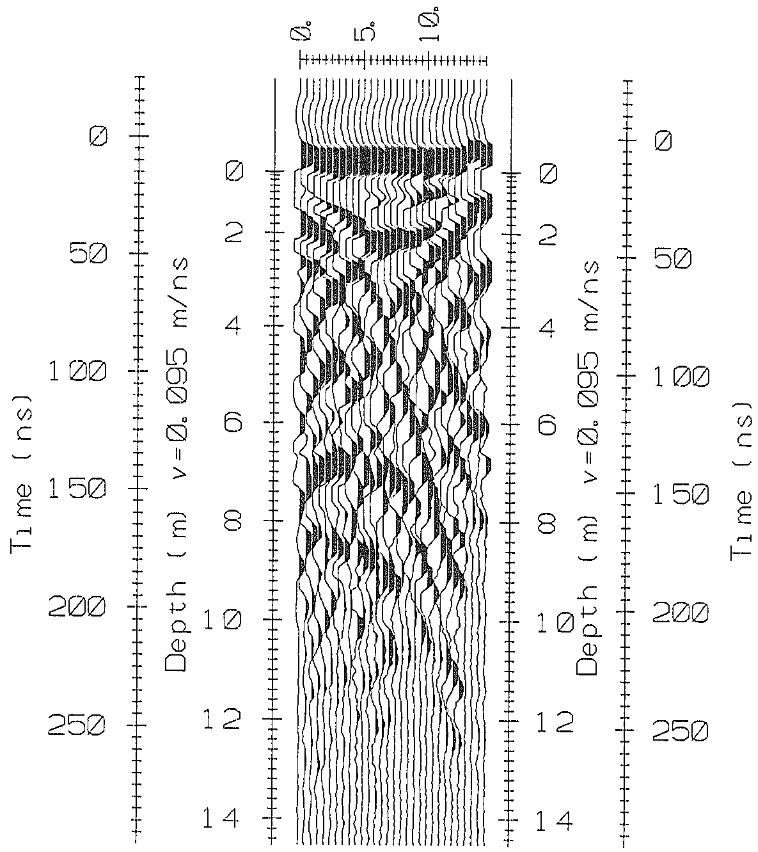
130.
135.
140.
145.
150.
155.
160.
165.
Depth (m) v=0.095 m/ns
0
2
4
6
8
10
12
14
Time (ns)
0
50
100
150
200
250
Cross 2
Cross 1



LITTLE SMITH CREEK - LONG PROFILE 2 - 50 MHz - JULY 6

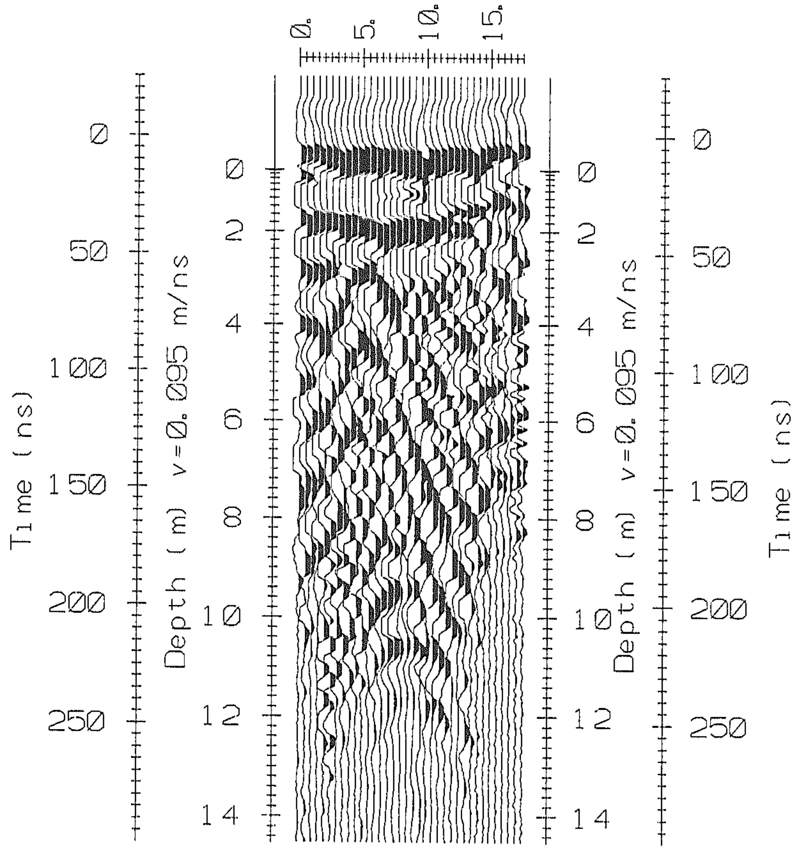


120.
125.
130.
135.
140.
145.
150.
155.
160.
165.
170.
deeper thaw
Depth (m) v=0.095 m/ns
0
2
4
6
8
10
12
14
Time (ns)
0
50
100
150
200
250

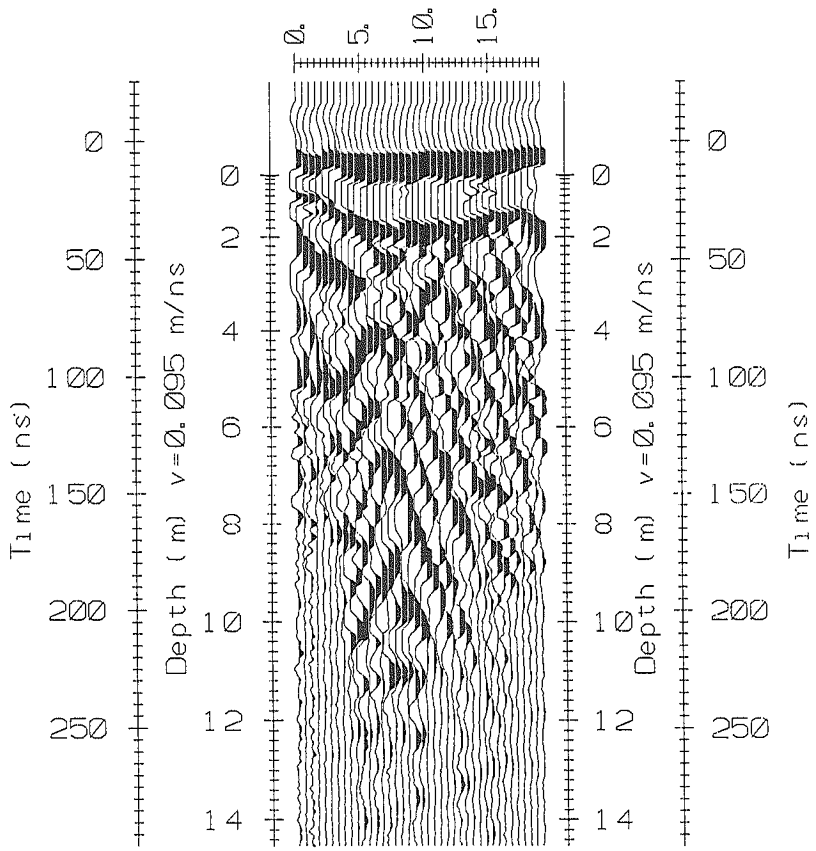


note loss of horizontal resolution with increased station spacing

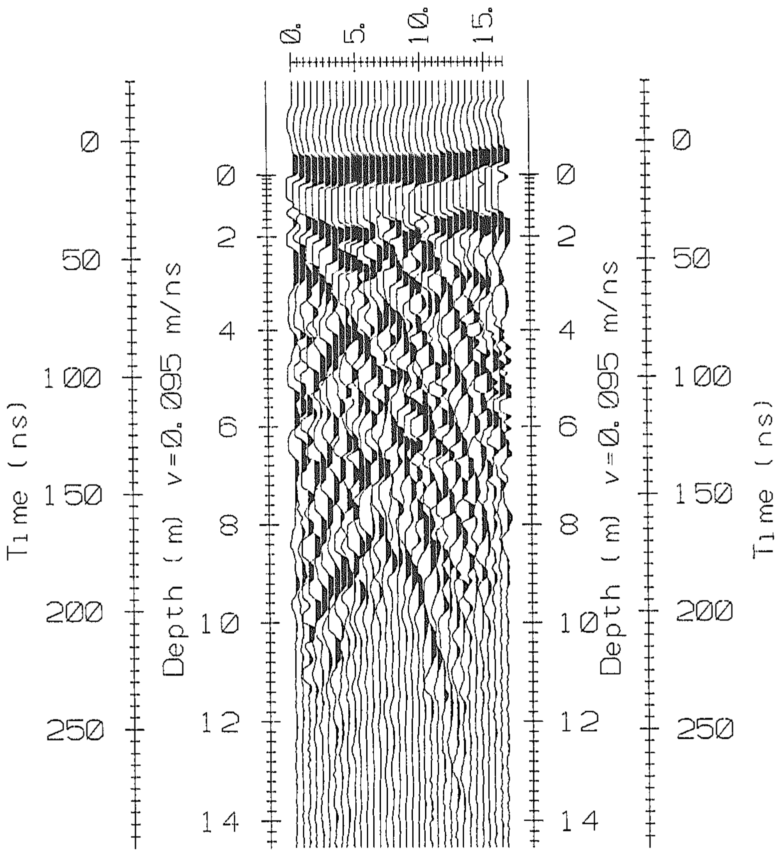
LITTLE SMITH CREEK - CROSS PROFILE 1 - 50 MHz - JULY 6



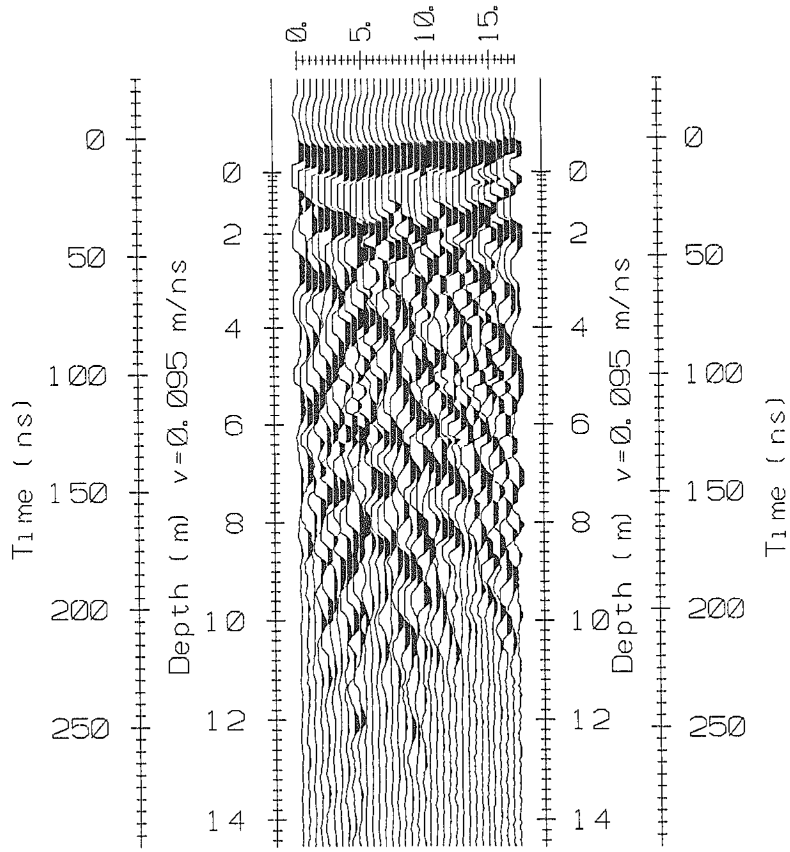
LITTLE SMITH CREEK - CROSS PROFILE 2 - 50 MHz - JULY 6



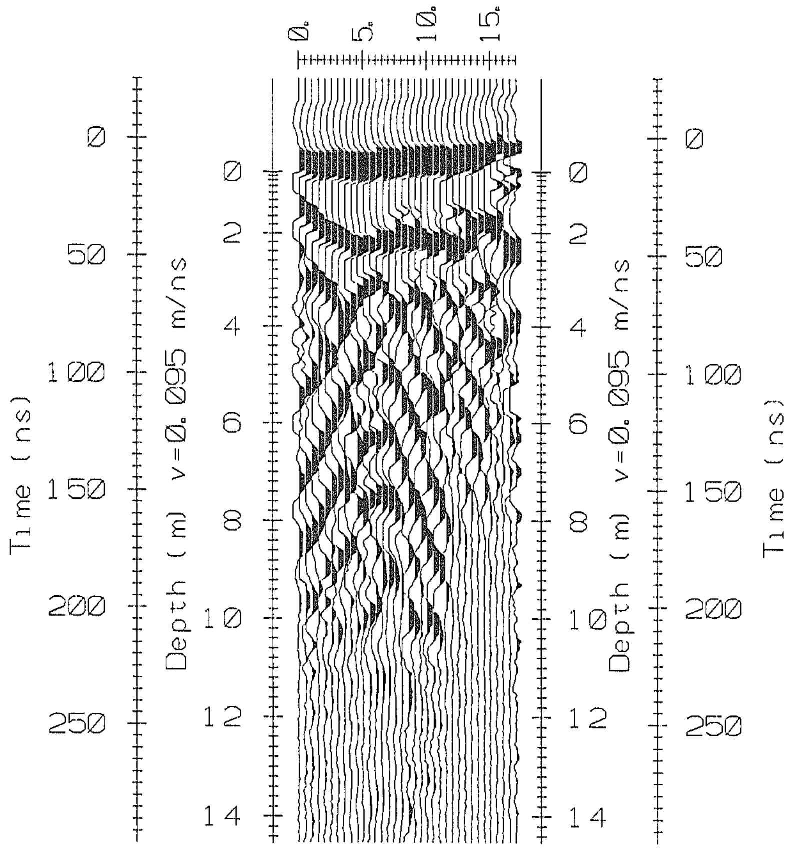
LITTLE SMITH CREEK - CROSS PROFILE 3 - 50 MHz - JULY 6



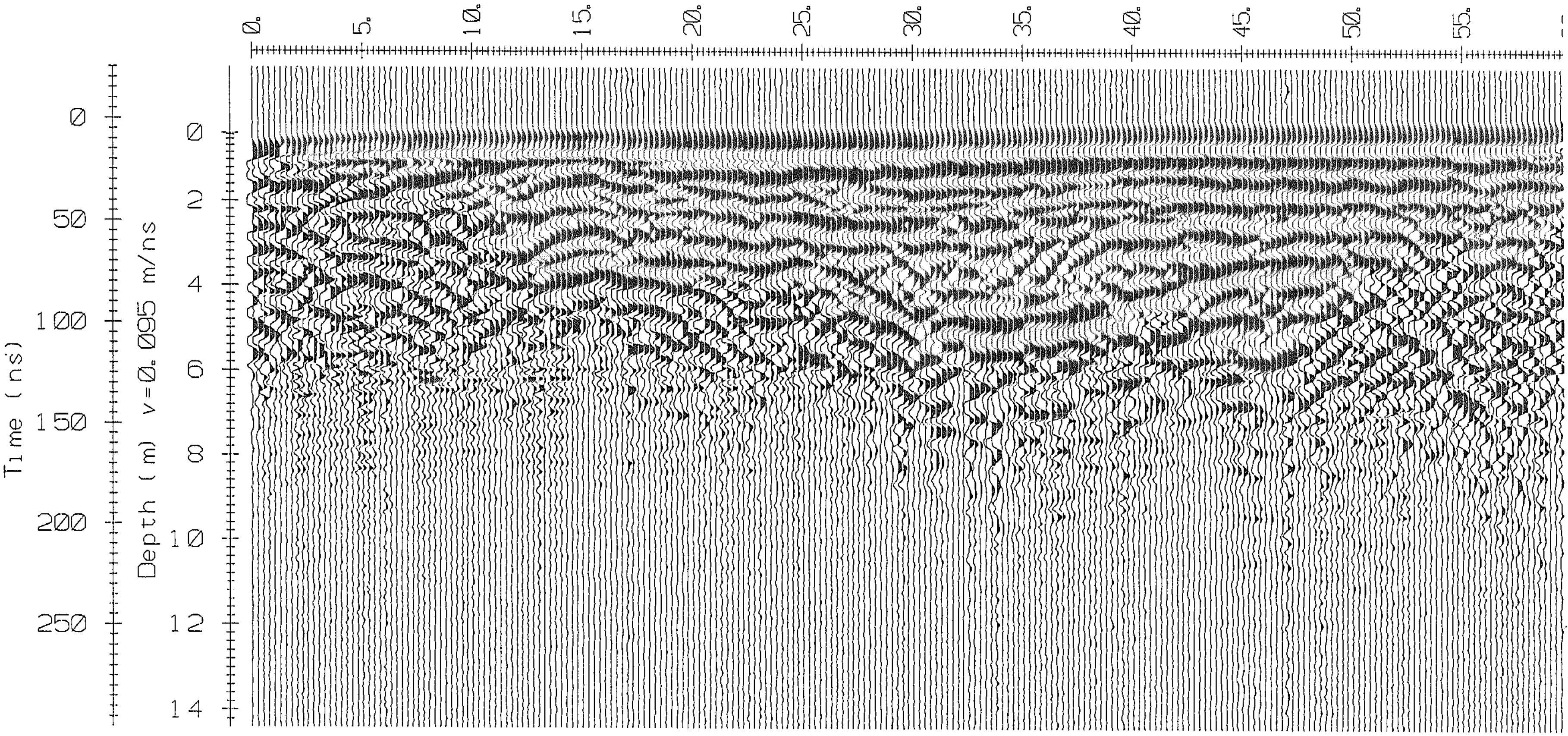
LITTLE SMITH CREEK - CROSS PROFILE 4 - 50 MHz - JULY 6



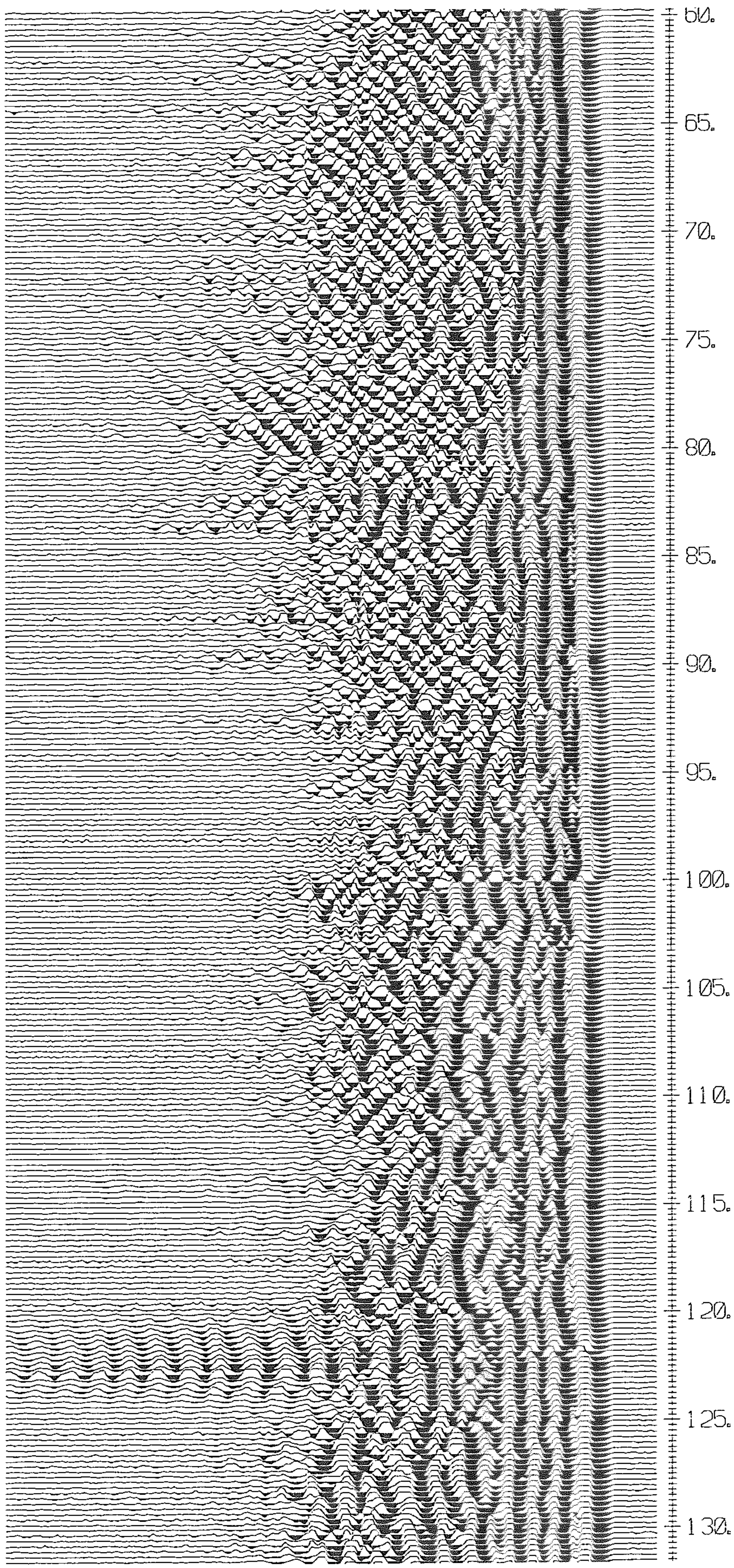
LITTLE SMITH CREEK - CROSS PROFILE 5 - 50 MHz - JULY 6



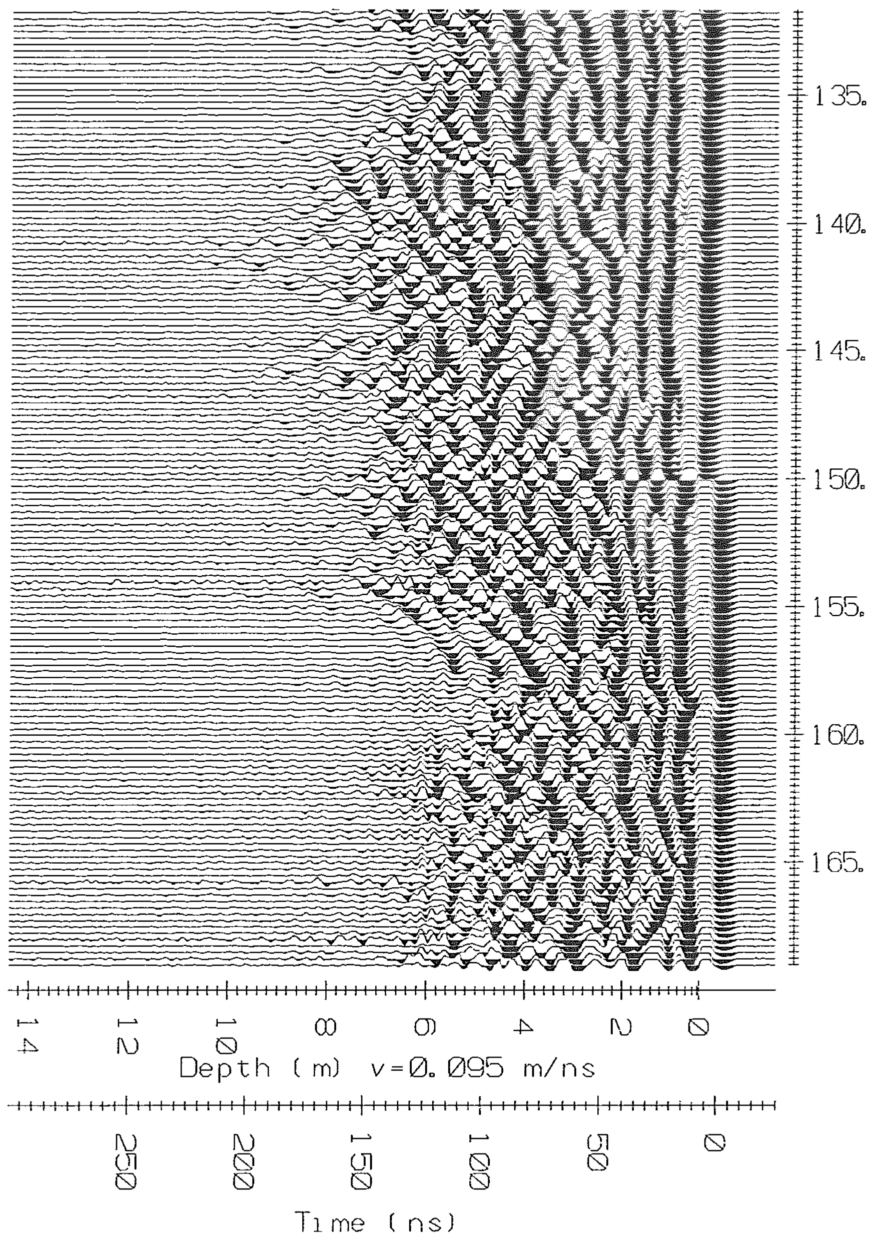
LITTLE SMITH CREEK - CROSS PROFILE 6 - 50 MHz - JULY 6



LITTLE SMITH CREEK - LONG PROFILE 1 - 100 MHz - JULY 7

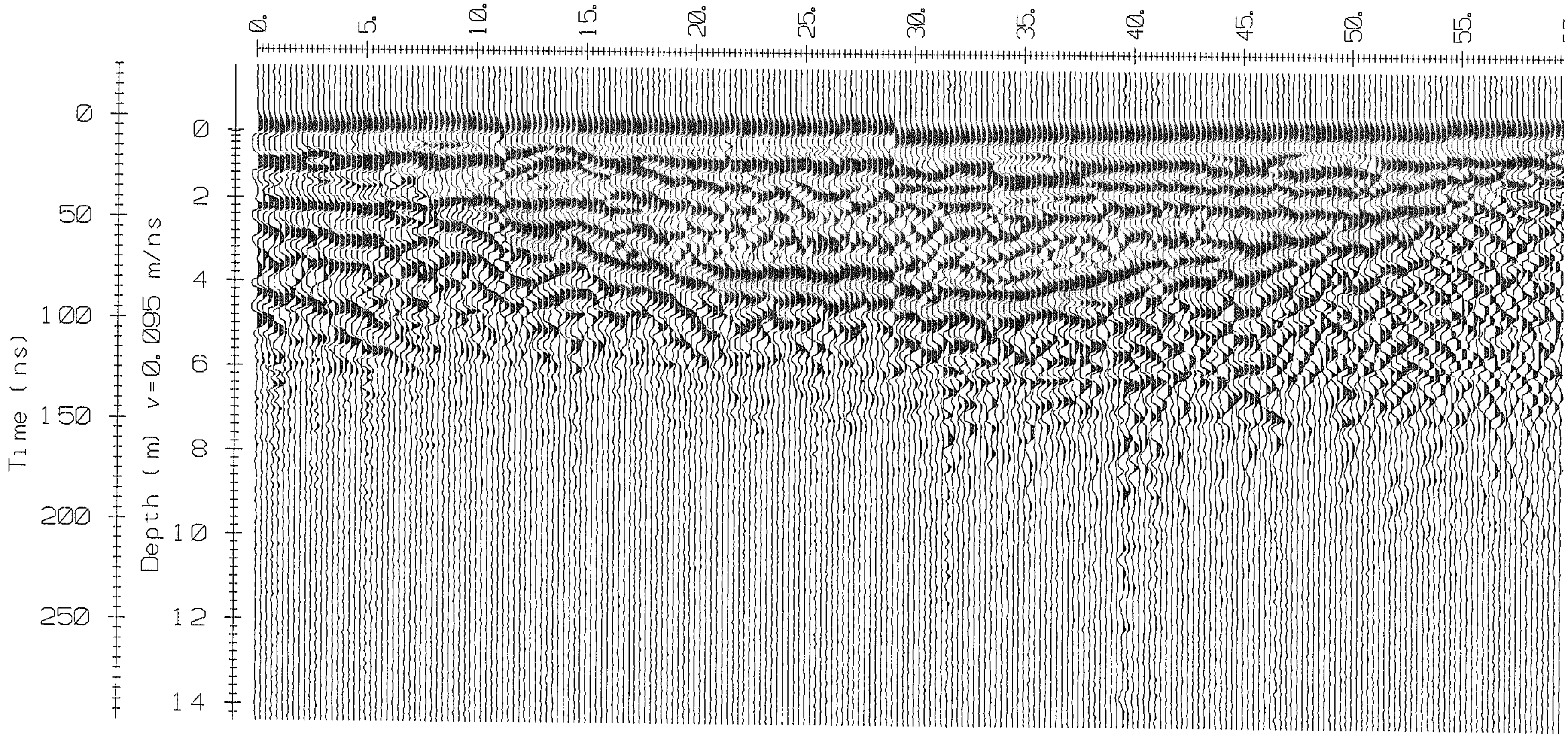


60.
65.
70.
75.
80.
85.
90.
95.
100.
105.
110.
115.
120.
125.
130.

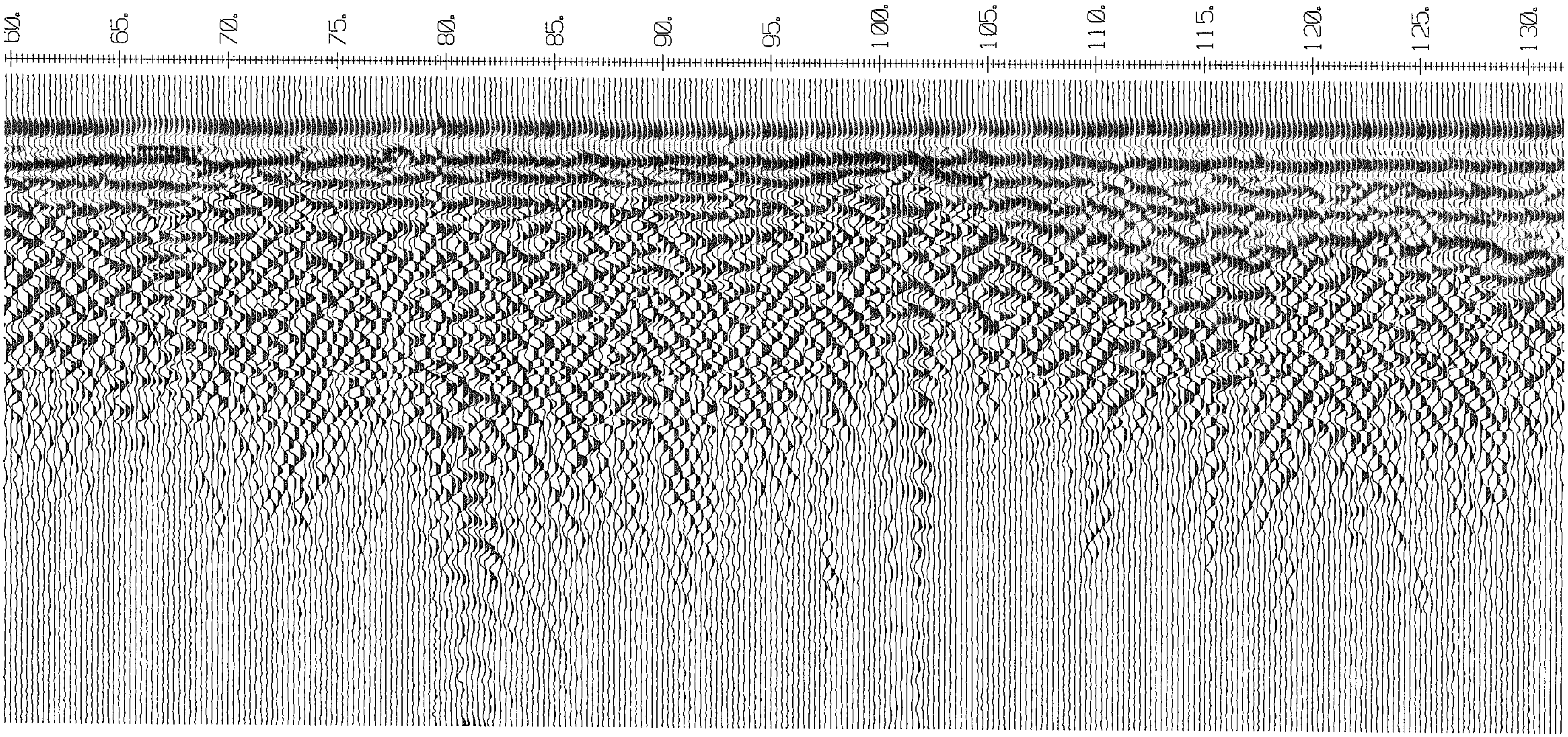


135.
140.
145.
150.
155.
160.
165.
14
12
10
8
6
4
2
0
Depth (m) v=0.095 m/ns
250
200
150
100
50
0
Time (ns)

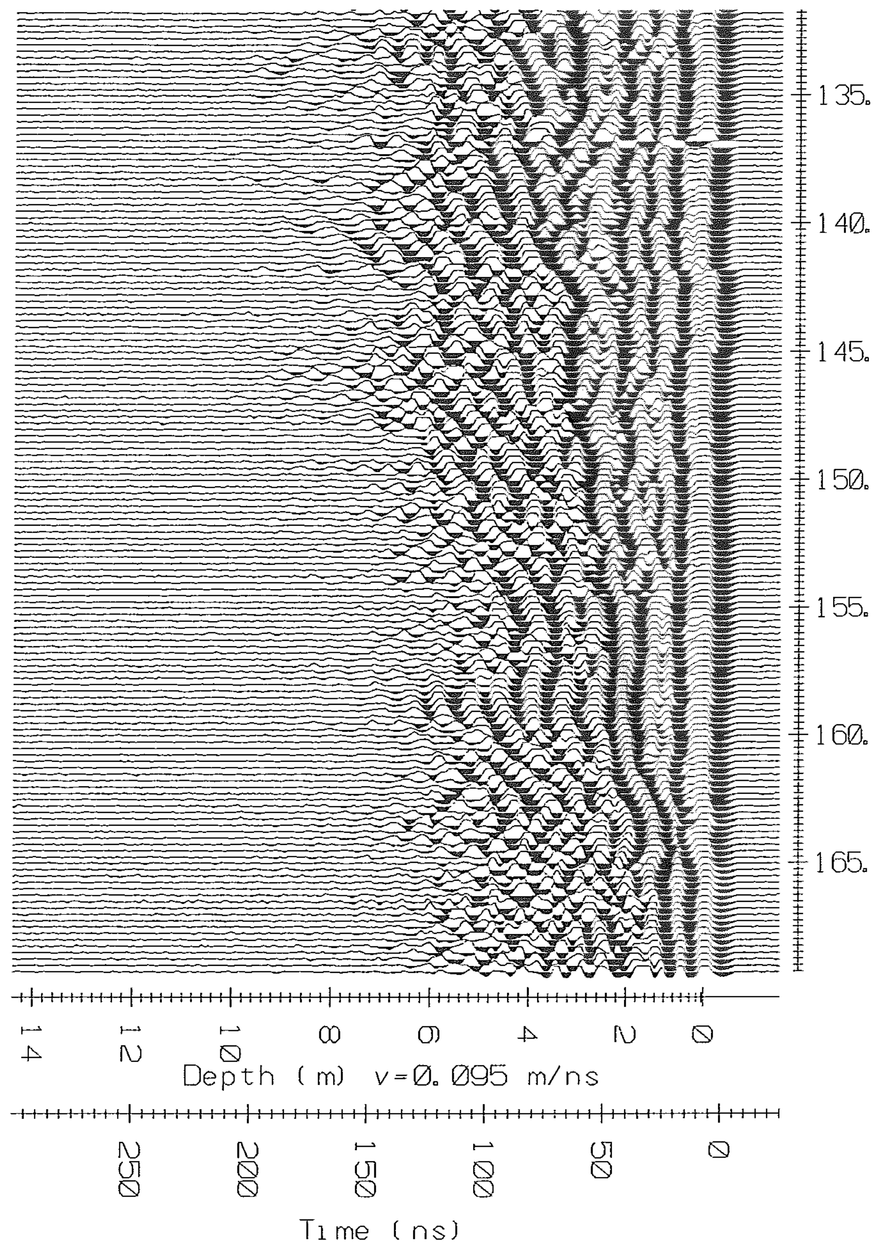
interpreted depth of thaw

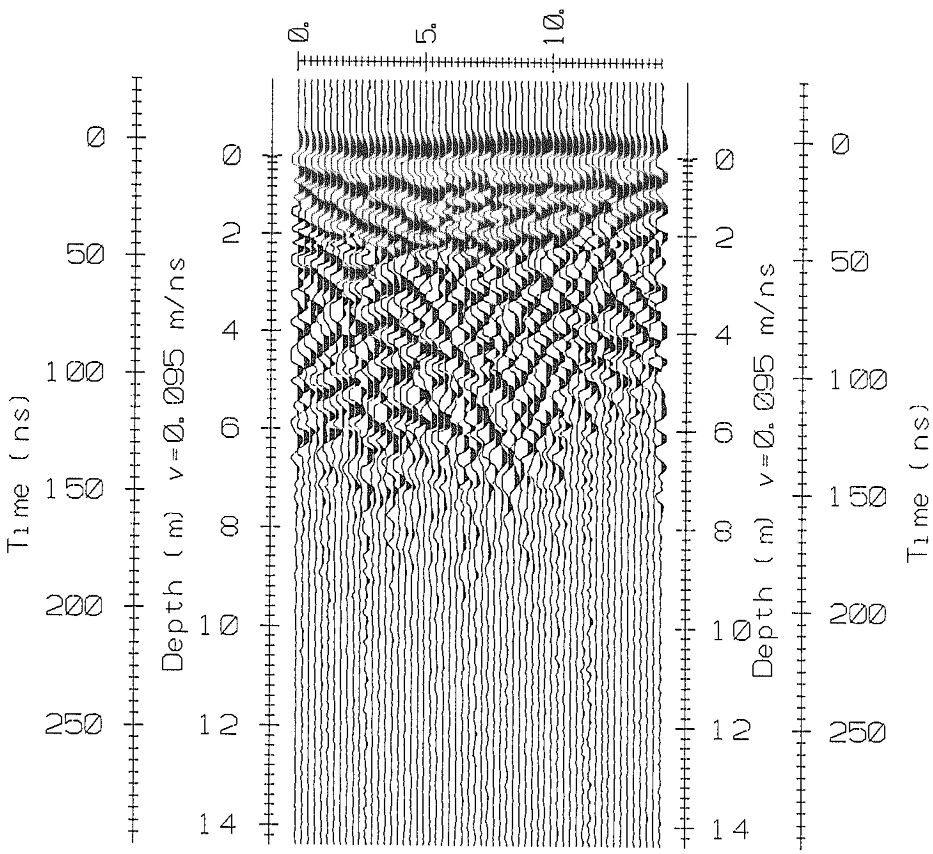


LITTLE SMITH CREEK - LONG PROFILE 2 - 100 MHz - JULY 7

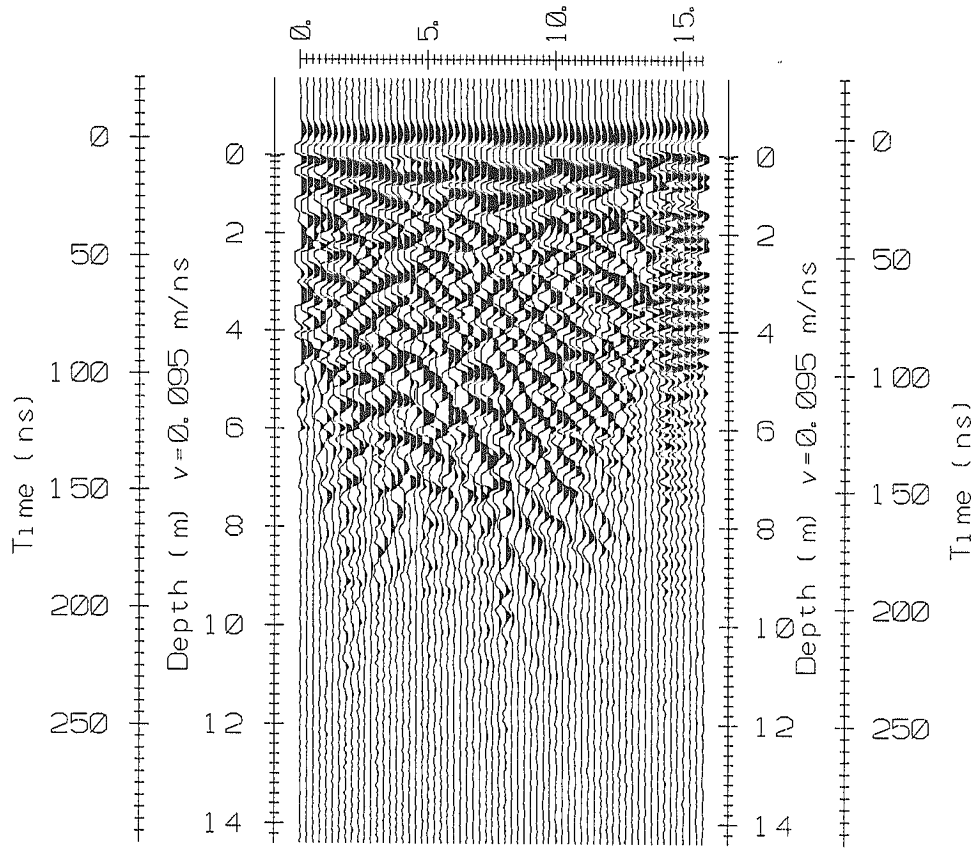


60.
65.
70.
75.
80.
85.
90.
95.
100.
105.
110.
115.
120.
125.
130.

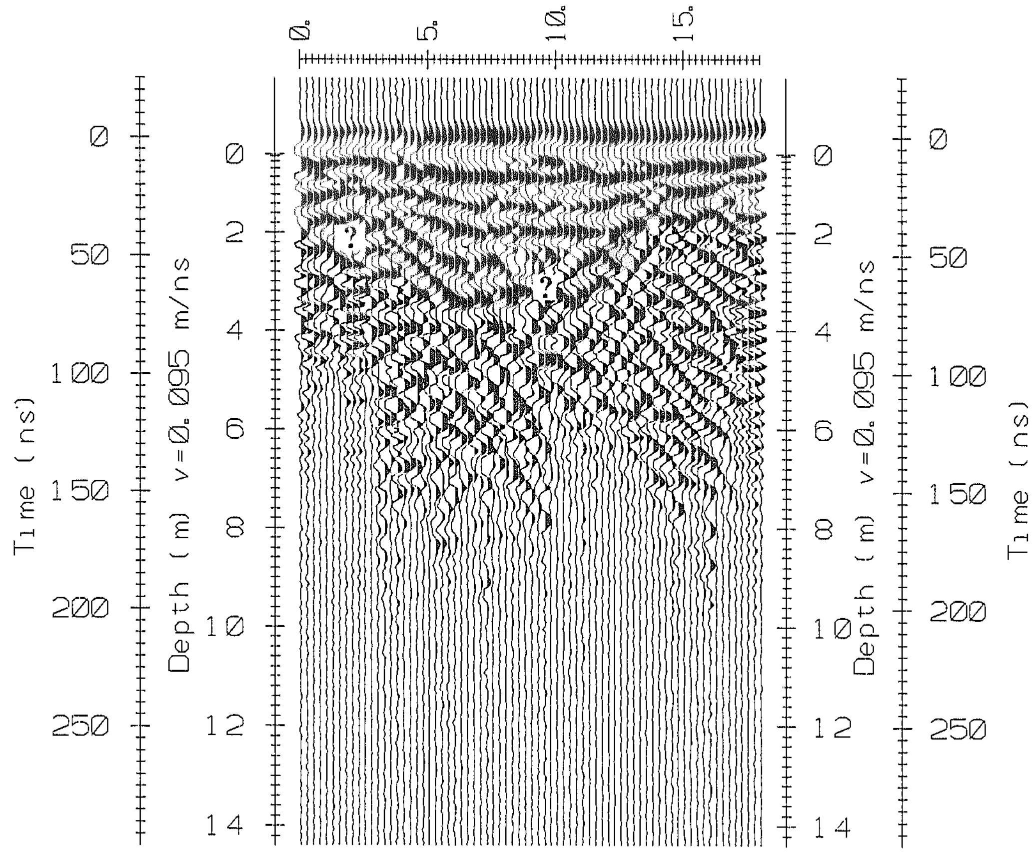

135.
140.
145.
150.
155.
160.
165.
14
12
10
8
6
4
2
0
Depth (m) v=0.095 m/ns
250
200
150
100
50
0
Time (ns)



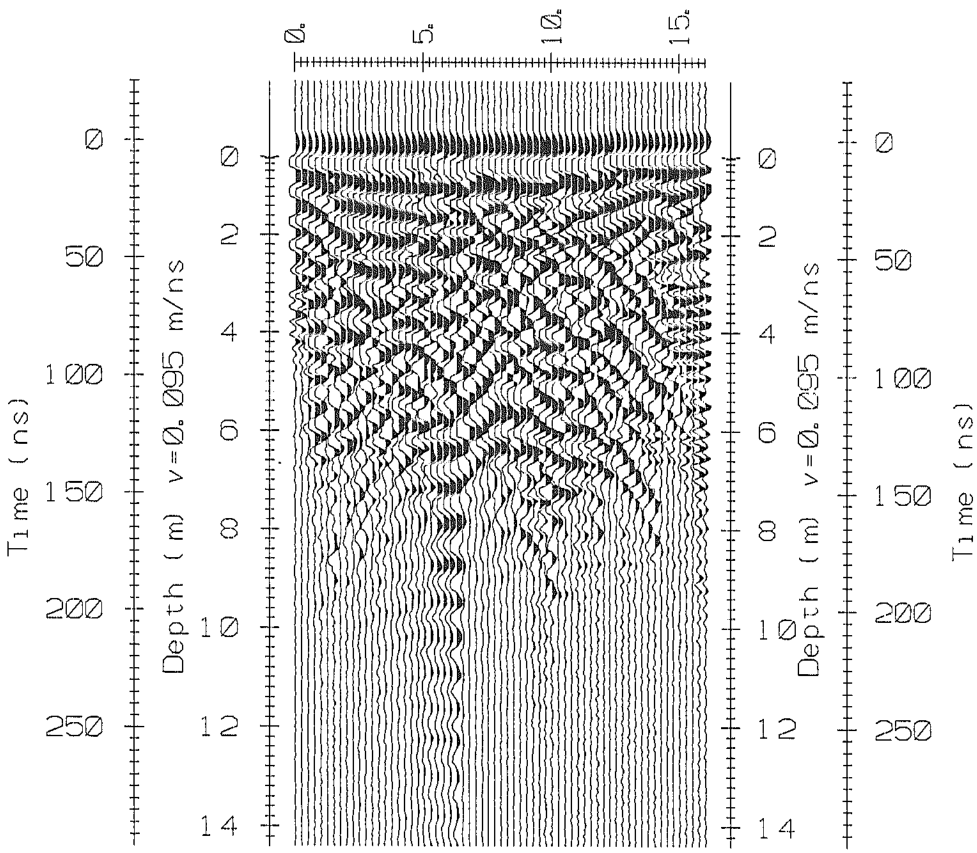
LITTLE SMITH CREEK - CROSS PROFILE 1 - 100 MHz - JULY 7



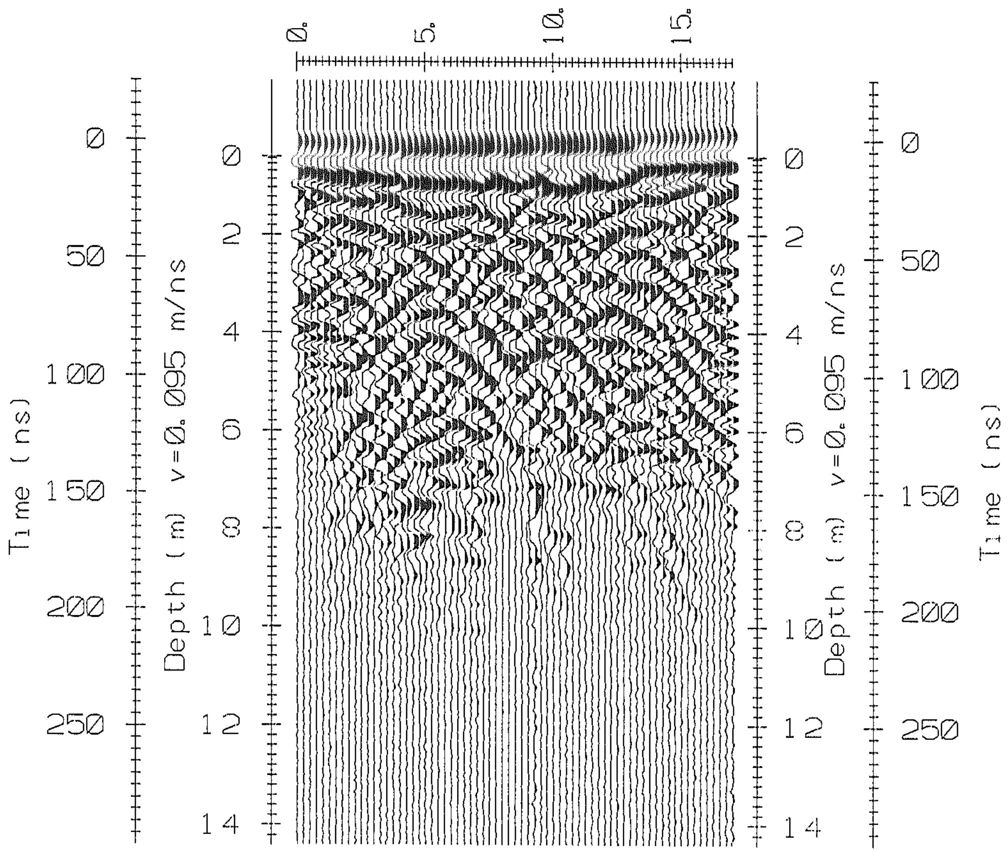
LITTLE SMITH CREEK - CROSS PROFILE 2 - 100 MHz - JULY 7



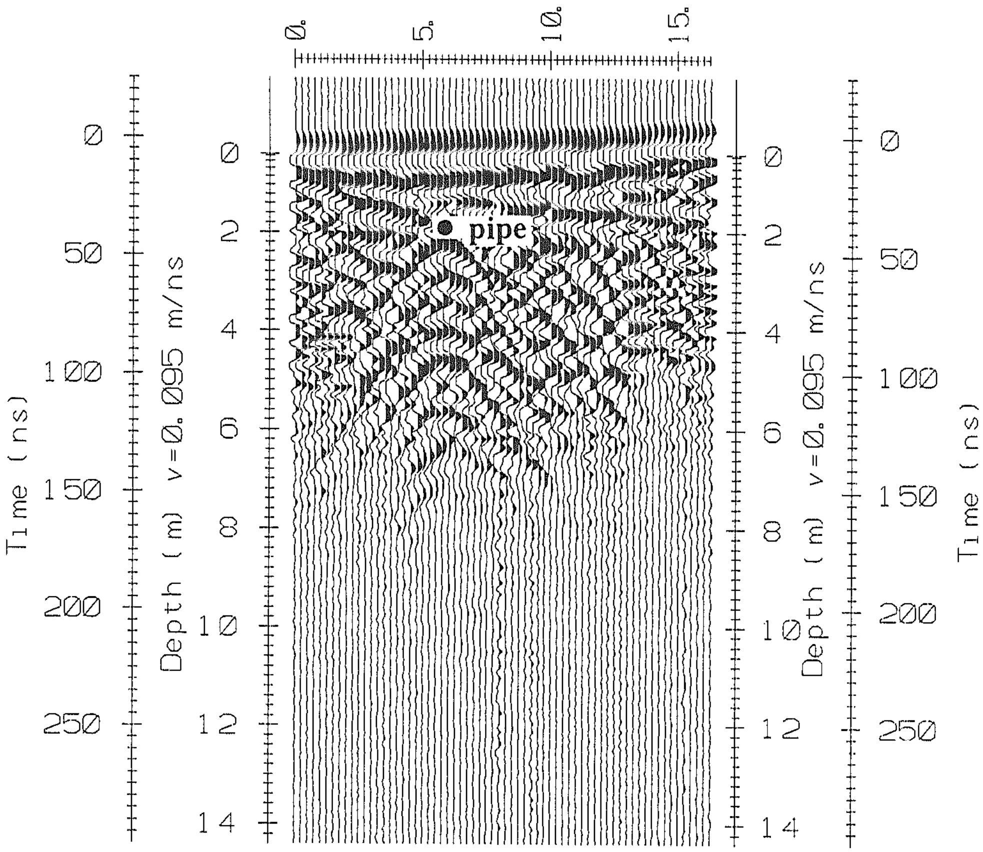
LITTLE SMITH CREEK - CROSS PROFILE 3 - 100 MHz - JULY 7



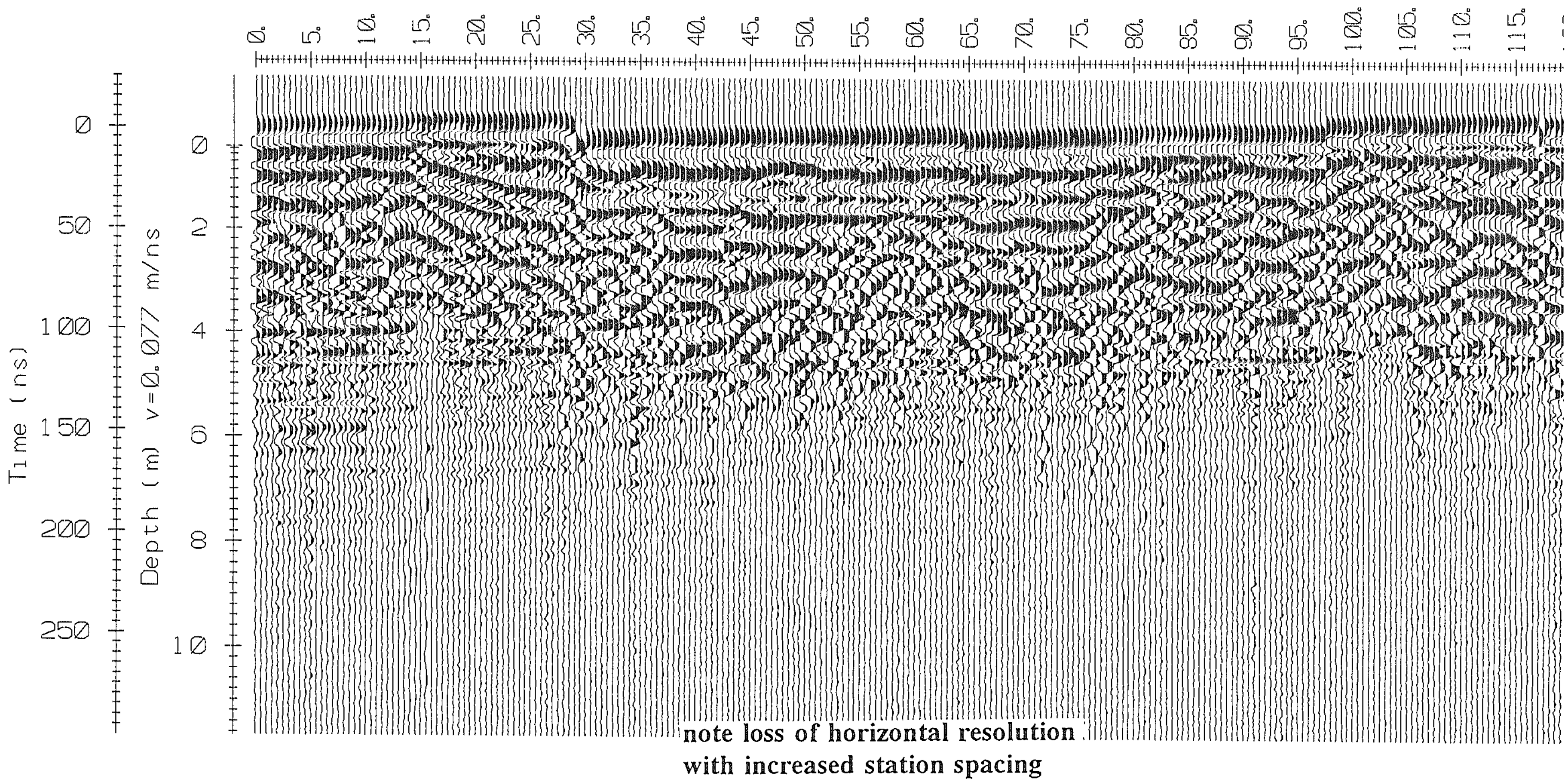
LITTLE SMITH CREEK - CROSS PROFILE 4 - 100 MHz - JULY 7



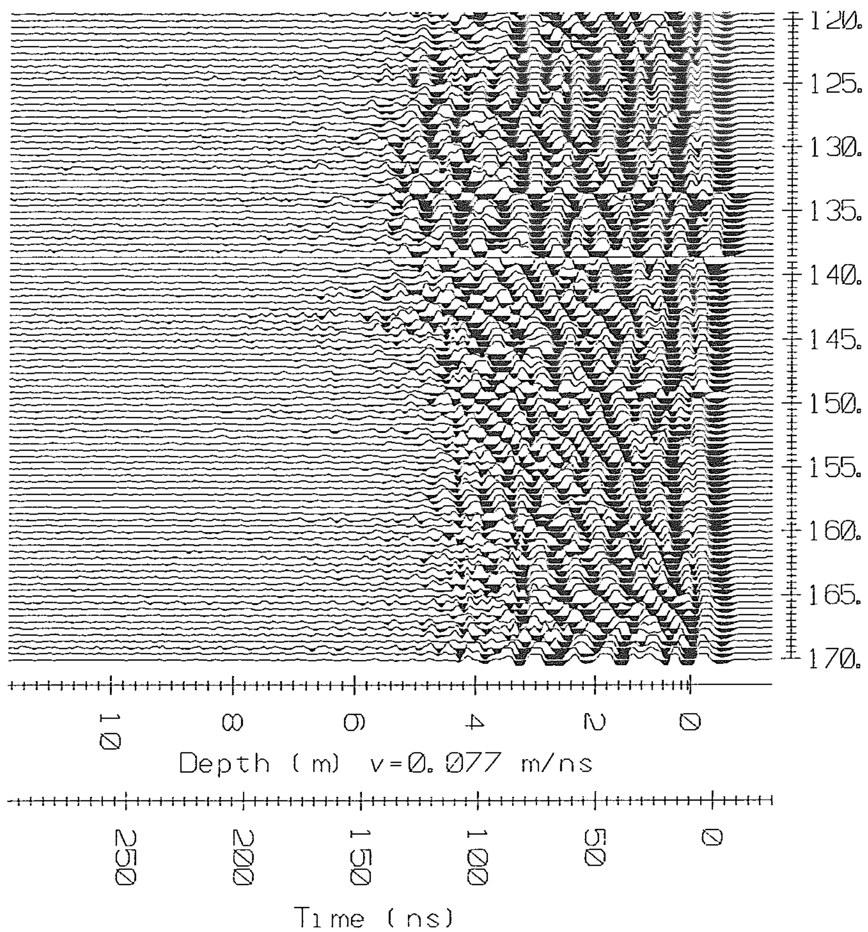
LITTLE SMITH CREEK - CROSS PROFILE 5 - 100 MHz - JULY 7



LITTLE SMITH CREEK - CROSS PROFILE 6 - 100 MHz - JULY 7

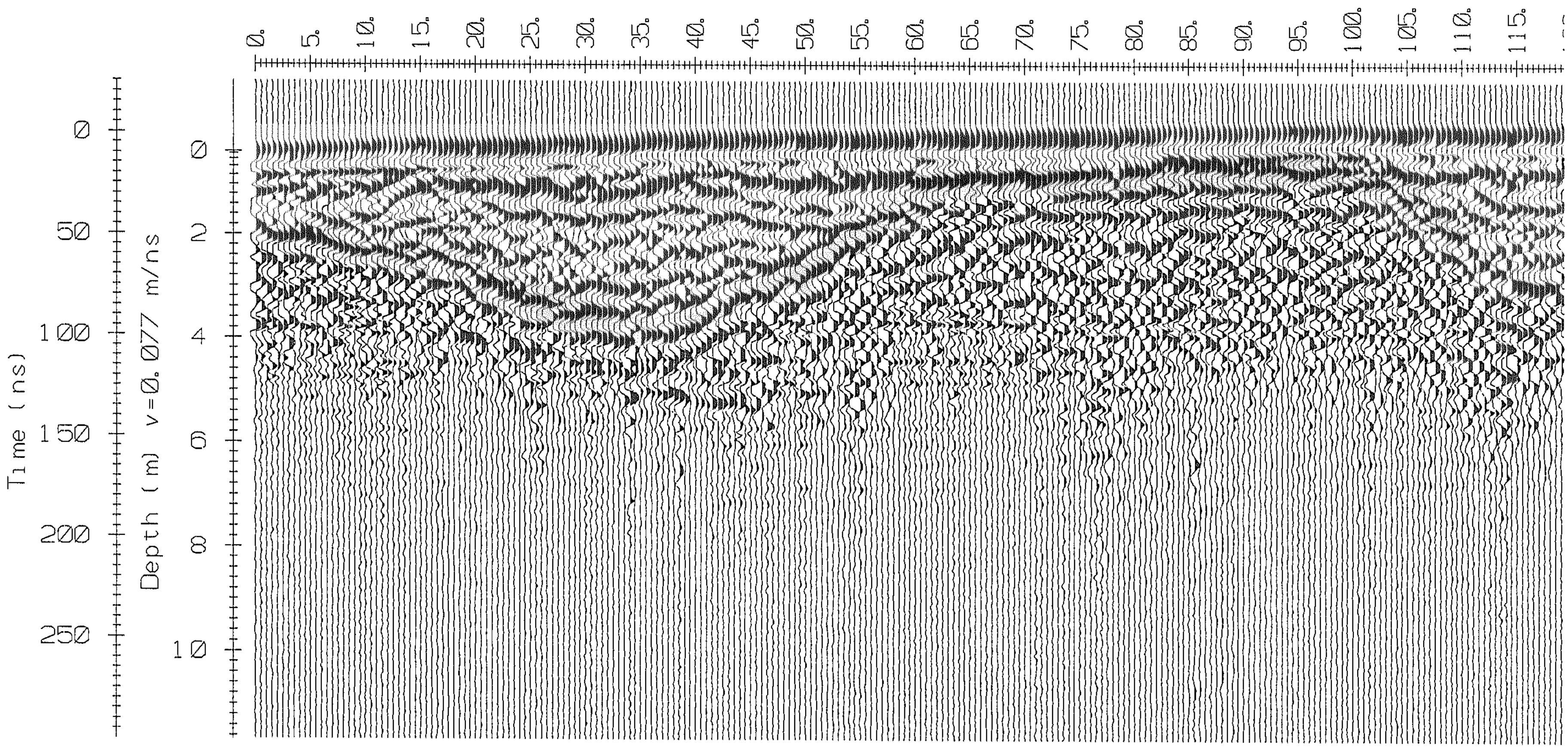


LITTLE SMITH CREEK - LONG PROFILE 1 - 100 MHz - AUGUST 19

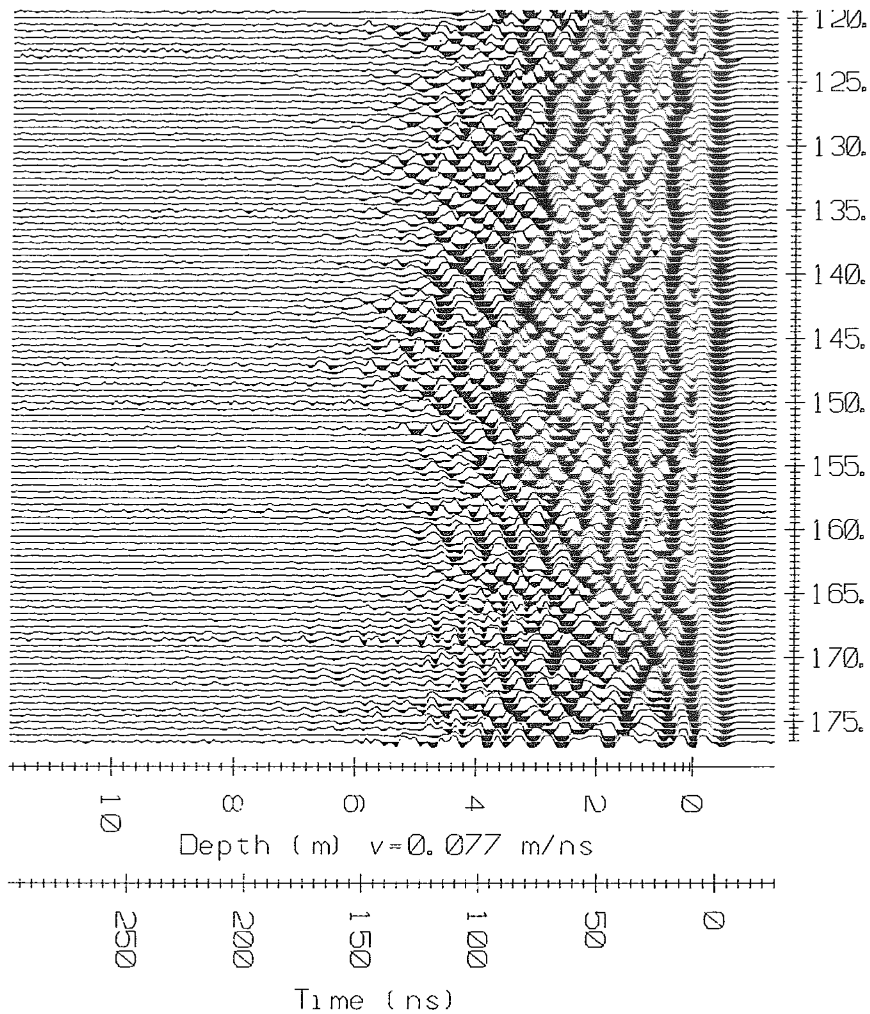


120.
125.
130.
135.
140.
145.
150.
155.
160.
165.
170.
10
8
6
4
2
0
Depth (m) v=0.077 m/ns
250
200
150
100
50
0
Time (ns)

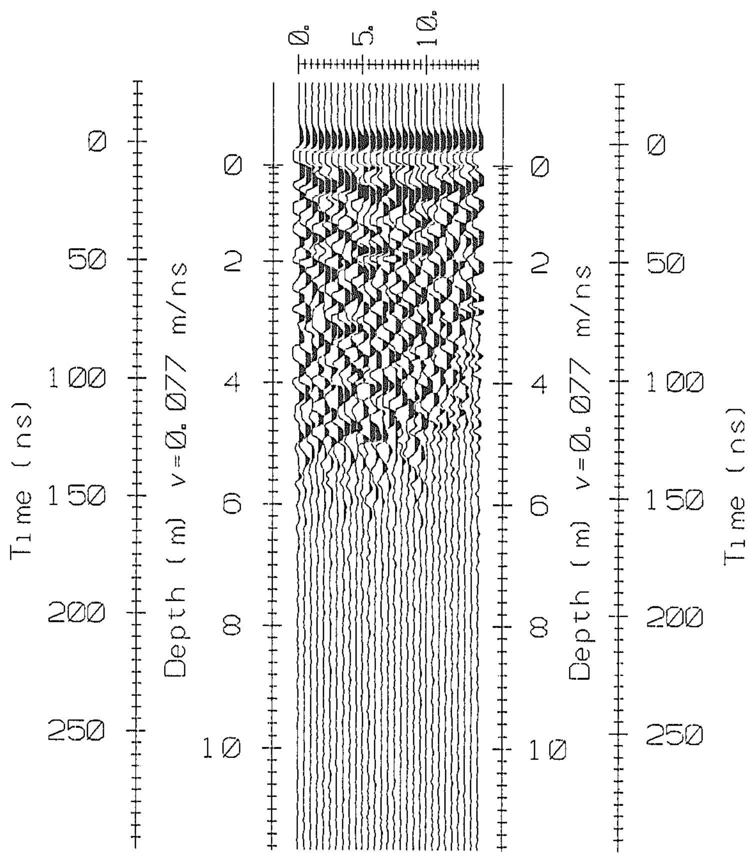
interpreted depth of thaw



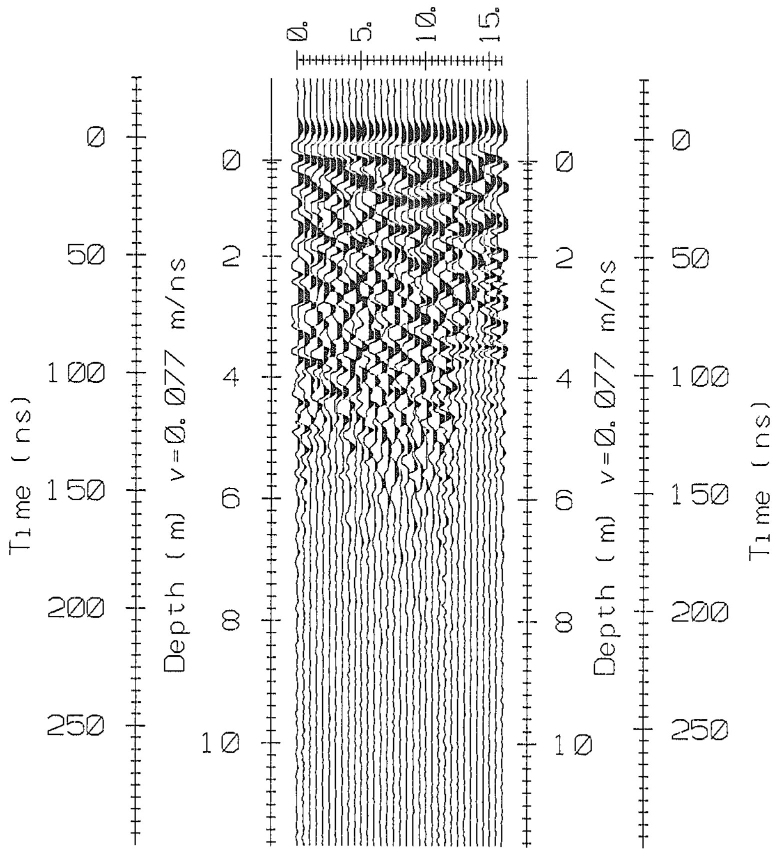
LITTLE SMITH CREEK - LONG PROFILE 2 - 100 MHz - AUGUST 19



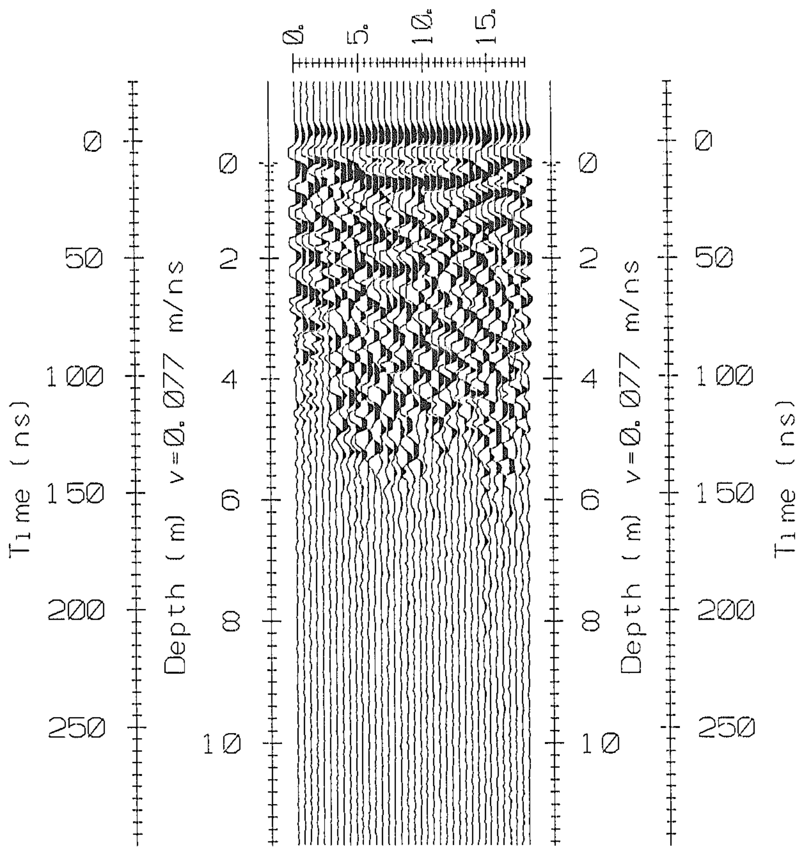
120.
125.
130.
135.
140.
145.
150.
155.
160.
165.
170.
175.
10
8
6
4
2
0
Depth (m) v=0.077 m/ns
250
200
150
100
50
0
Time (ns)



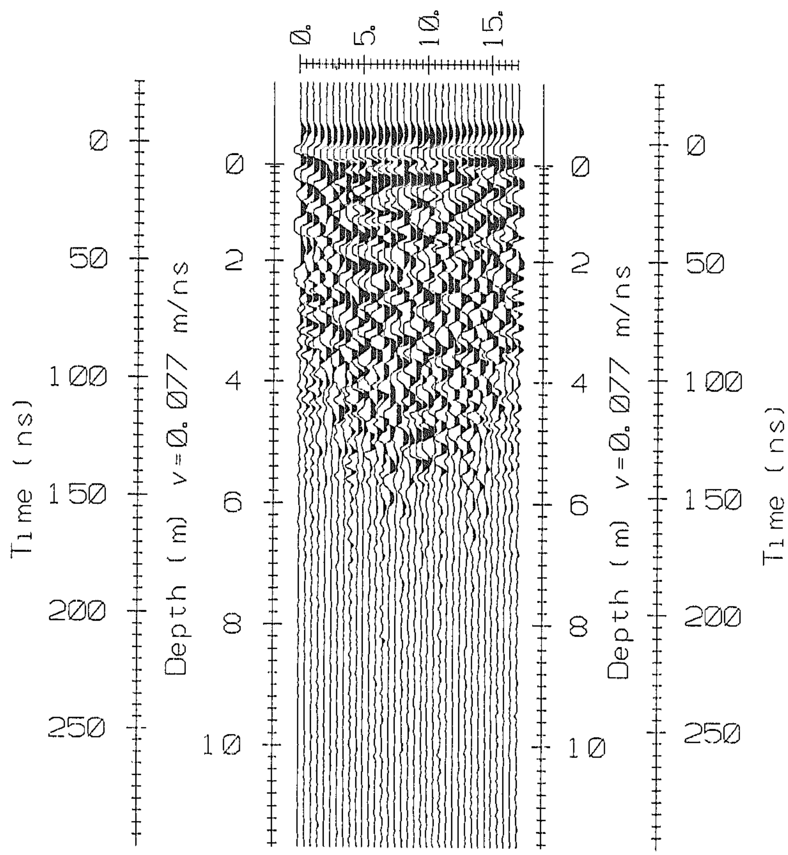
LITTLE SMITH CREEK - CROSS PROFILE 1 - 100 MHz - AUGUST 19



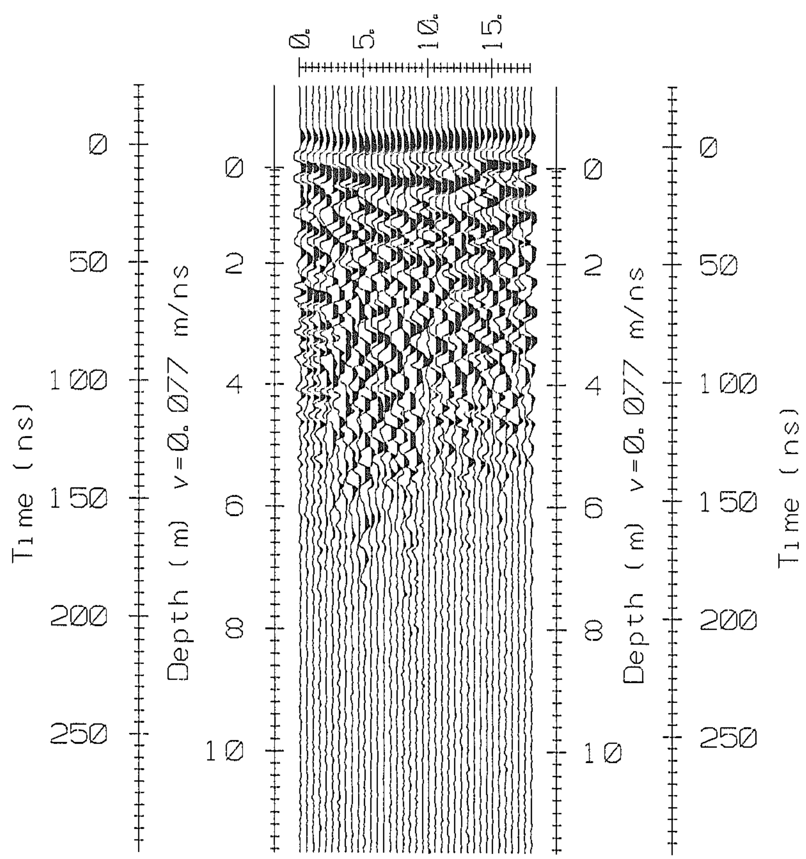
LITTLE SMITH CREEK - CROSS PROFILE 2 - 100 MHz - AUGUST 19



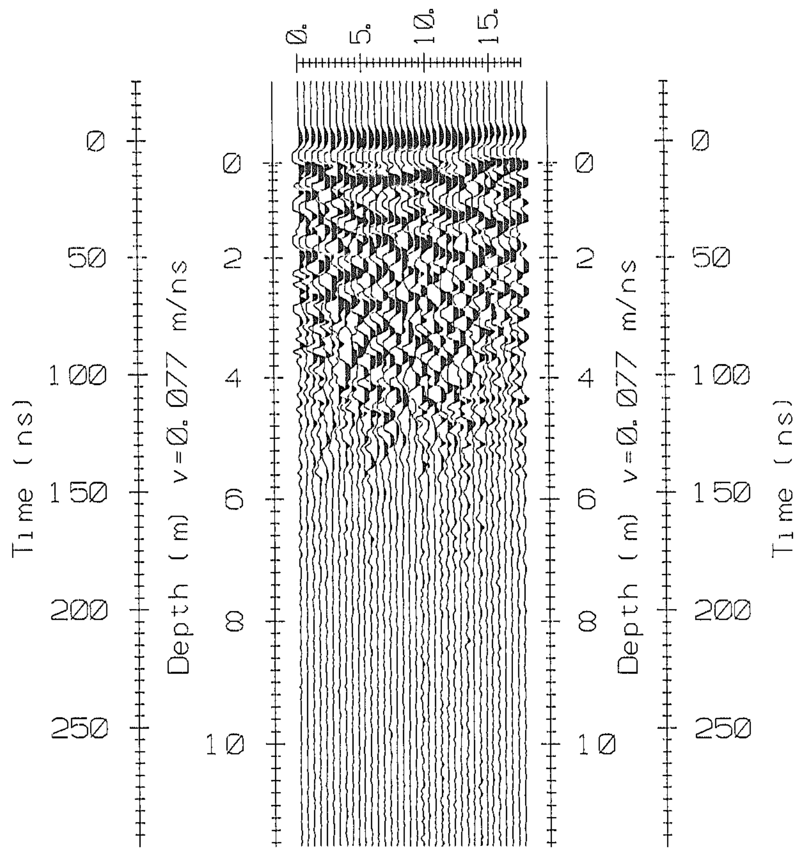
LITTLE SMITH CREEK - CROSS PROFILE 3 - 100 MHz - AUGUST 19



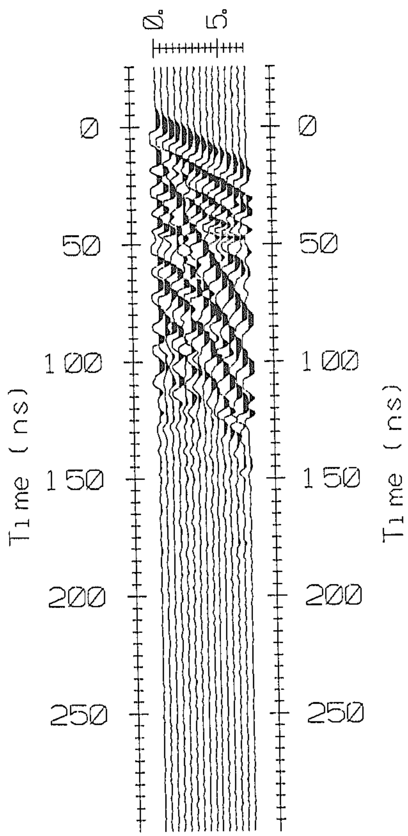
LITTLE SMITH CREEK - CROSS PROFILE 4 - 100 MHz - AUGUST 19



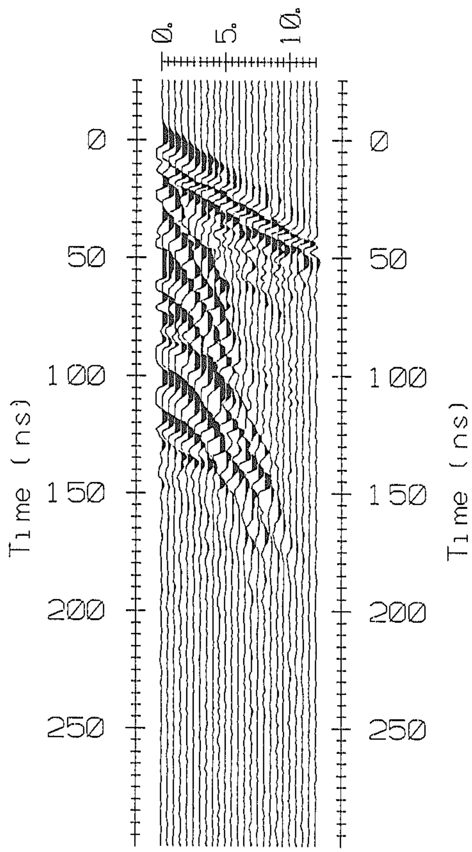
LITTLE SMITH CREEK - CROSS PROFILE 5 - 100 MHz - AUGUST 19



LITTLE SMITH CREEK - CROSS PROFILE 6 - 100 MHz - AUGUST 19



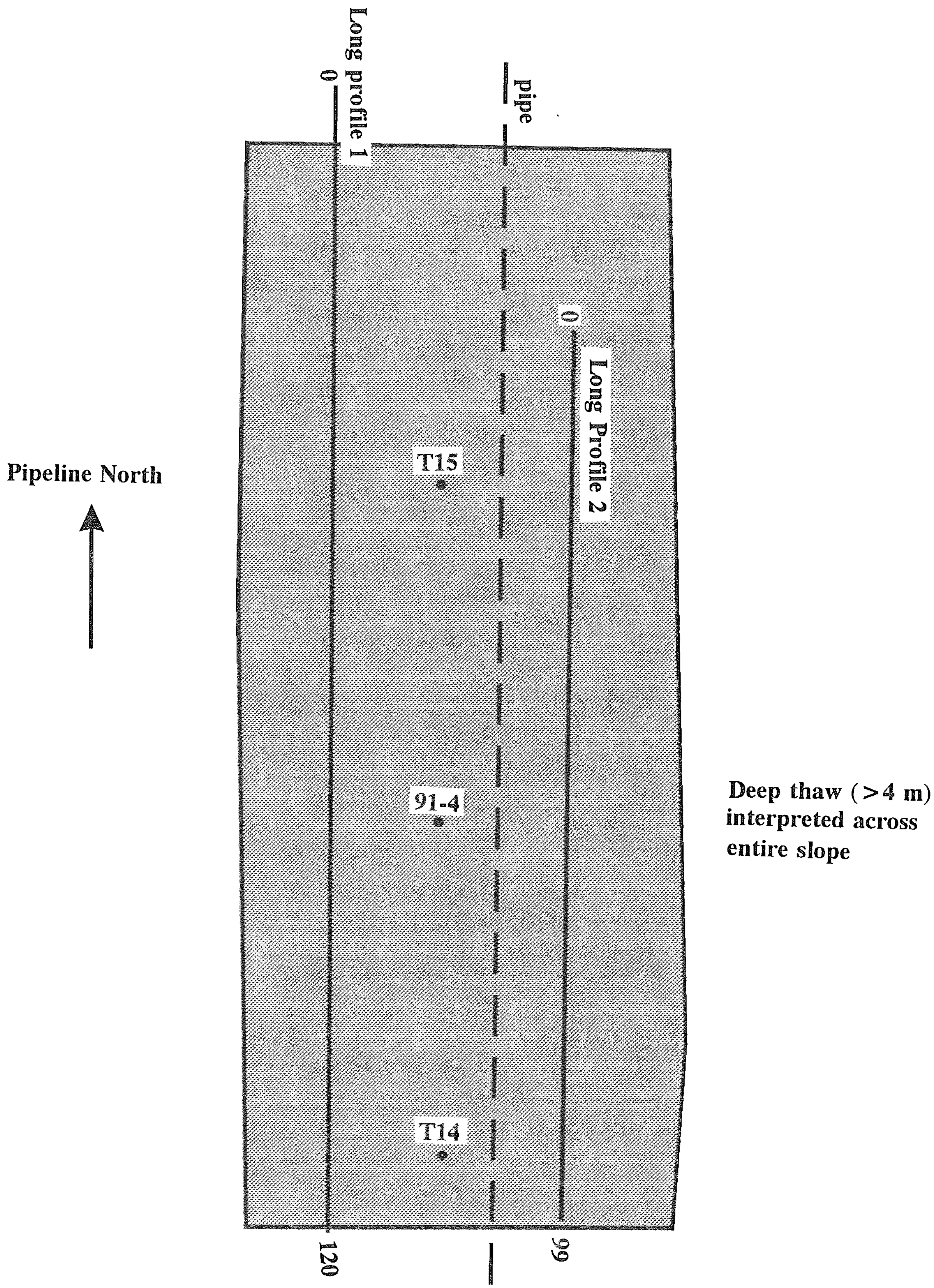
LITTLE SMITH CREEK - CMP - JULY 7



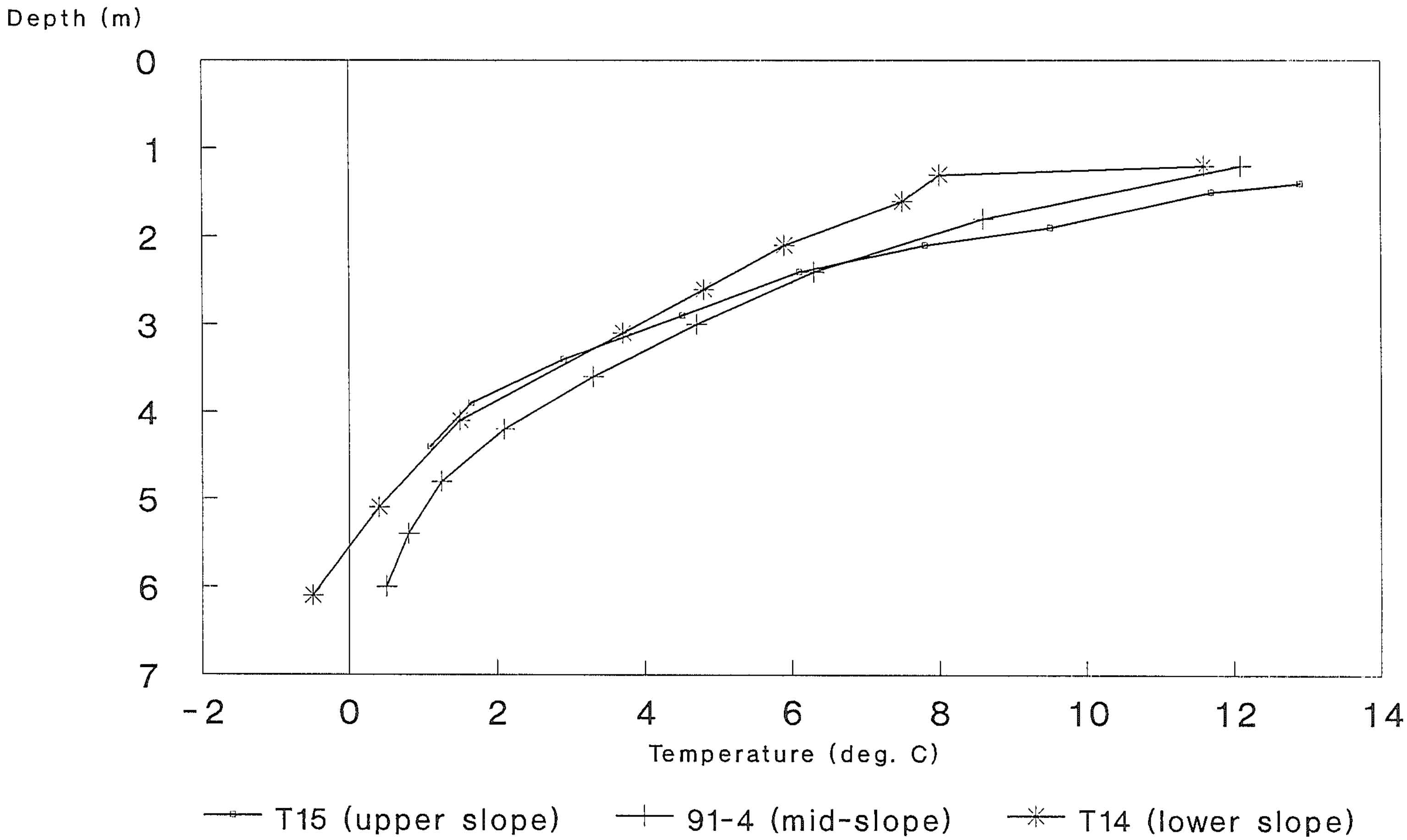
LITTLE SMITH CREEK - CMP - AUGUST 19

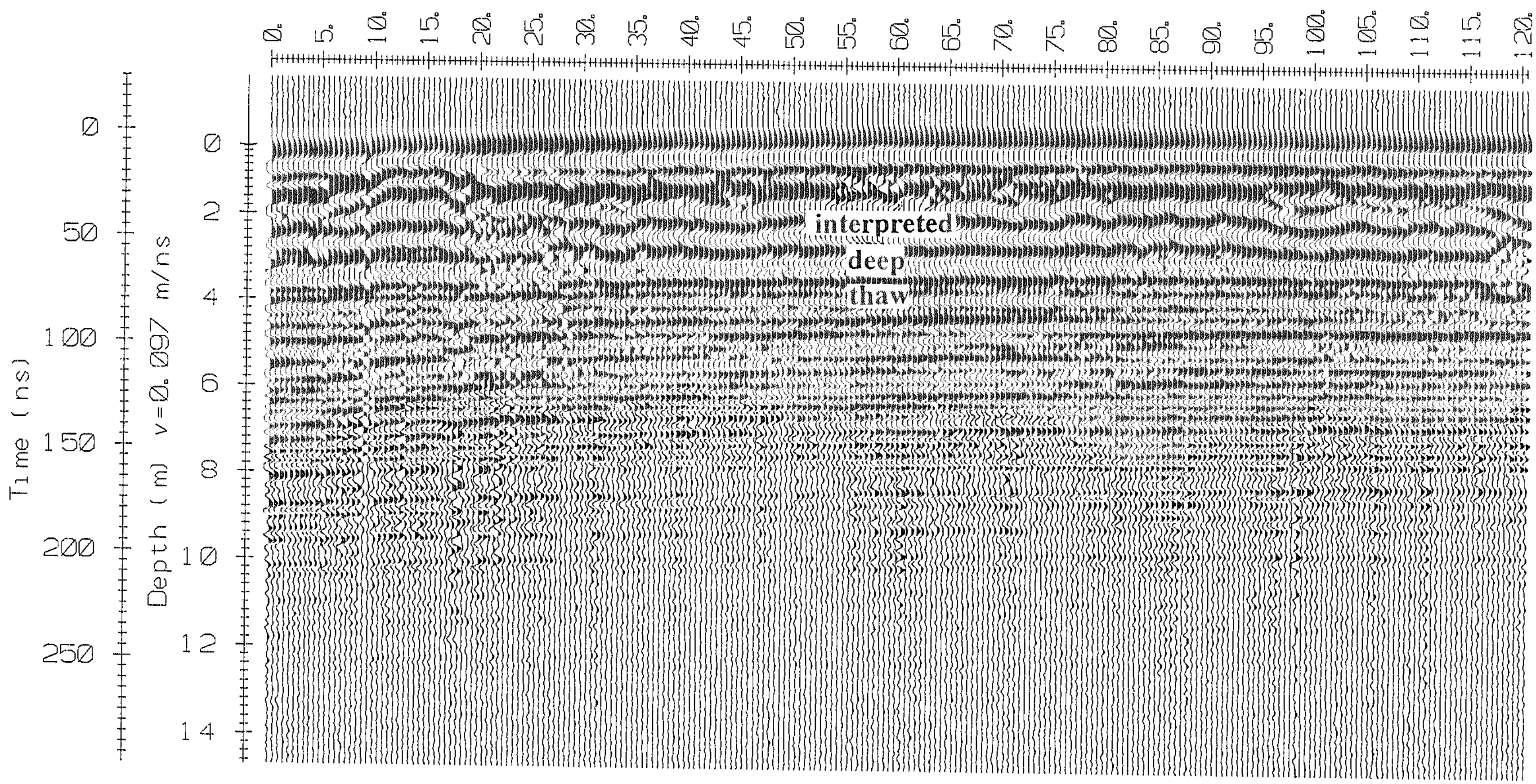
STEEP CREEK NORTH (SLOPE 62)

Not to Scale

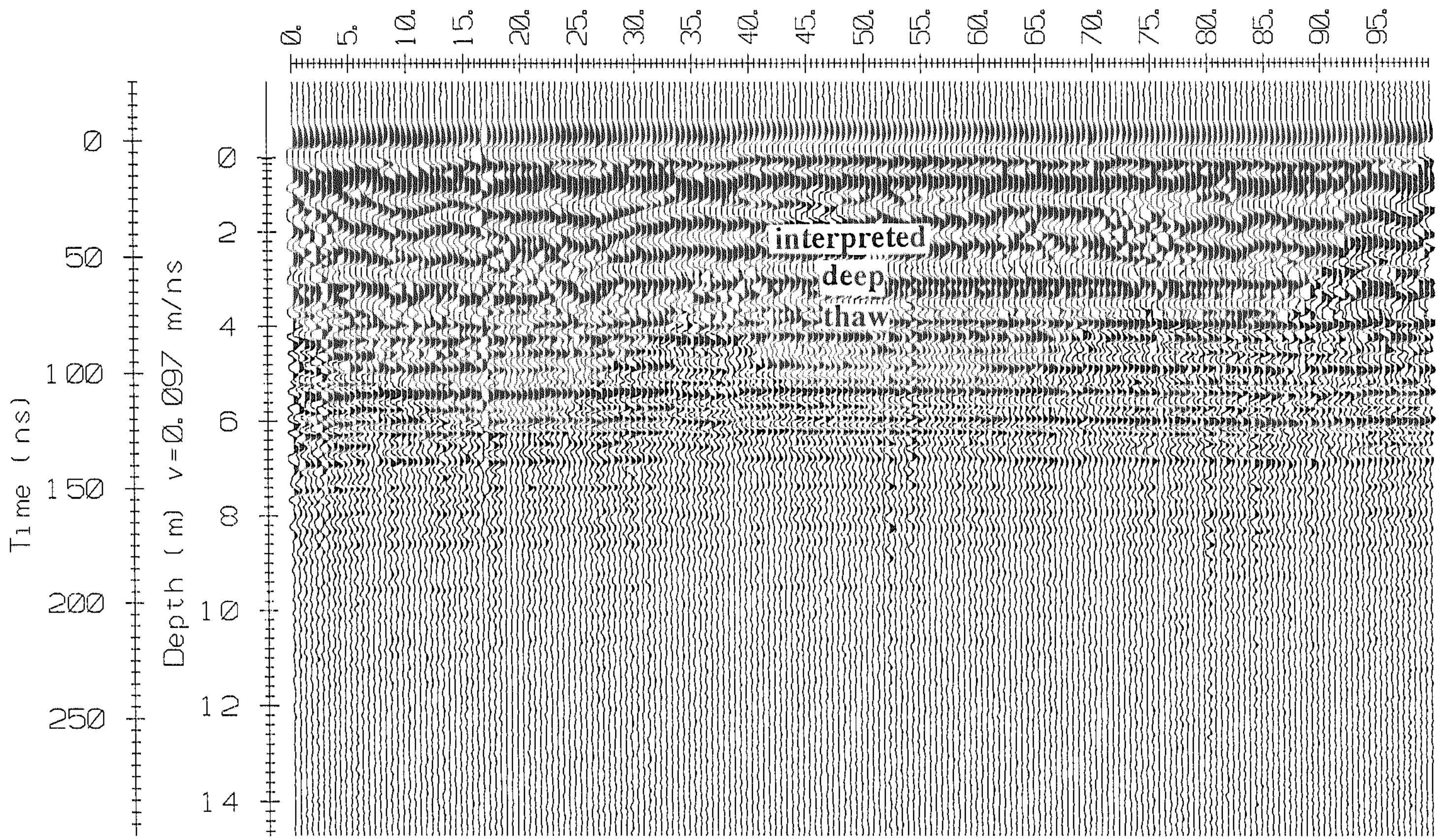


Steep Creek North, kp 194.6
August 28
1994

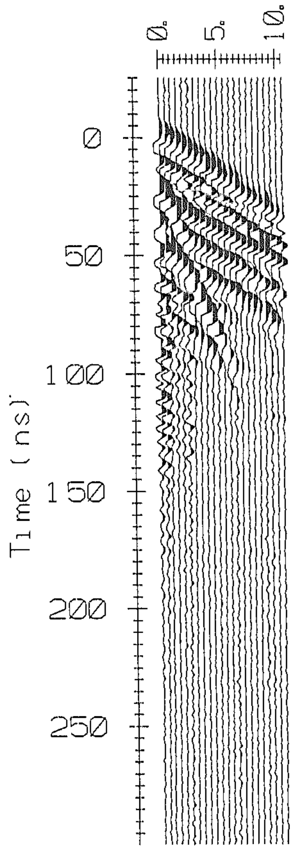




SLOPE 62 (kp 194) - LONG PROFILE 1 - 100 MHz - AUGUST 28



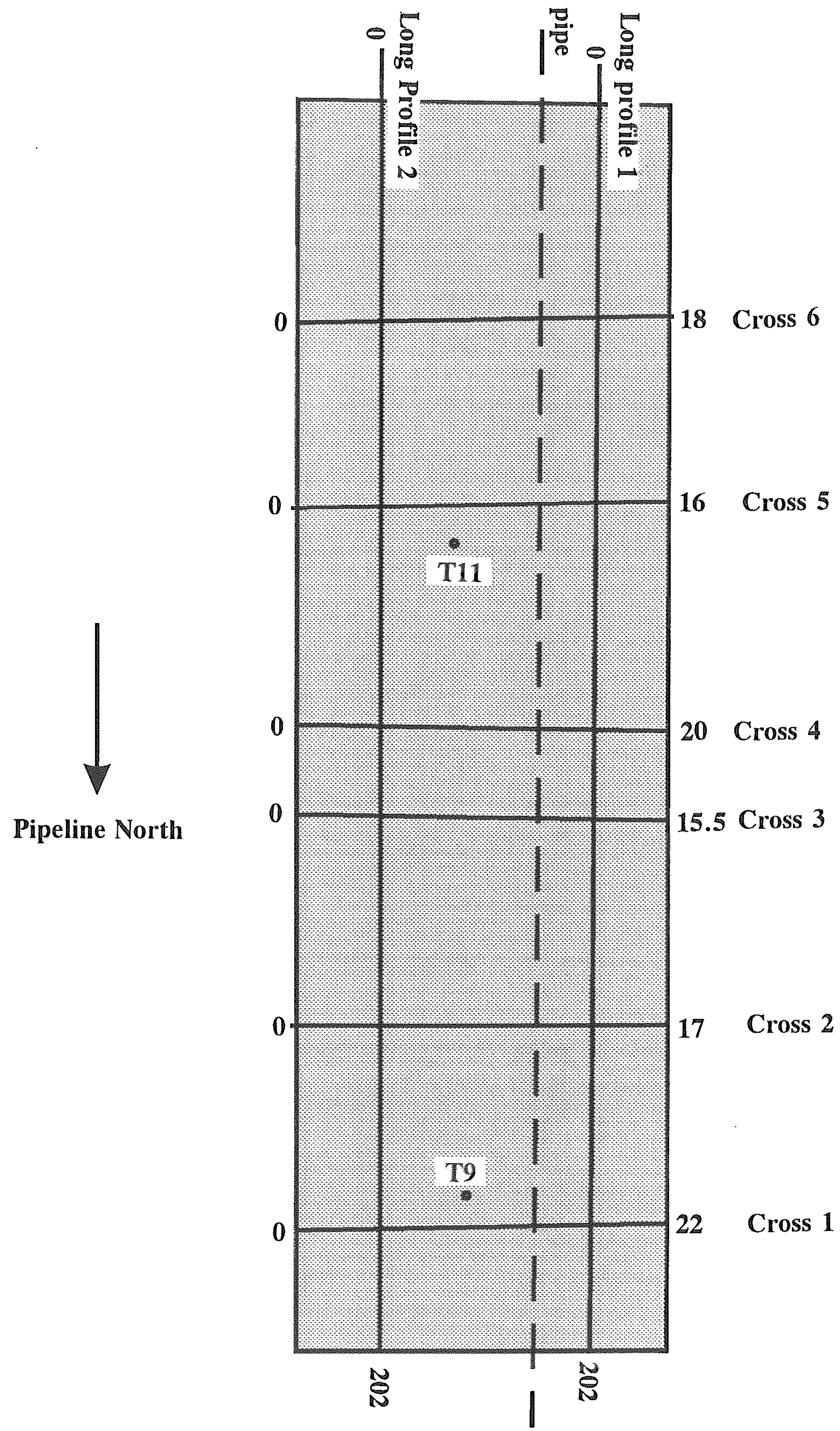
SLOPE 62 (kp 194) - LONG PROFILE 2 - 100 MHz - AUGUST 28

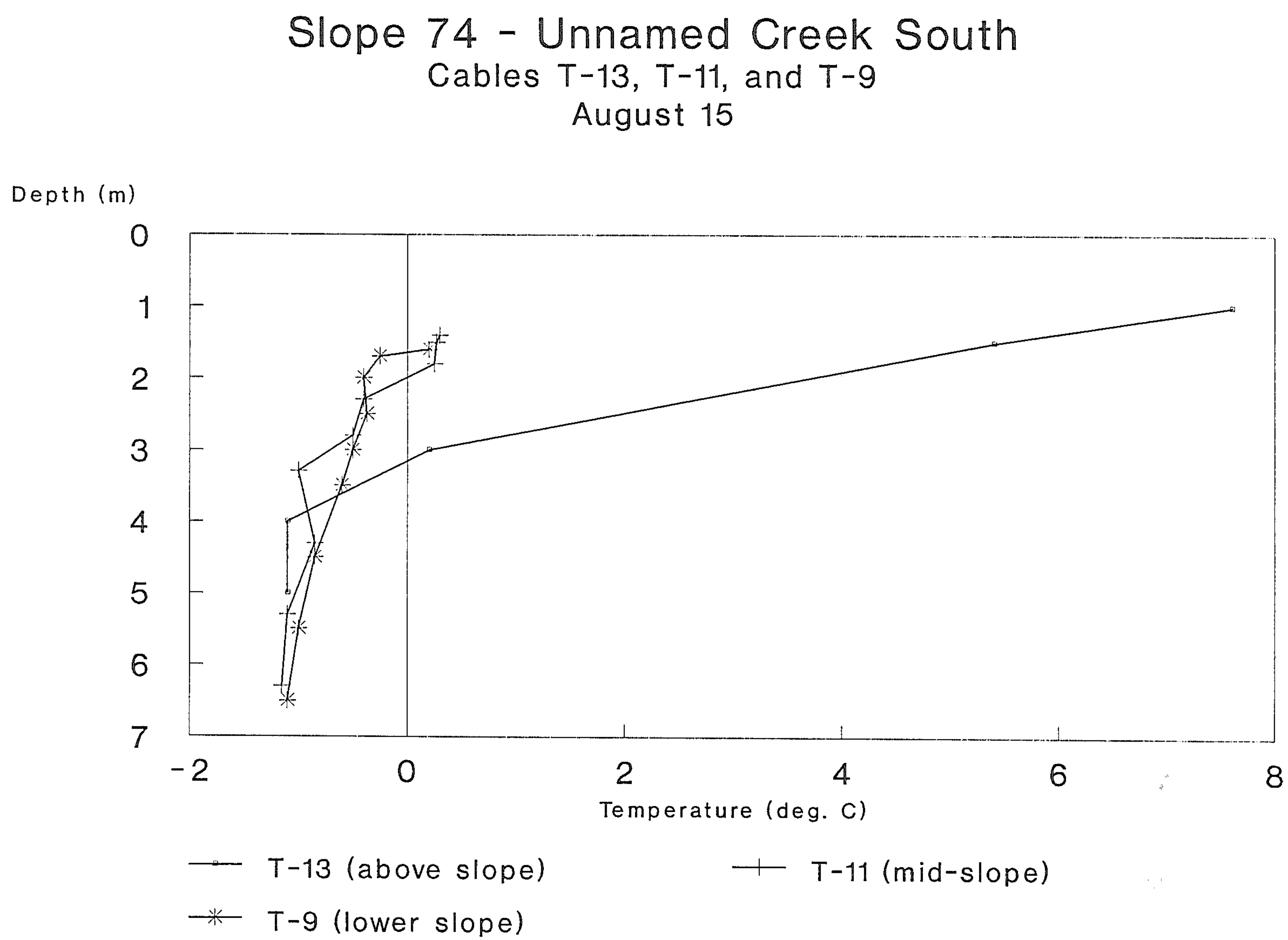


SLOPE 62 (kp 194) - CMP - AUGUST 28

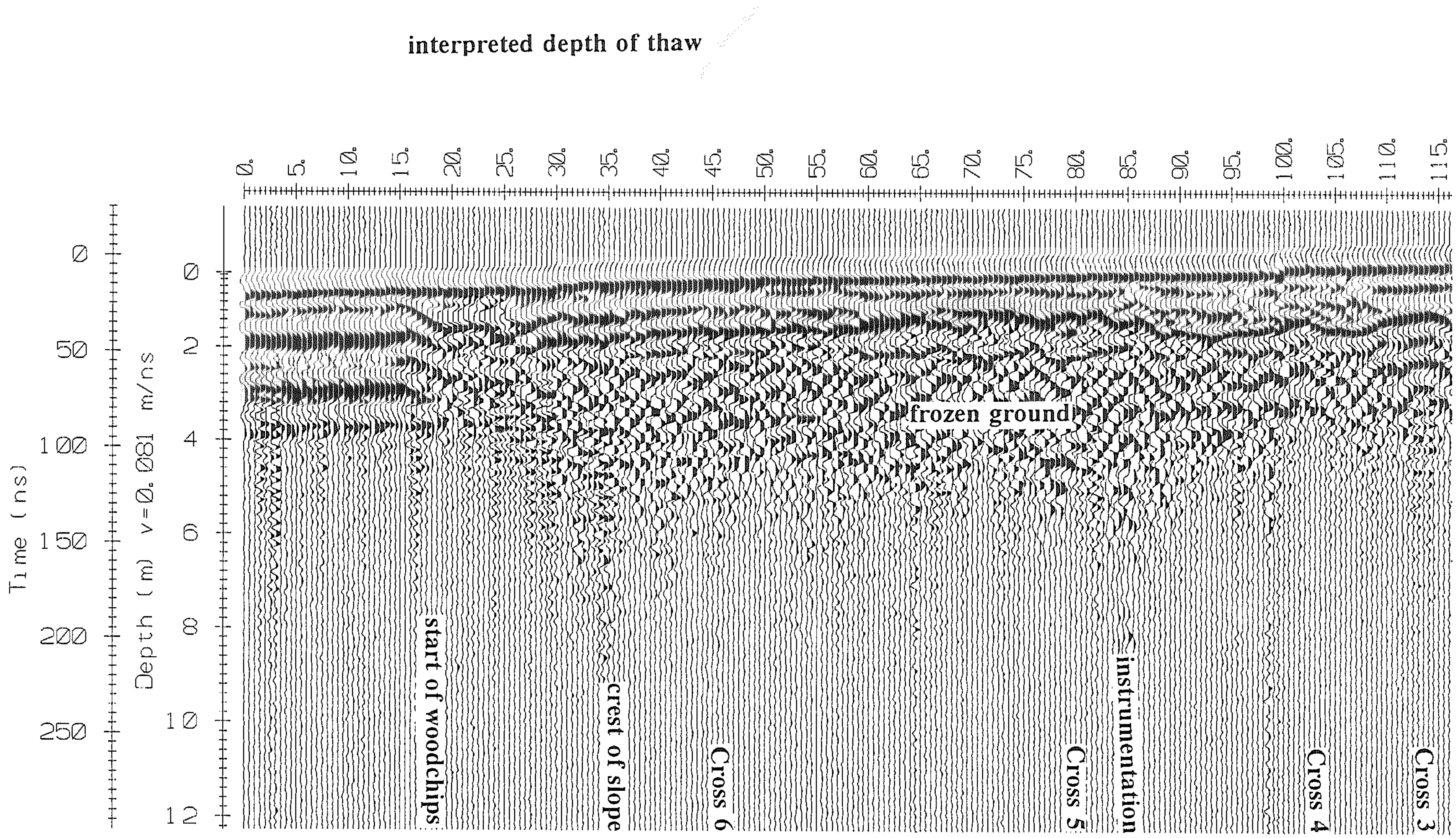
SLOPE 74 (kp 271)

Not to Scale

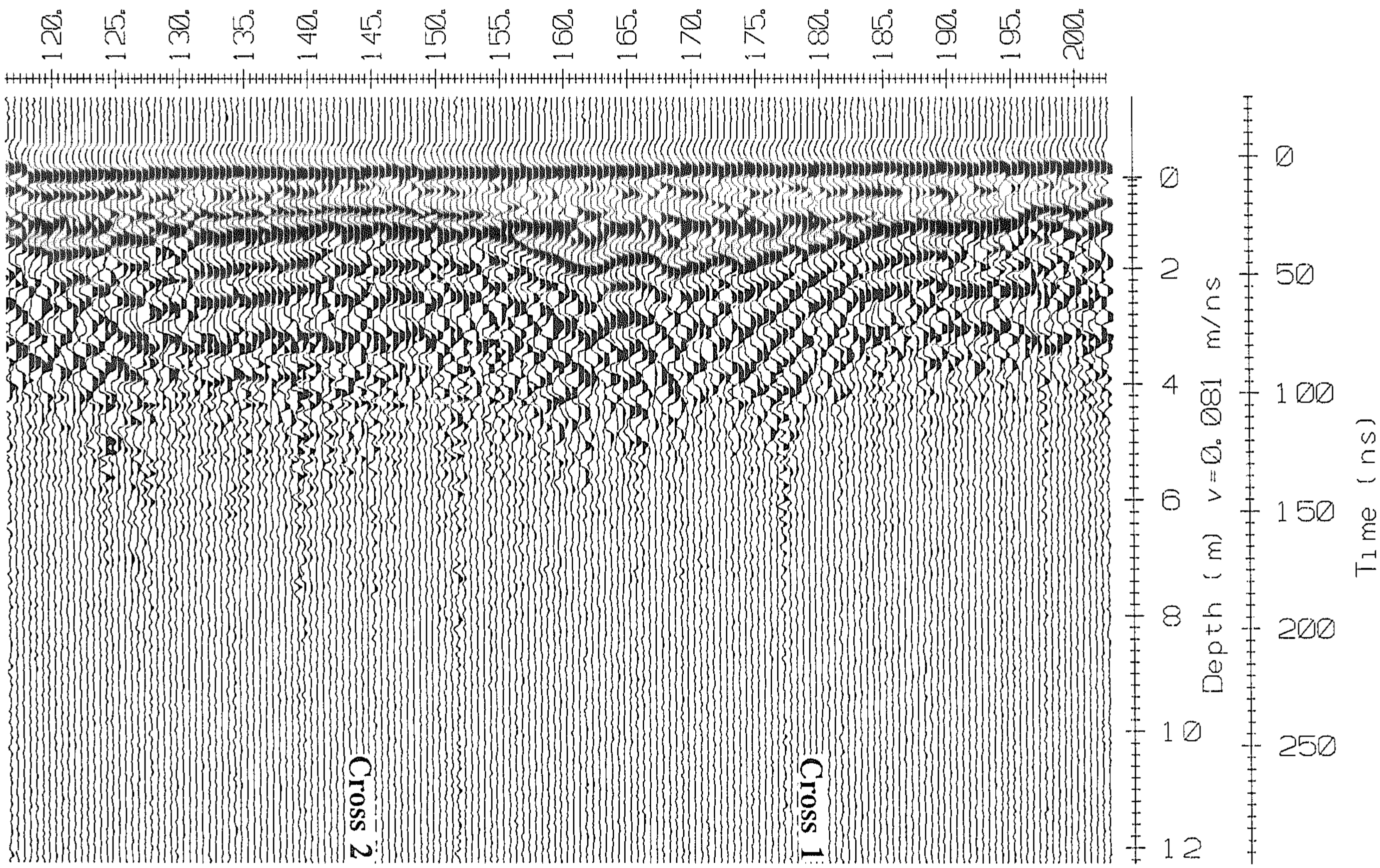




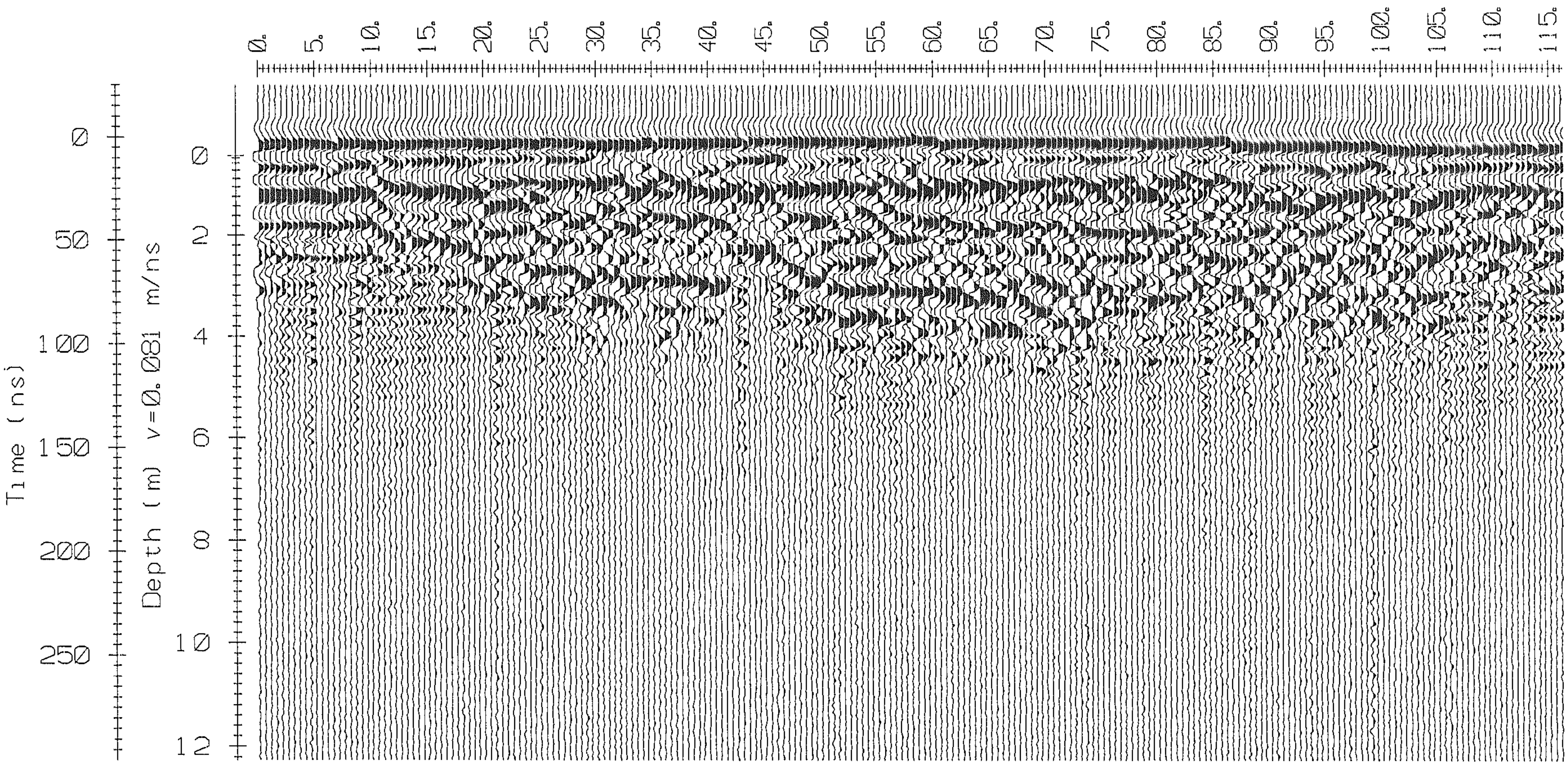
Slope 74 - Unnamed Creek South
Cables T-13, T-11, and T-9
August 15
Depth (m)
0
1
2
3
4
5
6
7
-2
0
2
4
6
8
Temperature (deg. C)
T-13 (above slope)
T-11 (mid-slope)
T-9 (lower slope)



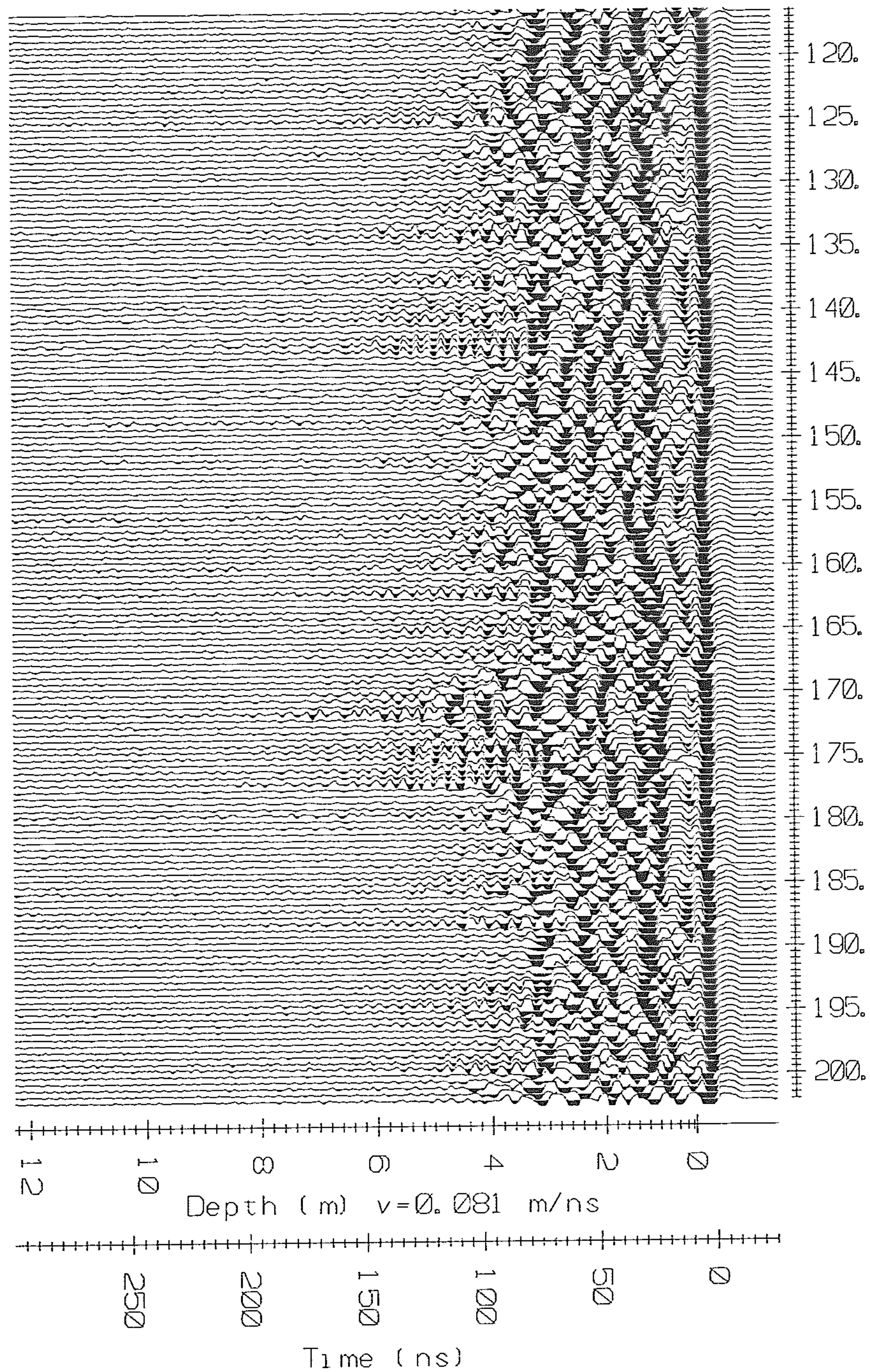
SLOPE 74 (kp 271.3) - LONG PROFILE 1 - 100 MHz - JULY 15



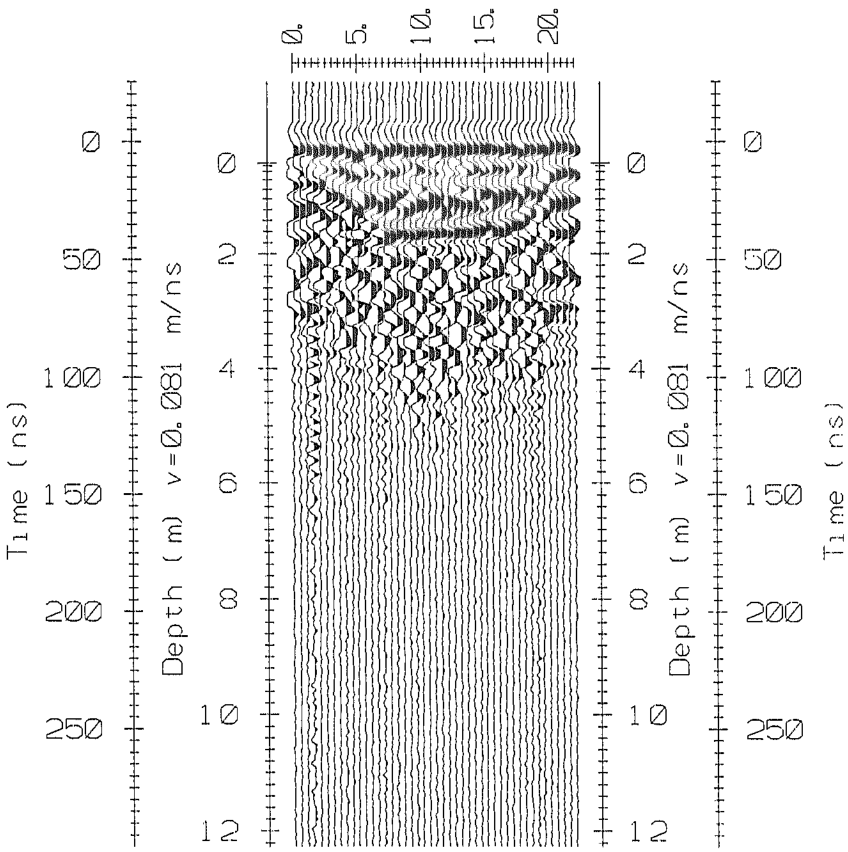
120. 125. 130. 135. 140. 145. 150. 155. 160. 165. 170. 175. 180. 185. 190. 195. 200.
0 2 4 6 8 10 12
Depth (m) v=0.081 m/ns
0 50 100 150 200 250
Time (ns)
Cross 2
Cross 1



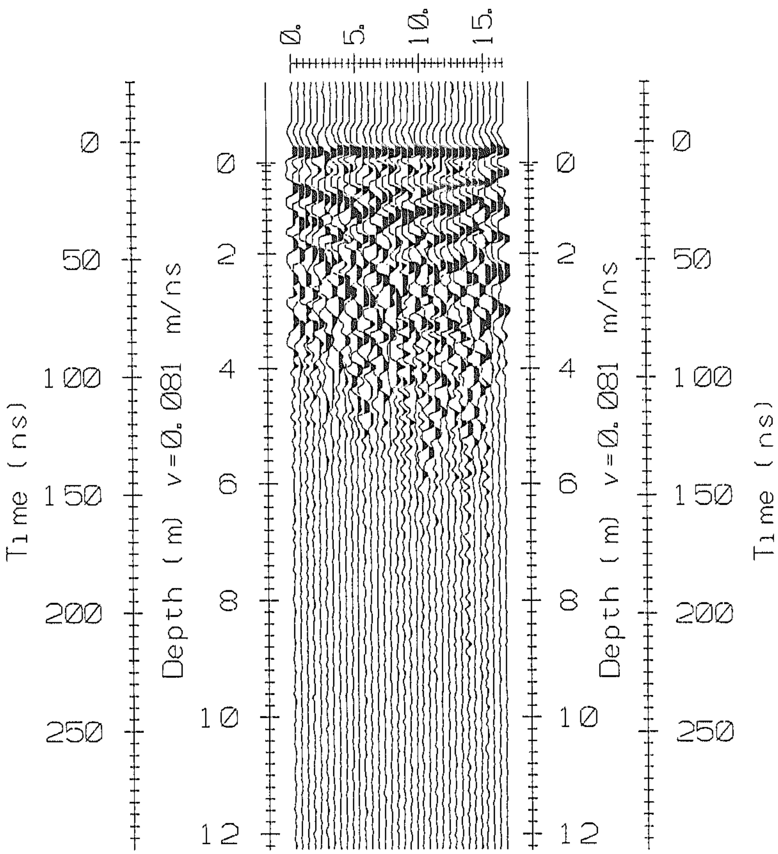
SLOPE 74 (kp 271.3) - LONG PROFILE 2 - 100 MHz - JULY 15



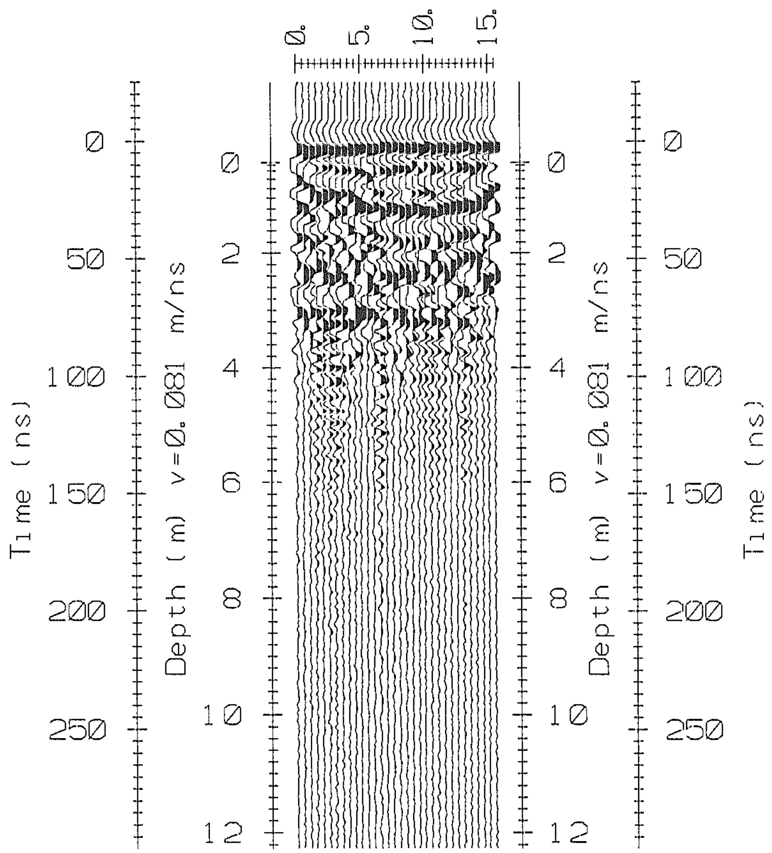
120. 125. 130. 135. 140. 145. 150. 155. 160. 165. 170. 175. 180. 185. 190. 195. 200.
12 10 8 6 4 2 0
Depth (m) v=0.081 m/ns
250 200 150 100 50 0
Time (ns)



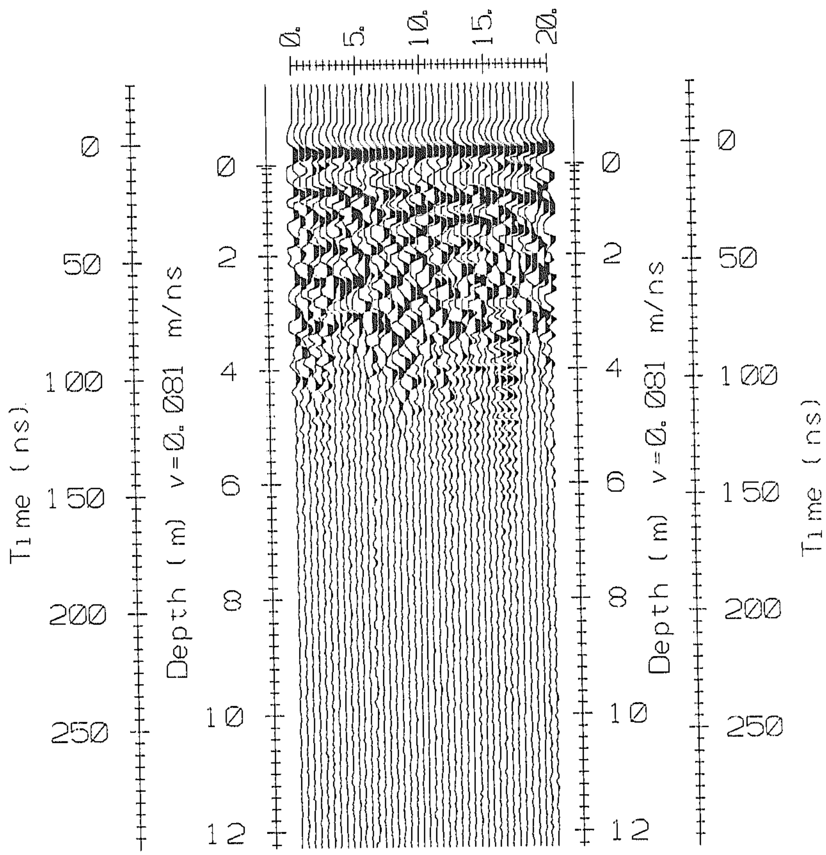
SLOPE 74 (kp 271.3) - CROSS PROFILE 1 - 100 MHz - JULY 15



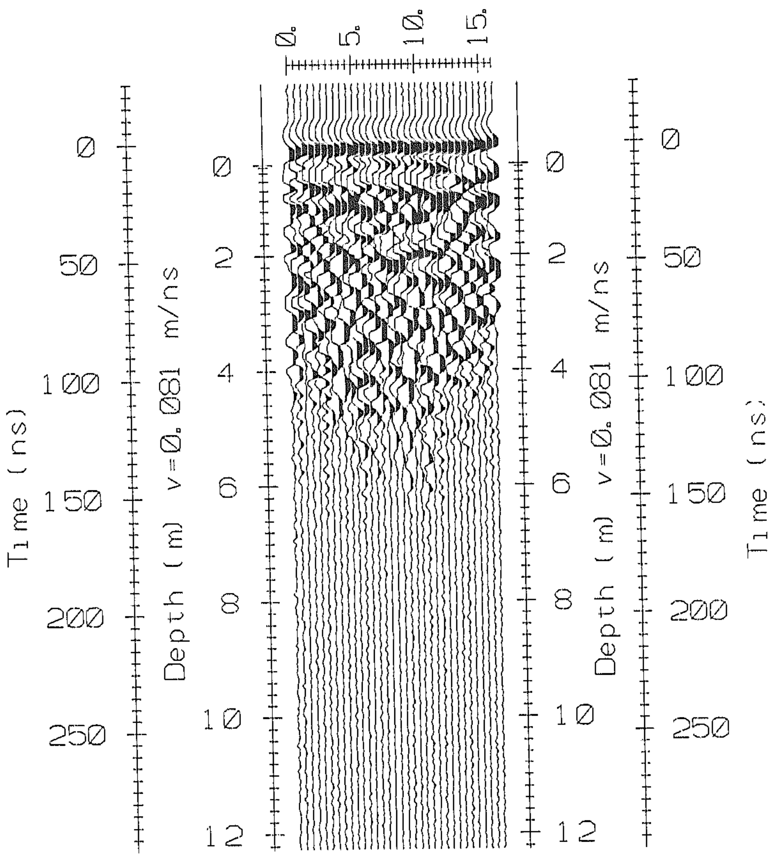
SLOPE 74 (kp 271.3) - CROSS PROFILE 2 - 100 MHz - JULY 15



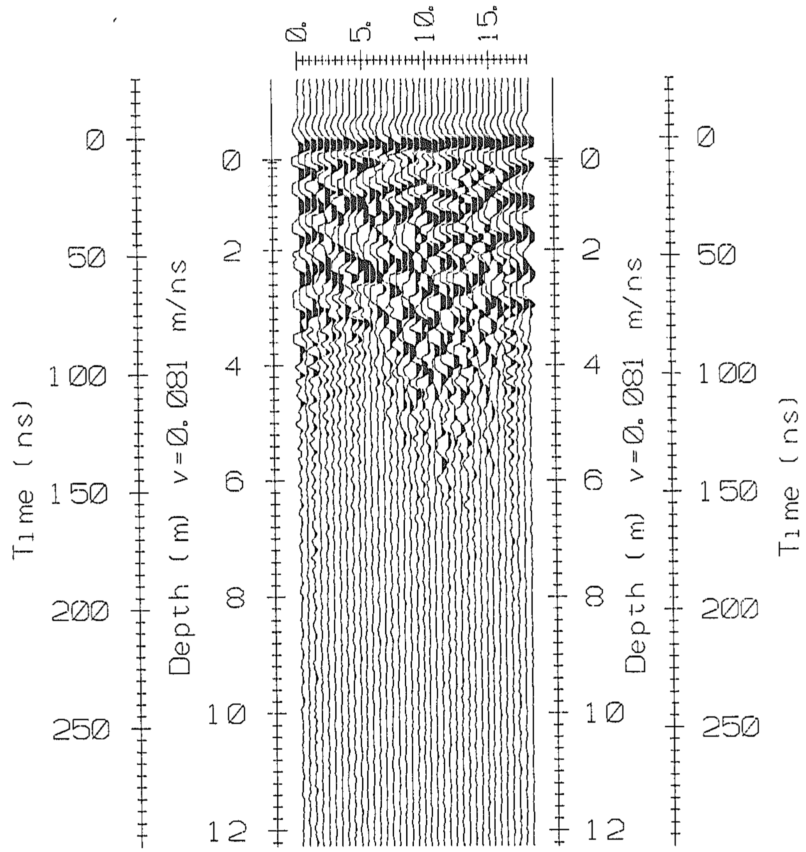
SLOPE 74 (kp 271.3) - CROSS PROFILE 3 - 100 MHz - JULY 15



SLOPE 74 (kp 271.3) - CROSS PROFILE 4 - 100 MHz - JULY 15

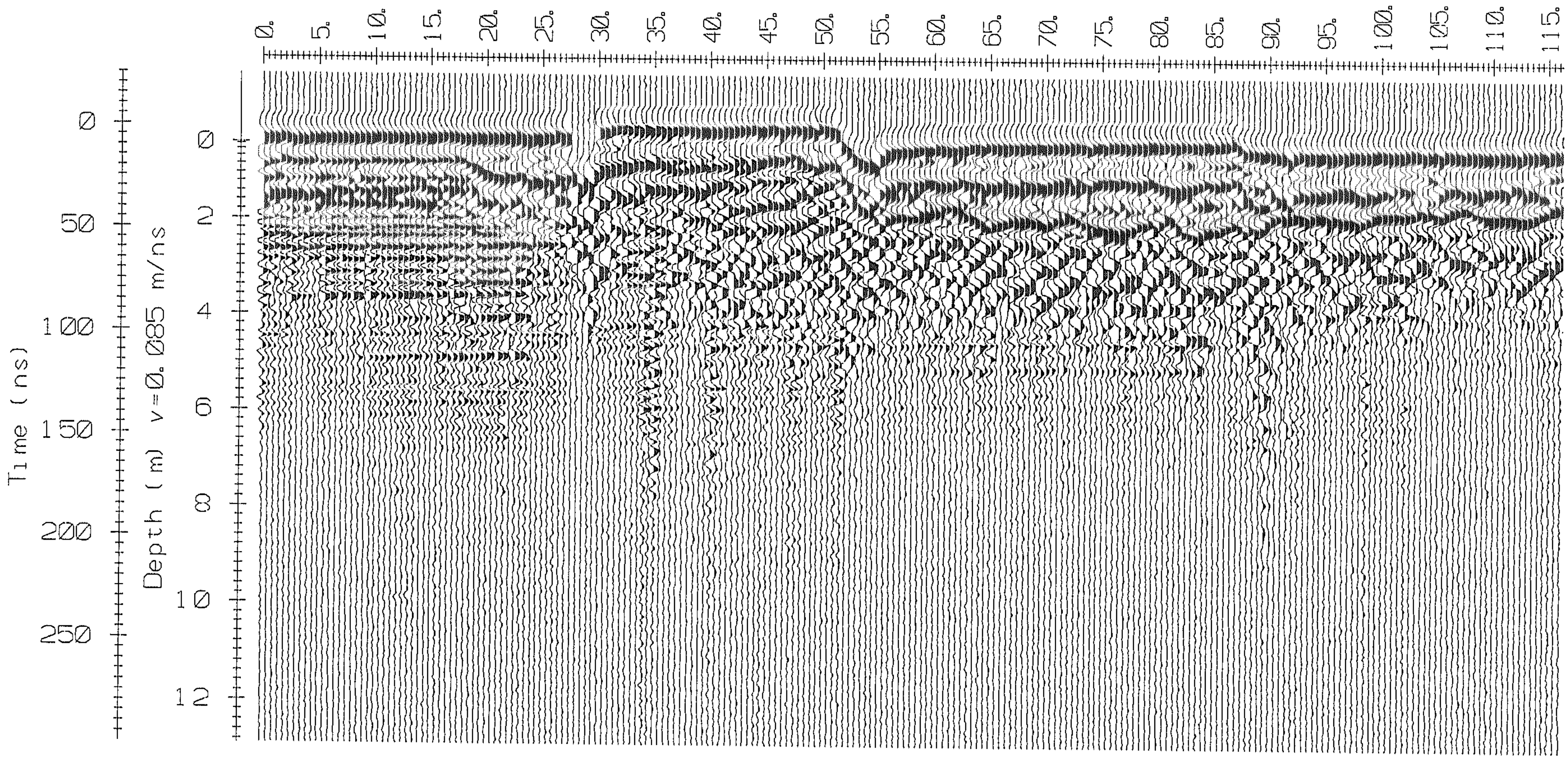


SLOPE 74 (kp 271.3) - CROSS PROFILE 5 - 100 MHz - JULY 15

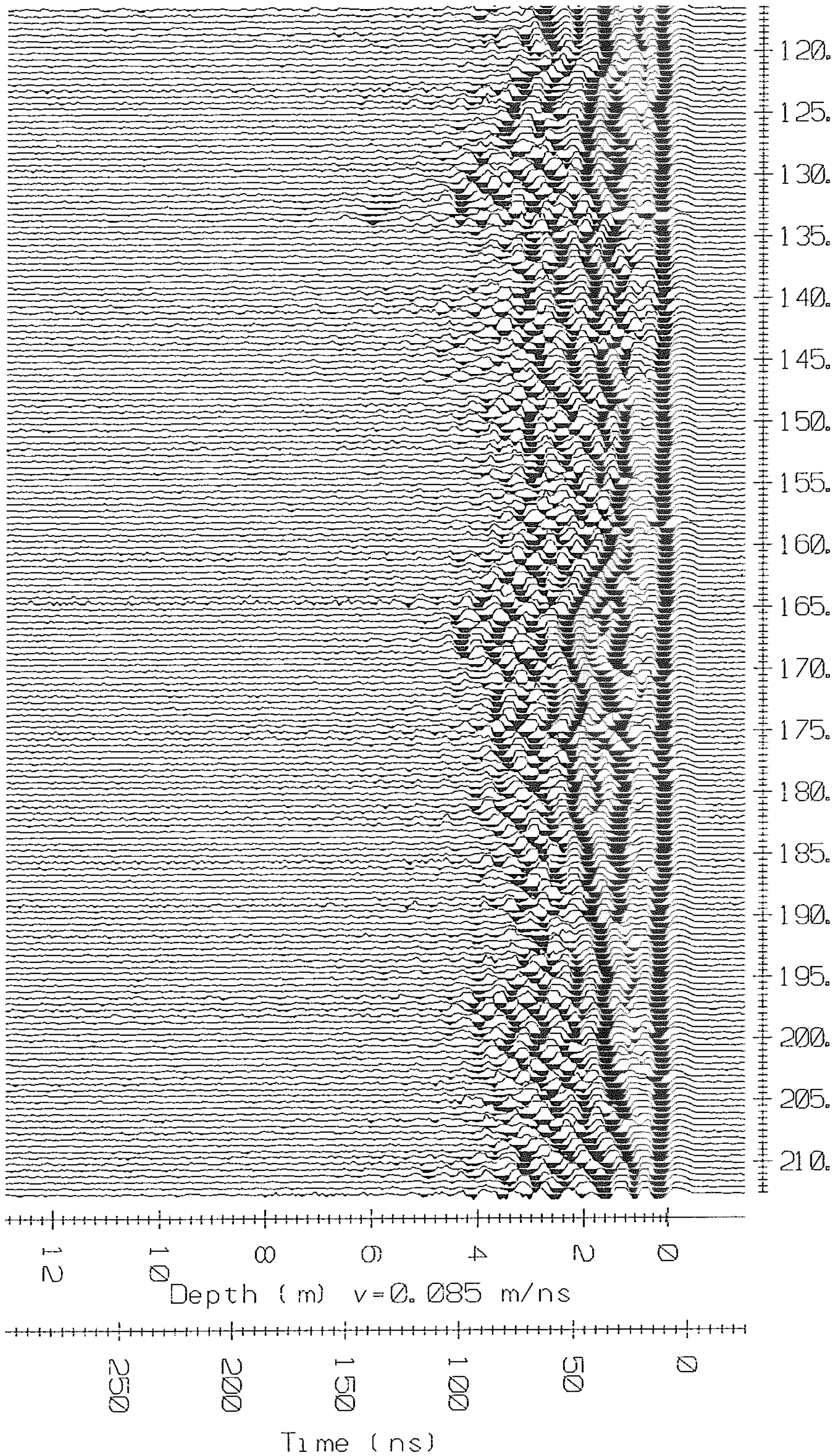


SLOPE 74 (kp 271.3) - CROSS PROFILE 6 - 100 MHz - JULY 15

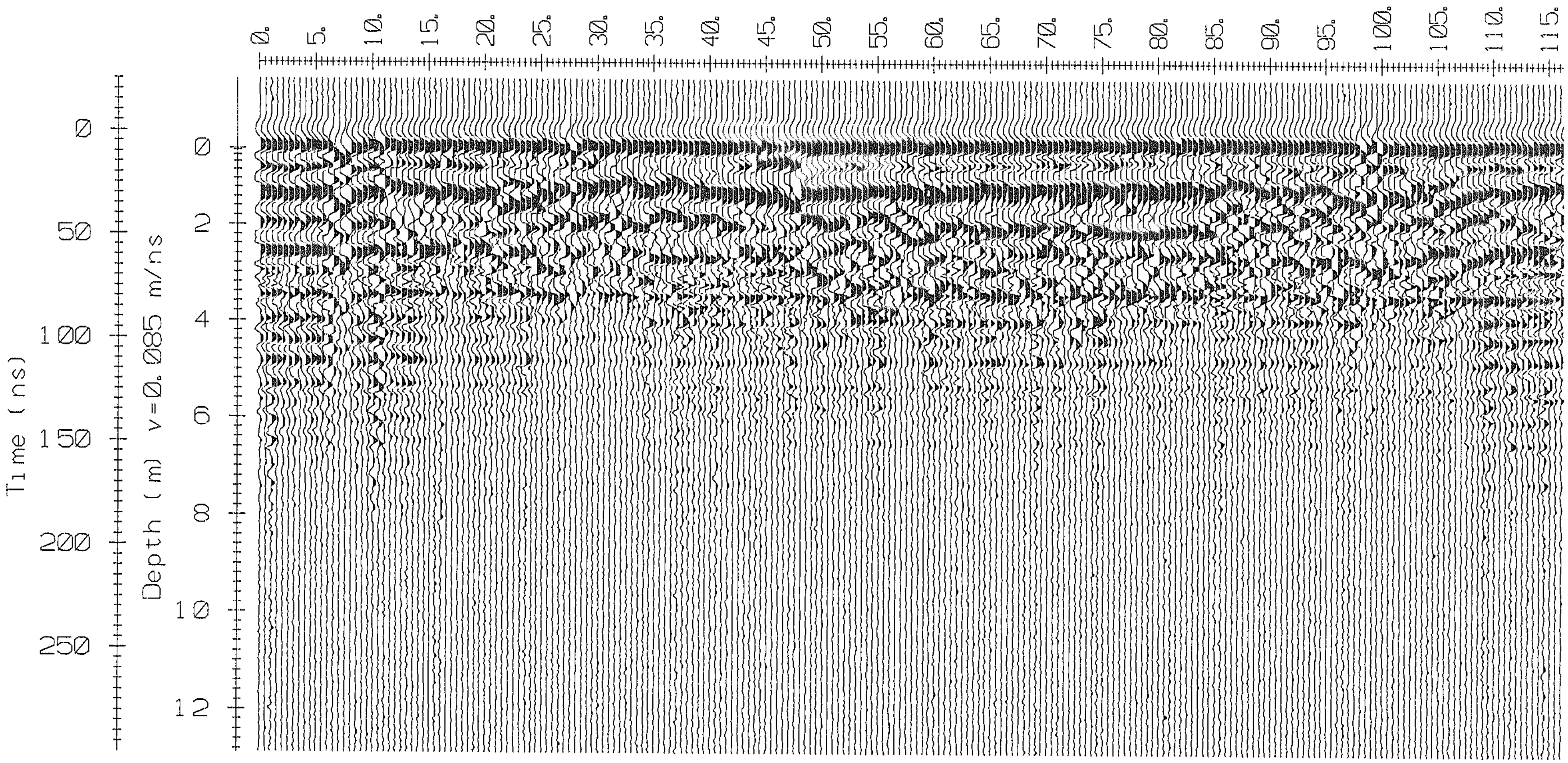
interpreted depth of thaw



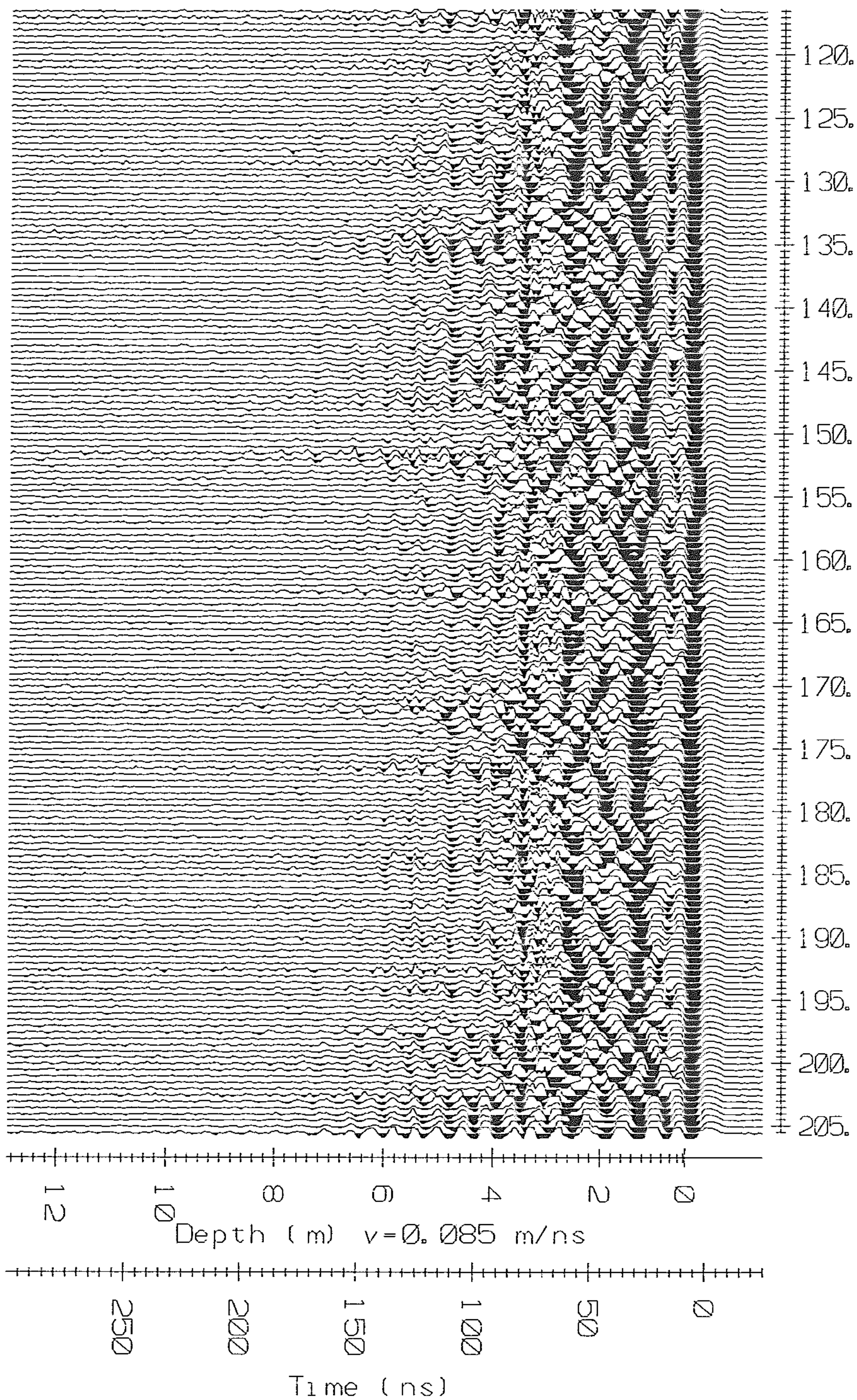
SLOPE 74 (kp 271.3) - LONG PROFILE 1 - 100 MHz - AUGUST 27



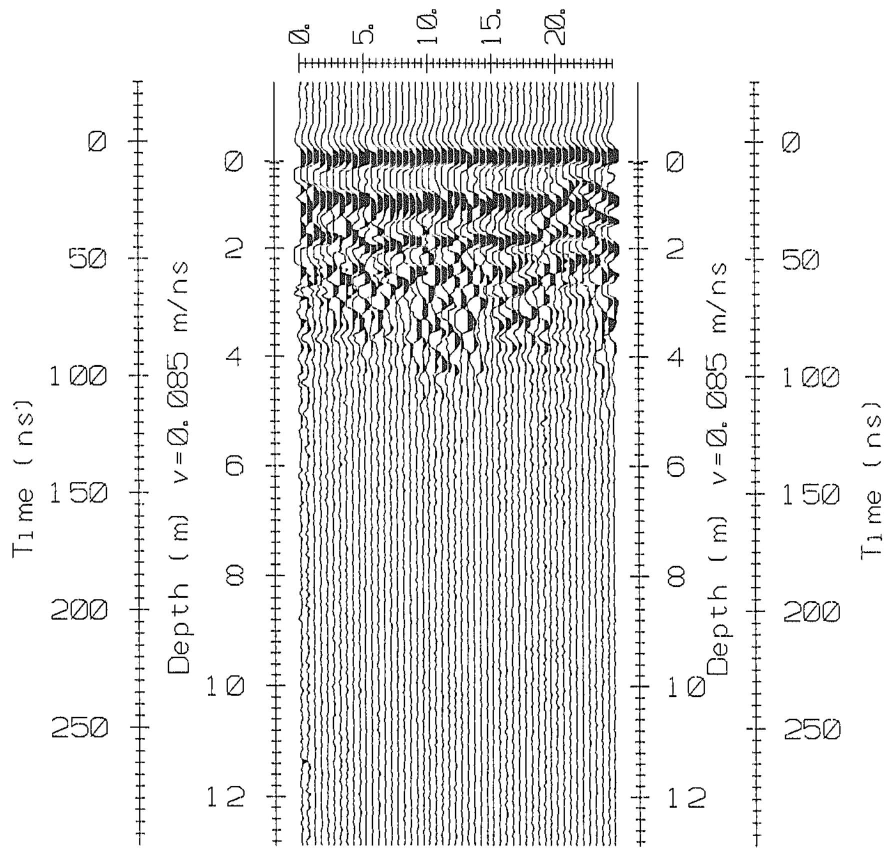
120.
125.
130.
135.
140.
145.
150.
155.
160.
165.
170.
175.
180.
185.
190.
195.
200.
205.
210.
12
10
8
6
4
2
0
Depth (m) v=0.085 m/ns
250
200
150
100
50
0
Time (ns)



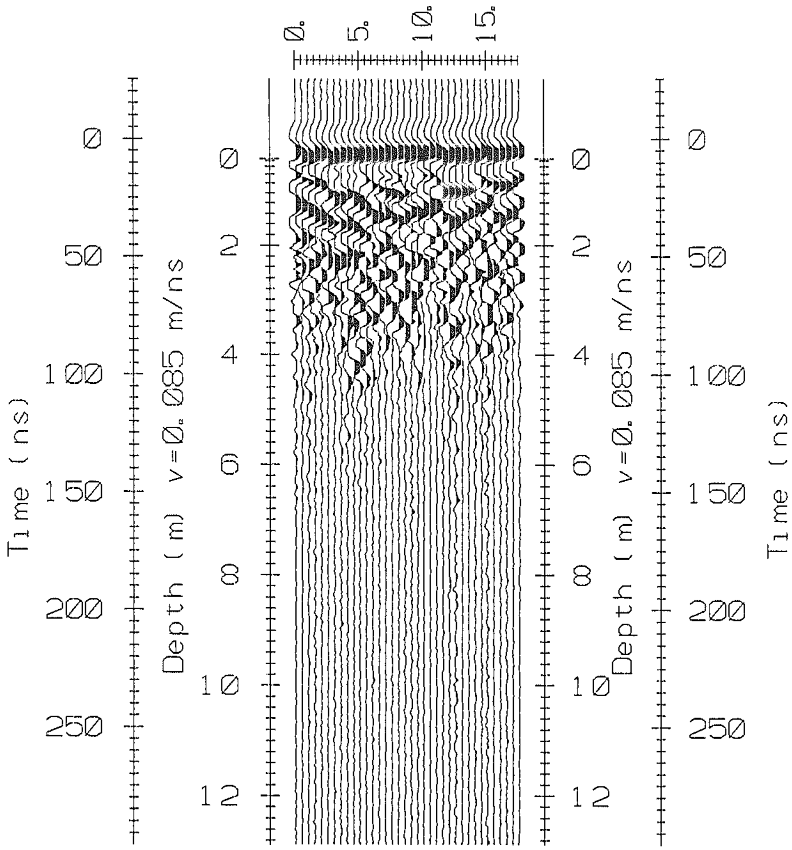
SLOPE 74 (kp 271.3) - LONG PROFILE 2 - 100 MHz - AUGUST 27



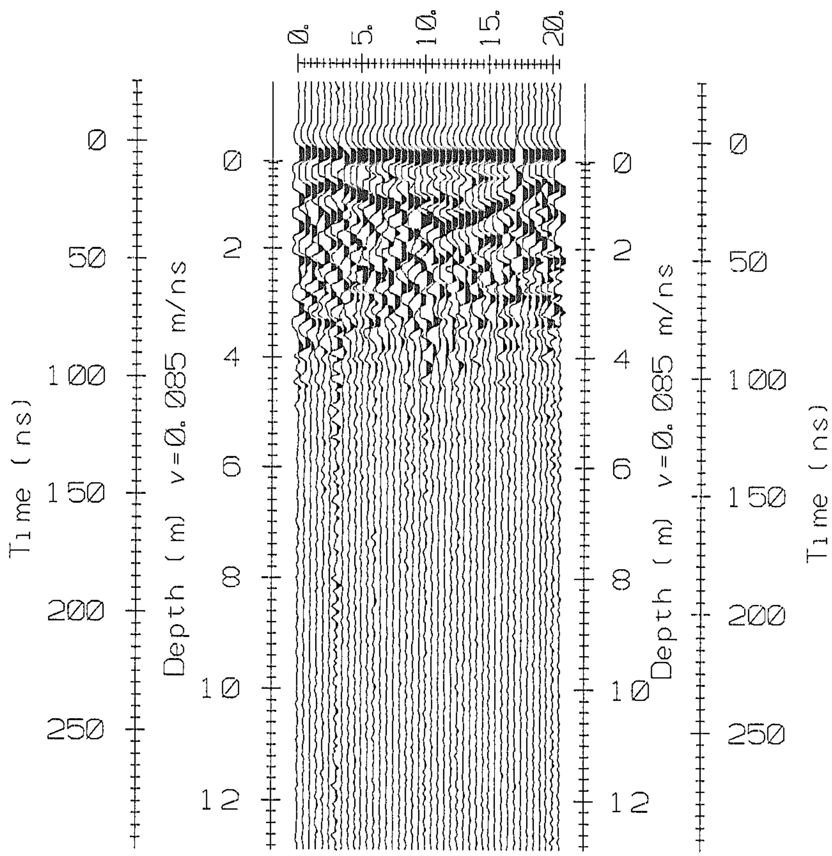
120.
125.
130.
135.
140.
145.
150.
155.
160.
165.
170.
175.
180.
185.
190.
195.
200.
205.
Depth (m) v=0.085 m/ns
12
10
8
6
4
2
0
Time (ns)
250
200
150
100
50
0



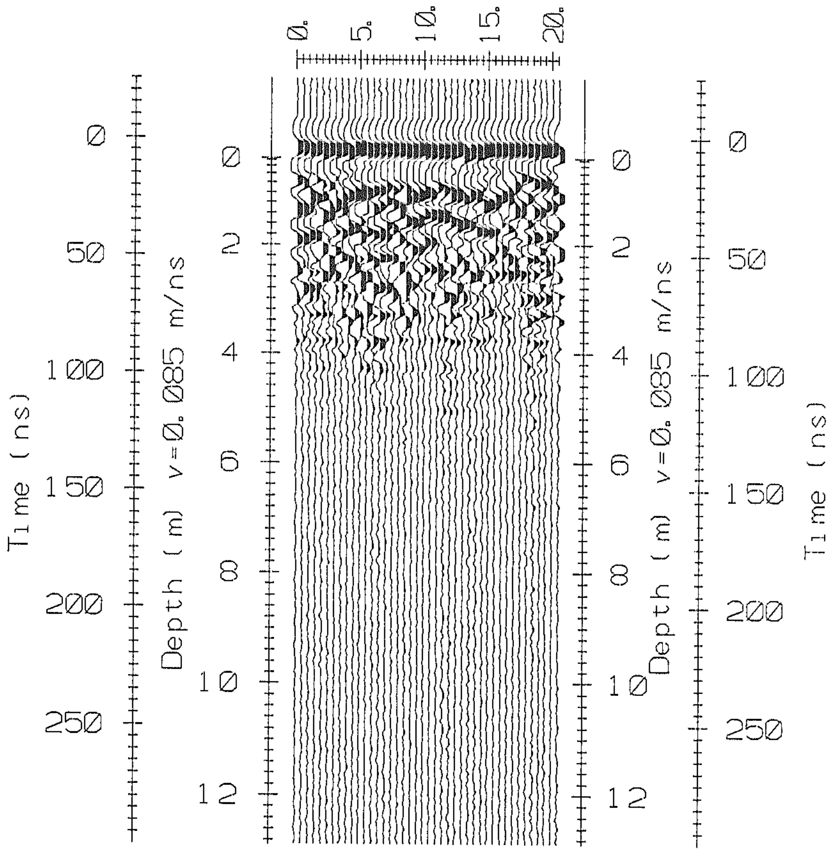
SLOPE 74 (kp 271.3) - CROSS PROFILE 1 - 100 MHz - AUGUST 27



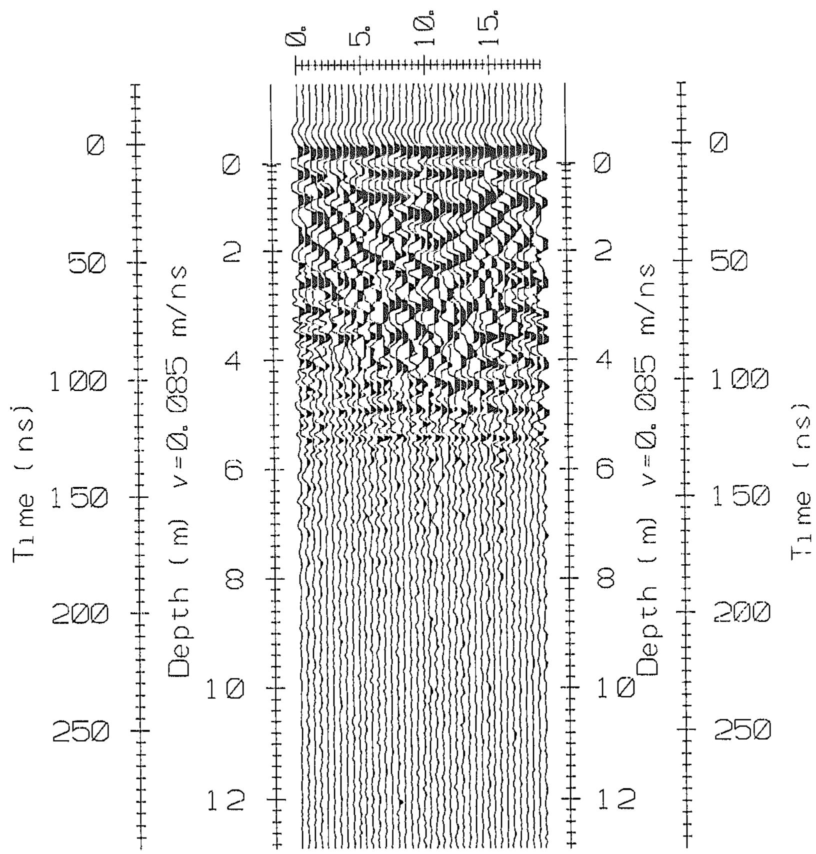
SLOPE 74 (kp 271.3) - CROSS PROFILE 2 - 100 MHz - AUGUST 27



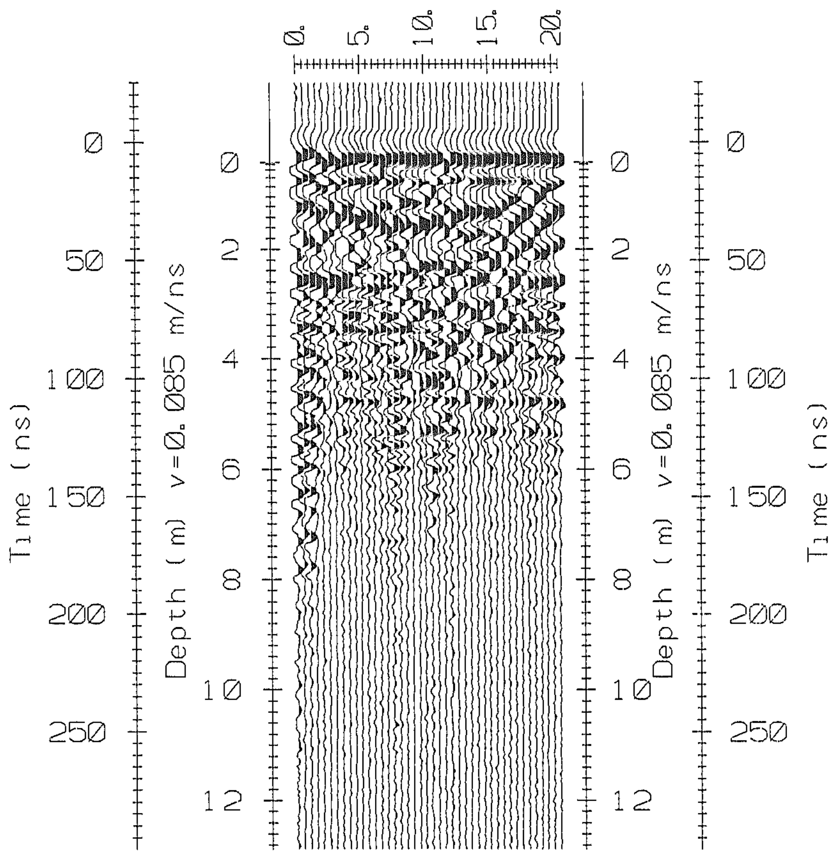
SLOPE 74 (kp 271.3) - CROSS PROFILE 3 - 100 MHz - AUGUST 27



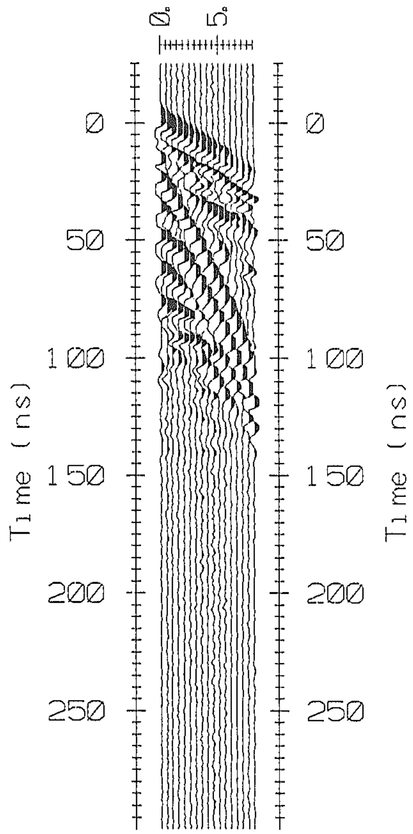
SLOPE 74 (kp 271.3) - CROSS PROFILE 4 - 100 MHz - AUGUST 27



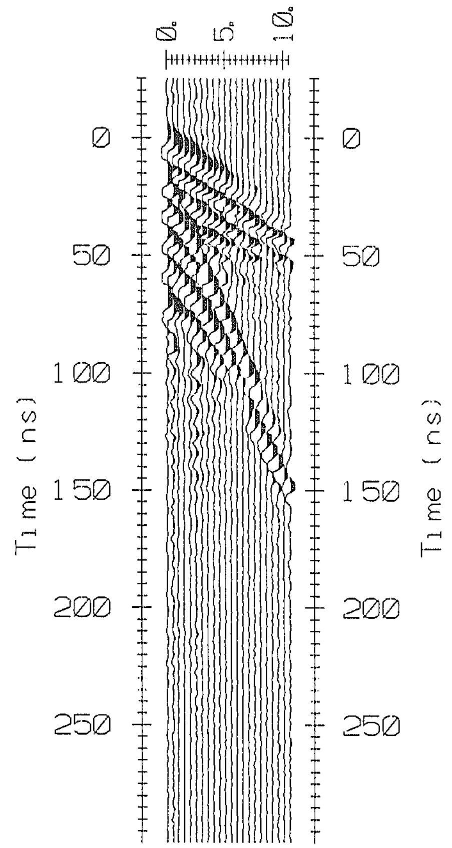
SLOPE 74 (kp 271.3) - CROSS PROFILE 5 - 100 MHz - AUGUST 27



SLOPE 74 (kp 271.3) - CROSS PROFILE 6 - 100 MHz - AUGUST 27



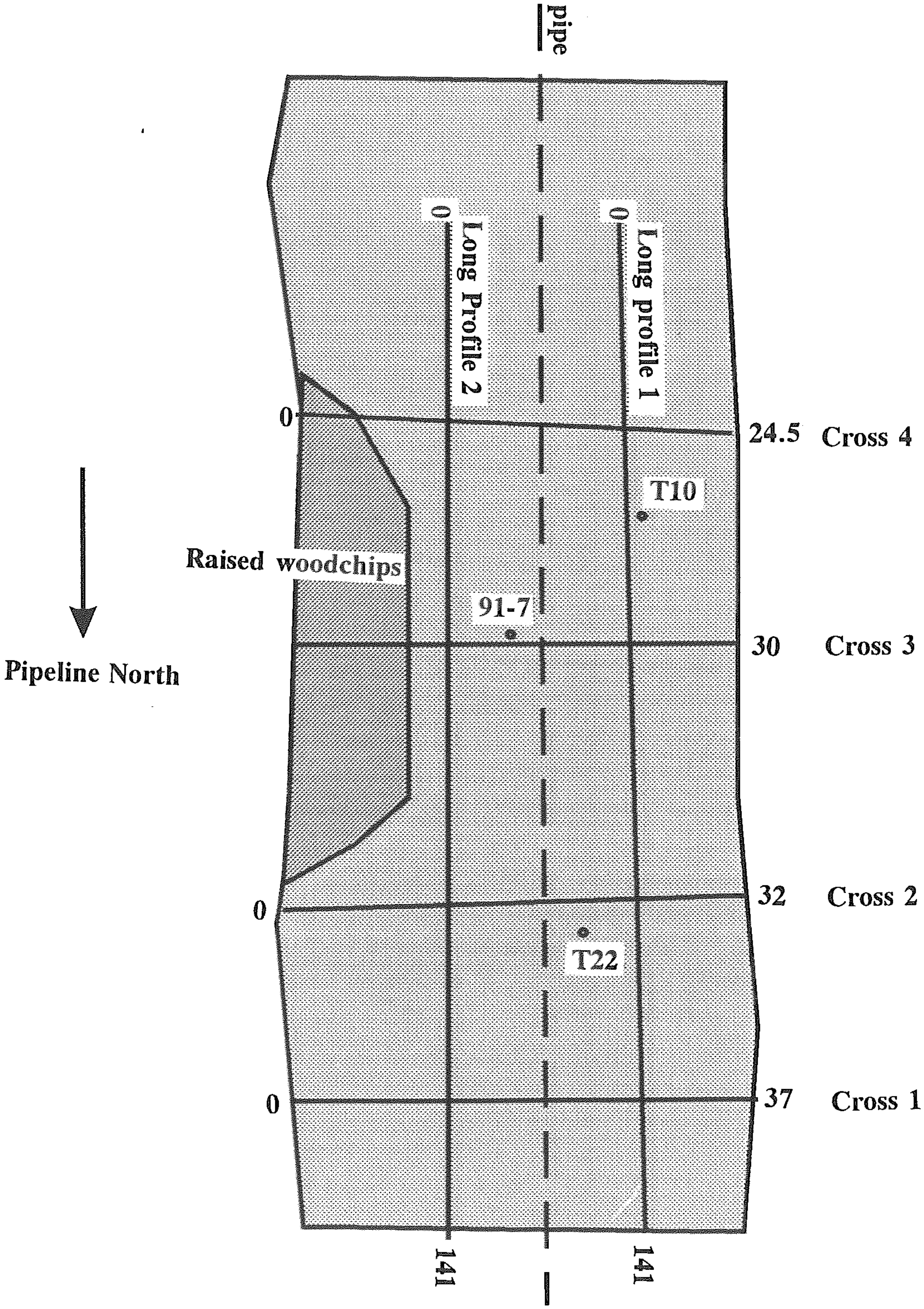
SLOPE 74 (kp 271.3) - CMP - JULY 15

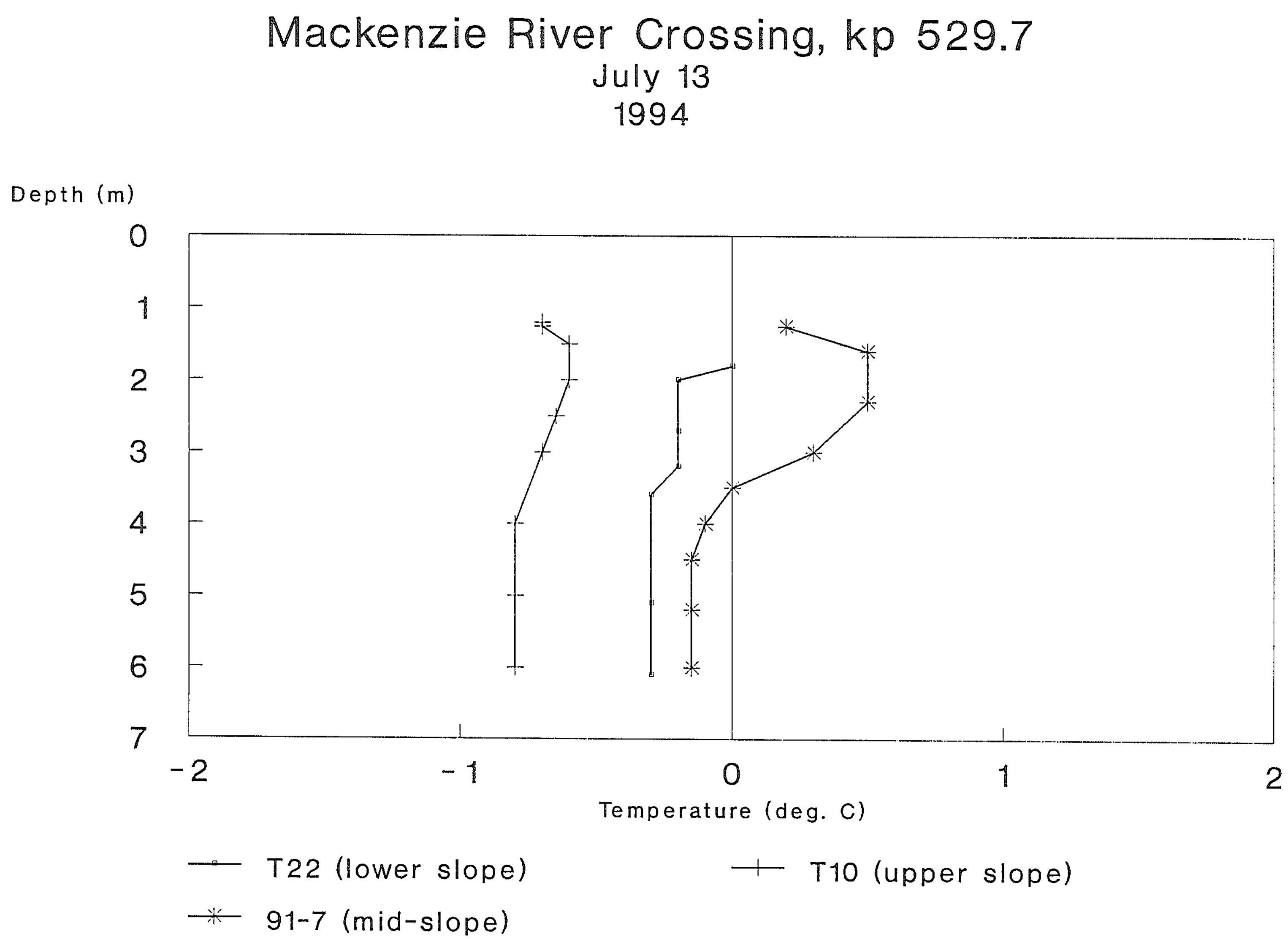


SLOPE 74 (kp 271.3) - CMP - AUGUST 27

MACKENZIE CROSSING

Not to Scale

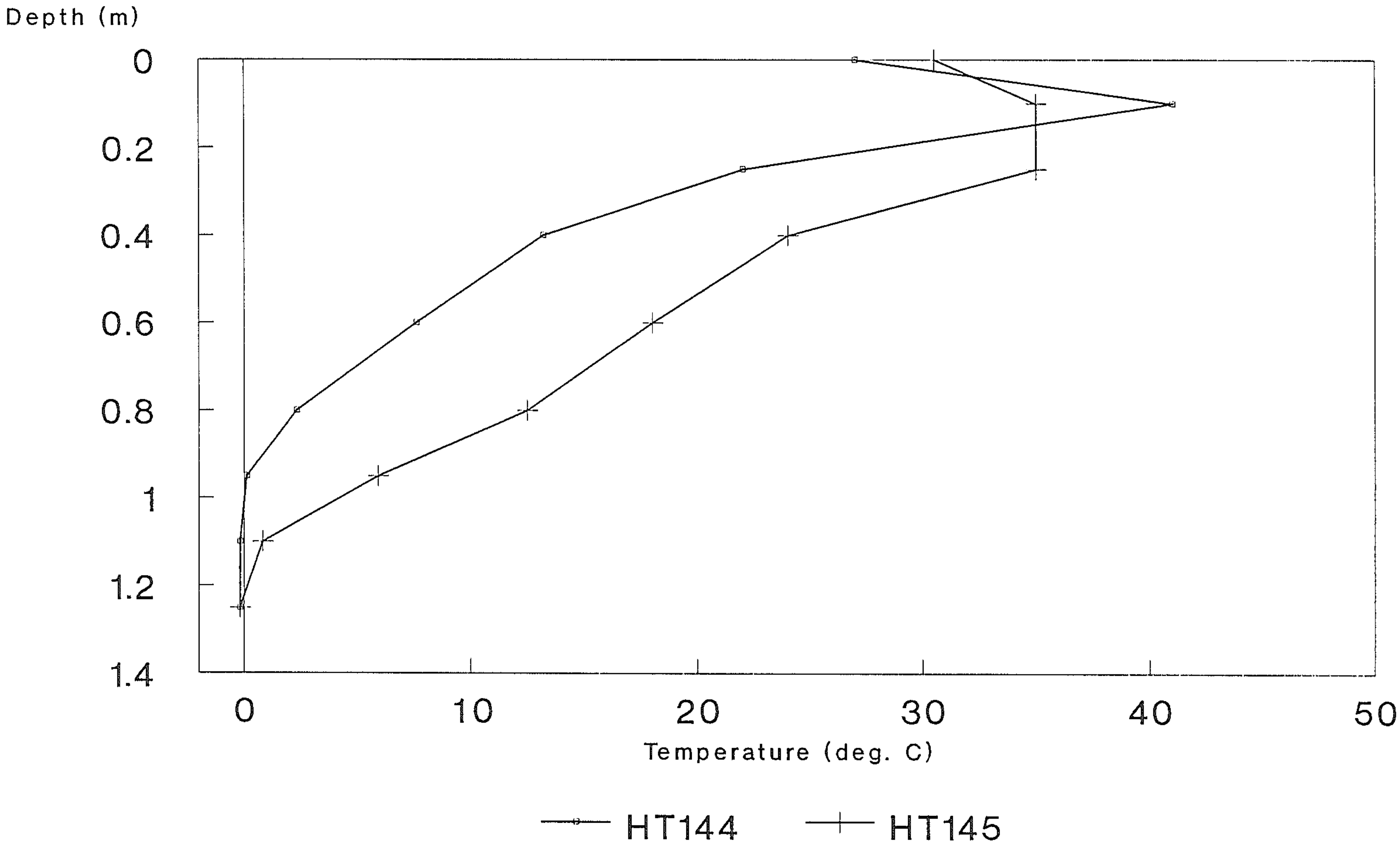


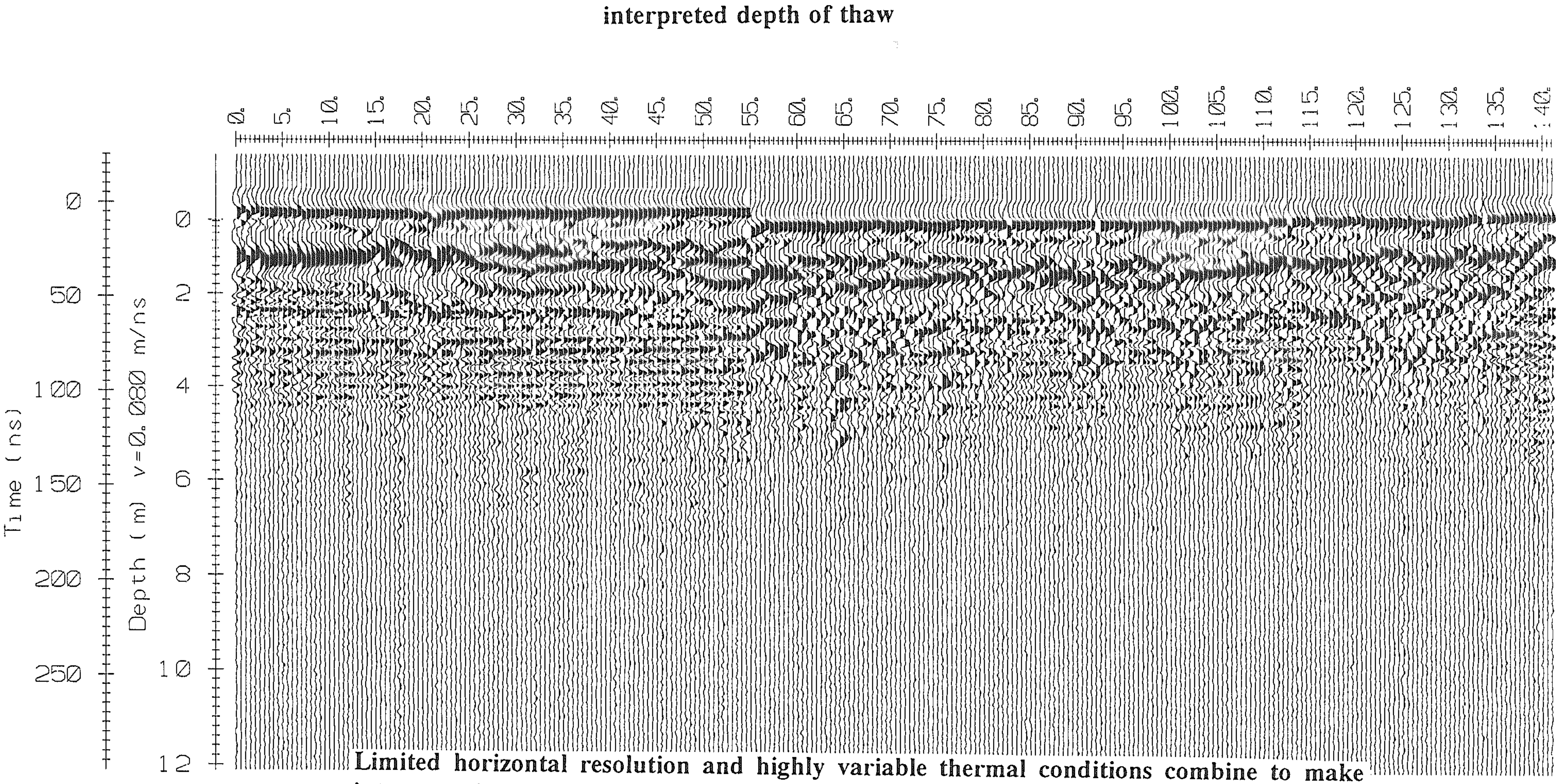

Mackenzie River Crossing, kp 529.7
July 13
1994
Depth (m)
0
1
2
3
4
5
6
7
-2
-1
0
1
2
Temperature (deg. C)
T22 (lower slope)
T10 (upper slope)
91-7 (mid-slope)

Mackenzie River Crossing, kp 529.7

July 13, 1994

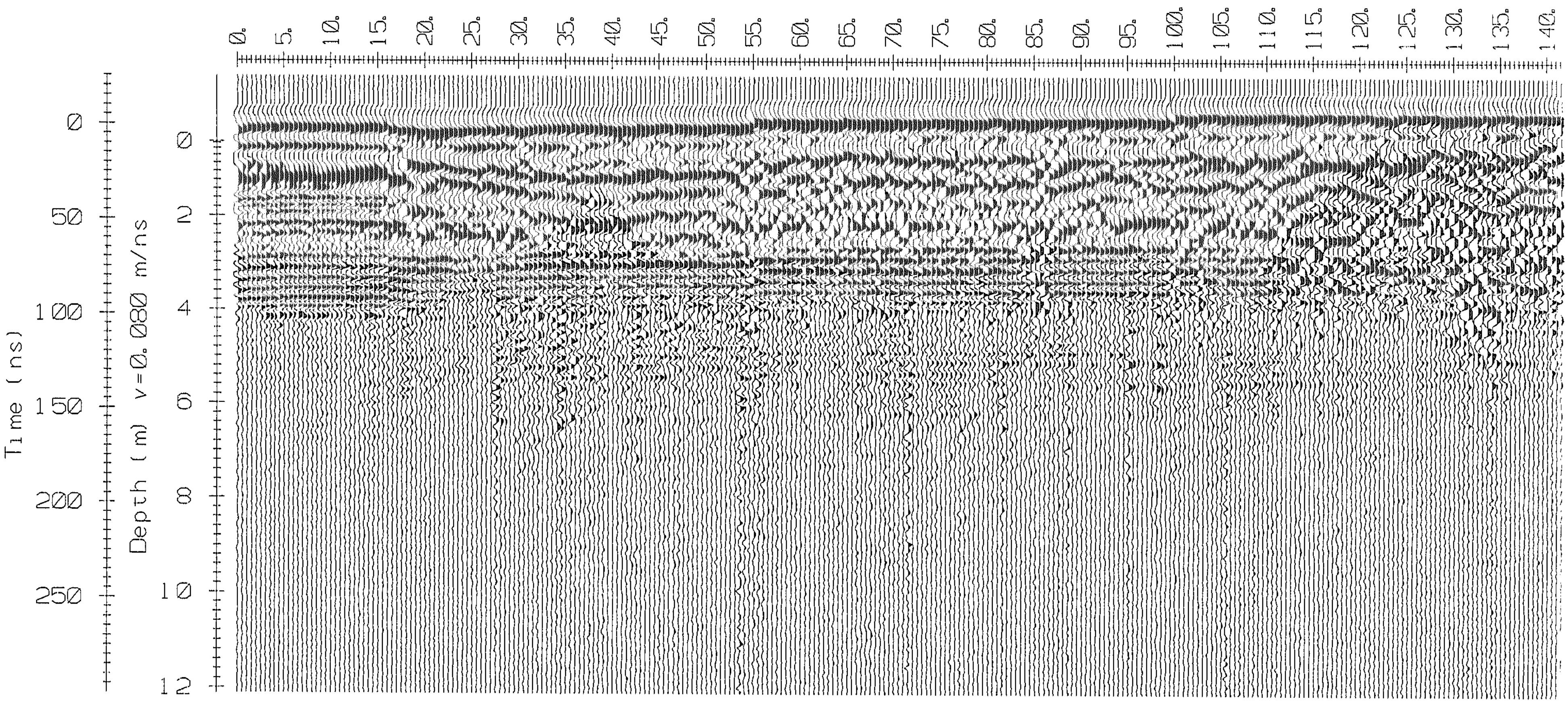
Woodchip thermistors



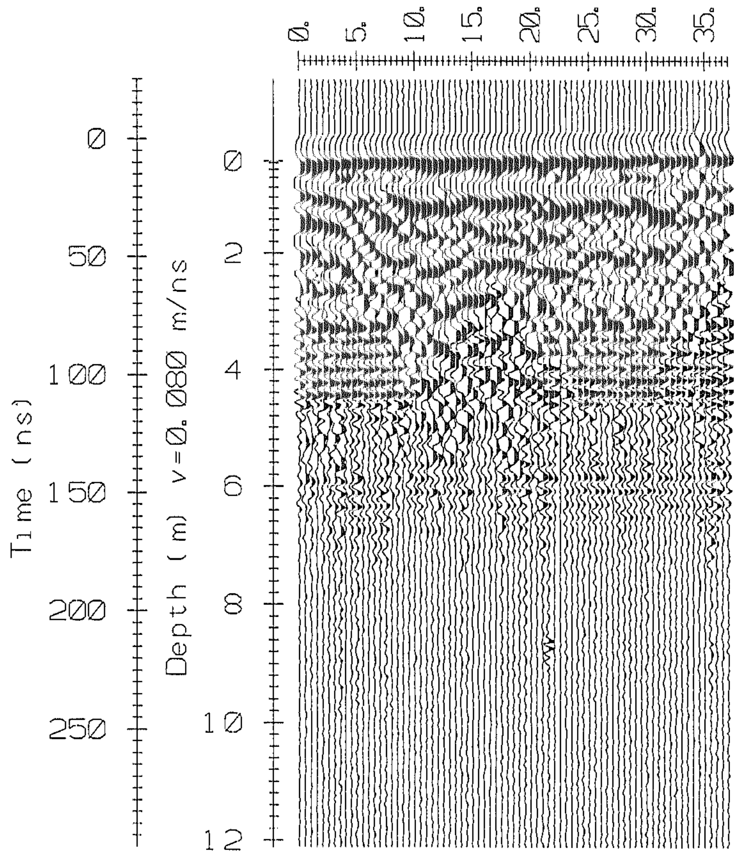


Limited horizontal resolution and highly variable thermal conditions combine to make interpretations for this slope difficult.

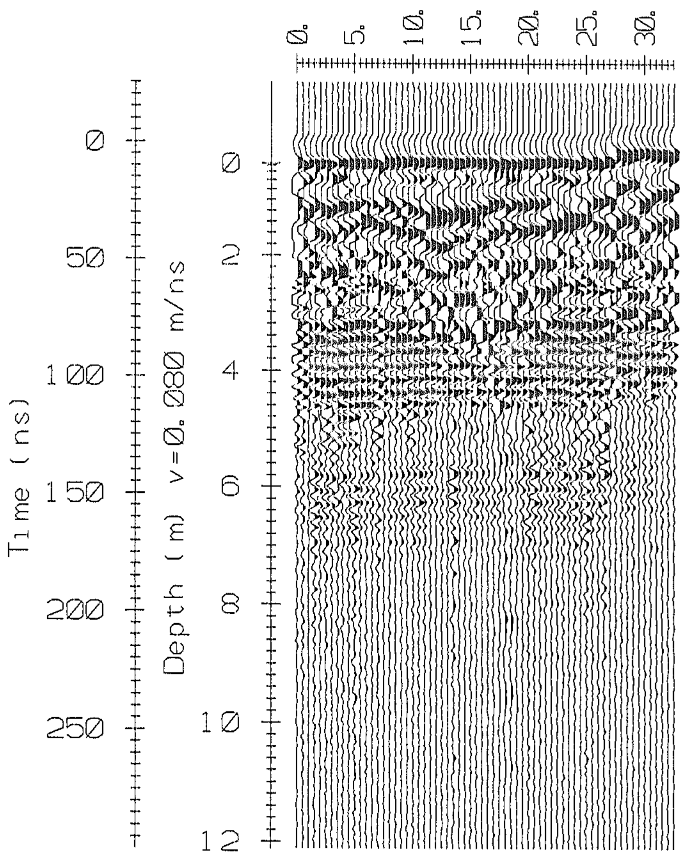
MACKENZIE RIVER - LONG PROFILE 1 - 100 MHz - JULY 13



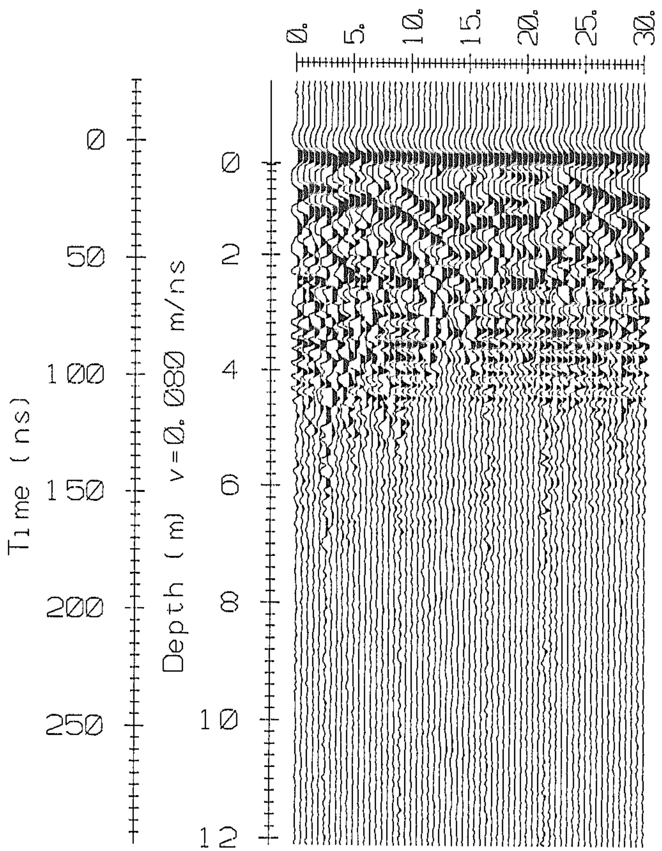
MACKENZIE RIVER - LONG PROFILE 2 - 100 MHz - JULY 13



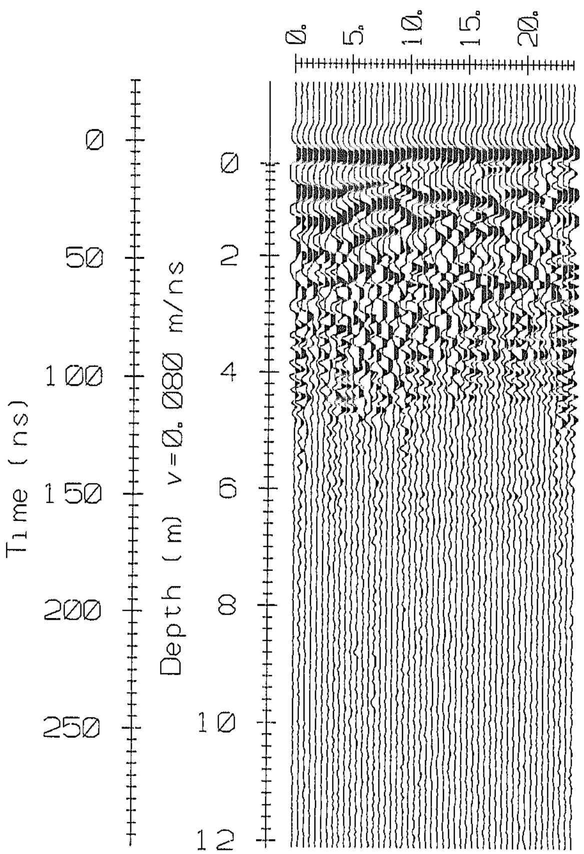
MACKENZIE RIVER - CROSS PROFILE 1 - 100 MHz - JULY 13



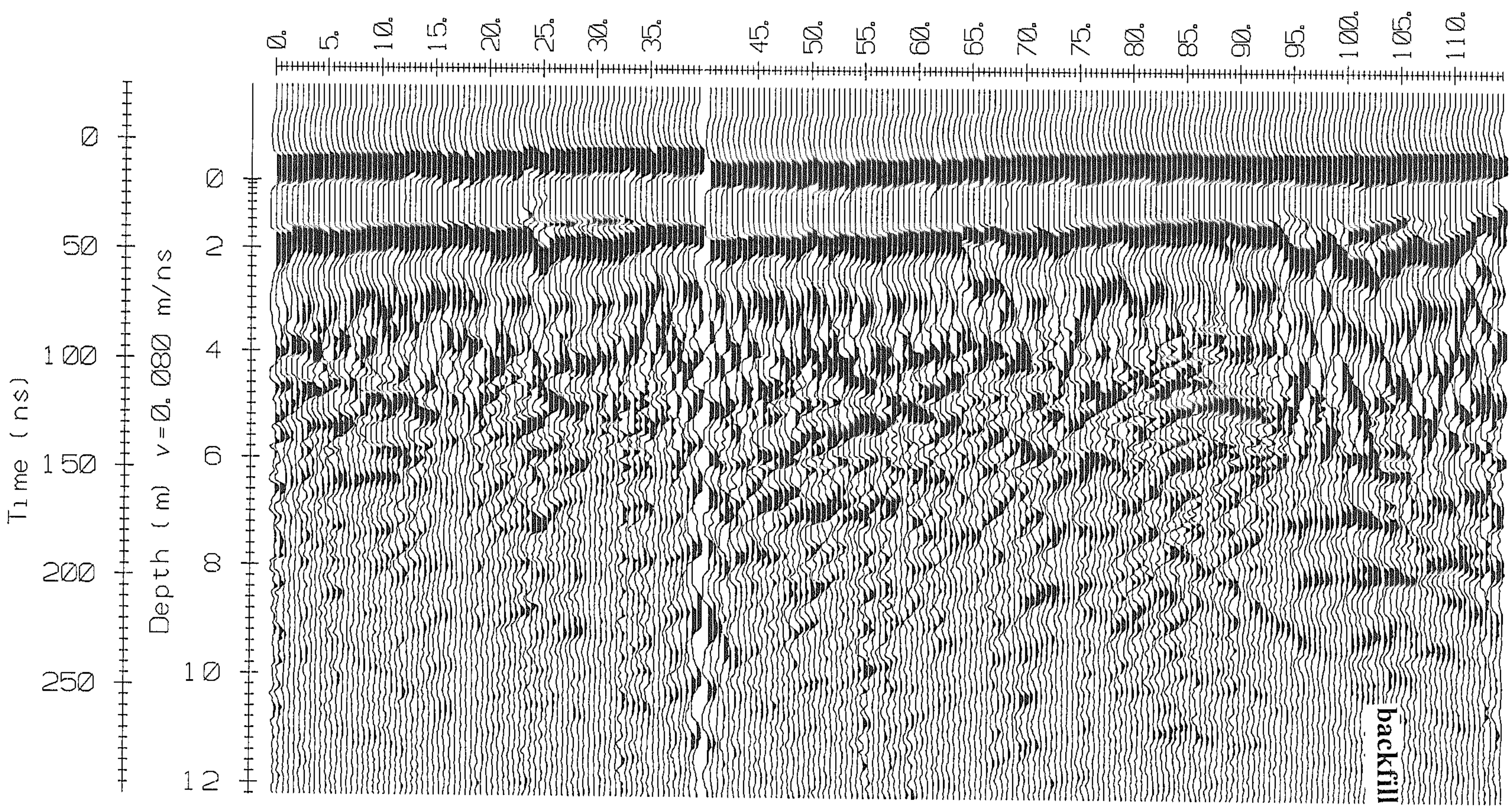
MACKENZIE RIVER - CROSS PROFILE 2 - 100 MHz - JULY 13



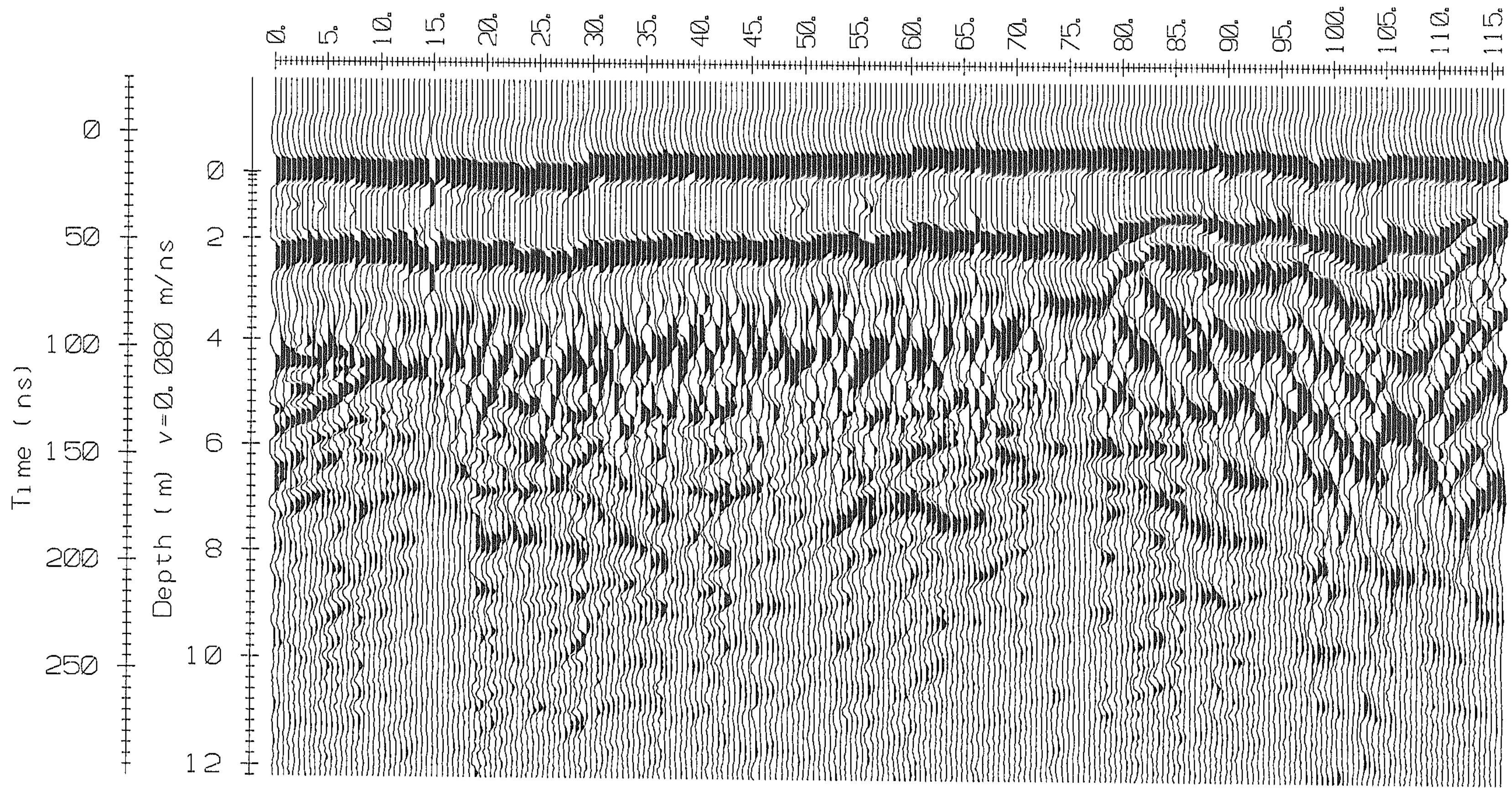
MACKENZIE RIVER - CROSS PROFILE 3 - 100 MHz - JULY 13



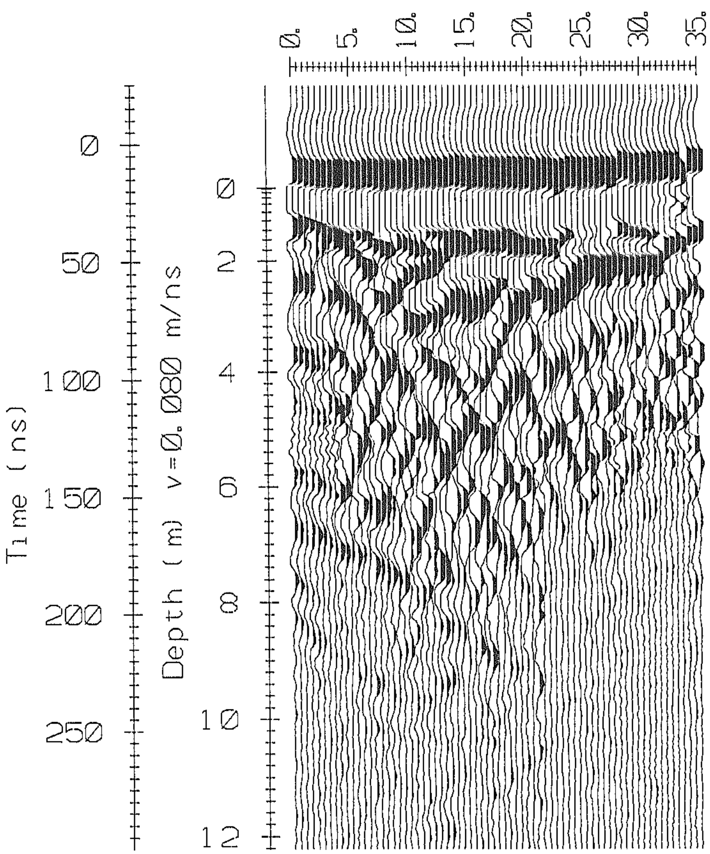
MACKENZIE RIVER - CROSS PROFILE 4 - 100 MHz - JULY 13



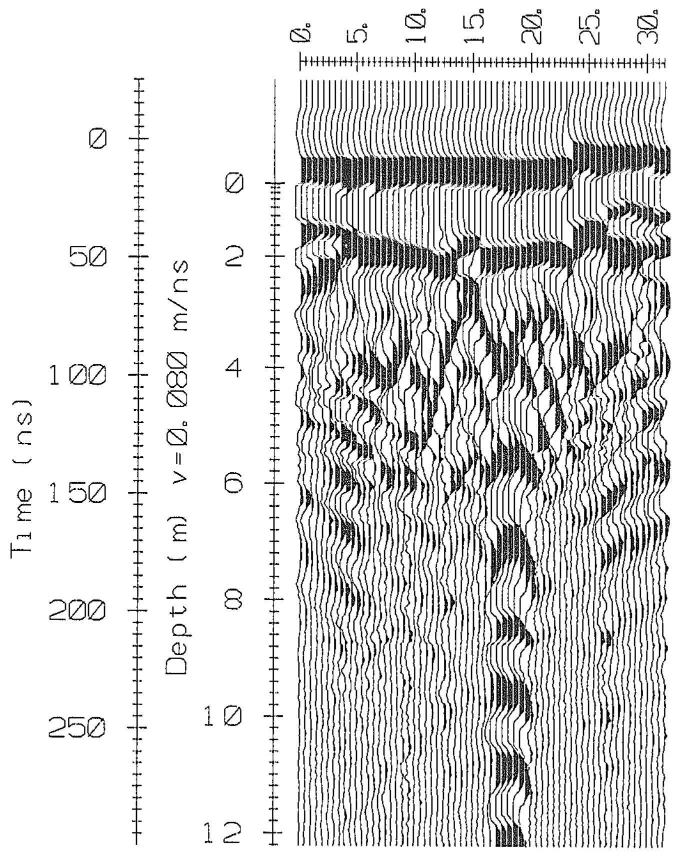
MACKENZIE RIVER - LONG PROFILE 1 - 50 MHz - JULY 12



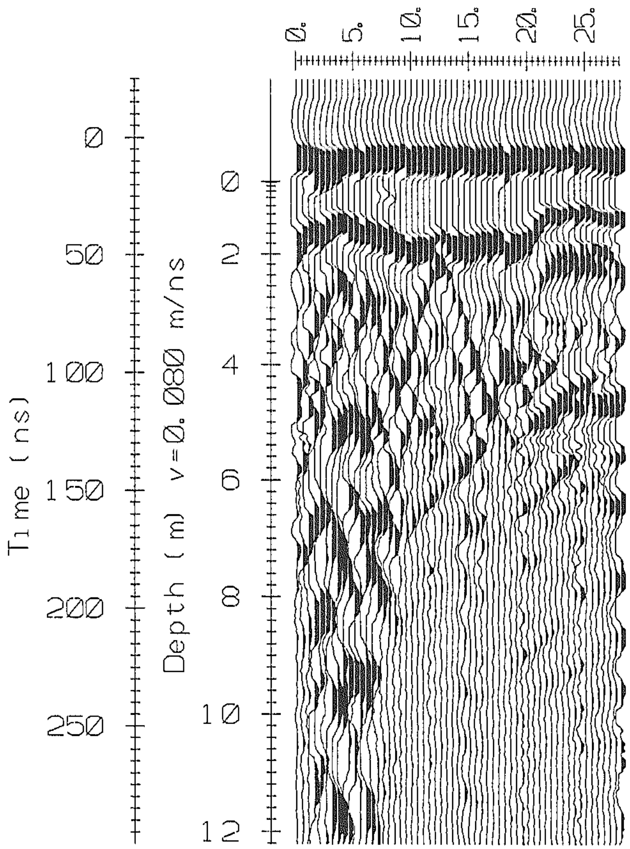
MACKENZIE RIVER - LONG PROFILE 2 - 50 MHz - JULY 12



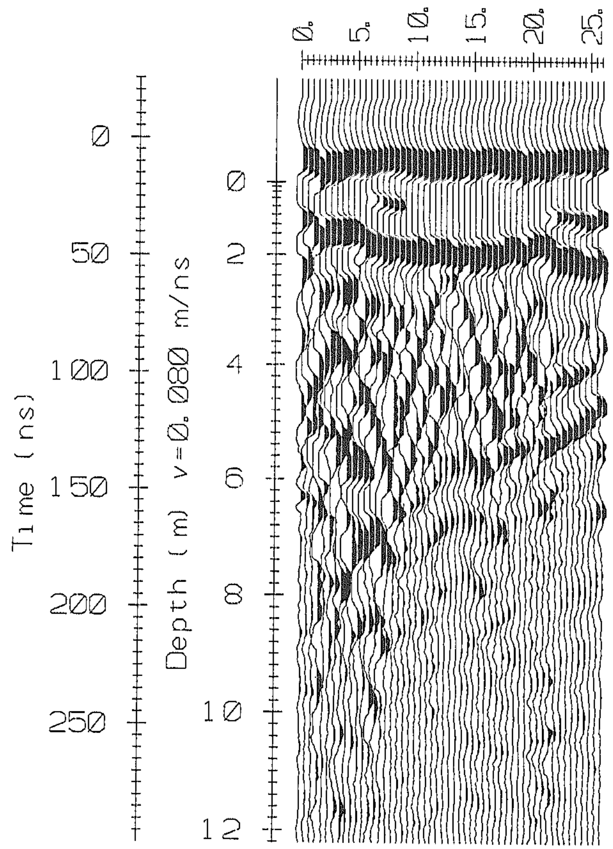
MACKENZIE RIVER - CROSS PROFILE 1 - 50 MHz - JULY 12



MACKENZIE RIVER - CROSS PROFILE 2 - 50 MHz - JULY 12



MACKENZIE RIVER - CROSS PROFILE 3 - 50 MHz - JULY 12



MACKENZIE RIVER - CROSS PROFILE 4 - 50 MHz - JULY 12