

Near-Surface Faceted Crystals Formed by Diurnal Recrystallization: A Case Study of Weak Layer Formation in the Mountain Snowpack and Its Contribution to Snow Avalanches

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Abstract

In the winter of 1995–96 we investigated the temperature and vapor pressure gradient conditions associated with the formation of faceted crystals that develop in the upper levels of the snowpack due to diurnal recrystallization. We used an array of six thermocouples connected to a datalogger to continuously measure snow temperatures in the region from 0.005 m above the snow surface to 0.20 m below the snow surface. Measurements during clear sky conditions in March showed temperature gradients in excess of $200^{\circ}\text{C m}^{-1}$ at night in the top 0.05 m of the snowpack, with the temperature gradient shifting direction and exceeding $100^{\circ}\text{C m}^{-1}$ through this layer during the day. These temperature gradients resulted in vapor pressure gradients which exceeded 25 mb m^{-1} during the day and at night. During this time, a significant weak layer of 1 mm faceted snow formed within 36 h. Widespread avalanche activity occurred for up to 9 d after this layer was buried by 0.50 m of snow.

Introduction

Weak layers in the complex, stratified mountain snowpack are a prerequisite for slab avalanche release (Bader and Salm, 1990). The purpose of this research is to observe and document the formation of a specific type of weak layer that has not been extensively examined in the literature. In southwest Montana, our investigations of large backcountry avalanches over the past six years indicate that 96% of the weak layers consisted of faceted crystals such as near-surface facets, surface hoar, and depth hoar. The most common weak layers (59% of the avalanches analyzed) are composed of near-surface faceted crystals (Birkeland et al., 1996; Birkeland, 1998, this volume). These layers are formed through three primary processes: 1) Radiation recrystallization, 2) Melt-layer recrystallization, and 3) Diurnal recrystallization (Birkeland, 1998, this volume). Our data show that the predominant process forming these layers in southwest Montana is diurnal recrystallization. Of the avalanches we observed with weak layers of near-surface faceted crystals, 73% failed on layers formed due to diurnal recrystallization. These avalanches occurred on slopes facing from east to northwest (Table 1), and were not associated with the crusts one would expect to find under layers of near-surface faceted crystals formed by either melt-layer or radiation recrystallization.

In general, weak layers of faceted crystals form due to vapor pressure gradients, which are a result of temperature gradients in the seasonal snowpack (Armstrong, 1985). In diurnal recrystallization, strong temperature gradients result from temperature differences between the fluctuating snow surface temperature and the relatively constant temperature 0.30 m below the snow surface (Birkeland, 1998, this volume). Though some research has been conducted in this area, no studies have comprehensively investigated the diurnal temperature swings, and resultant temperature and vapor pressure gradients, that lead to the formation of these dangerous and persistent weak layers in

many mid-latitude mountain ranges. LaChapelle and Armstrong (1977) and Armstrong (1985) made measurements of these diurnal temperature swings in the San Juan mountains of Colorado, but did not analyze the resultant temperature and vapor pressure gradients, or the types of weak layers they might form. Fukuzawa and Akitaya (1993), on the other hand, documented the formation of a weak layer of near-surface faceted snow in Japan, and measured strong night-time temperature gradients. However, they did not analyze the temperature gradients present during the day or the vapor pressure gradient conditions. Fierz (in press) investigated changes in strength of a layer of near-surface faceted crystals after they were buried, but did not reconstruct the formation of the weak layer in detail. Finally, Stratton (1977) observed the formation of near-surface faceted crystals due to diurnal recrystallization, but did not make quantitative measurements of the processes that formed them. Thus, the purpose of this study is to observe near-surface faceted crystals formed by diurnal recrystallization in the field, to document the specific temperature and vapor pressure gradient conditions associated with their formation, and to observe their contribution to avalanche release.

Methods

TEMPERATURE GRADIENT MEASUREMENTS

In order to measure temperature gradients, we constructed a thermocouple array using six copper constantine type J thermocouples. We placed each thermocouple in a 0.0017-m-diameter, 0.06-m-long stainless steel tube, exposed 0.002 m of the junction at the end of the tube, epoxied the ends to keep moisture out, and mounted the tubes perpendicular to a white PVC plastic pipe. The top two thermocouples were mounted 0.01 m apart and the remaining four thermocouples were mounted at 0.05 m intervals below them. This arrangement allowed us to measure

TABLE 1

Predominant slope aspect associated with 30 backcountry avalanches in southwest Montana observed to have a weak layer of near-surface faceted snow

Predominant aspect	N	NE	NW	E	W	SW	SE	S
No. avalanches	1	13	1	7	0	6	2	0
	(3%)	(43%)	(3%)	(23%)		(20%)	(7%)	

the temperature right above and below the snow surface, as well as the temperatures in the upper 0.20 m of the snowpack at 0.05 m intervals.

We attached the thermocouple array, calibrated in the Montana State University cold lab, to a Campbell CR21 datalogger. Since the datalogger had limited memory, we conducted our measurements in an easily accessible, flat, open study area at 1830 m in elevation at the base of the Bridger Range (Fig. 1). We inserted the thermocouple apparatus into a small hole in the snow, and reset it after new snowfall, melting, or settling. Since the array freely settled with the snowpack, it typically maintained the same approximate position with respect to the snow surface for several days at a time. We collected data from early February to April 1996 during periods which appeared favorable to near-surface faceted crystal growth through diurnal recrystallization, and calculated temperature gradients through the upper snowpack.

Two sources of potential error exist with our measurements. First, we did not precisely measure the location of the snow surface. Nyberg (1938) demonstrated the importance of deter-

mining exactly the snow surface location when measuring air temperatures in the inversion layer right above the snow surface. We placed the thermocouple array into the snow with one thermocouple 0.005 m above the snow surface and the next thermocouple 0.005 m below the snow surface. In the data for this paper, we situated the array before data collection and checked it afterwards. Though it appeared to be in the same location with respect to the snow surface at the end of the data collection, a possible error of several mm (up to 4) could exist. Since the distance between the different thermocouples in the array is fixed, the temperature gradients measured between any two thermocouples is accurate, though the exact location of that gradient within the snowpack might vary by up to 4 mm. A second source of possible error is that the thermocouples themselves could have been heated up by solar radiation penetrating the snow during the day. Since the thermocouples higher in the snowpack would receive more radiation, this would tend to increase the temperature gradients measured during the day by an uncertain amount. In future research we are working to minimize the effects of this incoming radiation on the thermocouple array.

VAPOR PRESSURE GRADIENT CALCULATIONS

We calculated vapor pressure gradients using methods developed by Armstrong (1985). Using the well-accepted assumption that intercrystalline spaces in snow are saturated with water vapor with respect to ice at the prevailing temperature, vapor pressure can be calculated using the Goff-Gratch formulation, an integration of the Clausius-Clapeyron equation (List, 1949):

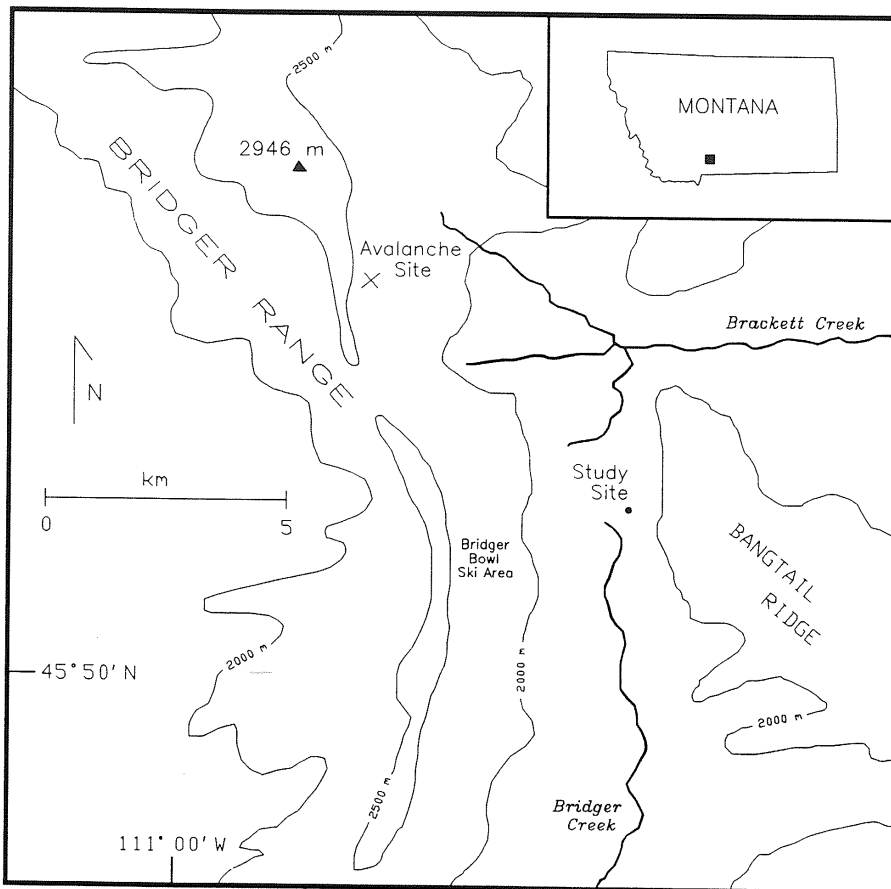


FIGURE 1. The flat, open study site is located about 20 km northeast of Bozeman, Montana, U.S.A., at the base of the Bridger Range at 1830 m in elevation. Bridger Bowl Ski Area is 3 km to the west-southwest; the backcountry avalanche triggered 9 d after the burial of the near-surface faceted crystals (see text) was approximately 7 km northwest of the study site.

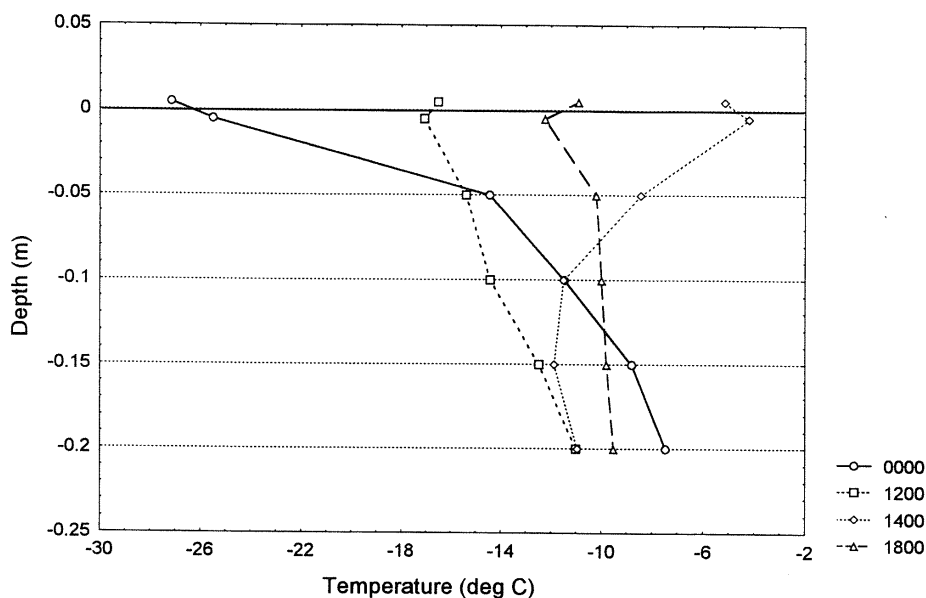


FIGURE 2. Near-surface temperature profiles observed at selected times on 25 March 1996.

$$\log_{10}e_i = -9.09718 ((T_o/T) - 1) - 3.56654 \log_{10}(T_o/T) + 0.876793(1 - (T/T_o)) + \log_{10}e_{io}$$

where:

e_i = saturation vapor pressure of a plane surface of pure ordinary water ice,

T = absolute (thermodynamic) temperature ($^{\circ}\text{K}$),

T_o = ice-point temperature (273.16 $^{\circ}\text{K}$), and

e_{io} = saturation pressure of pure ordinary water ice at ice-point temperature (0.0060273 standard atmosphere = 6.1071 mb).

Once vapor pressures were calculated, the resultant vapor pressure gradients were computed.

SNOWPACK INVESTIGATIONS

In the course of our avalanche forecasting work for the Gallatin National Forest Avalanche Center, we dug snow pits approximately 5 times per week throughout southwest Montana during the 1995–96 winter, and identified layers of near-surface faceted crystals using a 20-power Pentax monocular. When we observed layers of near-surface faceted snow in the Bridger Range (Fig. 1), we analyzed the snowpack temperature patterns at our nearby study site. Finally, when the layer of near-surface faceted crystals was buried by subsequent snowfall, we observed its contribution to avalanche formation.

Results and Discussion

FORMATION OF A LAYER OF NEAR-SURFACE FACETED SNOW BY DIURNAL RECRYSTALLIZATION

In March 1996, 0.05 to 0.10 m of new snow fell through our region before a short cold period. The cold and clear weather lasted two nights and a day, with a low temperature on the first night at the study plot of -20°C , followed by a day with temperatures up to -3°C and another night of -15°C . Subsequent observations revealed that the low-density new snow had metamorphosed into a layer of near-surface faceted crystals (up to 1 mm in size). Though near-surface faceted crystals can take several forms (Birkeland, 1998, this volume), these crystals were

similar to Akitaya's (1974) solid-type faceted crystals, or Class 4fa in the *International Classification for Seasonal Snow on the Ground* (Colbeck et al., 1990). We observed this layer of near-surface faceted crystals on a wide variety of aspects and elevations throughout southwest Montana, and we did not observe any surface hoar formation. On south- and east-facing slopes the layer of near-surface facets was located over a hard melt/freeze crust, while on northerly aspects it simply formed a loose cohesionless layer near the top of the snowpack.

After observing the formation of the near-surface faceted crystals, we analyzed the temperature conditions found at our study plot in the upper layers of the snow. Diurnal changes in the near-surface temperature profile were similar to those observed by Alley et al. (1990) in the summer in Greenland, and by LaChapelle and Armstrong (1977) in the San Juan Mountains in Colorado (Fig. 2). At midnight the snow surface was quite cold, resulting in a strong negative temperature gradient through the upper snowpack. By noon the snow surface was warming, while the previous night's cold temperatures resulted in cooler temperatures from 0.05 to 0.20 m below the snow surface. At 1400 h the snow surface had continued to warm and the temperature gradient was again strong, but the direction of the gradient had reversed. By 1800 h the pattern was starting to return to the same conditions observed during the previous night, with the upper surface cooling faster than the snow beneath it. Clearly, the snow surface went through wide swings in temperature, while the temperature 0.20 m below the surface was relatively constant.

Wide variations in surface temperature, combined with relatively consistent temperatures at depth, created large temperature gradients in the upper snowpack (Fig. 3). The temperature gradient in the upper 0.05 m of the snowpack was greater than $-200^{\circ}\text{C m}^{-1}$ for several hours during the night. By 1300 h the temperature gradient had changed directions in response to the warming snow surface, but the absolute magnitude of the gradient was still high ($100^{\circ}\text{C m}^{-1}$). Strong temperature gradients were not confined to the upper 0.05 m of the snowpack. The temperature gradient from 0.05 to 0.10 m below the surface was also high, exceeding $-50^{\circ}\text{C m}^{-1}$ at night and switching to greater than $50^{\circ}\text{C m}^{-1}$ by mid-day. In general, the magnitude of the

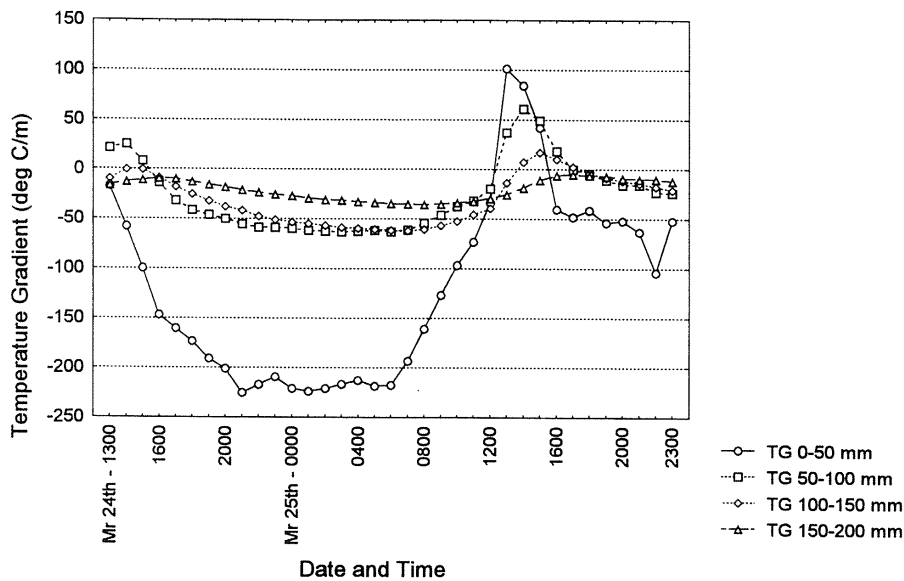


FIGURE 3. Near-surface temperature gradients at various depths on 24-25 March 1996.

temperature gradient through a given layer decreased considerably with increasing distance from the snow surface.

An extensive body of research documents the formation of faceted crystals under temperature gradient conditions, and the resultant vapor pressure gradients (e.g., Akitaya, 1974; Marbouty, 1980; Colbeck, 1982; Armstrong, 1985; Sturm and Benson, 1997). The magnitude of the vapor pressure gradient depends on the temperature gradient and the mean snow layer temperature, and values greater than 5 mb m^{-1} are sufficient to initiate faceted crystal growth (Armstrong, 1985). In this study, vapor pressure gradients were 500% greater than this threshold value, exceeding -25 mb m^{-1} during night and 25 mb m^{-1} during the day (Fig. 4). Our observations suggest that these extreme vapor pressure gradients metamorphosed low-density new snow into 1 mm near-surface faceted crystals in about 36 h, thus forming a significant weak layer. This observation agrees with the results of Armstrong (1985), which indicate that faceted crystals can form in less than 48 h when the vapor pressure gradient is 25 mb m^{-1} .

CONTRIBUTION OF A LAYER OF NEAR-SURFACE FACETED CRYSTALS TO AVALANCHE FORMATION

After the formation of this layer of near-surface faceted crystals by diurnal recrystallization, we carefully monitored subsequent snowfall to see how this layer would react to a new snow load. In the Bridger Range (Fig. 1) and in the Madison Range (located about 50 km southwest of our study site) the faceted crystals were immediately buried by 0.20 to 0.25 m of new snow over the next 3 d. Though the avalanche data we collected is largely anecdotal, avalanche workers and experienced backcountry skiers in the region agreed that the layer of near-surface faceted crystals formed an extremely sensitive weak layer. Bridger Bowl and Big Sky Ski Patrols reported widespread avalanching and weak snowpack conditions on all aspects during control work. In fact, at Big Sky Ski Area (located approximately 80 km southwest of the study site) single 2 kg explosive charges were sufficient to produce large avalanches which prop-

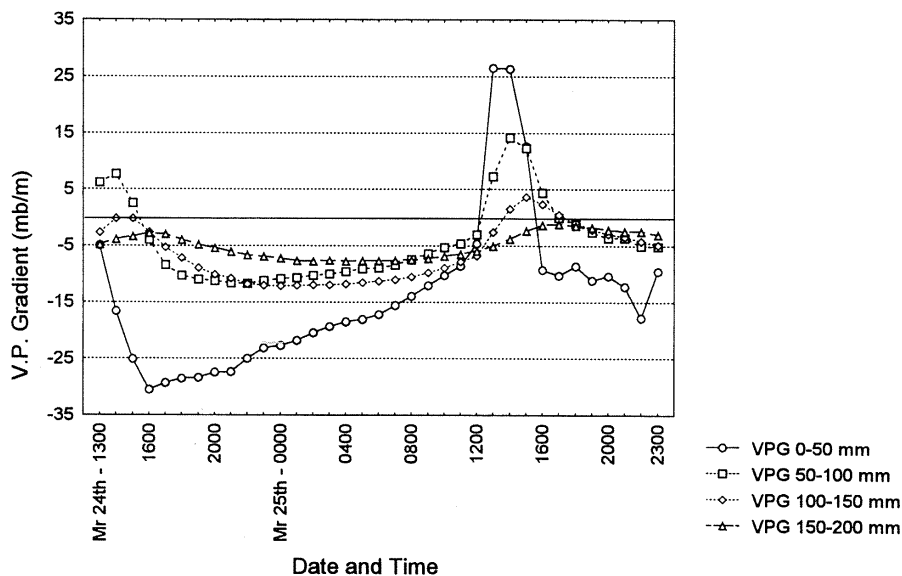


FIGURE 4. Near-surface vapor pressure gradients at various depths on 24-25 March 1996.

agated across several adjacent avalanche paths. In addition, we observed numerous spontaneous backcountry avalanches which failed on the layer of faceted crystals.

The near-surface faceted crystals also created an extraordinarily persistent weak layer. Five days after the layer had been buried there was still widespread collapsing and cracking of the snowpack and a few backcountry avalanches. Over 2 d another 0.20 m of snow fell in the Bridgers Range. Finally, 9 d after the layer had been buried, a skier triggered an avalanche on a 36°, southeast-facing slope at 2470 m in the Bridger Range (Fig. 1). The avalanche ran on the layer of faceted crystals formed near the surface. He was carried 150 vertical meters, but managed to stay on the surface of the slide and was not injured. On our visit to the site 2 d later the snow was still sensitive, and we were able to ski cut avalanches on adjacent slopes. This example demonstrates the persistent snowpack weaknesses created by diurnal recrystallization in the snowpack of southwest Montana.

Summary

Although numerous processes form weak layers in mountain snowpacks which are necessary for slab avalanches, our observations in southwest Montana indicate that weak layers of near-surface faceted crystals formed by diurnal recrystallization are common. Diurnal recrystallization occurs when large diurnal snow surface temperature changes exist due to cold, clear nights and relatively warmer, sunny days. The process is driven by extreme vapor pressure gradients which result from strong temperature gradients in the upper layers of the snowpack and is facilitated by low density surface snow. Once these weak layers of faceted crystals are formed and buried, they create persistent and dangerous weak layers, often resulting in avalanche release for weeks or even months.

The present research is preliminary and suggests several avenues for future work. More quantification of diurnal recrystallization is needed, including measures of changes in bonding, faceting, and strength with time during the bi-directional temperature cycles that characterize this process. Such work would benefit from photographs of the various crystals formed. Finally, an understanding of the spatial variations in diurnal recrystallization is important for determining future avalanche conditions. An improved knowledge of diurnal recrystallization will improve our understanding of weak layer formation and the resultant patterns of avalanches observed in the mountains.

Acknowledgments

We would like to thank G. H. Birkeland for editorial and cartographic assistance, and R. Armstrong and M. Sturm for their thoughtful reviews and numerous helpful comments.

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Ms submitted May 1997