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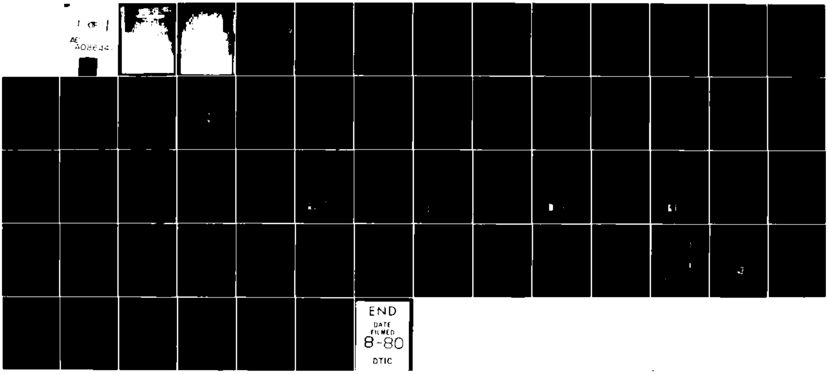

RESEARCH AND DEVELOPMENT BRANCH

DEPARTMENT OF NATIONAL DEFENCE
CANADA

DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL NOTE NO. 80-8

THE DEVELOPMENT OF SNOW PROPERTIES AND ITS EFFECT ON TRAFFICABILITY.

by

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with an appendix by W. Ferguson

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PROJECT NO.
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ABSTRACT

The properties of a given snowpack were monitored throughout a winter season in order to identify some of the factors most affecting vehicle mobility over snow. This activity was carried out as an aid to developing an improved snow classification system for purposes of mobility and to assess the use of snow strength testing devices as part of such a system.

Snowpit data were collected at the Land Engineering Test Establishment, DND Ottawa, during the winter of 1976-77 in combination with penetrometer tests of snow strength and studies of the tractive performance of an RN25-35 tracked carrier. It was found that temperature and free water content are the snow factors which are highly transient while changes in depth, density, grain size distribution, grain shape, crustal layer and bearing strength are usually perceptible over a period of days to weeks. As the winter season progresses snow strength undergoes a general increase with snow density while snow temperature approaches uniformity and crusts become more numerous. Grain shape and size distribution are indicative of the stages of snow metamorphism. All factors affect snow trafficability and appear to contribute to a useful characterization of deposited snow, hence it is suggested that these be included in a scheme for classification for mobility purposes. Snow strength and depth are readily associated with vehicle performance. Sensitive to most of these factors is the plate penetrometer which has potential for the predication of vehicle drawbar pull at 100% slip.

Penetrometer shortcomings are enumerated with a recommendation for greater automation in snow strength testing. Recommendations are also made for the most convenient environmental conditions for purposes of comparing the performance of vehicles.

RÉSUMÉ

Les propriétés d'un manteau nival donné ont été contrôlées pendant tout un hiver afin de mettre en évidence certains des facteurs qui influent le plus sur la mobilité des véhicules sur la neige. Ce contrôle a été effectué pour favoriser la mise au point d'un système amélioré de classification de la neige en fonction de la mobilité et pour étudier l'utilisation de dispositifs d'essai de résistance de la neige comme faisant partie intégrante de ce système.

Des données sur les bassins de neige ont été recueillies au Centre d'essais techniques (terre) du Ministère de la Défense, à Ottawa, pendant l'hiver 1976-77 ainsi que des essais de résistance de la neige au moyen d'un pénétromètre et des études sur la force de traction d'une chenillette de transport RN25-35. On a découvert que la température et la teneur en eau non congelée sont des facteurs éminemment transitoires, tandis que des variations de profondeur, de densité, de granulométrie, de forme des grains, de la croûte et de la capacité portante ne deviennent habituellement perceptibles qu'au bout de plusieurs jours et même de semaines. À mesure que s'avance l'hiver, la résistance de la neige augmente d'une façon générale ainsi que sa densité, mais sa température devient presque uniforme et sa croûte s'épaissit. La forme des grains et la granulométrie sont des indices du stade de métamorphose atteint par la neige. Tous les facteurs influent sur la praticabilité de la neige et semblent contribuer à une utile caractérisation de la neige accumulée; il est donc suggéré qu'ils fassent partie d'un projet de classification en fonction de la mobilité. La résistance et la profondeur de la neige sont directement associées aux performances. Le pénétromètre à plaque est sensible à tous ces facteurs et peut indiquer la force du véhicule au crochet de remorquage avec un coefficient de dérapage de 100%.

Les imperfections du pénétromètre sont énumérées avec la recommandation de recourir à une automatisation plus poussée dans les essais de résistance de la neige. Les conditions idéales d'environnement ont été aussi recommandées afin de pouvoir comparer les performances des véhicules.

INTRODUCTION

The purpose of the present report is to report changes in a given snow pack throughout the winter season and to become acquainted with vehicle performance in snow of known physical properties. This study arose out of a continuing need to determine those environmental factors which are likely to most affect vehicle mobility over snow. The study also was to serve as the field complement to laboratory work (1) in the development of a penetrometer as an aid to predicting vehicle mobility or assessing the trafficability of snow. (The term snow trafficability has not been defined as yet by the International Society for Terrain Vehicle Systems (ISTVS). For the present it is suggested that it be defined as snow strength relative to firm ground both in vertical compression and in horizontal displacement after compression of the snow to the depth a given vehicle would sink. These two components of strength should indicate the degree to which vehicular traffic can be supported.) Strength tests in snow and vehicular performance have been known to vary considerably over the course of a day, a week, or a season. In order to account for these variations and distinguish them from errors of observation it was considered advisable to chart the scale and rapidity of certain changes throughout the winter season. Also the absolute values of these snow factors require continuing documentation in this relatively new field of oversnow mobility.

In support of this activity is the need for a classification system oriented toward the needs of predicting vehicle mobility. A variety of snow classification systems have been presented in the literature (1,2,3) for the purpose of field descriptions of a general nature. In particular the international snow classification system serves as a starting point for the acquisition of field data. But such a system does not take into account snow characteristics under the dynamic loading associated with mobility. There are extensive general descriptions (4,5,6,7) of snow across Canada which provide a background against which to make classifications for trafficability on a nation wide scale. These descriptions should serve as a useful guide as the present snow classification activity expands.

It was emphasized at a recent conference on snow properties (8) that its variability makes classification and generalization very difficult. At present there is no universal classification system for describing snow trafficability. There have been numerous efforts to establish a methodology for prediction of soil behaviour (9,10,11). But for snow the problem is made more complicated by the fact that it is strain rate sensitive (12,13), a compressible medium, and varies greatly with time and location. Interaction of wheels and tracks with sand and clays remains an active field of investigation while in the case of snow such information is very limited. Yet the methodology must be sufficiently well established in order to usefully extend snow investigations to the arctic and subarctic areas of Canada where there may be a national defence interest.

The snow of the Ottawa region was considered to be a suitable and conveniently situated medium for study. Land Engineering Test Establishment (LETE) near Ottawa contains a variety of terrain types (open land, swamp, forest) and houses the RN 25-35 tracked laying vehicle which was made available for testing. Hence application was made for the use of LETE facilities during possibly two winter seasons. As a result snow studies began in December 1976 on LETE project number 0J547. These studies continued until March 1977.

EXPERIMENTAL PROCEDURE

Two experimental sites were partitioned off at LETE for the exclusive use of DREO for the winter season. These sites comprised (a) an open, firm and level area of ground which shall be designated site 1, and (b) a swampy area both semi open and open, i.e. site 2. The locations of these sites are shown on the sketch map of Figure 1. The methods used during the winter seasons may conveniently be divided into three types: 1. snowpit techniques, 2. penetrometry, and 3. vehicle performance studies.

The techniques of snowpit studies were acquired during the previous winter season in Schefferville, Quebec (14). Limited manpower necessitated the curtailment of some types of data, but those taken were considered to be the most relevant, profiles of density, temperature, grain size distribution, and water content. The first two items were taken by conventional means (15,16). A set of hand seives was used to obtain grain size. Percentage water content with respect to sample weight was obtained in mild weather at air temperature above -5°C using a centrifuge method (17,18). In addition to these four variables, the occurrence of crusts was recorded, and the state of grain development and bonding was monitored. In support of such baseline data, weather observations were obtained from the Ottawa weather office of the Atmospheric Environment Service. Usually observations of temperature and relative humidity taken on site were very close to those of the weather office. Grain analysis was carried out with either a low power stereo microscope or hand lens.

Snow strength profiles were obtained with a hand held penetrometer (see Appendix A). The design used was based on one by the Soil Mechanics Research Laboratory of McGill University and was intended for easier handling. This is described in Appendix A. One of the types of head attachment used was the vane-cone, the supporting theory of which is described in detail elsewhere (11). The theory however is limited at present to applications in mineral soils. The design used was unfortunately oversensitive to the total

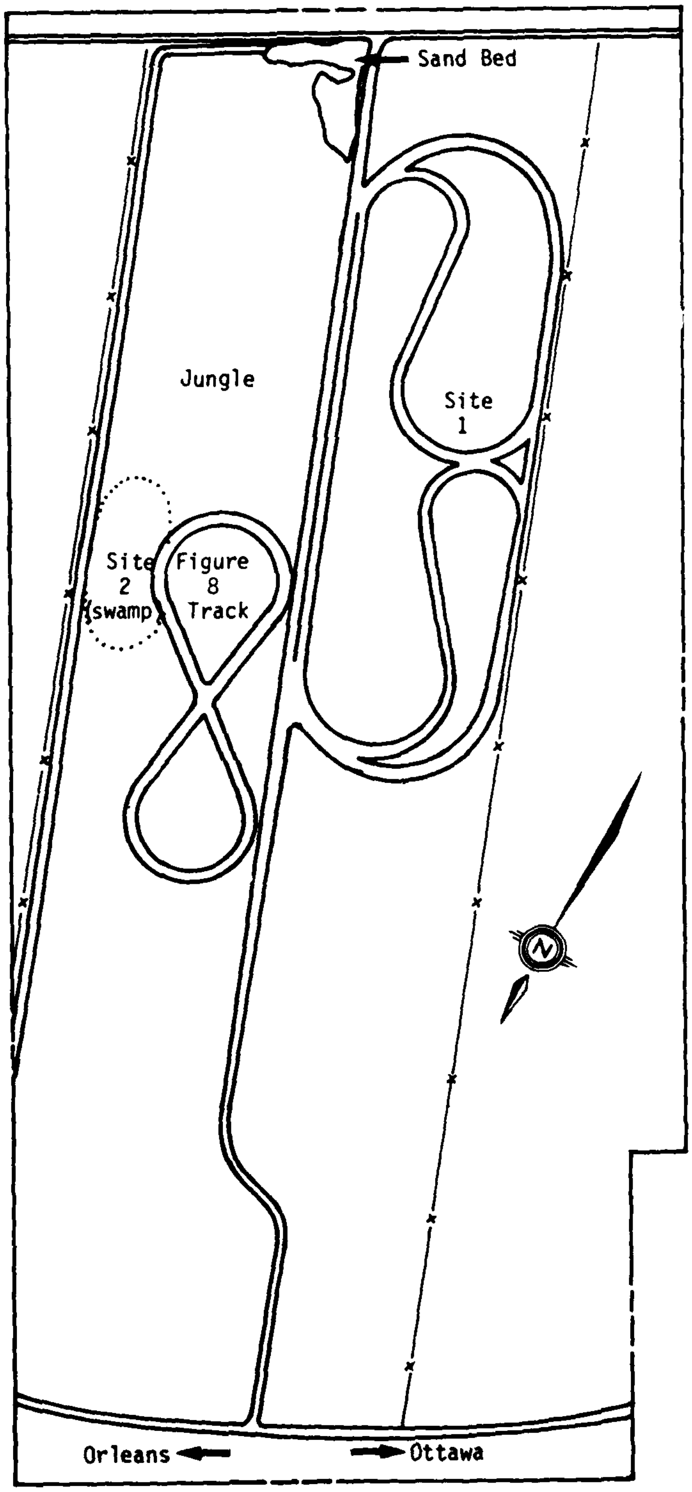

Figure 1: Sketch Map of LETE Property Showing Sites of Snow Studies

weight of the penetrometer and a lighter improved version has since been constructed at DREO*. An alternative type of head used was a circular plate in accordance with the plate penetrometer theory which in recent years has been associated with Bekker (9). The plate allowed for easier control for obtaining a pressure-sinkage profile. In one case a shear experiment was carried out using a plate fitted with crossed vanes (Appendix A). This case was not unlike that employing the crossed vanes of the vane-cone penetrometer. For trafficability assessment purposes the use of a vertically applied pressure is probably to be preferred to the horizontally applied NRC snow hardness tester. Hence the latter does not enter into graphical representation of the snow cover strength vs. depth.

Along with other facilities LETE also made available an RN 25-35 tracked carrier and provided for measurement of drawbar pull at zero and 100% slip at known ground speeds and vehicle weight. For this measurement a General Motors servo indicator was used.

The winter season was unexpectedly short and the vehicle did not become available till early March. Hence testing with a vehicle took place in snow that was representative of spring time only. During tests the RN 25-35 was set in motion at a high constant speed towing an APC M113. Its path was alongside a straight line of stakes with a known spacing. The LETE photography team recorded the event for later measurement of ground speed. Drawbar pull was measured on a dial dynamometer as a percentage of gross vehicle weight both at zero slip and in complete stall. Continuous recording of slip throughout its range was not available.

The month of January had to be omitted from the field season at LETE in order that the present investigator could gain some experience with the performance of a variety of military pattern vehicles in shallow snow at Camp Wainwright Alberta. The results of this activity are reported in Appendix B. Work was resumed at LETE during February and March, i.e. until snow cover was discontinuous and accessibility to the sites by muddy roads proved too difficult.

RESULTS

DEVELOPMENT OF SNOW PROPERTIES

A very coarse monitoring of the changes in snow properties throughout the course of the winter 1976-77 in Ottawa was carried out. These changes are reported sequentially beginning in mid December.

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* The McGill Laboratory later built a lighter and improved version of the penetrometer.

The first testing period was December 15, 16 and 17 at LETE. Even at this early stage of the winter, snow density had undergone a degree of uniform compaction on the lower 75% of depth (Figure 2). The newly fallen surficial snow quickly acquired a density of 150 kg/m^3. Water content was variable with time and location with the limits roughly of zero to ten percent by weight. The temperature profile was stable, linear and close to freezing throughout the period. Metamorphism in its earliest stages was evident throughout the depth of the snow pack. Surface dendrites were metamorphosed to platelets with spines still visible. The surficial portion of snow constituted the coarsest portion of the snow pack (Figure 3). This period was followed by a sleet storm and an accumulation of 0.11 m in ten days.

Data collection was resumed on December 30 at which time a surficial ice layer was present (Figure 4). Upon testing the vane-cone apparatus it was found that force could be measured only at the newly formed ice layer. Upon penetrating this layer, the penetrometer would plunge uncontrollably to the base of the snow pack. It was decided that a lighter hand held apparatus should be used as well as a weaker more sensitive spring in order to detect the torque resistance of snow above and below ice layers. By the end of December snow grains below the ice layer were acquiring a coarse and loose texture characteristic of depth hoar.

During the month of January, snow investigations were shifted to Camp Wainwright, Alberta in order to observe a variety of military vehicles operating in shallow snow. The results are described in Appendix B.

Upon returning to LETE investigations of snow in the Ottawa region were resumed. Snow accumulation was now over 0.56 m on level ground. Air temperature for January averaged -14°C while winds were west at 15 km/hr. Grain size distribution was now changed with the coarsest grains near the base of the snow pack. Even over a period of two days in February (Figure 5) it was apparent that transformations in texture were occurring throughout the entire snow depth. Through settling and compaction, the snow at depth had reached a density of 300 kg/m^3 by the beginning of February. The ice layer that formed in December was now submerged to 0.5m. This layer persisted as the lowermost crust over the balance of the winter.

During February the temperature profile appeared fairly stable below 0.3 m from the upper surface of snow. As air temperature fluctuated, so did the snow pack temperature down to at least 0.4 m (Figure 6). The slightly denser snow of February 2 may account for the apparent increased strength in plate pressure-sinkage tests (Figure 7). It was now clear to what extent snow temperature and intergranular bonding would have contributed to bulk strength. The upper half of the snow pack being slightly warmer on the first day may have promoted intergranular sliding (19) although the snow granularity and looseness of the second day would also have been conducive to sliding. The rate of penetrometer loading may also be a factor, but this was kept as uniform as possible. A series of automated load-sinkage tests might resolve the question of load rate effect on snow strength.

The slopes of the pressure-sinkage graphs for February 2 are not parallel and hence the Bekker parameters (9) k_c and k_ϕ are not both positive. The parameter, n, (9) was obtained from an average value of slope for purposes

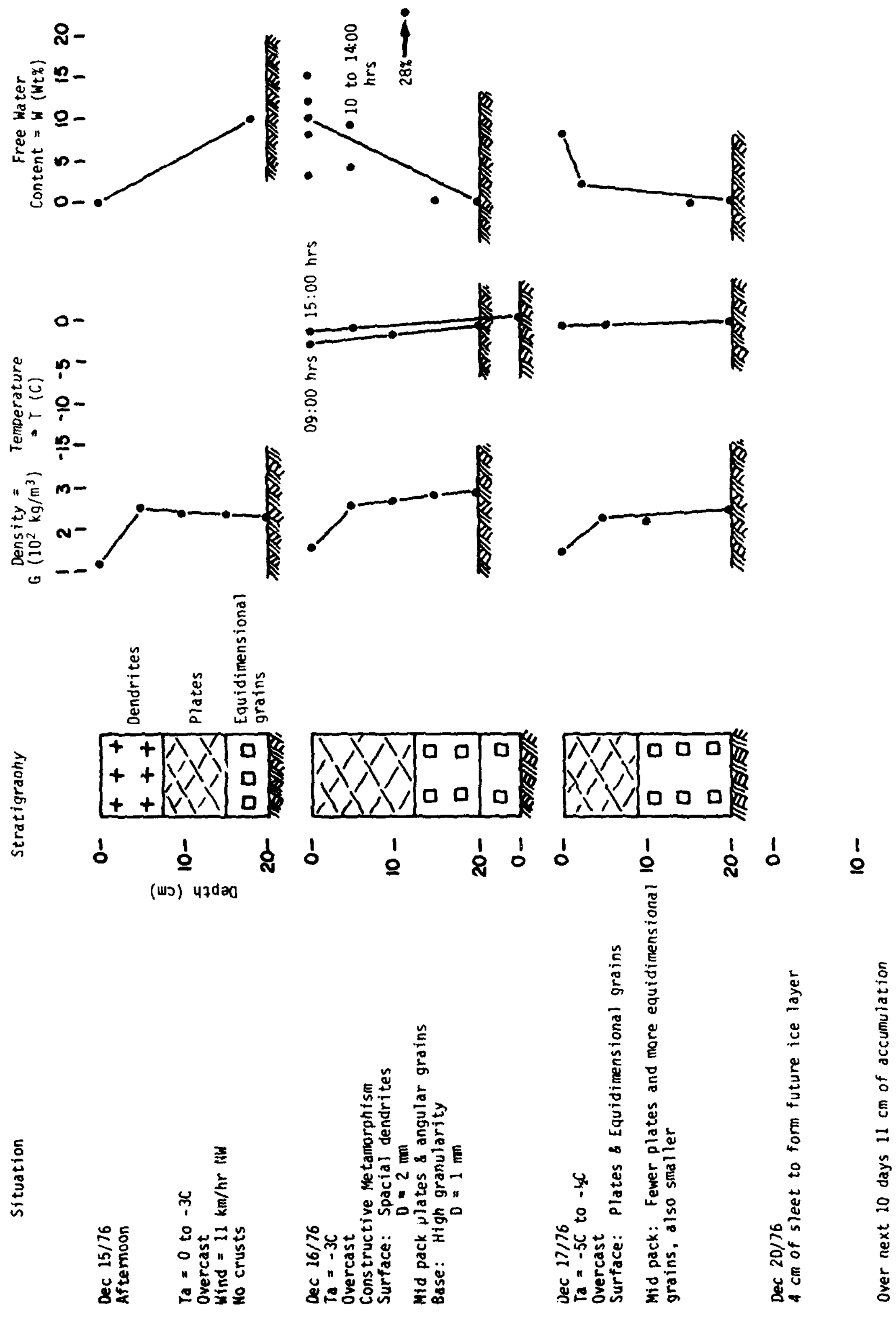


Figure 2: Snow Pit Data - Site 1 Dec 15-17/76

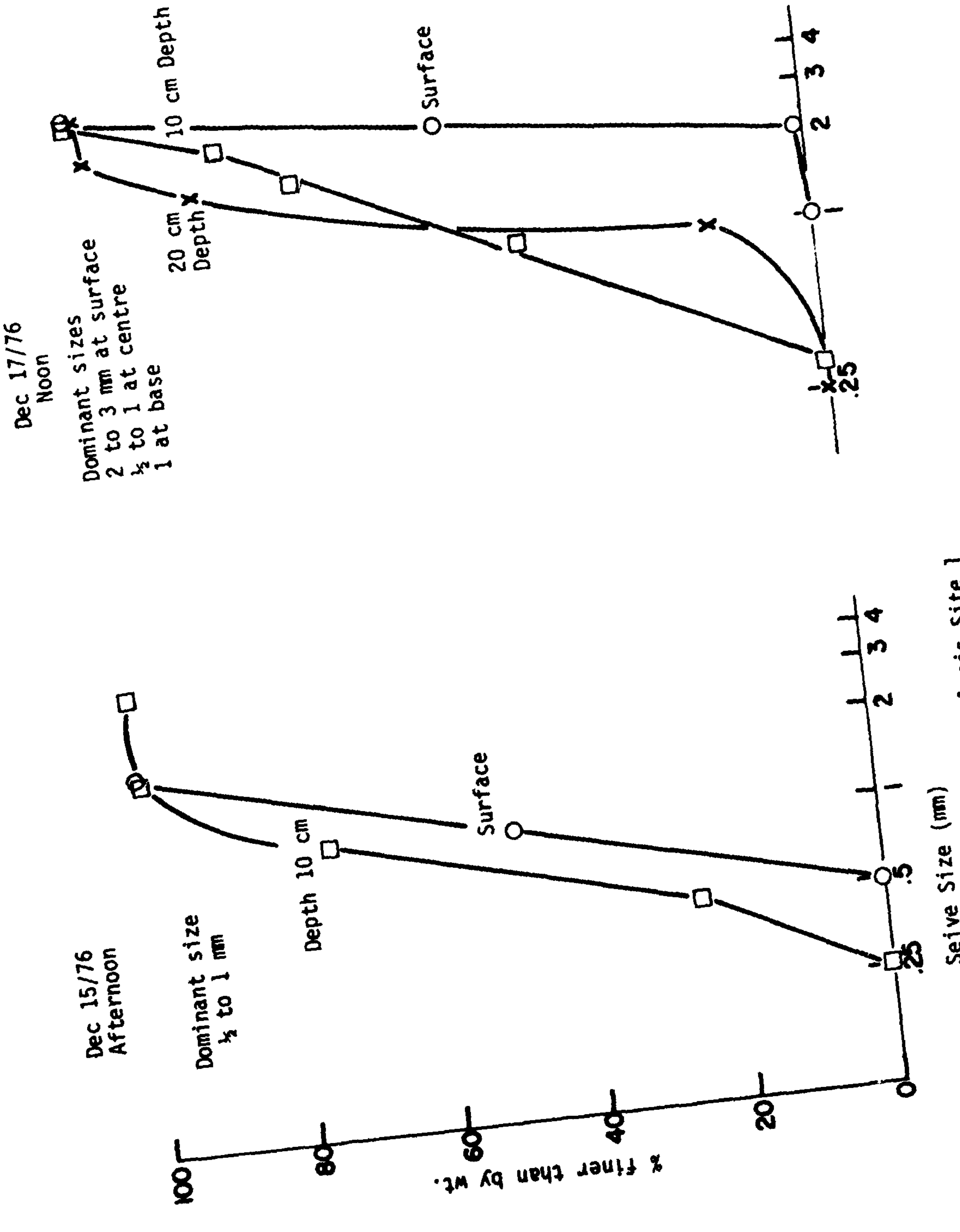


Figure 3: Sieve Analysis Site 1

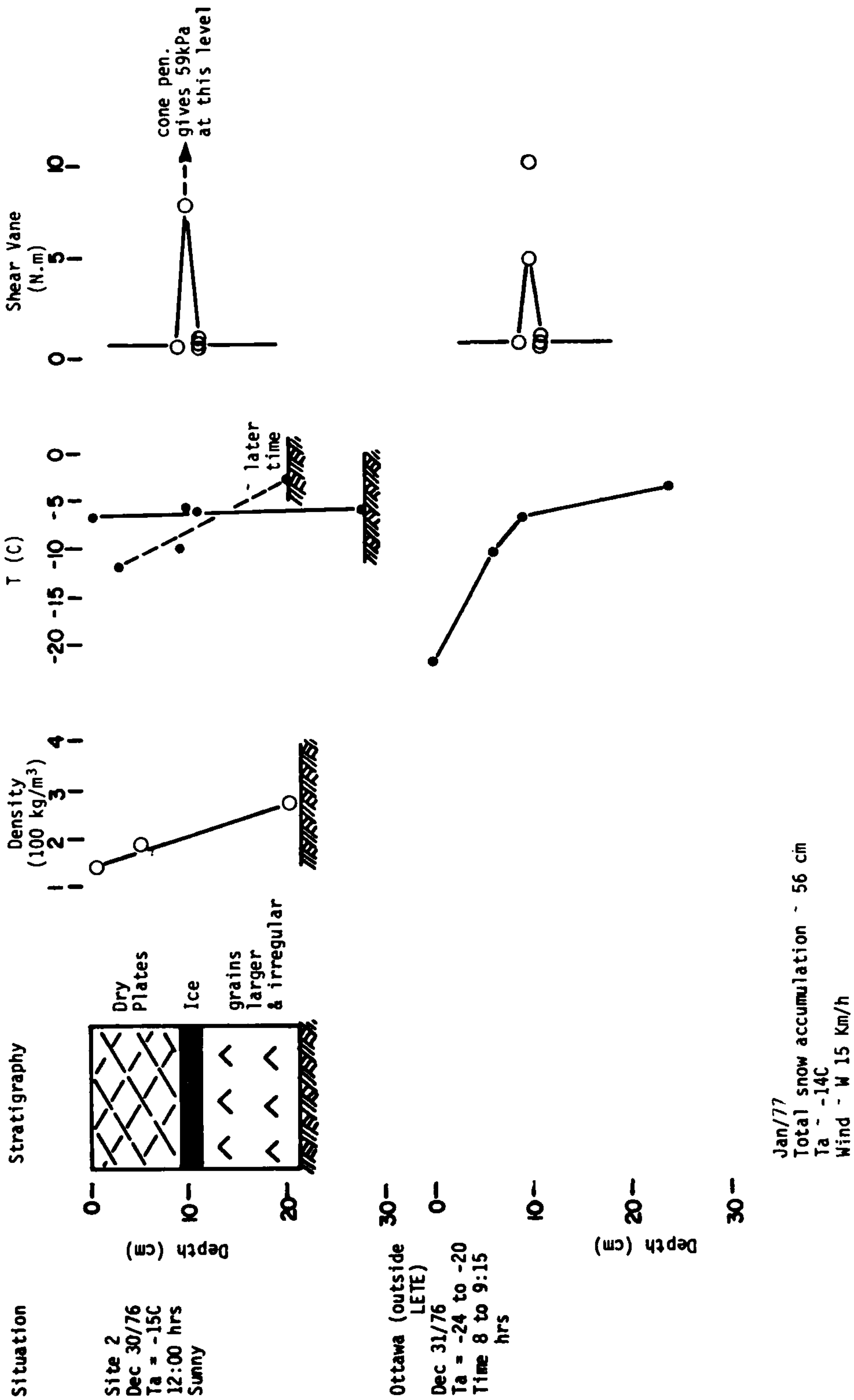


Figure 4: Snow Pit Data Dec. 30-31/76

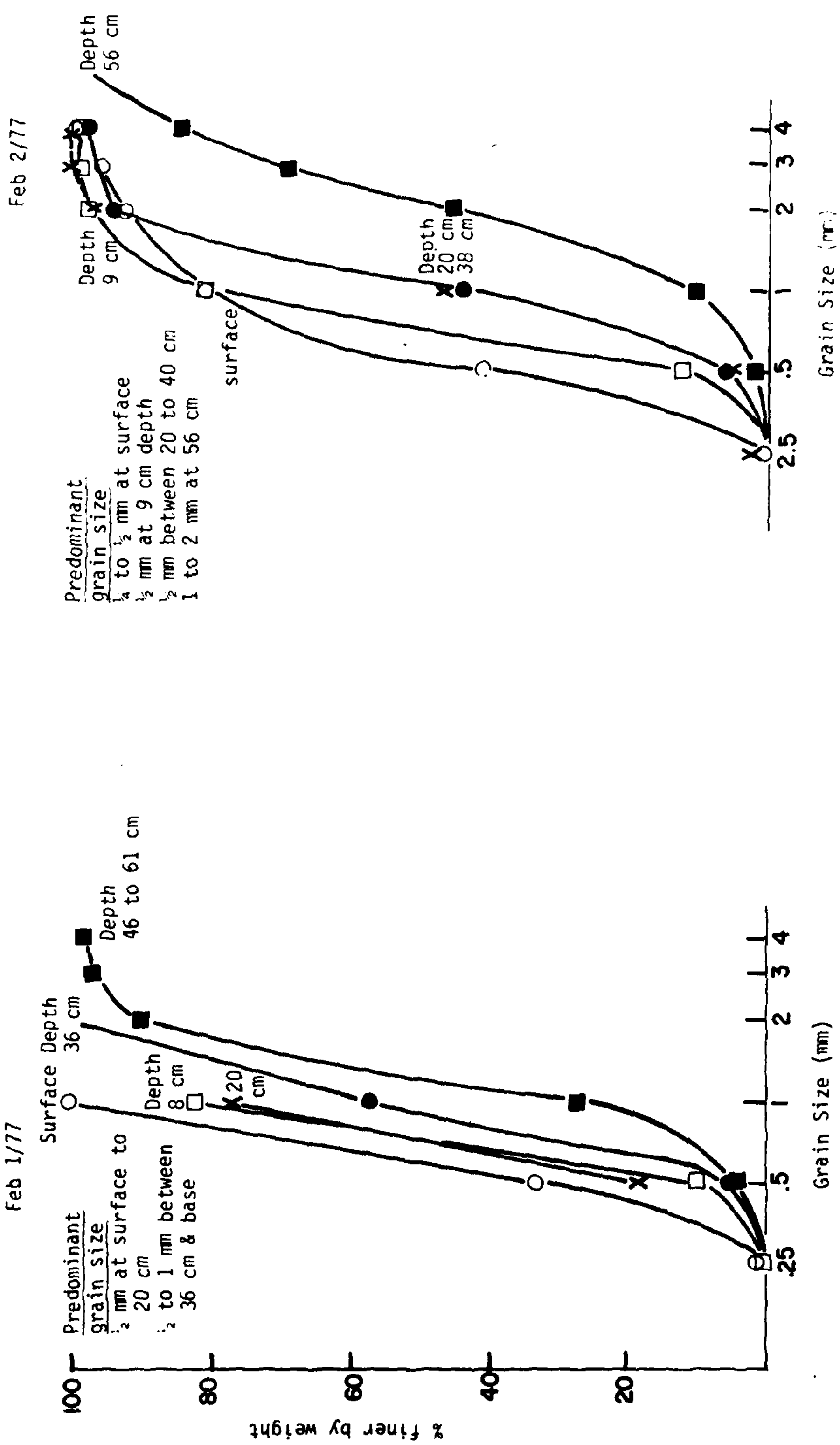


Figure 5: Sieve Analysis Site 1, Feb 1-2/77

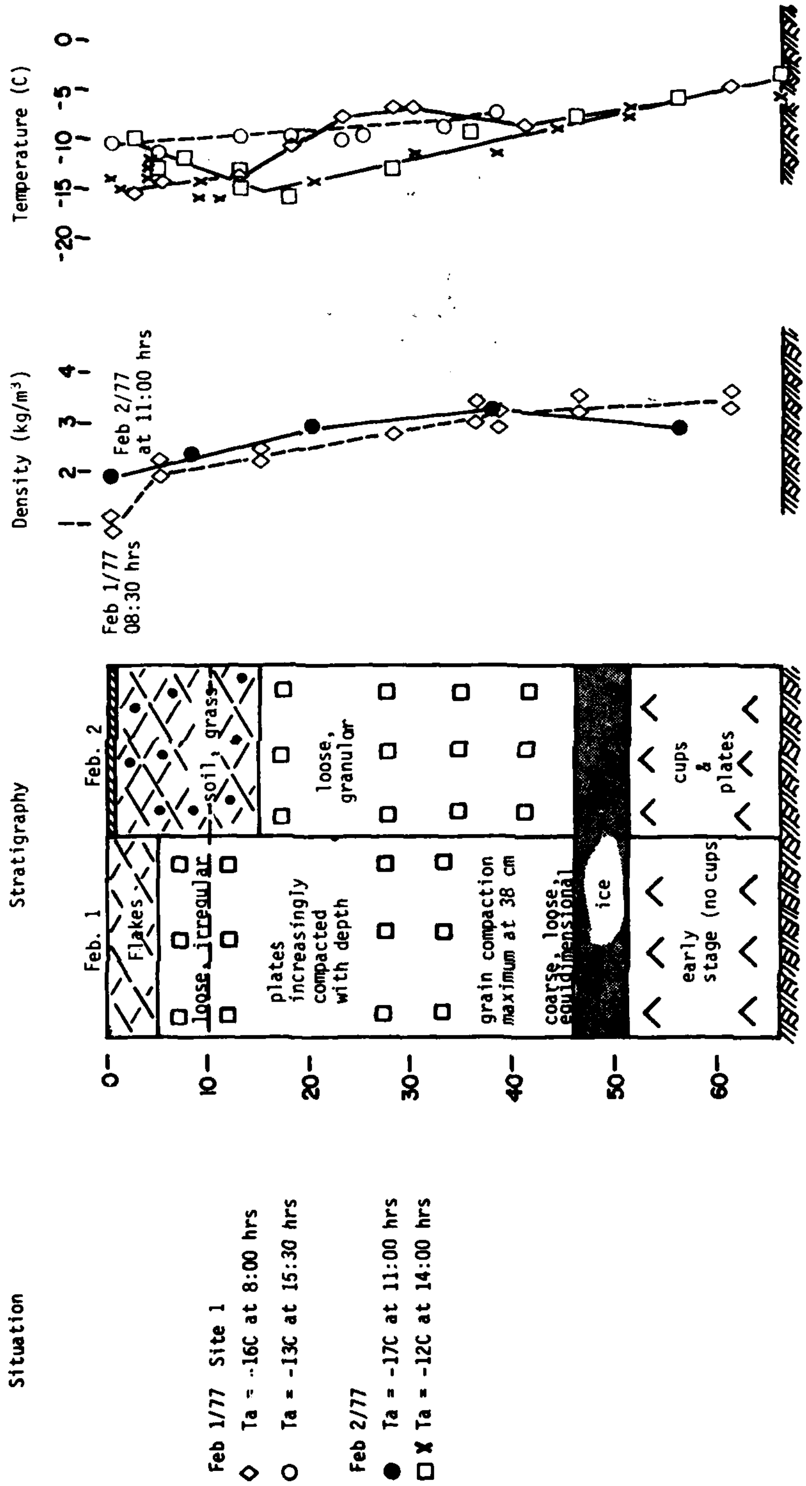


Figure 6: Snow Pit Studies Site 1 Feb 1-2/77

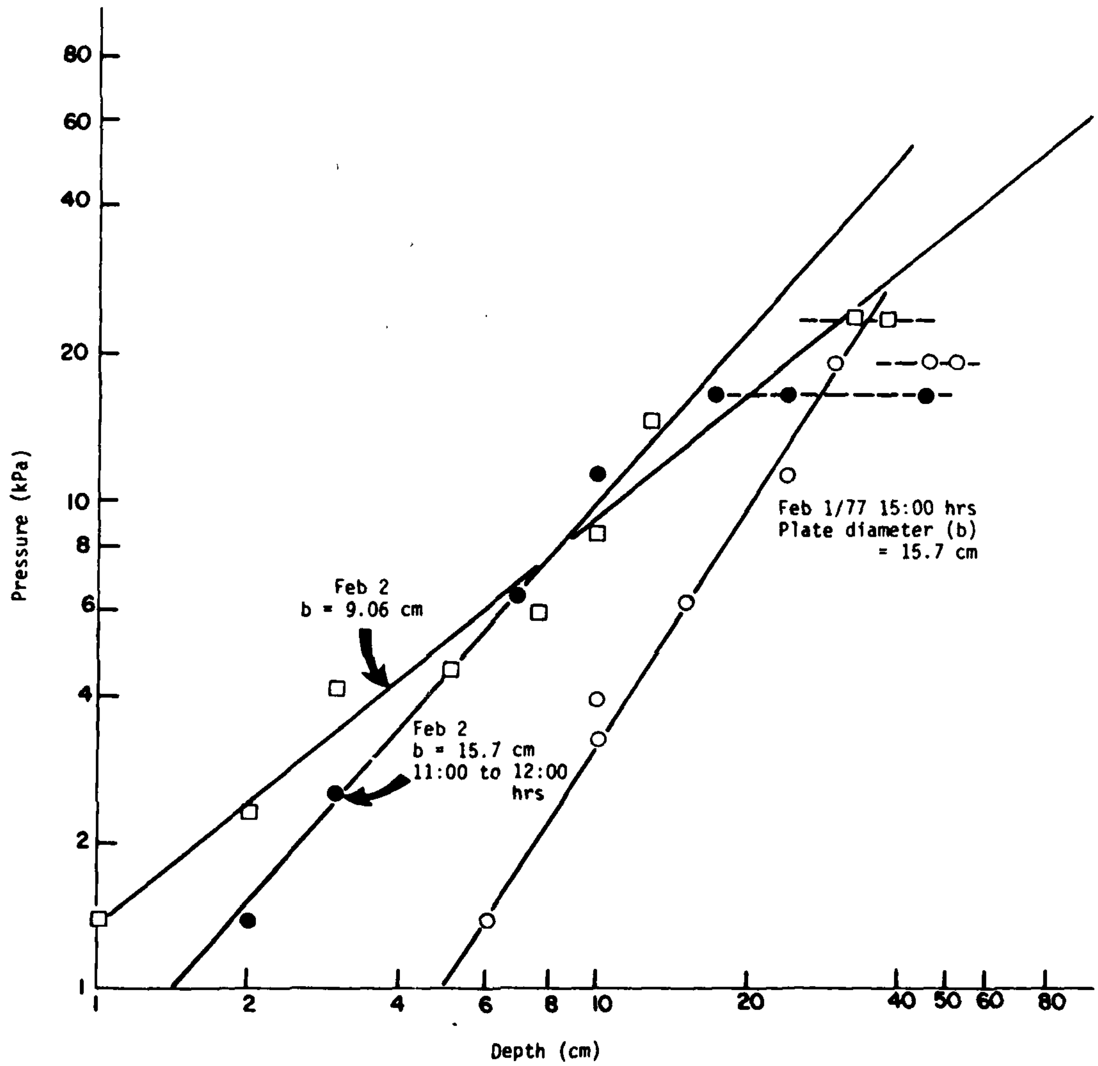


Figure 7 Plate Pressure vs Depth Site 1 Feb 1-2/77

Note: Snow appears weaker on Feb 1

of calculating drawbar pull. The procedure was considered admissible provided slope values were within a few percent of the average. Note the break in linearity in the load-sinkage graphs beyond 0.15 m depth suggesting the existence of a pressure threshold. This characteristic of plate test results has been observed at Keweenaw Research Centre also (20). The pressure threshold or plateau may in turn be related to the stress bulb intersecting the more rigid base of the snow pack. This possibility was not investigated although Bekker (9) has reported that a larger plate will "sense" the base at a shallower depth. The graphs may indicate this, the base in this case being a false one at the ice crust situated at 0.46 m. The pressure levelling off is probably evidence that the snow beneath the plate penetrometer has entered a purely plastic state (21).

The next period of study was February 10 to 12. The pack now contained a layer 0.1 m thick of freshly fallen snow. Snow density at the base reached 400 kg/m^3 while snow above that shows in Figure 8 a lag in its progression to higher density. At the same time the temperature of the upper 0.03 to 0.2 m of snow fluctuates with the air temperature while the remainder of the pack remains stable at about -4 to -5°C (Figures 8, 9 and 10). A brief thaw period arose in mid February making water content of the snow a measurable quantity. The warmest portion of the snow being at the surface, its water content was relatively high. The upper 0.1 m could be compacted easily. Grain size at 0.25 m depth had grown to about 3 mm, about 3 times that at the surface (Figure 11). Snow pack strength appeared to be increasing with time during this period (Figure 12). Between February 15 and 16 air temperature dropped significantly yet snow profile temperature lagged at first then appeared to adjust to the new colder temperature with the effect evident to about 0.35 m in a 0.65 m snow pack (Figure 13). The snow depth was now highly packed even though the air temperature became very cold (-20°C). Probably water at the surface filtered down leaving the surface relatively cold and dry. Water content though present could not be measured at such a low air temperature. New ice crusts had now formed. Grain size distribution at each depth of measurement showed a clear progression of increasing coarseness with depth (Figure 11). The pressure sinkage graph of Figure 14, for February 17 indicates that the snow pack is measurably stronger than on February 1 presumably because of the snow moistness or relative compactability even though water content could not be measured by centrifugal means. The temperature-depth graph of February 17 (Figure 15) again confirmed the flexibility of snow temperature within the top 0.25 m of depth. Additional ice crusts were now present. By February 28, a thick surface crust had formed and the pack was almost isothermal at -3.5°C (Figure 16).

On March 3 the first vehicle test was carried out using an RN 25-35 track laying vehicle. The weather was clear and sunny while the snow was highly packing. Snow profile temperature near the surface quickly changed as air temperature rose. Even at depth the temperature measurements were unusually scattered (Figure 17). Density below the surface crust was virtually constant at 300 kg/m^3 while water content measures below 10%. Depth hoar grains were now very coarse compared to the bulk of the snow pack (Figure 18). The compressive strength of the snow was measurably stronger than on February 17. An important contribution to this strength was probably the several ice crusts that were present.

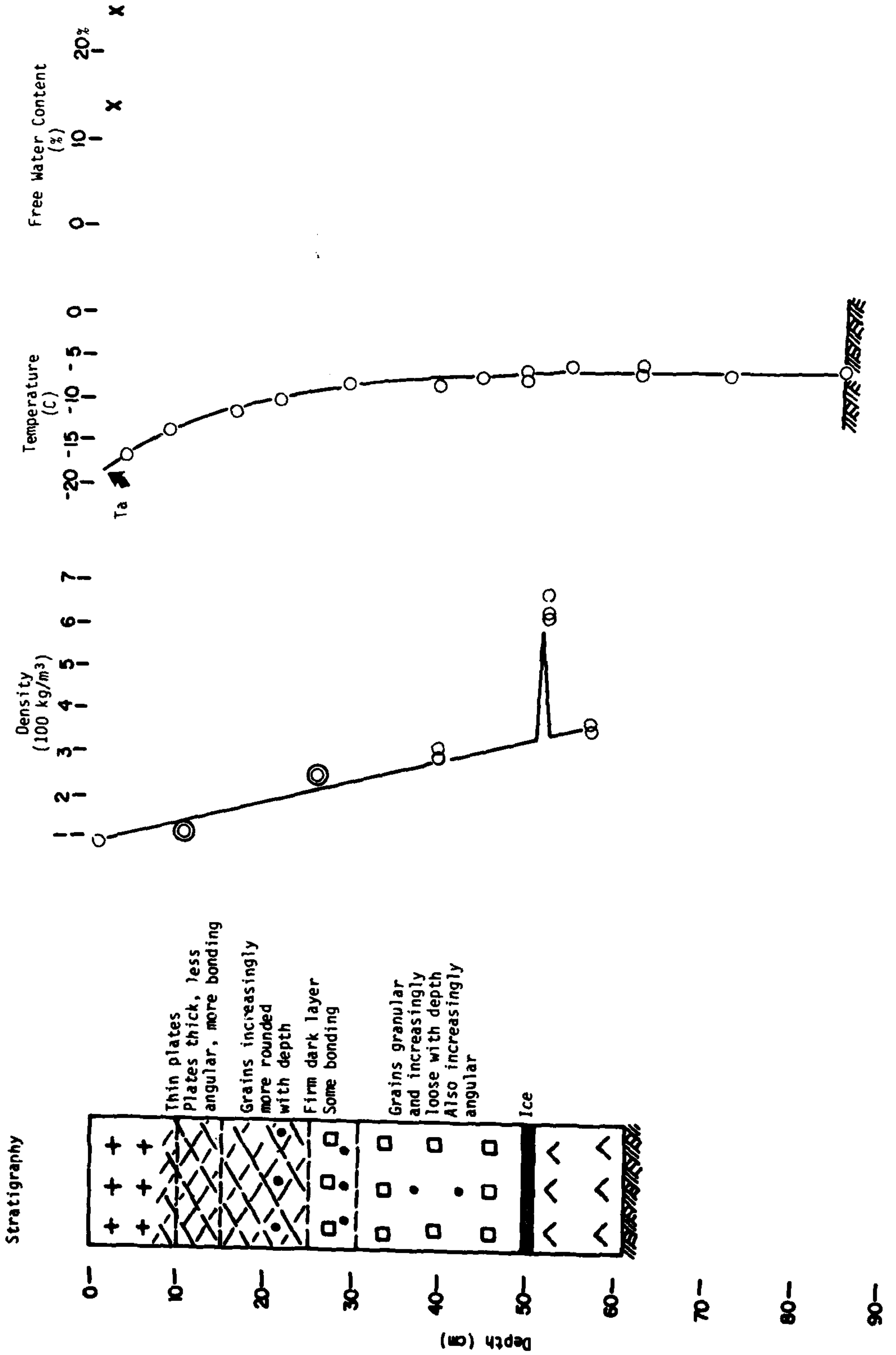


Figure 8: Snow Pit Data Site 1, Feb 10/77

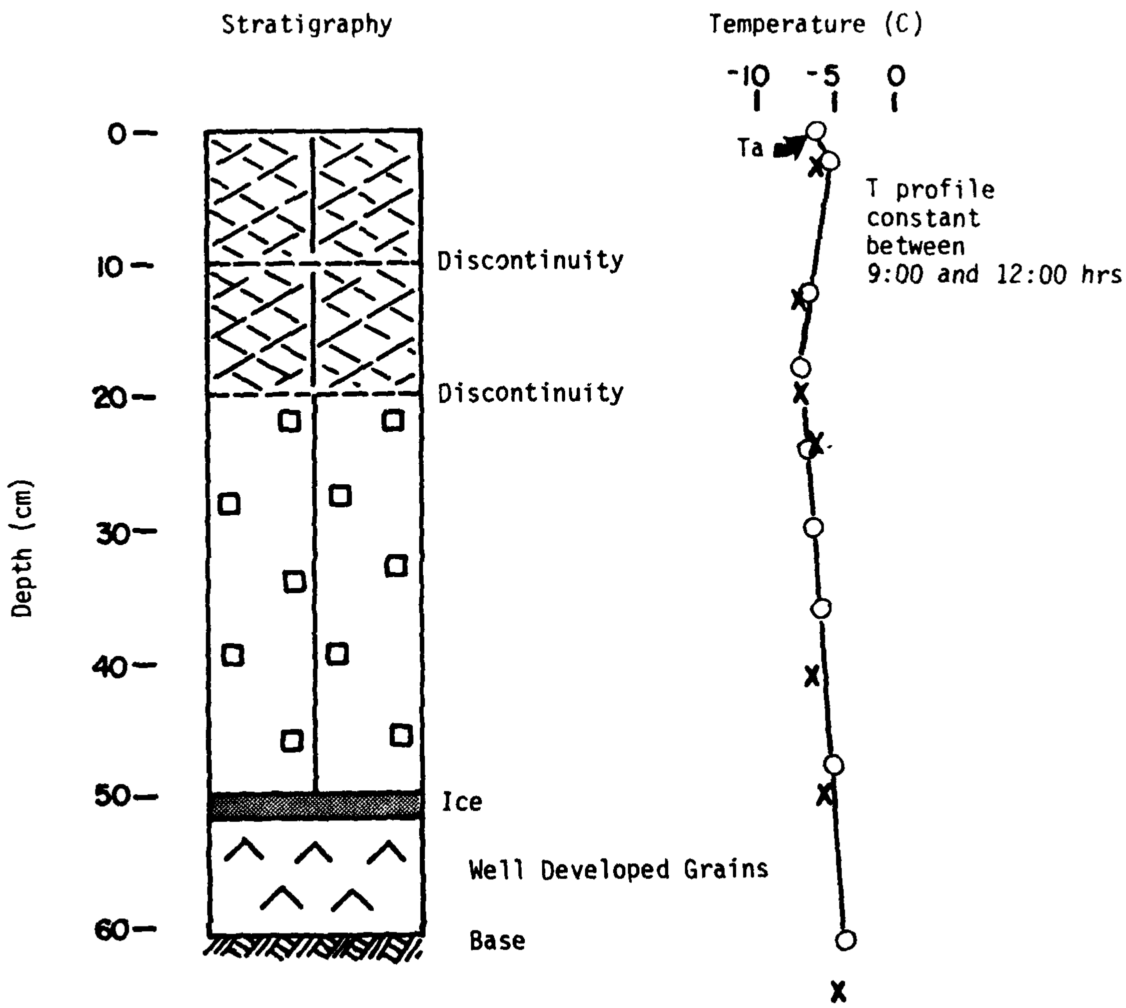


Figure 9: Snow Pit Data Site 1, Feb. 11/77

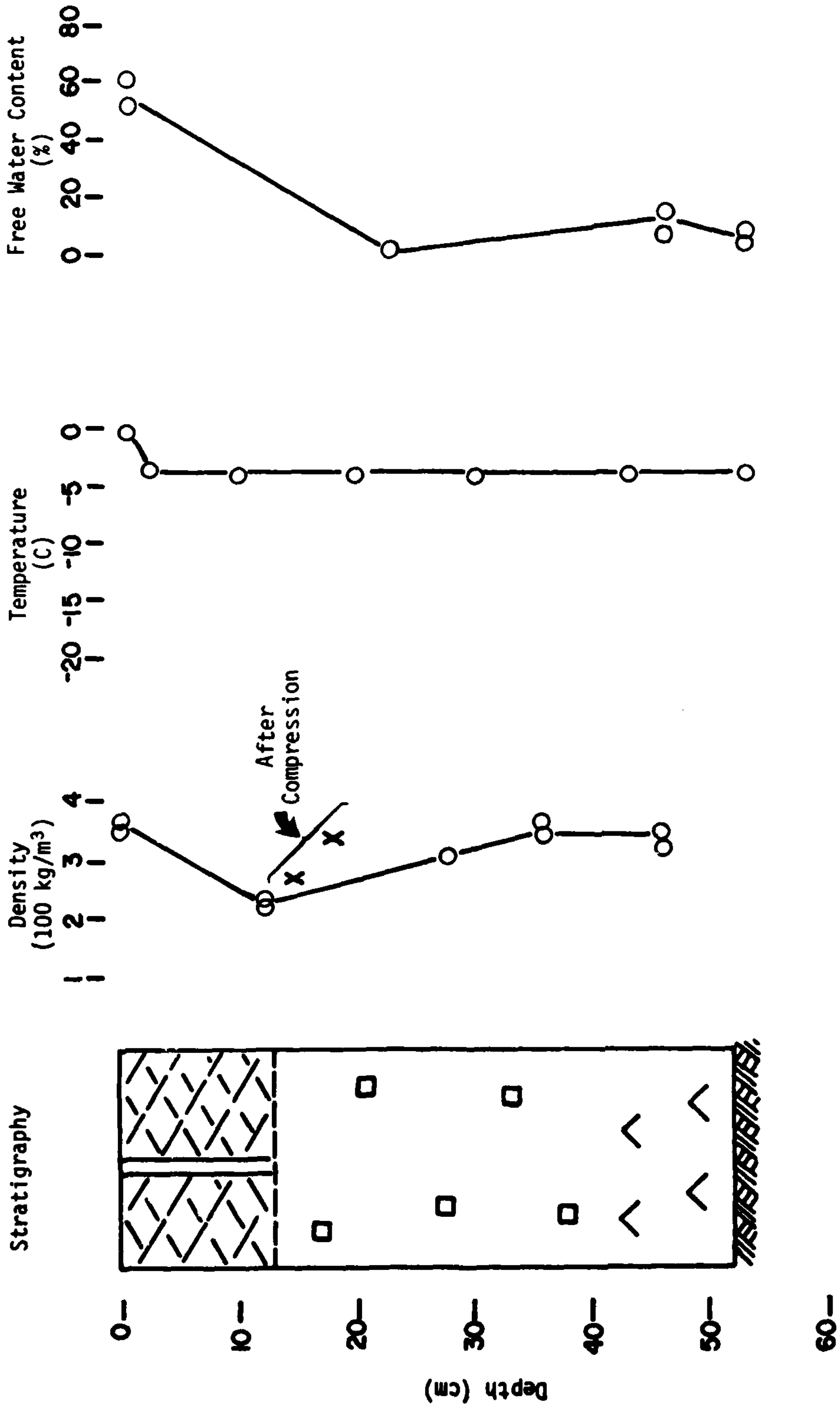


Figure 10: Snow Pit Data Site 1, Feb 12

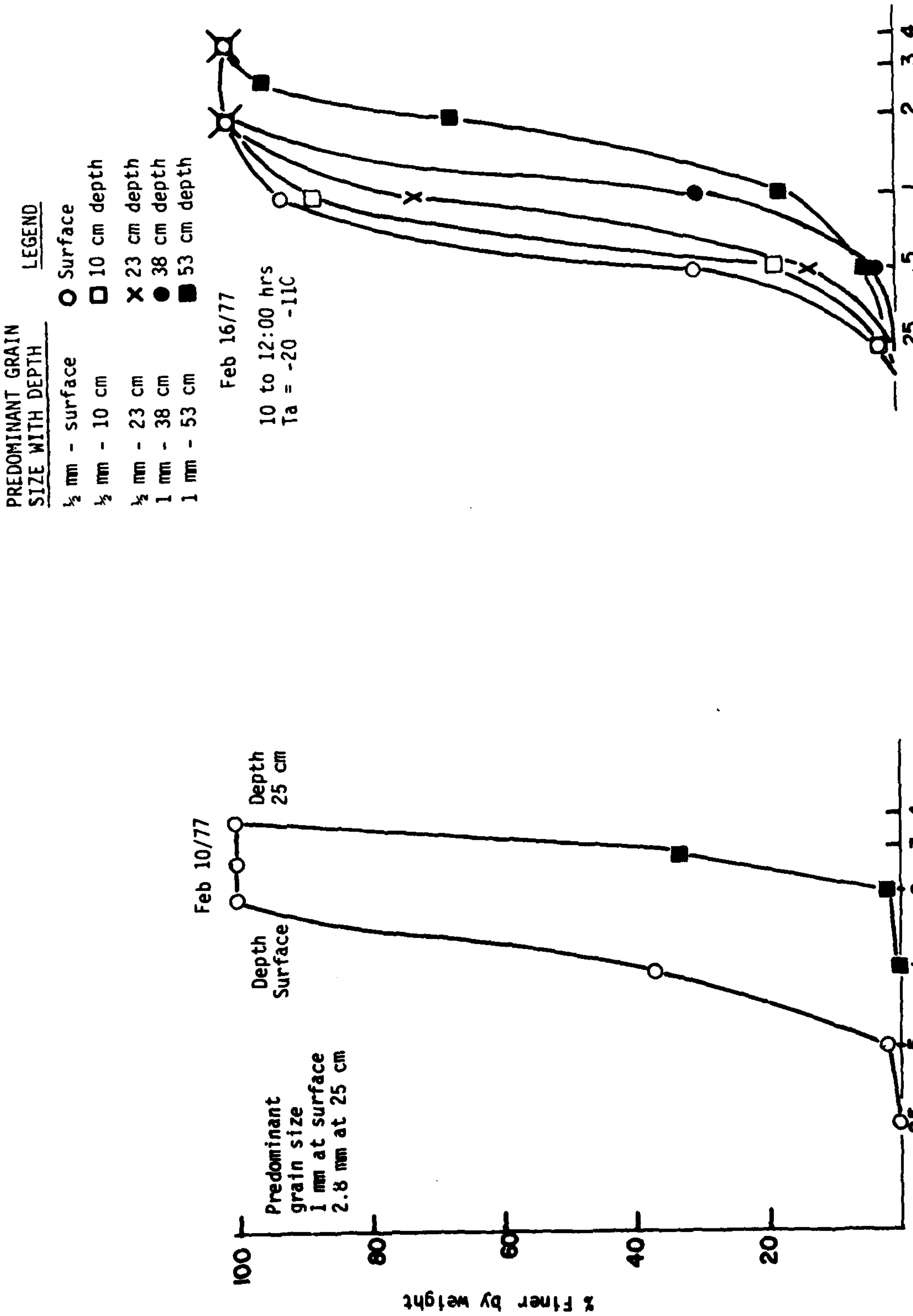


Figure 11: Seive Analysis Site 1

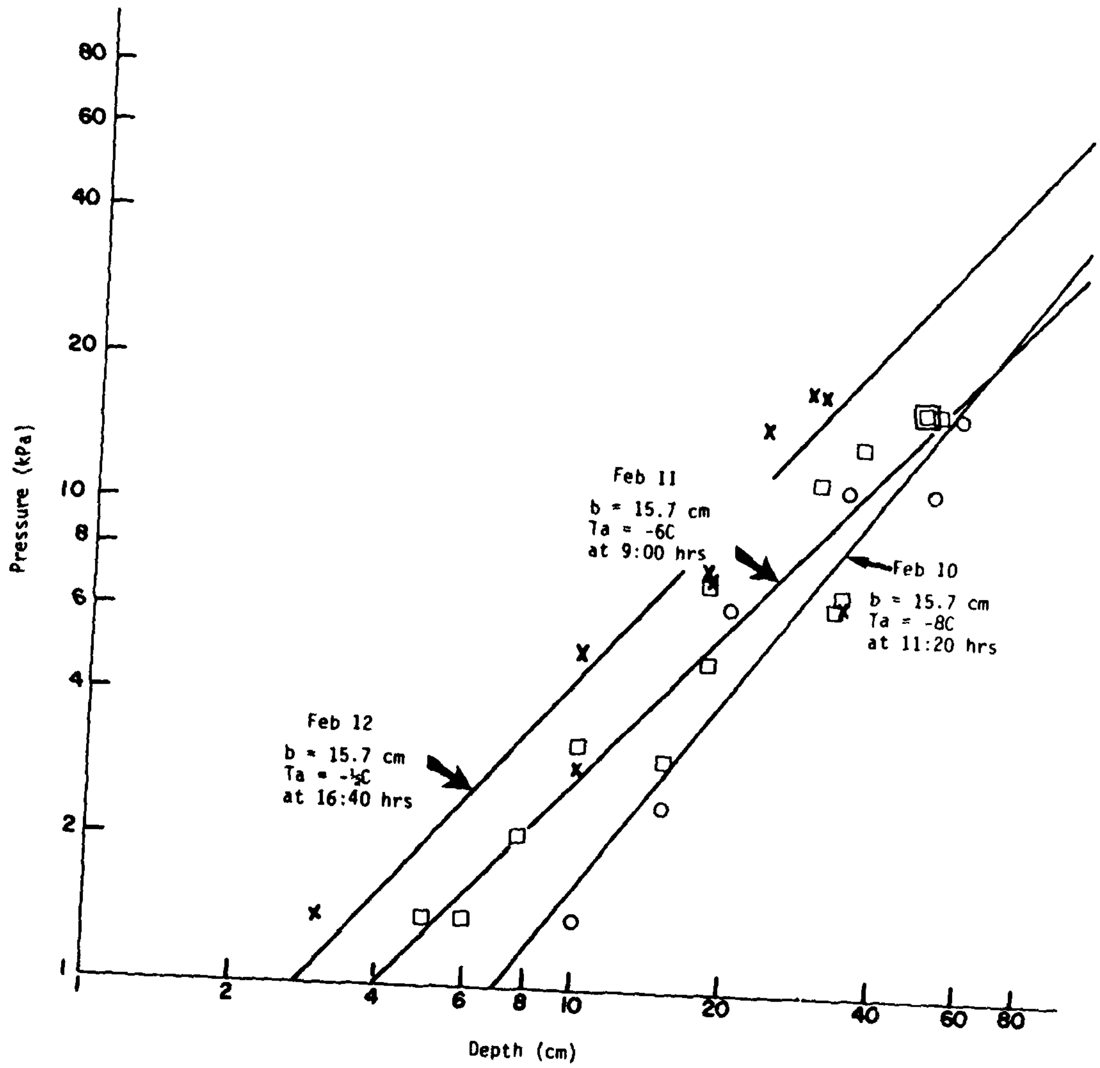


Figure 12: Plate Pressure vs. Depth Site 1, Feb 10-12/77

Note: Apparent strengthening of pack with time

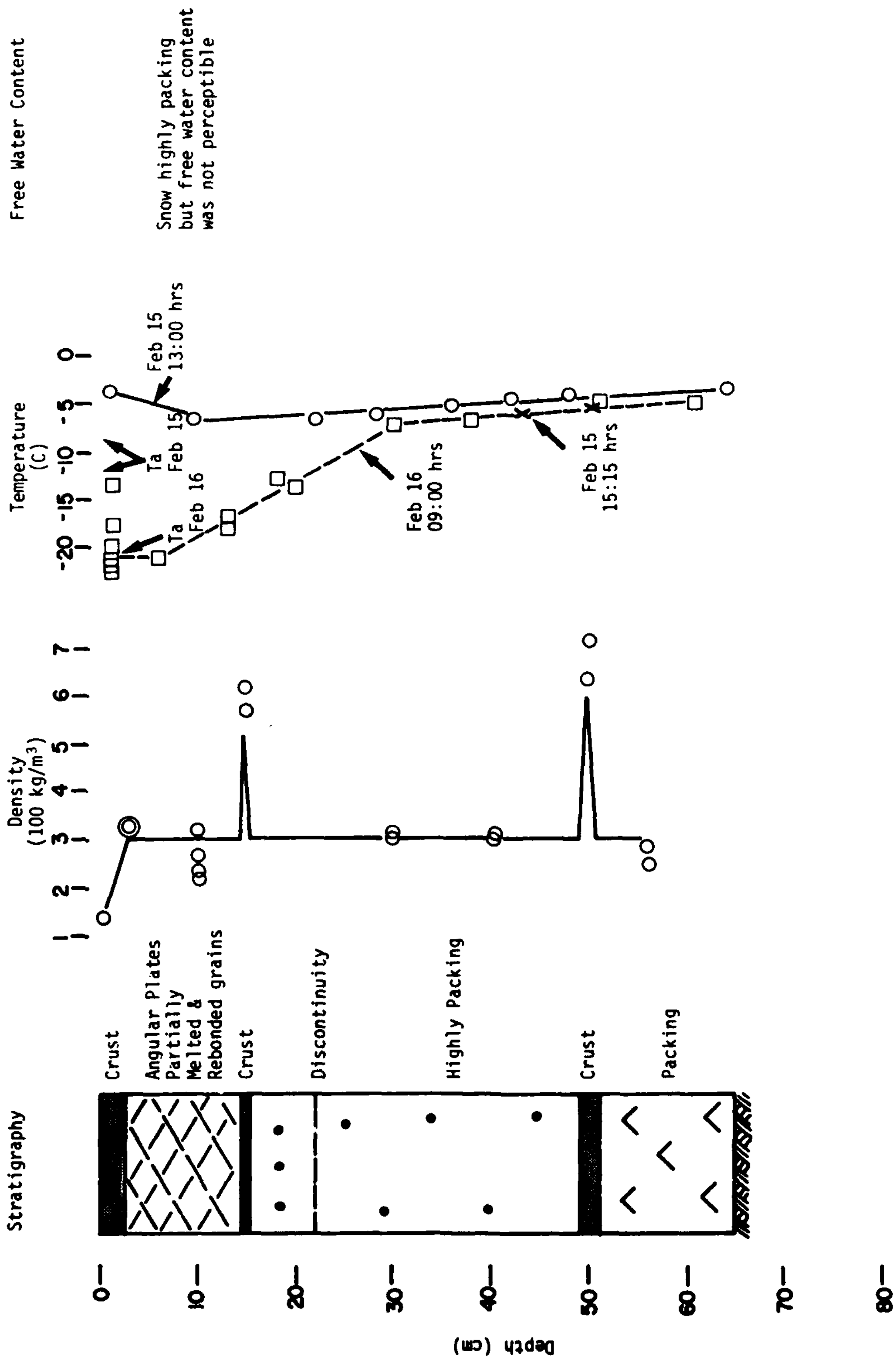


Figure 13: Snow Pit Data Site 1, February 15-16/77

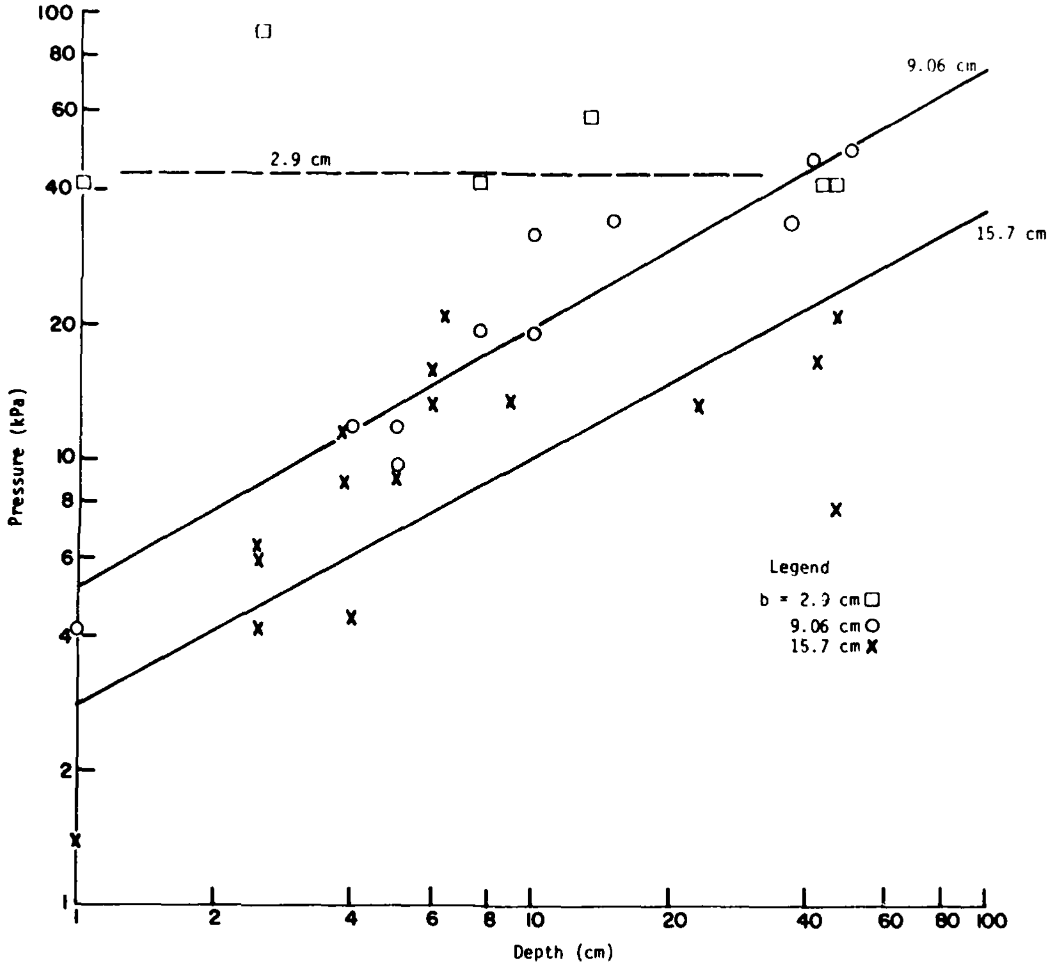


Figure 14: Plate Pressure vs. Depth Site 1, Feb 17/77

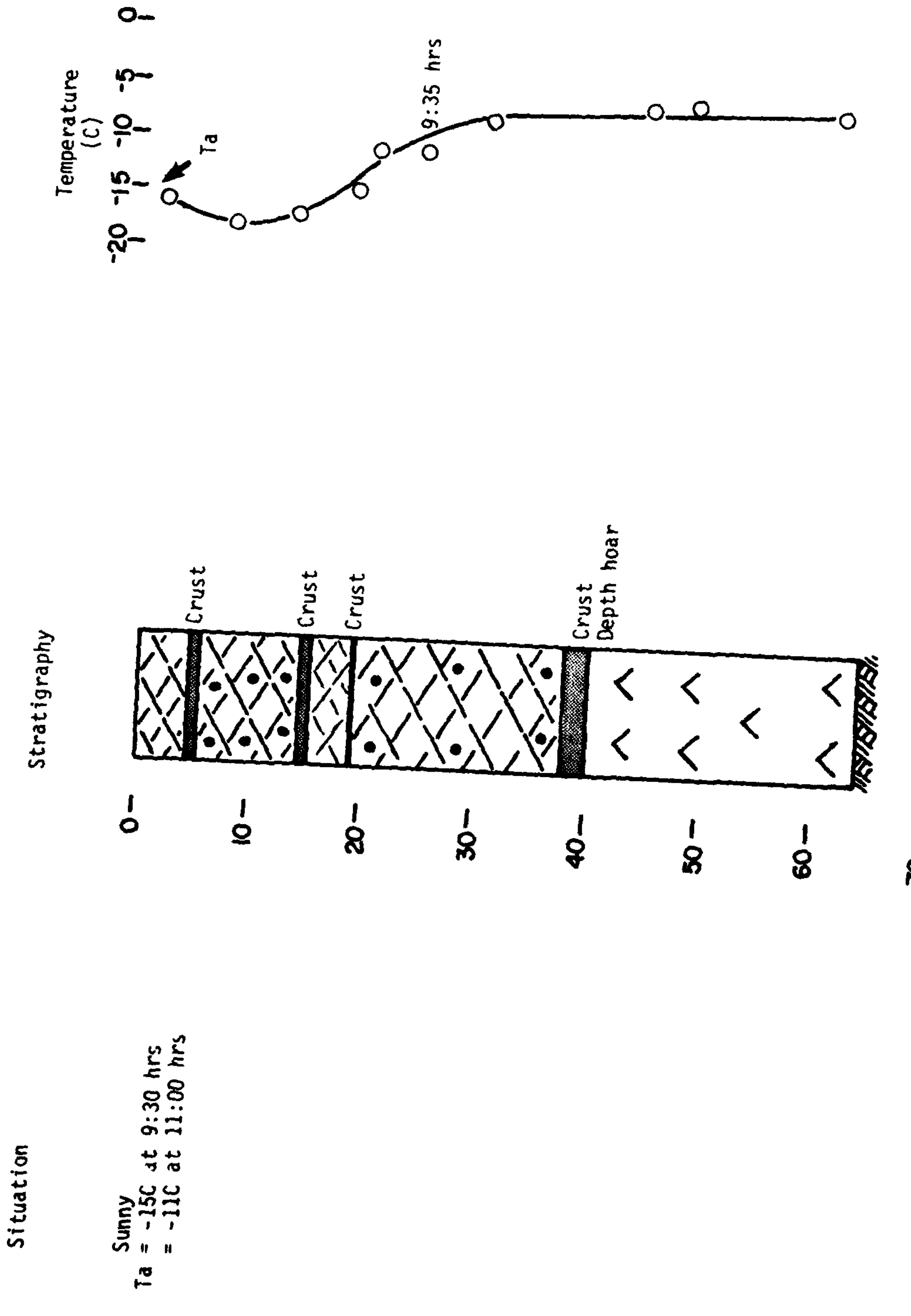


Figure 15: Snow Pit Data Site 1, February 17/77

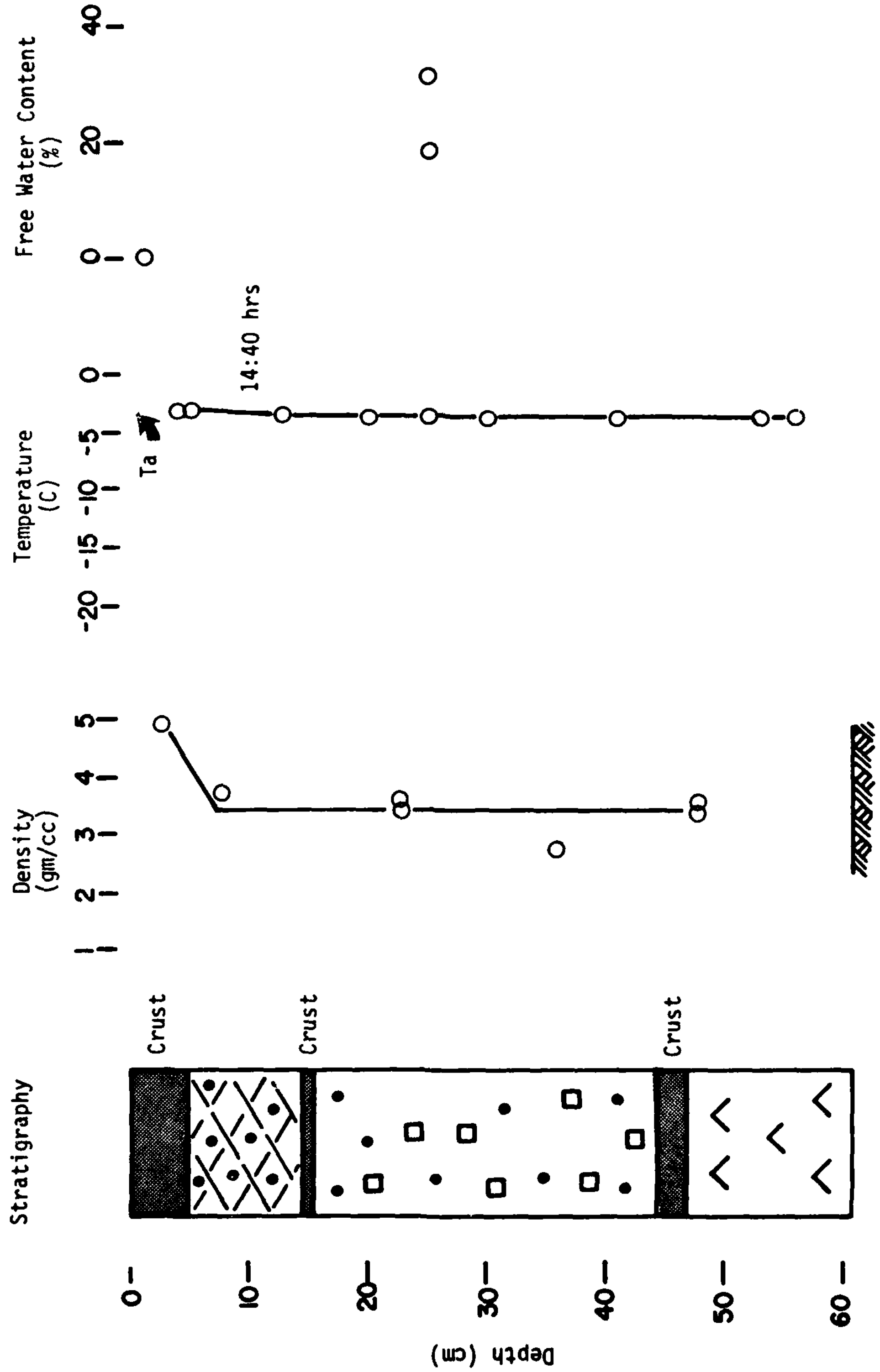


Figure 16: Snow Pit Data Site 1, February 28/77

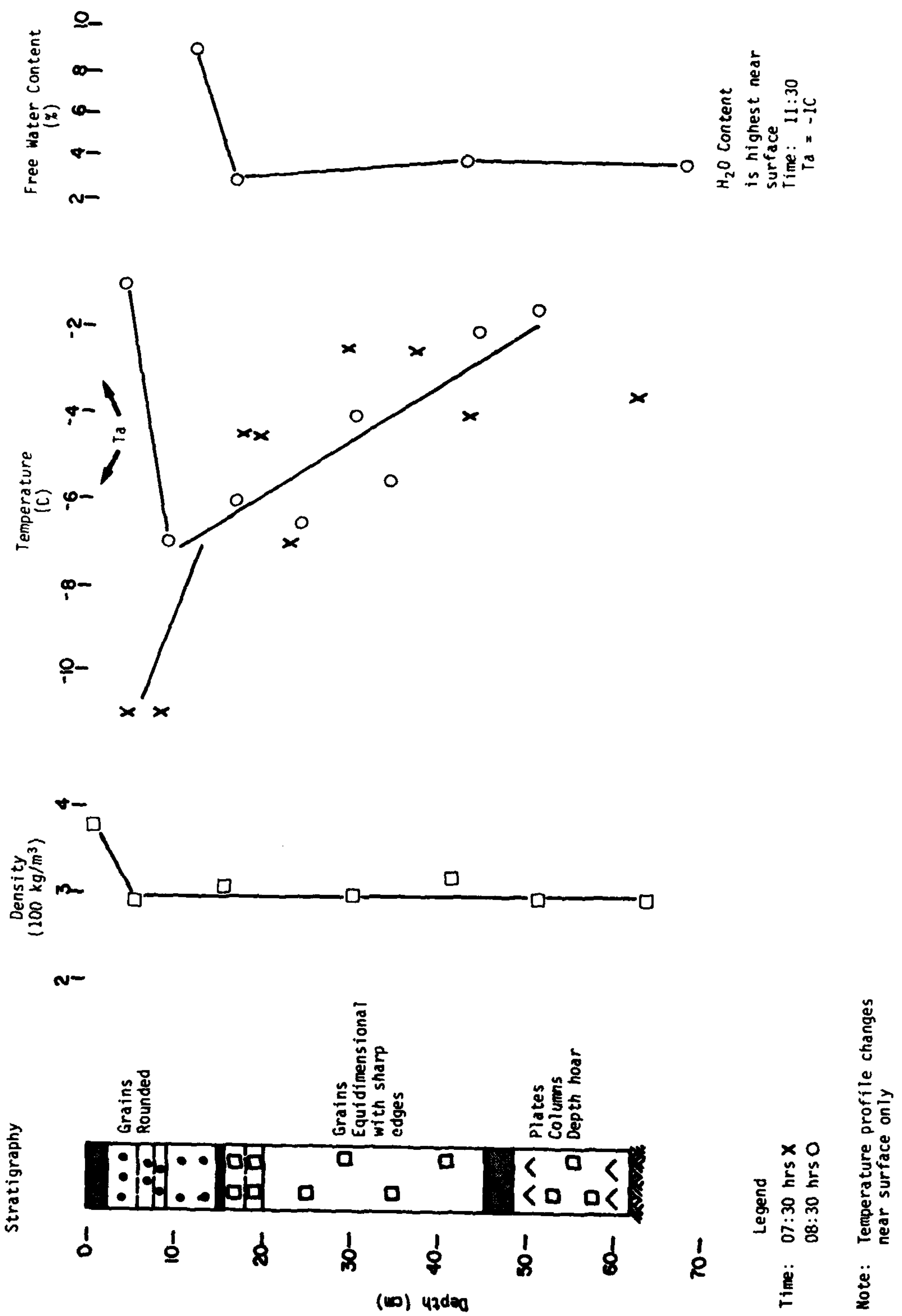


Figure 17: Snow Pit Data Site 1, March 3/77

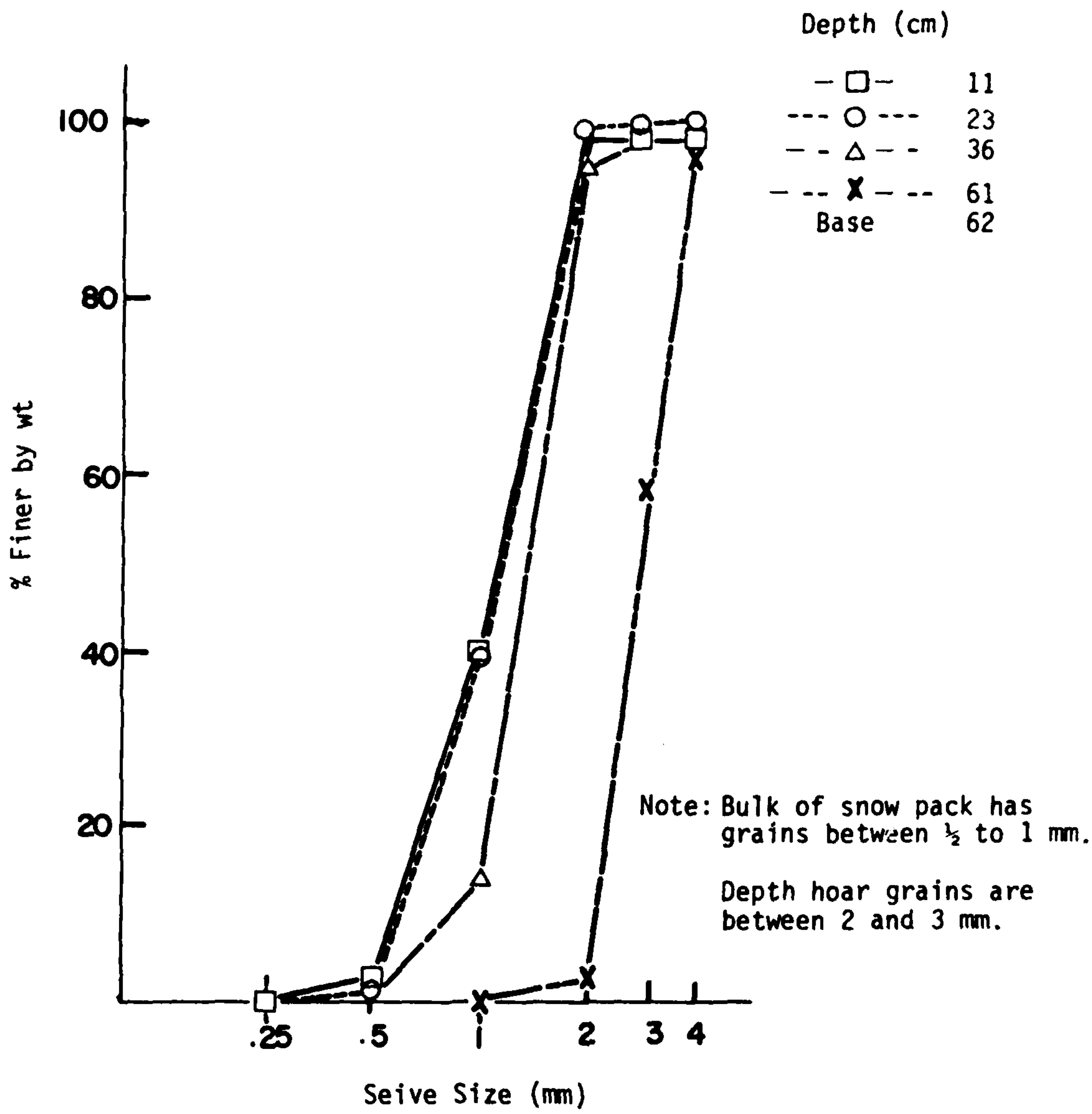


Figure 18: Seive Analysis Site 1, March 3/77 08:00 hrs

After passage of the vehicle, vane-cone measurements, plate penetrometer measurements, and density were taken both in the track and in initial state snow. Vane-cone measurements were very difficult to obtain and in initial state snow the instrument would sink through the lower most crust while in compressed snow penetration was difficult to control. No useful results were obtained in shear. Results obtained with the plate penetrometer are given in Figure 19.

A prediction of drawbar pull on the basis of data obtained from the plate penetrometer was attempted and will be described below. More meaningful perhaps was a comparison with data of a second vehicle test on March 10. The number of tests that could be carried out was severely limited because of the early disappearance of snow.

On March 4, ice crusts were numerous (Figure 20). Density was high and uniform as was temperature. In early morning water content was not measurable except at the depth hoar level. By mid afternoon crusts within 0.1 m of the surface had disappeared only to reform by early next morning. Snow compression strength though not showing a linear load sinkage relation (Figure 21) with the 9 cm disc, did indicate ever increasing values with the approach of the spring.

By March 10 vehicle tests were resumed in snow with the highest values of snow temperature, density and water content yet recorded during the field season (Figure 22). The surface crust was now thicker and consisted of bonded coarse grains 3 to 4 mm in diameter. The RN 25-35 drawbar pull performance was double that of March 3 but the explanation for this was not clear. The relative contributions to improved drawbar performance by such factors as the shallowness of snow on firm ground and the very high compactability of wet snow would have to be determined by further experiment. A pressure sinkage determination was carried out on the following day under virtually the same conditions (Figure 23). It is noteworthy that there was apparently a general decrease in the strength of the snow pack since March 3. This would suggest that the shallow snow conditions under which the vehicle was operating contributed most to the improved performance. The results of snow analysis are reported in Figures 24 and 25.

March 12 was the final day of testing for the season as large patches of bare ground were appearing. Testing was done outside LETE. It was of interest to determine the possible extremes of free water content and density under very mild weather conditions. It appears in Figure 26 that the high snow density of 400 to 500 kg/m^3 was largely attributable to the very large water content which now approximated 20% with a peak at 55%. The latter value may have been due to a water accumulation at the surface of the lowermost ice crust.

OVERSNOW TESTS OF THE RN 25-35

During two days in spring, vehicle tests were carried out. In support of these tests some snow data were obtained. The results of these

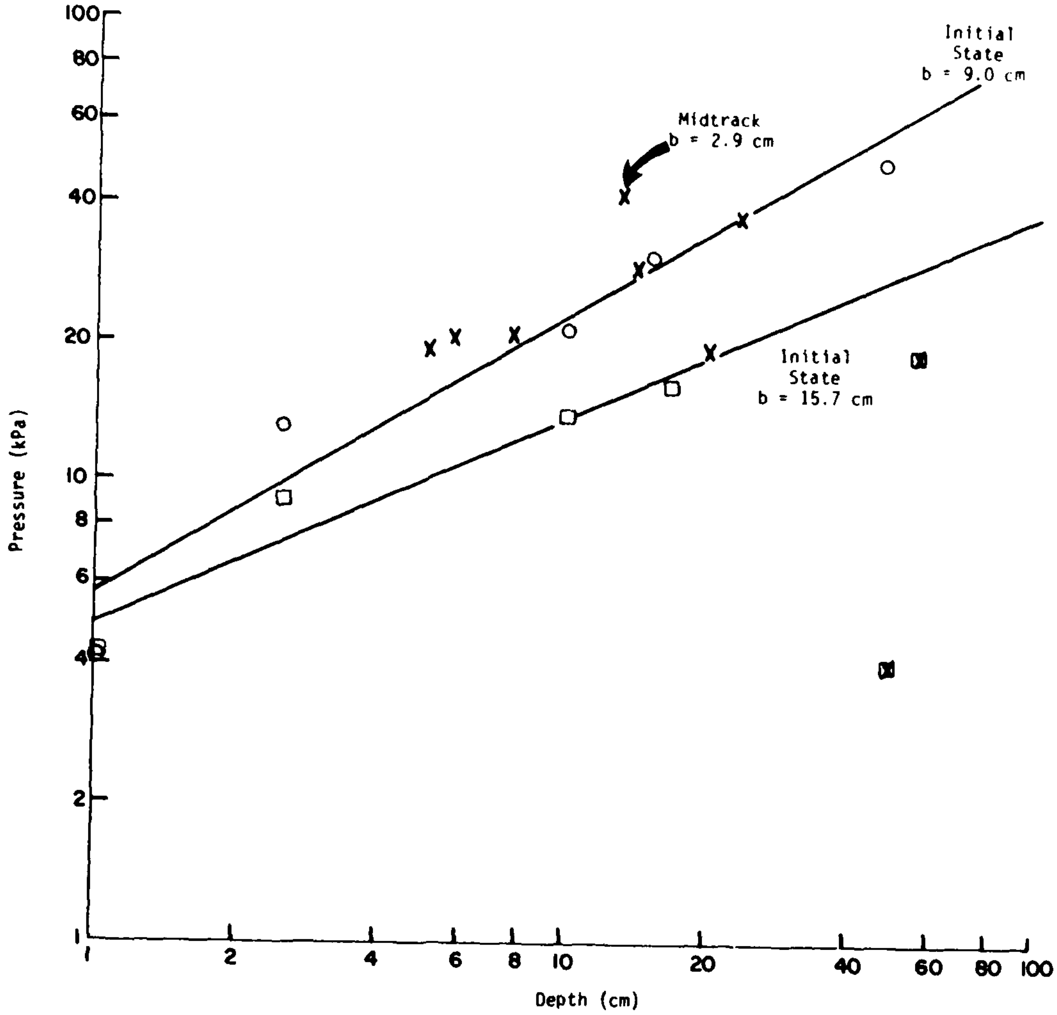


Figure 19: Plate Pressure vs. Depth Site 1, March 3/77

Note: For X multiply vertical scale by 10.

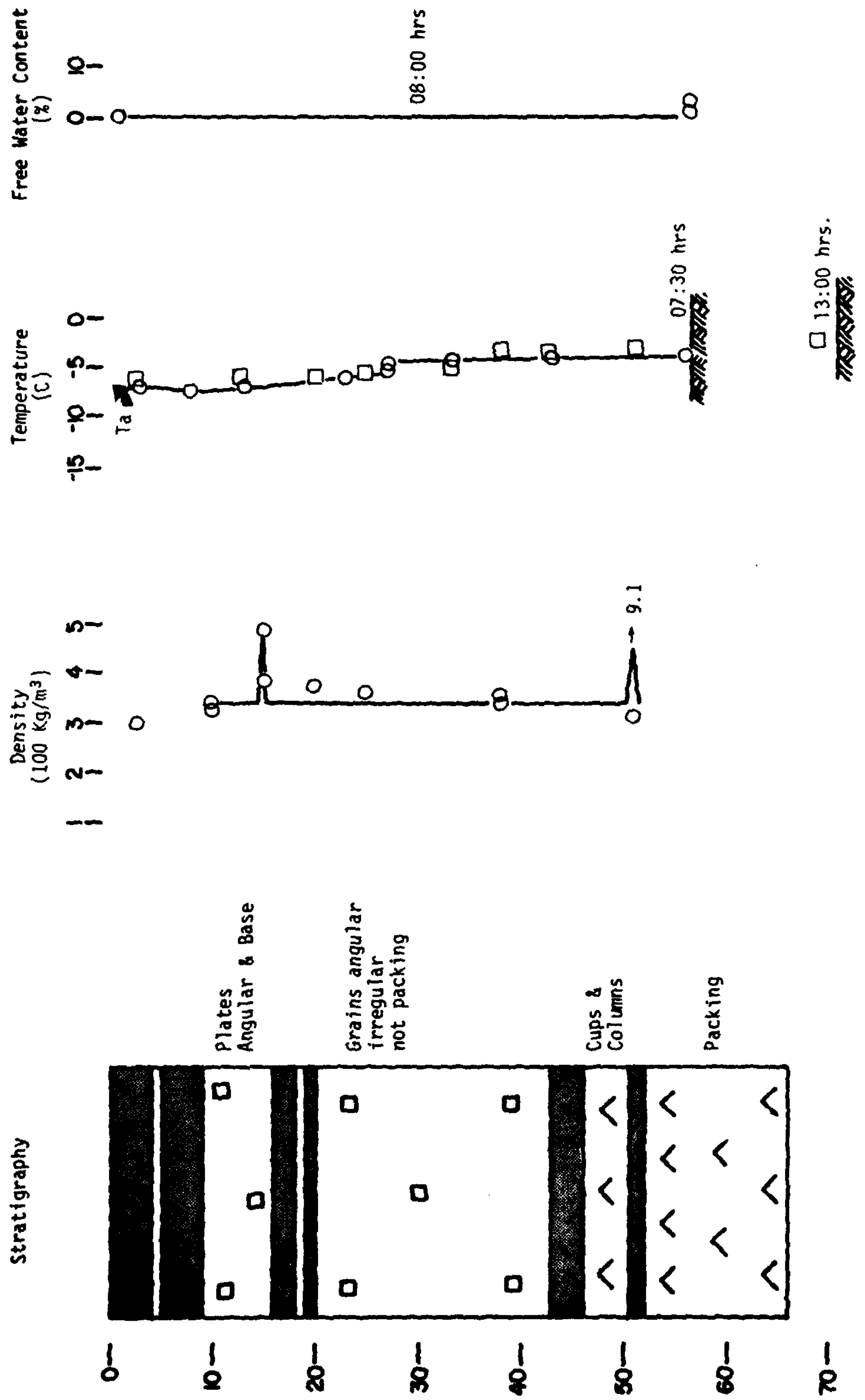


Figure 20: Snow Pit Data Site 2, March 4/77

Note: Winds 25 km/hr and freezing rain

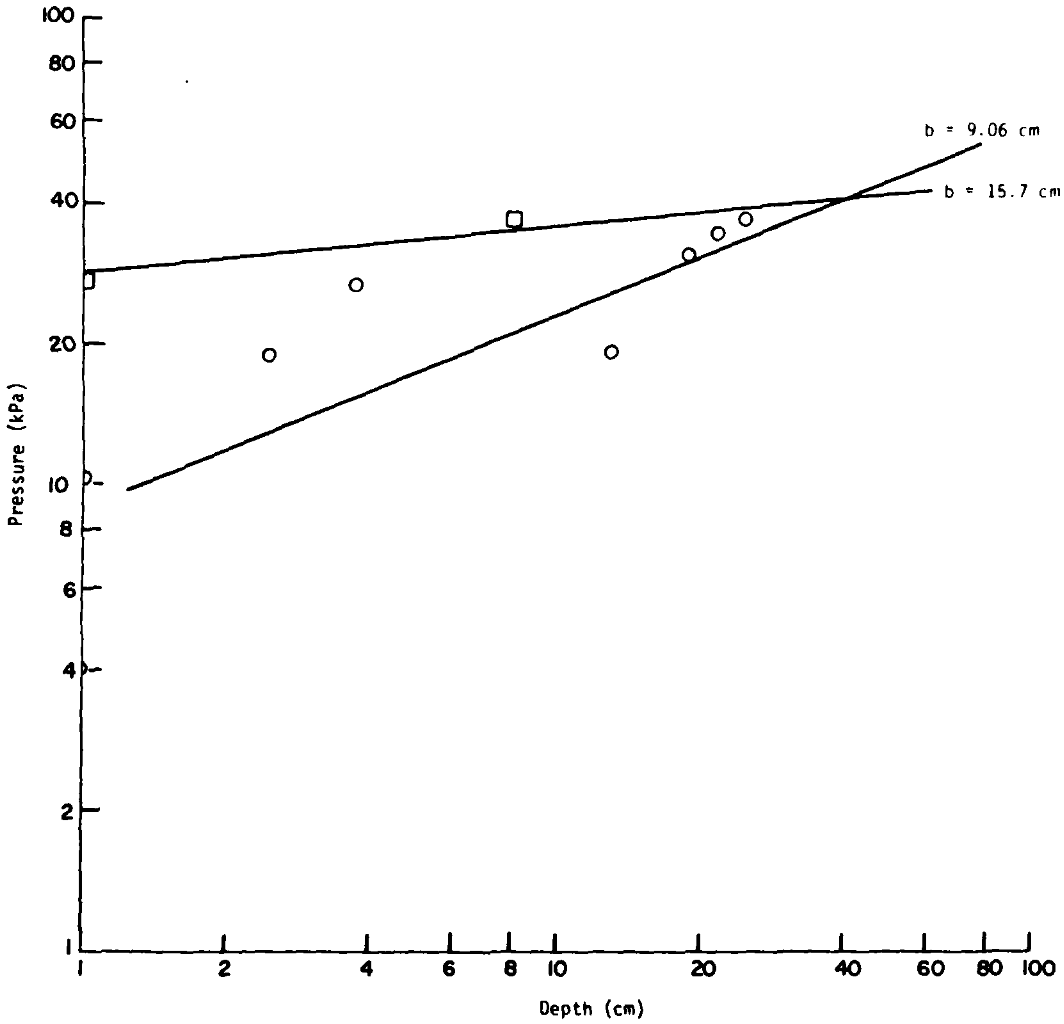
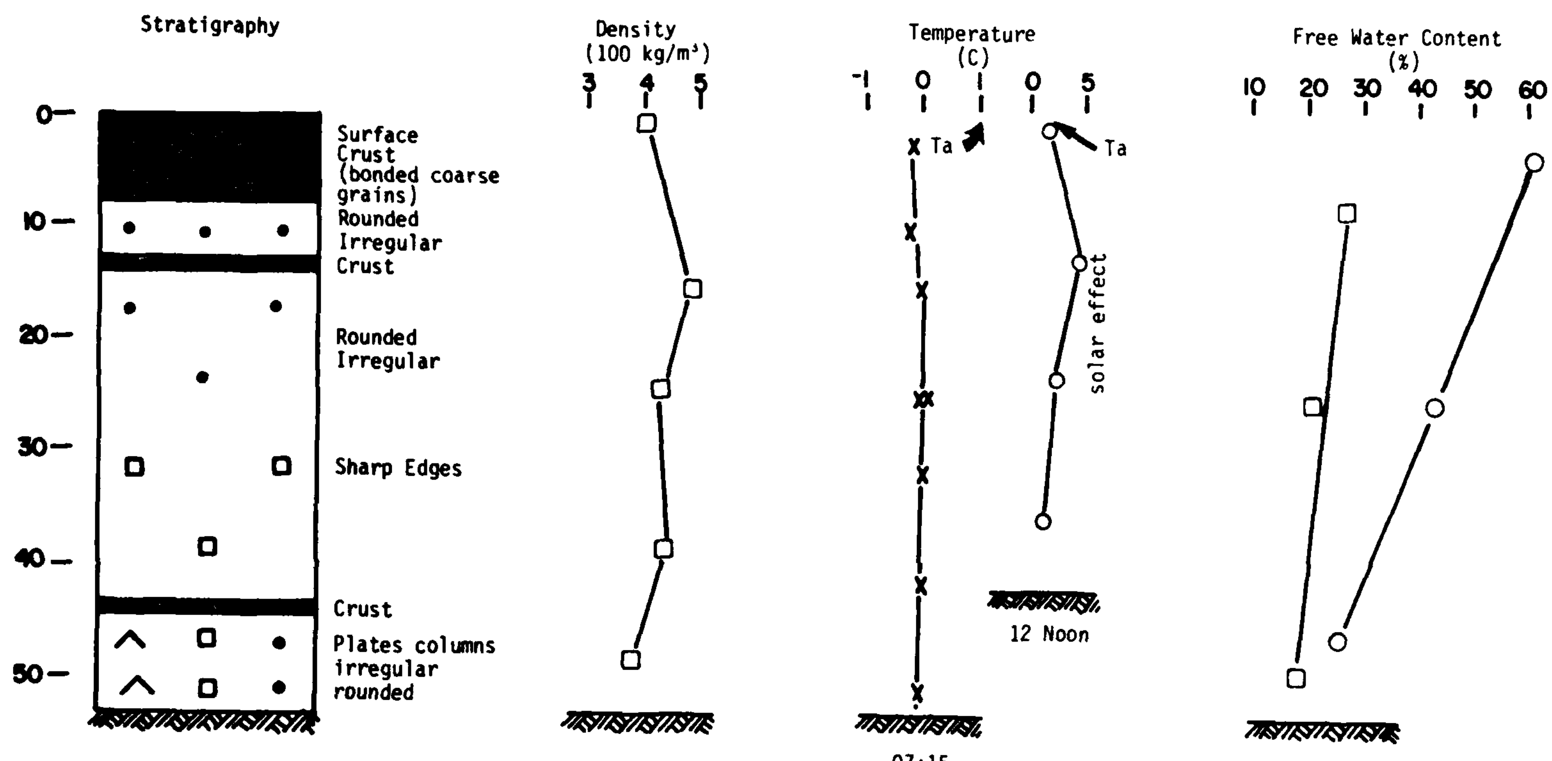


Figure 21: Plate Pressure vs. Depth Site 2, March 4/77



Note: Surface crust turns soft by about 12:00 hrs

Note: Snow is packing
Weather is very sunny and warm
Above OC snow temperatures are a solar effect only. Snow is in fact isothermal near OC.
Density is high due to substantial water content

Figure 22: Snow Pit Data Site 2, March 10/77

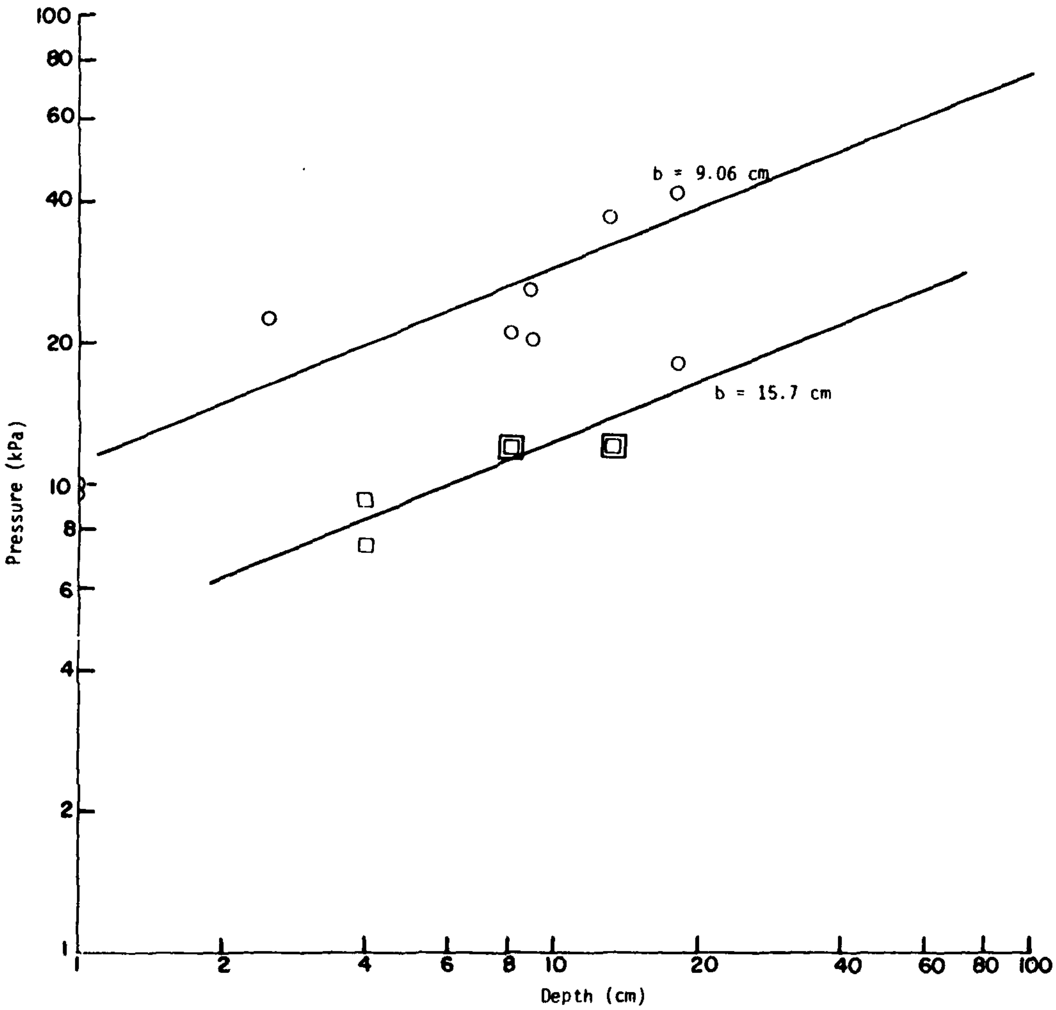


Figure 23: Plate Pressure vs. Depth Site 2, March 11/77

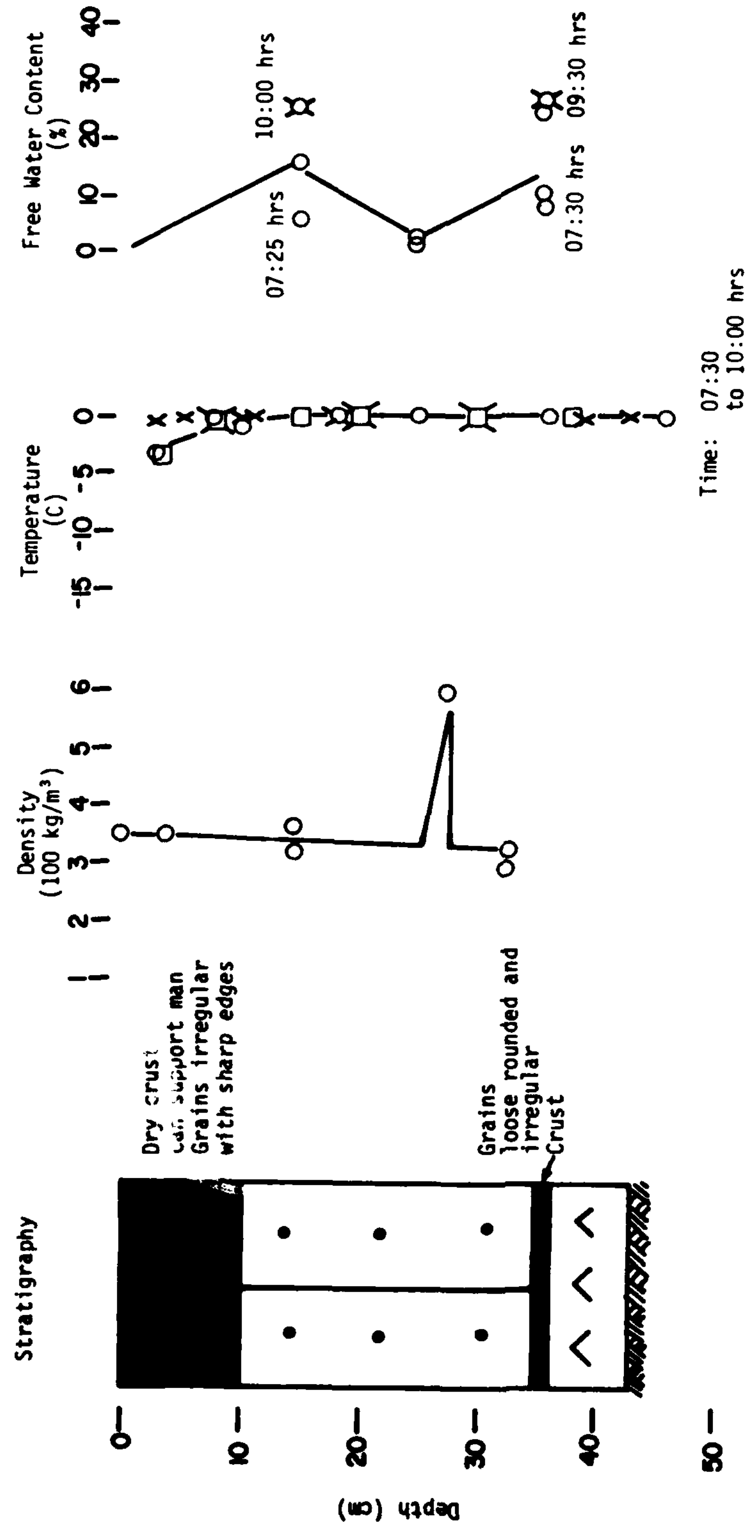


Figure 24: Snow Pit Data Site 2, March 11/77

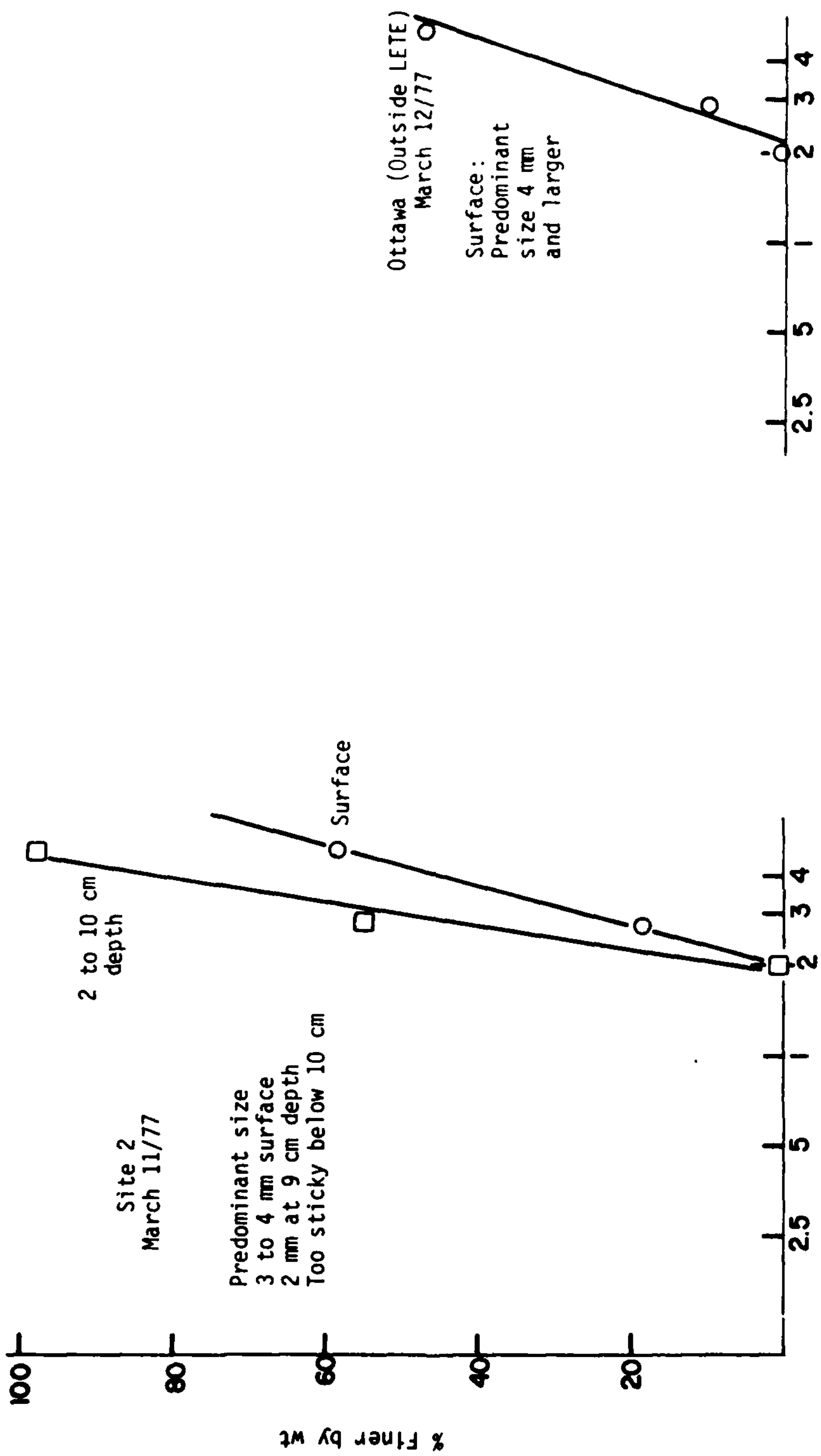


Figure 25: Seive Analysis

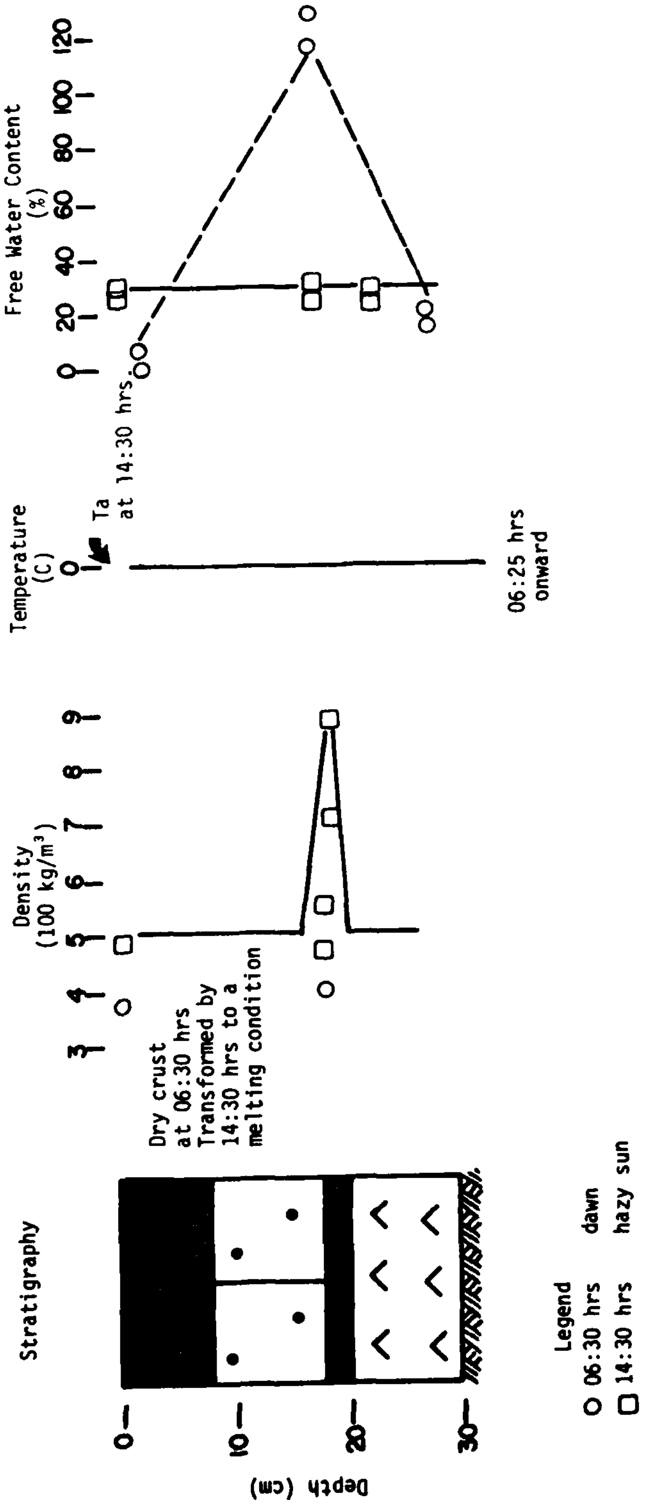


Figure 26: Snow Pit Data Ottawa, March 12/77

tests are given below.

In the late morning of March 3, the RN 25-35 weighing 63 kN was tested in pull to stall near the figure 8 test track at LETE. The initial velocity was 0.9 to 1.8 m/s. Drawbar pull increased from 11% of gross weight at 0% slip to 14% of gross weight at 100% slip. In the early afternoon the vehicle was run over level snow about 0.4 km from this site. Vehicle trim was about 1 degree while the snow was compacted to about half of its original depth, i.e. from 61 cm to 30 cm. The lowermost snow crust at 46 cm depth was broken or cracked during vehicle passage.

With the air temperature at 0°C, snow density was meassured in the trace of the right track:

TABLE I

Snow Compaction by Vehicle

Depth (cm)	Density (kg/m^3)
3	480
20	430
25	410

The density of initial state snow was 300 kg/m^3. Thus a measurable degree of snow compaction occurred almost to the base of the snow pack.

A further measure of snow deformation was obtained with a vane-cone penetrometer designed by Yong and Youssef (11). Cone index values were obtained both in the track trace and in initial state snow. Values are given in Table II.

TABLE II

Cone Index Values (C.I.) in Track Trace

Depth (cm)	C.I. (psi)
2	24 (mid track)
7.6	28 (mid track)
18	31,38 (mid track)
20	38 (mid track)
10	43 (edge of track)
33 to base	43 (edge of track)

C.I. of Initial State Snow

0 to 43	less than 4
0 to 51	less than 4
52	29 (effect of ice crust)

A shear penetrometer designed at DREO was used to measure torque resistance of snow. The head used was the vane-cone. In initial state snow no resistance could be detected. In snow compacted by passage of the RN 25-35 the torque resistance was greater than the elastic tolerance of the spring of the shear penetrometer.

A further measure of snow strength was obtained with a plate penetrometer. This was used only in initial state snow. With plates of 9.06 cm and 15.7 cm diameter a high linearity was obtained in logarithmic plots of pressure vs. depth. The Bekker parameters obtained were:

$$n = 0.52$$

$$k_c = 0.186 \text{ kg/cm}^{n+1}$$

$$k_o = 0.0382 \text{ kg/cm}^{n+2}$$

A plate of 2.9 cm diameter was found to be too small for this experiment. This was because the shear component of total resistance to vertical compaction was too high. Linearity of the data in this case was very poor.

On the following day under essentially the same snow conditions near the figure eight track, a shear test was carried out using a platform and grousers, i.e. a rectangular shear plate of the type described by Bekker (9). The snow moduli were sensitive to depth of testing but linearity of the data when plotted in a Mohr-Coulomb relationship was good. The results are given in Table III.

TABLE III

Friction and Cohesion

Depth (cm)	Angle of Friction ($\emptyset^1$)	Coefficient of Cohesion (kPa)
18	8°	1.3
25	26°	0.99

A test at the snow surface was not carried out because of the presence of a crust. This crust would have rendered the intended measurements meaningless. Thus it was removed for purposes of measurement at greater depth.

On March 10 a pull to stall experiment near the figure eight track was carried out using an M113 command post as the anchor vehicle and the RN 25-35 as the test vehicle. Initial velocity was as before. For the initial condition of zero slip, the drawbar pull measured as 23% of gross weight. At 100% slip the pull had increased to 29% of gross weight. With a track pressure of 13.8 kP_a sinkage was 13 to 18 cm leaving 23 cm of compacted snow from an initial depth of 38 cm.

Snow compaction by the vehicle was measurable. Density increased from an initial value of 530 kg/m^3 to a final value of 690 kg/m^3 at the left track and 640 kg/m^3 at the right.

The following day plate penetrometer tests were carried out under conditions that were considered to be very similar to those of March 10. Using plates of 9.06 cm and 15.7 cm diameter good linearity was obtained in logarithmic plots of pressure vs penetration in initial state snow. The following parametric values were obtained:

$$n = 0.41$$

$$k_c = 1.49 \text{ kg/cm}^{n+1}$$

$$k_\phi = -0.0468 \text{ kg/cm}^{n+2}$$

Grousers platform tests on the same type of snow yielded:

$$\text{Angle of friction } (\phi) = 21°$$

$$\text{Coefficient of cohension} = 1.18 \text{ kP}_a$$

In the latter tests a clear trend and linearity of Mohr-Coulomb data was difficult to obtain. The inherent compressibility of snow probably reduces the linearity. Goodness of fit in this case was only 0.55.

With such limited snow data, calculations of drawbar pull are of limited usefulness. In addition results are very sensitive to exponential terms in formulae for motion resistance, i.e. the accuracy of the exponent n and the pressure distribution on each track affect drawbar pull calculations profoundly. A sample calculation was nevertheless carried out. The following formula from Bekker (9) was applied:

$$DP = H - R_c - R_b$$

where DP = drawbar pull

H = gross tractive effort

R_c = motion resistance due to compaction

R_b = motion resistance due to ploughing

In addition to the above snow parameters and vehicle weight the following numerical values were used:

Horizontal deformation modulus (K) = 3.4 cm (assumed (9))

Track width (b) = 85 cm

Track contact length (ℓ) = 264 cm

Slip (i) = 1 (corresponding to 100% slip rate).

Pressure distribution on each track was assumed to be uniform. Those c and ϕ values that were nearest the snow surface were employed. Tabulation of drawbar pull for purposes of comparison are given in Table IV.

TABLE IV

Drawbar Pull

Date	Measured (kN)	Calculated (kN)
March 3, 4	8.7	3.2
March 10, 11	17.9	5.2

In the present case calculations are conservative by a factor of about 3 although the trend is comparable. The result is largely fortuitous. Sources of experimental error are numerous and cannot be fully ascertained. Some confidence can be placed in the order of magnitude of the calculated values however. Contributing errors would be related to the following:

1. All tests were not carried out concurrently.

2. There is an important human influence on penetrometer results. The technique of force application is not consistent.

3. Snow crust layers influence penetrometer results by introducing scatter to the data.

4. The pressure distribution is not known at the track/snow interface.

5. The appropriate c and ϕ values are not known as these vary with snow depth. The Rankine-Terzaghi passive earth pressure theory may not be directly applicable to snow.

The expression for R_c (9) contains exponential factors which are sensitive to the value n and the pressure distribution of the track. Explicitly stated, the expression for R_c is given as:

$$R_c = \frac{1}{(n+1)(k_c+bk_\phi)^{1/n}} \left[\frac{W}{\ell}\right]^{\frac{n+1}{n}}$$

Where n, k_c, k_ϕ and ℓ have been defined and W is weight on one track.

Future work must at least take careful account of such factors.

DISCUSSION

This study constitutes another stage preparatory to snow classification and vehicle performance prediction in the Canadian North. Evidently Ottawa snow is in a state of measurable change continually throughout the winter. These changes are very sensitive to alterations in weather conditions, particularly air temperature, and are initially felt to depths of 10 to 20 cm. A relatively stable period is in cold, calm weather particularly at night as would be expected. The night time period might be ideal for comparative vehicle testing. During the 1976 to 77 season snow conditions deteriorated perhaps more rapidly than usual with the approach of spring. Snow conditions though widely changeable between night and day appear to be essentially repeatable at a given hour of each day providing weather conditions are diurnally consistent.

The snow history for the winter season is broadly summarized as follows: By mid December snow had accumulated to a depth of 20 cm. Settling and some compaction at depth had taken place while dendrites were altering to ever thickening platelets. Over the ensuing 3 days as settling advanced, surface dendrites changed to platelets while at depth grains were more equidimensional in losing their platelet character. Grains both at the surface and base appeared to undergo a constructive metamorphism while those in mid pack appeared to be reducing in size. Temperature, water content, and density profiles were fairly uniform except near the surface. This period was followed by a heavy sleet storm which was responsible for the formation of an ice layer neighbouring the base of the pack throughout the balance of the winter. With ever decreasing air temperatures by the end of December the snow pack profile of temperature was now altered down to a depth of 0.1 m. The above ice layer portion was dry platelets and that below was now dry depth hoar composed of irregular grains of increased size. During the month of January the snow pack depth doubled reaching about 0.6 m. The density below 0.2 m from the top surface and above the depth hoar layer was around 300 kg/m^3 with the progressive compaction and bonding of platelets. The dominant grain size was 1/2 mm with diameters varying from 0.3 mm at the surface to 1.5 mm at the base. The depth hoar showed by February 2 a progression toward columnar and cup shaped grains. The density was high though the texture was loose. From February to March the compressive strength of the snow pack, as measured with a plate penetrometer indicated a general increase in the upper 0.3 m of snow. This was probably due to increasingly moist snow conditions with the approach of spring. However changes in strength are difficult to explain in detail, particularly when there is no control on rate of penetration. Other influences may be the nature of the solid, liquid and vapour combinations at intergranular boundaries. Thus snow that does not pack easily may be subject to intergranular sliding due to the presence of a water film and therefore appear weaker than colder snow. When the water film is large enough and packing through regelation occurs, then snow with increasing temperature close to melting may appear stronger. The state of compaction due to settling and grain shape may also play a role. Although differences in the state of the snow pack between February 1 and 12 are apparent, studies that would include all of the above factors were not sufficiently detailed to account for the strength discrepancy between Figures 7 and 12. Over the first half of February water content and density increased while snow profile temperature fluctuated in the upper layers with changing air temperatures. Depth hoar became well developed, while the intermediate portion became granular and the top 12 cm showed packing tendencies. It is the snow of February 2 that appears anomalous in strength. The snow continued to be packing during subsequent days with the result that on February 17 snow resistance had increased. New ice crusts were now also appearing. It is considered that the dense highly settled snow contributed more to the snow pack compressive strength than did the snow crusts. The crusts produced anomalies in the pressure depth relation but the trend of graphs in Figure 14 is probably unaltered by their presence. The crust at 0.4 m depth did limit total penetration of the penetrometer however to about that depth. As usual, temperature profiles were observed to fluctuate with air temperature to mid depth of the snow pack. By the end of February snow was almost isothermal just below freezing and overall density was over 300 kg/m^3. Throughout the first half of March the snow pack became shallow, progressively more moist in day time and more coarse grained at night, stronger through compaction and more dense. Ice crusts were numerous at night and early morning, but not present during vehicle and penetrometer tests in mid day except for that crust just above the depth hoar. Grain shape by mid March was altering from irregular to that of rounded. This would represent the final stage before melting.

The vehicle tests at LETE indicated that drawbar pull was approximately doubled over seven days. Two terrain factors probably contribute to this result:

1. The shallowness of snow, and

2. The degree of snow compaction as manifested by the increased density of snow after vehicular passage.

As results would indicate, snow depth was the major factor in the present case.

With the plate penetrometer and a knowledge of simple vehicle parameters such as gross weight and track dimensions, a very conservative estimate of vehicle drawbar pull at 100% slip was possible. There were, however, several serious problems in the handling of a man operated penetrometer. Among these are the following:

1. Lack of uniform motion in penetration or shear.

2. Lack of control of penetration or shear rate.

3. The available range of vertically and horizontally applied stress does not match the range of snow strength.

4. To date, penetrometers have not been designed to measure and record continuously with time such variables as applied pressure, displacement, and rate of deformation.

5. The degree of human influence on recording and interpretation.

The vane-cone penetrometer also displayed shortcommings in the lack of stability of the system during penetration. Too often the cone head would sink through soft snow under the weight of the penetrometer and thus not show a force reading. In addition upon breaking through a crust layer the operator could not control its descent to the snow base. Readings were equally difficult in shear. In order to achieve stability of the vane-cone during usage, a wide angle cone may be preferable. Alternatively if a 30 degree cone continues to be employed, then the snow might first be conditioned by a plate penetrometer to enable cone usage under known snow strength conditions.

An automatically operated penetrometer such as the bevameter (9) might aid in overcoming some of these problems. Consequently human and environmental influences should be distinguishable.

The rectangular shear plate was useful for obtaining additional snow factors: cohesion (c) and friction (ϕ). The values obtained for damp snow were $c \simeq 1$ kPa and $\phi = 8°$ to $26°$. The device used was rather cumbersome. Preferable would be the shear device of a conventional bevameter or a suitable hand held shear penetrometer.

Snow conditions have only been described in a cursory fashion. However several influential parameters which must have a bearing on snow classification are:

1. Snow depth and stress bulb size.
2. Strength-depth profile.
3. Crusts (number, thickness, strength, density).
4. General background description of the snow pack such as temperature, density, water content, grain size, grain shape, compactability, albedo and perhaps other optical factors which would affect interpretation by remote sensing.

Numbers 3 and 4 would be particularly useful for purposes of vehicle comparison testing, laboratory simulation, vehicle performance prediction, and explaining discrepancies in vehicle performance or strength profile results. It is of interest that in the present study density was monotonic in its development. Grain size development progressed in one direction with one inversion i.e. near the beginning of winter when the surface grains became finer than the grains at the base of the pack. Temperatures fluctuated down to mid pack depth with changes in air temperature. Free water content when measurable by centrifuge was sensitive to temperature changes above -5°C and varied greatly with time and depth. Crusts progressed in number and strength with time till they became very sensitive to nocturnal and daylight temperatures. The snow strength profile progressed toward increasing strength levels throughout the winter. This paralleled the increase in snow density and the proliferation of crustal layers of increasing strength.

Apart from changes in the weather and the almost immediate response of the upper half of the snow pack, the most influential snow parameters on mobility are probably:

1. depth.
2. strength.

The strength in turn is determined by:

1. density and resistance to compaction.
2. nature of intergranular bonding.
3. crustal layers.

Recommended comparative testing conditions for CF vehicles are enumerated as follows:

1. The location should be on a well defined terrain type of sufficient area for testing purposes.

2. The weather should be relatively stable for the time interval of testing with diurnally low amplitude variation and 24 hour periodicity. Such conditions would allow tests to be conducted at a certain time of day or night for a period of several days. Morning snow conditions may be very different from afternoon conditions. Such a complication should be avoided.

3. The snow conditions should be classified using snow pit and penetrometer techniques concurrently with vehicle tests.

CONCLUSIONS

Changing snow conditions throughout a winter season have been monitored. Some of the observations provide supporting material for snow classification for mobility in the Ottawa region. The following conclusions are interim and should be followed eventually by a generally agreed upon classification procedure:

1. Some initial experience has been gained with vehicle testing in snow.

2. Differences between shallow and deep snow conditions are evident in measured snow strength profiles and drawbar pull results.

3. The plate penetrometer applied vertically may serve as a useful indicator of the strength of the snow pack for purposes of characterizing its bulk properties.

4. Problems in the handling of the vane-cone and plate penetrometers have been enumerated. As a result, automation to some degree is recommended.

5. Highly conservative predictions of drawbar pull at 100% slip are possible with the plate penetrometer.

6. The progress and rapidity of changes in snow has been charted.

7. The range and example values of some snow variables have been determined. These include friction, cohesion temperature, water content, density and grain size.

8. Snow classification should include the following items:

a) depth and stress bulb size relative to the total depth or relative to the first major crust in the proximity of the top surface.

b) crusts i.e. number, thickness, and strength or density.

c) strength-depth profile with correlation to vehicle performance.

d) other snow properties as supporting information on environmental conditions. These should include temperature, density, water content, and grain size.

Such classification items are important for snow experiments that require repeatability of results, for vehicle performance comparisons and for laboratory simulation.

9. Initial recommendations have been made for the best environmental conditions for the purpose of comparing the performance of vehicles.

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APPENDIX A

DREO PENETROMETER

The manual application of bearing and shear loads to a snow medium is of interest as a convenient means of determining snow strength. Loads that are applied in this way cause deformations that define parameters which may be used to predict the reaction of snow to the loads of a moving vehicle. A device for this purpose was a vane-cone penetrometer designed at McGill University. This is a portable load transmitting instrument which employs a proving ring and dial indicator to measure applied bearing load while using a torsion spring and a graduated dial or ring to measure angular rotation. Experience gained from field testing indicated where some improvements might be made.

Snow strength varies widely from that which is heavily compacted by passing vehicles or high speed winds to that which is in an uncompacted newly deposited state. A single torsion spring cannot be expected to cover the required range of shear strength. Hence a design of penetrometer was conceived at DREO to allow for the possible spread of shear strengths. The DREO penetrometer utilized two torsion springs for measuring torque. These springs are in the working range of a) 0 to 20 lbs - in. and b) 0 to 120 lbs - in..

In combination with the two torsion springs are two proving rings which are used to measure bearing strength thereby allowing for coverage of a wider range of snow conditions. The proving rings have ranges of a) 0 to 50 lbs and b) 0 to 250 lbs.

Thus the DREO penetrometer is, as a result, a modular device. The stronger torsion spring and proving ring have been fitted together to work as one unit. This unit is attached to extension rods and sensing heads to complete a rather sturdy design of penetrometer. The spring-proving ring unit may be exchanged for a weaker spring-proving ring combination for greater sensitivity. Calibration curves for both torsion springs and proving rings are given on graphs A1 to A4.

Drawing D-100 (Figure A5) illustrates the DREO penetrometer. This consists of three major components: a) proving ring, b) shear component, c) vane-cone head. Shown in drawing D101 (Figure A6) are further details to which the following description applies. The bearing load is transmitted by the user through the handles to the top mounting block of the proving ring. A bearing is provided on this portion to prevent torque loads in the proving ring and vane-cone head during vertical penetration. A dial indicator logs the vertical deformation of the proving ring. The indicator is from soil test, model LC-2, with 10 turns and 0.0001 inches per division. Load values may be read from a calibration curve for the proving ring.

The shear unit consists of five major components: a) the upper section, b) spring, c) bearings, d) ring, and e) lower section. Both the upper and lower sections contain one of the spring ends. The lower section is connected to the shaft which is suspended by bearings. The lower section will rotate about the upper section, resisted only by the spring tension. The applied torque is provided manually through the lower set of handles. With vane-cone placed in the snow the spring will twist, carrying the ring along the threads on the lower cage until the applied torque exceeds the shear resistance of the snow. When this point is reached, the vane-cone shears the snow allowing the spring tension to move the lower section until it reaches rest. As the lower section moves to rest it carries the ring on its threads. The ring remains in this position until reset to zero and the angular rotation is read directly from the ring. Graduations on the ring provide a quantitative value of rotation. The resulting torque is interpreted from the calibration curve for the spring.

A variety of testing head designs may be used with this penetrometer. Among these are a range of plate sizes, vane-plates, vane-cones and a plate fitted with simulated grousers. These are illustrated in drawing D-102 (Figure A7).

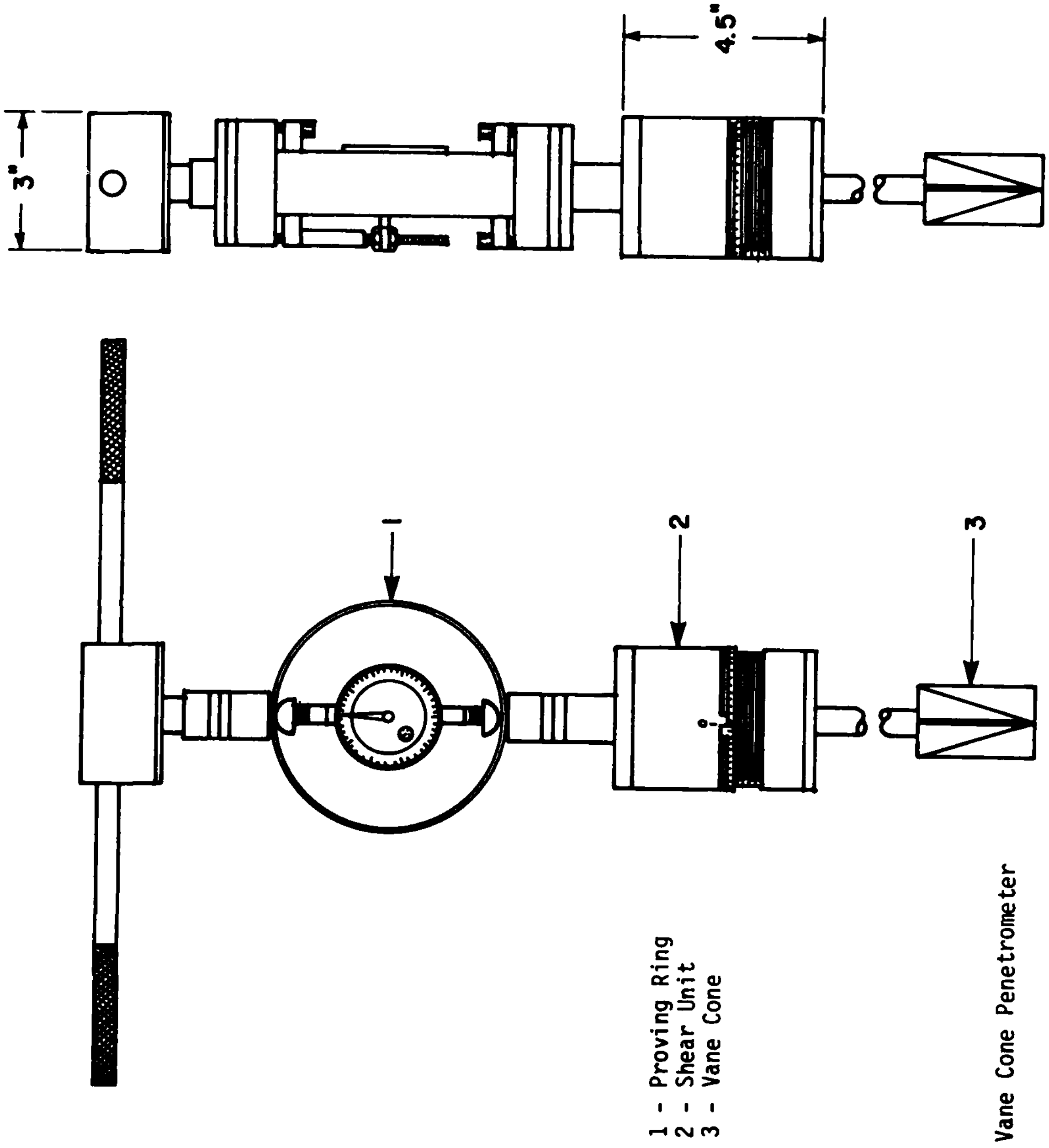
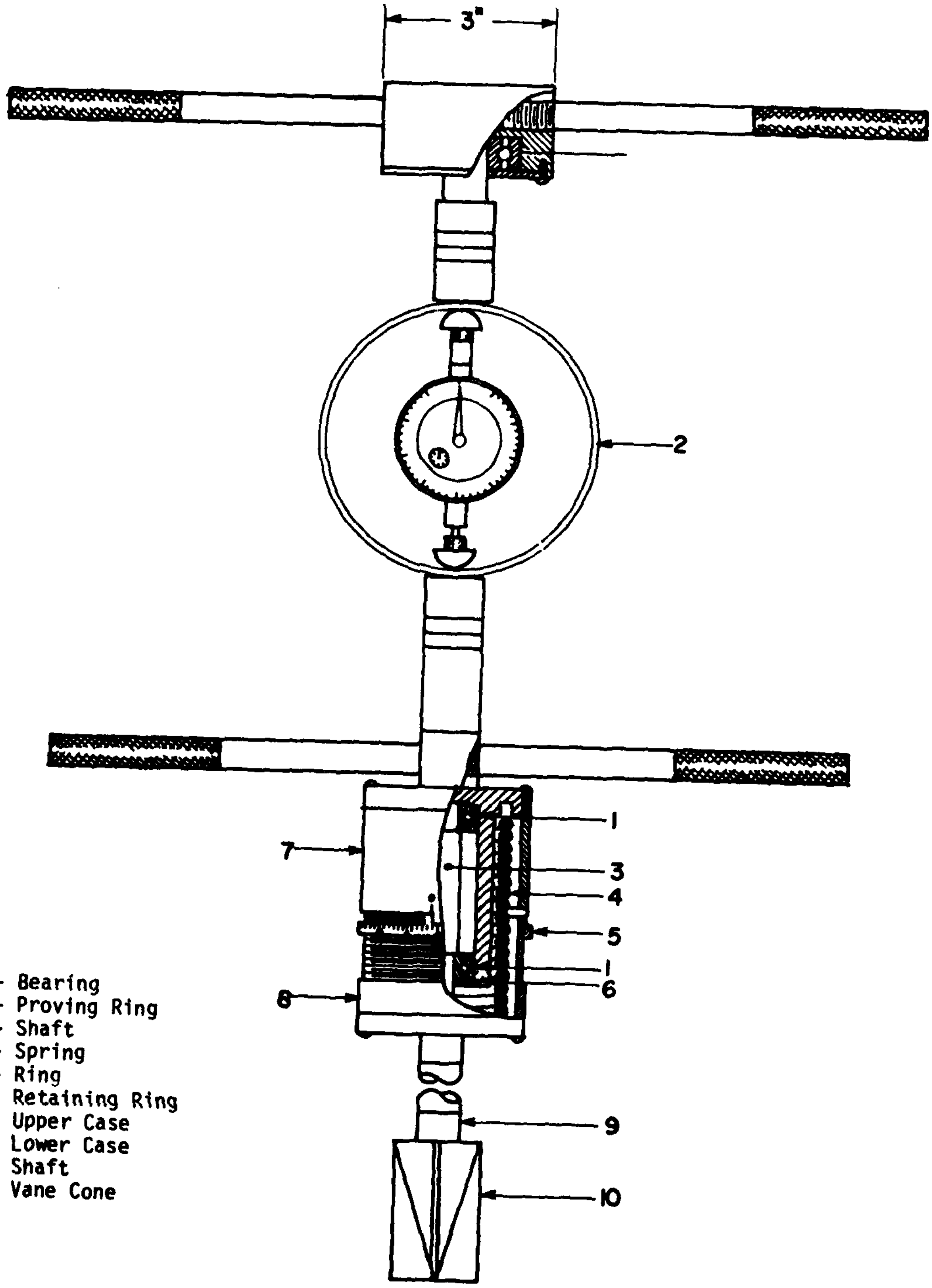


Figure A1: Vane Cone Penetrometer



1 - Bearing
2 - Proving Ring
3 - Shaft
4 - Spring
5 - Ring
6 - Retaining Ring
7 - Upper Case
8 - Lower Case
9 - Shaft
10 - Vane Cone

Figure A2: Vane Cone Penetrometer

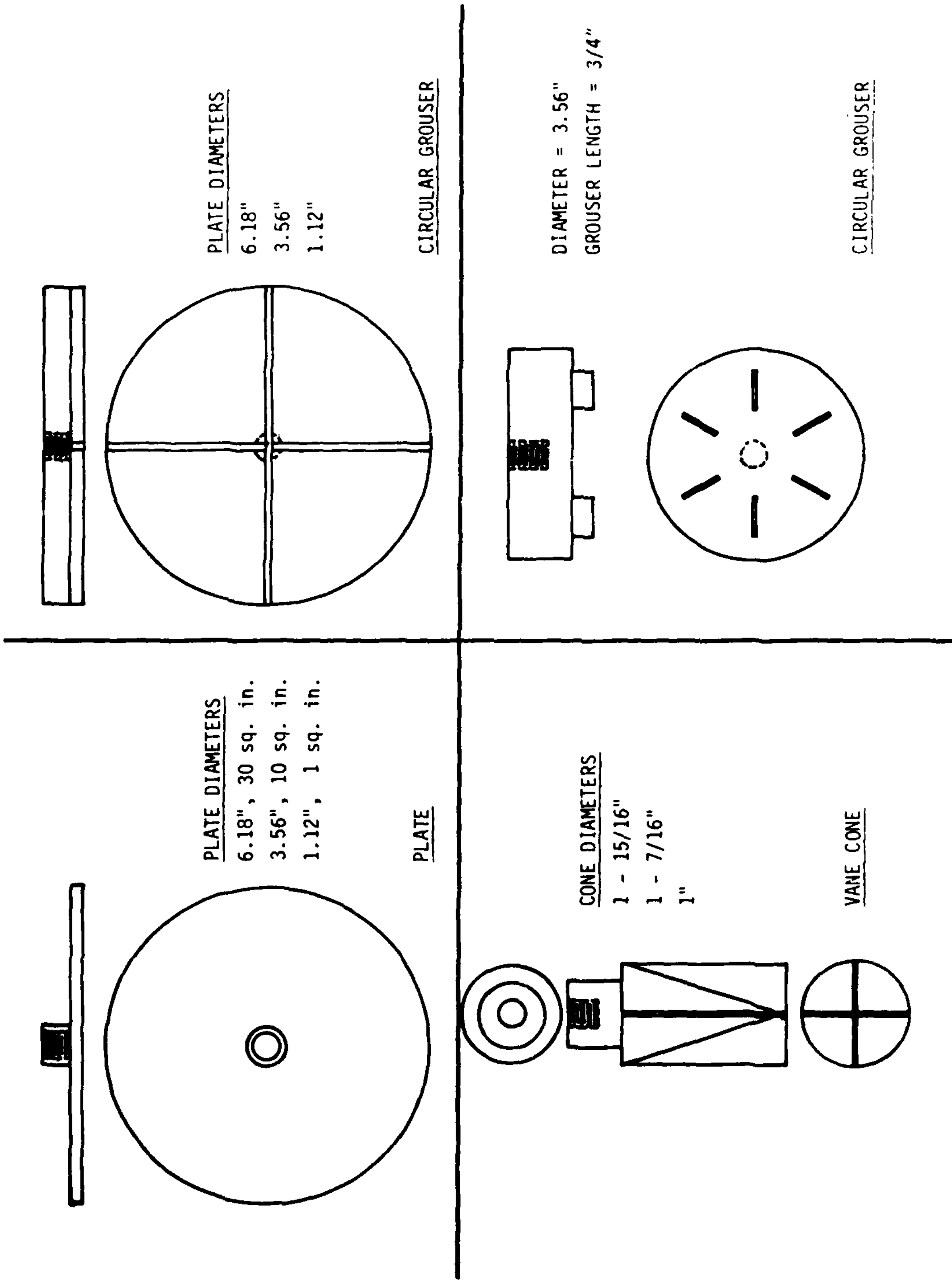


Figure A3: Penetrometer Attachments

APPENDIX B

VEHICLE-SNOW INTERACTION NEAR CAMP WAINWRIGHT, ALBERTA

Between January 15 and 21, 1977 a visit was made to the site of Exercise Rapier Thrust V at Camp Wainwright (a detachment of CFB Calgary). The visit provided an opportunity to observe vehicle-snow interaction for a wide variety of military vehicles which are in current use by the Canadian Forces. It was anticipated that an understanding of practical problems in oversnow mobility during a military operation might be acquired through discussion with users and through observation of vehicle performance in known snow conditions.

In order to carry out this objective I camped with No. 1 Service Battalion which was under the command of Col. Pospisle. This was about 10 miles east of Camp Wainwright barracks. During a round of visits made on the first day it was determined that the battalion located behind the front lines consisted of 3 groups: (1) a group responsible for transportation under Maj. Reinhartis which handled jeeps, 1-1/4 and 2-1/2 and 5 ton trucks. The 5 ton trucks were of the cargo carrier type; (2) maintenance company under Maj. Watkins which handled the M816 - 5 ton Diesel recovery truck and APC 113A1 track laying vehicle and (3) the administration for transportation and maintenance.

With the permission of Log Ops the surrounding terrain was scouted for a suitable test site. The terrain consists of gentle hills, clumps of shrub and dense clusters of small trees. An area called Coyote Hill, 2 miles north of the command post for No. 1 Service Battalion was decided upon. This was a particularly favourable location for the testing of service vehicles as it contained an expanse of open level ground and a broad 23% slope suitable for vehicle manoeuvers. In addition the area was covered by 7 to 10 inches of undisturbed snow. Trees and shrubs were almost non existent and tall grasses were not immediately visible but rather lay flat under the weight of snow.

Over succeeding days the following vehicles were tested in the order listed at the above site.

1. 5 ton cargo truck 6 x 6 M813 A1 w/w, 6 wheels with army treads
2. 1-1/4 (5/4) ton chevrolet cargo van, 4 x 4, with 4 wheels and civilian treads

3. Jeep (1/4 ton), 4 x 4, M15 1A2, 4 wheel base with army treads
4. APC 113A1 track laying vehicle
5. 5 ton recovery vehicle (wrecker) 6 x 6 M816 w/e, 10 wheel base with civilian treads.

RESULTS

The following observations are presented in a diary format: -

January 17, 9:30 am:- The pack was seven inches deep with a one inch snow crust at three inches depth. Below this was very loose depth hoar containing coarse platelets and columnar crystals. The temperature vs depth profile increased from the surface at -11C to -9C at the base. Air temperature was -13.5 C and the sky was overcast. The snow above the 3 inch level contained dendritic needles and was considered soft. The 5 ton cargo truck on traversing level ground in low gear broke through to the depth hoar layer and experienced a significant amount of slip. The trace of tread was intermittent. The snow was highly compressed to 1 to 2 inches thickness, but displayed no fracture structure in cross section. Ploughing in what may be considered shallow snow was non existent. The truck made its way about half way up the 23% grade of a 300 to 400 foot sloped traverse. At the point of immobility the snow pack was 9 inches in depth. The wheels excavated clay at the base of the depth hoar. A second and third attempt on the same track produced even shorter traverses up the grade.

3:20 pm:- The air temperature was now -9½C. The pack cross section showed two thin crusts, at 2 inches and 5 inches. The surface was close to air temperature and the base was about -5C. Depth hoar occupied the layer below the second crust. The 1-1/4 ton truck compressed the snow to 1-1/2 inches and to a lesser firmness than the 5 ton truck. On the slope the same result as with the 5 ton truck was obtained i.e. 100% slip on depth hoar at mid traverse.

January 18, 9:15 am:- The weather became very mild and sunny. The air temperature was now -1.5C. The snow pack cross section showed two 1/4 inch crusts at two inches and three inches. In the area sampled the snow depth was only 4-1/2 inches with the depth hoar occupying that below the uppermost crust. The top 2 inches was in a state of change involving broadening of needles to platelet dendrites. Snow temperature was about -3°C i.e., constant. The testing of a 1-1/4 ton truck with a new driver produced the usual immobility part way up the slope. On a second attempt the driver used a path scew to a normal approach of the hill. Again the truck was immobilized. In addition to the effect of depth hoar there was also the effect of a 1/4 inch thickness of ice at the base of the snow on this path.

11:30 am:- Air temperature was +3C and the surface of the snow pack became slightly sticky. A snow cross section showed a 1/4 inch crust occupied 2-1/2 inches below that. The total depth of virgin snow was 7½ inches. Snow temperature was still constant at -3°C. The jeep made a five inch rut and compressed snow to 2-1/2 inches. There was barely any detectable trace of treads in the snow track. The snow was not rigidly compacted in the wake of the vehicle on level ground. The vehicle's climbing ability was very poor. 100% slip took place near the base of the slope.

3:15 pm:- The air temperature reached 1-1/4 C as a new cross section of virgin level snow was studied. The top 1-1/2 inches were soft while the next 2 inches were relatively firmly packed. Depth hoar occupied the next four inches making a total depth of 7-1/2 inches. The surface temperature was -1C while the base read 0C. The passage of the APC highly compacted the snow to about 1 inch. About half way up the hill the driver turned in order to make an oblique cross hill traverse. On a second try the vehicle was completely immobilized on a direct (normal) climb. Then veering at a small angle the APC scaled the hill but at a very high percentage of slip. In another exercise the vehicle exhibited much side slipping on uphill and downhill turns.

January 19, 1:45 pm:- The weather was mild and sunny. The snow now had a 1/2 inch weak crust at the surface (refrozen after surface melting). Below this were 3 inches of snow platelets and a 1/8 inch thick crust followed by 5-1/2 inches of depth hoar. Air temperature was -1-1/2C and snow temperature at the surface measured -1C and at the base -2-1/2C. Half way up hill the 5 ton wrecker experienced 100% slip. Snow packed into an icy base thus reducing friction. Snow compacted into clumps with slippage and breakage of the tread traces. Evidently bonding at high temperature and foot print pressure of all snow crystals (platelets and depth hoar) took place.

January 20, 3:00 pm:- Air temperature was about -1/2C. The snow on the slope was 7 inches deep of which the middle firm portion down to 3 inches from the surface was highly packing. No crusts were present. At the foot of the hill crusts were present and the snow was less packing. Hence snow properties appear to be very sensitive to precise location and weather.

It would have been of interest to observe the performance of a snowmobile in this region. It is possible that with its light foot print pressure it could scale the slope by not breaking through to the depth hoar layer.

CONCLUSIONS

The following general conclusions are drawn from the results presented:-

1. All vehicles tested suffered immobility when moving directly up a 23% grade. These vehicles experienced 100% slip upon breaking through to the depth hoar layer. The APC managed to scale the slope through superior manoeuverability i.e. by the use of turns.

2. At low snow temperatures (below -2C) slipping led to shallow excavation of the frozen ground to no avail.

3. At high snow temperatures (above -2C) slipping led to the formation of ice or slippery compacted snow thereby ensuring continued immobility.

4. The 6 psi footprint of the APC was evidently sufficiently high to produce snow compaction, some soil aggression and tufting of grass to negotiate the hill.

5. All vehicles sank virtually to the base of the seven to 10 inch deep soft snow pack. Thus the pack could clearly be classified.

6. The effect of three days of near freezing temperatures was to slightly alter the surface of level snow through the formation of a thin crust. Snow on the slope was packing down to, but not including the depth hoar.

7. Snow crusts were extensive but did not occur uniformly throughout the area.

8. It would have been of interest to test a very light vehicle such as a snow mobile in this area.

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13. ABSTRACT

The properties of a given snowpack were monitored throughout a winter season in order to identify some of the factors most affecting vehicle mobility over snow. This activity was carried out as an aid to developing an improved snow classification system for purposes of mobility and to assess the use of snow strength testing devices as part of such a system.

Snowpit data were collected at the Land Engineering Test Establishment, DND Ottawa, during the winter of 1976-77 in combination with penetrometer tests of snow strength and studies of the tractive performance of an RN25-35 tracked carrier. It was found that temperature and free water content are the snow factors which are highly transient while changes in depth, density, grain size distribution, grain shape, crustal layer and bearing strength are usually perceptible over a period of days to weeks. As the winter season progresses snow strength undergoes a general increase with snow density while snow temperature approaches uniformity and crusts become more numerous. Grain shape and size distribution are indicative of the stages of snow metamorphism.

Penetrometer shortcomings are enumerated with a recommendation for greater automation in snow strength testing. Recommendations are also made for the most convenient environmental conditions for purposes of comparing the performance of vehicles.

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