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Authors: Hood, Eran, Scheler, Kent, and Carter, Peter

Source: Arctic, Antarctic, and Alpine Research, 37(3) : 316-322

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(2005)037[0316:NFCFAS]2.0.CO;2

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Arctic, Antarctic, and Alpine Research, Vol. 37, No. 3, 2005, pp. 316–322

Near-surface Faceted Crystal Formation and Snow Stability in a High-latitude Maritime Snow Climate, Juneau, Alaska

Eran Hood‡*
Kent Scheler† and*
Peter Carter†

*Environmental Science Program,
University of Alaska Southeast,
11120 Glacier Highway, Juneau,
AK 99801, U.S.A.
†Southeast Alaska Avalanche Center,
Juneau, AK 99801, U.S.A.
‡Corresponding author.
eran.hood@uas.alaska.edu

Abstract

The City and Borough of Juneau, Alaska, has several major avalanche paths located in close proximity to population centers and is routinely affected by avalanche activity. As a result, developing a better understanding of the snowpack conditions that lead to avalanche cycles is of great interest. This study investigates temperature and vapor pressure gradients associated with near-surface faceted crystal formation in the high-latitude maritime snow climate of southeast Alaska. Here we report on two episodes in March and April 2003 in which temperature gradients measured in the upper 25 cm of the snowpack were in excess of 70°C m^{-1}. These temperature gradients were associated with strong near-surface vapor pressure gradients that exceeded 5 mb m^{-1} for up to 48 h. During both episodes, faceted crystals 1–2 mm in diameter were observed to form near the surface of the snowpack. Field tests performed simultaneously at the study site demonstrated pronounced instabilities associated with the newly formed faceted crystals. Furthermore, avalanche activity was observed following both periods. Investigations of proximate avalanches showed that wind-loaded dry slabs were running on layers of near-surface faceted crystals.

Introduction

Seasonal snowcovers are heterogeneous media that typically exhibit a complex stratigraphic composition. The physical properties of individual layers within the snowpack are determined by the grain structure at the time of deposition and the rate and type of subsequent ice crystal metamorphism. During the metamorphic process, the development of layers in the snowpack with low shear strength is of primary importance for the release of slab avalanches (Langham, 1981; McClung and Schaerer, 1999). Snowpack weak layers are often associated with the development of faceted snow crystals, which can grow relatively rapidly in low density snow subject to high temperature gradients (Armstrong, 1985). Layers of faceted crystals are characteristically weak because of the thin, poorly developed bonds between ice grains. As a result, processes related to the development of faceted crystals have been the subject of myriad avalanche-related studies.

Much of the past research on faceted crystals has focused on the basal layers of the snowpack and the snowpack surface because of the widespread observation of depth hoar and surface hoar, which are extreme examples of faceted crystal growth (e.g., Akitaya, 1974; Colbeck, 1982; Sturm and Benson, 1997; McClung and Schaerer, 1999). However, kinetic grain growth close beneath the snowpack surface, which results in the formation of near-surface faceted crystals, has recently received more attention. Near-surface faceted crystals are formed under conditions with strong vapor pressure gradients near the snow surface. These vapor pressure gradients are a result of large temperature gradients driven by either diurnal temperature cycling or solar radiation inputs at the snow surface (Colbeck, 1989). Temperature gradients in near-surface snowpack layers can be well in excess of 100°C m^{-1} (Fukuzawa and Akitaya, 1993; Birkeland et al., 1998), and are often much higher than those measured in basal snowpack layers. Low-density snow at the surface of the snowpack can undergo rapid kinetic metamorphism when subjected to temperature gradients of this magnitude, with 1–2 mm faceted crystals forming within periods of several days (Birkeland et al., 1998).

Near-surface faceted crystals have been documented in a wide variety of snow climates including mid-latitude continental (Birkeland et al., 1998), mid-latitude maritime (Fukuzawa and Akitaya, 1993), and high-elevation tropical (Hardy et al., 2001). Colbeck (1989) derived temperature fields near the snow surface in order to explain growth rates of near-surface faceted crystal in high-elevation and polar environments, and studies during the ALERT 2000 campaign documented near-surface faceted crystals in arctic snowpacks (Dominé et al., 2002; Albert et al., 2002). The development of near-surface faceted crystal layers is of concern to avalanche forecasters because the burial of these layers by new snow is commonly associated with widespread avalanche activity. To illustrate, investigations of large backcountry avalanches in southwestern Montana showed that 59% of avalanches analyzed ran on weak layers comprised of near-surface faceted crystals (Birkeland, 1998). The purpose of this study is to document the conditions associated with the growth of near-surface faceted crystals in the high-latitude maritime snow climate of Juneau, Alaska. Further, the contribution of layers of near-surface faceted crystals to instabilities within the snowpack is assessed using field tests for snowpack stability.

Methods

STUDY SITE

The study site at Fish Creek Knob is a bench on the northeast ridge of Mount Ben Stewart on Douglas Island, 8 km southwest of Juneau, Alaska (58°16′29″N and 134°31′48″W). The site is located in a flat 20 m × 40 m open area just below treeline at 700 m a.s.l. (Fig. 1). A meteorological tower at the site monitors wind speed and direction with an RM Young 05103 anemometer, temperature and relative humidity with a Visala HMP45C sensor, and net radiation with a REBS Q7 net radiometer. Additionally, a snow depth sensor (CSC ultrasonic distance sensor) allows observation of snow accumulation during storms. The anemometer was mounted at 10 m, and the temperature and relative humidity sensors were mounted at 4.3 m on

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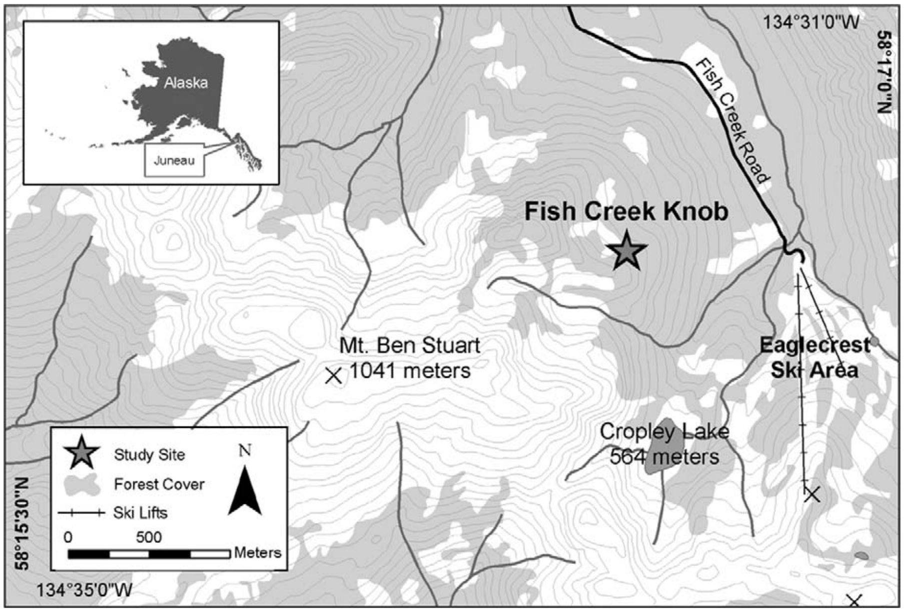


FIGURE 1. Fish Creek Knob study site at 700 m elevation on Douglas Island near Juneau, Alaska.

the tower. Average temperature at the site during the study period in March and April 2003 was –3.7°C (SD = 6.1°C). Average wind speed was 2.1 m s^{-1} (SD = 1.5 m s^{-1}), indicating that the site is largely protected from the high winds that scour the surrounding topography. This site is maintained and used in a joint effort by the University of Alaska Southeast (UAS) and the Southeast Alaska Avalanche Center (SAAC).

SNOWPACK MEASUREMENTS

Snowpack temperature gradients were measured using a 1-m snowpack temperature probe consisting of a thermocouple array mounted in a white PVC pipe 50 mm in diameter. Holes were drilled in the PVC pipe every 10 cm between 0 and 70 cm height and every 5 cm between 70 and 100 cm. A high accuracy thermocouple (HOBO, –40° to 100°C ± 0.5°C accuracy) was mounted in each opening protruding 4 cm from the probe, and the holes were sealed with putty to keep moisture from entering the probe. The sensors were oriented in a spiraling array around the probe in order to minimize interference with snowpack settling (Fierz, 1998). The remaining void space in the temperature probe was filled with insulation foam. At least 5 days prior to the beginning of each study period, the temperature probe was inserted into the snowpack in close proximity (<5 m) to the meteorological tower. The probe was inserted until the 70 cm sensor was flush with the snow surface, leaving the remaining 6 sensors (30 cm) exposed to collect natural snow deposition. Temperature was recorded from all 14 sensors at 5-minute intervals and was stored in four HOBO H8 4-channel data loggers mounted on the top of the probe.

Because the snowpack temperature probe was not in contact with the ground, we assumed that it settled with the snowpack, thus maintaining a constant position relative to the surface of the snow. Throughout the season, the probe was reset after snowfall buried the uppermost sensors and after periods of excessive settling. Several researchers have noted problems with temperature gradient measurements being affected by solar heating of temperature sensors in the upper levels of the snowpack during daytime hours (Birkeland et al., 1998; Fierz, 1998). At our site there is virtually no direct solar radiation in winter months because of the high-latitude, northeast aspect, and shading from the surrounding forest.

The study site was visited at least weekly, and pits were dug at a designated area within 20 m of the temperature probe. In each pit, snow stratigraphy including grain size and shape was recorded by visual characterization following Colbeck et al. (1990). In addition, snow density, hardness, and temperature were recorded for each unique layer identified in the snowpack. Standard field stability tests were also performed to identify weak layers within the snowpack. These tests included the compression test (CT) and the shovel shear test (ST) (Jamieson, 1999; Canadian Avalanche Association, 2002). Additionally, avalanche activity around the field site was closely monitored and fracture lines were investigated whenever possible to identify sliding layers.

TEMPERATURE AND VAPOR PRESSURE GRADIENT CALCULATIONS

The temperature gradient (°C m^{-1}) between sensors in the upper 25 cm of the snowpack was calculated at 5-minute intervals and averaged hourly according to the following equation:

$$\text{Temperature gradient}_{1-2} = (t_1 - t_2) \times [100\ \text{cm}/(d_2 - d_1)], \qquad (1)$$

where:

t_1 = temperature at the upper sensor in °C
t_2 = temperature at the lower sensor in °C
d_1 = depth of the upper sensor in cm (snow surface = 0 cm)
d_2 = depth of the lower sensor in cm.

Vapor pressures at the sensors in the upper 25 cm of the snowpack were calculated following the method of Armstrong (1985) and Birkeland et al. (1998), which assumes that the pore spaces in the snowpack are saturated with water vapor with respect to ice at the temperature measured by the sensor. Vapor pressure gradients (mb m^{-1}) between sensors were then calculated in the same fashion as the temperature gradients.

Results and Discussion

The snowpack temperature probe recorded three consecutive months of data during February–April of 2003. Here we report on two events during which the absolute magnitude of temperature gradients in the upper 25 cm of the snowpack exceeded 70°C m^{-1}.

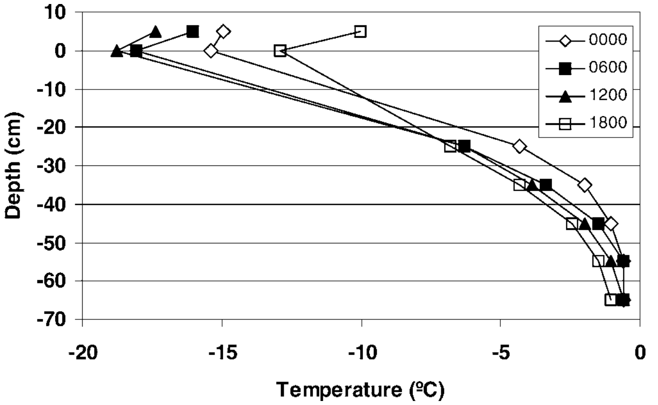


FIGURE 2. Near-surface snow temperature profiles observed at 6-h intervals on 7 March 2003.

EVENT 1: 6–7 MARCH 2003

The first event was characterized by cold, dry conditions at the study site with a temperature range of –9.3°C to –19.1°C at the meteorological tower and no new snowfall during the 2-day period. A thin layer of wind-blown snow covered a melt-freeze crust, and the surface of the snowpack was at the 95-cm point on the 1-m temperature probe. During this period, a faulty datalogger caused temperature data to be lost from the four probes at the 5- to 20-cm depths in the snowpack. The temperature profile recorded in the snowpack showed very low temperatures at the snow surface during both day- and night-time hours on 7 March (Fig. 2). Furthermore, snowpack temperature increased rapidly with depth, approaching –6°C at the 25 cm depth and 0°C at the 65 cm depth.

The low surface temperatures in combination with relatively stable temperatures at depth in the snowcover resulted in strong temperature gradients near the snow surface. The temperature gradient in the 0- to 25-cm layer of the snowpack during this event was consistently larger than –30°C m^{-1} and reached a maximum of nearly –80°C m^{-1} on the evening of 6 March (Fig. 3a). The temperature gradient was strongest during the first day and decreased as heat was lost from the snowpack on 7 March. The temperature gradients reported here are somewhat smaller than those reported for montane snowpacks in southwestern Montana (Birkeland et al., 1998) and Japan (Fukuzawa and Akitaya, 1993); however, the loss of data from the thermocouples at the 5- to 20-cm depths precluded us from measuring snowpack temperatures immediately below the snow surface where temperature gradients are typically strongest.

The strong temperature gradients in the 0- to 25-cm layer of the snowpack during 6–7 March resulted in vapor pressure gradients across this layer that ranged from –5.7 to –18.5 mb m^{-1} (Fig. 3b). Thus, during the entire 2-day period, the vapor pressure gradient in the near surface of the snowpack had an absolute value greater than the 5 mb m^{-1} threshold necessary for kinetic growth of faceted crystals (Armstrong, 1985). Field investigations following the 6–7 March event showed that near-surface faceted crystals up to 2 mm in diameter had developed near the snowpack surface. On 11 March, a snowpit at the study site documented a layer of 2-mm faceted crystals approximately 10 cm below the snow surface (Fig. 4). This faceted layer was not present in the previous snowpit profile collected at the site on 4 March, suggesting that the facets likely formed during the 6–7 March event documented here. It is alternatively possible that the faceted layer formed earlier and was not documented on 4 March because the faceted layer was spatially discontinuous. However, the formation of faceted crystals during the 6–7 March event would be consistent with previous results showing that well-developed faceted crystals can form in a period of 1–2 days under persistently strong ($\gg$5 mb m^{-1}) vapor pressure gradients (Armstrong, 1985; Fukuzawa and Akitaya, 1993; Birkeland et al., 1998).

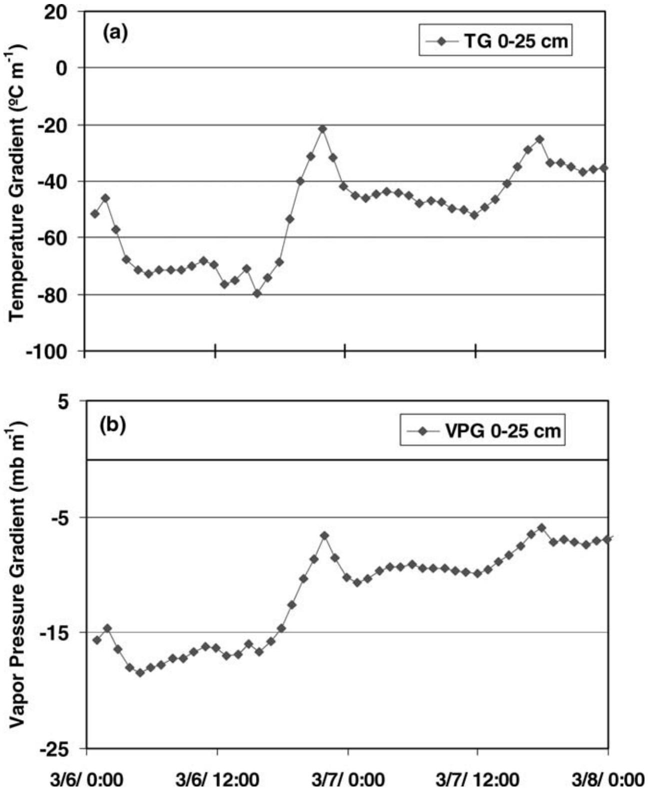
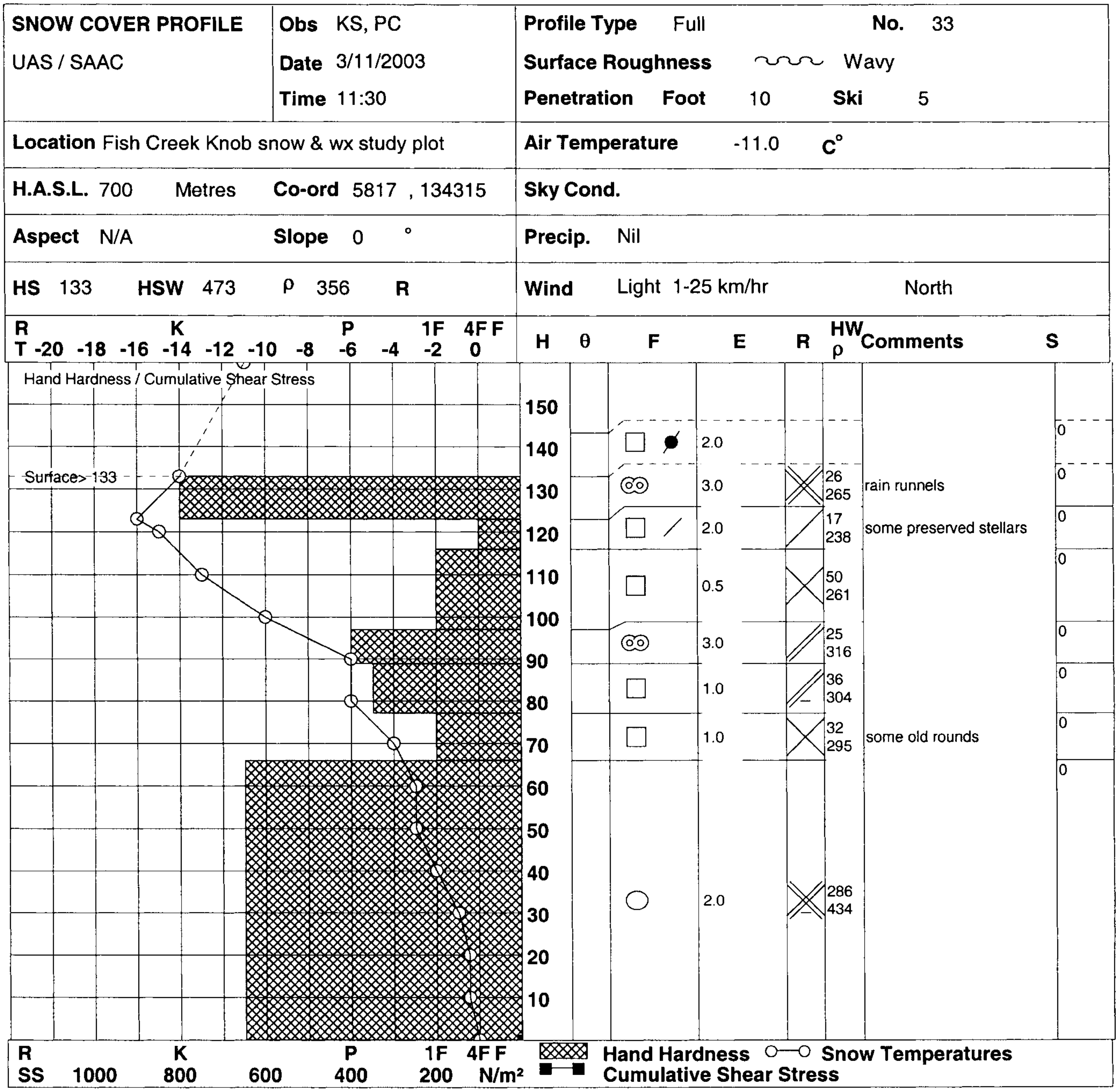


FIGURE 3. Near-surface temperature (a) and vapor pressure (b) gradient in the 0- to 25-cm layer in the snowpack on 6–8 March 2003.

Stability tests and avalanche activity proximal to the site demonstrated that the newly formed facets were associated with instabilities in the upper layers of the snowpack. On 9 March, a natural release avalanche 2 km south of the study site was investigated by field personnel. The fracture profile showed that the sliding layer was comprised of 2 mm faceted crystals buried under a 30 cm wind slab (data not shown). Stability tests performed at the study site on 11 March showed a pronounced instability in the snowpack associated with the faceted layer 10 cm below the snow surface (Table 1). This faceted crystal layer was subsequently buried by ∼32 cm of snow during a storm on 13–14 March 2003. Stability tests performed at the study site and at the nearby Eaglecrest Ski area during the period 13–17 March showed that the recently buried facets continued to be associated with weak layers in the upper portion of the snowpack (Table 1). Previous research has shown that near-surface faceted crystals can persist for more than 2 months in high-elevation continental climates (Fierz, 1998). Our results demonstrate that near-surface faceted crystals can persist on the order of 10 days or more in the relatively warm maritime climate in southeast Alaska.

EVENT 2: 4–5 APRIL 2003

The second event was characterized by generally higher air temperatures at the meteorological tower (3.5°C to –13.6°C), particularly during daytime hours when temperatures were close to 0°C. There was no new snowfall during this period, and snow density in the upper 10 cm of the snowpack was 220 kg m^{-3}. The snowpack surface was at the 80-cm mark on the 1-m snowpack temperature probe. The temperature profile in the snowpack showed a diurnal shift, with temperatures decreasing toward the snow surface during night-time hours and increasing toward the snow surface during the day



SNOW COVER PROFILE UAS / SAAC	**Obs** KS, PC **Date** 3/11/2003 **Time** 11:30	**Profile Type** Full **No.** 33 **Surface Roughness** ∿∿∿ Wavy **Penetration** **Foot** 10 **Ski** 5
Location Fish Creek Knob snow & wx study plot		**Air Temperature** -11.0 C°
H.A.S.L. 700 Metres	**Co-ord** 5817 , 134315	**Sky Cond.**
Aspect N/A	**Slope** 0 °	**Precip.** Nil
HS 133 **HSW** 473 **ρ** 356 **R**		**Wind** Light 1-25 km/hr North

H	θ	F	E	R	HW ρ	Comments	S
		□ ⁄●	2.0				0
		◎◎	3.0		26 265	rain runnels	0
		□ ⁄	2.0		17 238	some preserved stellars	0
		□	0.5		50 261		0
		◎◎	3.0		25 316		0
		□	1.0		36 304		0
		□	1.0		32 295	some old rounds	0
		○	2.0		286 434		0

FIGURE 4. Snowpit profile from the study site on 11 March 2003. Note the layer of 2-mm faceted crystals at the 120-cm level.

(Fig. 5). Similar to the results of Birkeland et al. (1998) in Montana, the snow surface was coldest during early morning hours and warmest in the early afternoon. During the 2-day period, the diurnal swing in temperature did not penetrate below the 30-cm depth in the snowpack, and snow temperature increased to about –2°C by the 50-cm depth.

The strong diurnal fluctuation in surface temperature in conjunction with relatively constant temperatures below the 30-cm depth resulted in a strong temperature gradient near the snow surface that shifted directions between day and night (Fig. 6a). The temperature gradient was strongest in the upper 5 cm of the snowpack during night-time hours (–50°C m^{-1} to –70°C m^{-1}) but was also substantial during the middle of the day (20°C m^{-1} to 50°C m^{-1}). Temperature gradients in the 5- to 10-cm and 10- to 20-cm layers of the snowpack were also elevated, although the absolute magnitude of these gradients was typically 50% or less of the temperature gradient in the top 5 cm of the snowpack. This strong decrease in the temperature gradient with increasing distance from the snow surface suggests that the maximum temperature gradients measured for the 0- to 20-cm layer during the first event on 6–7 March (–80°C m^{-1}) likely corresponded to temperature gradients with an absolute value of well in excess of 100°C m^{-1} in the 0- to 5-cm layer at the surface of the snowpack.

Unlike the temperature gradient, which peaked during the night, the highest vapor pressure gradient (19 mb m^{-1}) measured in the 4–5 April event occurred during the day when snow temperatures near the surface were higher (Fig. 6b). However, vapor pressure gradients were consistently high during night-time hours, decreasing below –12 mb m^{-1} for more than 11 h on the night of 4 April. Overall, the vapor pressure gradient in the top 5 cm of the snowpack during 4–5 April had an absolute magnitude of greater than 5 mb m^{-1} for all but 7 h of the 48-h period.

TABLE 1

Field stability tests (CT = compression test; ST = shovel shear test). Star denotes tests conducted at the Eaglecrest Ski Area 1.5 km SE of the study site.

Date	Test (result)	Depth (cm)	Grain type (size)
11 March	CT (very easy)	10	Facets (2 mm)
13 March*	CT (moderate)	40	Facets (2 mm)
16 March	CT (very easy)	45	Facets (1.5 mm)
17 March*	ST (hard)	58	Facets (1 mm)

Similar to the March event, the high vapor pressure gradients in the top 5 cm of the snowpack resulted in the development of near-surface faceted crystals that acted as a weak layer when loaded with new snow. On 6–7 April, 21 cm of new snow fell at Fish Creek Knob. Although no stability tests were conducted at the site immediately after this snowfall event, field personnel triggered a size 2 avalanche approximately 2 km southeast of the study site on 8 April. A fracture profile of the slide identified 2-mm facets as the weak layer underlying a 50-cm wind-loaded slab (Fig. 7). This avalanche is further evidence that near-surface faceted crystals are responsible for snowpack weaknesses in the high-latitude maritime environment of southeast Alaska. At this time, the spatial variability associated with the formation of near-surface faceted crystals near our study site is not well understood. The collection of more spatially distributed field data would allow us to evaluate the extent to which the snowpack conditions and metamorphic processes documented at our site may be representative of conditions across the upper Fish Creek watershed where the Eaglecrest Ski Area is located.

CONDITIONS ASSOCIATED WITH DEVELOPMENT OF NEAR-SURFACE FACETED CRYSTALS

Strong temperature gradients near the surface of seasonal snowcovers can result from variations in both temperature and solar radiation at the snow surface. Birkeland (1998) describes three processes associated with the development of near-surface faceted crystals: radiation recrystallization, melt-layer recrystallization, and diurnal recrystallization. Our results in the maritime snow climate of Southeast Alaska document the growth of near-surface faceted crystals by the latter two processes: melt-layer recrystallization and diurnal recrystallization. In the first event in March, 12 cm of new snow fell over 2 days prior to the event during a storm in which air temperatures decreased from +0.8°C to less than –9°C by the end of the second day. As a result, the snow deposited at the end of the storm was cold and dry relative to the warm, wet snow at the outset of the storm. The storm was followed by a period of high pressure with offshore flow bringing cold continental air from northern Canada into the Alaska panhandle. This pattern resulted in persistent, strong negative temperature and vapor pressure gradients near the snow surface. These conditions are nearly identical to those described by Birkeland (1998) for melt-layer recrystallization following a rain/wet snow event.

The second event in April documented near-surface faceted crystal growth resulting from diurnal recrystallization. Pronounced fluctuations in the snow surface temperature relative to the snow temperature at the 30-cm depth resulted in strong negative vapor gradients at night and strong positive vapor gradients during the day. One important difference from the process of diurnal recrystallization described by Birkeland (1998) is that at our site the daytime heating of the snow surface was driven by diurnal shifts in air temperature rather than by direct inputs of solar radiation, which are minimal in the winter and early spring months.

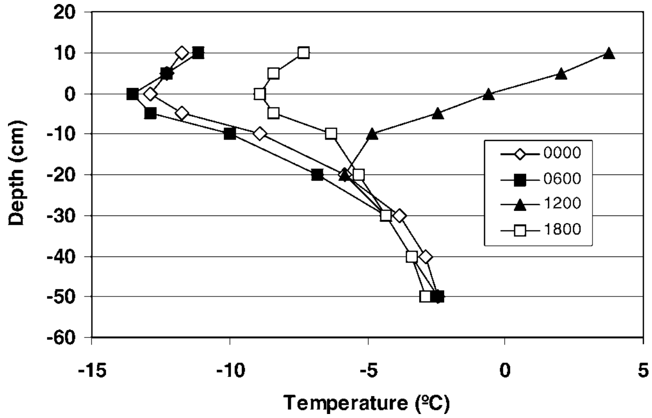


FIGURE 5. Near-surface snow temperature profiles observed at 6-h intervals on 5 April 2003.

In both events, the temperature gradients and resulting vapor pressure gradients near the snow surface produced faceted crystals up to 2 mm in diameter in a period of several days. The meteorological differences between the two episodes suggest that in the snow climate of southeast Alaska there are a variety of synoptic conditions that can produce the strong near-surface vapor pressure gradients necessary for the growth of near-surface faceted crystals. It is also important to note that the kinetic growth processes in both episodes were greatly enhanced by the presence of low-density snow (<250 kg m^{-3}) at the snowpack surface. Thus, in maritime climates where rain on snow events are common, the availability of near-surface snow with sufficient pore space to allow rapid vapor transport between snow grains is likely an important limiting factor for the growth of near-surface faceted crystals. In the future, we hope to develop a better

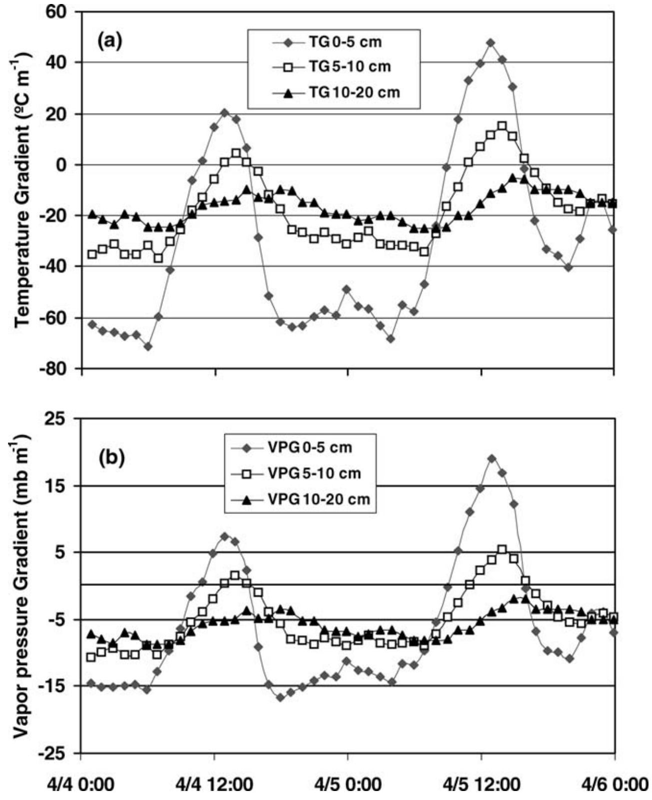
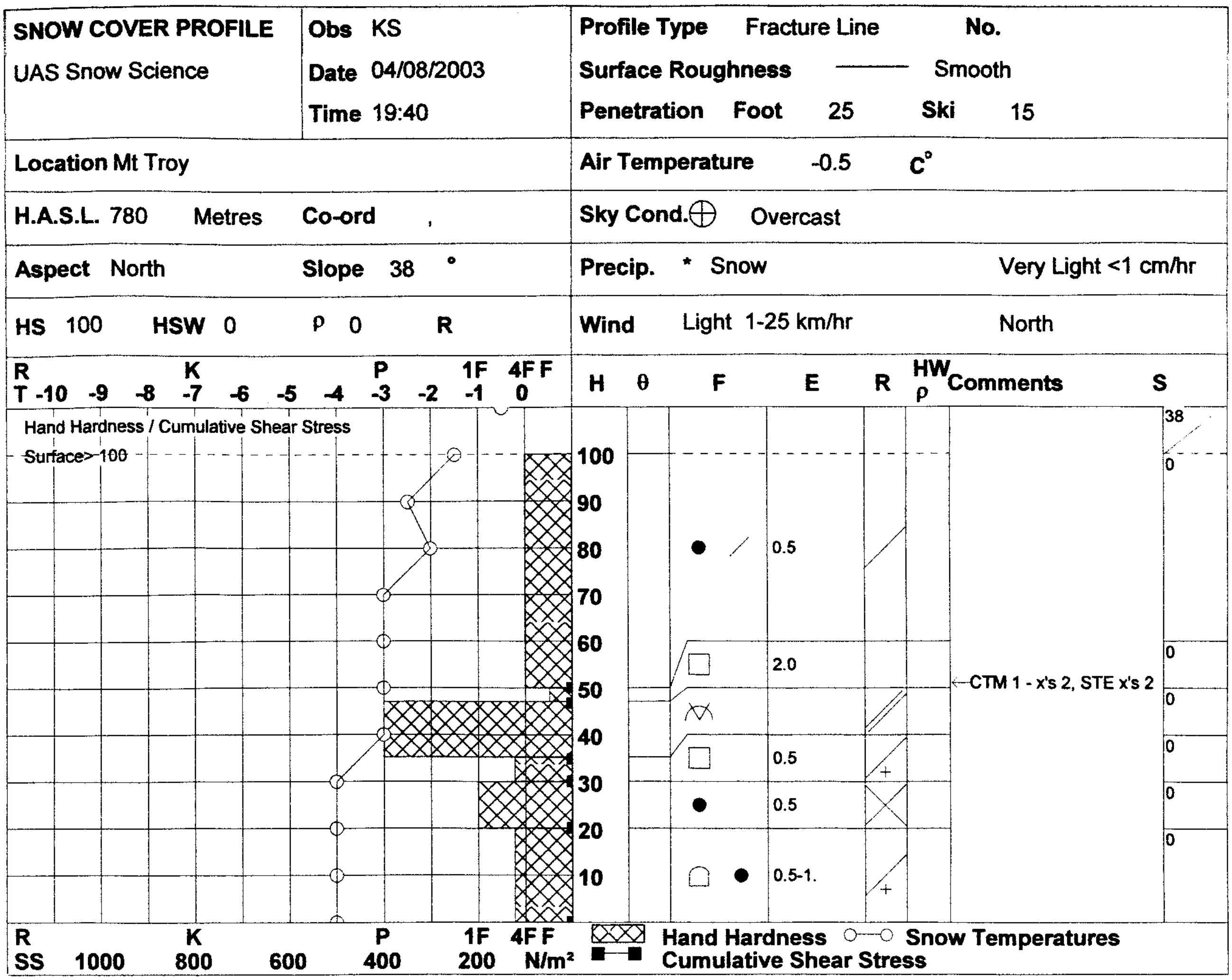


FIGURE 6. Near-surface temperature (a) and vapor pressure (b) gradients at three depths in the snowpack on 4–5 April 2003.



SNOW COVER PROFILE
UAS Snow Science

Obs KS
Date 04/08/2003
Time 19:40

Profile Type Fracture Line **No.**
Surface Roughness ——— Smooth
Penetration Foot 25 **Ski** 15

Location Mt Troy
Air Temperature -0.5 C°

H.A.S.L. 780 Metres **Co-ord** ,
Sky Cond.⊕ Overcast

Aspect North **Slope** 38 °
Precip. * Snow Very Light <1 cm/hr

HS 100 **HSW** 0 ρ 0 **R**
Wind Light 1-25 km/hr North

Stability: Fair

Hazard above treeline: Considerable

This is the fracture line profile of an unexpected human triggered size 2 avalanche. The crown averaged 30cm deep and propagated 100-150m along a gully. The avalanche ran 150m.

FIGURE 7. Fracture line profile from an avalanche triggered by field personnel on 8 April. Note that the sliding layer was 2-mm faceted crystals buried 50 cm beneath the snow surface.

understanding of the interaction between climatic conditions and conditions at the snowpack surface in order to provide timely predictions of the development of near-surface faceted crystal layers and the avalanche cycles associated with their presence in the snowpack in this region.

Acknowledgments

Funding for this project was provided by the Chancellor's Special Project Fund at the University of Alaska Southeast and from the Natural Resources Fund at the University of Alaska. Shannon Seifert provided the map for Figure 1. Kevin Krein, Hans-Werner Jacobi, and an anonymous reviewer provided helpful comments on the manuscript. Bill Glude of the Southeast Alaska Avalanche Center provided guidance in developing the project. Sarah Carter, Brian Davies and the Eaglecrest Ski Patrol helped with data collection. Ben Haight and Dan Phillips of Haight & Associates provided electronic and logistical support, and Julia Ruthford of the National Weather Service provided programming assistance. Coastal Helicopters provided logistical support. Thanks also to the many UAS Environmental Science students who helped out with fieldwork at the site.

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Revised ms submitted September 2004