Arctic and Alpine Research, Vol. 30, No. 2, 1998, pp. 193–199

Terminology and Predominant Processes Associated with the Formation of Weak Layers of Near-Surface Faceted Crystals in the Mountain Snowpack

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Abstract

Although recent observations indicate that weak layers of near-surface faceted crystals are widely associated with snow avalanches, little research has addressed these layers. Further, current research has been hindered by an absence of a framework with which to discuss their formation. This paper proposes terminology and describes three predominant processes observed in mid-latitude mountains which result in extreme near-surface temperature gradients, thereby forming near-surface faceted crystals: radiation recrystallization, melt-layer recrystallization, and diurnal recrystallization. It is hoped that this framework will improve scientific discussion and theory-building related to the formation and spatial distribution of near-surface faceted crystals.

Introduction

Snow avalanches are a significant, life-threatening hazard in mountain environments, killing more people in the United States on an average annual basis than earthquakes or other landslide hazards (Voight et al., 1990). Weak layers in the highly stratified seasonal snowpack are critical for the formation of slab avalanches (Bader and Salm, 1990), and their characteristics have been the focus of a number of studies (recent examples include Föhn, 1994; Jamieson, 1995). The purpose of this paper is to provide background, introduce new terminology, and describe and classify the processes associated with the formation of weak layers of faceted crystals near the snow surface. Although some previous work has identified these crystals and described the resultant weak layers, no organized terminology exists for the variety of the crystals formed or the different processes which form them. The ultimate goal of this paper is to provide a framework that clarifies earlier work and that provides a theoretical context for future discussion and research concerning a specific snowpack weakness associated with slab avalanche formation.

The occurrence of snow avalanches is intimately tied to the characteristics of the seasonal snowpack, which has a highly complex, layered structure. Differences between snow layers occur as a result of unique storm events, which vary in snowfall amount, temperature, temperature trend, new snow density, and associated wind. Once snow is deposited on the ground, it may also be subject to rapid metamorphic changes which further differentiate the various layers. It is the relationship between these snowpack layers which determines the type of avalanche which may occur. The first type, loose snow avalanches, occur when the surface snow is relatively cohesionless and the slope angle is steeper than the angle of repose. These avalanches result when a small amount of snow slips out of place and moves downslope, encountering and entraining other cohesionless snow. Loose snow slides are fairly easy to predict, and thus present only a small degree of hazard (Voight et al., 1990). In contrast, slab avalanches can involve large volumes of snow, are extremely difficult to predict, and present a major threat to life and property. Slab avalanches occur in snowpacks where a relatively cohesive slab lies over the top of a less cohesive weak layer, and require that the stresses on the snow slab exceed the strength holding it in place. Common stresses added to the slab which may trigger avalanches include new or wind-blown snow, falling cornices, explosives, or the weight of a person on the slope. In order to understand and predict slab avalanches, a comprehensive knowledge of the processes that form weak layers is critical, since this is where initial failure occurs (Bader and Salm, 1990).

Although weak layers may be formed by a number of different types of snow crystals, such as graupel or low density layers of newly fallen stellars, faceted crystals have been long recognized as forming the most significant weak layers (e.g., Seligman, 1936; Jamieson, 1995). Faceted crystal development occurs as a result of metamorphic processes within the snowpack and on the snow surface. To describe this process in general terms, strong temperature gradients lead to vapor pressure gradients and the movement of water vapor through the snowpack or onto the snow surface. The moving vapor is deposited on the surface of individual snow grains, resulting in the growth of larger, angular faceted crystals. These crystals have poor intergranular bonding, are relatively strong in compression (minimal settlement) and weak in shear, and typically experience minimal changes in texture as long as they remain subfreezing. Due to their weak shear strength and minimal changes in a subfreezing snowpack, they form persistent weak layers.

Most past and present faceted crystal research focuses on depth hoar and surface hoar, two widely known and recognized weak layers. Many investigations of faceted crystals have studied the basal layer of large faceted crystals known as depth hoar (some of the many examples include de Quervain, 1954; Giddings and LaChapelle, 1961; Bradley et al., 1977; Perla, 1978; Marbouty, 1980; Sturm and Benson, 1997). Akitaya (1974) made exhaustive laboratory examinations of depth hoar development and defined various crystal types and strength changes. As with depth hoar, there is a significant (and growing) body of research on surface hoar formation (i.e., Lang et al., 1984; Colbeck, 1988; Hachikubo et al., 1994; Hachikubo and Akitaya, 1996; Davis et al., 1996) and its contribution to dangerous snowpack instability (Jamieson, 1995). In addition, general texts on avalanches commonly include detailed explanations of depth hoar and surface hoar growth and their role in avalanche formation (Perla and Martinelli, 1978; Daffern, 1992; McClung and

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TABLE 1

Weak layers associated with large (generally Class 3 or larger [Perla and Martinelli, 1978]) backcountry avalanches investigated in southwest Montana, 1990–91 to 1995–96

	Type of weak layer			
Total avalanches investigated	Near-surface faceted crystals	Surface hoar	Depth hoar	Other
51	30 (59%)	16 (31%)	3 (6%)	2 (4%)

Shaerer, 1993; Fredston and Fesler, 1994). The research and attention on depth hoar and surface hoar are well deserved, since both of these faceted crystals create undeniably dangerous and persistent weak layers.

Despite this extensive body of research, relatively little work directly addresses the formation of faceted crystals in the near-surface layer. These crystals, termed *near-surface faceted crystals,* are defined as Class 4sf in the *International Classification for Seasonal Snow on the Ground* (ICSSG; Colbeck et al., 1990), though this classification overlooks that the crystals often grow larger than 0.5 mm and can develop into advanced forms. During seven seasons of backcountry avalanche forecasting in southwest Montana, we have observed that these crystals often form dangerous weak layers. Investigations of 51 backcountry avalanches (typically Class 3 or larger [Perla and Martinelli, 1978]) in southwest Montana are shown in Table 1. The weak layer in nearly two-thirds (59%) of these slides was a layer of small-grained (mostly up to 1 mm, but sometimes as large as 1.5 or 2.0 mm) faceted crystals formed near the surface before being subsequently buried. Nearly a third (31%) of the slides failed on surface hoar, which was often sitting over the top of a layer of small faceted crystals formed near the surface. Only 6% of the slides failed on basal depth hoar, while 4% failed on other weak layers. Furthermore, reports from Alaska (Fesler, pers. comm., 1997), Colorado (Gleason, pers. comm., 1996; Williams, pers. comm., 1996), and Utah (Tremper, pers. comm., 1996) suggest that near-surface faceted crystals form important weak layers in those geographic areas. Thus, in spite of their role in avalanche formation in several mountain regions in the United States, near-surface faceted crystals have received far less attention in the scientific and popular literature than depth hoar or surface hoar. The processes which form these layers are discussed briefly, if at all, in popular texts, and have only been minimally addressed by scientific research.

Perhaps a limiting factor in the ability of avalanche scientists and practitioners to discuss the forms and processes associated with near-surface faceted crystals is the absence of well-defined terminology. Although the ICSSG (Colbeck et al., 1990) refers to them generically as small faceted crystals, avalanche workers often refer to these unique layers as "recrystallized snow," but this term is not particularly useful since all faceted snow has been "recrystallized." Stratton (1977) called these layers "upper level temperature gradient snow," which describes the location in which they are found and the conditions which form them, but which is out-dated due to the term "temperature gradient" (Colbeck et al., 1990). Others have called these layers "depth hoar growth in the surface layer" (Fukuzawa and Akitaya, 1993), but that confuses the processes associated with depth hoar formation (typically longer duration, lower magnitude temperature gradients in higher density snow) with the unique processes involved in forming faceted grains near the snow surface (typically shorter duration, higher magnitude temperature gradients in lower density snow). Colbeck (1989), while never naming the crystals, refers to "near-surface growth" of faceted crystals. This paper expands on Colbeck's terminology, defining *near-surface faceted crystals* as snow formed by near-surface vapor pressure gradients resulting from temperature gradients near the snow surface (typically within the upper 0.20 m of the snowpack).

Processes Associated with Near-Surface Faceted Crystals

The formation of near-surface faceted crystals requires strong near-surface temperature gradients. These temperature gradients, in turn, result in strong vapor pressure gradients and faceted crystal formation. Typically, temperature gradients in the near-surface layers are much higher (i.e., Fukuzawa and Akitaya, 1993; Birkeland et al., 1998, this volume) and densities are much lower than in basal layers of the snowpack, resulting in rapid metamorphic changes in the snow crystal structure.

The combination of field observations and a review of the available literature reveal three predominant processes that result in near-surface temperature gradients, and may thus form near-surface faceted crystals. It is important to realize that these processes can take place simultaneously in complex combinations, and that some combination of the three end products could exist in the same part of the snow cover such that an observer might not be able to determine the exact genesis of a layer after the fact. Nevertheless, I delineate each process separately for clarity. The following discussion will describe three processes, termed *radiation recrystallization, melt-layer recrystallization,* and *diurnal recrystallization.* The characteristics of the three processes are summarized in Table 2.

RADIATION RECRYSTALLIZATION

A well-documented process for the formation of near-surface faceted crystals is *radiation recrystallization,* a term first defined by LaChapelle (1970) and later discussed in detail by Armstrong (1985). This process takes place in the upper few centimeters of the snowpack on southerly aspects on clear, sunny days, and occurs preferentially at low latitudes and high altitudes. Solar radiation penetrates the snowpack and is absorbed just below the snow surface, causing snow temperatures to increase and sometimes creating a melt layer. At the same time, the snow at the surface is loosing heat by longwave radiation losses. This can create extreme vapor pressure gradients (50 to 100 mb m^{-1}) in the upper snowpack, resulting in significant recrystallization within hours (Armstrong, 1985). The end result is the rapid formation of faceted crystals, often over a melt-freeze crust (Fig. 1).

LaChapelle and Armstrong (1977) and Armstrong (1985) documented the formation of near-surface faceted crystals through radiation recrystallization in the San Juan Mountains of southwestern Colorado, and also noted that buried layers of these crystals were a significant contributor to avalanche formation. Radiation recrystallization has also been observed in southwest Montana, though a delicate balance between incoming shortwave and outgoing longwave radiation is required. If solar radiation input is excessive, the surface snow will melt, destroying any possible weak layer formation. Likewise, if too little solar radiation is available, temperature gradients will not be sufficient to form near-surface faceted crystals. Due to these limitations, I

TABLE 2

Characteristics of three types of near-surface faceted crystal formation

	Radiation recrystallization	Melt-layer recrystallization	Diurnal recrystallization
Unique conditions	Precise balance between incoming shortwave and outgoing longwave radiation	Combination of a relatively warm old snow surface and a subsequent cold snowfall	Not a surface or boundary interface phenomenon, can involve 0.10 to 0.15 m of snow thickness, bi-directional gradient
Source/sink of temperature gradient	*Source*: incoming shortwave radiation warms the subsurface snow *Sink*: snow surface cools due to longwave radiation losses	*Source*: melt-layer formed by incoming shortwave radiation or rain *Sink*: cold snow deposited on the melt layer	*Source*: relatively warm subsurface snow (night) or snow surface (day) *Sink*: relatively cold snow surface (night) or subsurface snow (day)
Direction of temperature gradient	Negative (uni-directional)	Negative (uni-directional)	Negative at night and positive during the day (bi-directional)
Crystal forms typically observed	Small faceted grains (ICSSG[a] Class 4fa, 4sf, or 5cp)	Small faceted grains (ICSSG[a] Class 4fa, 4sf or 5cp)	Small faceted grains (ICSSG[a] Class 4fa, 4sf or 5cp), stellar arms with facets (intermediate between Class 4sf and 2dc), long needle-like grains with faceted ends (like Akitaya's (1974) depth hoar needles)
Location found	Southerly aspects	Southerly aspects when the melt layer is caused by sun, all aspects when the melt layer is due to rain	All aspects and elevations
References	LaChapelle (1970); LaChapelle and Armstrong (1979), Armstrong (1985)	Fukuzawa and Akitaya (1993); Jamieson (1997)	Stratton (1977); Fukuzawa and Akitaya (1993); Fierz (in press); Birkeland et al. (1998, this volume)

[a] International Classification for Seasonal Snow on the Ground (Colbeck et al., 1990).

have observed radiation recrystallization only occasionally in southwest Montana.

MELT-LAYER RECRYSTALLIZATION

A second process that forms near-surface faceted crystals is *melt-layer recrystallization.* In this process, a melt-layer of wet snow is formed by either incoming solar radiation or rain. While the melt-layer is still wet, new snow falls on the wet snow layer. This results in strong temperature gradients between the melt-layer (which is 0°C until it refreezes, a process which may take some time due to the latent heat that is released during freezing) and the new, colder snow (Fig. 2). The process is further enhanced when the new snow layer is thin and has a low density, and a clear, cold night immediately follows the snowfall. The end effect is a strong negative temperature gradient (up to 100 to 200°C m^{-1} [Fukuzawa and Akitaya, 1993]) which results in the formation of a layer of near-surface faceted crystals over the top of the former melt-layer, which has now refrozen into an ice crust. When these layers are subsequently buried, widespread avalanching often results.

Understanding the synoptic conditions that lead to melt-layer recrystallization helps in predicting the formation of these layers. If the saturated surface is a result of incoming solar radiation, then a sunny day might be followed by a light snowfall. The synoptic scenario is more complicated when rain saturates the snow. For western North America such conditions might include a warm, moist southwesterly flow ahead (east) of a cold front, resulting in mountain rains and a saturated snow surface as a trough approaches the area (Steenburgh et al., 1997). Once the trough passes the flow shifts to a colder northwesterly flow, which may deposit new, colder snow on top of the warm, wet surface. Ideally, a cold core high pressure ridge prevails shortly thereafter, resulting in a clear nighttime skies that enhance the cooling of the already cold low-density surface snow.

Melt-layer recrystallization has been discussed by Armstrong (1985) and documented by Fukuzawa and Akitaya (1993), who observed the formation of near-surface faceted crystals on a southerly facing slope in northern Hokkaido, Japan. After sunny weather resulted in a melted snow surface, 2 cm of fresh snow fell on the wet surface. A cold, clear night, with large longwave radiation losses, followed. Strong temperature gradients (100 to 300°C m^{-1}) in the upper snowpack led to extremely rapid crystal growth rates resulting in the formation of 1 mm faceted crystals in one night. Subsequent laboratory studies focused on the lower snow densities (as low as 80 kg m^{-3}) and higher temperature gradients (100 to 200°C m^{-1}) generally associated with the formation of near-surface faceted crystals. Up until that time, all laboratory studies had focused on the smaller temperature gradients (<100°C m^{-1}), higher snow densities (>180 kg m^{-3}) and longer time scales (tens of days) associated with basal depth hoar development (Fukuzawa and Akitaya, 1993).

Melt-layer recrystallization has also been observed by avalanche workers in western North America. A rain event in British Columbia in November of 1996, followed by snowfall and cold weather, created a layer of near-surface faceted snow that resulted in avalanches through the following March (Jamieson, 1997). Further, in early January 1997 a widespread rain event affected much of the Rocky Mountains. Subsequent snowfall over the saturated snow surface resulted in the formation of near-surface faceted crystals in Utah and Wyoming. These layers were later responsible for widespread avalanche formation (Tremper, pers. comm., 1997; Elder, pers. comm., 1997).

DIURNAL RECRYSTALLIZATION

Diurnal recrystallization describes a third, and perhaps more widespread, process which forms near-surface faceted crystals. Since snow is an excellent insulator, temperatures with-

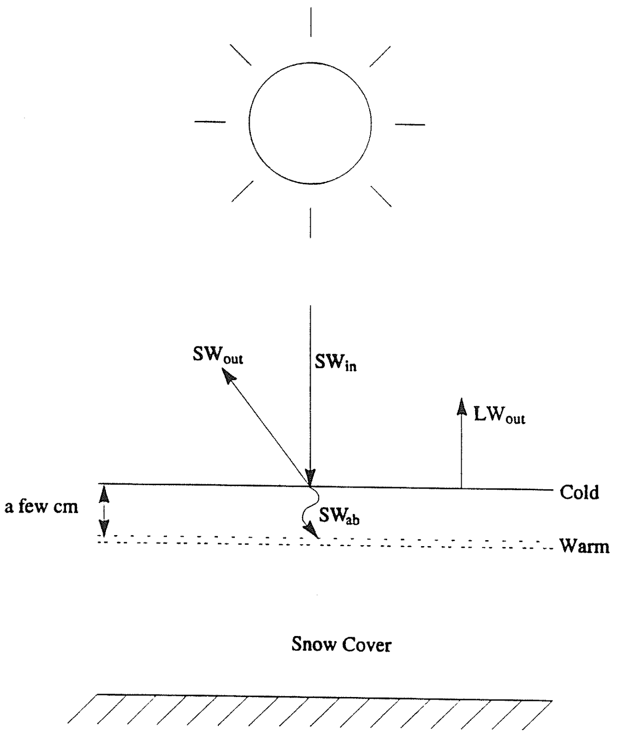

FIGURE 1. Radiation recrystallization occurs preferentially on southerly (southeast to southwest) aspects in response to a delicate balance between incoming and outgoing radiation. When incoming shortwave radiation (SW_{in}) reaches the snow surface, most is reflected (SW_{out}). Some shortwave radiation is absorbed (SW_{ab}), however, and warms the subsurface snow, sometimes creating a melt-layer. Meanwhile, outgoing longwave radiation (LW_{out}) cools the snow surface, resulting in a strong temperature gradient between the warm subsurface snow and the cooler snow surface, and the formation of near-surface faceted crystals.

in the snowpack change slowly. The temperature 0.30 m below the surface changes little, if at all, on a daily basis (Armstrong, 1985), and represents a sort of diurnal "average." Thus, large changes in the snow surface temperature result in strong temperature gradients in the near-surface layers due to the temperature difference between the cooling and warming snow surface and the relatively consistent temperature 0.30 m below the snow surface (Fig. 3). These temperature patterns have been documented in the arctic snowpack of Greenland in the summer, where they lead to the formation of faceted crystals that can be later used as markers in snow pits and ice cores (Alley et al., 1990) and in the winter snowpack of mid-latitude mountains (LaChapelle and Armstrong, 1977; Birkeland et al., 1998, this volume). In mid-latitude mountains, ideal conditions for diurnal recrystallization occur in winter when clear, cold nights (with strong longwave radiation losses from the snow surface) are followed by clear, but subfreezing, days. The process is further facilitated by low-density surface snow with maximum pore space to allow maximum temperature gradients between adjacent grains, enhanced vapor transport, and faceted crystal growth. Temperature gradients exceeding 200°C m^{-1} and vapor pressure gradients in excess of 25 mb m^{-1} have been measured under such conditions (Fukuzawa and Akitaya, 1993; Birkeland et al., 1998, this volume). Temperature gradients are negative at night and positive during the day, resulting in bi-directional faceting of the snow crystals. Observations in southwest Montana have shown that 73% of 30 avalanches which failed on layers of near-surface faceted crystals were the result of diurnal recrystallization (Birkeland et al., 1998, this volume).

Though these layers can form in just a day or two under ideal conditions, the most advanced layers of diurnally recrystallized near-surface facets are exposed to bi-directional temperature gradients for several days. Ideal synoptic conditions for such conditions in western North America are persistent high pressure ridges (especially blocking ridges, such as high over low [Rex] blocks or omega blocks) which result in prolonged periods of clear, cool weather. Several weeks of high pressure

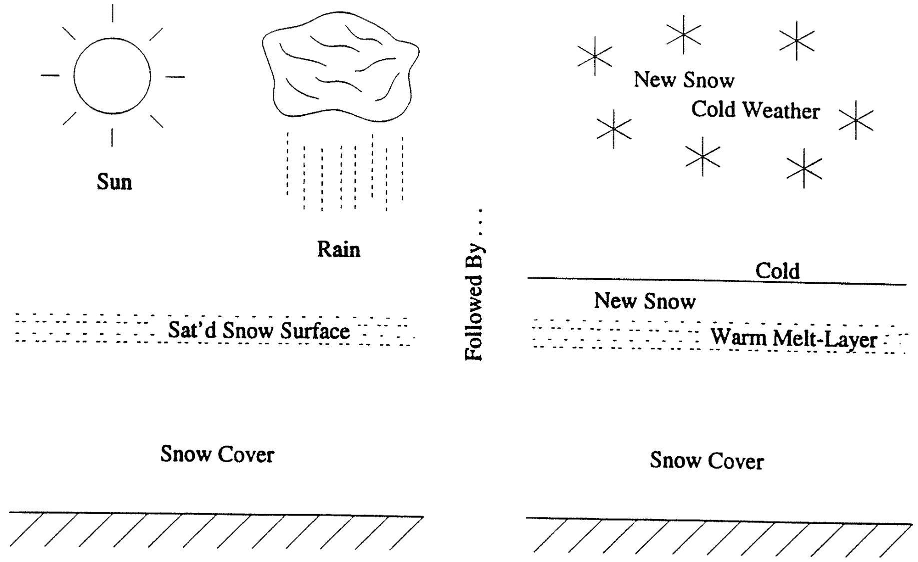

FIGURE 2. Melt-layer recrystallization occurs after rain or warm weather raises the temperature of the snow surface to the melting point. If this warm surface is subsequently buried by new snow as temperatures drop, a strong temperature gradient forms between the relatively warm melt-layer and the colder new snow, resulting in the formation of near-surface faceted crystals. This process is enhanced if the new snow layer is thin and has a low-density, and if the new snow is followed by a cold, clear night.

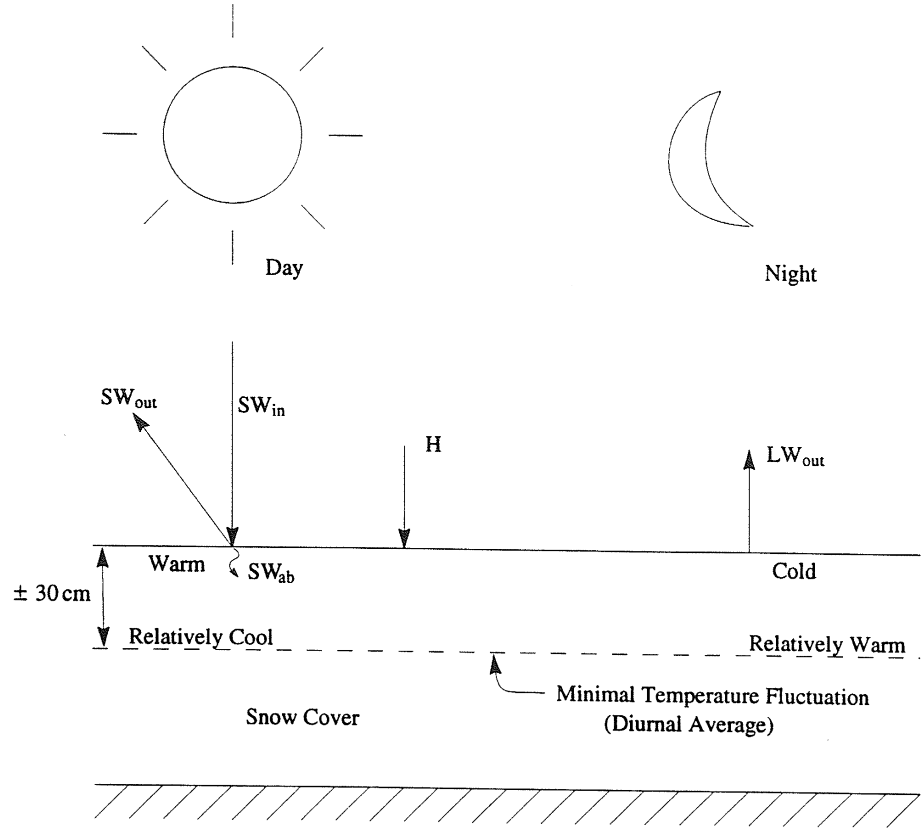

FIGURE 3. Diurnal recrystallization occurs in mid-latitude mountains when cold, clear nights alternate with warm days. While the temperature 0.30 m below the snow surface remains relatively constant, snow surface temperatures change dramatically in response to changes in the diurnal surface energy balance. The surface becomes extremely cold at night (largely in response to longwave radiation losses (LW_{out})) and warms during the day (primarily due to incoming sensible heat (H) and some absorbed shortwave radiation (SW_{abs})). The end result is strong negative temperature gradients at night, followed by strong positive temperature gradients during the day, resulting in the formation of near-surface faceted crystals.

conditions prevailing over the eastern Swiss Alps in January of 1997 created a weak layer of faceted snow that was later responsible for several fatal skier-triggered avalanches (Fierz, in press).

While little scientific work addresses the process of diurnal recrystallization in mid-latitude mountains, avalanche workers have recognized its importance. For example, Stratton (1977) observed diurnal recrystallization resulting in near-surface faceted crystals and their contribution to avalanche formation in Utah. He suggests that clear days with radiation inputs just below that needed for melting, cold clear nights, and low density (less than 100 kg m^{-3}) surface snow are contributors to the formation of what he termed "upper level temperature gradient" or U.L.T.G. snow. He also noted that the faceted crystals were often associated with thin, overlying crusts on southerly aspects, observing that particularly dangerous avalanche conditions existed when the crusts were overloaded by new or windblown snow until they collapsed into the weaker, underlying snow.

More recently, Fukuzawa and Akitaya (1993) measured the nocturnal temperature gradients associated with diurnal recrystallization and observed the resultant crystals, but did not look at daytime gradients. Colbeck (1989) mathematically described wide diurnal temperature swings in the upper snowpack and subsequent temperature gradients. He mentions that these processes form faceted snow layers most often in polar snow, or in seasonal snow at high altitudes, although he also states that growth rates near the snow surface in the seasonal snowpack could be much greater than at the soil-snow interface. Fierz (in press) studied a layer of snow in the Swiss Alps that underwent intensive diurnal recrystallization for two weeks, creating well developed faceted crystals. After burial the resultant weak layer persisted in the snowpack for several months.

Finally, Birkeland et al. (1998, this volume) continuously measured the bi-directional temperature gradients and calculated the associated vapor pressure gradients associated with the formation of a layer of near-surface faceted crystals through diurnal recrystallization. In about 36 h a layer of near-surface faceted crystals was formed by strong and fluctuating temperature gradients with crystal sizes of approximately 1 mm. After this layer was buried, avalanche activity was observed for the following 9 d.

At the Gallatin National Forest Avalanche Center, we have observed layers of near-surface faceted crystals formed by diurnal recrystallization on all slope aspects, and at elevations from 1700 to 3400 m throughout southwest Montana. Layers formed on south-facing slopes, or late in the season, are often associated with crusts, while layers formed on northerly aspects usually are not. Typically, diurnal recrystallization is limited to the upper 0.15 m of the snowpack, with the weakest snow commonly at or just under the snow surface. The faceted crystals may develop a number of different forms, depending on the initial grain form, the density of the surface layer, and the intensity and duration of the snow surface temperature fluctuations. We have observed four main crystal forms: (1) small grained (<0.5 mm) beginning faceted crystals (Class 4sf in the ICSSG [Colbeck et al., 1990]), (2) medium to large grained (1.5 mm or more) advanced facets (sometimes with striations) (Class 4fa or 5cp in the ICSSG [Colbeck et al., 1990]), (3) stringy snow that looks like needles with facets (similar to smaller versions (around 1 mm) of Akitaya's (1974) depth hoar needles; such forms have also been reported by Marbouty [1980]), and (4) well-preserved stellars, or parts of stellars, with facets (not clearly classified, intermediate between Class 2dc and Class 4sf of the ICSSG [Colbeck et al., 1990], but with some larger grain sizes). Like other faceted crystals, layers of near-surface faceted snow are not easily compressible; well-developed layers will commonly maintain a "fist" hand hardness (Colbeck et al., 1990) for days or weeks after being buried. In addition, variations in the snow surface temperature patterns at different locations lead to different amounts of faceted crystal growth at different elevations and aspects. Thus, the process of diurnal recrystallization, like all processes in the mountain snowpack, is spatially heterogeneous.

Summary

Although avalanche workers agree that near-surface faceted crystals commonly form weak layers in the snowpack throughout western North America, research into the processes which form these crystals is still in its early stages. This paper proposes terminology for near-surface faceted snow, and discusses three predominant processes which form these layers: radiation recrystallization, melt-layer recrystallization, and diurnal recrystallization. It is hoped that this framework will improve scientific discussion and theory-building related to the formation of weak layers of near-surface faceted crystals.

Two areas of research need to be addressed in order to advance our knowledge of this specific weak layer. First, research is needed concerning the extreme temperature gradients which form near-surface faceted snow and the bi-directional temperature gradients present in diurnal recrystallization. This work would benefit from a combination of field and laboratory studies. Second, investigations should focus on the contribution of weak layers composed of near-surface faceted crystals to avalanche formation. In particular, studies concerning the spatial variations of near-surface faceted snow growth would be helpful for understanding the distribution of weak layers and the resultant pattern of avalanche activity. The framework presented in this paper provides a means through which present and future avalanche research can address the formation of these dangerous and persistent weak layers in the mountain snowpack.

Acknowledgments

I had numerous discussions with R. Johnson about this work. G. H. Birkeland and C. Mock gave useful comments on the manuscript, and L. McKittrick helped with the figures. Subsequent insightful reviews by R. Armstrong and M. Sturm greatly improved this paper.

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Ms submitted May 1997