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Growth Characteristics of Hoarfrost With Respect to Avalanche Occurrence

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16. Abstract

Hoarfrost formation in a maritime inversion climate has been studied via inferred snow/air interface temperatures, vertical temperature profiles of the interface, and application of dew point hygrometry. Two dominant growth situations have been discerned. The first involved highly saturated air near the interface and strong radiational cooling of the snow surface, producing a wide variety of crystal sizes (1-6mm). The second showed strong radiational cooling of the snow surface in an undersaturated environment with secondary introduction of water vapour from the presence of supercooled clouds. The latter often showed accelerated growth, the formation of large dendritic crystals (8-15mm) in short time periods (less than four hours).

Subsequent snowfalls of increasing water equivalent on surface hoar beds resulted in numerous direct action avalanches. Threshold crystal size for bed layer weakness varied widely (0.7-15mm) and was related to old snow surface roughness and new snow precipitation characteristics.

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GROWTH CHARACTERISTICS OF HOARFROST WITH RESPECT TO AVALANCHE OCCURRENCE

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<u>FINAL PROJECT REPORT</u>

Research Project PS 385

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1. INTRODUCTION

Two deposited forms of snow exist, rime, and hoarfrost. The major distinction between these two types is the phase change of water for formation. Rime accretes on physical objects from turbulent transport of supercooled water droplets. As the droplets impinge on physical objects they freeze; rime exhibits an amorphous structure. Hoarfrost forms from the quasi-turbulent deposition of water vapour, directly onto a surface whose temperature is lower than that of the vapour. It exhibits crystalline structure typical of all ice grown from vapour. Much confusion is still found in the literature, especially those documents translated to English from Russian, as to which is rime and which is hoarfrost.

Hoarfrost growth cycles and related avalanche activity had been documented at Snoqualmie Pass, Washington during the 1982-83 winters by the WSDOT Avalanche Control Section (Breyfogle, 1983). Thirty percent of that winter's avalanche cycles relative to highway operations involved hoarfrost as a shear layer. As kinetic growth processes are less common to maritime climates, loading rates on these layers are critical in forecasting hazards to the highway. Contact with other practicing field personnel, Fitzgerald (1984) and Sundin (1985), in the intermountain region revealed few, if any, avalanche events related to buried surface hoar layers.

Nakaya (1954) related the first studies of hoarfrost during initial attempts to grow snow crystals from water vapour. A similarity in growth was noticed between artificially produced frost crystals and natural snowflakes. Buried layers of hoarfrost (surface hoar) have long been recognized as potential weak layers for avalanche initiation. The contributions of Lang (1985) have given solid evidence on the low shear strength of these hoar layers during different states of metamorphism. Gubler (1982, 1985) has developed remote sensing apparatus for avalanche warning systems which gives good correlation between relative humidity and inferred snow surface temperatures favoring hoarfrost deposition.

The purpose of the study was to develop a better understanding of the environmental relationships promoting hoarfrost accumulation. Dew point temperature, inferred snow surface temperature, and vertical snow/air temperature profiles were measured at the study plot. Preexisting snow surface density and metamorphic state were documented. Field studies were employed to relate measurable growth from observations in the study plot to remote sites. Fractureline profiles and water equivalent amounts were used to quantify the significance of surface hoar bed thickness with respect to avalanche occurrence.

2. SITE AND ENVIRONMENT

2.1 Introduction

The Snoqualmie Pass corridor, in the central Washington Cascades, occupies a broad topographical drainage system, with elevations ranging from 701m to 1920m. Average snowfall is 12m per year at the WSDOT study plot, 918m. The low elevation snow climate and proximity of avalanche slopes to Interstate 90 provides a unique avalanche control environment. Figure 2.1 relates the maritime nature of the climate for the last "average" winter and those months relative to hoarfrost growth. 1984-85 also showed the greatest number of hoarfrost producing nights during the study.

Relative humidity (RH) at the study plot during the morning observation averaged 81 percent during winter, 1985-86. Ample supply of water vapour is essential to any condensation process, and in part accounted for hoarfrost growth on 75 nights during the winters 1984-85 and 1985-86. The prevailing weather patterns, regardless of dominant climate, will dictate current snowpack metamorphism. This was well illustrated by Moore (1982), in his description of temperature gradient weakening of crusts in maritime climates. The formation of hoarfrost follows similar departures from the climate classification.

2.2 Inversion Climate

Major passes along the central Washington Cascades are highly subject to a boundary layer climate regime. This is induced by surface wind patterns governed by local east-west pressure gradients and differing free air wind direction and speed as described by Lachapelle, et al. (1978) and Marriot and Moore (1984). Despite the maritime nature of the climate, easterly surface flow often produces an inversion dominate climate below the 1190m elevation, where inverted lapse rates of 19°C per 1000m can occur. These inversion periods can be related to regional synoptic conditions, or can be nocturnal in nature. Hence the effect of the cold air regime can last from hours to multiple days (Marriot and Moore, 1984).

Hoarfrost growth was found to be strongly correlated with cold easterly flow. Growth was also found to be dependent on the elevational limits of the cold air, with 80 percent of the growth occurring in the inversion layer or along its peripheral boundaries. Effectiveness as an avalanche producer was determined by post growth weather and was less dependent upon elevation. Hoarfrost occurrence was typical of early and mid winter high pressure, November through February.

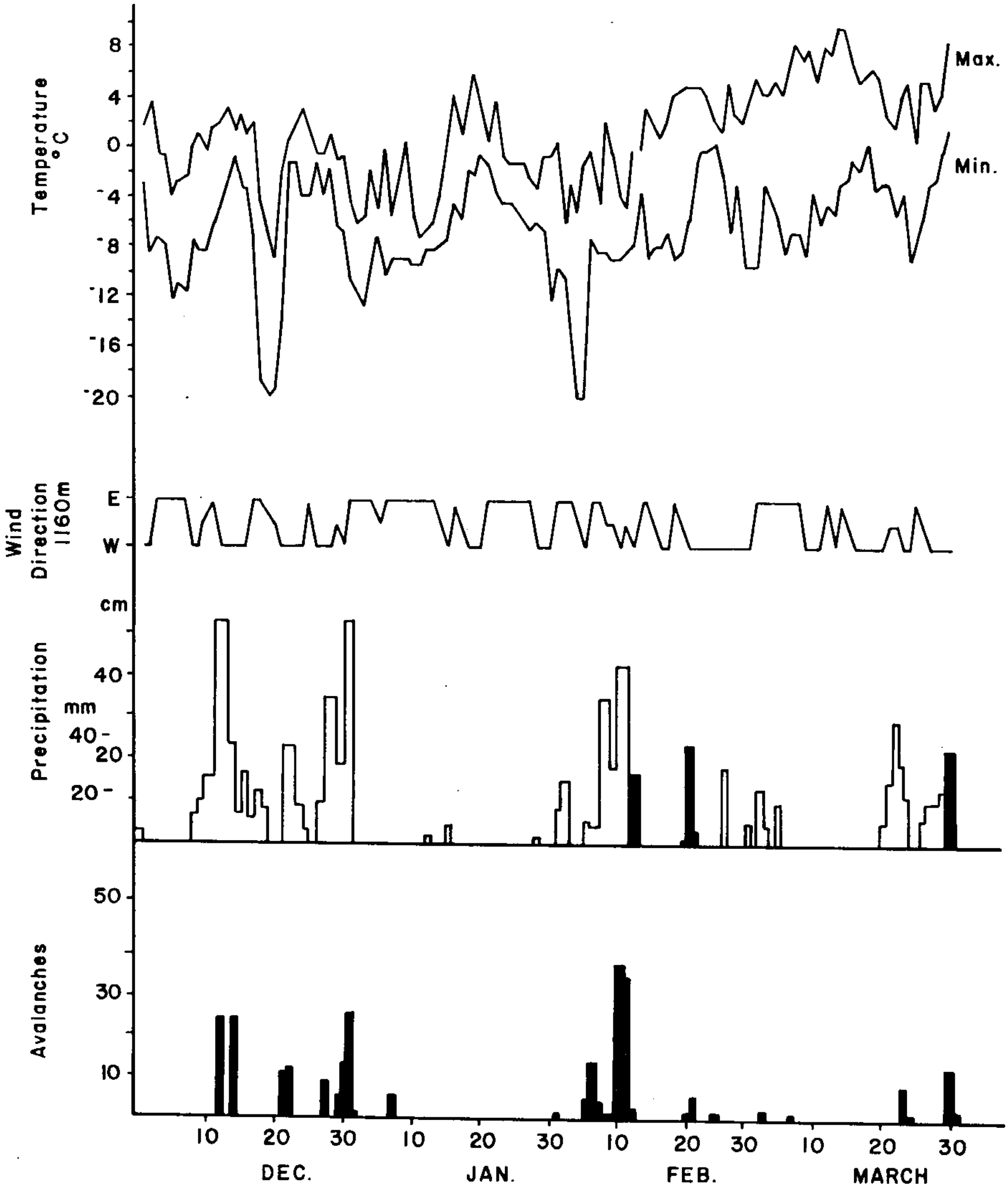


Figure. 2.1

Climate Parameters, Winter 1984 - 1985

Growth did occur during March, but no related avalanche events have been documented. Low elevation accounts for rapid sublimation of surface hoar beds during early spring. High pressure regimes which settle over eastern Washington are also significantly warmer than those of mid winter, deleting the basis for cold easterly flow.

2.3 Peripheral Zone

During regional inversions ($10^{1-3}km^2$) the occurrence of stratus cells and decks was common. Topographic inversions are semi-closed systems. Water vapour from evaporation, sublimation, and continued cold air drainage will be contained within in the system; nocturnal heat loss eventually cools the layer to the dew point. These are supercooled clouds with riming, and snowfall of very low density typical of developed stratus decks. The upper boundary layer of the inversion displayed fluctuating temperatures and humidity characteristics.

Field observations have shown that this boundary layer, termed the 'peripheral zone', provides a favorable depositional environment for hoarfrost. A similar situation has been reported by Linkletter and Warburton (1976) on the Ross Ice Shelf. Because the outer surfaces of stratus and fog are active radiators (Oke, 1978), a vapour gradient flux is established if the overlying air is less humid. The peripheral zone assumes the negative radiative flux of the stratus and the depth of cold air increases with time if wind speeds of the overlying air are low (<4m/s). In this situation, north to southeast free winds favor the development of cold air domes with a thickness of 60 to 100m.

Figure 2.2 shows the fluctuations during a period of multi-night peripheral zone growth. RH values are relatively low the night of January 7-8 with temperatures near freezing, no hoarfrost deposition was noted the day of the 8th. The night of January 8-9 air temperature dropped while the RH increased, vertical movement of the stratus placed the station at 1204m in the peripheral zone at 1900 to 2200 hours; a similar cycle could be noted on the following night. Growth occurred during both these periods (Figure 2.3). The fine coating of rime droplets indicated a semistationary position of the stratus, during deposition, followed by a rise in elevation. Conditions at the study plot, 918m, during the period were overcast or obscured with rime accretion to 15mm.

Horizontal as well as vertical motion of these cloud decks are dependent on many meteorologic factors. The rate of rise and stationary qualities of the stratus will be controlling factors in any growth situation. It suffices to say the fluctuations presented a highly variable factor of where hoarfrost deposition would be.

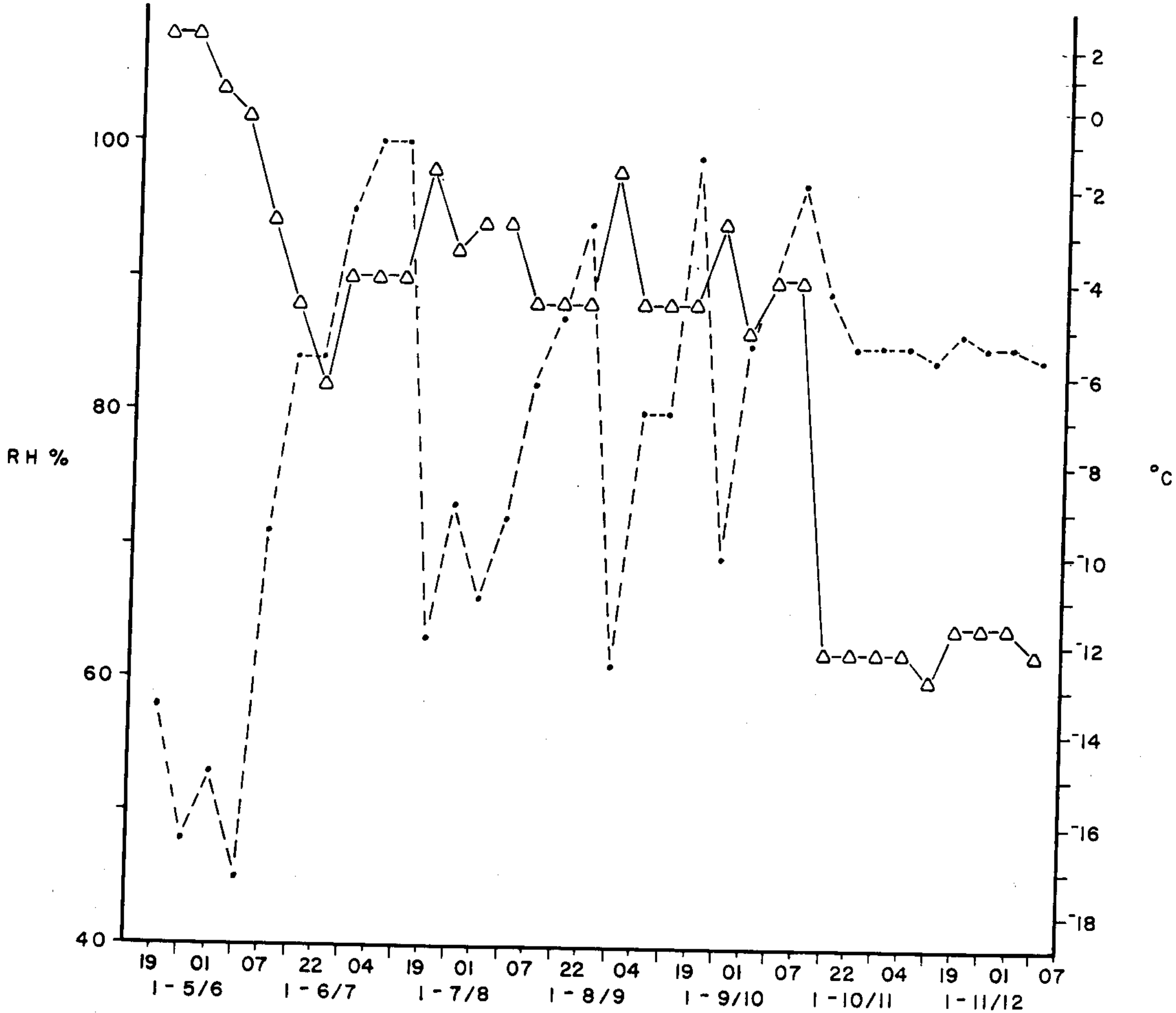
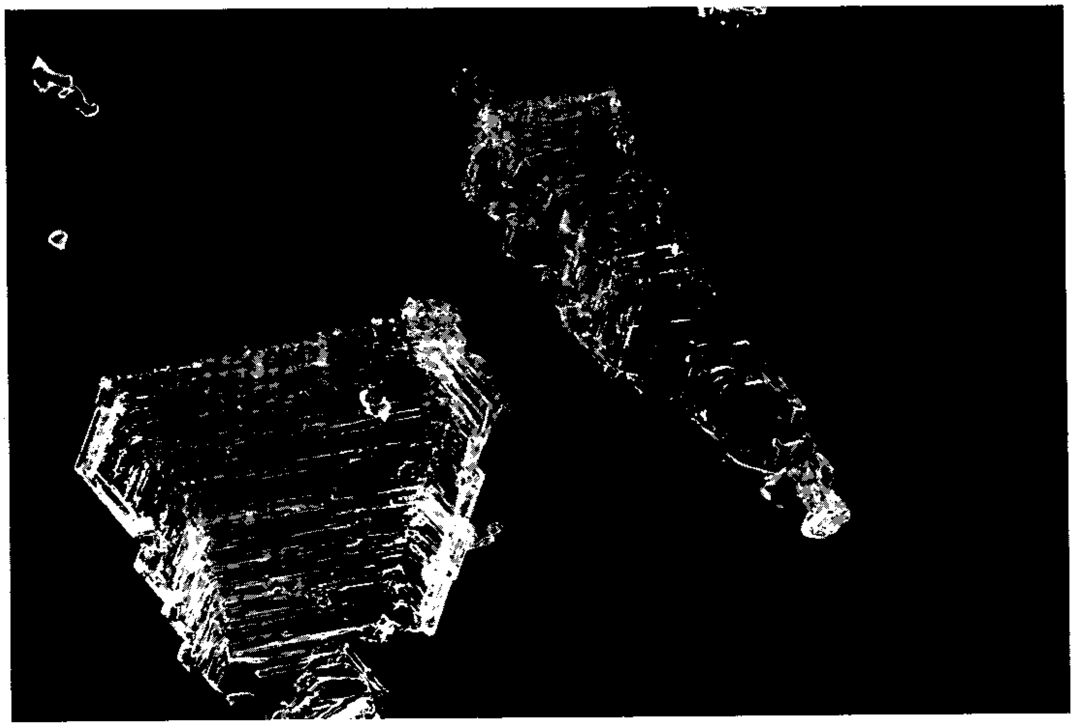


Figure. 2.2 Temperature (Δ) and RH (•) with respect to Time at 1204m
1 - 5/11 - 85



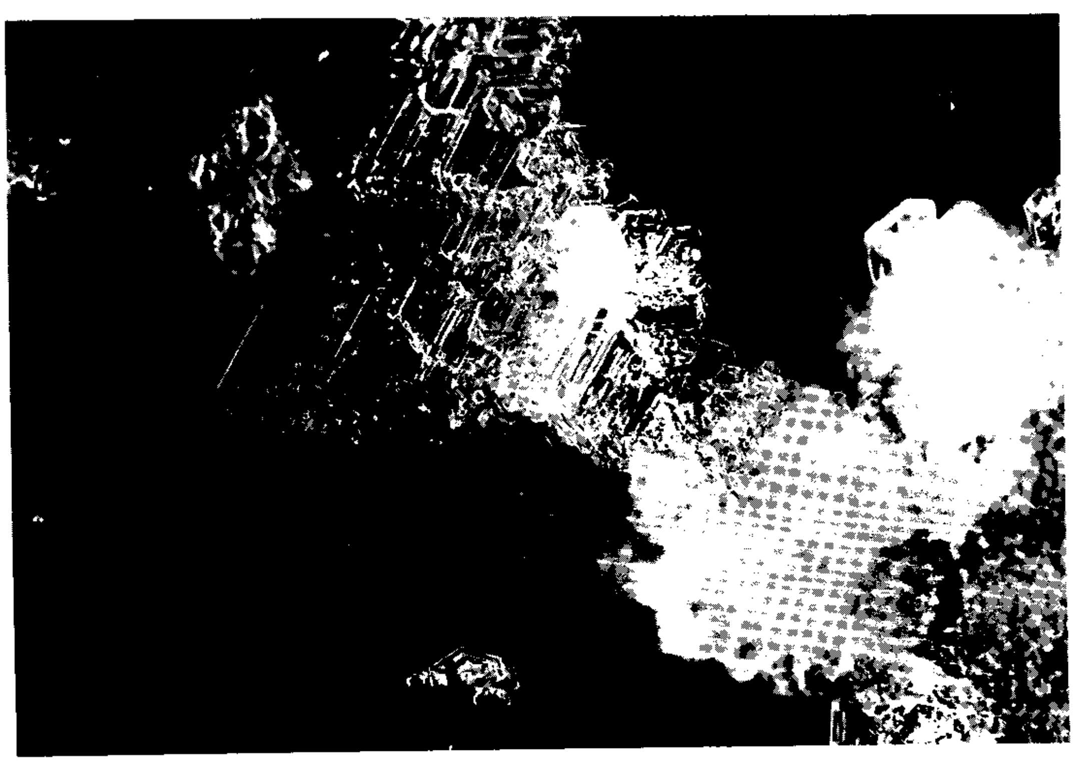


Figure 2.3

Peripheral Zone Growth 1-9/10-86

3. INSTRUMENTATION

3.1 Introduction

Instrument orientated field studies were conducted during the 1984-85 and 1985-86 winters at the WSDOT avalanche control study plot (918m) on Snoqualmie Pass. The choice of instrumentation needed to quantify values important to hoarfrost growth observed in the field, and to develop a basis to explain these mechanics in terms of the following:

1. Temperature depression.
2. Vapour sources.
3. Remote terrain.

3.2 Temperature Sensors

The inferred snow surface temperature system developed by Gubler (1982) was used for calculating the degree of radiational cooling. This system is based on the principle that a mirror has the same emissivity as snow. It allows the use of a single parameter in determining temperature depression, which proved desirable in terms of forecasting. A YSI 44003A thermistor was the sensing element, which is a low cost, easily replaceable unit. The thermistor was soldered to a 20 gauge land line and given ample coatings of 3M Scotchkote to ensure waterproofing. The thermistor bead rested within 1mm of the mirror when placed in the field. An adjustable clamp allowed the assembly to be raised or lowered on a vertical support; movement relative to the snow showed little effect on recorded temperature values. The actual depression temperature was considered important, so the land line was connected directly to a Rustrack #288 stripchart recorder, giving a continuous record of radiational cooling. Gubler's apparatus incorporated an added thermistor which measured air temperature, the final value recorded being the difference between ambient and mirror temperatures. This sensor was used in January through March 1984-85 and again during November through March 1985-86.

To determine the validity of the inferred snow surface sensor, a thermistor stack was employed during the field studies of 1985-86. The device was similar to that of Lang (1985), differing only in the actual sensing units (thermistors vs. thermocouples). This device relates the temperature gradient vertically through the snow/air interface, numerically expressing the existence (or nonexistence) of the inversion layer necessary for hoarfrost crystallization. During selected nights, the thermistor stack was placed in the study plot, measuring temperature profiles at 5mm and 25mm above the snow surface and -10mm below the surface. From the previous year's study, it was noted that temperature variations with the mirror sensor would vary at the rate of 6^{o}C/hr during a five minute interval. The temperature average of a five minute period was decided upon in determining spot readings with the thermistor stack. This device was also used at remote sites for relating the effects of isolation on developed surface hoar beds.

3.3 Humidity Measurements

The amount of water vapour pressure present in the atmosphere is very difficult to measure accurately. During November 1985 an afternoon was spent with Phil Taylor, of Hydro-Tech, working the "bugs" out of the sensor to be used in this study. A direct comparison between a hand-held relative humidity probe and a dew point sensor showed a difference of 8 percent in a steady state environment. Application of the values found in this research were considered instrument specific.

Continuous humidity measurements were recorded at the study plot during the 1985-86 winter from mid-November until the end of March. A DEW-10 chilled mirror hygrometer (Figure 3.1) was used for this purpose, owing to the variation of water vapour pressure with temperature and continuity of data where temperature was a prime element. This was reflected in the analysis of data, as the correlation between dew point temperature and ambient, or inferred snow surface temperatures proved to be significant while the relationship between relative humidity and like temperatures was very low.

Factory specifications for proper installation required the sensor be mounted inside a duct with an aspiration rate of 45m/min; this was maintained by an exhaust fan placed near the top end of the duct. The sensor electronics were very temperature sensitive and produced erratic recordings when ambient temperatures were below 0°C. It became necessary to wrap the electronics (which were outside the duct) with a segment of heat tape, and over insulate this part to avoid heat contamination of the air being sampled. Excessive power needs and the stated problems created a "trade off" situation for desired data and environmental adaptability of the sensor. The assembled duct and sensor were mounted in the study plot on a free-standing rail to allow vertical movement of the unit.

The combination of equipment used and the topography of the study plot played an important role. The turbulent transport of air in the vicinity of the fan affected an area 25m in diameter. It became necessary to look outside this range to ensure accurate growth measurements. The study plot sits in a small depression, close to a meter lower than surrounding terrain, which had a marked effect on vapour transport. The plot is also surrounded by thick timber which showed continual lack of hoarfrost growth within 1m. The closest wind sensor was 244m higher than the study plot, leaving wind speed estimates to subjective means.

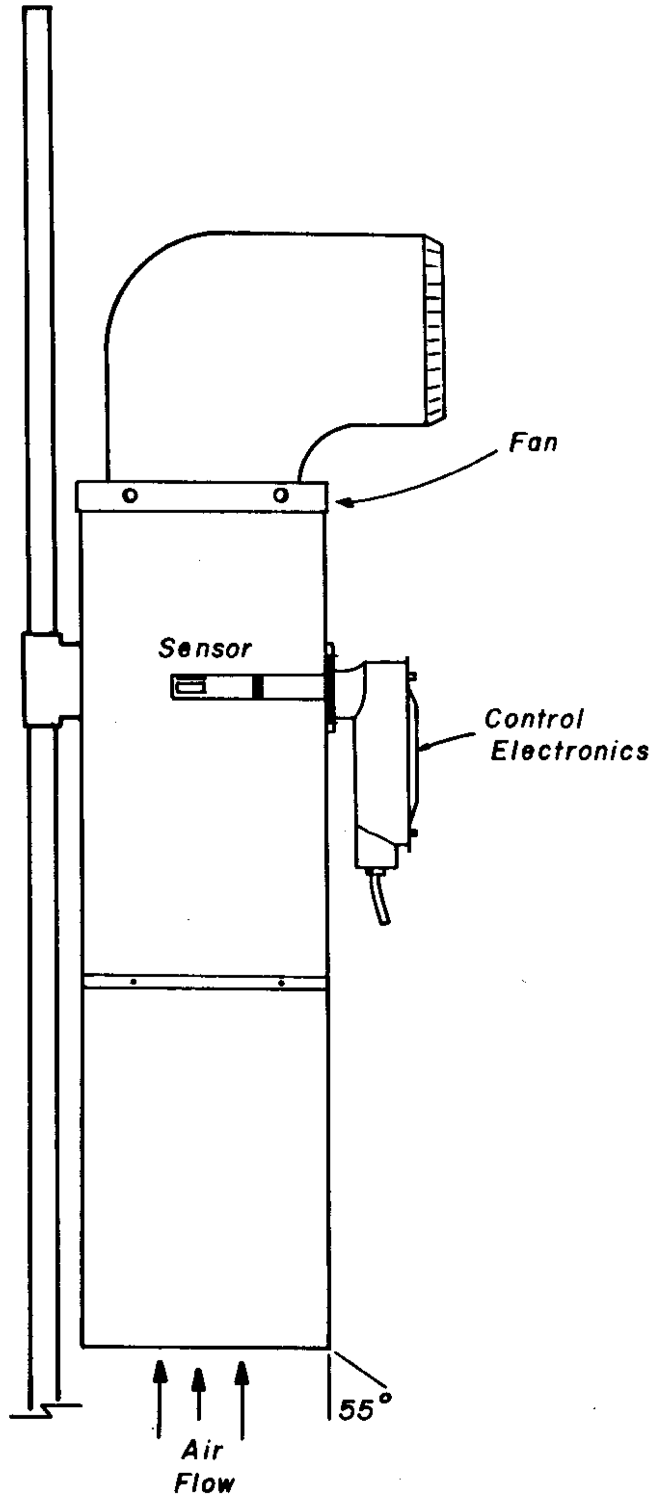


Figure: 3.1
Dew Point Hygometer

3.4 Photomacrography

To aid in the assessment of crystal growth, a photographic record was maintained for each hoarfrost growth cycle. A 35mm camera system, similar to that developed by Weir (1983), was used for this purpose. A high quality "macro" lens gave the best results when reversed; typical exposures were f5.6 - f8 at 1/15 of a second using Kodak Plus-X film. The low aperture range was necessary to avoid inherent diffraction, once past the 1:1 range of magnification (Lefkowitz 1982). A combination of reflected and low oblique transmitted illumination was used in the system, as described by LaChapelle (1969).

Disaggregated grain samples were photographed at 2.5x life size on the negative. This technique was favored because most field observers will examine individual crystals from this perspective. Knowing the degree of magnification also allowed exact determination of crystal size. Crystals less than 7mm were enlarged to 15x in the darkroom. The prints helped maintain a degree of objectiveness in data interpretation, which usually occurred well after field observations. Photomacrography was also used to compare growth and the varying states of metamorphism between the study plot and remote sites.

3.5 Field Studies

During periods of hoarfrost deposition, regular field trips to avalanche starting zones were conducted. Qualitative information from field studies proved invaluable in understanding the effects of aspect, elevation, and terrain on hoarfrost growth away from the study plot. Areas of study pertinent to highway operations were: Rampart Ridge, the East Snow Shed, Slide Curve, Airplane Curve, West Shed, Mile Post 50, and Granite Mountain slide paths. These sites were all below 1220m. For rapid access of a larger elevation range (976-1585m), the Alpental ski area facilities were used. Site specific information and snow surface characteristics were recorded where fresh accumulations of surface hoar existed.

4. CORRELATION TESTS

Data from the study plot was run through correlation tests to estimate the consistency of recorded values during nights on which hoarfrost crystallization occurred. Average values of the actual growth periods were used. A discussion of trends from the graphs follows (refer to Figures 4.1 through 4.9).

4.1 A strong linear relationship exists between air and mirror temperatures (snow surface). Mean depression from ambient temperature is 3.0°C. Limited growth in air temperatures <10°C suggests aridity of cold high pressure. Mirror temperature signature was very strong for low stratus and midlevel clouds, allowing good interpretation from the stripchart.

4.2 The inferred snow surface temperature is approximately 1°C warmer than the true snow surface. The mirror gives consistent and relative results for radiational cooling.

4.3 The mean mirror temperature was 1.6°C less than mean dew point temperature. Since dew point is a reflection on the amount of vapour pressure in the air, the snow is supersaturated. The most suitable growth range, defined by mirror temperatures was -7 to -13°C. These values were within the greatest saturation vapour pressure difference between water and ice and consistently produced the largest crystals.

4.4 For temperature ranges between -2 and -17°C, a minimum relative humidity of 70 percent was necessary for hoarfrost crystallization.

4.5 Supersaturation, with respect to ice, was calculated (Marriot, 1986, personal communication) by determining the actual vapour pressure of the ambient air and relating this to the saturation vapour pressure of the air at the snow surface. This was an estimated value, as no actual determinations were made at the snow surface. However, values derived in this manner did agree well with Mason, et al. (1962) and Kobayshi (1961) for the transition from sector plate to dendritic growth forms.

4.6 As expected, more available water vapour produces larger crystals. Wide scatter was due to turbulence at the snow surface and cloud cover, reducing radiational cooling. However, the development of large crystal growth over a wide range of supersaturation may be related to the rapid growth zone at air temperatures of -14 to -16°C for crystals grown from vapour (Hallet, 1965).

4.7 This reinforces the variability of hoarfrost growth with aspect and elevation. Most importantly, the mean crystal size in the study plot is smaller, by a factor of two, than those found at remote sites.

4.8 Conclusions

Though good correlation coefficients were found for some parameters (4.1, 4.2, 4.3, 4.6), the many variables that enter into hoarfrost formation make application of regression equations somewhat unrealistic for operational forecasting of growth. The lack of quantitative information on turbulence from wind is perhaps the most critical information. Wind instruments currently employed by avalanche technicians are not sensitive enough to measure the low turbulence that affects hoarfrost growth.

At best, the regression equations (4.1 and 4.3) could be applicable for remote sites where telemetry is available, and the starting zone areas are inaccessible. Given air temperature and dew point, a determination could be made if hoarfrost has formed. Added intuitive interpretation on the part of the technician would provide the most meaningful analysis.

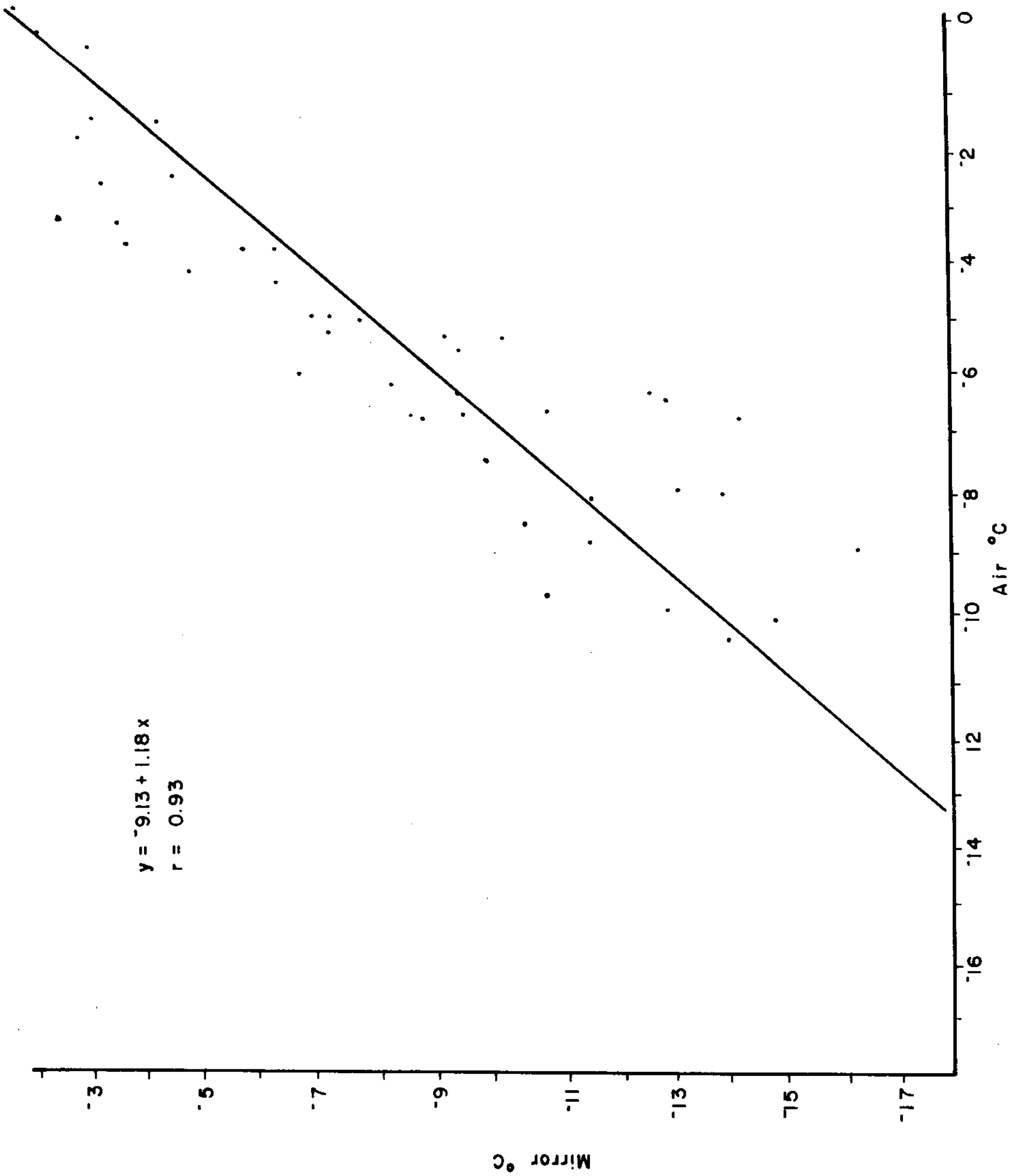


Figure 4.1

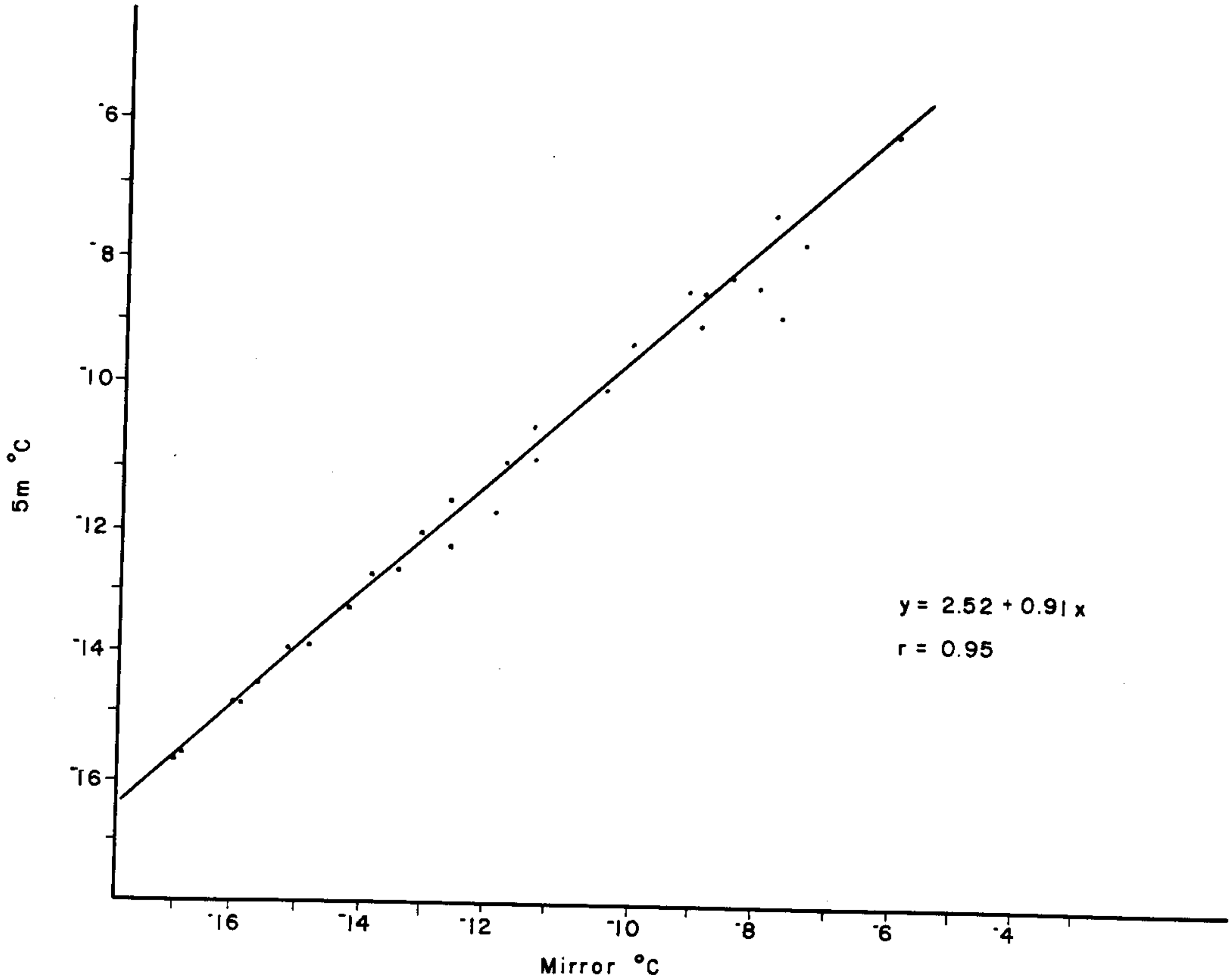


Figure 4.2

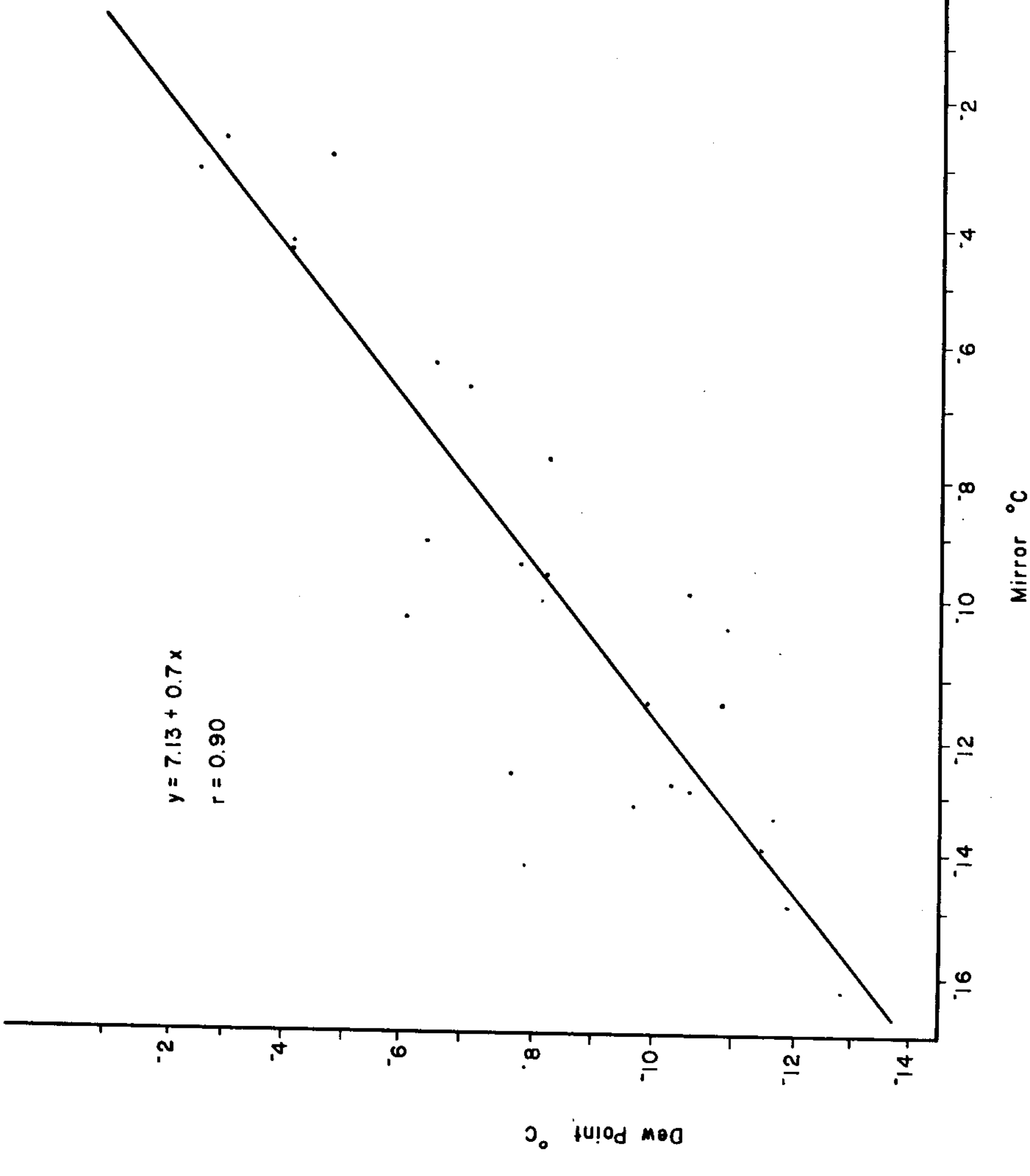
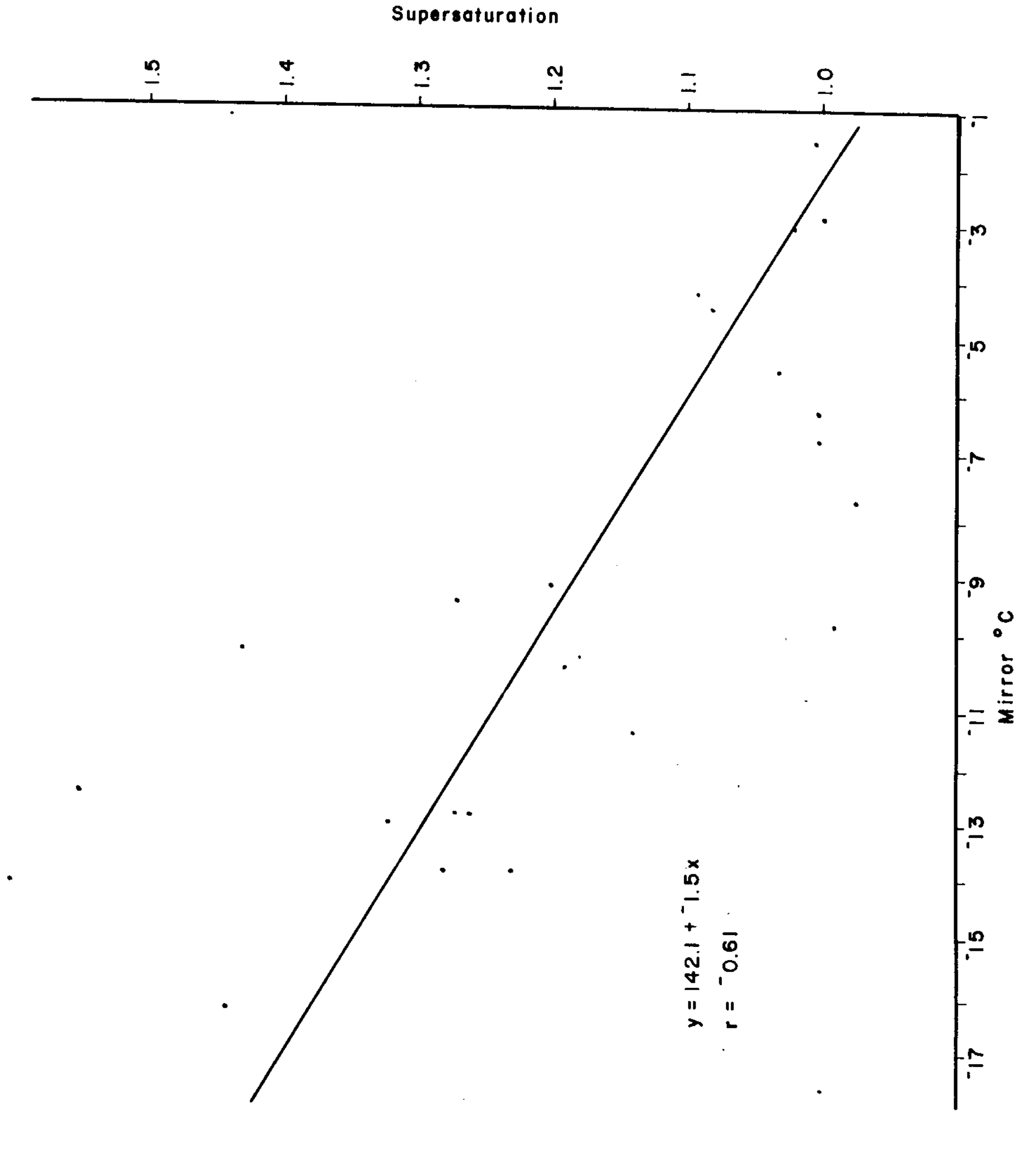


Figure 4.3



Supersaturation
1.5
1.4
1.3
1.2
1.1
1.0
Mirror °C
-1
-3
-5
-7
-9
-11
-13
-15
-17
y = 142.1 + -1.5x
r = -0.61

Figure 4.4

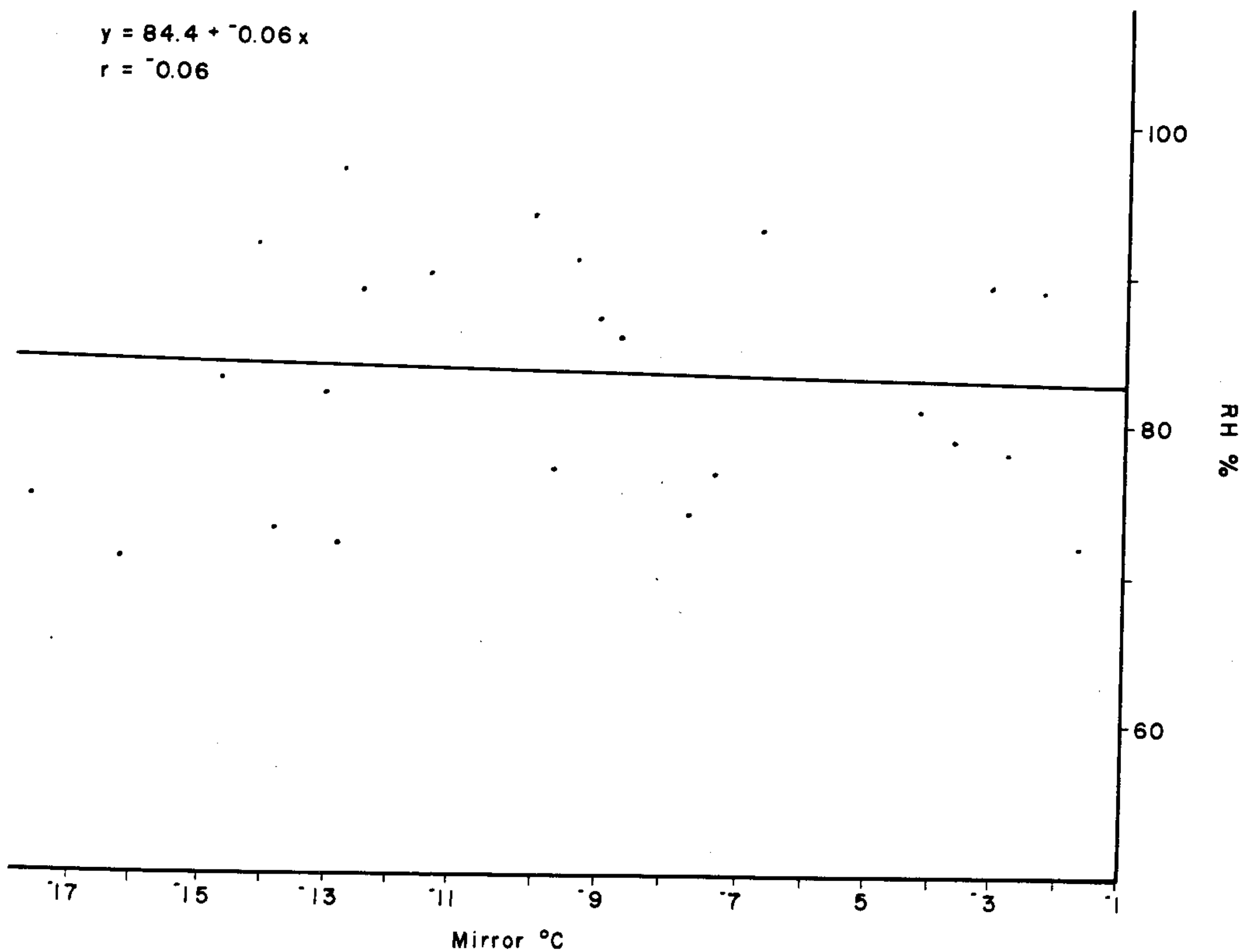


Figure 4.5

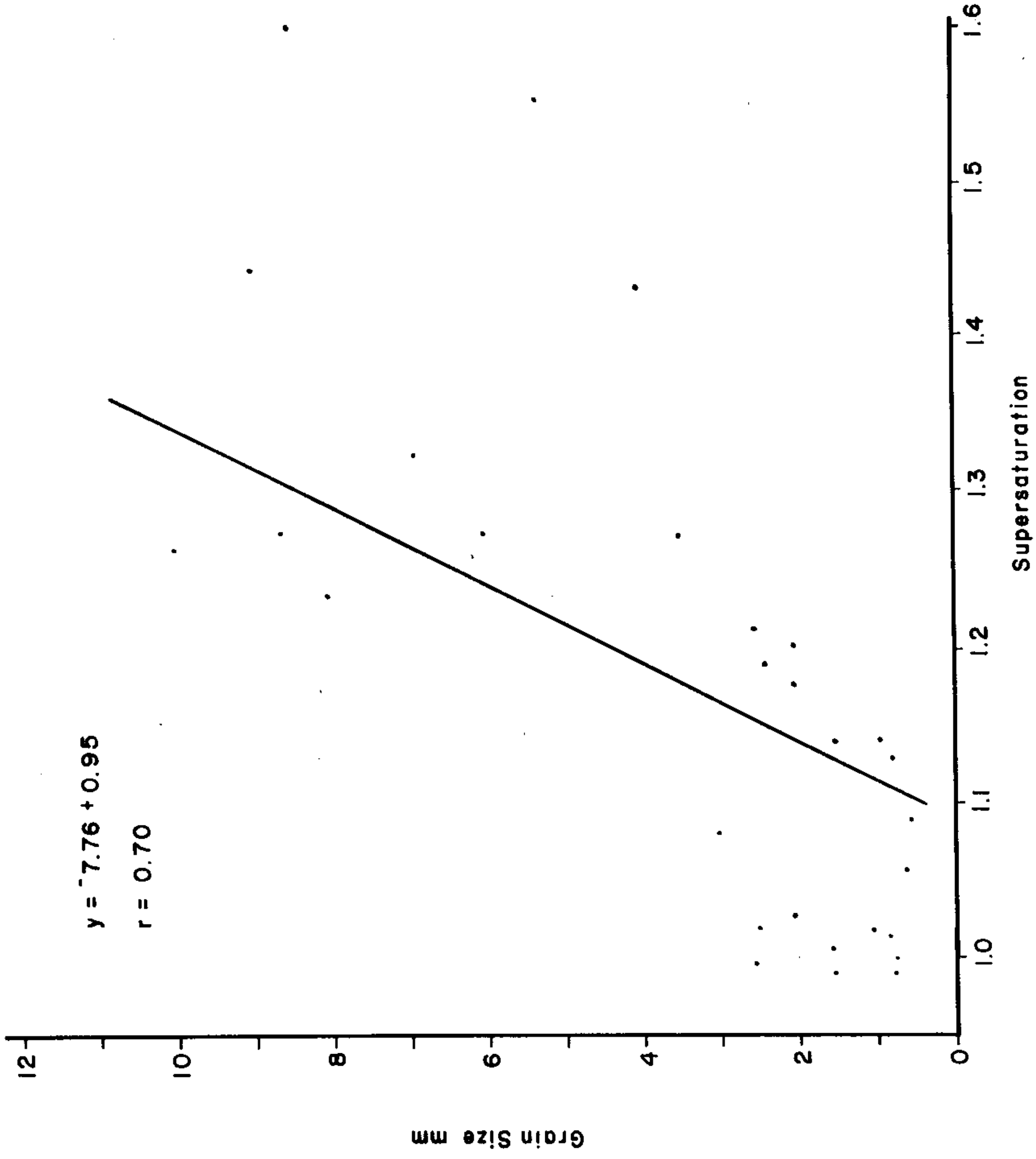

y = ⁻7.76 + 0.95
r = 0.70
Grain Size mm
12
10
8
6
4
2
0
1.0
1.1
1.2
1.3
1.4
1.5
1.6
Supersaturation

Figure 4.6

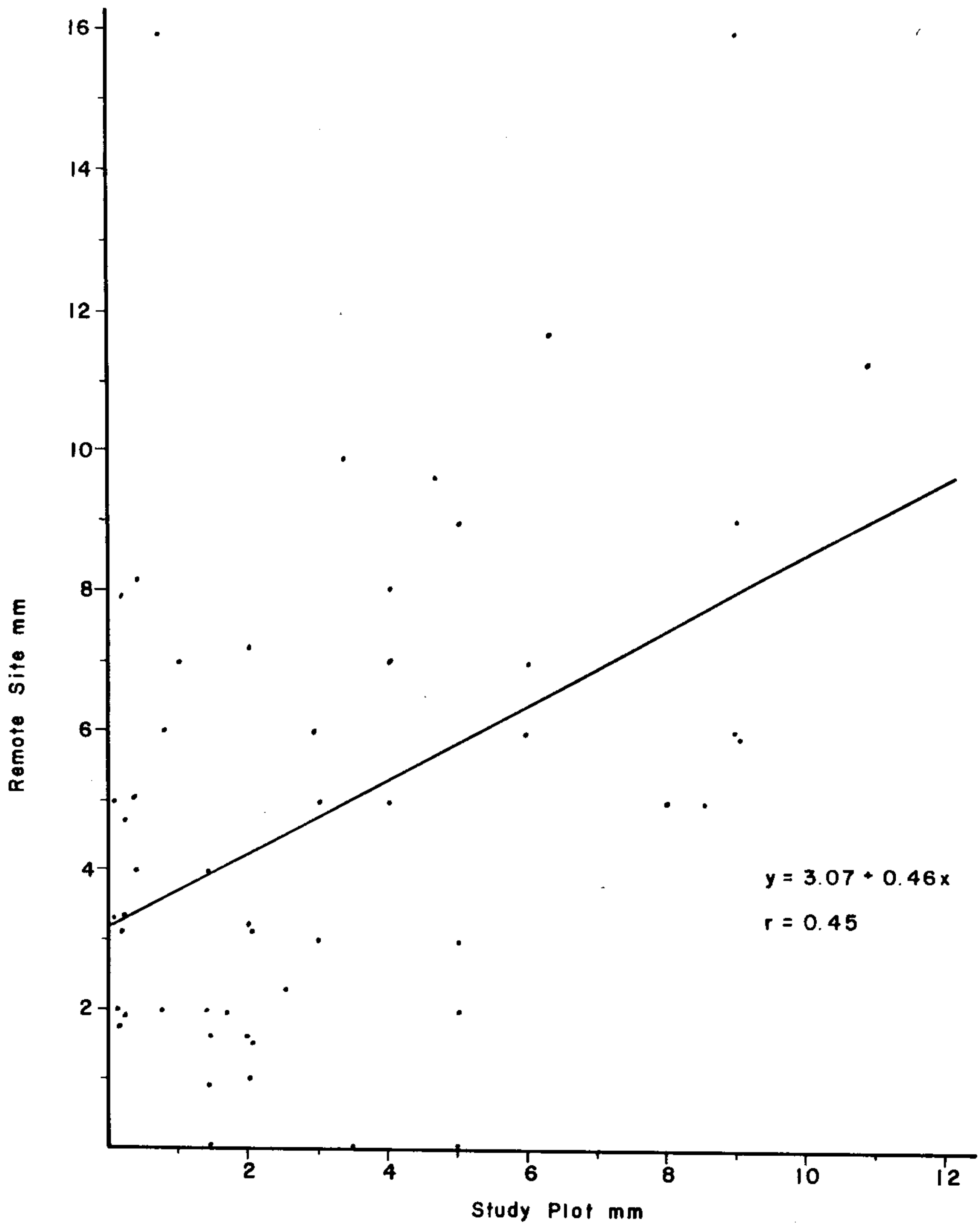

16
14
12
10
8
6
4
2
Remote Site mm
2
4
6
8
10
12
Study Plot mm
y = 3.07 + 0.46x
r = 0.45

Figure 4.7

5. CASE STUDIES

A series of case studies representative of the project are presented. They describe the formation and metamorphism of crystals at the study plot and at remote sites, and effects as a shear layer during February, 1986.

5.1 Study No. 1: Growth in the Study Plot February 6-7, 1986

1600h: Maximum temperature of 6.7°C occurred at 1345h. Clear skies have been present during the day with westerly winds at 3-6m/s. Dew point is currently -0.5°C with a relative humidity (RH) of 60 percent (refer to Figure 5.1). The snow surface is soft and moist. A "wind tree", consisting of feathers attached at various heights to a rod, is placed in the snow along with the thermistor stack.

1900h: Clear ski conditions persist; the mirror thermistor is cooling at a rate of 5.5°C/hr (Figure 5.2). A temperature gradient of 196°C/m exists between the -10mm and +5mm thermistors. Very small (0.3mm) square grains are forming on a 1mm crust at the snow surface.

2100h: Conditions are isothermal between +5 and +25mm, slight air movement is noted at 10cm above the snow. An average gradient of 150°C/m has been maintained for the last three hours between -10 and +5mm. Small stacks of square grains to 0.8mm exist above the snow surface and small needle rime (2mm) has developed on the side of the dew point duct. Thin stratus lie to the southeast and southwest of the plot.

2200h: The plot is obscured in fog; visibility is 20m. The mirror thermistor has overreacted to the loss of radiational cooling by 20 percent. Needle rime to 5mm has formed on the duct. Slight air movement is noted from +5 to +75cm above the snow.

2400h: Radiational cooling under clear skies has been almost linear for all snow thermistors since 2220h, at a rate of 3.2°C/hr. A sheen of mist 3m deep covers the study plot. A positive temperature gradient of 30°C/m exists between +5 to +25mm. RH is 70 percent; no new growth is noted on the snow.

0200h: RH is steadily rising; a transition from square grains to plate growth is occurring on the snow surface.

0500h: A stationary stratus deck sits 0.8km SE of the plot; clear sky conditions persist directly overhead. The +5mm temperature has reached a low of -17.7°C, with a gradient of 90°C/m. Sector plates to 0.7mm have formed on the snow, while small dendrites (<2mm) are growing on the "wind tree".

0630h: The low stratus obscures the study plot. Maximum crystal size on the snow surface is 3-4mm; 6-11mm dendrites

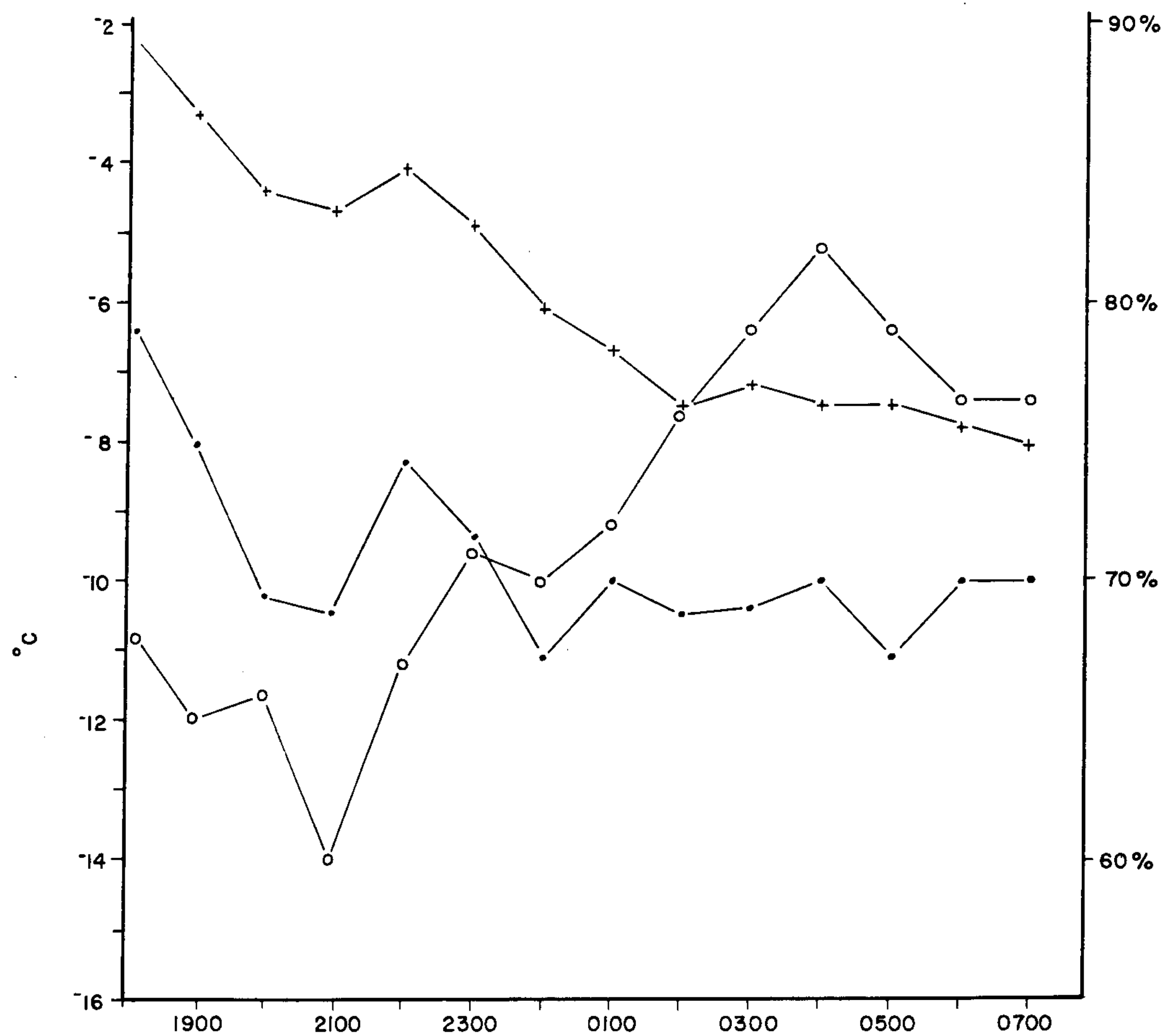


Fig. 5.1 Dew Point (•), RH (o), and Temperature (+) with respect to Time
2-6/7-86

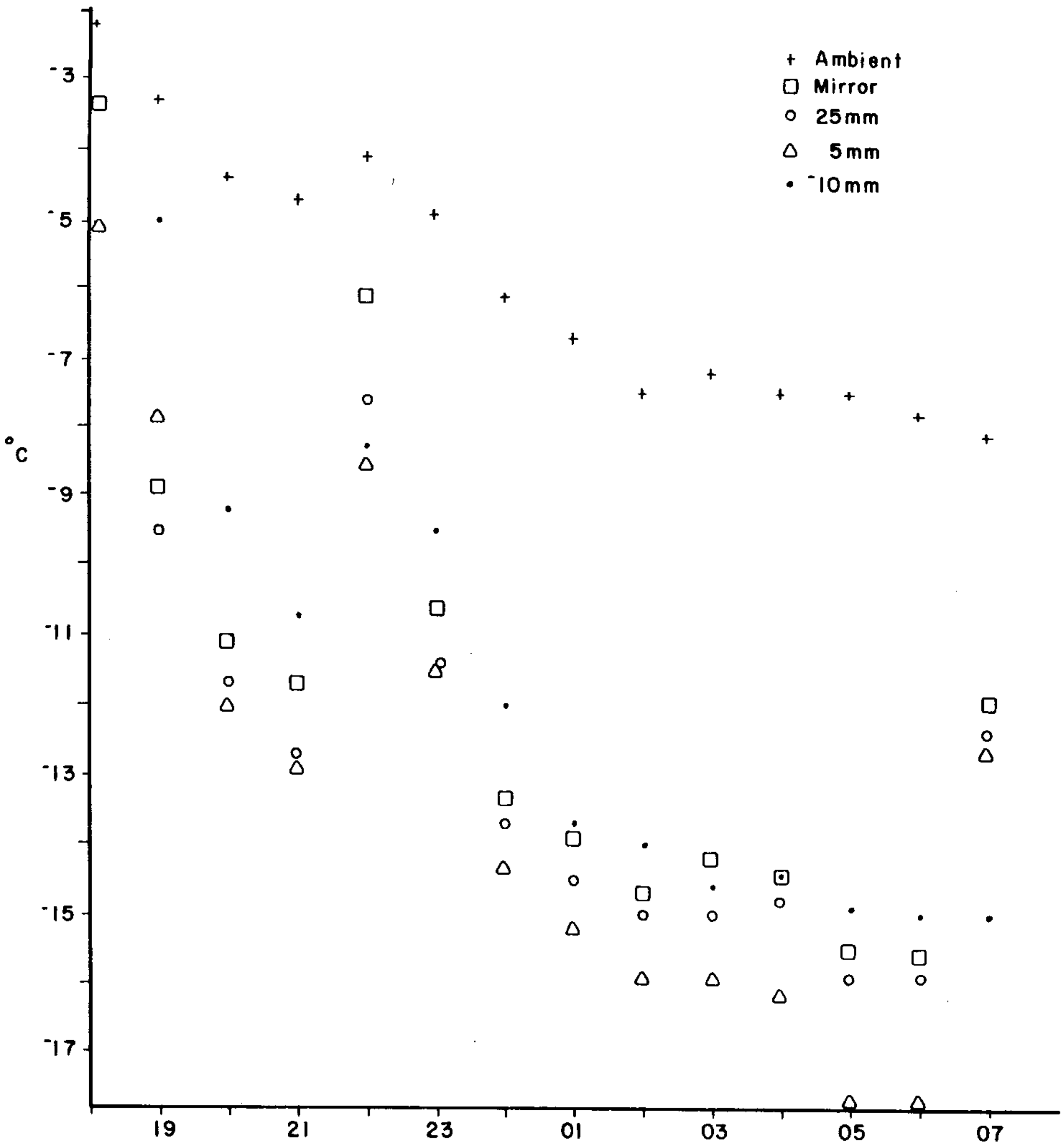


Figure. 5.2

Time Temperature Profile 2-6/7-86

have grown on the snow stacks and wind trees (Figure 5.3), between 8 and 14cm above the snow surface. They exhibit a directional nature, facing southeast.

Average temperature gradient at the snow surface was 59°C/m with an RH of 76 percent for the hours 2400 to 0600. All hoarfrost crystals melted in the study plot during the day of February 7.

5.2 Study No. 2: Remote Sites

Field trips on February 7 and 8, 1986 showed significant hoarfrost growth of varying size with respect to elevation and aspect (Figure 5.4). February 9, 1986 was the last day of growth in the study plot, which was confined to small plate growth on the tips of existing crystals.

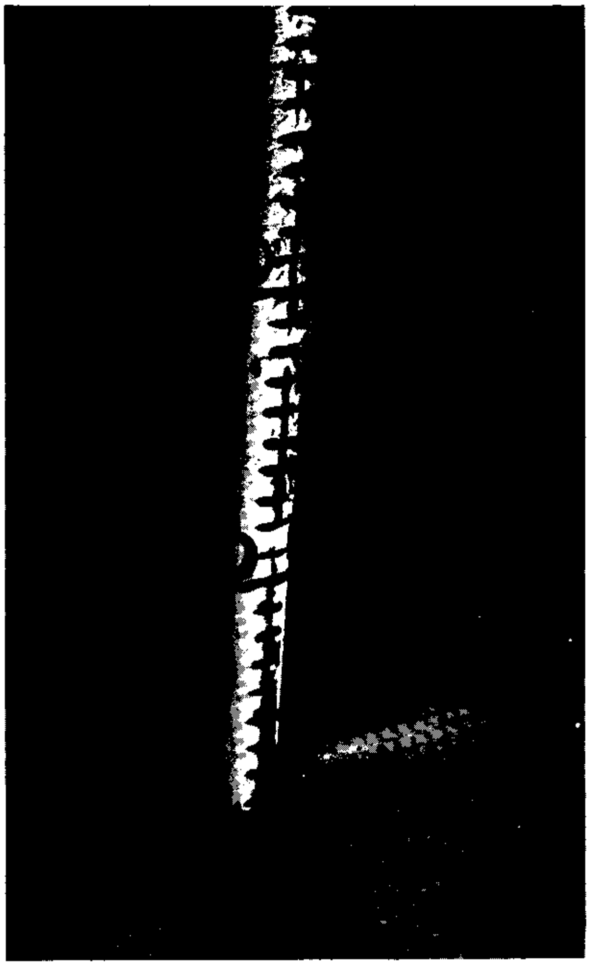
By February 12, 1986, melt freeze cycles had occurred below 1260m and moderate east winds had destroyed most surface hoar beds above 1230m. A second field was made to a meadow near Divide Lake (1158m) where slopes of various aspects were in close proximity. At this elevation slopes of southeast through east aspects had beds of 4-6mm sector plates, and northeast to northwest slopes had well developed beds of 8-15mm dendrites. Southerly through westerly slopes consisted of breakable crust with no evidence of hoarfrost.

A 1-2mm suncrust was noted on the tips of the large dendritic crystals. A closer look at the vertical temperature profile through these crystals, with the aid of the thermistor stack, is shown in Figure 5.5. At the initial readings, the crystals were in total shade. By 1230h, air temperature has risen to -1°C with an established gradient of 130°C/m between the snow surface and +25mm. At 1250h, air temperature has reached freezing,with the crystal periphery becoming moist as direct sunlite glances off of it. Continuous temperature recordings from the 1160m WSDOT instruments indicate that this was the warmest period of the 12th.

This particular bed of crystals was standing at 50° to vertical. The added weight to the crystal tips had been sufficient to lean the hoars away from their initial nucleation axis of 60 to 70 degrees (Lang, 1984). Subjective compression and shear tests are done on suncrusted vs. noncrusted crystals.

Initial impression is the ice web at the periphery will hold more force in compression.

Directional Growth



Dendrite from Stack, 12x

Snow Surface Growth

Figure 5.3

Differing Growth Habits 2-7-86

DATE	LOCATION	ELEVATION	ASPECT	CRYSTAL	SIZE
2-6-86	Alpental	1310m	W	Plate	.25mm
2-7-86	Alpental	1524m	S	Dendritic	10mm
2-8-86	East Shed	1065m	E	Plate	5mm
	East Shed	1158m	NE	Plate	6
	East Shed	1150m	SE	Plate	6
	East Shed	1158m	SW	Plate	5
	Gun Tower	1158m	NE	Plate	6
	Slide Curve	1040m	SW	None	0
	Mt. Snoqualmie	1036	W	Dendritic	10
	Mt. Snoqualmie	1220	E-N	Plate Dendritic	8 10
	Mt. Snoqualmie	>1500	E-N	Plates	4
2-9-86	Divide Lake	1158	NE	Dendritic	10-20
	Windy Pass	1120	N S	Dendritic Dendritic	10 25mm
	Nordic Pass	1220	N	Plate	4

Figure 5.4

Variability of Hoarfrost Growth with Respect to Elevation, Aspect, and Size

5.3 Study No. 3: Avalanche Activity

On the morning of February 14, 1986, the first snowfall in two weeks is recorded at the 0700h observation; 20cm of new snow with a water equivalent (WE) of $1.4 g/cm^2$. The bottom 2cm consists of unrimed plate crystals, which overlie the remaining surface hoar.

By the night of February 15, 1986, 55cm of increasing density snow had fallen. At 2100h, air temperature at 1160m had jumped from -6°C to 0°C in 20 minutes. WSDOT Avalanche Technicians witnessed a large natural release (SS-N-3) from a clearcut behind the East Snow Shed. The slide washed over the road within headlight range of their snowcat. The consequences, had they been 100m further along their route, would have been serious. A well developed bed of surface hoar had been noted on these slopes prior to the storm cycle and a similar situation had been documented at the same location during 1982. Nine SS-N-2/3 slides were documented during this cycle; all were <1180m on east to northerly exposures.

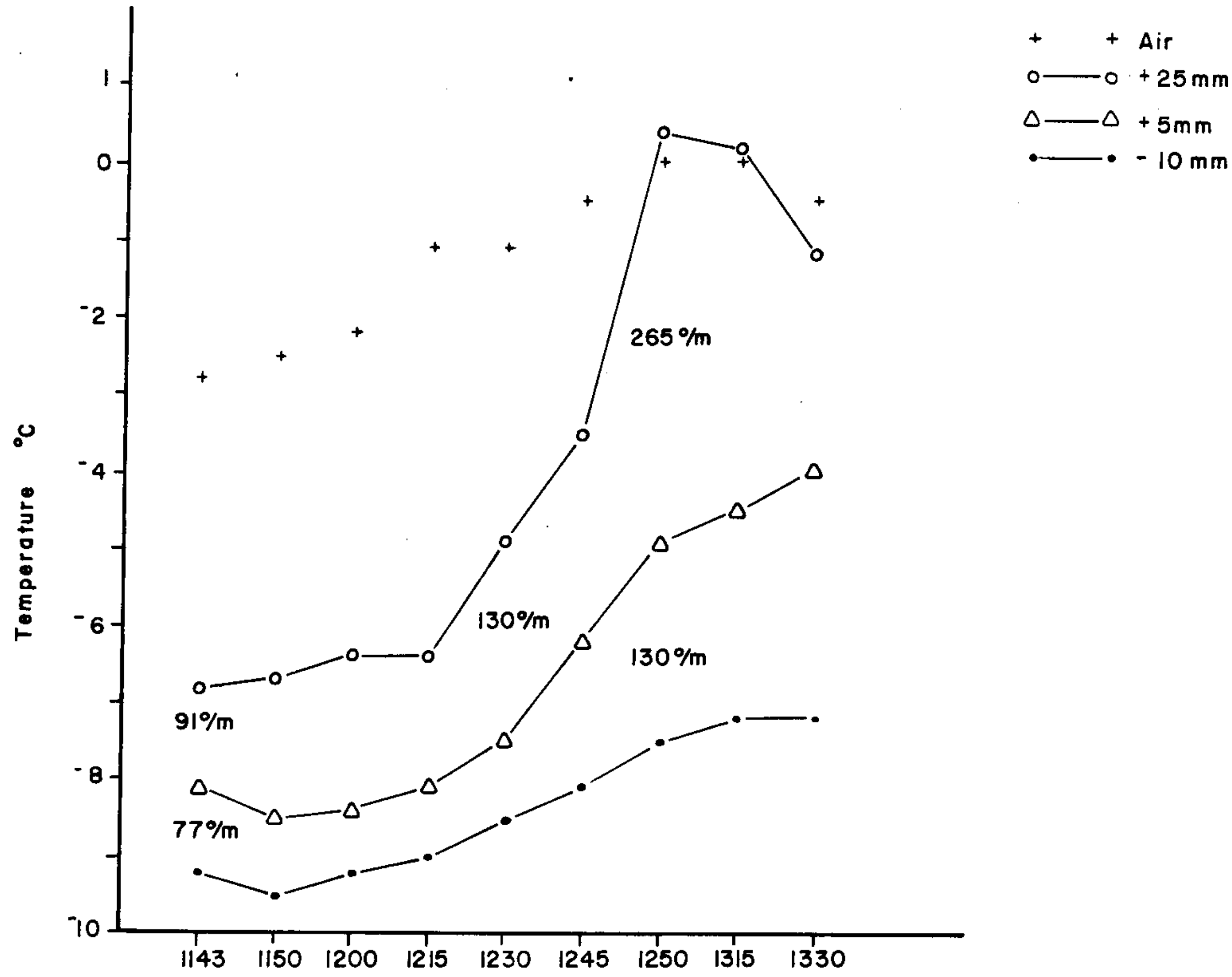


Figure. 5.5 Time Temperature Profile, 2/12/86, of Surface Hoar Bed

6. GROWTH MECHANICS

6.1 Growth Situations

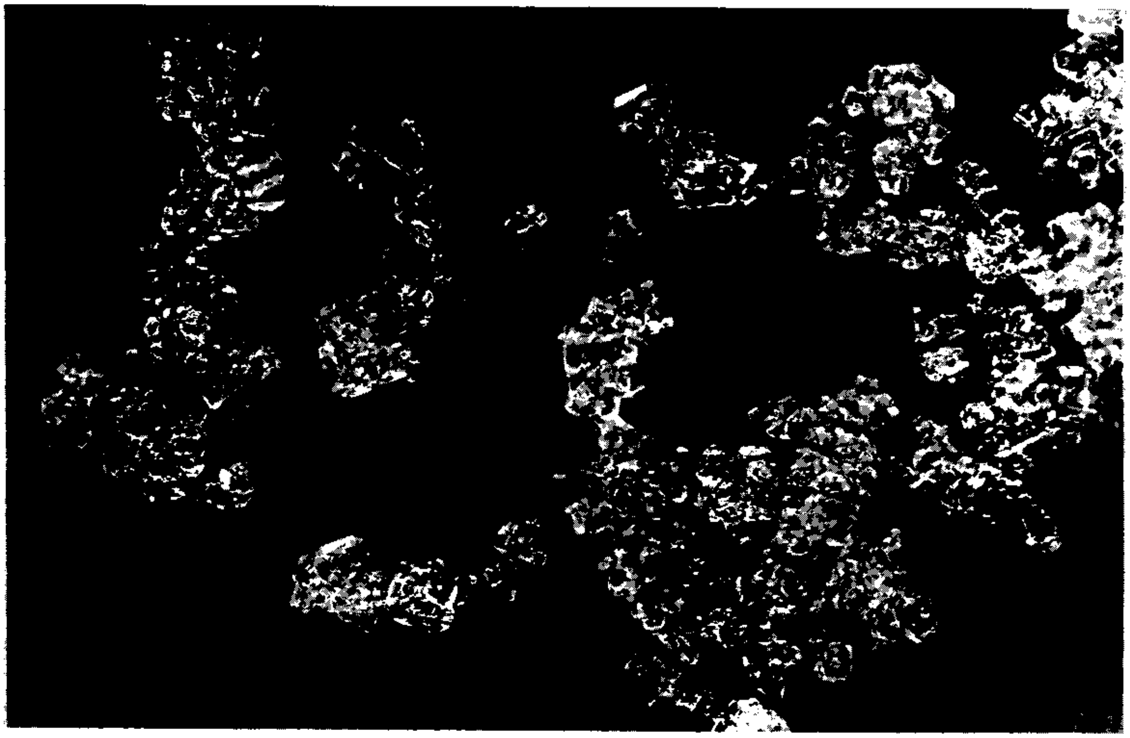
Two dominant growth situations have been discerned from instrument and field observations. The first involved frontal passage or diurnal heating of the snow surface under low wind conditions, leaving a highly saturated environment at the snow/air interface. Clearing at the onset of radiational cooling quickly lowers the snow surface to the dew point and deposition occurs. A wide range of crystal sizes occurred under these conditions often producing beds of increased crystal numbers per unit area. The second situation showed strong radiational cooling in an undersaturated environment with secondary introduction of water vapour sources from increased relative humidity during early morning hours, or the proximity of supercooled clouds (peripheral zone). A trend was seen for higher relative humidity in early (2000-2400h) or later (0300-0700h) periods during nights of growth. The disruption of growth due to this effect was most likely site oriented.

The mass flux of vapour from the snow to the air is assumed to be negligible for potential condensate necessary for hoarfrost growth (Lang, 1985). While this is true, vapour flux from the strong snow-air temperature gradients of early night radiational cooling continually produced "germ seeds" or square grained crystals (Figure 6.1A) on the snow. This recrystallization process was most pronounced when the snow surface consisted of crusts or equilibrium growth grains. In turn, these grains acted as nucleation sites, providing a more favorable position to atmospheric vapour supply. A typical transition being for "germ seed" development, to needle, to plate (Figure 6.1B) growth; following the temperature controlled habit changes characteristic of crystals grown from vapour (Kobayashi, 1961).

6.2 Growth Rates

Growth rates derived from Lang (1984) showed sector plates developing at 2mm/hr under large temperature gradients (300°C/m). In Section 5.1, the presence of small gradients produced a rate of 0.7mm/hr. However, the growth of crystals on the total stake (Figure 4.3B) occurred at a rate of 5mm/hr. Though growth perpendicular to the vapour flux is not necessarily relative to the snow surface, it does indicate that dendritic growth forms are diffusion limited, building condensate into the crystal, close to the rate at which it is delivered (Shaw & Mason, 1954). In the case of "territorial growth" where large dendritic forms are randomly placed amongst a bed of smaller sector plates (Figure 6.2A), it is obvious that dendritic growth was preferential to vapour flux

A: Germ Seeds



B: Germ — Needle — Plate

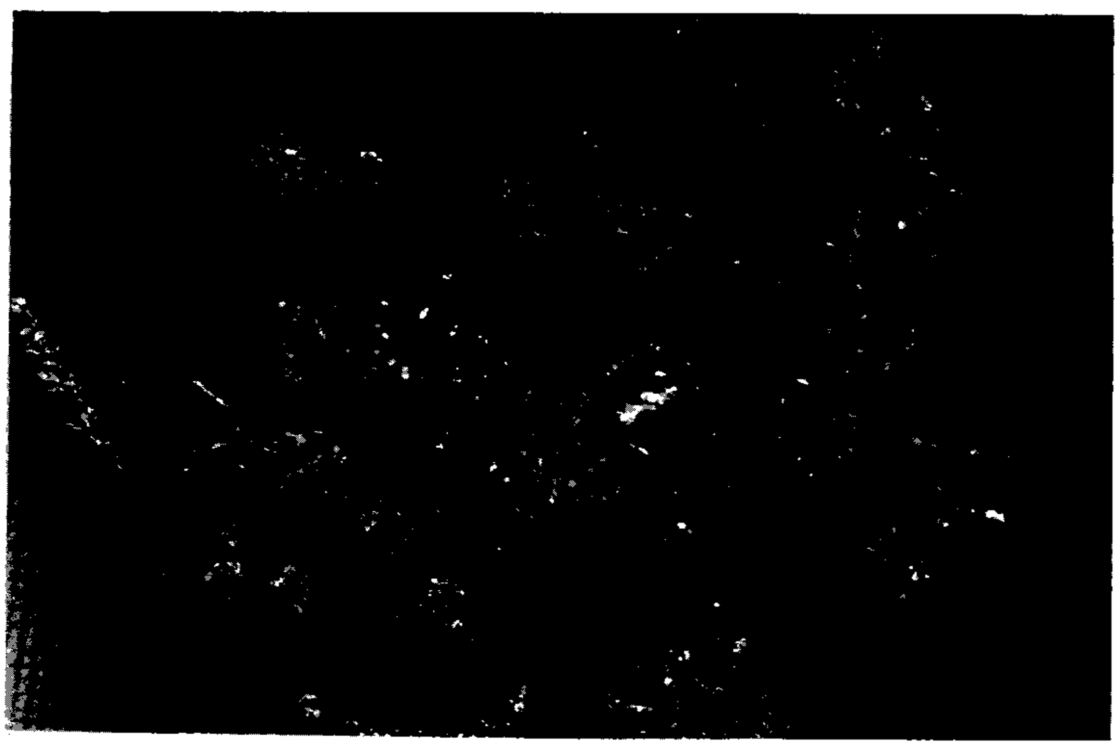


Figure 6.1

Recrystallization and Transition of Habit

from the right. A vapour "shadow" developed on the left of the plate axis and branching sector plates have grown indicative of surface limited growth under low saturations.

Under clear sky nights, dendritic forms were noted to develop on instrument wires, which hung below the bottom of the dew point duct, and occasionally on the outside corners of the duct itself (Figure 6.2B). Growth on the duct was within 2cm of the corners and at 55^{o} to 65^{o} to the vertical axis (refer to Figure 3.2). Air movement through the duct was calculated at 1.5m/s. Taking the cosine of these angles times the flow rate, air movement at the corners could be 0.75 to 0.85 m/s; this being a rough approximation of a complex boundary layer flow. In the presence of supercooled clouds, these areas showed soft rime accretion, which needs a minimum speed of 0.5 to 0.7m/s to form (Hallet and Mossop, 1974; Baranowski, 1977).

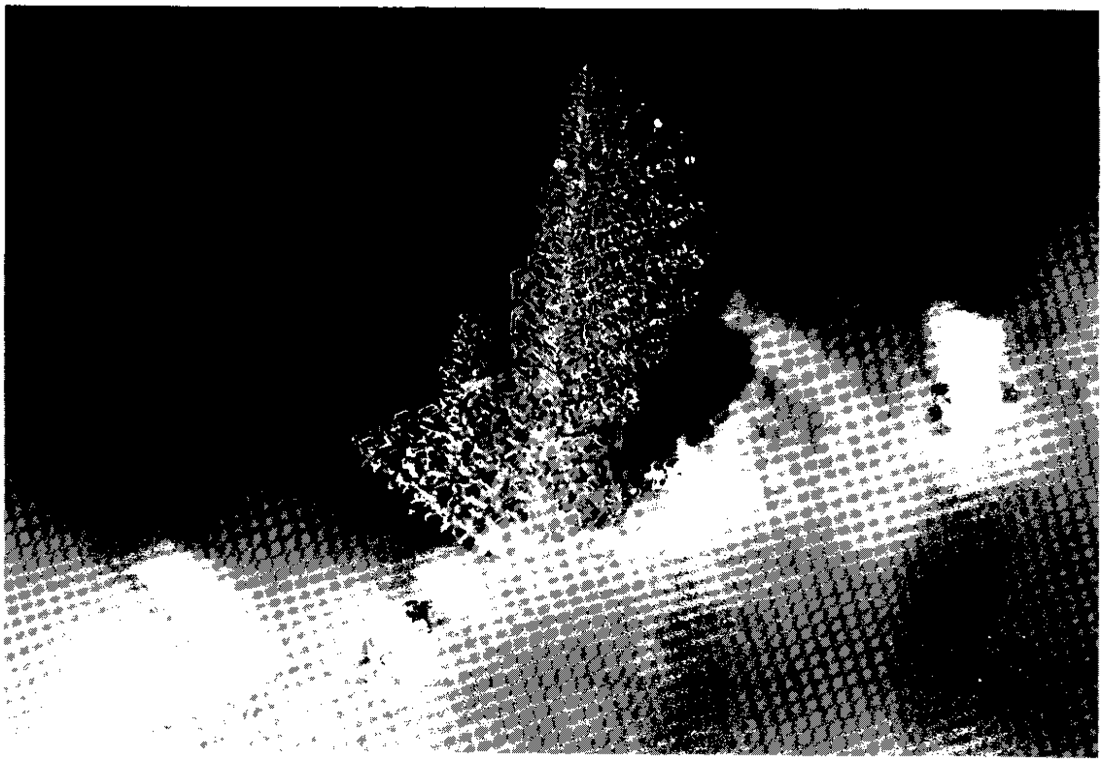
In terms of operational snow safety, this suggests that under optimal humidity and temperature conditions, significant crystal growth can be reached in periods of less than four hours. The proximity of such accelerated growth to avalanche slopes, followed by rapid frontal onset, can provide high instability with little awareness on the part of snow safety personnel.

6.3 Summary

Many growth nights at the study plot showed small crystal sizes in the presence of small temperature gradients at the snow/air interface (5.1) despite strong radiational cooling registered by the mirror and supersaturations of 120 percent. This suggests that the temperature inversion at the interface and the depth of development is regulated by air turbulence. Theoretically, "territorial growth" can be explained by initial existence of the conditions stated above. At a later time, turbulence reaches a threshold value: those points in the most favorable position to the vapor-rich flow see accelerated growth. The number of large crystals are limited by the degree of supersaturation and duration of vapour flux orientated towards the crystal.

The total vapour flux and ability to mix with the snow/air interface is critical for formation. The depositional environment most suitable for growth can be seen as quasi-turbulent. If the air is to calm, the rate of vapour deposition will exceed the delivery rate. Removal of latent heat will be negligible depressing the temperature inversion. Turbulence, past a threshold speed, will offset radiational cooling of the snow surface and the inversion will be destroyed.

A: insitu Territorial



B: Growth from Duct, 12 x

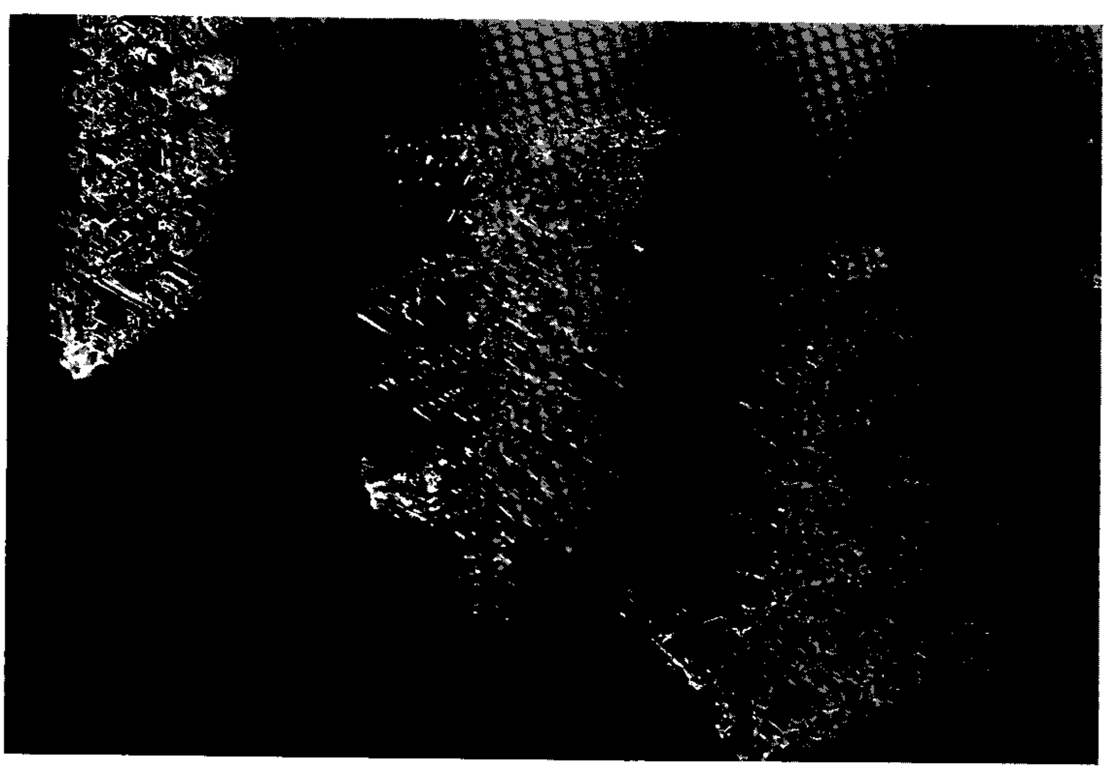


Figure 6.2

Territorial Dendite and Duct Growth

7. HOARFROST AND AVALANCHE OCCURRENCE

7.1 Introduction

Due to the fragile nature of the crystals, effectiveness as a shear layer is very dependent on postgrowth weather. Despite the large number of hoarfrost growth cycles, only 27 percent provided documented shear layers for avalanche events. The dynamic weather changes of maritime climate abated the majority of surface hoar beds below 1300m via melt-freeze cycles (36 percent), freezing rain (17 percent), warm (0°-$^{-}1^{\circ}$C) snowfall (14 percent), or rain (6 percent). Above 1300m, wind was the major destructive agent; however, low wind conditions can bury or redeposit developed beds of surface hoar without destroying the layer. In cases of quick loading conditions of high density snow, the rate of accumulation was found to destroy the layer or facilitate avalanches. The pattern of rapidly decreasing stability and avalanches, followed by a trend towards stability between old and new snow, was repeatable where hoarfrost was a factor. Developed beds of surface hoar with a high density of crystal numbers per unit area showed a greater tendency to be buried.

The effect of where a hoarfrost layer exists within an avalanche path can also be important. Variability in the location of buried layers was high, leaving isolated pockets of surface hoar over large starting zones. This creates zones of weakness and strength within any one area; triggered small slides have propagated over larger areas (Conway, 1984). In similar situations, poor explosive placement or initial ski cutting has failed to trigger buried hoarfrost layers. The second controller, anticipating the slope is stable, inadvertently triggers the slide jeopardizing safety to himself and other personnel. The presence of hoarfrost in lower track and runout regions was common due to the elevation limits of growth. This allows a false sense of security to the recreationalist who traverses the track, judging the danger area exists only in the starting zone. Bed surface failure in transition and runout zones can allow slides to run well past projected distances which is of direct concern to highway operations.

7.2 Critical Loading

Calculating threshold loads for buried layers can be very difficult due to the excessive rate of loading in short time periods and freezing level jumps inherent to the climate. Fracture line profiles are often senseless due to rain following avalanche activity, altering subtle layering of the snowpack. Further complicating the matter is the time necessary to gather quantitative snowpit data which is often unavailable when control work is being performed.

In lieu of water equivalent (WE) from the fracture line, calculated WE has been used from the study plot in Figure 7.1. These values show close relation to starting zones less than 1200m along the I-90 corridor. It also allows a good basis for future forecasting. Precipitation intensity (PI) was the rate at which critical load was reached and releases began.

Cold, low density snowfall with minimal wind transport was common to those surface hoar layer's initial loading of Figure 7.1. Depending on the depth of cold snow, a protective buffer zone covered the layer, insulating it from immediate destruction and effectively increasing the depth of the weak layer. The following precipitation patterns showed increasing density snowfall and PI rates prior to instability. The events of 12-15-82 and 2-9-85 were not related to freezing level jumps (air temperatures of <-3°C); the rest involved warming or rain with final loading.

An initial goal was to determine if a threshold depth of surface hoar crystals was necessary to be an effective weak layer. During field studies of 1982-83, most related avalanches had a mean crystal size of 7mm. By March of 1985 it was apparent that old surface roughness and the size of overlying hoar crystals was related to instability (Figure 7.1). Very small grains cannot be dismissed as effective shears.

7.3 Durability in Seasonal Snowpacks

Figures 7.2 and 7.3 illustrates the differences that can be encountered between controlled and uncontrolled starting zones and the possibilities of long-term existence of buried surface hoar layers. Both profiles share similar aspect, slope angle, and elevation. Routine control work had left a crust in Figure 7.2 on which 3-5mm hoar plates had grown. The layers had been buried for 15 days when control work coincided with warming temperatures and light rain. Initial explosive tests and ski cutting produced negative results. A cornice charge ten minutes later, down-ridge and off the slope, released a slide near the crater of the first charge. A contributing factor in the postcontrol release was little compressional support in the starting zone.

The basal stratigraphy of Figure 7.3 differs considerably. Increased overburden pressure of the 17th had compressed the 7-9mm bed of dendritic crystals to 3mm; the crystal structure had undergone little change at this time. Multiple shear layers were found prior to the buried layer of hoarfrost, no natural releases occurred to the buried layer at later dates. By March 1 the snow pack had warmed to -0.5°C at the depth of the hoarfrost layer. Increased settlement and snow temperatures had destroyed the layer.

Date	Size mm	Snow Surface	W.E. gm/cm2	P.I. cm/hr	Crown cm	Slide
12-15-82	12	soft	8.1	1.7	89	SS-AS-3
1-3-83	20	soft	3.2	1.5	40	SS-N-3^{x4}
1-24-84	5	crust	6.2	1.9	30	SS-N-3
2-9-85	1-2	crust	8.6	1.2	109	SS-AS-3^{x2}
2-16-86	5-6	crust	6.7	1.4	64	SS-N-3^{x9}

Figure 7.1

Critical Loads of Buried Surface Hoar Layers

7.3 Durability in Seasonal Snowpacks (Cont.)

The possibility of slope failure in the second snow profile was most likely if a suitable trigger had been provided. The significance of the crust in Figure 7.2 can only be speculative, but demonstrates the need to base stability evaluation on information from the starting zone. From tensile strength tests conducted by Russo (1986, personal communication), increased density snow shows logarithmic increases in strength. In a maritime climate, this provides a series of endoskeletons which can shield the snowpack from large slope failure. However, given proper weather and snowpack conditions, the potential for climax avalanches should not be disregarded when buried surface hoar layers exist.

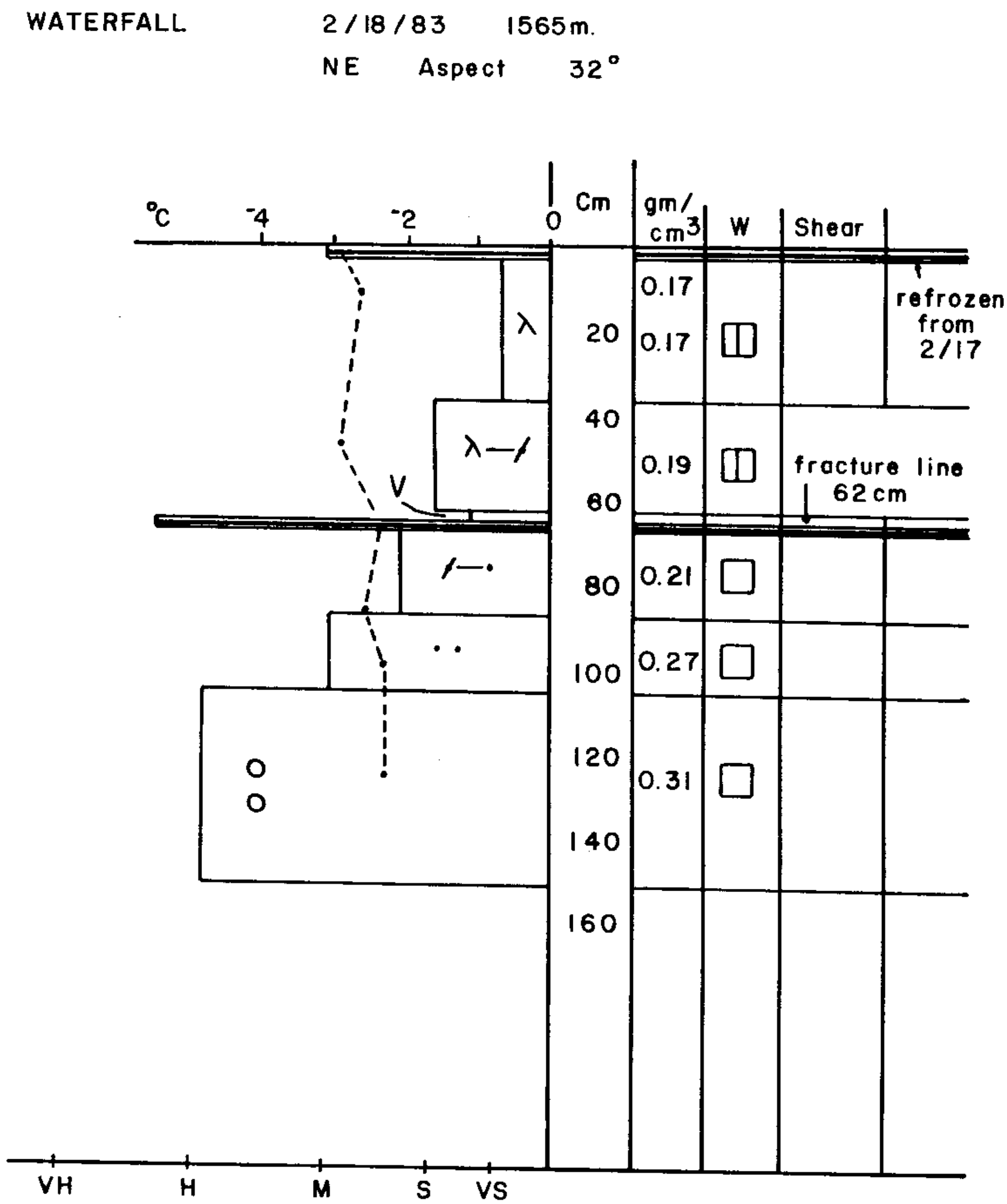


Figure. 7.2
Data Pit from Controlled Starting Zone

DISPOSAL RIDGE 2/19/83 1555m.
North Aspect 33° ∡

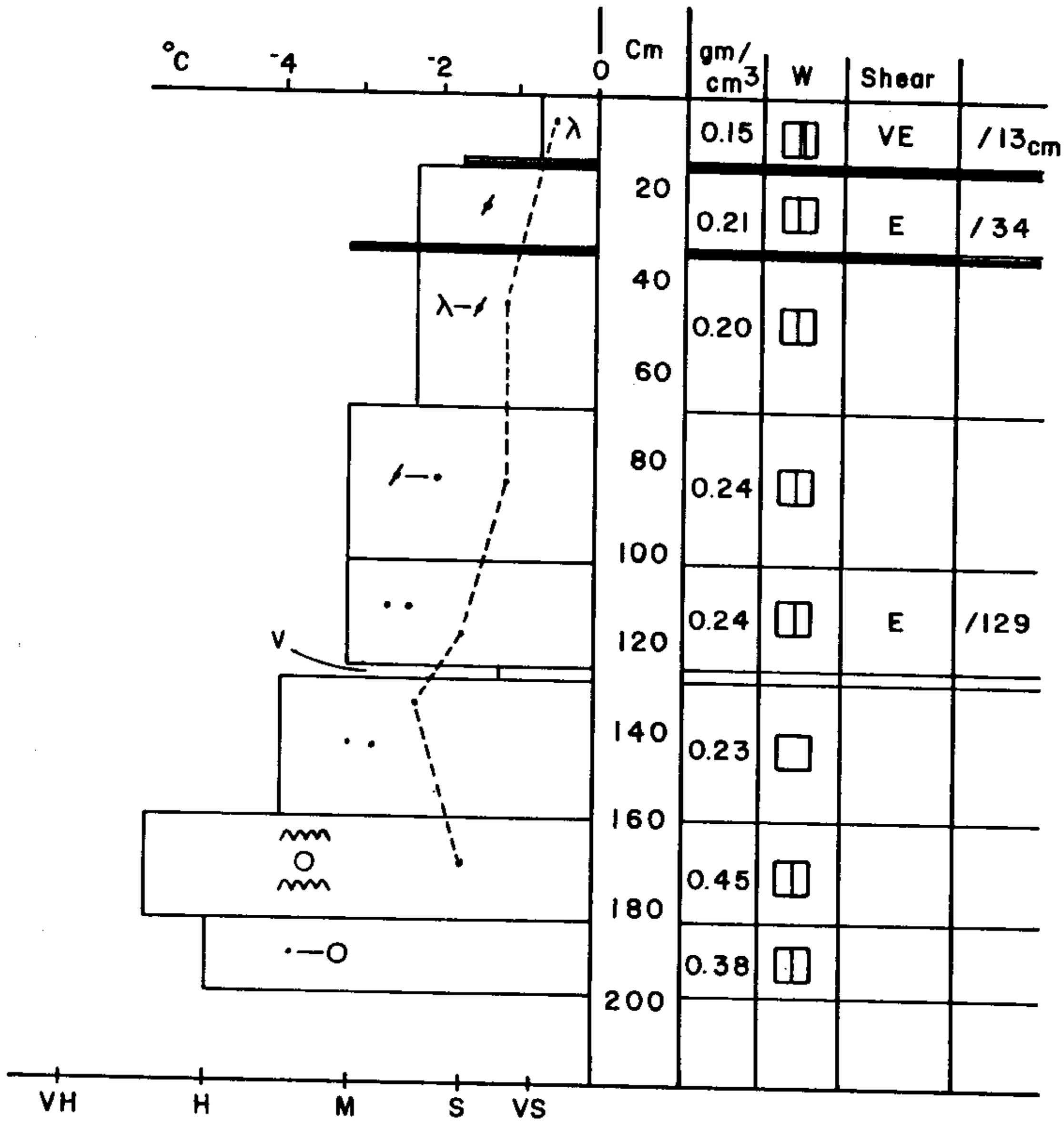


Figure: 7.3
Data Pit from Uncontrolled Starting Zone

8. CONCLUSIONS AND RECOMMENDATIONS

Hoarfrost growth has been correlated with anticyclones lying over eastern Washington, resulting in cold easterly flow and topographic inversions around the cascade crest. Growth was found to be greatest within the inversion layer or along its peripheral boundary. Two conditions must exist simultaneously for hoarfrost crystallization. Sufficient water vapor must be available and a developed temperature inversion must be present at the snow surface. Under optimal temperature and humidity conditions significant crystal growth (10-15mm) can be reached in periods of less than four hours.

Since surface hoar develops and persists during defined conditions, growth and related avalanche events can be forecast. Repetition of all experimental procedures is not necessarily recommended for field practitioners unless site specific information is desired. Proper detection and monitoring of hoarfrost should begin with:

1. Recognition of the prime factors, critical relative humidity values (>70%), and the use of multi-level air temperature sensors (allowing definition of topographic inversion depth) during radiation nights.

2. Due to the high spatial variation of growth from site to site, snow safety personnel shall document all periods of hoarfrost observed in the study plot, identify potential target paths that show reoccurring growth and rely on <u>field observations</u> in these areas for future stability decisions. The use of a 20x hand lens is recommended as crystal structures of 1-2mm are easily missed under lower magnifications. Documentation of snow conditions which underlie developed hoar beds are equally important as old snow roughness has been related to shear layer weakness hoarfrost crystals.

3. Postgrowth weather patterns will determine of hoarfrost beds are destroyed or buried. High intensity snowfall on developed beds usually resulted in very direct action avalanches. Initial low intensity snowfall was found to allow larger loads to accumulate on these layers. Once buried hoarfrost layers can be easily missed in pit profiles. Field observations, prior knowledge of snow stratigraphy, and site specific shear tests provided the most reliable forms of detection. Mean values of 6.6mm (sd=1.9) of water equivalent and a precipitation intensity of 13mm/hr (sd=0.5) was found critical to large avalanche releases.

   Long term burial of hoarfrost in the snowpack was less than 25 days, due to the dynamic weather changes and fast settlement rates inherent to the climate. However, given proper weather and snowpack conditions, the potential for climax avalanches should not be disregarded, as the layers do not gain strength quickly.

4. Avalanche control measures may need to be altered if hoarfrost is a stability factor. Spatial variability of buried surface hoar layers can leave isolated pockets over large starting zones. Poor explosive placement or initial ski cutting has resulted in hazardous post control release situations. Proper timing of control work (relative to freezing level jumps or rapid loading) and the use of large (10-20kg) aerial detonations is recommended.

   Due to the elevational limits of growth, buried layers may exist only in track or transitional zones of an avalanche path. This allows more snow to be incorporated in an avalanche, enabling it to travel further with increased debris deposited on the highway. Prior knowledge of this condition can ensure the presence of adequate maintenance equipment, to avoid increased downtime during post control snow removal.

The information presented is certainly site specific and most relevant to low elevation maritime climates. For the I-90 corridor, the areas of greatest concern are the East Shed, Slide Curve, Rampart Ridge, Airplane Curve, and the West Shed avalanche paths. The remaining paths west of the summit showed little growth due to strong katabatic winds in the presence of easterly flow or related avalanche activity due to strong insolation on south facing paths. This does not preclude the possibility of hoarfrost related events in these areas. From an operational level the results of the project have fulfilled the initial goals. Increased capacity in stability evaluations has produced more timely control measures and innovations in control methods for problem areas.

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