OBSERVATIONS ON THE GROWTH PROCESS AND STRENGTH CHARACTERISTICS OF SURFACE HOAR

R.M. Lang[1], B.R. Leo[2], and R.L. Brown[3]

ABSTRACT

A field study conducted during the winter months of 1982-83 and 1983-84 at the Big Sky Ski Area, Big Sky, Montana, indicated that nocturnal clear-sky radiative heat loss from the snow surface did not necessarily predispose condensation onto the surface, even in the presence of temperature gradients in excess of 200°C/m. The initiation of "surface hoar" growth corresponded to a variety of atmospheric and snow surface conditions.

Mechanical shear strength tests, conducted on established surface hoar layers, indicated that although a layer would become visually undetectable, shear strength remained too low to measure for extended periods of time.

INTRODUCTION

Surface hoar crystals are hexagonal plate-type crystals which form by deposition of water vapour onto the snow surface during the night. Due to their lack of intercrystalline bonding and weak attachment to the surface, accumulations of surface hoar are mechanically very weak. When such layers are buried by subsequent snowfall, they provide excellent failure planes; the disaggregate crystals may act as lubricating layers, increasing the potential for slab avalanches. These same hoar crystals may also form a deposit on the surface of aircraft, changing the aerodynamic properties of the wings sufficiently to cause take-off problems (Henson and Longley, 1944).

To our knowledge, no previous thorough quantitative study of surface hoar has been conducted. Qualitatively, it has long been understood that surface hoar normally develops during cold, clear nights, when radiative cooling causes the snow surface temperature to fall below that of the contacting air. If the boundary layer air becomes supersaturated with respect to the contacting ice surfaces, condensation occurs.

Proximate snowfall on a surface hoar layer results in an extremely unstable condition in the snowpack, conducive to slab avalanches. It has been suggested that "in many cases, surface hoar instability is relatively short-lived, lasting for only one or two storms," (Perla and Martinelli, 1976). This is a widely accepted hypothesis but relatively few clarifying measurements have been made.

The purpose of this investigation was to more fully understand the formation, physical properties and subsequent metamorphism of surface hoar. To accomplish this, a detailed field study has been carried out. A correlation of progressive surface hoar development with near-surface snow and air temperatures, snow surface temperature, initial snow surface conditions, lower air movement, and general atmospheric conditions was determined. Shear strength tests were conducted on established hoar layers and observations were made in order to determine the conditions under which the layer would metamorphose to a more stable form.

SITES AND INSTRUMENTATION

Night-time growth observations were made at a large, topographically flat area, Big Sky Ski Area, Big Sky, Montana. The area is relatively free from any obstacles which could cause significant back-radiation to the snow surface. Measurements were made on numerous occasions during the winter months of 1982-83 and 1983-84, and in only a few cases did actual surface hoar development occur.

Profiles of temperature were obtained hourly by using two separate stacks of copper-constantan thermocouples (Fig. 1). Temperatures were obtained at .5, 1.0, 1.5, 2.0, 3.0, and 4.0 cm above the snow surface, at the surface, and at depths of 1.0 and 2.0 cm in the snow. During each experiment, one thermocouple was shielded with an aluminum cone in order to determine radiational effects on temperature measurements. No significant changes were detected at any level with this method.

[1]Graduate student, Civil Engineering and Engineering Mechanics, Montana State University, Bozeman, Montana 59717-0001.
[2]Ipso-Facto Photography, 420 Tower Road, Belgrade, Montana 59714.
[3]Professor, Civil Engineering and Engineering Mechanics, Montana State University, Bozeman, Montana 59717-0001.

Any significant near-surface horizontal air movement was detected by placing "flags" of net-type material at various levels.

Mechanical strength measurements were conducted on an undisturbed, north-facing slope. The standard shear frame (Roch, 1966) is considered by most to be "user-dependent", and consistently repeatable test results are very difficult to obtain. This mechanism was therefore considered unsuitable for our

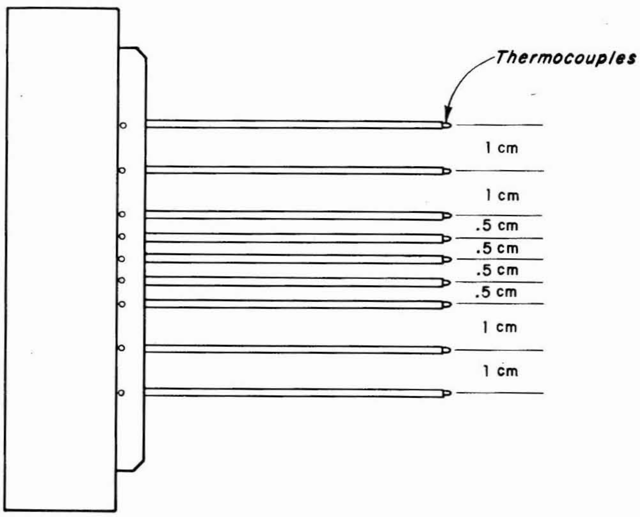

Figure 1. Thermocouple stack.

purposes. A modification of this device (Brown and Oakberg, 1982) was used instead. This revised shear frame provides a more equally distributed force throughout the snow sample than does the former model by eliminating the compartments and introducing a series of small protrusions, each of which absorbs a small portion of the compressive force exerted on the sample (Fig. 2). A further improvement is achieved by relocating the "pull" device and gauge to the base of the frame so that angular deviations from layer parallel do not occur, reducing "user-dependence", and giving a more consistently accurate measure of actual shear strength.

The area of the modified frame is .0001 m^2. The maximum variation on a given layer at a certain stage, when performing ten tests as suggested by Perla (1977), was less than 200 Pa. A slow "rate of pull" was used, and tests were not limited to one "user".

Shear strength measurements and a photographic record of the deterioration of the hoar crystals were made on a weekly basis.

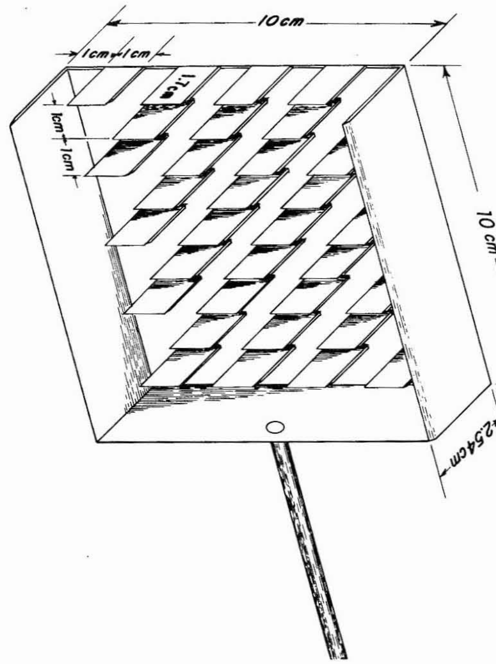

Figure 2. Modified shear frame, underside view.

CASE STUDIES

The results of two representative field studies are primarily described. The first is a night-time growth study in which surface hoar was deposited to an average height of 1.0-1.5 cm. The second describes a series of shear strength tests and a photographic record of an established layer.

Study 1, 29-30 January 1984;

<u>1500</u> <u>MST</u>; The snow surface was composed of freshly fallen, stellar and rimed-stellar snow. A heavy cumulus cloud cover, accompanying the passage of a cold front, had lingered all day.

<u>1800</u> <u>MST</u>; Only a few cirrus and altocumulus lenticularis cloud forms remained. The air adjacent to the surface was nearly isothermal at approximately -13.0°C, although a gradient in excess of +200°C/m had already been established between the snow surface (-14.8°C) and air .5 cm above the surface (-13.4°C). A negative temperature gradient had been established in the snow adjacent to the surface; snow temperature at 2.0 cm below the surface was approximately -14.1°C. (See Fig. 3 for temperature transitions with time).

<u>1900</u> <u>MST</u>; Skies were perfectly clear. The snow surface had cooled to -16.6°C. The adjacent snow and air were cooling at slightly lower rates. No hoar growth was noticeable.

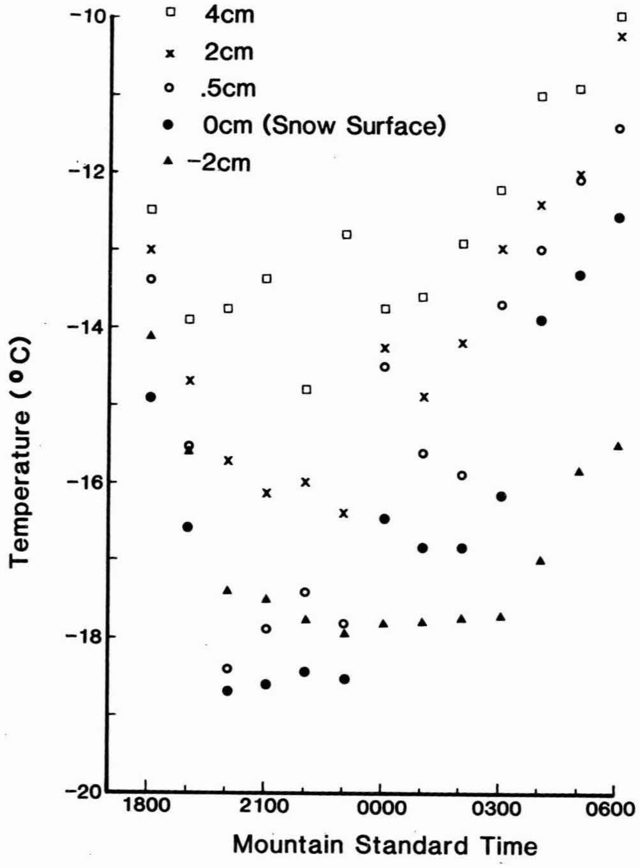

Figure 3. Temperature with respect to time at selected levels.

2000 MST; The snow surface temperature had reached it's minimum of -18.7°C. The air-snow surface temperature gradient was nearly linear at approximately + 140°C/m. Similarly the snow-snow surface temperature gradient was nearly linear at approximately -80°C/m. Sector plates had accumulated to an average height of .25 cm.

2300 MST; The snow at the measured depth 1.0 cm had become nearly isothermal with respect to the snow surface. The maximum temperature difference between the snow surface (-18.5°C) and the air at +4.0 cm (-13.2°C) had been reached. The hoar crystals were approximately .5-.7 cm high.

0000 MST; The maximum positive temperature gradient (+ 380°C/m) between the snow surface (-16.4°C) and the adjacent air at +.5 cm (-14.5°C) was attained. (Note: in other case studies the gradient here reached in excess of +300°C/m). A positive gradient (+ 70°C/m) had been established between the snow at -2.0 cm (-17.8°C) and the snow surface (-16.4°C). (This phenomena of temperature gradient "reversal" in the snow was consistently observed to occur.)

0300 MST; The hoar plates reached their maximum size of 1.0-1.5 cm in height. No secondary growth features were observed.

0600 MST; The experiment was terminated. No horizontal air motion within 1.0 m of the snow surface had been detected all night. A positive temperature gradient in both the snow and the air persisted until this time. A time average of the overall temperature during the maximum growth period (between 2000 MST and 0300 MST) is represented in Figure 4. Note that overall effect of the temperature gradient reversal in the upper 2.0 cm of the snow is an isothermal time average.

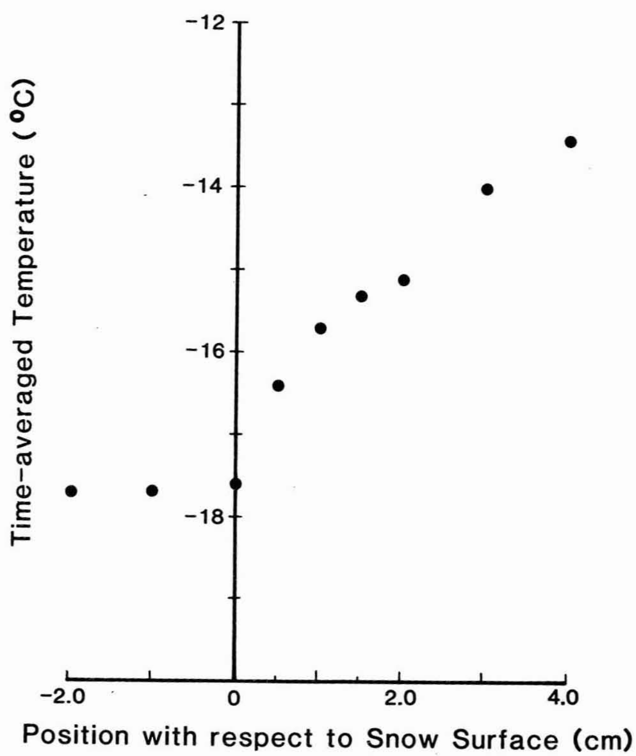

Figure 4. Time-averaged temperature profile for 2000-0300 MST, 29-30 January. Zero position is snow surface.

Study 2, 20 January - 10 March 1983;

20 January; Extremely well-developed surface hoar, averaging 4.0-5.0 cm in height, had

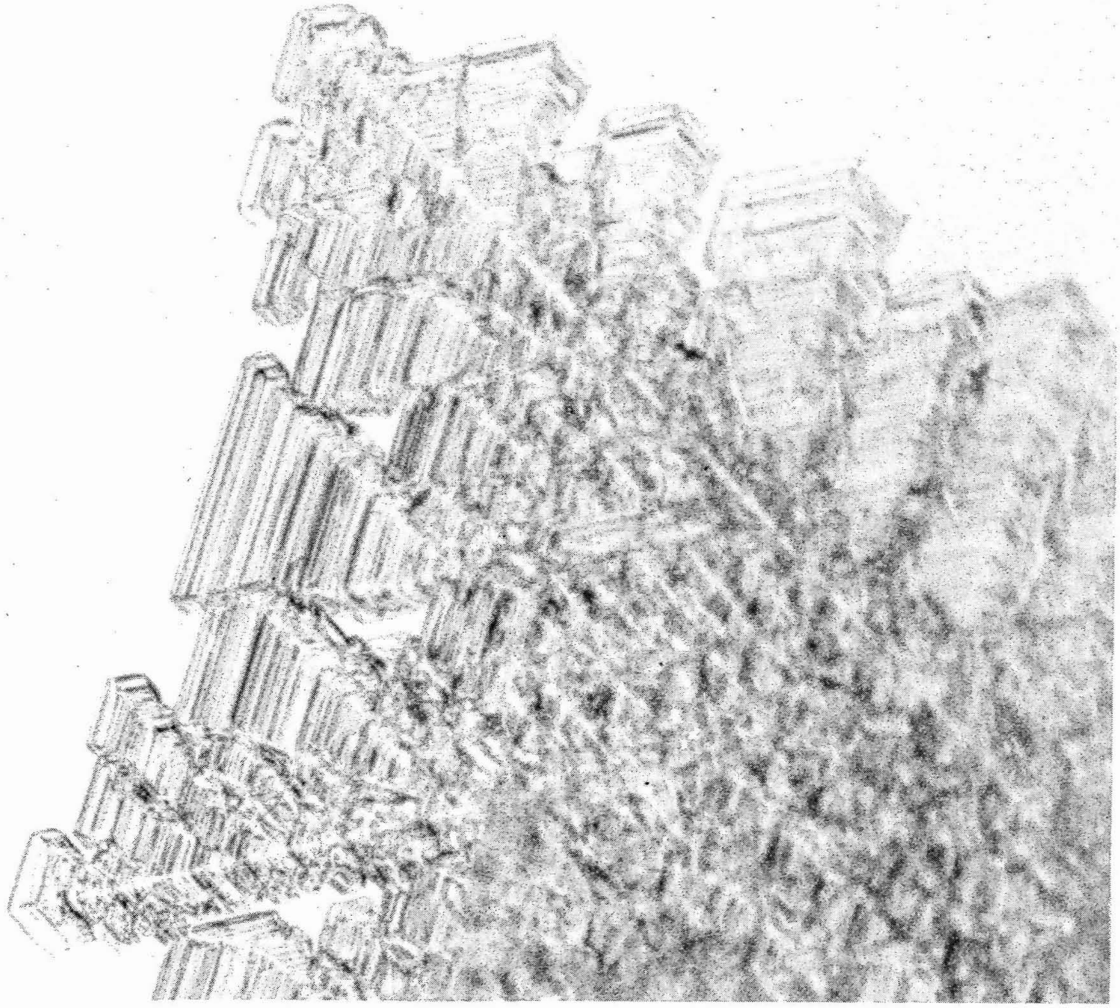

Figure 5. Upper portion of a single surface hoar crystal in situ, on the snow surface at 1100 MST, 20 January, 1983.

been deposited onto the snow surface during two previous nights (18-19 and 19-20 January). Time lapse photography of a single crystal in situ, between 1100 and 1400 MST, during which time clear-sky conditions persisted, was conducted in order to determine the effects of insolation on the crystal. The photographs revealed that the typical "feathery" or dendritic secondary growth features of the hoar are an aggregation of separately developing sector plates oriented either on or at 60° to the predominant a-axis (Fig. 5), as reported by Mason, et al, 1963. Three hours of insolation served to reduce the individual peripheral plates by insignificant amounts in comparison to the total size of entire crystal (Fig. 6). A temperature gradient, in excess of +200°C/m, between the base and top of the crystal persisted throughout this time.

<u>27 January</u>; The layer was covered by 10 cm of low density snow. Structural changes of the surface hoar were minimal. It was very well adhered to the adjacent snow above, but shear strength at the base of the layer was too low to measure (i.e. less than 25 Pa).

<u>3 February</u>; The peripheral edges of the crystals had rounded and pore spaces had become loosely filled with granular snow. Basal shear strength had increased to an average of 35 Pa.

<u>11 February</u>; The layer was buried under 46 cm of low density snow, but was still recognizable, although individual crystals had deteriorated into a more "axial" form. The average basal shear strength had slightly decreased to an unmeasureable average.

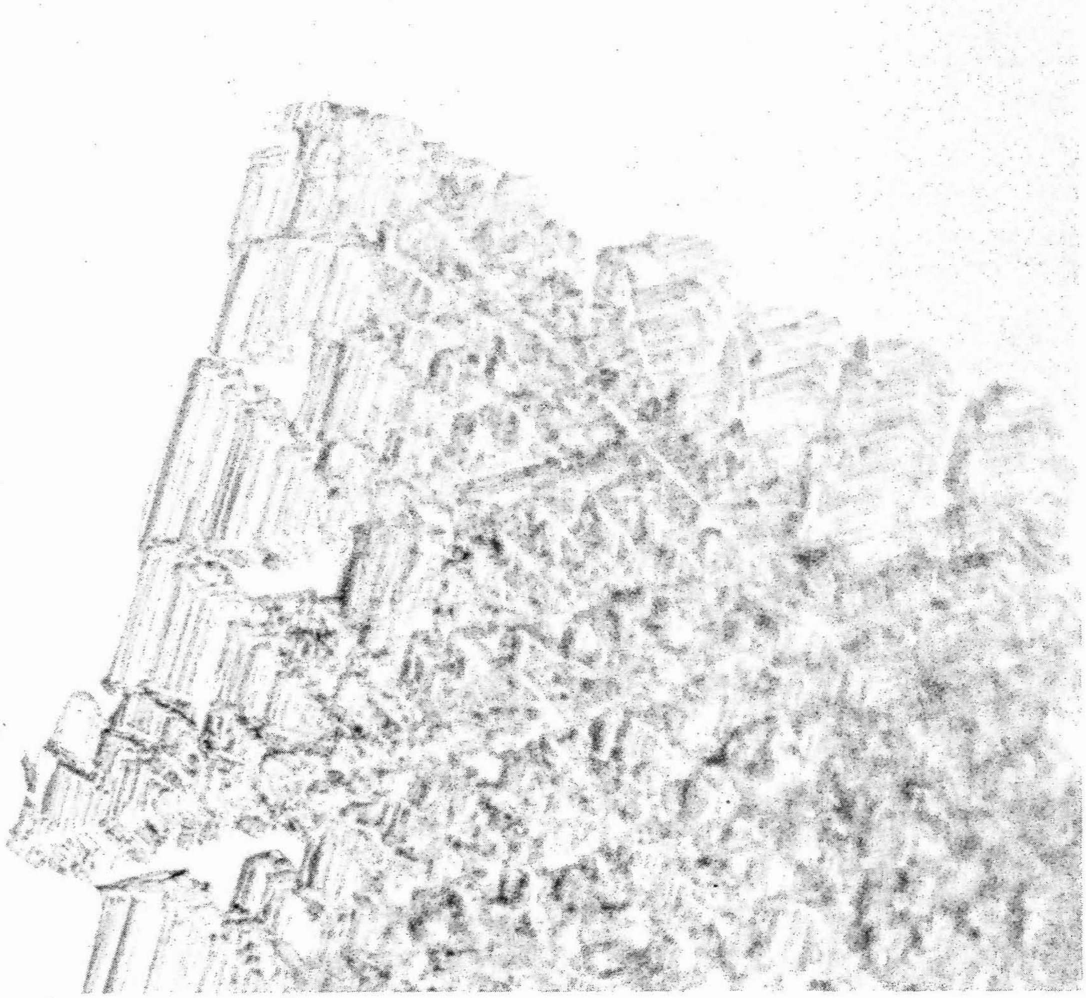

Figure 6. Same crystal as in Fig. 5, after three hours of insolation.

4 March; The layer had become nearly "hollow", (Fig. 7), i.e. the crystals had deteriorated such that only the largest remained visible. The snow below was now composed entirely of well-rounded grains. Basal shear strength had increased to approximately 110 Pa.

10 March; It was very difficult to detect the layer, yet the crystals were still quite large (Fig. 8). The layer was obscure due to the degree of rounding of the hoar edges and bonding of the hoar to well-rounded grains which had completely filled the pore spaces. Average basal shear strength was 390 Pa.

After this date, free water in the snow pack destroyed the layer.

DISCUSSION

It is a well-established fact that the basic habit of snow crystals grown under laboratory conditions from the vapour phase depends primarily on temperature (Nakaya, 1954; Kobayashi, 1961; Hallett and Mason, 1958). Observations in the present study agree very well with the transition temperatures reported by Kobayashi (1961), which induce changes in preferential growth along the a-axis (plates) to c-axis (needles or columns) growth or vice-versa. When the snow surface cooled to temperatures measured to be less than -21°C the end result was needle-like growth on the snow surface. During plate-like growth (i.e. what is considered to be actual surface "hoar"), measured snow surface temperatures ranged approximately between -12.5°C and -21°C. On numerous occasions, plates would begin to form on the snow surface, but as the snow surface temperature would continue to fall, needle-type growth would predominate.

In either case, the crystals would retain the orientation of their initial nucleation site; an axis of an existing surface crystal. Sector plates and needles were usually oriented within a few degrees of surface normal, i.e. along the temperature gradient. Crystals exhibiting secondary growth features, such as "feathery" or dendritic hoar or "rimed" needles, were oriented more randomly, but within 60° of surface-normal. (This phenomena is probably more gravity-related, rather than having some relationship to excess vapour density.)

It should be noted that temperature differences were found to exist between the surface of a newly formed ice crystal and the air-vapour region directly adjacent to the surface, although our equipment was incapable of reliably determining the exact magnitude of these differences. However, this phenomena suggests that any explicit formulation of the microphysics should consider the effect of interfacial resistance on the condensation rate; the temperature "jump" at the ice-vapour interface is due to the simultaneous processes of condensation and sublimation taking place at the interface (Schrage, 1953). Studies have shown that in a vapour-liquid condensation process, this effect is most pronounced at low saturation temperatures and for small values of the condensation coefficient (Minkowycz and Sparrow, 1966), which is certainly the case for ice crystals grown from atmospheric vapour.

A large near-surface air temperature gradient, due to nocturnal clear sky conditions, is insufficient in itself for significant condensation onto the snow surface to occur. Any slight horizontal air motion near the surface was observed to prohibit growth (due to vapour removal), although temperature gradients would increase by nearly threefold.

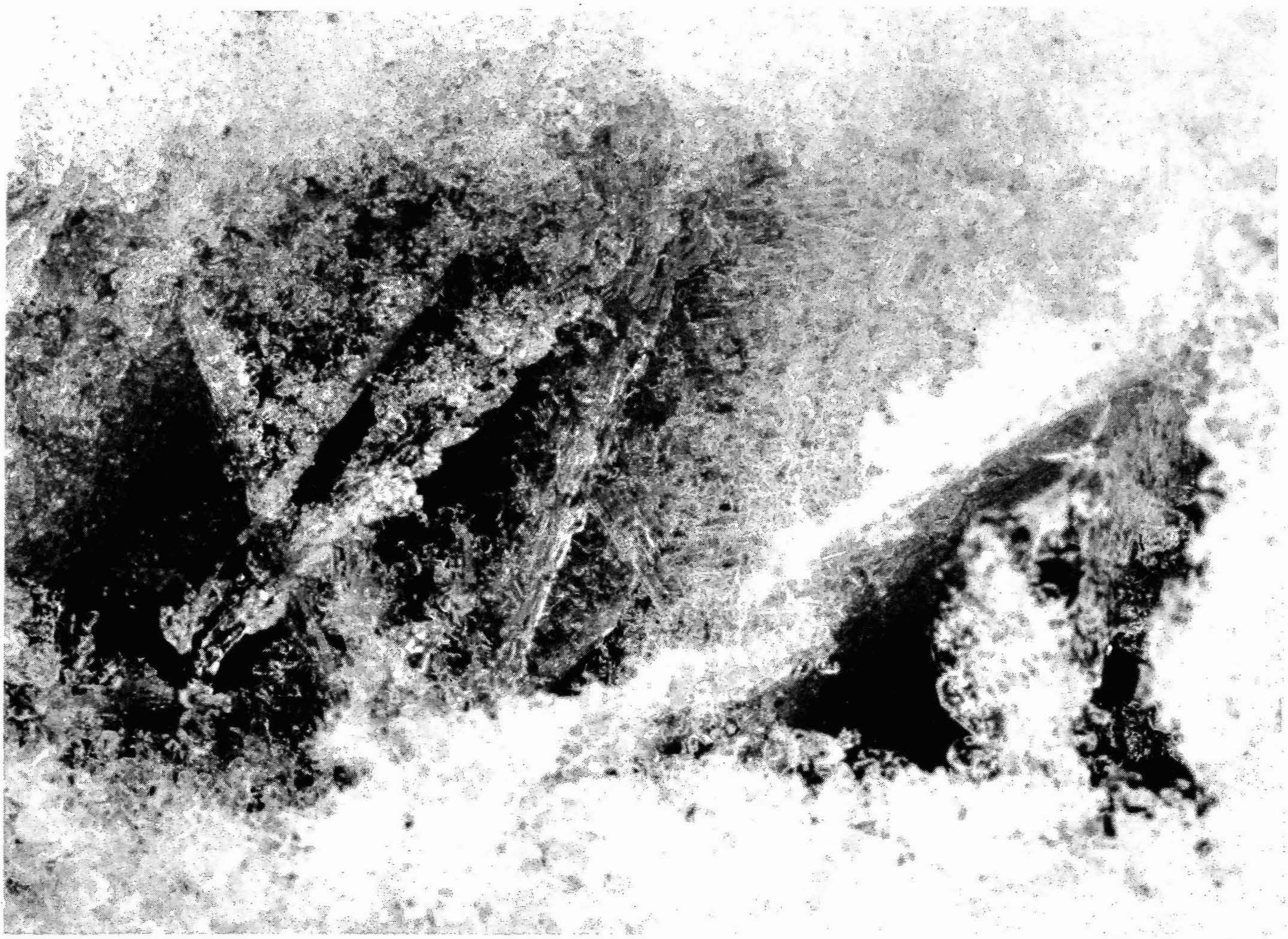

Figure 7. In Situ surface hoar layer, 43 days old.

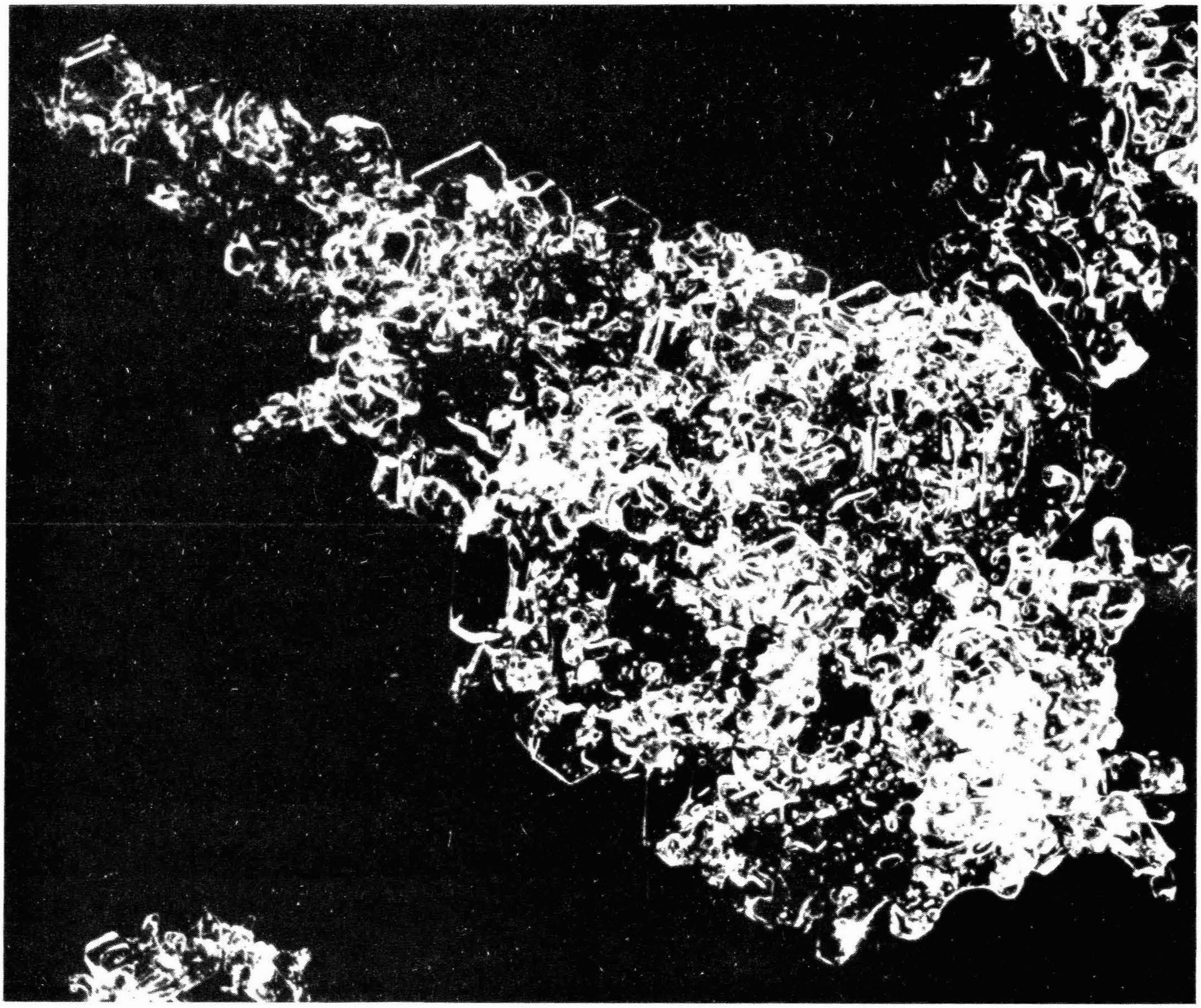

Figure 8. Single surface hoar crystal, approximately 2.6 cm in height, 50 days old.

Cloud cover conditions during the day must also be taken into consideration. If overcast skies prevail during the day, then subsequent clearing of the cloud cover at night causes the snow surface to cool rapidly to the dewpoint. Such conditions normally occur after the passage of a cold front, during which time the air near the snow surface acquires a high humidity due to heavy cloud cover and/or recent snow accumulation associated with the front. After the frontal passage, air pressure rises, skies clear and temperature drops. This sequence of events may not be endemic to more humid regions, or prerequisite during spring conditions, when surface hoar may develop at temperatures near 0°C.

It is also noteworthy that, although the net loss of heat from various ground surfaces during a high cirrus-type cloud cover is reported to be as great as when the sky is clear (Henson and Longley, 1944), the presence of high cirruform did interfere with long-wave radiational cooling of the snow surface, and hence vapour flux to the surface. Similarly, it was observed that even during rapid growth rates, hoar would not form within concavities on the snow surface, which implies that back radiation from within an incurvature is sufficient to prevent adequate surface cooling.

The assumption that surface hoar instability rapidly subsides is extremely dangerous. Our studies indicate that hoar layers remain indefinitely in progressively more deteriorated forms, obscured by the presence of rounded grains which have either "sifted down" into the pore spaces or perhaps formed from the mass lost from the perimeters of the hoar crystals themselves. In all cases, a dramatic change in snowpack conditions, such as in the preceding example (Study 2), is required to completely destroy a hoar layer. Of course, the smaller the hoar crystals, the more rapidly they are obscured. In some cases, hoar layers may be nearly unnoticeable, even at the snow surface immediately after their formation. Unfortunately, the initial basal shear strength of all surface hoar, whether a small sector plate or a large dendrite, is nearly non-existent.

Field practitioners are strongly advised to mark surface hoar layers, regardless of the degree of the development of the hoar. Employment of some method of measuring shear strength should be routine in any stability evaluation.

In conclusion, it is sufficient to say that the snow surface is remarkably dynamic. Heat and mass transfer processes at the snow surface are not easily explainable and demand further attention.

ACKNOWLEDGMENTS

The authors would like to express thanks to the staff and management of the Big Sky Ski Area, whose cooperation was an invaluable asset to the project. This project was funded under NSF Grant No. CEE 7318476.

REFERENCES

Brown, R.L. and Oakberg, R. 1982. Personal Communication.

Hallet, J. and Mason B.J. 1958. The Influence of Temperature and Supersaturation on the Habit of Ice Crystals Grown from the Vapor. Proc. Roy. Soc. Lond, A(247), 440-453.

Henson, E.W. and Longley, R.W. 1944. Meteorology Theoretical and Applied. John Wiley & Sons, Inc., New York.

Kobayashi, T. 1961. The Growth of Snow Crystals at Low Supersaturation. Phil. Mag. 6, 1363-1370.

Mason, B.J., Bryant, G.W., and Von Den Heuval. 1963. The Growth Habit and Surface Structure of Ice Crystals. Phil. Mag. 8, 505-526.

Minkowycz, W.J. and Sparrow, E.M. 1966. Condensation Heat Transfer in the Presence of Noncondensables, Interfacial Resistance, and Diffusion. Int. J. Heat Mass Trans. Vol. 9, 1125-1144.

Nakaya, U. 1954. Snow Crystals. Harvard Univ. Press, Cambridge, Mass.

Perla, R.I. and Martinelli, M. Jr. 1976. Avalanche Handbook. U.S. Dept. Agric., Agric. Handb. 489.

Perla, R. 1977. Slab Avalanche Measurements. Canadian Geotechnical Journal. Vol. 14, No. 2, 206-213.

Roch, A. 1966. Les Variations De La Resistance De La Neige. Int. Ass. Sci. Hydrol. Publ. No. 69, 86-99.

Schrage, R.W. 1953. A Theoretical Study of Interphase Mass Transfer. Columbia Univ. Press, New York.