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THE EFFECTS OF SLOPE ASPECT ON THE FORMATION OF SURFACE HOAR AND DIURNALLY RECRYSTALIZED NEAR-SURFACE FACETED CRYSTALS: IMPLICATIONS FOR AVALANCHE FORECASTING

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ABSTRACT: This study presents evidence that slope aspect plays a significant role in the formation, size, type, and extent of surface hoar and near-surface faceted crystals. Experimental stations were placed on the north and south-facing aspects of Pioneer Mountain in southwest Montana to measure wind speed and direction, snow temperatures from 0.1m above the snow surface to 0.35m below the snow surface, incoming and outgoing shortwave radiation, and snow surface temperature. Each time a surface hoar or near-surface faceted crystal layer formed, snowpack and meteorological variables were gathered and snow crystals were collected, measured, characterized and photographed so that crystal size and structure could be compared between aspects. Persistent weak layers formed on January 9-10, 2004, and January 12-13, 2004. Results show a statistically significant difference in the size of surface hoar and near-surface faceted crystals based on slope aspect. During these two periods, better developed near-surface facets formed on south-facing slopes, while surface hoar crystals grew larger at the north-facing study site. These aspect dependent differences are important for assessing mountain range scale spatial variability and may also play a role at smaller scales due to subtle aspect changes. The results of this research may help us better understand some of the differences in weak layer formation on different aspects which, in turn, lead to different avalanche conditions.

KEYWORDS: avalanche, avalanche forecasting, large scale spatial variability, surface hoar, diurnally recrystalized near-surface faceted crystals, temperature and vapor pressure gradients

1. INTRODUCTION

This paper presents evidence that slope aspect plays a significant role in the mountain range scale spatial variability of surface hoar and diurnally recrystalized near-surface faceted crystals and may also play a role in the variability of weak layers at smaller scales.

In the last 18 years 2,694 people have been killed in avalanches in reporting countries worldwide. In the United States 492 lives were lost, with 41 of those fatalities occurring in Montana where this study was conducted. This year, in North America alone, 21 people were killed by avalanches (www.geosurvey.state.co.us/avalanche). In fact, Voight et al. (1990) found that, on an average annual basis, in the United States more fatalities are attributed to avalanches than to earthquakes and other landslide hazards with economic losses due to avalanches exceeding a million dollars a year.

Weak layers in a seasonally stratified snowpack are known to be the most common failure plane for avalanches (McClung and Schaerer, 1993). Föhn (1992) found that 80% of all weak layers found in an alpine snowpack consist of faceted crystals, and Birkeland (1998), working in southwest Montana, found that out of 51 avalanches from 1991-1996, most (46) failed on a layer formed at or near the snow surface. Of those 46 avalanches, 30 (59%) were attributed to near-surface faceted crystals and 16 (31%) to buried layers of surface hoar. Jamieson (1999), studying surface hoar in the Columbia Mountains of western Canada, found that surface hoar was implicated in 34% of fatal slab avalanches.

This study investigated two types of faceted crystals that form under similar meteorological conditions at or near the snow surface: surface hoar and diurnally recrystalized near-surface faceted crystals. Surface hoar develops due to meteorological conditions that

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cause large temperature gradients at the snow/air interface. On cold, clear nights longwave radiation losses from the snow surface cool the snow to well below the temperature of the adjacent air, creating large temperature gradients at the snow/air interface. Water vapor moves down the ensuing vapor pressure gradient from the warmer higher pressure air to the cooler lower pressure snow surface where it condenses, forming feather-like facets. Colbeck et al. (1990) classified these crystals as type 7sh, surface hoar, and noted that they are fragile with extremely low shear strength.

The meteorological processes contributing to the formation of surface hoar and its mechanical properties have been the subject of a sizable body of research. Lang et al. (1984), Colbeck (1988), Hachikubo and Akitaya (1997a,b), Höller (1998), and Hachikubo (2000), have all studied the meteorological processes contributing to the formation of surface hoar. Colbeck (1988) showed theoretically that it is necessary to have turbulent transfer, mixing, for surface hoar to grow. He theorized that molecular diffusion of water vapor from the air to the snow surface is not sufficient alone to grow surface hoar and that wind must aid in the process. Hachikubo and Akitaya (1997a,b) later confirmed Colbeck’s findings, dispelling the theory that surface hoar forms only on nights with no perceptible wind. They showed the importance of measuring the wind speed when looking at surface hoar formation, concluding that wind speeds of 1 - 2 m/s at a height of 1m above the surface are necessary for maximum surface hoar formation. Jamieson and Johnston (1999) and Jamieson and Schweizer (2000) have extensively measured the mechanical strength of buried surface hoar layers.

Although many noteworthy studies have been conducted on the meteorological conditions necessary for the formation of surface hoar and on the strength and strength changes over time of this persistent weak layer, no research has focused on slope aspect as a deterministic factor for surface hoar formation.

Diurnally recrystalized near-surface faceted crystals, the other type of faceted crystal studied here, are named because of their formation by temperature gradients in the top 0.3m of the snowpack (Birkeland 1998). Diurnal recrystalization is a complex process. Armstrong (1985) found that the type and extent of metamorphism is directly related to the magnitude of the vapor pressure gradient, which depends on the temperature gradient and the average temperature of the layer. Armstrong (1985) also found that for beginning facets to form at temperatures close to 0˚C, a temperature gradient of 5mb/m is necessary. LaChapelle and Armstrong (1977) and Armstrong (1985) also recognized that there are diurnal fluctuations in temperature in the upper 0.3m of the snowpack and that the temperature at and below 0.3m remains relatively constant. As a result, temperature gradients form, which, in turn, create vapor pressure gradients and faceting.

Birkeland (1998) noted three different mechanisms for the formation of near-surface faceted crystals: radiation recrystalization, melt layer recrystalization, and diurnal recrystalization. Near-surface faceted layers formed by diurnal recrystalization, referred to here as near-surface facets, are the only type that is addressed in this research. Birkeland et al. (1998) also measured near-surface temperatures, calculated vapor pressure gradients, and studied a diurnally recrystalized near-surface faceted layer and its resultant avalanche activity for 9 days after its formation. Fukuzawa and Akitaya (1993) studied near-surface faceted crystals on two different occasions and grew these crystals in a cold lab. Recently, McElwaine et al. (2000) observed and attempted to model a layer of near-surface faceted crystals which formed the weak layer of the Niseko Haru no Taki avalanche, and Hardy et al. (2001) recognized the importance of high inputs of shortwave radiation and day-time absorption of solar radiation in the formation of a layer of near-surface faceted crystals in the Bolivian Andes.

Again the role that slope aspect plays in the formation of near-surface faceted layers has not been addressed in the literature. Birkeland et al. (1998) in their summary statement suggested that more quantification of near-surface faceting is necessary. Specifically, they called for studies on changes in bonding, faceting, and strength with time and space to help determine future avalanche conditions which has led, in part, to the research presented here.

2. RESEARCH METHODS

2.1 Site Description

This study was conducted at The Yellowstone Mountain Club on Pioneer Mountain in the Madison Range of southwest

Montana near Big Sky (Figure 1). Classified as an intermountain snow climate by Mock and Birkeland (2000), the Madison Range receives an average of 6m of snow a year and is favored by storms on a westerly flow that are strong enough to persist across the large ranges to the west.

To study the role that slope aspect plays in the formation of surface hoar and near-surface faceted crystals, experimental stations were placed on the north (0˚ compass bearing at 2532 meters on a 30˚ slope) and south (187˚ compass bearing at 2757 meters on a 30˚ slope) aspects of Pioneer Mountain. Both sites were situated on scree slopes, with large sky views, in areas surrounded by trees which limited the effects of blowing and drifting snow.

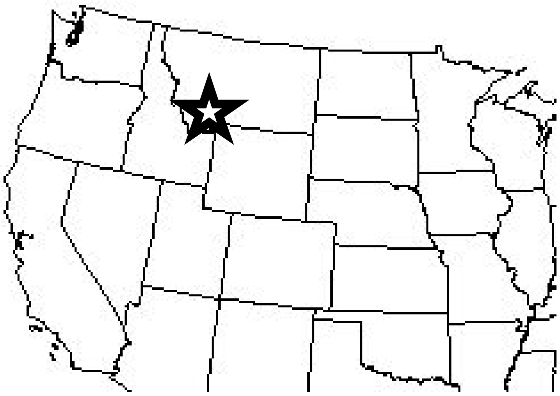

Figure 1: Location of the study site at The Yellowstone Mountain Club on Pioneer Mountain in the Madison Mountain Range of southwest Montana.

2.2 Measurements of Meteorological Variables

Each site was outfitted with a Met One 034A anemometer which was fixed to a movable arm. The anemometer measured wind speed and direction at 1m above the snow surface.

Air and snow temperatures were measured with a thermocouple array at each site. The arrays consisted of a stack of type-T copper-constantine thermocouple wires, mounted in graphite tubes of diameter 0.3mm and placed through a wooden dowel rod. Temperatures were measured at 3 second intervals every 0.05m from 0.1m above the snow-surface to 0.35m below the snow surface and were averaged for each hour.

The arrays were carefully inserted into the snow, as close to slope perpendicular as possible, and the entire apparatus was rotated ¼ turn to get the wire ends in contact with undisturbed snow. The arrays were checked often and were reset after each snow or when they visually appeared askew. The arrays seemed to settle with the snowpack and were carefully monitored in an attempt to gather the most precise data possible.

Incoming and outgoing short-wave radiation was measured with LI-COR pyranometers. The pyranometers were placed slope parallel and back to back, one measuring incoming shortwave radiation and one measuring reflected shortwave radiation. From these instruments a net shortwave balance was calculated.

Snow surface temperatures were also measured with an Everest Interscience 4000.4ZL infrared surface thermometer mounted at slope parallel on the arm next to the pyranometers.

Data such as snow water equivalent, snow depth, temperature, relative humidity, and wind speed and direction were also used. These data were collected by The Yellowstone Club Snow Safety Department at two sites: one site at 2182m, at the base of Pioneer Mountain and the other approximately 150m below the ridge line at 2857m.

2.3 Measurements of Faceted Crystals

To compare the extent of faceting, every other day snow crystals were collected at the snow surface and from 0.05m below the snow surface. Field measurements and digital photographs were taken. The crystals were then placed in a solution of Iso-Octane, labeled, and placed in a freezer. Each week the crystals were transported to the Montana State University Cold Lab. In the lab, fifteen randomly selected crystals from each collection were photographed under a microscope at varying magnifications, classified, and then measured across their longest axis so that size comparisons between aspects could be made.

2.4 Calculations

Hourly calculations were made for each study site from December 15, 2003, to April 15, 2004. Temperature gradients were calculated for each 0.05m increment from 0.10m above the surface to 0.35m below the surface. The minimum and maximum temperature gradients for each day were also calculated.

Vapor pressure gradients were calculated in 0.05m increments using the Goff-Gratch Formulation for the saturation vapor pressure over a surface of pure water and pure ice (List, 1951; Armstrong, 1985; Birkeland et al., 1998). The hourly net shortwave radiation balance (a measure of absorbed shortwave radiation) was also calculated by subtracting the outgoing shortwave from the incoming shortwave radiation.

3. RESULTS/DISCUSSION

Two faceting events occurred during the second week of January, 2004. The first event was a surface hoar layer that formed on January 9th - 10th, 2004. The second event, which occurred on January 12th - 13th, included two layers, a surface hoar layer and a layer of near-surface faceted crystals.

3.1 Weather Conditions

By the end of November 2003, The Yellowstone Club had received 0.89m of snow at the 2857m study site, and on the last day of November the settled snow base was only 0.5m. By the end of December 2003, most of the in-area terrain was open, and on the last day of December the annual snow total had risen to 2.48m and the settled snow base to 1.19m. The first day of January 2004 began with a small disturbance from the southwest, dropping 0.15m of snow with 0.005m of water. The ridge top winds were moderate from the southwest. Another 0.1m of snow with 0.014m of water fell over the next few days. On January 8, 0.2m of snow with 0.009m of water fell, bringing the settled snow base to 1.37m. The ridge top winds averaged 6m/s from the 244˚ compass direction. Avalanche control results on the morning of the 8th consisted mostly of new snow class 2 avalanches.

The morning (0700h) meteorological observations on January 9, 2004, reported broken skies, wind speeds averaging 6m/s from the southwest at the ridge tops, air temperature of -2.6˚C, and relative humidity of 91%. The afternoon (1600h) meteorological observations indicated that the skies had become overcast, the ridge top winds were 6.3m/s from the southwest, the temperature had risen to 0.3˚C, and the relative humidity was 82%. On the morning of January 10, 2004, a surface hoar layer was observed between 2133m and 2743m. No new snow fell, the ridge top winds were moderate, and the skies remained scattered until the morning of the 12th.

The 0700h daily meteorological observations on January 12, 2004, reported clear skies in the morning, ridge top winds averaging 6m/s from the southwest, and air temperatures around -4˚C. At 1600h the skies were again scattered, but clear skies prevailed through most of the night and into the morning of January 13th, 2004.

3.2 Surface Hoar Layer January 10, 2004

A surface hoar layer formed during the early evening of January 9th. Crystals were collected at the snow surface and also at 0.05m below the surface from the south-facing study site at about 0815h on the morning of January 10th. The crystals were clearly identifiable as type 7sh, feather-shaped, surface hoar as characterized by Colbeck et al. (1990).

At about 0900h the same procedures were used to sample the north-facing site and crystals were collected. The crystals could also be easily identified as surface hoar and appeared to be larger and better developed than those from the south-facing slope.

The crystals were carefully transported from The Yellowstone Club to the Montana State University Cold Lab where they were characterized and photographed under controlled conditions. Fifteen randomly selected snow crystals from each aspect were measured across their longest axis and a median crystal size was obtained.

Laboratory measurements showed that the crystals that formed on the north-facing aspect were larger and better developed, with more striations, than those collected on the south-facing aspect. The median size for crystals on the north-facing aspect was 6mm and on the south-facing aspect was 3mm (Figure 2). Photographs (Figures 3a and b) show the size difference, between aspects, of some of the surface hoar crystals.

Since the size of the surface hoar crystals that formed on January 9th - 10th was noticeably different between aspects, the meteorological variables known to cause the growth of surface hoar were compared between the sites to determine why this large difference in crystal formation occurred (Table 1).

The temperature gradients between the air and snow surface for the 24 hour period leading up to the faceting event on the north-facing site were much larger than those on the south-facing site (Figure 4). These large temperature differences between the snow and the air caused a larger vapor pressure gradient, and water vapor from the air was deposited on the snow surface producing larger surface hoar crystals.

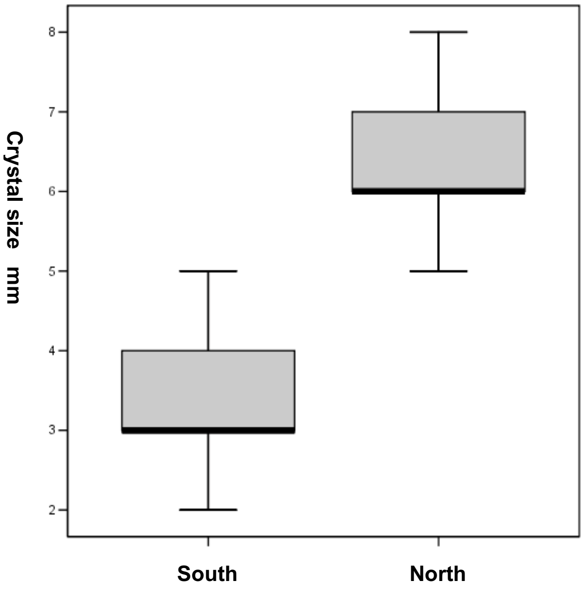

Figure 2: Box plot of crystal size in mm on January 10, 2004, versus slope aspect. The dark line is the median. The box shows the inter-quartile range. The whiskers show, the minimum and maximum values.

This difference in temperature gradient was caused by greater inputs of shortwave solar radiation during the day on the south-facing aspect, leading to an overall warmer snowpack. The nightly, longwave radiation losses had to first overcome the daytime shortwave radiation gains before the snow surface was cooled enough to form a substantial temperature gradient with the air. At night the longwave radiation losses at the north-facing site, which did not receive as much shortwave radiation during the day, did not have to overcome big shortwave gains. Therefore, a stronger temperature gradient formed more quickly on the north-facing site.

The higher average snow surface temperature (-7˚C) on the south-facing site resulted from the large amount of absorbed net shortwave radiation (321w/m^2) (about two times greater than on the north-facing site). As a result more energy was stored in the near-surface layers of the snowpack on the south-

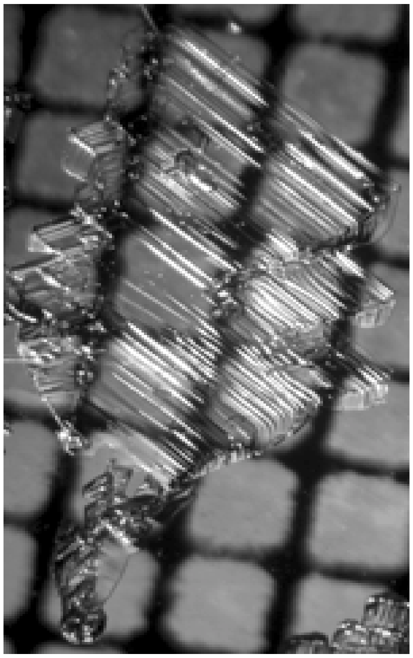

Figure 3a: Photograph of a 6mm surface hoar crystal harvested from the north-facing site on January 10th.

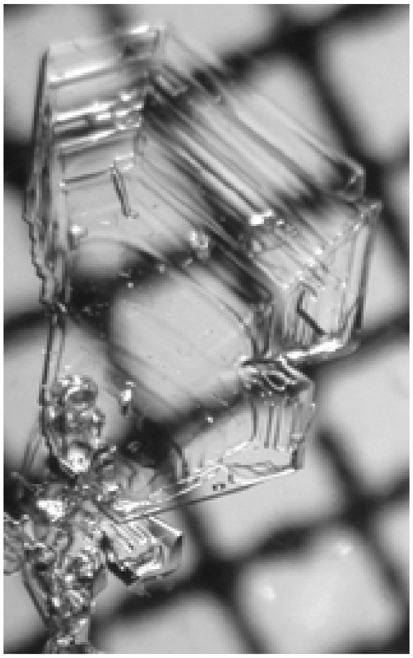

Figure 3b: Photograph of a 4mm surface hoar crystal harvested from the south-facing site on January 10th.

	Max TG ˚C/m	Min TG ˚C/m	Max VPG mb/m	Min VPG mb/m	Net Sw Total 24h w/m^2	Max Surface Temp ˚C	Min Surface Temp ˚C	Avg. Surf Temp ˚C	Avg. Wind Speed m/s
South 0.05 - 0m	55.6	-2	19.2	-1.4	321.1	-0.1	-12.5	-7.24	3.4
North 0.05 - 0m	92.1	-6.8	26	-2.2	181.2	-2.4	-14.2	-9.9	2.1

Table 1: Compares the maximum and minimum temperature and vapor pressure gradients, as well as the net or total absorbed shortwave radiation, the maximum, minimum, and average snow surface temperatures, and the average wind speed for 24h surrounding the surface hoar event on January 10th on both aspects.

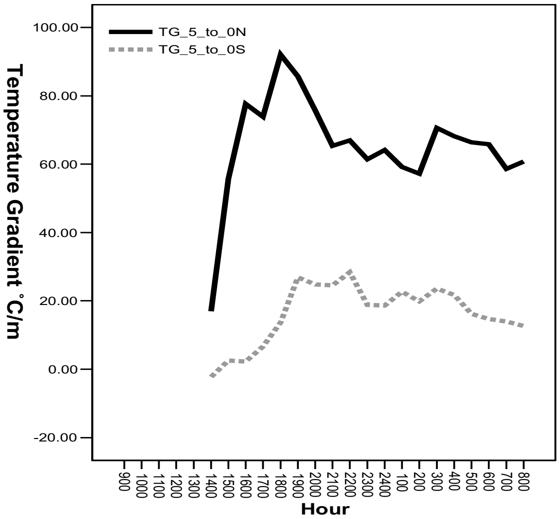

Figure 4: Temperature gradient which formed from January 9 – 10 at the snow/air interface. The gradient on the north-facing aspect is larger than the gradient on the south-facing aspect

facing site. The north-facing site, which did not absorb as much shortwave radiation (181w/m^2), did not have to cool as much to create a significant temperature gradient. Consequently the north-facing site had a larger temperature gradient (92˚C/m) than the south-facing site (56˚C/m).

The wind speed at both sites (Figure 5) was close to the range reported by Colbeck (1988) and Hachikubo and Akitaya (1997 a, b) for optimal surface hoar formation and, although the average speed at the south-facing site was about 1m/s higher, its role was considered equal for the sake of this discussion.

The relative humidity was measured at only one location. It was considered to remain relatively constant throughout the massif (Figure 6).

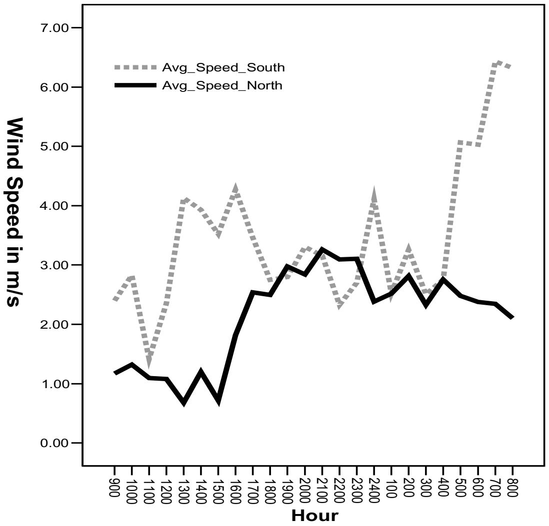

Figure 5: Average hourly wind speed for the north-facing and south-facing sites for the 24h surrounding the surface hoar event on January 10th.

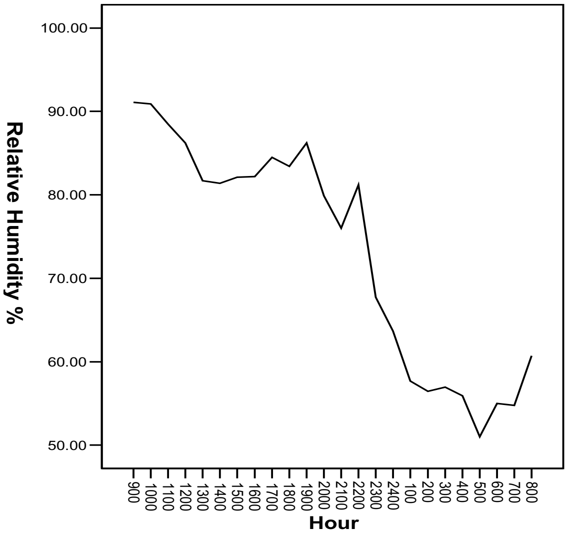

Figure 6: Relative humidity (%) for the 24h surrounding the surface hoar formation on January 10th measured at 2857m.

Findings also indicated statistically significant differences between the temperature gradients, vapor pressure gradients, and snow surface temperatures between aspects on that day.

3.3 Faceted Layers January 13, 2004

On the morning of January 13, 2004, a new surface hoar layer and a layer of near-surface faceted crystals were noted at the south-facing site at 0815h.

The north-facing site was visited at about 0900h. Again, as on January 10th, there was a surface hoar layer present. There was also evidence of a near-surface faceted layer just below (0.05m) the snow surface.

As on January 10th, the surface hoar crystals grew larger at the north-facing site (median of 8mm) than on the south-facing site (6mm). Figure 7 shows the crystal size difference between aspects, and Figures 8 a and b are photographs of the surface hoar crystals collected on January 13th from the north-facing and south-facing sites.

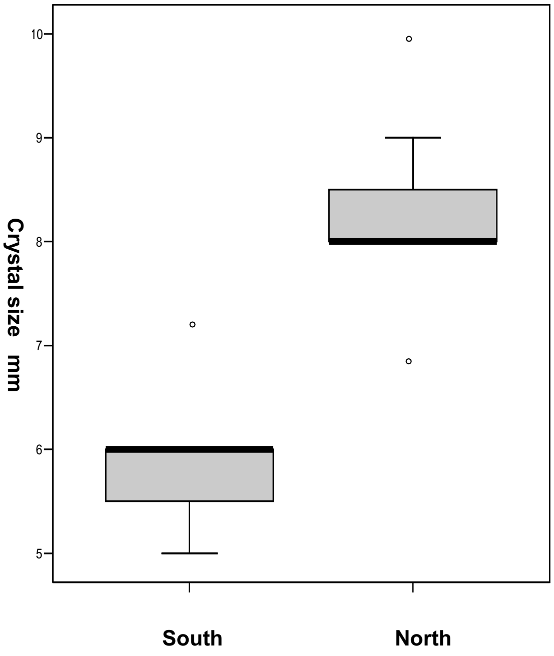

Figure 7: Box plot of crystal size (mm) on January 13, 2004, versus slope aspect. The dark line is the median. The box shows the inter-quartile range and the whiskers, show the minimum and maximum values that are not outlying (circles).

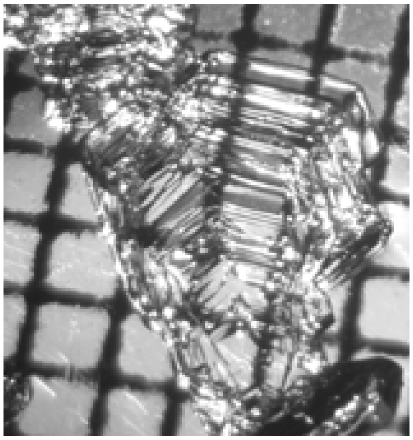

Figure 8a: Photograph of a 6mm surface hoar harvested from the south-facing site on January 13th.

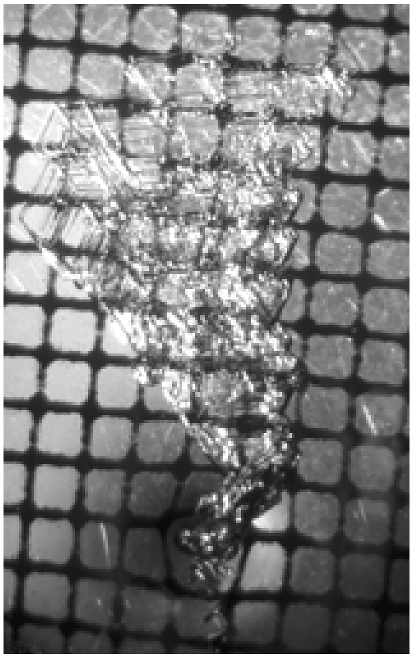

Figure 8b: Photograph of a 10mm surface hoar crystal harvested from the north-facing site on January 13th.

A comparison of meteorological variables (Table 2) confirmed previous findings. The same mechanisms seem to have affected the size of the surface hoar crystals on January 13th as on January 10th. The temperature gradient on the north-facing site (112˚C/m) was again much larger than that on the south-facing site (67˚C/m), which had more (587w/m^2) total absorbed shortwave radiation.

	Max TG ˚C/m	Min TG ˚C/m	Max VPG mb/m	Min VPG mb/m	Net Sw Total 24h w/m^2	Max Surface Temp ˚C	Min Surface Temp ˚C	Avg. Surf Temp ˚C	Avg. Wind Speed m/s
South 0.05 - 0m	66.7	-30.6	21.9	-20.5	587	-0.4	-11.1	-7	3.6
South 0 - Under 0.05m	125.8	-59.6	62.9	-49	––––––	––––––	––––––	––––––	––––––
North 0.05 - 0m	111.7	85.8	32.8	18.2	55	-10.3	-15.1	-12.5	2.0
North 0 - Under 0.05m	-15.2	-59	-3.75	-11.4	––––––	––––––	––––––	––––––	––––––

Table 2: Compares the maximum and minimum temperature and vapor pressure gradients as well as the net or total absorbed shortwave radiation, the maximum/minimum, and average snow surface temperatures and the average wind speed for 24h surrounding the faceting event on January 13th on both aspects at the snow/air interface and also from the snow surface to 0.05m under the snow.

The average hourly temperature gradient at the snow/air interface for 24 hours surrounding the faceting event on January 13th indicated a larger gradient on the north-facing site than on the south-facing site (Figure 9). Findings also indicated a statistically significant difference between the temperature gradients, vapor pressure gradients, snow surface temperatures, and net shortwave radiation between sites.

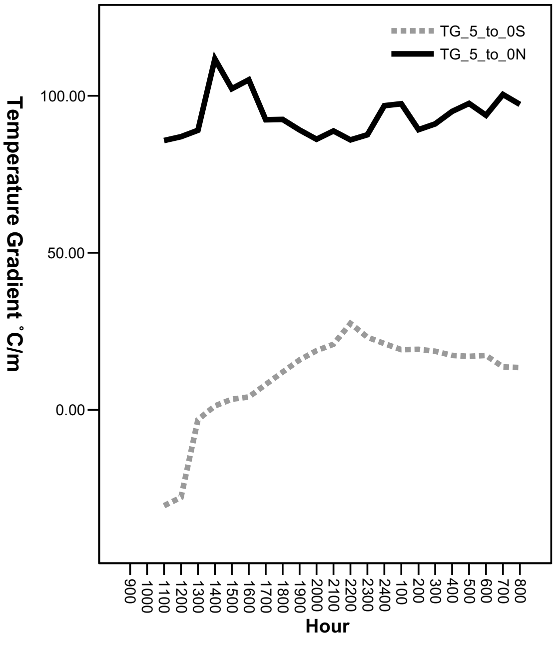

Figure 9: Temperature gradient which formed from January 12 – 13 at the snow/air interface.

Although the processes which formed these two distinct weak layers were different, many of the same meteorological processes that lead to surface hoar formation also contributed to the formation of near-surface faceted crystals.

Because of the small size of the near-surface faceted crystals (< 0.5mm), it was difficult to determine size differences. Although we were unable to obtain good crystal size measurements, close visual inspection in the lab revealed that the near-surface facets that formed on the south-facing site were better developed than those on the north-facing site, showing more angulations, striations, and even cupping (Figures 10 a and b).

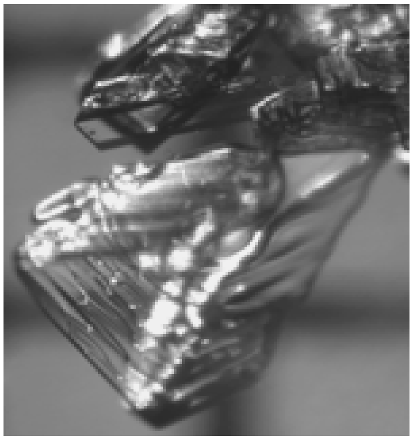

Figure 10a: Photograph of a 1mm near-surface faceted crystal harvested from the south-facing site on January 13th. Note the cup shape and the striations.

Figure 10b: Photograph of a 0.5mm near-surface faceted crystal harvested from the north-facing site on January 13th.

The temperature gradient from the snow surface to 0.05m below the surface (Figure 11) showed large diurnal temperature swings on the south-facing site, but not on the north-facing site. These large diurnal swings led to more well developed near-surface faceted crystals on the south-facing site. During the day large gains of net shortwave radiation (587w/m^2) on the south facing site warmed the snow surface and caused large temperature gradients (126˚C/m) between the warmer surface snow and the colder snow beneath. A subsequent movement of water vapor ensued and facets were formed. The north-facing site did not absorb as much shortwave radiation (55w/m^2), so the snow surface was not warmed as much and positive daytime temperature gradients did not form (Figure 11).

At night longwave radiation losses eventually caught up to the shortwave radiation gains at the south-facing site and a negative temperature gradient formed (Figure 11). The shortwave gains, however, were hard to overcome and the gradient did not reach the maximum obtained during the day. With less absorbed shortwave radiation during the day at the north-facing site, the layers below the snow surface received little radiation and were, subsequently, not warmed. Thus, at night there was a smaller temperature gradient between the warmer snow below and the cooler snow surface.

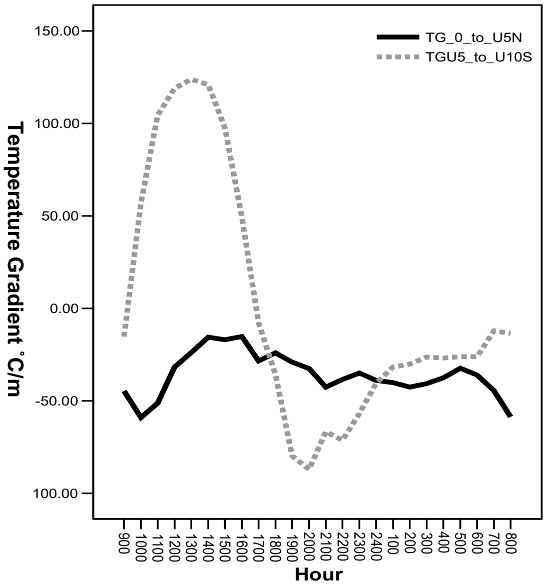

Figure 11: Graph of the temperature gradient from the snow surface to 0.05m below the snow surface for 24h surrounding the faceting event on January 13th. Note the large shift in gradient on the south-facing site which formed crystal 10a.

4. CONCLUSIONS

A clear difference between the size and characteristics of surface hoar and near-surface faceted crystals on two different aspects was found. Surface hoar grew larger and showed more striations at the north-facing site than at the south-facing site, but near-surface faceted crystals were better developed at the south-facing site than at the north-facing site. This difference was most likely due to the relatively larger shortwave solar gains that occurred at the south-facing site relative to the north-facing site.

For surface hoar formation, the large solar radiation gains on the south-facing aspect during the day impeded surface hoar crystal formation at night because the longwave radiation losses had trouble overcoming the shortwave gains from the day. Therefore, the snow surface temperatures were higher at the south-facing site than the at north-facing site.

For near-surface faceted crystals, the increased solar radiation gains on the south-facing aspect during the day warmed the upper levels of the snow surface to well above the temperature of the snow below, and a large temperature gradient was formed, with warmer snow over colder snow. On the north-facing aspect the smaller shortwave gains barely warmed the snow surface and no temperature gradient was formed. The net result was an overall higher temperature gradient within the near-surface snow on the south-facing aspect relative to the north-facing aspect.

These results have implications for backcountry avalanche forecasts, which attempt to predict patterns of avalanche activity and snow stability over large regions. First, this work shows that surface hoar layers may be unevenly spread across terrain, with larger crystals forming on some aspects during the same surface hoar forming event. This might well affect the patterns of future avalanche activity on that layer. Second, this study demonstrates that some weak layers may form more effectively on south-facing aspects than on north-facing aspects. Though the eventual persistence of a weak layer will depend on when and how it gets buried, this study demonstrates that some general rules of thumb relating more stable mid-winter conditions to sunnier slopes might not hold under certain conditions. In summary, this research points out the importance of carefully documenting the formation of different weak layers on different aspects for the reliable prediction of patterns of avalanche activity on buried weak layers.

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