Studies on surface hoar : formation and physical properties
by Renee Maria Lang

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering Mechanics
Montana State University

Abstract:
Field studies on surface hoar were conducted during the winter months of 1982-83 and 1983-84, at the Big Sky Ski Area, Big Sky, Montana. 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.

The initiation of surface hoar growth was dependent on a variety of near-surface and atmospheric conditions. Nocturnal clear-sky radiative heat loss from the snow surface did not necessarily predispose condensation onto the surface, although near-surface air temperature gradients would be in excess of +200°C/m.

A steady-state approximation for conservation of mass and momentum, in conjunction with the temperature data, predicts that surface crystal growth cannot be a diffusion limited process.

STUDIES ON SURFACE HOAR: FORMATION AND PHYSICAL PROPERTIES

by

Renee Maria Lang

A thesis submitted in partial fulfillment of the requirements for the degree

of

Master of Science

in

Engineering Mechanics

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 1985

APPROVAL

of a thesis submitted by

Renee Maria Lang

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

May 15, 1985 — Theodore E. Lang

Date — Chairperson, Graduate Committee

Approved for the Major Department

May 15, 1985 — Theodore E. Lang

Date — Head, Major Department

Approved for the College of Graduate Studies

5-20-85 — M. Malone

Date — Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Dean of Libraries when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my permission.

Signature ______________________

Date 15 May 1985

ACKNOWLEDGMENTS

I would like to express thanks to Brian R. Leo for his special photographic skills, and to Dr. Robert L. Brown for allowing me the freedom to investigate this topic.

The work reported here was done under National Science Foundation Grant No. CEE 7318476.

TABLE OF CONTENTS

LIST OF FIGURES

Figures

ABSTRACT

Field studies on surface hoar were conducted during the winter months of 1982-83 and 1983-84, at the Big Sky Ski Area, Big Sky, Montana. 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.

The initiation of surface hoar growth was dependent on a variety of near-surface and atmospheric conditions. Nocturnal clear-sky radiative heat loss from the snow surface did not necessarily predispose condensation onto the surface, although near-surface air temperature gradients would be in excess of +200°C/m.

A steady-state approximation for conservation of mass and momentum, in conjunction with the temperature data, predicts that surface crystal growth cannot be a diffusion limited process.

CHAPTER ONE

INTRODUCTION

Surface hoar crystals are conventionally defined as plate-type ice 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 snow surface, accumulations of surface hoar form layers which are mechanically weak in shear. When such layers are buried by a subsequent snowfall, they provide excellent failure planes. The disaggregate crystals may act as lubricating layers, increasing the potential for slab avalanches. These same type of 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 my knowledge, no previous thorough quantitative study of surface hoar growth has been conducted. Qualitatively, it has long been understood that surface hoar crystals normally develop during cold clear nights, when radiative cooling causes the snow surface temperature to fall below that of the contacting air. If the interfacial air becomes supersaturated with respect to the contacting ice surfaces, condensation occurs.

Subsequent snowfall on a surface hoar layer results in a mechanically 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, yet relatively few clarifying measurements have been made.

The initiation of an avalanche is inevitably linked to shear failure within the snowpack. Hence, the shear strength of the various layers of snow within a seasonal snowpack is a reliable indicator of slab avalanche stability/instability, and has been investigated by many authors (Haefeli, 1939; Roch, 1966; Keeler and Weeks, 1967; Martinelli, 1971; Voitkovsky, 1977; Perla, 1977; Perla, Beck, and Cheng, 1982). Attempts to correlate shear strength to parameters such as snow density, temperature and crystal size have produced erratic results (e.g., Perla et al., 1982). The most significant comparative measure of shear strength within a given layer of snow seems to be the degree of intercrystalline bonding, which is directly related to crystal morphology.

Although all ice crystals which occur at atmospheric temperatures and pressure possess the same basic hexagonal crystalline structure (the hexad symmetry axis is the c-axis, and perpendicular to it are the three a-axes at 60° to each other), they exhibit a large variety of shapes. The more spherical forms of ice crystals are sometimes referred to as equilibrium growth forms, since they are known to develop under isothermal or near-isothermal conditions (Colbeck, 1982). These spherical grains are usually associated with a high degree of intercrystalline bonding. Within the snowpack, they develop at the expense of the more faceted forms. Layers of these grains or clusters will remain mechanically stable unless free water is present within the snowpack. Faceted forms of ice crystals, or the kinetic growth forms, can be completely cohesionless. This is especially true in the case of plate-type (i.e., preferential growth along the a-axes) ice crystals such as surface hoar. Furthermore, when the nucleation site of a surface hoar crystal is a pre-existing snow crystal, it is also ineffectively bonded at that point. Hence, once incorporated into the snowpack, a layer of surface hoar crystals form a shear failure plane. The layer remains weak until the individual crystals metamorphose into a more mechanically stable form. This, of course, cannot occur unless the kinetic growth form becomes thermodynamically unstable with respect to its environment.

The basic crystal habit of kinetic growth forms is governed by temperature (Nakaya, 1954; Shaw and Mason, 1955; Kobayashi, 1957, 1961; Hallett and Mason, 1958). Observed changes in habit are not a consequence of changes in the diffusion field but are dependent on some temperature sensitive property of the crystal surface (Mason et al., 1963). Under laboratory conditions, preferential a-axis growth was found to occur within two sharply defined temperature regimes (Fig. 1), 0°C to -4°C, and -10°C to -22°C (Kobayashi, 1961). The secondary growth features, such as the "feathery" or "dendritic" extensions of plates, commonly associated with surface hoar (Fig. 2), are a consequence of degree of excess vapour density. Hence, surface hoar growth should occur only at temperatures where the crystal may begin as a thin plate and at some degree of supersaturation (Mason et al., 1963).

However, the growth of ice crystals under various laboratory conditions cannot be expected to describe the condensation process at a snow surface of ever-changing temperature exposed to the atmosphere. 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. Shear strength tests were conducted on established surface hoar layers and observations were made in order to determine the conditions under which the layer would metamorphose to a more stable equilibrium form. A correlation of progressive surface hoar development on a snow surface, with near-surface snow and air temperatures, snow surface temperature, initial snow surface conditions, horizontal air motion, and general atmospheric conditions was determined. The temperature and condensation rate data were used concomitantly with expressions for conservation of mass and momentum, and diffusive vapour flux in order to estimate some of the broader aspects of mass transport phenomena at a snow surface.

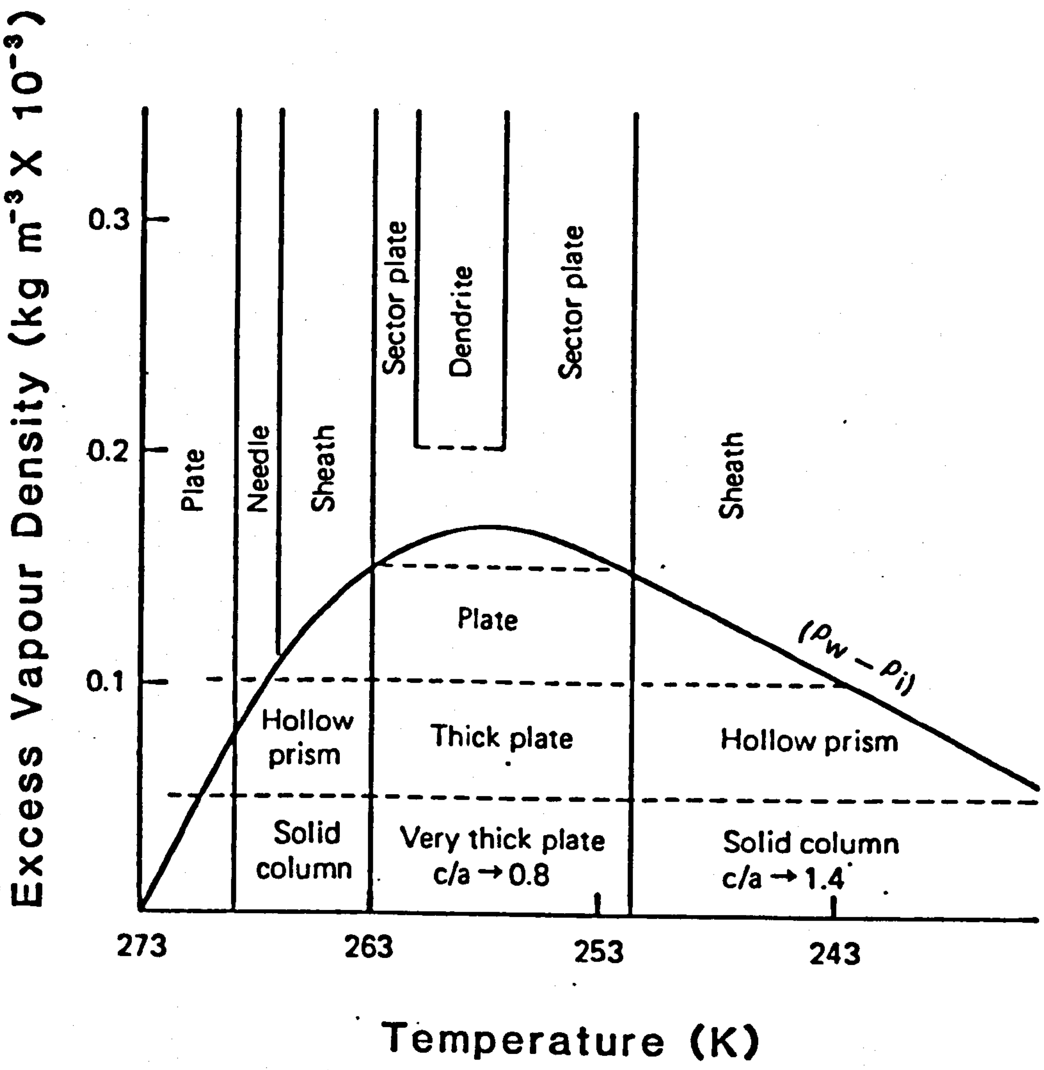

Figure 1. Crystal habit of ice grown in the atmosphere based on temperature and excess vapour density (Kobayashi, 1961).

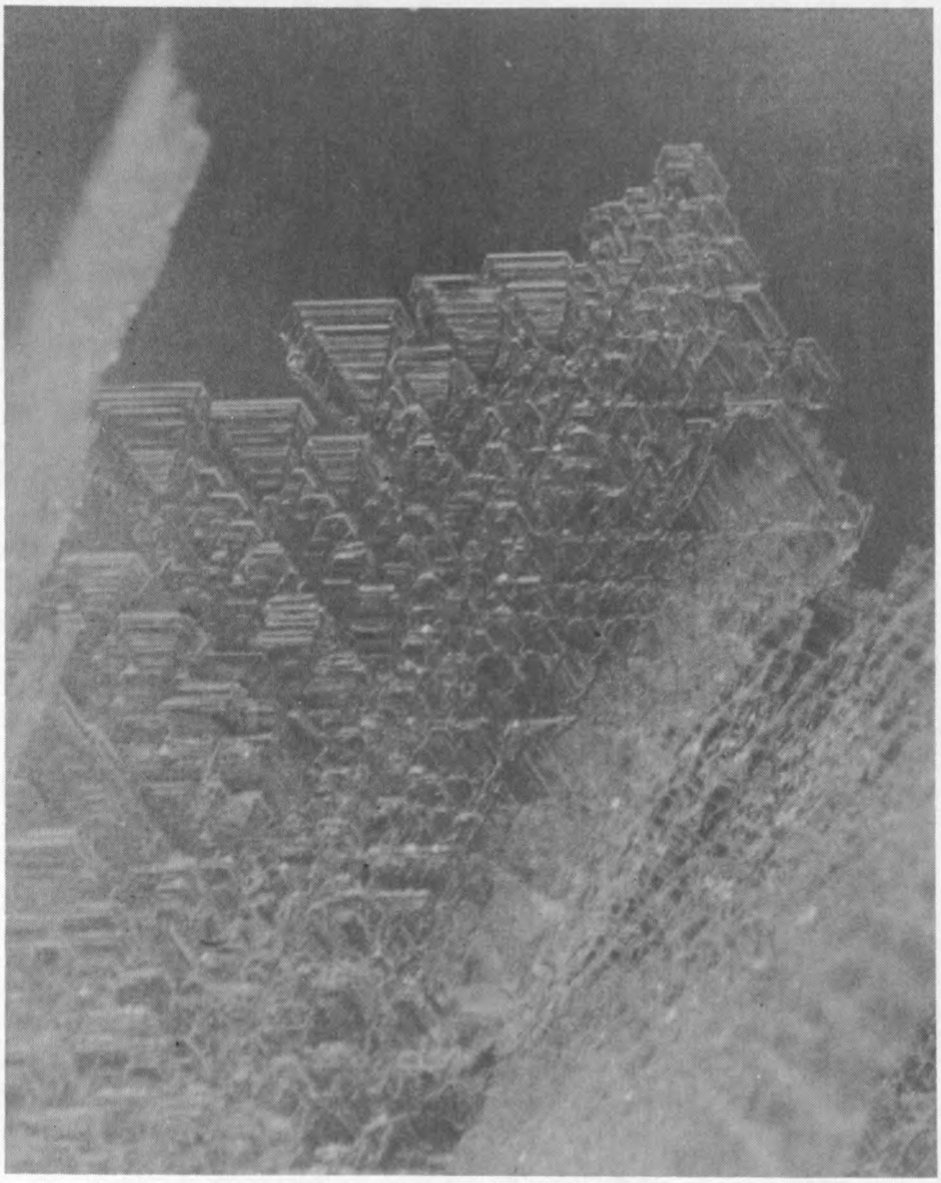

Figure 2. Group of surface hoar crystals exhibiting secondary growth features.

CHAPTER TWO

SITES AND INSTRUMENTATION

Night-time observations of surface crystal growth were made at a large, topographically flat area (elevation 2680 m) located within the 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. 3). 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.

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

Time-lapse photography was used, with limited success, in order to obtain an estimate of the condensation rate.

General weather patterns were also recorded.

Shear strength measurements on established surface hoar layers were conducted on an undisturbed north-facing slope located within the Big Sky Ski Area, Big Sky, Montana. Due to the fragile nature of surface hoar, it must be tested "in situ." Devices developed previously for testing the shear strength of alpine snow have not displayed consistent

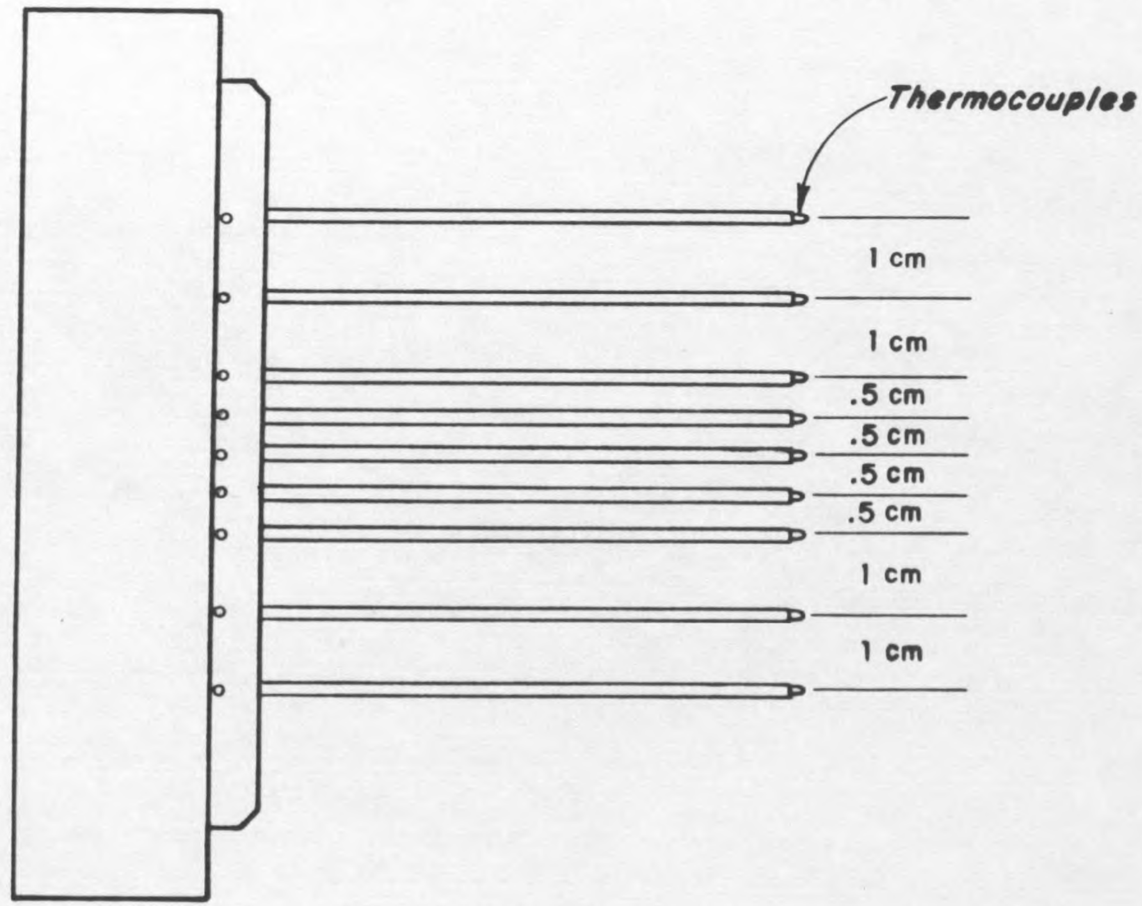

Figure 3. Thermocouple stack.

results. Furthermore, they are not sensitive enough to give a measurable value of shear strength for such low strength layers such as surface hoar. These mechanisms were therefore considered unsuitable. A modification of the device commonly referred to as the standard shear "frame" (Roch, 1966) was used instead. This revised shear "frame" (Brown and Oakberg, 1982) provides a more equally distributed force throughout the snow sample by introducing a series of small protrusions, each of which absorbs a small portion of the compressive force exerted on the snow sample during testing (Figs. 4 and 5). The "pull" device and gauge are located at the base of the frame such that angular deviations from a direction parallel to the layer do not occur, thereby 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 were made on a weekly basis.

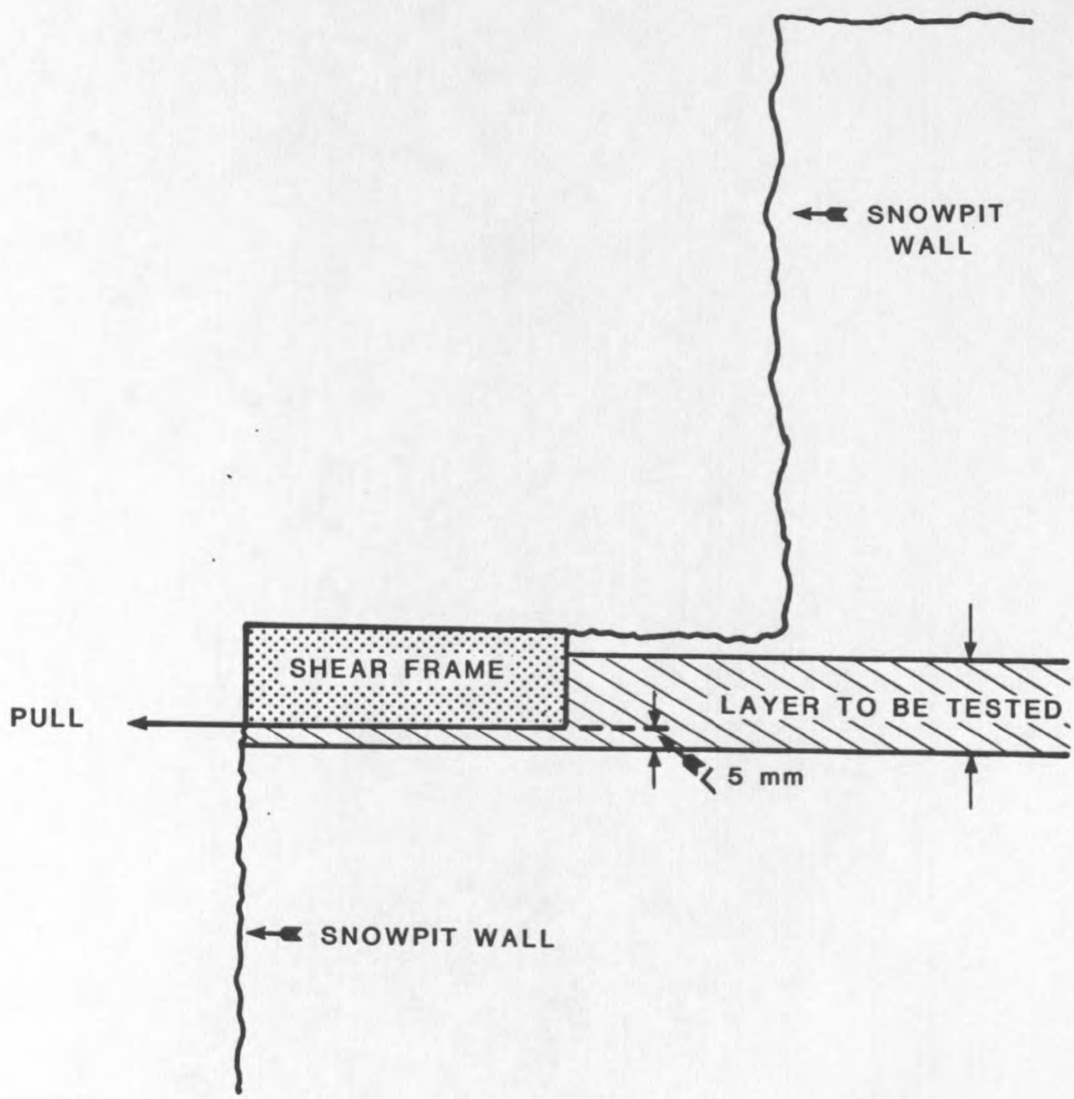

Figure 4. Use of shear frame.

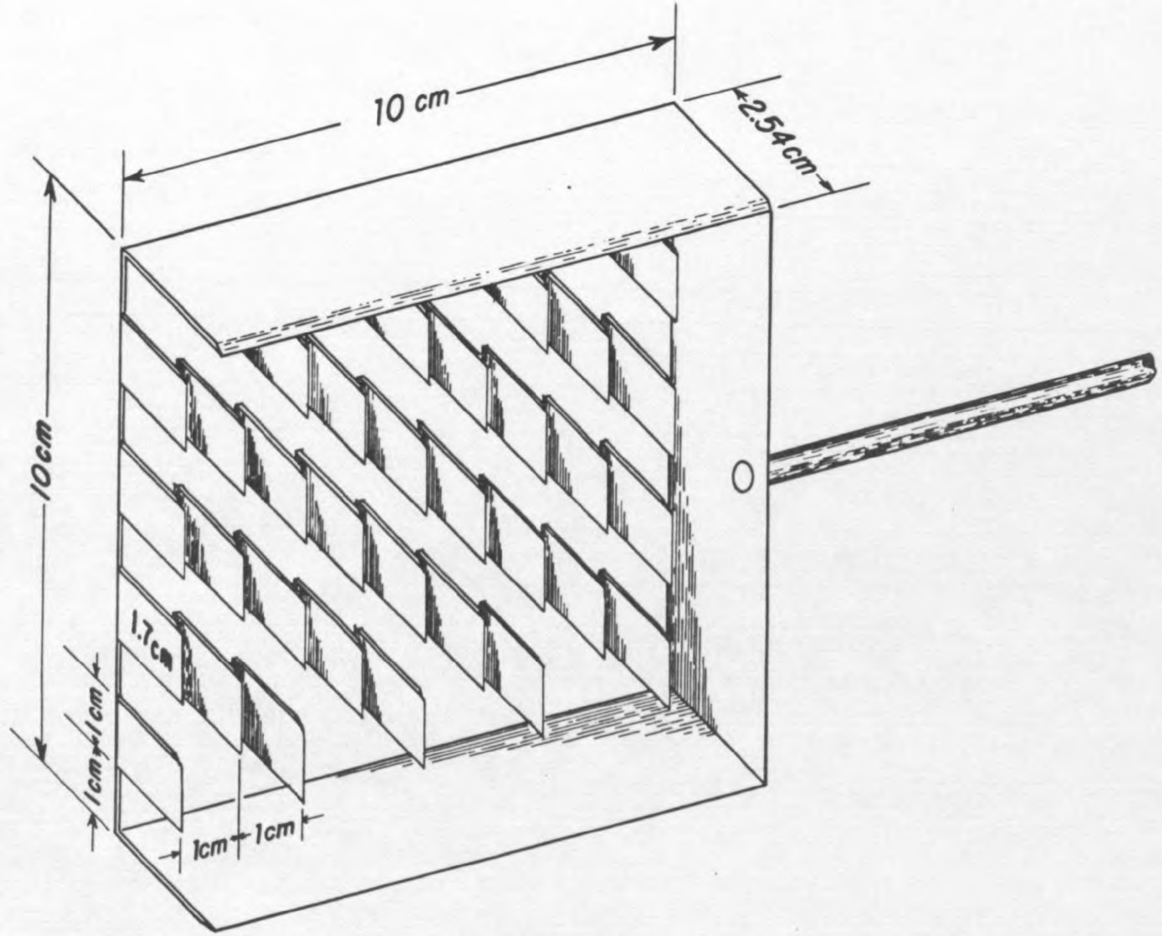

Figure 5. Modified shear frame, underside view.

CHAPTER THREE

CASE STUDIES

The results of three representative field studies are described. The first and second are nighttime growth studies in which surface hoar was deposited to an average height of 1.3 to 1.5 cm. It should be mentioned that in over 60% of observed cases, surface crystal growth did not occur under nocturnal clear-sky conditions. In many cases, needle-type growth (i.e., preferential growth along the c-axis) occurred, but shortly after sunrise the needles would be sublimated away. This may serve to explain why surface hoar is always described as plates (see for example, LaChapelle, 1969), while the term depth hoar is used to describe any kinetic growth form which develops within the snowpack. In all cases, measured temperature profiles were similar unless a strong breeze persisted or cirruform interferred. Time-averaged temperature profiles over the period of estimated maximum condensation were curve-fit by use of the Simplex method (Nedler and Mead, 1965; Caceci and Cacheris, 1984), adapted to run under the VAX/VMS operating system.

The third case study describes a series of shear strength tests and a photographic record of an established surface hoar layer.

Study 1, 29-30 January 1984

1500 MST — 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.

1800 MST — Only a few cirrus and altocumulus lenticularis cloud forms remained. The air between 1.0 and 4.0 cm above 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; the snow temperature at 2.0 cm below the surface was approximately -14.1°C (see Fig. 6 for temperature transitions at selected levels with respect to time).

1900 MST — 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, but macro-photography revealed that sector plates had begun to accumulate (Fig. 7).

2000 MST — Skies remained clear. The snow surface reached its minimum temperature 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 — Skies remained clear. 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 (-12.8°C) had been reached. The hoar crystals were approximately .5-.7 cm high.

0000 MST — Skies remained clear. The maximum positive temperature gradient (+380°C/m) between the original snow surface (-16.4°C) and the adjacent air at +.5 cm (-14.5°C) was attained. (Note: in most other case studies when condensation occurred the gradient at this time would be 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 phenomenon of temperature gradient reversal was also consistently observed to occur.)

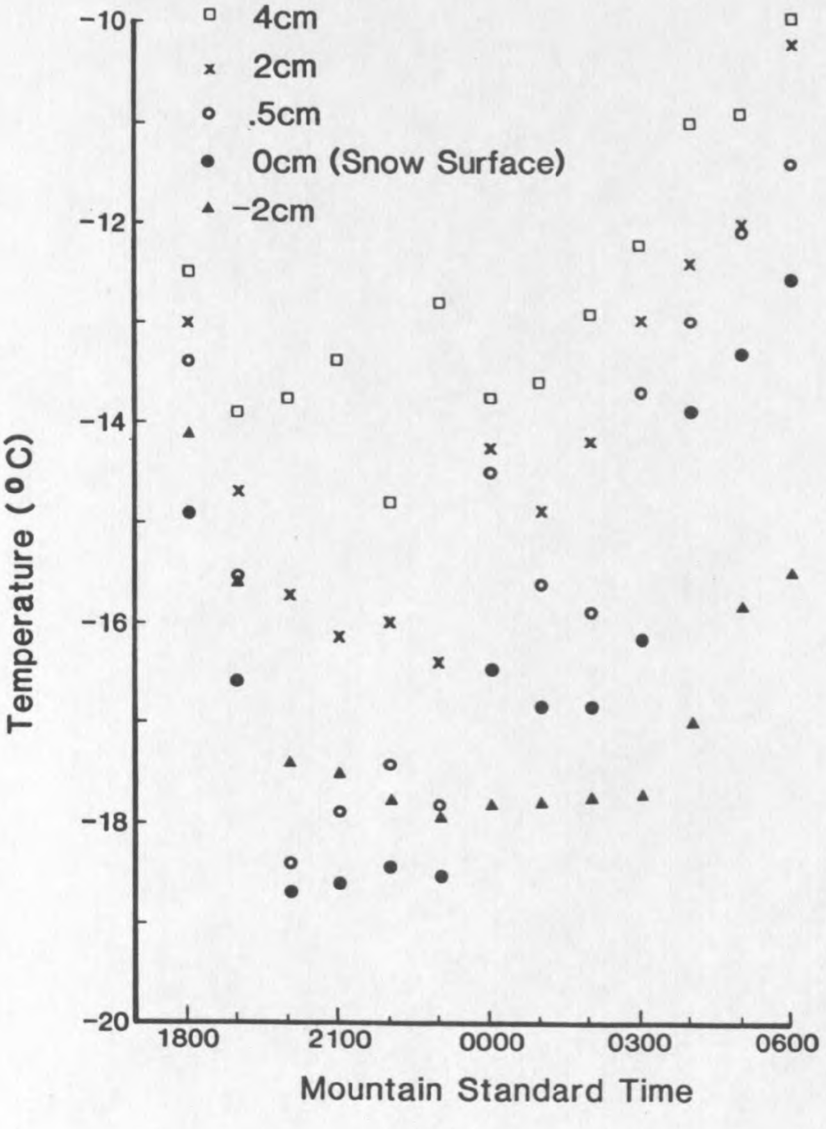

Figure 6. Temperature with respect to time at selected levels, 29-30 January 1984.

Figure 7. Accumulation of sector plates on the snow surface at approximately 1900 MST, 28-29 January. Wire diameter is < .5 mm.

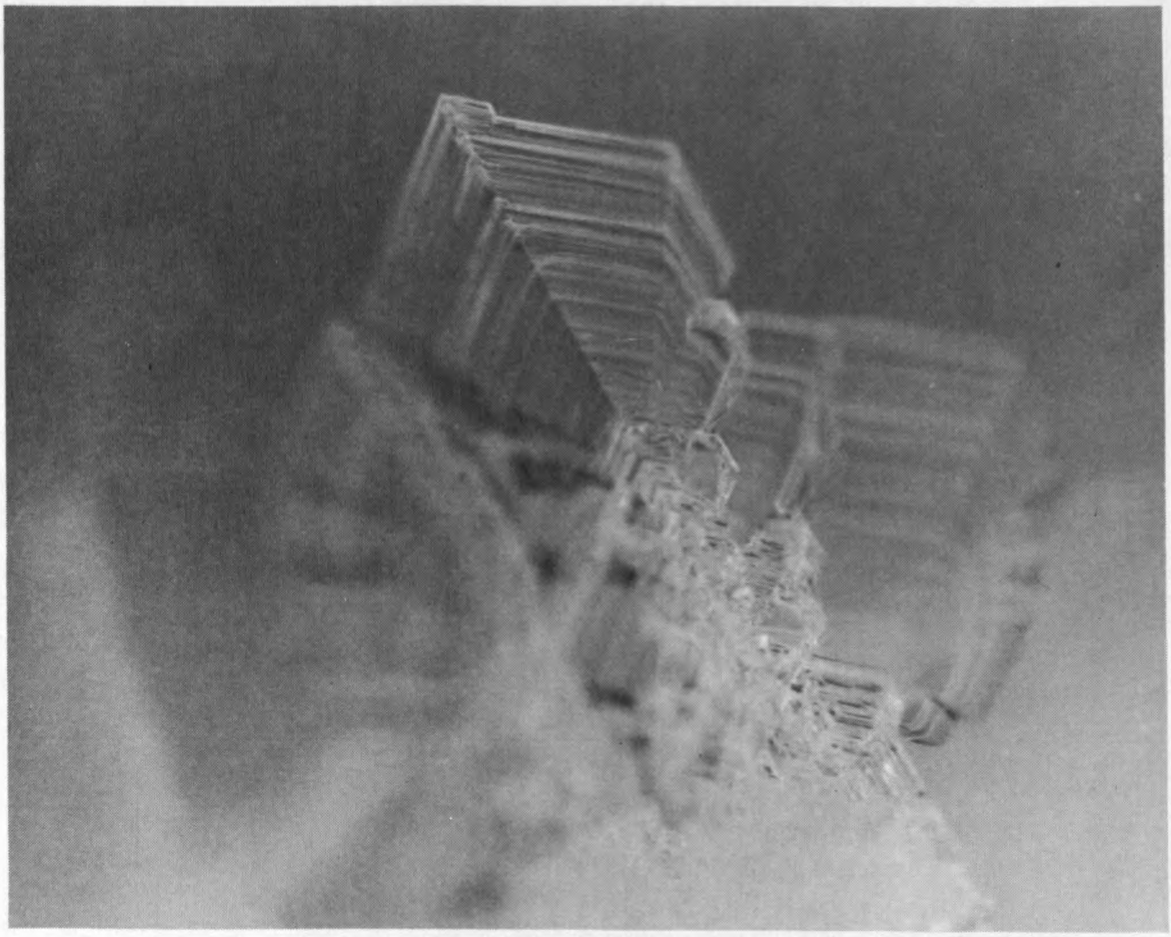

Figure 8. Sector plates, 0300 MST, 28-29 January.

0300 MST – Skies remained clear. The hoar plates reached their maximum size of 1.3-1.5 cm in height (Fig. 8). 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 air persisted until this time. Skies had remained clear all night.

A time-average of the overall temperatures during the maximum growth period (2000–0300 MST) is represented in Figure 9. Note that the overall effect of the temperature gradient reversal in the upper 2.0 cm of the snow is a near isothermal time-average. A curve-fit of the time-averaged temperature is represented in Figure 10.

Study 2, 27-28 February 1984

1500 MST – The snow surface was composed of stellar snow resulting from a storm which had occurred on 25-26 February. Cirrus cloud forms were present and a slight breeze persisted. Due to the frontal passage and the initial snow surface temperature (-9.7°C) hoar growth was expected. Two additional tests were conducted. A black plastic sheet 1 m^2 was placed onto a section of the snow surface, the plastic being intended to form a vapour barrier between the snow and the atmosphere. Hence if the vapour flux from the snow to the snow surface was significant in supplying vapour for condensation, then the amount of condensate onto the plastic should be minimal. Also, a stainless steel substrate 20 cm^2 was placed above the snow surface in order to determine how effectively the condensate would bond to the metal surface. Of course, due to the diverse properties of the various surfaces, the net accumulation of hoar was expected to be quite variable.

1800 MST – The breeze was persisting, but the skies had cleared. A temperature gradient of approximately +380°C/m had been established between the snow surface (-15.8°C) and the air at .5 cm above the surface (-13.9°C). A negative temperature

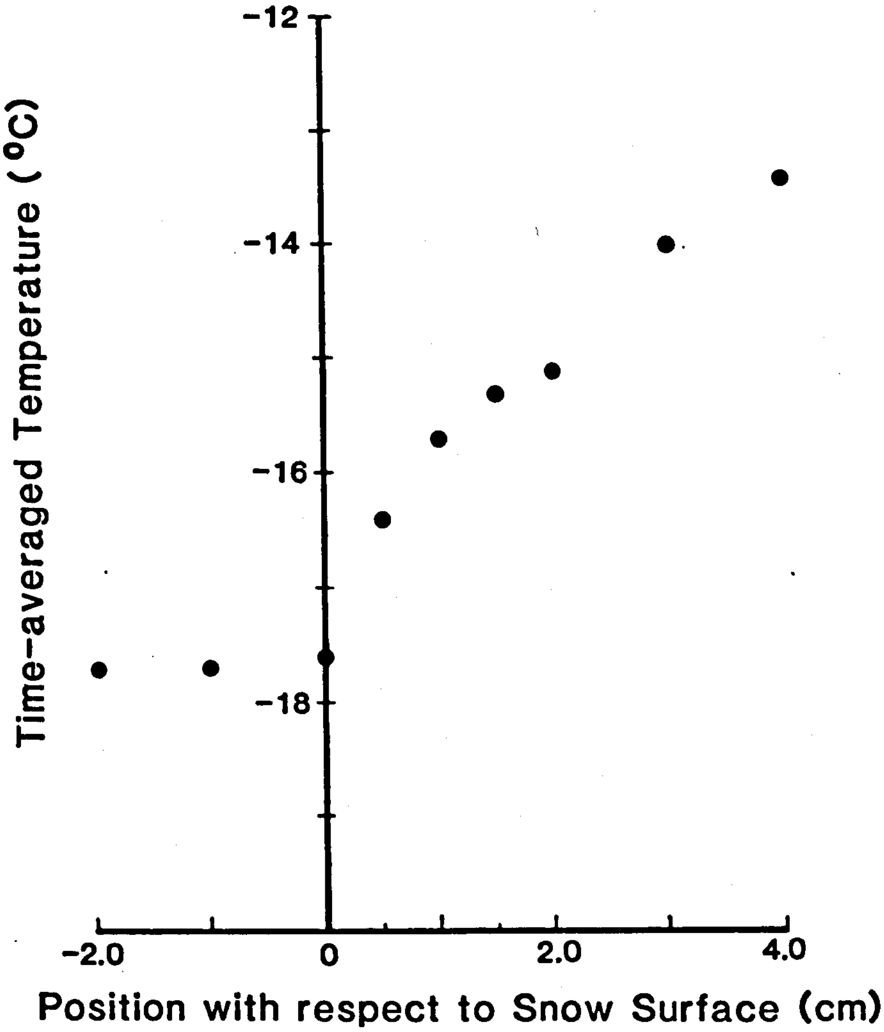

Figure 9. Time-averaged temperature profile for 2000–0300 MST, 29-30 January. Zero position is original snow surface.

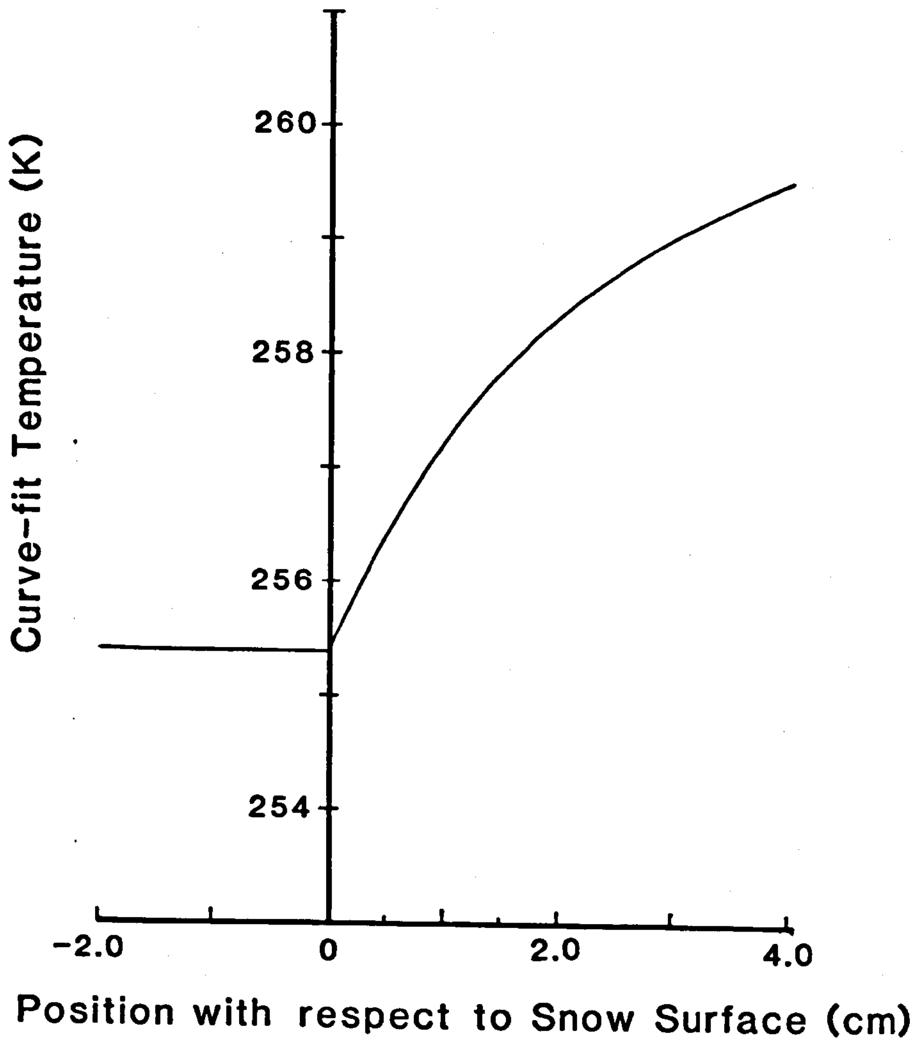

Figure 10. Curve-fit temperature profile. For $z > 0$, $\Theta \doteq (6.86z/(2.64 + z)) + 255.55$.

gradient (approximately -99°C/m) had been established in the snow adjacent to the surface.

1900 MST — No breeze was detectable. The snow surface had continued to cool to approximately -18.7°C. The air had cooled very rapidly at the levels less than 2.0 cm, such that the temperature gradient in the air was approximately linear at +161°C/m. Similarly, a nearly linear negative gradient in the adjacent snow existed (approximately -108°C/m). (See Fig. 11 for temperature transitions w.r.t. time.) Skies were clear.

2100 MST — Sector plates had accumulated to an approximate average height of 0.5 cm on all surfaces. Skies remained clear and at this time a very large temperature difference existed between the original snow surface (-19.6°C) and the air at 0.5 cm (-16.5°C).

2200 MST — The air and snow at all levels reached their minimum temperatures. The snow surface temperature was at -20.5°C. Skies were clear.

0100 MST — The temperature gradient in the snow had reversed in the upper 1.0 cm to +5°C/m. The plates were approximately 1.0-1.2 cm in height on all surfaces. Skies remained clear.

0300 MST — The hoar plates reached their maximum average height of 1.2-1.5 cm. No secondary growth features were observed.

0600 MST — The experiment was terminated. Skies had remained clear throughout the night. No horizontal air motion was detected after 1900 MST. The plates were approximately the same size on all surfaces. The plates which had condensed onto the stainless steel substrate were more uniformly oriented in a surface normal direction, and were indeed firmly attached at their nucleation site.

The time-averaged temperature profile and curve-fit profile during the period of maximum observed condensation are presented in Figures 12 and 13, respectively. In