SR 178

AD 749245

Special Report 178

PHYSICAL PROPERTIES OF THE SNOW COVER IN THE FT. GREELY AREA, ALASKA

Carl S. Benson

August 1972

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

30

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP

3. REPORT TITLE

PHYSICAL PROPERTIES OF THE SNOW COVEF IN THE FT. GREELY AREA, ALASKA

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Carl S. Benson

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 1972	28	11

8a. CONTRACT OR GRANT NO. Grant DAAG 23-67-0356	9a. ORIGINATOR'S REPORT NUMBER(S) Special Report 178
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES Reproduced from best available copy.	12. SPONSORING MILITARY ACTIVITY U.S. Army Arctic Test Center Ft. Greely, Alaska

13. ABSTRACT

The Fort Greely area in the interior of Alaska is especially interesting because it has such a wide variety of snow types. It contains the low density snow, consisting mostly of depth hoar, which is typical of wind sheltered valleys. It also has hard windpacked snow in unforested places because of the prevalence of strong winds from Isabell Pass in the Alaska Range. The snow structure evolves through the winter in different ways, depending on exposure to wind and to temperature gradients in the snow. The effect of snow structure on vehicle traffic is extremely variable from place to place. This is documented by measurements of density, temperature, and ram hardness together with 21 photographs and 9 line drawings.

14. KEY WORDS

Alaska - snow cover
Snow
Snow cover
Surveys
Trafficability

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

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PREFACE

This report was prepared by Dr. Carl S Benson of the Geophysical Institute, University of Alaska (Expert, USA CRREL).

It was funded under Grant DAAG 23-67-0256 as part of a series of studies on the Delta River Project conducted by the U.S. Army Cold Regions Research and Engineering Laboratory for the U.S. Army Arctic Test Center, Ft. Greely, Alaska.

Other reports published as part of this series include:

Physical Characteristics of the Snow Cover, Ft. Greely, Alaska, 1966-67, by M.A. Bilello, R.E. Bates and J. Riley. USA CRREL Technical Report 230, 1970.

Hydrologic Reconnaissance of the Delta River and its Drainage Basin, by S.L. Dingman, H.R. Samide, D.L. Saboe, M.J. Lynch and C.W. Slaughter. USA CRREL Research Report 262, 1971.

Trafficability Studies on Snow Covered Terrain, by G. Abele. October 1967.

The author wishes to acknowledge Dr. Herbert H. Rasche, Chief of the Research and Development Office at Ft. Wainwright, Alaska, and Mr. James A. Bender, formerly Chief of the Research Division, USA CRREL, for making it possible to conduct these studies, and to Pfc. James Riley for making weekly snow cover observations.

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PHYSICAL PROPERTIES OF THE SNOW COVER IN THE FT. GREELY AREA, ALASKA

by

Carl S. Benson

INTRODUCTION

Snow cover of interior Alaska

The winter climate of the interior lowlands of Alaska, where most of the population is located, is typified by cold air and calm winds. The snow-covered surface favors the development of strong surface inversions which restrict the calm, cold air to a surface layer 50 to 100 m thick. However, hills such as those around Fairbanks effectively "poke through" the inversion layer which lies in the flats. Thermograph records from points on Birch Hill (Fairbanks) can be used as an approximation of the free air temperature at those levels (Benson 1965, p. 51).

The snow cover lying within the altitude range spanned by the inversion layer is subject to negligible winds – often through the entire winter. It is also subjected to very low temperatures at its upper surface for several months. However, the ground beneath the snow does not experience temperatures below −5° or −10°C, so strong temperature gradients prevail in the snow. This leads to extensive depth hoar development. The snowpack is often referred to by residents as being "soft and fluffy"; the average density is generally less than 0.20 g cm^{-3}.

The dense air in the surface inversion layer is virtually detached from the air above (Benson 1965), and winds in the upper air mass can be strong (Gotaas and Benson 1964). Occasionally the boundary between the dense, calm air in the valleys and the windy air aloft may be seen in the form of a frost line on the forest. Delicate frost crystals cover the branches of trees below the boundary, while the trees above are free of frost. This might be explained partly by the fact that the lower temperatures below the boundary cause more condensation and crystal growth. However, the boundary has been observed to be very sharp following wind action at higher levels while negligible winds occurred below. The boundary layer in the Fairbanks area lies slightly more than 100 m above the valley floor, just above the steepest inversion layer (Benson 1965).

Hard-packed wind slabs develop on top of Ester Dome, about 600 m above the flats just west of Fairbanks. These slabs consist of fine grains (< 1 mm) which are firmly bonded; the density values generally range from 0.35 to 0.45 g cm^{-3}. At 200 m above the Tanana Valley, for example on top of Birch Hill, the snow shows little wind packing, as in the valleys below. About 300 m above the valley floor wind action on the snow becomes noticeable, and significant wind packing occurs every winter at altitudes in excess of 400 m.

Although it is not possible at present to express wind packing as a function of altitude, it is possible to give an altitude of demarcation which may be useful from an operational point of view. In the Fairbanks area this altitude is about 300 m above the valley floor. Above this altitude the snowpack consists of wind-packed layers overlying depth hoar layers. The depth hoar layers vary in thickness from 20 cm down to about 1 cm at the base. In wooded areas the wind packing may be absent. But wind slabs are common above timberline and where the forest cover is thin. Below this altitude the snowpack may be predominantly depth hoar.

Fort Greely area

The Fort Greely area differs from most of interior Alaska in that it is more frequently exposed to winds at the surface. This produces more drifting and packing of the snow at lower altitudes than is observed in most locations. The winds also break up the strong, long-lasting surface inversion which is common over much of the interior, and cause the surface air temperature to be higher than in other interior areas. Winds from Isabell Pass in the Alaska Range frequently produce wind-packed snow even at the lowest levels. Altitude is not important to the distribution of wind packing as it is in most of interior Alaska, such as the Yukon flats and the Fairbanks-Fort Wainwright area. In the Fort Greely area, wind packing is found wherever open, exposed areas exist.

Another important aspect of the Fort Greely snow cover is its great variability. This is really not a separate aspect but merely a consequence of the variation in exposure to wind action which exists in the area. All varieties of snow cover exist and the variation from one type to another is often experienced over short distances of about 500 m or less. The best way to demonstrate this is to cut holes in the snow cover in several representative areas and measure snow temperature, density, grain size and resistance to penetration. However, this takes a great deal of time because one must not only look at the snow cover in several places on one day, but observe the way it varies over the winter.

The snow from the first storms in October generally does not melt until spring. Its physical characteristics change during the winter under the action of two important factors: wind action and the temperature gradient. These may act separately or in combination. The final stage is melting with its associated "rotten snow," which is the most difficult of all to travel across or through.

The following discussion is liberally illustrated with photographs and diagrams. This is the best way to describe the complexity of the snow cover of the Ft. Greely area. A careful study of these diagrams which primarily show temperature and density profiles at various times of the year will be rewarding to the reader who desires to gain a better understanding of the snow cover in the Fort Greely area. The examples seen in this area are representative of several major types of snow cover which are found in other parts of Alaska.

OBSERVATIONS

Data were obtained each week from several sites in different environmental settings within the Ft. Greely area. The main variable from one site to the next was wind exposure. The sites with complete sets of data are:

Site	*Wind exposure*
1. Forest	In forest, no wind exposure, no drifting
2. NBC	Near forest, no drifting
3. Davy Crockett	Near forest, negligible drifting
4. Traffic	Near forest, extreme drifting
5. 33 Mile Loop	Several sites used, variable drifting
6. Jarvis Creek	Exposed and drifted

The locations of the sites are indicated in Figure 1. The 33 Mile Loop site involved measurements at the following points:

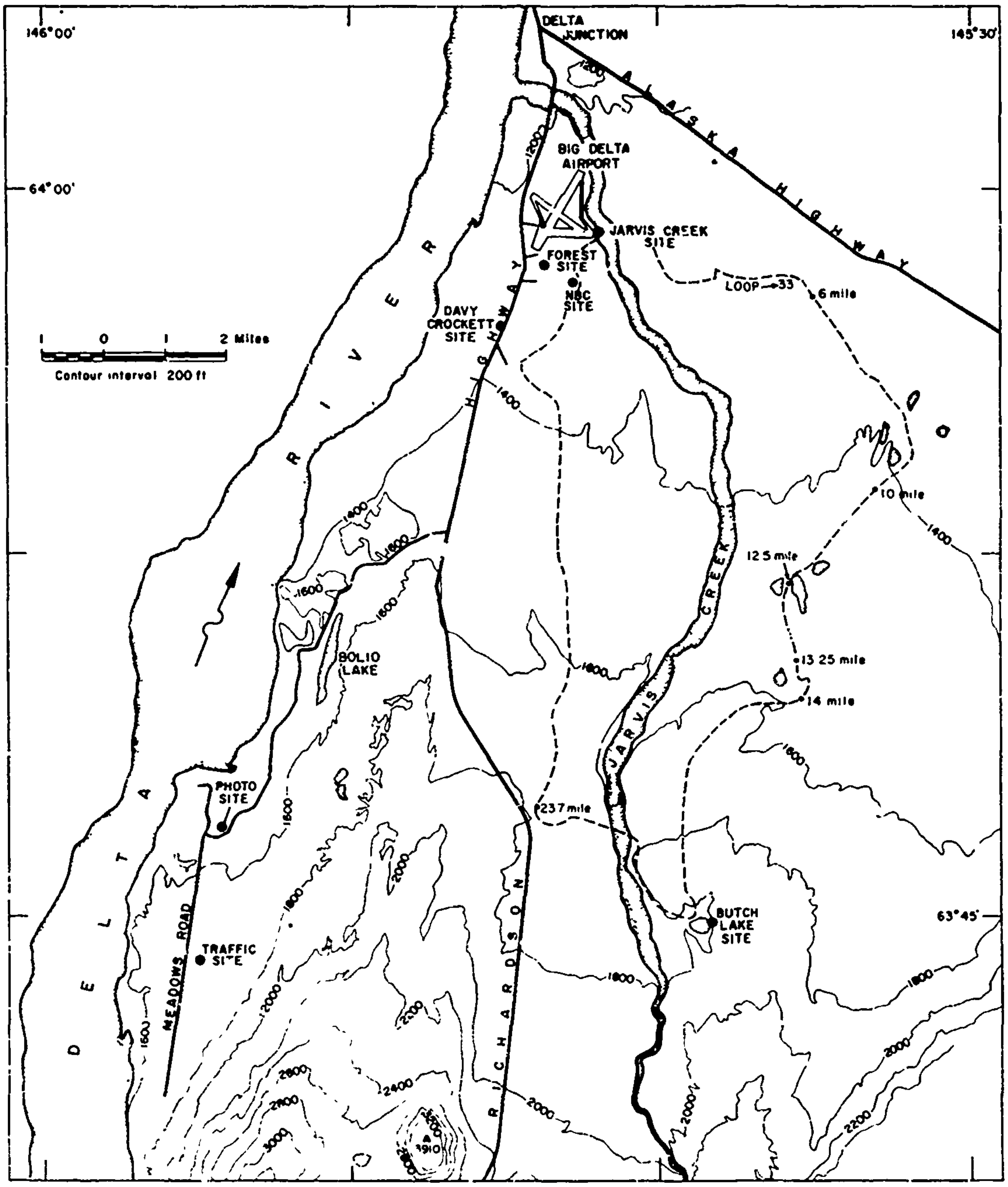


Figure 1. Test sites.

Mile point on 33 Mile Loop	*Number of observations*
6.0	1
10.0	1
12.5	1
13.25	1
14.0	2
23.7	13

Selected data have been extracted and summarized in nine line drawings and twenty-one photographs. These include a drawing and a photo for the Butch Lake Site which was included as an extreme example of wind-packed snow, in contrast to the Forest Site which, by virtue of its forest location, experienced no wind packing.

Forest Site

Figure 2 shows six representative temperature and density profiles measured at the Forest Site. As snow accumulates, the stress on the underlying layers increases, causing the snow density to increase. However, the strong temperature gradient acting across the snow causes an upward migration of water vapor which forms low density depth hoar at the base of the snowpack. The depth hoar layer thickens as the winter progresses. This will be discussed more completely below; for the present we are interested in showing the net effect on density of the snowpack.

This is very well illustrated at the Forest Site, where the density of the entire snowpack remains low all winter long (Fig. 2). The lower one-half or one-third of the snowpack consists of depth hoar with virtually no strength during most of the winter. The density is generally about 0.20 g cm^{-3} and only near the end of the snow season, after some surface melt has occurred, does it reach values as high as 0.25 g cm^{-3}. In this manner the snow differs significantly from arctic or polar snow which is generally subjected to some wind action. Snow density in Greenland, Antarctica, or the arctic slope of the Brooks Range seldom goes below 0.25 g cm^{-3}.

The density does not increase with depth in the Forest Site snow cover as one might expect. Instead, it remains nearly constant or shows a decrease from top to bottom. This is most apparent at the bottom of the snowpack. The density of snow in the upper layers increases progressively with time, but the density of the layers near the ground increases to a limiting value of about 0.23 g cm^{-3}. When the density of the overlying layers reaches this value, the entire snowpack has constant density. When the density of the upper layers exceeds 0.24 it also exceeds that of the underlying layers. This situation becomes most clearly apparent near the end of the winter. When some melting occurs in the snow, the difference in density between the upper and lower layers becomes more pronounced (Fig. 2, curve 6, 17 April 1967) and the snowpack becomes "rotten" very quickly. During the winter a packed trail like that shown in Figure 2 can easily support men on foot. When spring comes, the trail as well as the surrounding snow cover fails to support foot traffic and it becomes difficult to move about.

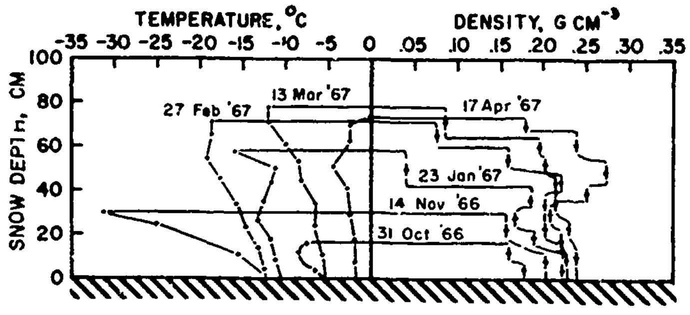


Figure 2. Temperature and density profiles in the snow at the Forest Site.

Profile no.	*Date*
1	*31 Oct 1966*
2	*14 Nov 1966*
3	*23 Jan 1967*
4	*27 Feb 1967*
5	*13 Mar 1967*
6	*17 Apr 1967*

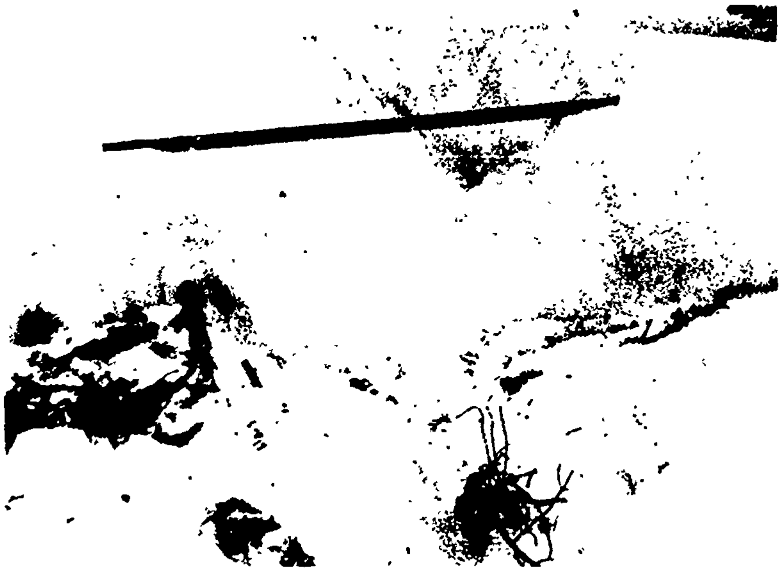


Figure 3. Section cut across foot path to Forest Site.

A section was cut and exposed to reveal the compact structure under the path. The undisturbed snow adjacent to the path was 45 cm thick, and the bottom 15 cm consisted of loose depth hoar. The compacted snow in the path was 23 cm thick. Thus, the surface of the path was 22 cm below the snow surface; however, when a man stepped off the path his foot penetrated deeper than 22 cm and passed into the weak depth hoar layer. During the spring thaw, when melting temperatures penetrated to the bottom of the snowpack, it became increasingly difficult to walk on the path, and the surrounding rotten, wet snow was penetrated completely by a man on foot.

Figure 4. Forest Site, 16 February 1967.

The snow was 60 cm deep in the pit where the meter stick is exposed in the left foreground. It was 43 cm deep near the tree in the center of the photograph. There was no evidence of melting in the snowpack on this date. The snow temperature profile from the snow surface to the soil/snow interface is influenced by the depth of the snow because the ground is cooled more where the snow cover is thinnest. Near the tree, where the depth was 43 cm, the bottom temperature was -13°C and the top temperature was 21°C. At the meter stick, where the depth was 60 cm, the bottom temperature was -10°C and the top temperature was -19°C.

Figure 5. Forest Site, 15 April 1967.

The snow surface topography was accentuated by the beginning of melting. The snow was 70 cm deep in the pit where the meter stick is exposed, but was less than 30 cm deep near the trees. The minimum temperature in the snowpack when this pit was examined, at 0930, was -4°C with -1°C at the bottom. Wetting of the snow by meltwater had been restricted to the top 30 cm. This produced the higher density values in the upper layers shown in curve 6 of Figure 2. Ice lenses and layers which formed on certain horizontal stratigraphic planes in the upper 20 cm of the snow are visible in this photograph.

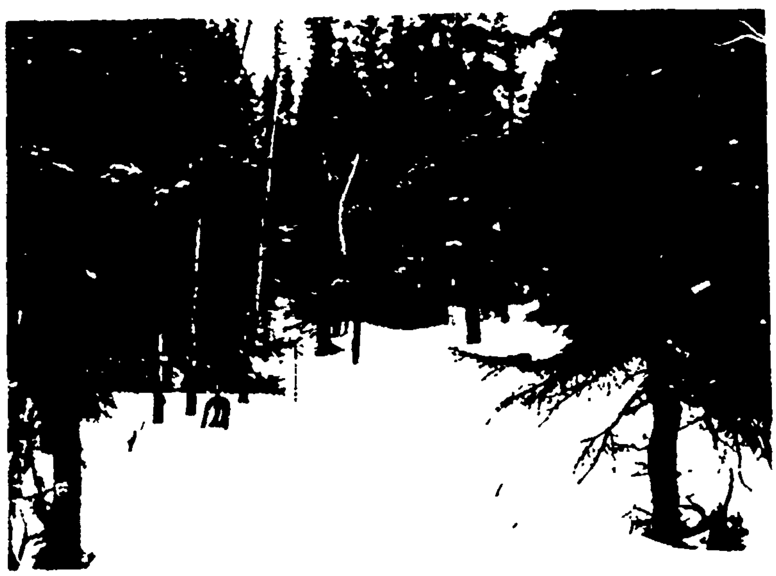


Figure 6. Snow surface topography in spring near Forest Site, 15 April 1967.

The snowpack was approaching the condition of poorest trafficability. It was necessary to remain on the foot trail to keep from sinking well above knee level. The density of the top half of the snowpack was significantly higher than that of the bottom half. Within 2 weeks patches of ground were exposed around the trees.

The depth of snow in the forested areas varies greatly as shown in Figures 4, 5 and 6. The variability must be considered when selecting a site for measurement and when interpreting the data obtained. The range of depth values encountered in areas like those shown in Figures 4, 5 and 6 was from 20 to 80 cm during the 1966-67 winter. According to Freeman (1968) this snowpack was deeper than average. In general, the snow cover at the Forest Site is much like that of the lowlands all over interior Alaska.

NBC Site

The snow cover at the NBC Site was not as deep as that at the Forest Site. The maximum depth of 50 cm was observed on 23 January (curve 4 of Fig. 7) and on 3 April. Only five depth values in excess of 40 cm were observed. The depth of the snowpack varied considerably from time to time, but this was primarily due to the variable topography under it. This site was located in a clearing which was protected from wind drifting by the surrounding forest. Scanty vegetation was present and the snow cover was characterized by depth hoar. On 15 April the snow had begun to melt at the surface but the depth hoar crystals were not greatly modified by the melting. Curve 5 of Figure 7 shows this quite clearly since the density of the upper 10 cm is 0.34 g cm^{-3}, whereas the bottom depth hoar has barely reached a density of 0.21 g cm^{-3}. Figure 8 is a photograph of a thin section cut through the snow represented by curve 5 of Figure 7. There is an icy crust 22 cm from the bottom which separates the depth hoar from the melt-affected layer above. Meltwater percolates downward along bits of vegetation as may be seen in Figure 8. In this case the downward percolating meltwater has refrozen to form clusters of ice crystals on the grass.

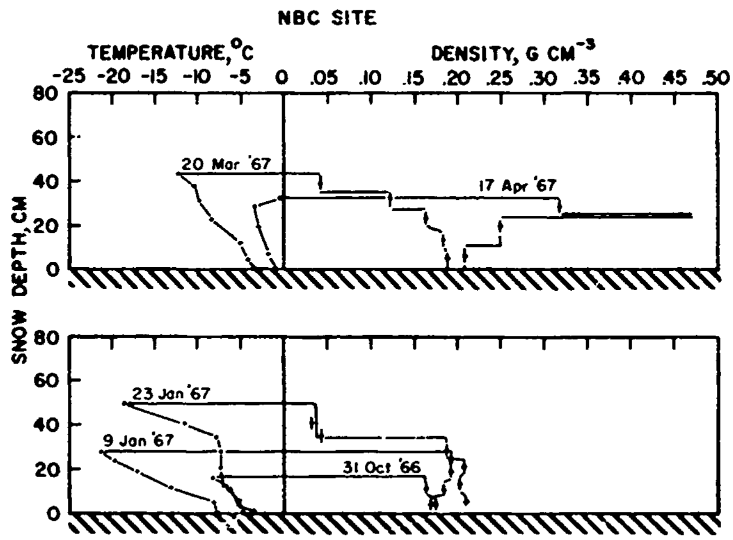


Figure 7. Temperature and density profiles in the snow at the NBC Site.

Profile no.	Date
1	31 Oct 1966
2	9 Jan 1967
3	23 Jan 1967
4	20 Mar 1967
5	17 Apr 1967

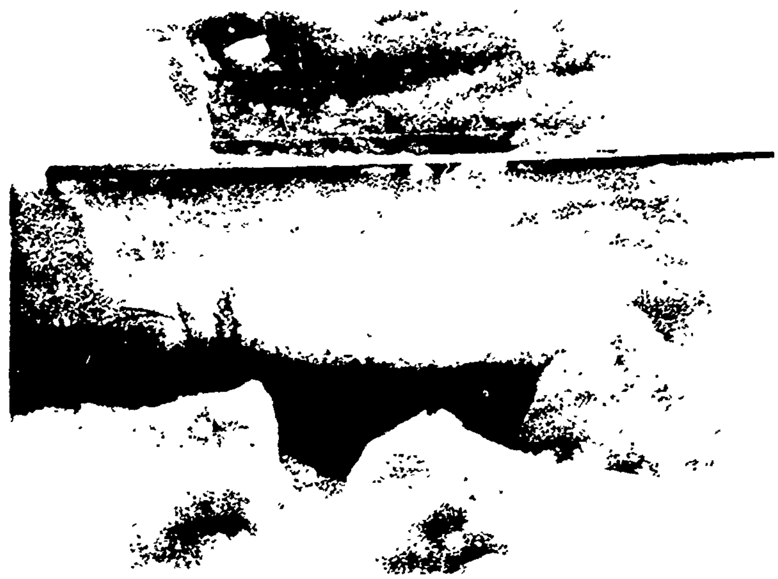


Figure 8. Thin section of snow cover at NBC Site, 15 April 1967.

This thin section was made by cutting away the snow on either side of a thin slab which was photographed using transmitted sunlight. The snowpack was 30 cm thick and its temperature and density profiles constitute curve 5 in Figure 7. The upper 10 cm had experienced some wetting and an icy crust was present 22 cm above the ground level. Below the icy crust the snowpack consisted of depth hoar crystals which had not yet been destroyed by melting. The depth hoar was especially coarse-grained in the bottom 10 cm, and individual crystals were to 1.5 cm in length.

Davy Crockett Site

The snow cover at the Davy Crockett Site was much like that at the NBC Site, except that it was shallower and less variable. It was typified by depth hoar and negligible wind drifting. The three profiles in Figure 9 summarize most of the weekly data on snow density obtained at this site; however, the snow temperatures went to lower values than those shown. Figure 10 shows a typical winter cross section of the snow. Figure 11 shows the same snowpack during the onset of the melting season.

Photo Site on the Bolio Lake Road

The snowpack at the Photo Site consisted primarily of depth hoar crystals at the base with soft, loose snow above. An example of soft, coarse grained layers interbedded with harder, finer grained wind-packed layers is shown in Figures 12, 13 and 14. The snow was cut away with a shovel to expose the structure of a drifted area adjacent to the north side of the road; the walls of the excavation were made photogenic by trimming and smoothing with a shovel.

As with many places in the Ft. Greely area the snow cover at this site was characterized by variability. The snow depth varied from less than 40 to slightly greater than 70 cm along one 3-m section. The density variation between the wind-packed and softer layers is significant; the values were 0.34 g cm^{-3} and less than 0.20 g cm^{-3} respectively. The bottom layer consisted of depth hoar with very loose structure. Also, the effect of vegetation is to weaken the total top-to-bottom snow structure (see Fig. 13 and 14).

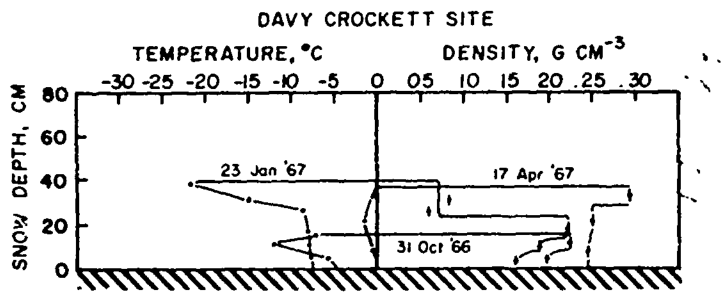


Figure 9. Snow temperature and density profiles at the Davy Crockett Site.

Profile no.	*Date*
1	*31 Oct 1967*
2	*23 Jan 1967*
3	*17 Apr 1967*

Figure 10. Test pit at Davy Crockett Site, 16 February 1967.

The total depth of the snowpack as seen on the meter stick was 37 cm. The coarse-grained depth hoar crystals may be seen in the bottom 10 cm. Depth hoar crystals occupied the bottom 20 cm of the snowpack and the crystal size was largest near the bottom. The average density of the entire snowpack was 0.20 g cm⁻³. Individual values were as follows:

Height above soil surface (cm)	*Density (g cm⁻³)*
35	*0.166*
25	*0.204*
17	*0.218*
9	*0.204*
4	*0.208*

The snow temperature was -5.5°C at the bottom and -15.5°C at the top.

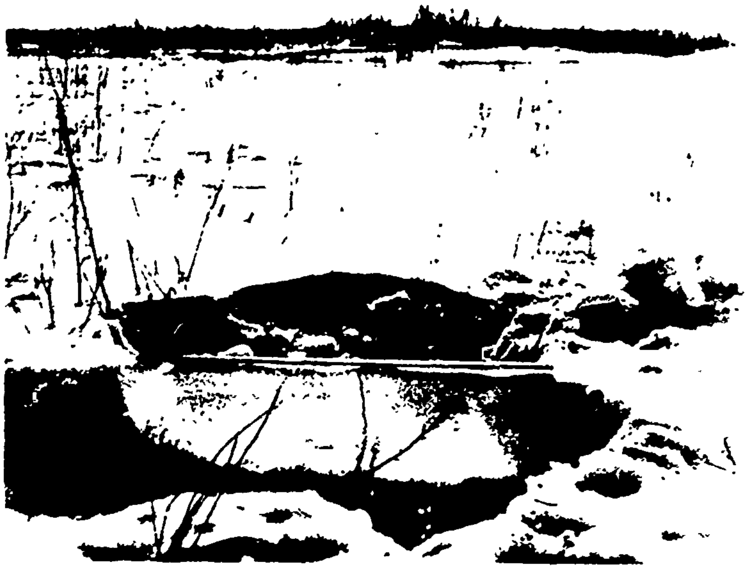


Figure 11. Thin section of snow cover at Davy Crockett Site, 15 April 1967.

This thin section was made by cutting away the snow on either side of a thin slab which was oriented so that the sun could shine through it, as in Figure 8. The total snow depth varied from 29 to 30 cm. Meltwater had percolated through the snowpack and the temperature was 0°C from top to bottom. There was an ice crust 20 cm above the soil surface; the top 10 cm was melt-bonded rounded medium grain size snow, the lowest 10 cm was depth hoar. The depth hoar crystals were mostly bonded together by melt action but good crystals were preserved where willows protruded through the snowpack. The average density of this snowpack was 0.28 g cm^{-3} which is a significant increase over that shown in Figure 10. Density profile 3 in Figure 9 is representative of this snow section.

Figure 12. Exposed section of wind-packed snow layers at Photo Site.

Wind-packed layers alternated with softer layers and the base of the snowpack consisted of depth hoar crystals. The effect of vegetation in controlling the depth of snow in this windswept area shows at the top of the photo.

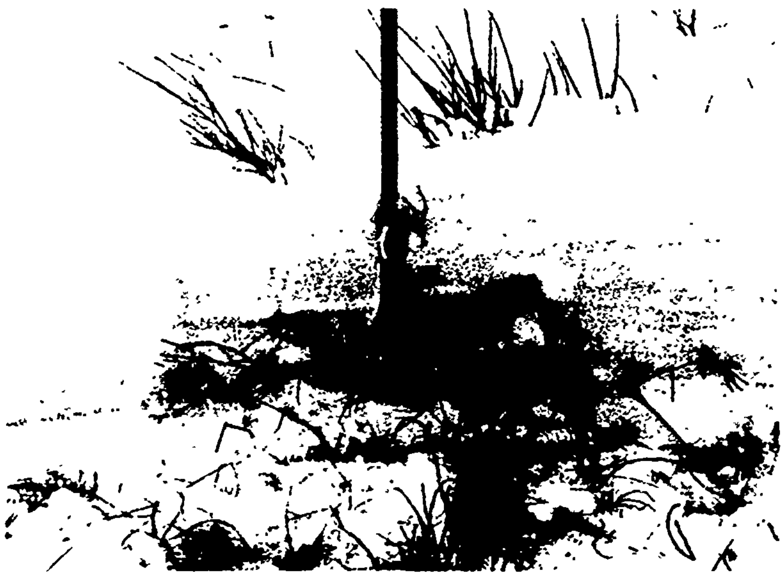


Figure 13. Exposed section at Photo Site with vegetation in depth hoar.

The total depth of snow in this section was 42 cm. The lowest 22 cm was depth hoar and had large cavernous spaces in it because of the brush. The wind-packed layer at 28 to 30 cm was hard and fine grained, and it thickened to the right. The total snowpack had low strength even though some wind-packed layers were present in it.

Figure 14. Exposed section at Photo Site with vegetation.

This photo was taken along the same section as Figures 12 and 13. It shows the variable thickness of individual layers and the enhancement of vertical growth of depth hoar crystals by dry grass and willows which penetrate the entire snowpack.

Traffic Site

Wind action produces extreme variability in the snow cover at this site. Indeed, comparing this site with others like the Butch Lake or Forest Sites indicates why it is impossible to give a simple one-parameter description of the snow cover in the Ft. Greely area. Typical depth-density profiles with stratigraphic sections included are shown in Figure 16. The stratigraphic symbols are explained in Figure 15. All of the measurements shown in Figure 16 were made within 10 m of one another.

Figures 17, 18 and 19 show snow pits at the site. The wind slab near the top of the snowpack in Figure 19 varied in thickness. Figure 20 shows a place where it was especially well developed. Its density was 0.495 g cm^{-3} and its hard, brittle nature may be seen in Figure 21. It was poorly supported by the depth hoar beneath it, yet was very strong. The ram hardness values of the slab (Fig. 16) exceeded 160 kgf even though it was only 18 cm thick, and the Rammsonde penetrated by fracturing it as if it were mounted on a pair of sawhorses. The strength of wind slabs in this area is sometimes increased by small twig and leaf fragments which are blown about and deposited within the snow. This method of strengthening of wind slabs is analogous to strengthening ice by adding a small percentage of wood pulp to form "pykrete" (Perutz 1948).

Jarvis Creek Site

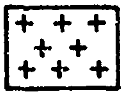
The Jarvis Creek Site is another example of wind-drifted snow layers interbedded with low density layers, some of which contain depth hoar. It had deeper snow cover than the other sites because of its location in the Creek Valley (Fig. 1). Representative profiles are shown in Figure 22.

Butch Lake Test Site

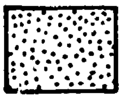
The Butch Lake Test Site was visited on 17 February and 14 April 1967. It lies west of Butch Lake and varies from a windswept flat area on the Jarvis Creek floodplain to fully forested areas (Fig. 1). Winds from the south produce very hard, thick wind slabs along the floodplain. The hard, wind-packed snow extends through the entire depth of the snowpack in some places and gives a gently rolling appearance to the surface (Fig. 24) but adjacent to these places it is thin or non-existent. The snow surface supports a man on foot for five to twenty paces and then unpredictably fails (Fig. 23). An M-116 oversnow vehicle was driven across the smooth snow cover of the flood-plain west of Butch Lake and the amount of track penetration varied from almost nothing to over 50 cm (Fig. 25). A section was carefully exposed at a place where track penetration changed signifi-cantly. The variable structure of the snow is clearly seen in this section (Fig. 26 and 27).

Time did not allow a complete investigation of the geometry of the hard, fine-grained snow layers nor could their specific causes be determined. They appear to be lens-shaped in vertical cross section and are probably elliptical in plan view with the long axes parallel to the wind. The den-sity in the wind slab material was significantly greater than 0.40 g cm^{-3} whereas the depth hoar underlying it was less than 0.20 g cm^{-3}. The loose snow between the extremes of depth hoar and wind slabs had density values in the range of 0.26 to 0.32 g cm^{-3}.

Figure 28 shows a test section exposed in the variable wind-packed region west of Butch Lake in April. Some meltwater had percolated into the upper wind slab in March but it was dry and hard on 15 April when this study was made. Density and temperature profiles were measured through the snowpack (Fig. 29).

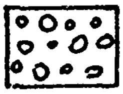


New snow, original crystal forms still recognizable.



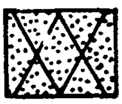
Fine- or very fine-grained snow, <1 mm.

Medium-grained snow, 1 to 2 mm.

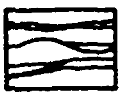


Coarse-grained snow, 2 to 4 mm.

Very coarse-grained snow, 4 mm.

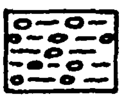


Wind slab, consisting of firmly bonded fine or very fine grains; from a little distance it has a dull, lusterless chalky appearance.*

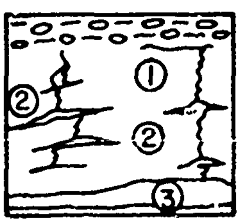


Wind crusts, paper thin layers of firmly bonded very fine grains.† A thin line is also used to indicate discontinuities between adjacent layers.

Depth hoar, or coarse, loosely bonded grains, often with well developed crystal faces.



Melt crust or iced firn, consisting of coarse grains with small lenses and irregularly shaped chunks of ice scattered throughout.



Ice masses in snow, formed by downward percolation from surface melt. These features are common on glaciers and occur in seasonal snow cover after the melting begins.

1. ice gland
2. ice lens
3. ice layer

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* Descriptive material on wind slabs is found in Seligman (1936, p. 159-205).

† The term *wind crust* is used here in a slightly different sense from that of Seligman (1936, p. 167).

Figure 15. Stratigraphic symbols.

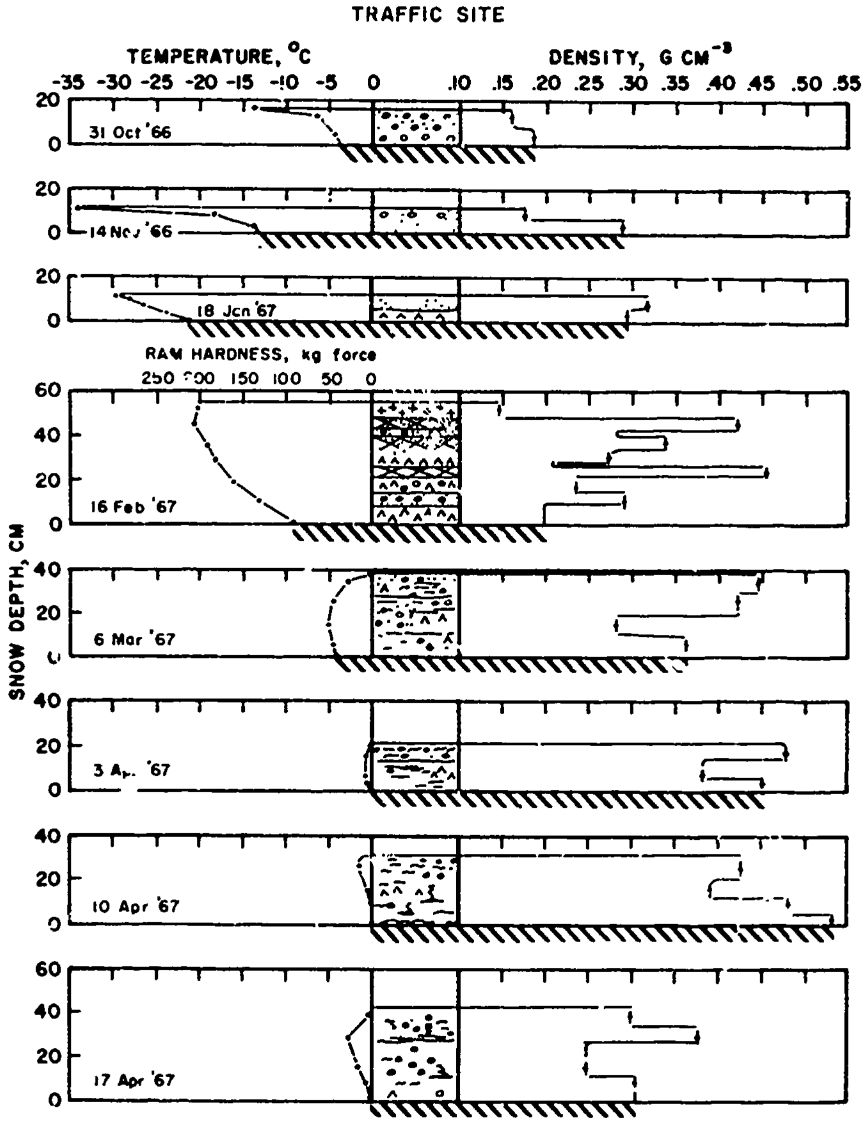

Figure 16. Snow stratigraphy profiles at the Traffic Site during the 1966-67 winter.

Figure 17. Type locality for weekly snow profiles at Traffic Site.

The thin snowpack (less than 20 cm thick) recorded in many of the profiles prior to 16 February 1967 was measured at this site. The level of snow on the snow measuring stake was recorded each week. This measurement was meaningless for the area as a whole as can be seen by the drifts in the background.

Figure 18. Traffic Site type locality in foreground with a second pit being examined 5 m away from it.

The snow was more than five times as deep as in the "type locality" pit in the foreground (see also Fig. 17). The depths were 55 and 10 cm respectively.

Figure 19. Test pit wall at Traffic Site, 16 February 1967.

The circles on the exposed wall indicate places where snow density measuring tubes were inserted. The alternating coarse- and fine-grained snow layers shown are represented graphically in Figure 16 in the profile for 16 February 1967. A Rammsonde penetrometer profile measured at this site is plotted to the left of the stratigraphic column in Figure 16. Note that the hard, wind-packed layer (see also Fig. 20, 21) near the top of this pit was so brittle that it fractured when the density tube was inserted. The layer at the base of the snowpack consisted of loosely bonded depth hoar crystals.

Figure 20. Hard wind slab at Traffic Site.

The wind slab shown in this photo was 18 cm thick. It was overlain by 8 cm of soft new snow and under it was 15-18 cm of coarse depth hoar. The density of the wind slab was 0.495 g cm^{-3} while that of the underlying depth hoar was about 0.20 g cm^{-3}. A section of the wind slab was removed with a saw for this photo. Its strength was increased by the presence of bits of vegetation which were incorporated into it. Thus, it formed a natural "Pykrete" (see Perutz 1948).

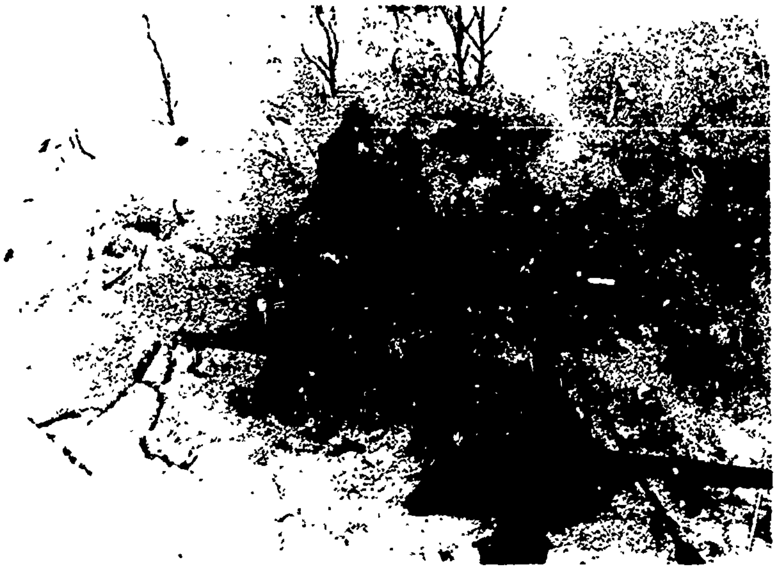

Figure 21. Fractured wind slab at Traffic Site.

The wind slab exposed in Figure 20 was broken by having a 200-lb man jump on it repeatedly until it fractured. The wind slab as exposed in Figure 20 was suspended over the structureless depth hoar and yet it took five or six jumps to cause the fracture shown in this photograph. In places where wind slabs such as this make firm contact with the ground (i.e. are not underlain by depth hoar), they would easily support light wheeled vehicles (Fig. 26 and 27).

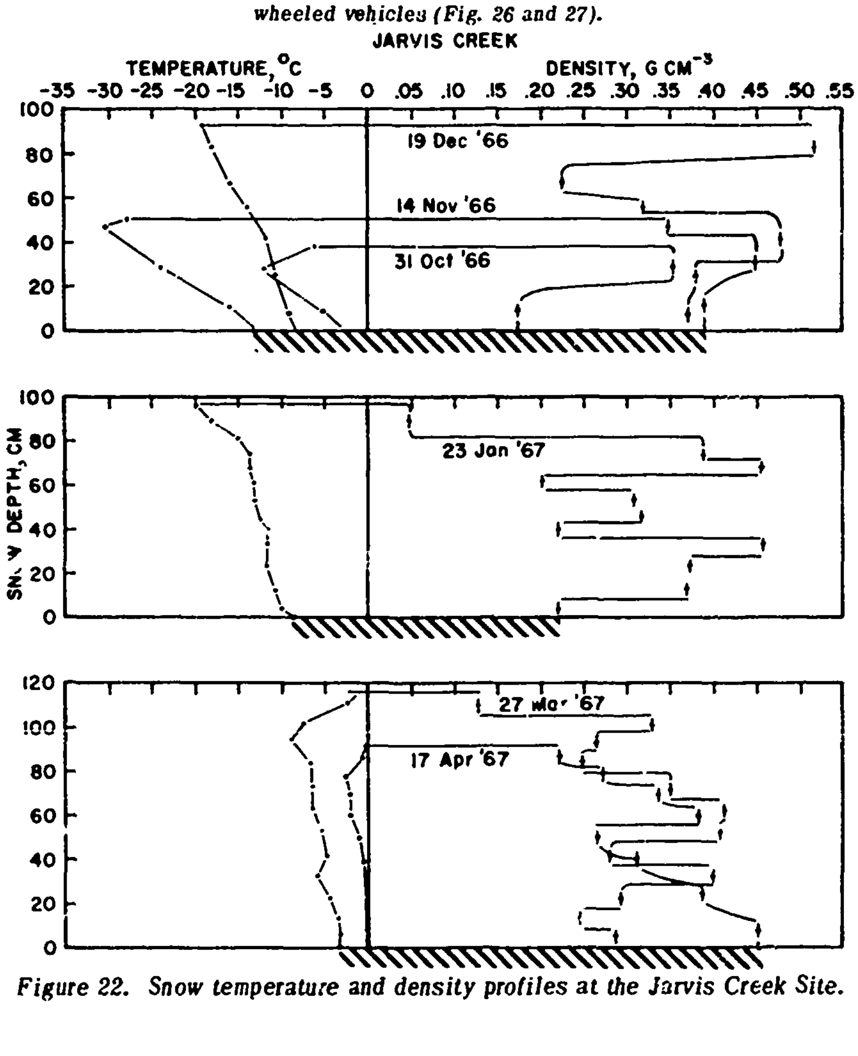

Figure 22. Snow temperature and density profiles at the Jarvis Creek Site.

Figure 23. Variable strength of snow surface near Butch Lake Site.

This photo was taken on a hill 1.5 km north of the hut at the Butch Lake Site (Fig. 1). In the foreground the snow surface failed and a man on foot penetrated to greater than knee depth. However, in the center and background the snow surface provided excellent support as shown by the footprints in the 3 cm of fresh snow cover on the surface of the wind slab.

Figure 24. Jarvis Creek floodplain near Butch Lake.

The gently rolling topography on the snow surface was produced by lenses of very hard, wind-packed snow alternating laterally with softer snow. Men on foot or in vehicles could travel across some of this surface without penetrating it whereas penetration of 50 to 75 cm occurred at intermediate places. It was not possible to visually predict when the surface would hold or fail.

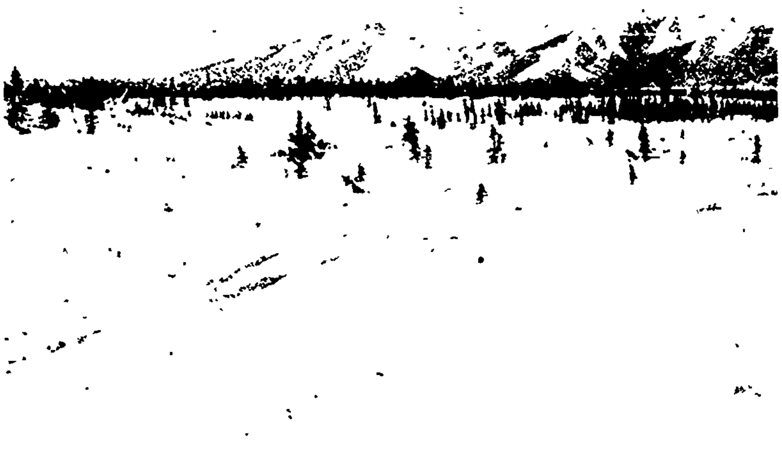

Figure 25. Vehicle track across snow surface shown in Figure 24.

In the left foreground the M116 oversnow vehicle sank into the snow to a depth of about 50 cm. The vehicle traveled from right to left. In the center there is a gentle rise in the surface topography which supported the vehicle with negligible track penetration (notice the track pad marks on the surface). To investigate the reason for this variable supporting characteristic of the snow a trench was carefully excavated in the undisturbed snow immediately to the right of the track. The results are shown in Figures 26 and 27.

Figure 26. Section exposed to show snow structure parallel to vehicle tracks.

The section exposed here was carefully cut so as to avoid disturbing the snow surface between the section and the tracks. Note the lens-shaped mass of fine-grained, hard, wind-packed snow lying behind the meter stick. The density of this snow was 0.46 g cm^{-3} whereas that of the snow in the foreground was 0.26 g cm^{-3}, and the depth hoar density at the base of the snowpack was less than 0.20 g cm^{-3}. The hard, wind-packed layer occupied the full depth of the snowpack for about 5 m along the direction of vehicle motion.

Figure 27. A side view of the section shown in Figure 26.

The meter stick is resting on the hard, wind-packed snow in a place where the soft new snow cover, about 3-5 cm thick, has been brushed away. The wind-packed snow was in direct contact with the soil surface under the meter stick. In general there was soft snow, often depth hoar, under the winter slab layers. An example of this is seen at the left where the wind slab lenses to a paper-thin layer. The vehicle, which was moving from right to left, began to sink into the snow near the place marked by the left end of the meter stick. This was caused by fracturing of the unsupported wind slab somewhat like the example in Figure 21. In places where the wind-packed snow penetrated to the bottom of the snowpack one could drive a normal passenger car without difficulty.

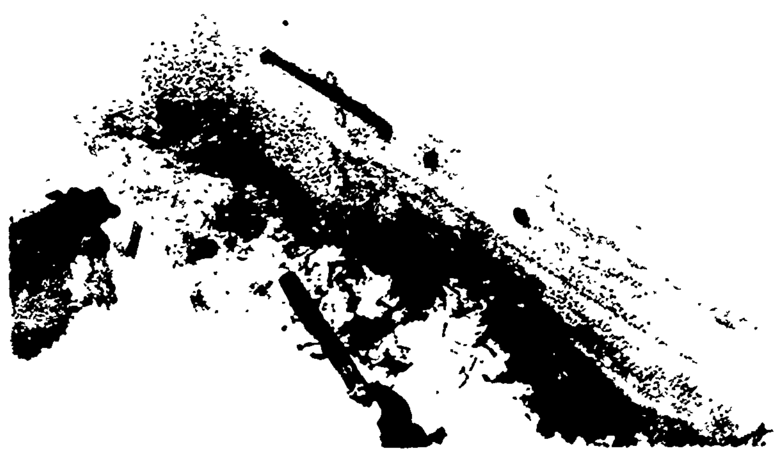

Figure 28. A section cut across wind-packed snow near Butch Lake, 15 April 1967.

This photograph records a test made in April which was similar to the February test shown in Figures 26 and 27. Some ice lenses were present in the lower part of the hard, wind-packed layer. They formed from downward percolating meltwater during March when some surface melting occurred. In this example the wind-packed snow was underlain by softer snow with depth hoar at the base of the snowpack.

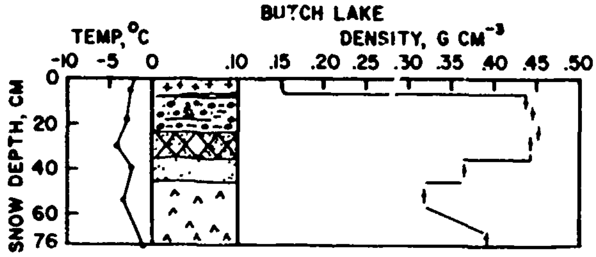

Figure 29. Snow stratigraphy profile at the Butch Lake Site, 15 April 1967.

These measurements were made at the midpoint of the meter stick shown on the test wall of Figure 28. Warm air temperatures in March caused some melting in the snowpack and meltwater percolation formed the ice lenses shown below the layer of new snow. Lower air temperatures in April stopped the melt action and the snowpack was quite dry and stable when the study recorded in Figures 28 and 29 was made.

DISCUSSION

The snow cover of the Ft. Greely area is variable both in terms of depth and structure. In general it consists of grains of ice about 1 mm in diameter with relatively low bearing capacity and strength. Two extreme cases also exist and are quite common in the Ft. Greely area: 1) depth hoar layers consisting of coarse (up to 1 or 2 cm in length) skeletal crystals with negligible cohesion between them and 2) wind-packed, fine-grained snow (grains of less than 1 mm diameter) in hard, well bonded, strong layers. The wind-packed layers often occur in 10- to 20-cm-thick slabs and are underlain by depth hoar layers which give poor support to the overlying slab.

Apart from the wind slabs the salient feature of the snow cover of interior Alaska is its low density. The best examples of this in the Ft. Greely area are from the Forest, Davy Crockett and NBC Sites (Fig. 2, 7 and 9). Throughout interior Alaska there are many places where almost the entire snowpack, 50 to 70 cm thick, consists of depth hoar with density less than 0.20 g cm^{-3} just before melting begins. These represent "final" density values for the depth hoar since it has been developing in the snowpack for 6 to 8 months, i.e. about 200 days. The final density for depth hoar in the Swiss Alps and in the mountains of Colorado and Utah averages about 0.28 g cm^{-3} after 100 to 150 days (Giddings and LaChapelle 1962, p. 2381). The depth hoar formed at the base of the first annual unit on the Greenland ice sheet can also be represented by the mean value of 0.28 g cm^{-3}. This is based on measurements from more than 100 pit studies in which the first year depth hoar density was nearly always within the range of 0.25 to 0.30 g cm^{-3} with the lower values being found at higher altitudes (Benson 1962). This representative depth hoar density value of 0.28 g cm^{-3} for mountain and ice sheet situations is significantly higher than the representative value of 0.20 g cm^{-3} for interior Alaska.

Formation of depth hoar

The ubiquity of depth hoar in Alaska is easily understood if one learns how it is formed. By assuming an idealized situation with no movement of air through the firn, Bader (1939) computed the amount of moisture transferred by diffusion alone. His result was of the order of mg cm^{-2} day^{-1} for the temperature range 0 to -10°C. Because this is so small, he concluded that movement of air through the snow is essential to significant transport of moisture within or between layers.

Winds, especially very gusty ones, produce rapid fluctuations of air pressure within the upper snow layers, and increase the rate of vapor transfer. As a result, material is redistributed within the upper layers, and some material is removed. The amount of moisture moved as vapor by the air through the snow depends on the temperature gradient and on wind. It also depends on the range of temperature involved because the vapor pressures are higher at higher temperatures. For example, the temperature range 0 to -10°C produces more than twice the difference in vapor pressure as the range -10 to -20°C (0.51 as compared with 1.56 mb) even though the temperature gradient is the same in each case.

Wind slabs

In the ideal development of the reference datum both extreme snow types, depth hoar and wind slabs, are involved. Their origins are often related, as sketched in the following argument. Part of the upward migrating water vapor escapes to the atmosphere, but the remainder is redeposited within the upper layers. According to Bader's computation for the case with no wind, these amounts are nearly equivalent. If new or drift snow is being deposited on the surface, this material will be indurated by the vapor deposited in it. The sublimed vapor will first fill in the cracks between grains, because vapor pressure is lowest there. This strengthens grain bonds and in the extreme case forms a wind slab. This process was described as wind packing by Seligman (1936, p. 200) who concluded:

". . . that wind-packing consists of the compacting of snow grains by the condensation of water vapour among them when subjected to the action of a moisture bearing wind. It is practically certain that at any rate some of this moisture is derived from the grains themselves We can therefore define wind-packing as a special form of firnification accelerated by a wet wind. The mechanism of the processes is probably one of wind-accelerated diffusion which may or may not be influenced by the pulsations or pressure variations of the wind."

Indeed, much of the moisture referred to as coming 'from the grains themselves" comes from the low density layer below the wind slab.

Depth hoar in interior Alaskan snow cover

The extreme development of depth hoar in interior Alaska snow cover may be understood by considering the prevailing conditions. The snowpack is shallow with 50 to 80 cm being a representative range of thickness. The bottom temperatures are generally -3 to -5°C and only rarely go as low as -10°C. The temperature on the snow surface is less than -10°C for about 5 months, less than -20°C for about 2 months, and reaches minimum values which go below -50°C. These conditions produce temperature gradients which are steeper and of longer duration than those in thick mountain or ice sheet snow covers. For example, if the snow surface temperature on the Greenland ice sheet was -45°C, the temperature 50 cm below the surface would be about -40°C (Benson 1962, p. 47), while in the seasonal snow cover of central Alaska it would be about -5°C. The Alaskan gradient is not only steeper, but includes higher temperatures, so it involves much higher absolute values of vapor pressure. In this example, the top 50 cm of interior Alaska seasonal snow cover has a vapor pressure difference 70 times greater than that in the Greenland case, even though the surface temperatures are equal in the two places: specifically the differences are 3.943 mb and 0.056 mb respectively. Also, on the Greenland ice sheet, strong upward-directed vapor pressure gradients exist only during the short fall season when they produce the annual reference datum described above. On the other hand, the seasonal snow cover of central Alaska is exposed to such gradients for more than 5 months.

The low density snow described above is obviously not unique to interior Alaska. It is found wherever cold (below -10°C), relatively calm air overlies a shallow seasonal snow cover for several months. A typical example is provided by the following observations made in a wooded area near Kapuskasing, Ontario, between 18 and 24 January 1954 (Benson 1954). The snow cover

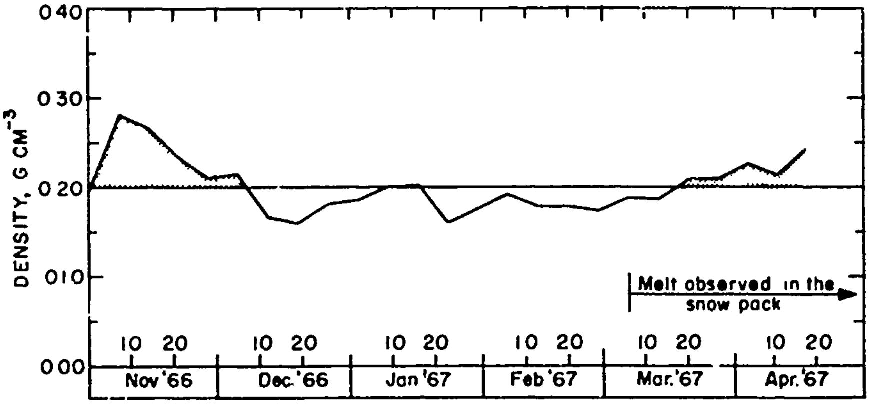

Figure 30. Density values measured at the bottom of the snowpack during the 1966-67 winter at the Davy Crockett Site.

was shallow, 28-56 cm, with temperatures of 0° to -2°C at the bottom and -15 to -35°C at the top. The temperature gradients averaged 0.4°C cm^{-1} with extreme ranges of 0.17 to 1.0°C cm^{-1}. With the exception of 5 cm of new snow on top, the entire snowpack was composed of loosely bonded depth hoar with density nearly constant at 0.20 g cm^{-3}.

Desiccation of the snowpack by vapor transfer

Experimentally, it is not easy to observe drying of the base of a snowpack by vapor transfer. However, the observations at Davy Crockett Site do show the effect. Measurements of snow density were made each week and the snow cover was fairly simple and homogeneous through the entire season as seen in Figures 10 and 11. The density value measured at the bottom of the snowpack each week is plotted against time in Figure 30. The values in November and through the first week of December 1966 are greater than 0.20 g cm^{-3}. After the second week in December they are consistently less than 0.20 g cm^{-3} until the middle of March 1967. Melt was observed in the snow-pack on 6 March as indicated in Figure 30. After the first appearance of melt in the snowpack the density of the lowest level increases again. The bottom density value which is recorded in this diagram was measured at a point about 5 cm above the base of the snowpack.

The decrease in density values at the base of the snowpack, and the fact that they remain low during the entire winter until the onset of melting, is interpreted as due to drying action produced by the vapor pressure gradient in the snow. Figure 30 is one of the best available examples of drying in the bottom of the snowpack. Experiments underway at the University of Alaska indicate that the drying action extends into the soil below the snow (Benson 1967).

RECOMMENDATIONS

The boundaries between hard-packed, wind-drifted snow and the soft depth hoar snow cover of the forested areas should be more clearly defined.

The variability in the snowpack from one year to the next should be investigated by long term studies; as indicated by Freeman (1967) the 1966-67 snowpack was unusually thick.

The effect of wind on the snow as a function of altitude should be investigated in the land which experiences strong surface winds along the Delta River and Jarvis Creek. In particular, this study should be made in comparison with studies in other areas of interior Alaska which are rarely exposed to strong surface winds such as the lowlands in the Fairbanks-Ft. Wainwright area.

A particularly interesting and important feature in the Ft. Greely area is the lenticular shaped wind-packed snow shown in Figures 24-29. The discontinuous nature of these wind slabs appears to be associated with turbulent action of the surface winds. However, the specific cause-and-effect relationship should be sought. These features were partly covered by new snow when I observed them but they may represent wave-like forms like those seen on top of Mt. Wrangell (4200 m) after strong wind storms in the winter. I saw and photographed "waves" of hard-packed snow on the broad, flat caldera of Mt. Wrangell in December 1963 which, although larger in wavelength, have some points in common with the partly buried features near Butch Lake. The same "waves in the snow" have been seen and described by Dolgushin (1961, p. 67) in Antarctica. Instead of waves, the hard wind slabs may be lens-shaped in three dimensions, i.e. oval or circular drifts controlled by wind action in combination with shrub-like vegetation which serve to start or stop a particular wind slab. The three-dimensional geometry of these features should be determined and, if possible, related to turbulent winds which cause them.

The conditions which form these wind-packed lenses affect the entire snowpack in some places. In this sense they are like the snow dunes observed on some arctic lakes (Benson 1967, p. 46-49). This differs from the general case in which a low density depth hoar layer is present underneath a wind slab.

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