NEAR-SURFACE FACETING ON SOUTH ASPECTS IN SOUTHWEST MONTANA

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ABSTRACT: In the winter seasons of 2006/2007 and 2007/2008, Montana State University researchers set up weather stations on north and south aspects to gather detailed meteorological and radiation data. During observation periods of about three months, the Yellowstone Club Ski Patrol recorded daily snow crystal observations and took photographs of the snow crystals within the top five centimeters of the snowpack at the two study plots, paying special attention to the location, frequency, timing, and intensity of the near-surface faceting events. The 2007/2008 season was characterized by above average snowfall and few periods of high pressure and throughout the winter facets grew more significantly than expected on south aspects. Using macroscopic photography in the field, six distinct radiation recrystallization events between 14 February and 9 April were documented. These observations correlated well with measured radiation data. Our results demonstrate that radiation recrystallization occurs in southwest Montana, that such faceting occurs more rapidly toward springtime, and that well-developed facets can form in the near-surface layers in a matter of hours. Improving our understanding of the formation and persistence of these weak layers will improve avalanche forecasting.

KEYWORDS: near-surface facets, radiation recrystallization, temperature gradients, southerly aspects, avalanche forecasting

1. INTRODUCTION

Avalanche practitioners have long recognized the hazards of weak layers in the mountain snowpack. Buried weak layers, generally composed of angular faceted crystals, provide the critical failure layer for slab avalanche release (McClung and Schaerer, 2006). Surface hoar and depth hoar are two types of weak layers composed of faceted crystals which have been studied extensively. The focus of this paper is on the formation of faceted grains in the near-surface seasonal snow cover on south facing slopes. Faceted crystals form in the snowpack when temperature gradients in the snow induce water vapor flux through the pore space. When temperature gradients reach a critical threshold (nominally 10°C/m), vapor movement causes faceted snow crystals to grow (Armstrong, 1985). These faceted crystal layers tend to be structurally weak and when subsequently buried, may present an avalanche hazard. Such crystal types can persist at depths in the snowpack, and can lead to short and long term avalanche cycles.

Three different near-surface faceting processes occur, commonly called diurnal recrystallization, melt-layer (or wet-layer) recrystallization, and radiation recrystallization (Birkeland, 1998). This paper targets radiation recrystallization, a process that creates extreme temperature gradients within the top one to two centimeters of the snowpack. Incoming shortwave (solar) radiation warms and often melts the snow subsurface and outgoing longwave radiation losses keep the snow surface cool and dry. Observations of radiation recrystallization were first made in the San Juan Mountains in southwest Colorado (LaChapelle, 1970; Armstrong, 1985) where the process was understood to be the result of high intensity shortwave inputs due to low latitude, and high rates of longwave cooling on the snow surface attributable to high altitude. In his characterization of near-surface faceting as Upper Level Temperature Gradient (ULTG) snow in the Wasatch Range in Utah, Stratton (1977) documented dry faceted crystals forming above a layer of subsurface melting caused by high intensity solar inputs on clear days on south facing slopes.

A growing body of research quantitatively describes the atmospheric and snowpack parameters needed to produce near-surface facets (McElwaine et al., 2000; Hardy et al., 2001;

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Colbeck and Jamieson, 2001; Jamieson and Fierz, 2004; Hood et al., 2005). In the first laboratory experiments to develop radiation recrystallized near surface facets, Morstad et al. (2007) were able to grow facets by controlling the long and short wave radiation balance. Not surprisingly, they found from those studies that the combination of large radiation driven near surface temperature gradients, warmer subfreezing temperatures and lower density snow enhanced the faceting development.

New snow density and new snow type likely plays a role in the growth rate of faceted crystals (Morstad et al., 2007). Adams and Miller (2003) have suggested that crystallographic growth in a snowpack is affected by existing snow crystal orientation. As for different shapes and forms of faceted crystals, Colbeck et al. (1990) classified faceted forms in the “International Classification of Seasonal Snow on the Ground” (ICSI) as solid faceted particles (4fa), small faceted crystals (4sf), cup-shaped crystals (5cp), and depth hoar columns (5dh). A few other faceted crystal types have been identified as being specific to the near surface process, such as the stringy or needle-like grains with faceted ends associated with complex cycles of rounding and faceting in the diurnal recrystallization process (Stratton, 1977; Birkeland, 1998). Moreover, radiation recrystallization is best categorized under the current ICSI (1990) as small faceted crystals (4sf). However, these forms can be larger than 0.5mm in size and will often present as small (<1mm) advanced forms of kinetic growth.

There have been few documented cases of radiation recrystallization outside of southwest Colorado and we have been unable to find thorough photographic field documentation of these crystals in the scientific literature except for some preliminary work by Stock et al. (1998) in Colorado. Another concern is the effects that inter annual variability plays on the occurrence of radiation recrystallization in areas of higher latitude. Therefore, the intent of this study is to carefully examine radiation recrystallization events, establish corresponding temperature gradients in the near-surface of the snowpack, and to capture each occurrence with macroscopic photography.

2. METHODS

2.1 *Study Site*

Throughout the study, members of the Yellowstone Club (YC) Ski Patrol conducted daily visits to two study plots on Pioneer Mountain in the Madison Range of southwest Montana. Both plots had been the site of previous research on surface hoar and near-surface faceting (Cooperstein et al., 2004) and on thermal modeling of snow surface temperature (Staples et al., 2006). The meteorological stations at these sites were enhanced for this study; additional radiation sensors were placed on a ridge to lessen terrestrial interference with the data and three additional weather stations that are for YC snow safety were also available. During daily visits to the two study plots, observers documented snow crystal types and sizes in the surface snow cover, collecting additional data and photographs when faceted forms were noted. The following paragraphs will give parameters, explanations, and other pertinent information as to the collection of our data.

Although observations and weather data from two sites located on opposite sides of Pioneer Mountain were collected, this paper only reports on data collected at the South plot (Figure 1). Near-surface facets were observed at the North plot; however, these were relatively less significant events, not formed by radiation recrystallization, and were often mixed with surface hoar events. The south weather station is located at 2757 meters, with an aspect of 187^{o} on a 30^{o} slope. Corresponding snowpit observations were performed a few meters away on a slope ranging from 25^{o} - 30^{o}. The site has a clear view of the sky, is surrounded by trees which limit the effects of blowing and drifting snow, and is on a scree slope. In addition to the South plot, observations and photos from the “Pinnacles” ski trail on Pioneer Mountain are referenced for one event. This slope is 28^{o} - 38^{o} with an aspect of 182^{o} at approximately 2800 meters.

Figure 1: South weather station, Pioneer Mountain, Yellowstone Club, Montana.

The site uses a Campbell Scientific, Inc. (CSI) CR10(x) data-logger to record air temperature and humidity (CSI CS215), snow depth (NovaLynx Corp.), snow surface temperature (Everest Interscience, Inc. 4000.4ZL), incoming longwave radiation (Precision Infared Radiometer, PIR, Eppley Lab., Inc.), slope parallel incoming and reflected shortwave radiation (LI-COR, Inc. Li200), wind speed and direction (Met One Instruments, Inc. 034B-L), and snow temperature taken from the surface at 2cm intervals to a 40cm depth(Omega Eng., Inc. type T thermocouples). All data are collected at three minute intervals, and averaged and recorded every half hour. In addition, horizontally oriented incoming shortwave and longwave radiation sensors (PIR and Precision Spectral Pyranometer, PSP, Eppley Lab., Inc.) are situated on a ridge to provide a generally unobstructed sky view.

2.2 *Observations*

Every day at each site, observations of snow crystals in surface snow pits were made in the undisturbed snow adjacent to the station. Written observations detailed this structure in the top 5cm. Crystal identification was made using a Brunel 8 x 30 ocular macroscope with a 10x loupe and included crystal size, type, extent of rime, and amount of metamorphism. Grain type and size were recorded in the field, entered into the daily log and photographed. These notes and images were then entered into a computer, to be examined and discussed with colleagues in a warm dry environment.

During the 2008 season over 2000 photos documented the surface snow cover at two study plots. Using the threaded loupe portions of the Brunel macroscope different cameras were fit with magnifying loupes (Figure 2). The resulting digital photographs allowed a high degree of optical magnification, and a reasonable degree of digital magnification beyond that. The cameras used were a Panasonic PV-500, Olympus SP-510 UZ, and a Nikon Coolpix. Our goal in taking field photographs was to document the strata in its general sense. Rather than harvesting and relying on a single crystal, our photographs provide a better estimation of an ‘average’ crystal type and size. Our main hurdle with the photographs continues to be depth of field: accordingly we were generally unable to take photos of crystals in situ, but rather took most of our photos of crystals disaggregated on a crystal card.

Figure 2: Photo being taken at study plot.

2.3 *Temperature Gradient Calculations*

For the purpose of this study, temperature gradient calculations were based on the depth to the top of the melt layer (assumed 0 ˚C) and the snow surface temperature. Although an accompanying melt layer is not a necessary component for the formation of radiation recrystallization (Morstad et al., 2007), all of the events discussed here presented a melt layer.

Temperature gradient = $(t_1 - t_2)$/d, where
t_1= temperature at the snow surface (˚C)
t_2= melt layer temperature (˚C)
d = distance from snow surface to melt layer (m)

3. RESULTS & DISSCUSSION

During this study six distinct radiation recrystallization events occurred at the south study plot. These events took place on 14 February, 6 March, 22 March, 3 April, 6 April, and 8-9 April, and are discussed in detail. Summary results for the six events are shown in Table 1. Several other observation days showed some degree of near-surface faceting on the south slope, including diurnally recrystallized facets from 18-22 February.

3.1 *Event 1: 14 February 2008*

Early February in southwest Montana was characterized by continuous snow showers. The

YC snow safety weather station at 2850 meters received 40mm of snow water equivalence (SWE) in the week preceding 14 February, with 20cm of new snow and 10mm of SWE which yields an average density of 50 kg/m^3 on the night of the 13th. On 14 February, a ridge of high pressure combined with cold temperatures came in after 10 consecutive days of snow. 20cm of snow and 10mm of SWE had fallen by 0600, when skies began to clear and temperatures began to drop. At this time, some surface hoar grew, and was responsible for the sector growths observed on the snow surface at our 1100 observation. It is important to note that at this time the air was -6.5˚C, and photographs reveal dry subsurface snow made up mostly of decomposing stellars and plates. At 1300, faceted crystals were observed and photographed in the Pinnacles in a 1cm thick layer of dry snow with underlying wet snow. These crystals were found only on south-facing slopes at this elevation and aspect. We returned to the south study plot at 1400 and noted the same effect: the once dry subsurface was wet, and the dry snow on the surface had metamorphosed into faceted forms. The shortwave gain peaked at 575W/m^2 and the temperature gradient in the top 1cm of the snowpack at 1400 was roughly 400˚C/m. Photos from the south study plot later that afternoon reveals the resulting radiation recrystallized snow forms. Continued high pressure and warm temperatures destroyed the layer of faceted crystals over the next three days.

3.2 *Event 2: 6 March 2008*

On 6 March, clear sky prevailed after 5 consecutive days of snow, totaling 25mm of SWE and over 30cm of new snow with a density of 82.5kg/m^3. The top 10cm of snow consisted of 2-3mm stellars and stellar fragments at 1100. Despite shortwave gains nearing 700W/m^2, the south study plot snow surface reached a high temperature of only -4˚C. During this time the subsurface began to melt and by 1330, the top 1cm of snow had recrystallized into faceted snow (Figure 3), overlying 4cm of moist snow. The snow surface continued to remain at a high of -4˚C. Faceted forms were primarily needle shaped cup crystals with striations, some with intact parallel orientations. The temperature gradient was approximately 400˚C/m at the time of the second observation. The faceted layer on top of the crust lasted through the next day, but was destroyed by subsequent warm temperatures.

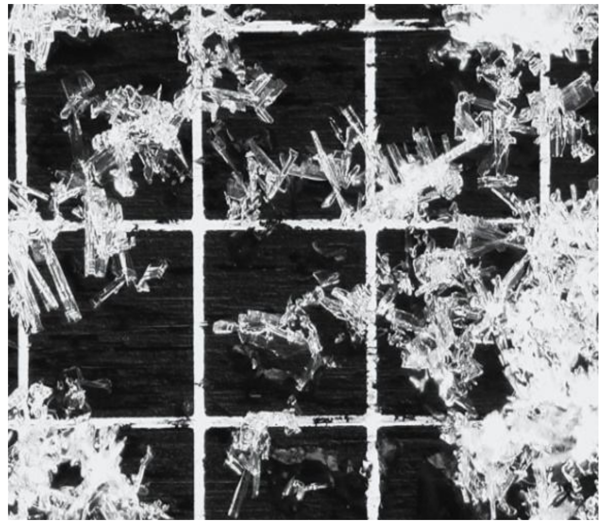

Figure 3: Facets at 1330, 3mm grid, 06-03-08.

3.3 *Event 3: 22 March 2008*

Snow showers leading up to 22 March brought 30cm of snow to Pioneer Mountain, which measured 29mm of SWE in the previous 4 days with an average density of 96kg/m^3. At 1345 on 22 March, observers noted 0.3-0.5mm facets in the top 1cm of the snow overlying a melt-layer. Shortwave gains reached 814W/m^2, yet the snow surface remained below -3.4˚C. The temperature gradient in the top 1cm of the snowpack at 1345 was 487˚C/m. Unfortunately we lack photographs of the snow surface immediately prior to this formation, but photos following this event are conclusive that faceted crystals indeed formed in the surface, and were not observed the previous day. These facets remained in the snowpack for a few days, but gradually deteriorated until they were no longer recognizable.

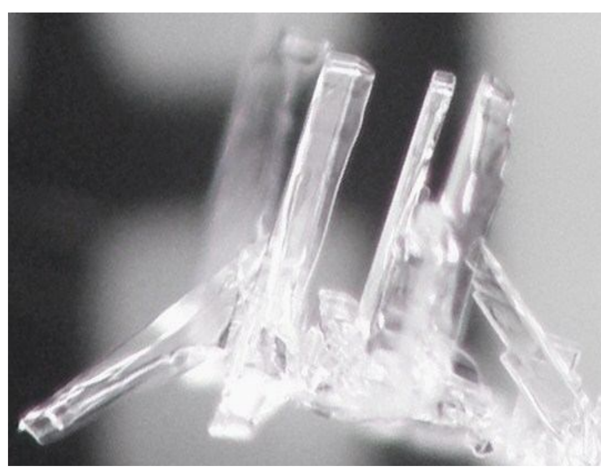

Figure 4: Facets at 1130, 1mm, 03-04-08.

3.4 *Event 4: 3 April 2008*

Early April weather was characterized by intermittent snow showers and below average temperatures. On 3 April, 0.5-1mm facets were observed in the snow surface at 1130 (Figure 4). Interestingly, these facets occurred in an interface with the new snow, and although many striated flute shaped facets in parallel orientations were observed, photos reveal a significant amount of intact new snow forms in the surface layer. Moreover, the snow 2-5cm down was composed of dry snow in the early stages of rounding with no melt layer to be found. Clear skies persisted through the day, with shortwave gains reaching upward of 840W/m^2, and snow surface temperature staying below -5˚C until noon, reaching a high of -2.2˚C at 1400. A second observation at 1430 revealed additional faceted growth (Figure 5) near the surface, with dry snow in the top 1cm and underlying melting snow. At 1430 the temperature gradient in the top 1cm of snow was 238˚C/m.

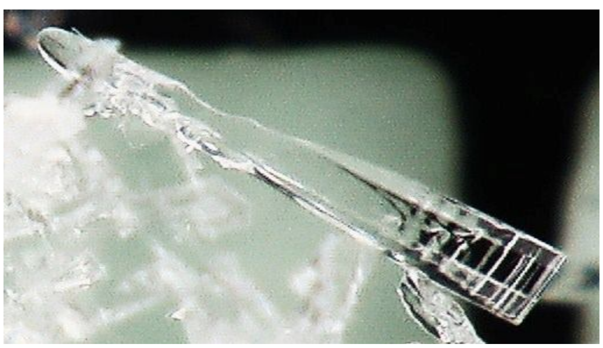

Figure 5: Facet at 1430, 0.75mm, 03-04-08.

3.5 *Event 5: 6 April 2008*

Continued intermittent showers deposited 5cm of new snow early in the morning on 6 April. Initial observation at 0930 revealed 2-4mm stellars with some signs of additional faceting on the arms of the stellars and some 0.5-1mm surface hoar in the mix. Beneath the surface was 0.5mm partly decomposed and 0.25mm highly decomposed snow transforming to rounds. Mostly clear skies with a high thin overcast were present throughout the day, with shortwave inputs reaching 837W/m^2 (Figure 6), and air and snow surface temperatures (Figure 7) remaining below -2.5˚C. A second set of observations, taken at 1430, shows 0.5-1.5mm facets (Figure 8 & 9) in the snow surface with melting snow below 1cm. At 1430 the temperature gradient in the top 1cm of snow was 338˚C/m.

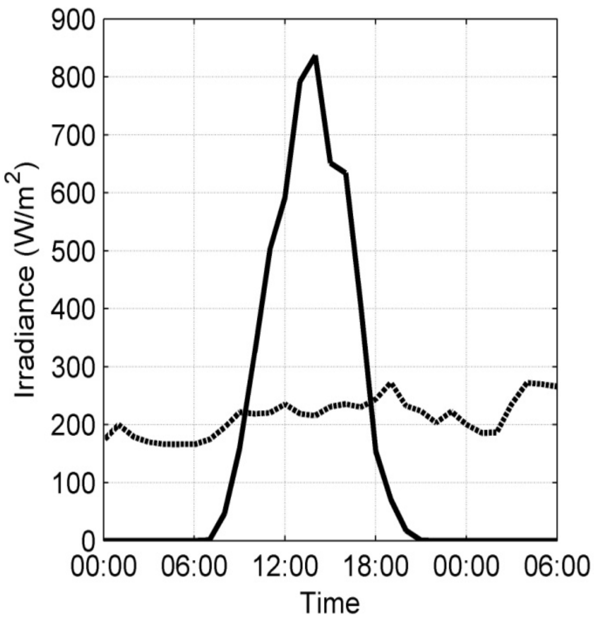

Figure 6: Graph of incoming shortwave radiation (solid line) and incoming longwave radiation (dashed line) for 6 April 2008 at the South study plot.

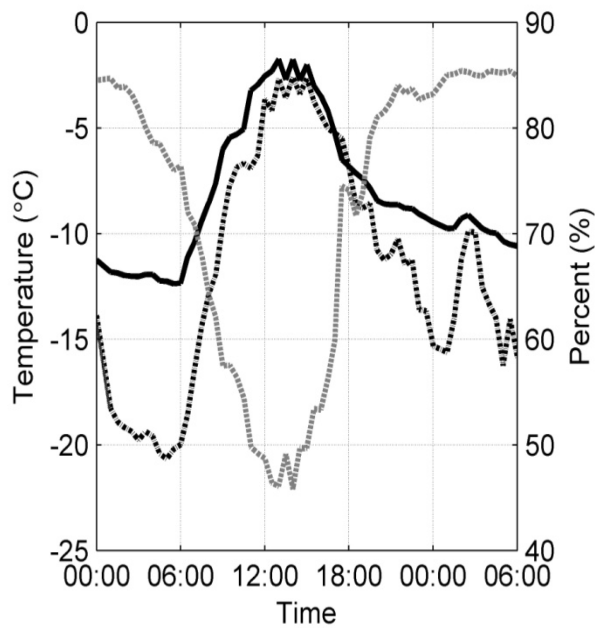

Figure 7: Graph of snow surface temperature (solid line), air temperature (black dashed line), and relative humidity (%, grey dashed line) for 6 April 2008 at the South study plot.

Date	Time	Crystal Size/Type Description	Temp. Gradient	SW Input
14-02-2008	1400	0.5-1mm, needle shapes & mixed facets	400°C/m	$575W/m^2$
06-03-2008	1330	0.5-1mm, striated flute shaped cup facets	400°C/m	$700W/m^2$
22-03-2008	1345	0.3-0.5mm, striated cups & sheath shaped facets	487°C/m	$814W/m^2$
03-04-2008	1130-1430	0.5-1mm, striated flute shaped cup facets	238°C/m	$840W/m^2$
06-04-2008	1430	0.5-1.5mm, striated flute shaped cup facets	338°C/m	$837W/m^2$
08-04-2008	--	1mm, needle & sheath shaped facets	--	$800W/m^2$

Table 1: Outline of radiation recrystallization events from the South study plot on Pioneer Mountain at the Yellowstone Club in southwest Montana.

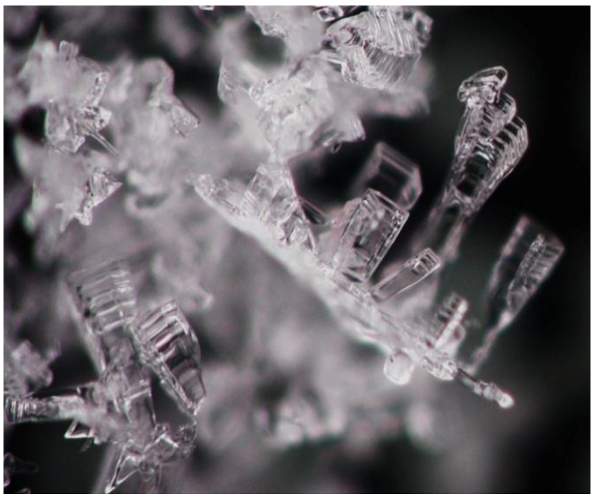

Figure 8: Facets at 1430, 0.5-1.5mm, 06-04-08.

3.6 *Event 6: 8-9 April 2008*

At 1000 on 8 April, observers noted 1mm rimed new snow at the south plot with no faceting reported, under partly cloudy skies. Later that day skies cleared and shortwave gains reached nearly $800W/m^2$ by 1200. No return visit was made to the study plot that afternoon, but the next morning at 0930 facets were found in a 3mm layer on top of a 5cm melt freeze crust. The snow surface temperature data coupled with the relative humidity of the air indicates that moisture was being deposited on the snow surface during the early morning hours of 9 April. Although the amount of deposition was very small, it would appear that some surface hoar was present in addition to the near-surface facets. At the time of the last observation at 1430 on 9 April, little additional faceting could be documented and 5cm of new snow quickly buried these facets. Again, high pressure followed this event destroying the near-surface facets within a day. It would appear that the 5cm of new snow was not thick enough to preserve the facets from daytime temperature spikes due to the associated high ambient air temperature and intense shortwave gains.

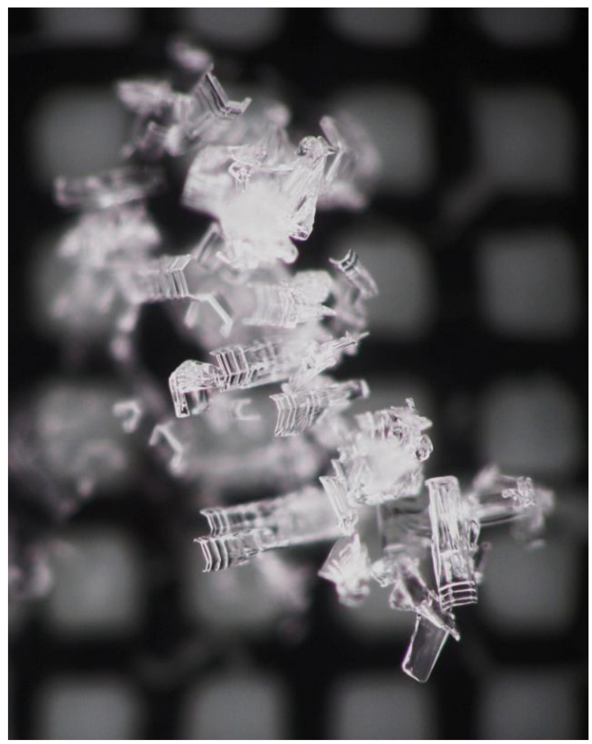

Figure 9: Facets at 1430, 1mm grid, 06-04-08.

4. CONCLUSIONS

Although the winter season of 2007/2008 in southwest Montana was characterized by few periods of high pressure, several radiation recrystallization events were observed on south facing slopes. Previously thought to occur only on occasion in this region (Birkeland, 1998), radiation recrystallization appears to form quite readily under desirable conditions. In particular, the frequency of events in April 2008 suggests that preferential growth of these facets occurs toward the spring when the incident angle of the sun allows for near slope perpendicular solar gain.

Perhaps the largest hurdle with this weak layer is our own ability to detect its formation. As we have seen, radiation recrystallization forms in only a matter of hours, usually between midday to early afternoon. While most of the forms were no larger than 1mm in size, our detailed photographic documentation reveals advanced facets in the near-surface that would be challenging, if not impossible, to identify with the naked eye. Furthermore the same conditions that produce these facets will just as readily destroy them if high pressure persists. However, if they are formed and buried, they can become a very dangerous persistent weak layer.

New insights into the formation of near-surface faceted crystals presented in this paper hints that radiation recrystallization might well be more common of a weak layer in southwest Montana and other mid-latitude regions than previously thought. From a practical perspective, careful attention will need to be paid to the snow surface on south facing aspects in order to detect radiation recrystallization.

ACKNOWLEDGEMENTS

A portion of this research was conducted with funding from National Science Foundation (Grant No. EAR - 0635977) and research grants from the 2000 International Snow Science Workshop and the American Avalanche Association. We wish to thank these sources as well as the Yellowstone Club and Montana State University for their support. Reviews of this paper by Karl Birkeland and Jordy Hendrikx provided several helpful comments. Special thanks go to everyone on the Yellowstone Club Ski Patrol for making this research possible.

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