Near-Surface Faceted Crystals: Conditions Necessary for Growth and Contribution to Avalanche Formation, Southwest Montana, U.S.A.

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Karl Birkeland1, Ron Johnson2, and Scott Schmidt3

Abstract

In the winter of 1995-96 we investigated the formation of faceted crystals that develop in the upper levels of the snowpack. We used an array of six thermocouples connected to a datalogger to measure hourly diurnal temperature changes 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 C/m at night in the top 0.05 m of the snowpack, with the temperature gradient shifting direction and exceeding 100 C/m through this layer during the day. A significant weak layer of faceted snow formed within 36 hours with a grain size of about 1 mm in the upper snowpack. Widespread avalanche activity occurred for up to nine days after this layer was buried by 0.50 m of snow.

Introduction

During seven seasons of backcountry avalanche forecasting in southwest Montana, we have observed the formation of layers of faceted crystals near the snow surface (Class 4b in the International Classification for Seasonal Snow on the Ground (Colbeck et al., 1990)). These layers, which commonly form between 0 and 0.15 m below the snow surface, consistently create significant snowpack weaknesses in our snowpack when they are subsequently buried. Often near-surface faceted snow is topped off with surface hoar, a well documented weak layer. However, near-surface faceted crystals without surface hoar may also create dangerous and lasting weak layers. We investigated 51 backcountry avalanches, typically Class 3 or larger (Perla and Martinelli, 1978), that usually involved backcountry skiers, snowmobilers, snowboarders and snowshoers (Table 1). The weak layer in nearly two-thirds (59%) of those slides was a layer of small-grained (mostly up to 1 mm, but sometimes as large as 1.5 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 near-surface faceted crystals. Only 6% of the slides failed on basal depth hoar, while 4% failed on other weak layers.

In spite of their role in avalanche formation in our area, and reports that they form a significant weakness in other regions, 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 near-surface faceted layers are discussed briefly, if at all, in popular texts, and have been minimally addressed by scientific research. The purpose of this study was to observe the formation of near-surface faceted crystals in the field, to document the specific conditions necessary for their formation, and to observe their contribution to avalanche formation.

Literature Review

Faceted crystals have long been recognized as a significant weak layer and a prime contributor to avalanche formation (Seligman, 1936). Most research on faceted crystals has focused on the formation of the basal layer of large faceted crystals, commonly called depth hoar (some of the many examples include: de Quervain, 1954; Giddings and LaChapelle, 1961; Bradley et al., 1977; Perla, 1978). Akitaya (1974) made exhaustive laboratory examinations of depth hoar development and defined various crystal types and strength changes. Surface hoar is another type of faceted crystal that forms a well recognized weak layer. 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 and others, 1994; Hachikubo and Akitaya, 1996; Davis et al., 1996). 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 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.

Although the formation of faceted crystals near and just beneath the snow surface has not been as widely recognized as the processes which form surface hoar or depth hoar, near-surface faceted crystals have previously been identified by many avalanche workers and some snow scientists as a significant weak layer. Stratton (1977) typed up two short papers related to near-surface faceted crystals and their contribution to avalanche formation in Utah. Clear days with radiation inputs just below that needed for melting, cold clear nights, and low density (less than 100 kg/m3) surface snow were cited as 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; this was particularly dangerous when those crusts were overloaded until they collapsed into the weaker, underlying snow.

Concurrent with Stratton's observations, LaChapelle and Armstrong (1977) and Armstrong (1985) investigated snow metamorphism in the San Juan mountains of Colorado. They measured diurnal temperature fluctuations and strong temperature gradients (leading to strong vapor pressure gradients) in the upper 0.25 m of the snowpack. Of primary interest was a special form of near-surface faceting on southerly aspects that they termed "radiation recrystallization", whereby solar radiation penetrates the snowpack and melts the snow a few centimeters below the surface, while the snow at the surface is cooled by longwave radiation losses. The end result is a strong temperature gradient in the upper couple of centimeters and the formation of faceted crystals over a melt freeze crust - a perfect recipe for slab avalanches when subsequently buried. Little mention is made of the effect of the diurnal temperature changes they measured on the snowpack on more northerly aspects, or how those changes might relate to avalanche conditions in those areas.

More recently, 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. Perhaps the most comprehensive research on near-surface faceted snow was conducted by Fukuzawa and Akitaya (1993), who observed the formation of near-surface faceted crystals on a southerly facing slope in northern Hokkaido, Japan. Large temperature gradients (10 to 300 C/m) led to extremely high crystal growth rates resulting in the formation of 1 mm faceted crystals in one night. They followed up their observations with laboratory studies that looked at the lower snow densities and higher temperature gradients generally associated with the formation of near-surface faceted crystals. Up until that time, all laboratory studies had focused on the smaller temperature gradients and higher snow densities found in the basal layers where depth hoar forms. Still, their research was primarily focused on southerly facing slopes, and the high temperature gradients that form above melt crusts on subsequent cold, clear nights.

In spite of the recognition of the processes that form near-surface faceted crystals, and the role of those layers in avalanche formation, little comprehensive field work has been done on this topic. Most previous research has focused on southerly facing slopes and the melt-freeze crusts that often accompany these layers on south aspects. In Montana, we have found that northerly facing slopes also have weak layers of near-surface faceted crystals. Of the 30 backcountry avalanches that failed on near-surface faceted snow noted in Table 1, 73% of them faced either northwest, north, northeast, or east and were not associated with crust layers, while 27% did have a more southerly aspect and were associated with crusts (Table 2). Our observations, and the preceding literature review, indicate that research is lacking in two main areas: 1) the formation of near-surface faceted crystals in a variety of snow climates and on northerly aspects, and 2) the role of large temperature gradient swings in forming these layers. In addition, there is no research documenting the formation of these layers in the Montana snowpack. The purpose of this study was to document the formation of near-surface faceted crystals in Montana, assess the conditions necessary for their growth, and observe their contribution to avalanche formation.

Terminology

Near-surface faceted snow has been known by a variety of names. Skiers and avalanche workers have called these layers "recrystallized snow", "spaghetti snow", "recycled powder", or "loud powder". Although we use these terms in our avalanche forecasts, they are not particularly useful since all snow that is faceted has been "recrystallized", and the other terms do not adequately describe the snow grains. Stratton (1977) called these layers "upper level temperature gradient snow", which describes the location in which they are found and the process that forms them, but which is out dated due the term "temperature gradient". 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 with the unique processes involved in forming faceted grains near the surface. "Radiation recrystallized" (LaChapelle and Armstrong, 1977) snow is descriptive, but refers to a special case of near-surface faceting that takes place on southerly aspects in response to a delicate balance between incoming solar radiation and outgoing longwave radiation. Colbeck (1989), while never naming the crystals, refers to "near-surface growth" of faceted crystals. In this study, we expand on Colbeck's terminology, defining "near-surface faceted crystals" as snow formed by near-surface vapor pressure gradients resulting from temperature gradients caused by diurnal snow surface temperature swings.

Informal Observations

We have noted the conditions associated with the formation of near-surface faceted crystals over the past seven seasons. Since the temperature of the snow 0.25 m below the surface is relatively constant over a 24 hour period (Armstrong, 1985), it is the magnitude of the daily change in the snow surface temperature that creates the upper level temperature gradients (and resulting vapor pressure gradients) driving the development of near-surface faceted crystals. Ideal conditions for this process in our snow climate appear to be sunny, relatively warm, subfreezing (around -10 C) days, followed by clear, cold (around -15 C) nights. Clear nights allow for maximum radiation cooling of the snow surface and can lead to snow surface temperatures far below the ambient air temperature. During the day, snow surface temperatures increase due to air temperature and, on some aspects, solar radiation inputs. The growth of near-surface faceted crystals is further facilitated by the presence of low density new snow at the snow surface, an observation previously noted by Stratton (1977).

We have found layers of near-surface faceted crystals forming on all slope aspects at elevations from 5500 to 11,000 feet. 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 associated with crusts. Typically, near-surface faceted crystal formation is limited to the upper 0.15 m of the snowpack, with the weakest snow commonly near the top of the layer. The faceted crystals may develop a number of different forms, depending on the starting grain form, the density of the surface layer, the intensity of the snow surface temperature swings, and the length of time the near-surface layer undergoes those temperature swings. Crystal types that we have observed include small grained (< 0.5 mm) beginning faceted grains, large grained (1.5 mm or more) advanced facets (sometimes with striations), stringy snow that looks like needles with facets, and perfectly preserved stellars, or parts of stellars, with facets. Like other faceted crystals, layers of near-surface faceted snow are not easily compressible; well developed layers will commonly maintain a "fist" hand hardness for days or weeks after being buried. In addition, variations in the snow surface temperature swings at different locations lead to different amounts of faceted crystal growth at different elevations and aspects. Thus, the process of near-surface faceted growth, like all processes in the mountain snowpack, is spatially heterogeneous.

Once deposited, near-surface faceted snow is a significant and surprisingly persistent weak layer in our region. As discussed earlier, nearly 60% of the large avalanches we investigated failed on weak layers of near-surface faceted crystals. These layers often produce avalanches more than a week after being buried, and in one extreme case during the 1991-92 season we observed an avalanche on a layer that had been buried for approximately 90 days.

Methods

In order to measure temperature gradients, we constructed a thermocouple array using six thermocouples mounted on a 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 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. Ideally we would have liked to measure temperature changes in the upper 0.30 m of the snowpack, but only six thermocouples were available.

The thermocouples, calibrated in the Montana State University cold lab, were attached to an older Campbell CR21 datalogger. Since we were not able to remotely access the datalogger (which had only limited memory), we conducted our measurements in an easily accessible location. The flat, open study area was at 6000 feet in elevation, and had some trees and a house nearby. We excavated a small hole and inserted the thermocouple apparatus into the snow. After new snowfall, melting, or settling, we reset thermocouples in the snow. We collected data from early February to April 1996 during periods which appeared favorable to near-surface faceted crystal growth. Finally, we analyzed the hourly data in a spreadsheet program.

We dug snow pits throughout southwest Montana during the 1995-96 winter in order to identify layers of near-surface faceted crystals. Snow crystals were identified with the aid of a 20 power Pentax monocular. After identifying a layer of near-surface faceted snow, we looked at the snowpack temperature patterns that led to its formation, and then followed the layer when it was subsequently buried to observe its contribution to avalanche formation.

Results/Discussion

Formation of a layer of near-surface faceted crystals and associated temperature conditions
In late December 1995, clear cold nights and relatively warm days combined to create a weak layer of near-surface faceted crystals and surface hoar throughout southwest Montana. Unfortunately, we did not have our thermocouples working, and therefore we missed the conditions that formed that layer. In late March 1996, we had two to four new inches of snow fall through our region before an unusual and short cold spell. The cold and clear spell lasted two nights and a day, with a low temperature on the first night of about -20 C, followed by a day with temperatures up to -3 C and another night of -15 C. Subsequent observations revealed that these conditions were sufficient to create a layer of near-surface faceted crystals (up to 1 mm in size) on a wide variety of aspects and elevations throughout southwest Montana. Surface hoar was not observed. On southerly and easterly facing slopes this layer 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 the formation of the layer of near-surface faceted crystals in March, we analyzed the temperature conditions found at our study plot in the upper layers of the snow. There was a total of 0.65 m of snow on the ground at the study plot. The diurnal changes in the near-surface temperature profile were similar to that observed by LaChapelle and Armstrong (1977) in the San Juan mountains in Colorado (Figure 1). 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 hours the snow surface had continued to warm and now the temperature gradient was again strong, but the direction of the gradient had reversed. By 1800 hours 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 the relatively consistent temperatures at depth, served to create large temperature gradients in the upper snowpack (Figure 2). The temperature gradient in the upper 0.05 m of the snowpack was greater than -200 C/m during the night. By 1300 hours the temperature gradient had changed directions in response to the warming snow surface, but the magnitude of the gradient was still high (100 C/m). The temperature gradient from 0.05 to 0.10 m below the surface was also high, exceeding -50 C/m at night and switching to greater than 50 C/m at mid day. In general, the magnitude of the temperature gradient through a given layer decreased with increasing distance from the snow surface.

It is important to point out that it is the vapor pressure gradient resulting from the temperature gradient which causes faceted crystal development (Armstrong, 1985). Vapor pressure gradients are a product of the temperature gradient and the mean snow layer temperature, and values greater than 5 mb/m are sufficient for faceted crystal growth (LaChapelle and Armstrong, 1977). However, since vapor pressure gradients are difficult to measure, temperature gradients are often used as a surrogate. Since we observed widespread faceting of the near-surface snow layers during this time, the magnitude of these temperature gradients led to sufficient vapor pressure gradients to rapidly form near-surface faceted snow.

Contribution of near-surface faceted crystals to avalanche formation

After the formation of this layer of near-surface faceted crystals, we carefully followed its subsequent burial to see how the layer would react to a new snow load. In the Bridger Range (located just north of Bozeman, Montana, and immediately west of our level study plot) and in the Madison Range (located south of Bozeman) the faceted crystals were immediately buried by 8 to 10 inches of new snow over the next three days. Bridger Bowl and Big Sky Ski Patrols reported widespread avalanching on all aspects during control work. There were also several natural backcountry avalanches which failed on the layer of faceted crystals.

Five days after the layer had been buried there was still widespread collapsing and cracking of the snowpack and a few backcountry avalanches. Over two days another 8 inches of snow fell in the Bridgers. Finally, nine days after the layer had been buried, a person out for a moonlight ski in the Bridger Range came over a rollover on a 36 degree, southeast facing slope at 8100 feet. He triggered a sizable slide that ran on the layer of faceted crystals formed near the surface. He was carried 500 vertical feet, but managed to stay on the surface of the slide and was not injured. On our visit to the site two days later the snow was still sensitive, and we were able to ski cut avalanches on adjacent slopes.

Summary

Faceted snow crystals formed near and just below the snow surface create significant weak layers in the snowpack of southwest Montana when they are subsequently buried. These layers are created by large diurnal temperature fluctuations of the snow surface caused by a combination of clear, cold nights with strong radiative cooling and relatively warmer, sunny days. The large diurnal temperature changes of the snow surface contrast sharply with the relatively constant temperature of the snowpack 0.25 m below the surface. The difference between the fluctuating snow surface temperature and the more consistent temperatures 0.25 m below the surface results in large temperature gradients, strong vapor pressure gradients, and the rapid formation of faceted snow.

More research is needed, specifically on: 1) the changing temperature gradients which form near-surface faceted snow, possibly involving laboratory work, 2) the numerous processes which drive those temperature gradients, 3) the spatial variations (especially due to changes in aspect and latitude) of near-surface faceted snow growth, and 4) the contribution of near-surface faceted snow to avalanche formation. Preliminary results from this study indicate that, in Montana, near-surface faceted snow is one of the most significant weak layers and deserves more attention in both the popular and scientific snow and avalanche literature.

Table 1: Weak layers associated with large (generally Class 3 or larger) backcountry avalanches investigated in southwest Montana, 1990-91 to 1995-96.

Total Avalanches

Investigated

Type of Weak Layer

Near-surface faceted crystals

Surface hoar

Depth hoar

Other

51

30

(59%)

16

(31%)

3

(6%)

2
(4%)

Table 2: Predominant slope aspect associated with 30 backcountry avalanches observed in southwest Montana to have a weak layer of near-surface faceted snow.

Predominant Aspect

N

NE

NW

E

W

SW

SE

S No. Avalanches 1

(3%)

13
(43%)

1
(3%)

7
(23%)

0 6
(20%)

2
(7%)

0
Figure Headings

Figure 1: Near-surface temperature profiles observed at selected times on March 25th, 1996.

Figure 2: Near-surface temperature gradients observed on March 24th-25th, 1996.

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