NEAR-SURFACE FACETED CRYSTAL GROWTH AND SNOW STABILITY IN A HIGH-LATITUDE MARITIME SNOW CLIMATE

Kent Scheler[1,2], Eran Hood[1], Peter Carter[2], Bill Glude[2]

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. However, due to a lack of funding and research, Juneau is largely unprepared for potentially catastrophic avalanche events. 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}. During both of these periods, faceted crystals 1-2 mm in diameter were observed to form near the surface of the snowpack. Field tests performed simultaneously at our 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 stratographic 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 (Gray and Male, 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 because of the widespread observation of depth hoar, which is an extreme example of faceted crystal growth. However, the growth of faceted crystals in the upper layers of the snowpack has recently received more attention as the role of these near-surface faceted crystals in the development of weak layers and subsequent snow avalanches has gained recognition. Near-surface faceted crystals have been documented in a wide variety of snow climates including: mid-latitude continental (Birkeland, 1998), mid-latitude maritime (Fukuzawa and Akitaya, 1993), and high-elevation tropical (Hardy et al., 2001). Moreover, Colbeck (1989) derived temperature fields near the snow surface in order to explain growth rates of near-surface faceted crystal in high-altitude and polar environments.

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 strong near-surface temperature gradients driven by either diurnal temperature cycling or solar radiation inputs (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. These large temperature gradients in low-density surface snow result in rapid kinetic metamorphism of snow crystals, with 1-2 mm faceted crystals forming within periods of several days (Birkeland et al., 1998). The subsequent burial of these faceted 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.

Poster presented Western Snow Conference 2003
[1] Environmental Science Program, University of Alaska Southeast, Juneau, AK
[2] Southeast Alaska Avalanche Center, Juneau, AK

METHODS

Study Site

Fish Creek Knob is a flat, open bench on the northeast ridge of Mount Ben Stewart on Douglas Island 8 km southwest of Juneau, Alaska. The study site is located just below treeline at 700 meters above sea level (Figure 1). A meteorological tower at the site monitors wind speed and direction, temperature, relative humidity, and net radiation. Additionally a sonic snow depth sensor allows observation of real time snow accumulation during storms. Average temperature at the site during the study period in March and April of 2003 was –3.7°C. Average windspeed was 2.1 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).

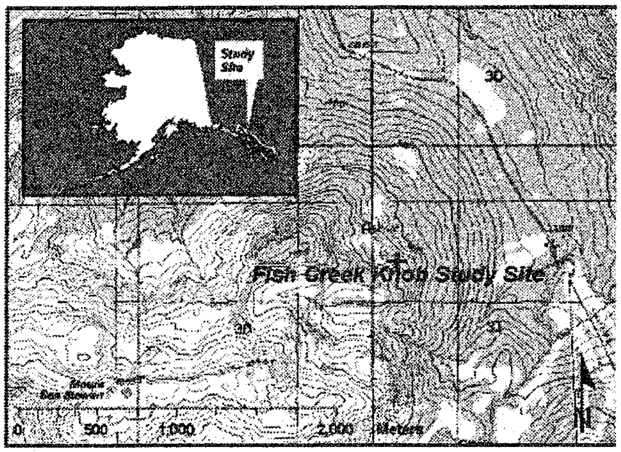


Figure 1. Fish Creek Knob study site at 700 m elevation on Douglas Island near Juneau, Alaska.

Snowpack Measurements

Snowpack temperature gradients were measured using a 1 m snowpack temperature probe consisting of a thermocouple array mounted in white PVC pipe. Holes were drilled in a spiraling line around the probe every 10cm up to 70cm, and every 5 cm between 70 cm and 1m. A high accuracy thermocouple (HOBO, -40° to 100° C ± 0.5° C) protruded from each hole. The remaining void space in the temperature probe was filled with insulation foam. The spiraling array around the temperature probe is designed to minimize interference between thermocouples. At 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 13 sensors at five-minute intervals and was stored to a HOBO data logger. Throughout the study period, the position of the temperature probe relative to the snow surface was monitored using the acoustic snow depth sensor mounted on the meteorological tower.

The study site was visited at least weekly and pits were dug at a designated area in close proximity to the temperature probe. In each pit, snow stratigraphy including grain size and type was recorded following the protocols described in Colbeck et al. (1990). In addition, snow density, hardness, and temperature were recorded for each unique layer identified in the snowpack. A series of standard field tests were also performed to identify weak layers within the snowpack. These tests included the compression test (CT) and the shovel shear test (ST). Avalanche activity around the filed site was also closely monitored and fracture lines were investigated whenever possible to identify sliding layers.

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 near-surface temperature gradients in the snowpack exceeded 50°C m^{-1}.

Event 1 – March 6-8, 2003

The first event was characterized by cold, dry conditions at the study site with a temperature range of –9.6°C to –18.9°C and no new snowfall during the three-day period. Data from the sonic depth sensor showed that the height of the snow surface decreased by <3cm due to settling so the position of the temperature probe was fairly constant relative to the snow surface. During this period, a faulty datalogger caused temperature data to be lost from the probes at the 5 cm and 15 cm depths in the snowpack. The temperature profile recorded in the snowpack showed very cold temperatures at the snow surface during both day and night time hours (Figure 3). Furthermore, snowpack temperature increased rapidly with depth approaching –5°C at the 25 cm depth and 0°C at the 65 cm depth.

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)

The cold 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 upper (0-25 cm) layer of the snowpack during this event was consistently above –20°C m^{-1} and as high as –50°C m^{-1} (Figure 4). The temperature gradient was generally strongest during the night when temperatures at the snow surface were coldest and increased slightly during the day with the warming of the snow surface. 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 and 15 cm depths precluded us from measuring snowpack temperature immediately below the snow surface where temperature gradients are typically strongest. Additionally, the temperature gradient in the 0-25 cm layer of the snowpack during this time period was 2-5 times the threshold value of 10°C m^{-1} commonly associated with faceted crystal growth (Armstrong, 1985).

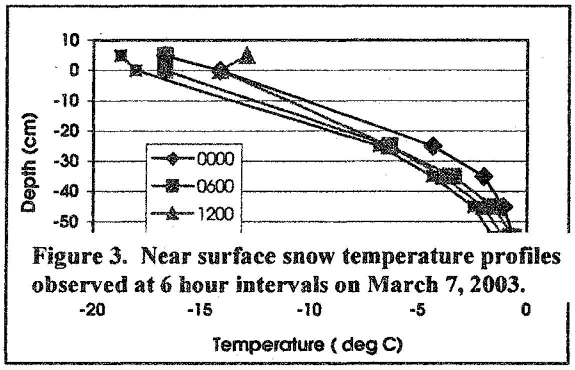
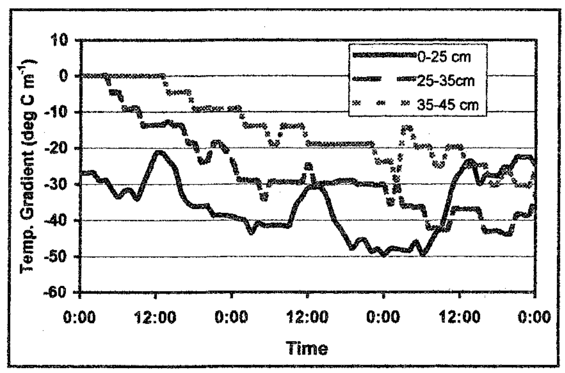


Figure 3. Near surface snow temperature profiles observed at 6 hour intervals on March 7, 2003.



Field investigations following the March 6-8 event documented the growth of near-surface faceted crystals that were up to 2 mm in diameter. Furthermore, stability tests and avalanche activity proximate to the site demonstrated that the newly formed facets were associated with instabilities in the upper layers of the snowpack. On March 9, 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 windslab (data not shown). On March 11, a snowpit at the study site documented a layer of 2 mm faceted crystals approximately 10 cm below the snow surface (Figure 5). This faceted layer was not present in the previous snowpit profile collected at the site on March 4 indicating that the facets formed during the March 6-8 event documented here. Stability tests performed at the site on March 11 showed a pronounced weak layer associated with the faceted layer 10 cm below the snow surface. This layer of near-surface faceted crystals was subsequently buried by ~32 cm of snow during a storm on March 13-14, 2003. Stability tests performed at the study site and the nearby Eaglecrest Ski area during the period March 13-17 showed that the recently-buried faceted crystals continued to be associated with weak layers in the upper portion of the snowpack (Table 1). These weak layers persisted for more than a week after they were formed on March 6-8.

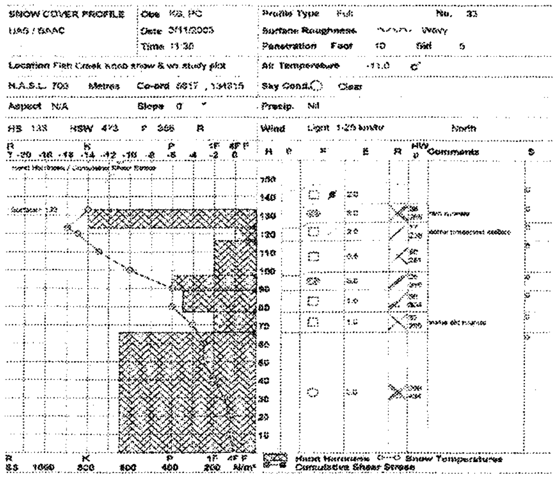


Table 1. Field stability tests (CT = compression test; ST = shear test). Star denotes tests conducted at the Eaglecrest Ski Area 1.5 km SE of the study site.

Event 2 – April 4-5, 2003

The second event was characterized by generally warmer conditions (0.5°C to –7.8°C), particularly during daytime hours when temperatures were close to 0°C. There was no new snowfall during this period and the height of the snow surface decreased by only 1 cm due to settling in the snowpack. The temperature profile in the snowpack showed a diurnal shift with temperatures decreasing temperatures toward the snow surface during night time hours and increasing toward the snow surface during the day (Figure 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 two-day period, the diurnal swing in temperature did not penetrate below the 30 cm depth in the snowpack, and snow temperature increased to close to –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 (Figure 6). The temperature gradient was strongest in 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 5-15 cm and 15-25 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 0-25 cm layer during the first event in this study (~50°C m^{-1}) likely corresponded to temperature gradients well in excess of 100°C m^{-1} in the top 5 cm of the snowpack.

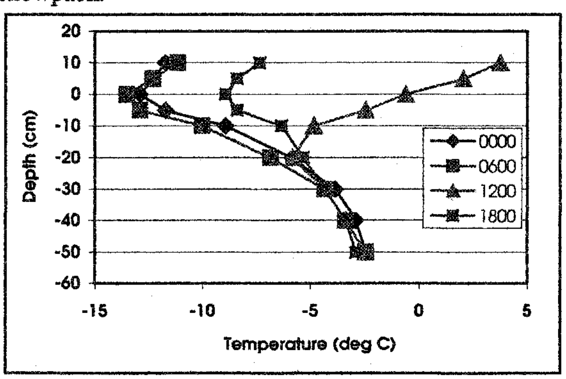


Figure 5. Near-surface snow temperature profiles observed at 6-hour intervals on April 5, 2003.

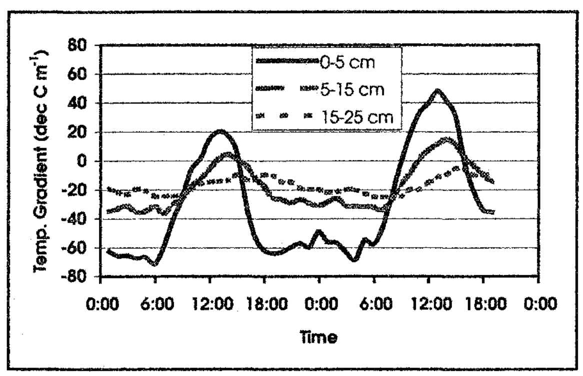


Figure 6. Near-surface temperature gradients at three depths in the snowpack on April 4-5, 2003.

On April 8th, soon after the event documented here, field personnel triggered an avalanche approximately 2 km southeast of the study site. A fracture profile of the slide identified 2mm facets as the weak layer underlying a 50 cm wind-loaded slab (Figure 7). This event further highlights the snowpack instabilities associated with the growth of near-surface faceted in the high-latitude maritime snowpack near Juneau, Alaska.

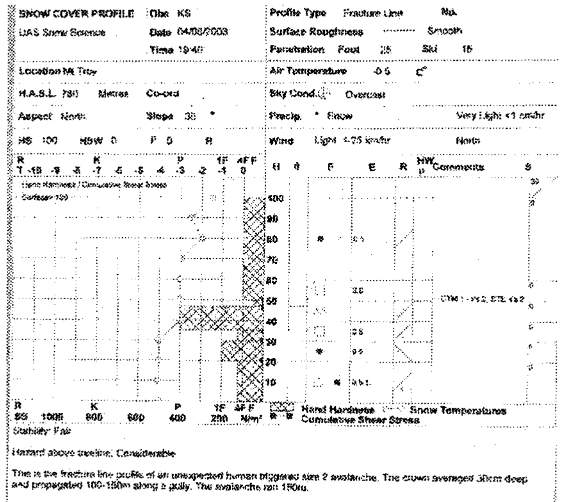


Figure 7. Fracture line profile from an avalanche triggered by field personnel on April 8. Note that the sliding layer was 2 mm faceted crystals buried 50 cm beneath the snow surface.

The development of strong temperature gradients near the surface of seasonal snowcovers can result from both variations in 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. In the maritime snow climate of southeast Alaska our results 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 two days prior to the event while air temperatures were quite warm (+0.8°C to –2.5°C). This storm was followed by a period of high pressure with very cold temperatures that resulted in the strong negative near-surface temperature gradients documented in the March event. 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 resulted in strong negative temperature gradients at night and strong positive temperature gradients during the day. These results suggest that there are a variety of synoptic conditions responsible for the growth of near-surface faceted crystals in the maritime snow climate of southeast Alaska. Developing a better understanding of these weather conditions will help in predicting both the development of these kinetic growth layers and the avalanche cycles associated with their presence in the snowpack in this region.

CONCLUSIONS

This research validates the effectiveness of the temperature probe at monitoring snowpack temperature gradients that contribute to the growth of near-surface faceted crystals. Snowapck temperature gradients in excess of 70°C m^{-1} were recorded in the maritime snowpack of southeast Alaska. These large temperaturegradients resulted in the rapid growth of faceted crystals 1-2 mm in diameter in the upper layers of the snowpack. Avalanches that occurred shortly after high temperature gradient events commonly failed on large facets underlying wind slabs. Our results demonstrate that near-surface faceted crystal growth due to extreme temperature gradients contributes to snowpack instabilities in high-latitude maritime snowpacks. Continued investigations into the development of these instabilities in Southeast Alaska will lead to better forecasting of catastrophic avalanche events in the Juneau area.

ACKNOWLEDGEMENTS

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. Carl Byers provided the map for Figure 1. Cathy Connor provided guidance in developing the project. Thanks to Sarah Carter, Brian Davies and the Eaglecrest Ski Patrol for helping 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 assiatance. Coastal Helicopters provided logistical support. Johnse Ostman, Mike Pando, Daryen Snyder, Shannon Seifert, Terry Schwartz, Kris Quinto, Megan Williams, and the entire ENVS snow hydrology class helped with fieldwork.

LITERATURE CITED

Armstrong, R. L., 1985. Metamorphism in a subfreezing, seasonal snow cover: The role of thermal and vapor pressure conditions. Ph.D. dissertation, Department of Geography, University of Colorado. 175 pp.

Birkeland, K.W., R.F. Johnson, and D.S.Schmidt, 1998. Near-surface faceted crystals formed by diurnal re-crystallization: A case study of weak layer formation in the mountain snowpack and its contribution to snow avalanches. *Arctic and Alpine Research*, 30, 200-204.

Birkeland, K.W., 1998. Terminology and predominant processes associated with the formation of weak layers of near-surface faceted crystals in the mountain snowpack. *Artic and Alpine Research*, 30, 193-199.

Colbeck, S.C. 1989. Snow-crystal growth with varying surface temperatures and radiation penetration. *Journal of Glaciology*, 35, 23-29.

Colbeck, S.C., E. Akitaya, R. Armstrong, H. Gubler, J. Lafeuille, K. Lied, D. McClung, and E. Morris, 1990. The international classification for snow on the ground. National Snow and Ice Data Center, Boulder, CO, 23 pp.

Fukuzawa, T. and E. Akitaya, 1993. Depth-hoar crystal growth in the surface layer under high temperature gradient. *Annals of Glaciology,* 18, 39-45.

Gray, D.M. & D.H. Male, 1981: Handbook of Snow: Principles, Processes Management & Use. Pergamon Press, Toronto. 275-278p.

Hardy, D., M. W. Williams, and C. Escobar, 2001. Near-surface faceted crystals and avalanche dynamics in high-elevation, tropical mountains of Bolivia. *Cold Regions Science and Technology*, 33 (2-3), 291-302.

McClung, D. & P. Schaerer, 1999. The Avalanche Handbook. Fifth printing, The Mountaineers, Seattle. 37-52p.