Characterization of a deep slab instability

Ethan Greene*
Forest Service Utah Avalanche Center, Salt Lake City, Utah
and
Greg Johnson
Forest Service Utah Avalanche Center, Logan, Utah

Abstract: In early January 2002, a warm and moist storm formed an ice crust on the snow surface throughout the Wasatch Mountains of northern Utah. Faceted snow layers that later formed above and below this ice crust were responsible for several periods of significant avalanche activity in the mountains near Salt Lake City. This lingering avalanche cycle was unique because the weak layer became very sensitive at several different times during the winter. During these periods natural, explosive released, and human triggered avalanches occurred. The focus of this paper is to discuss weather and snowpack parameters leading to the formation of the facet-crust combination and to describe the subsequent avalanche cycles and associated forecasting problems.

1 Introduction

Deep slab instabilities present a difficult forecasting problem for avalanche safety programs. This type of instability often causes large and dangerous avalanches with spatial and temporal patterns that are difficult to predict. In early January 2002, a warm and moist storm covered the snow surface in the Wasatch Mountains of northern Utah (Figure 1) with a hard ice layer. This layer was subsequently buried and faceted snow crystals formed above and below the crust. The faceted layers adjacent to this crust were responsible for numerous large natural, explosive released, and human triggered avalanches, including two fatalities. The purpose of this paper is to describe the formation, spatial and temporal patterns, and backcountry forecasting issues associated with this deep slab instability.

2 Facets and crusts

Faceted crystals that grow near the surface of the snowpack are classified into three formation categories: radiation recrystallization, melt-layer recrystallization, and diurnal recrystallization (Birkeland, 1998). In each category, a temperature gradient of a sufficient magnitude causes water vapor transport to occur at a rate where surface kinetics overcome the system's natural desire to reach thermodynamic equilibrium (Colbeck, 1983a). Rapid depositional growth occurs on surface steps and dislocations forming angular shaped crystals and eventually striated faces and cups.

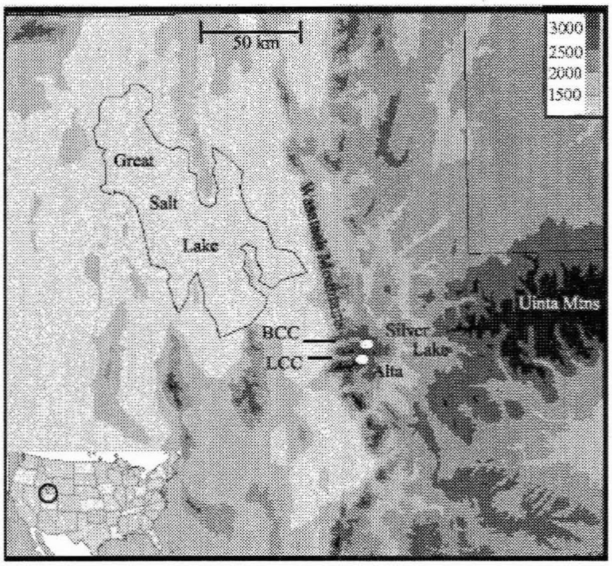

Figure 1: Map of northern Utah including the northern portion of the Wasatch Mountains and Big and Little Cottonwood Canyons. Observations used in this study were taken from study plots at the Alta Lifts Ski Area and Utah Department of Transportation Silver Lake study plot.

Faceted crystals have been observed adjacent to hard crust layers (Seligman, 1936; Moore, 1982; Fierz, 1998; Jamieson et. al 2001) and theoretical reasons for their development have been presented (Colbeck, 1983b; Adams and Brown, 1983; Colbeck, 1991; Birkeland, 1998; Colbeck and Jamieson, 2001). Adams and Brown (1983) used a heat and mass transfer model to examine the vapor-density difference (the difference in vapor density at pore center with an ice surface at the same temperature that is in equilibrium) in a

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**Corresponding author address:* Ethan Greene, Forest Service Utah Avalanche Center, 2242 W. North Temple, Salt Lake City, UT 84116; tel: 801-524-5304; fax: 801-524-4030;
email: greene@cnr.colostate.edu

layered snowpack. Their results indicate that the presence of an ice crust (high density layer) increased the vapor-density difference on both sides of the crust and could explain the growth of facets at a crust-snow interface. Colbeck (1991) investigated the transfer of heat and mass through the snowpack by examining the combined effects of conduction through the ice lattice and latent heat exchange from vapor diffusion through the pore space. He postulated that at the lower boundary of the ice-snow interface heat is readily transferred into the ice crust due to its high thermal conductivity, but the reduction in porosity would produce a locally higher vapor pressure gradient and possibly faceted crystal growth. At the upper ice-snow interface the high thermal conductivity of the crust could produce a locally higher temperature and temperature gradient, but this effect could be offset by increased sublimation at the crust's upper boundary. Colbeck and Jamieson (2001) examined a scenario where liquid water near or on the snow surface freezes forming an ice layer. As the liquid freezes it releases latent heat, which produces a temperature gradient. The temperature gradient produces faceted gains above the ice layer. In this case the freezing process produces both the ice crust and the temperature gradient that causes faceting.

Observational studies have shown that in the presence of a strong temperature gradient facets can form on snow grains within a matter of hours and grow to an appreciable size within days. Fukuwaza and Akitaya (1993) found that under a strong temperature gradient (159 °C/m) highly developed faceted snow grains developed overnight. Birkeland et. al (1998) measured diurnal swings in the temperature gradient and found a layer of faceted crystals with an average grain size of 1 mm formed within 36 hours. Jamieson and van Herwijnen (2002) simulated melt-layer recrystallization in a cold laboratory. They filled an insulated box with two layers of dry snow separated by a layer of saturated snow. The cold laboratory temperature was maintained between approximately -5°C and -15 °C. Temperatures within the snow sample (including the saturated layer) were recorded and snow grains were photographed every two hours. They observed sharp edges forming on the snow grains above the wet layer (within hours) and well-developed faceted crystals within 24 hours.

The factors that lead to avalanche activity on crust-facet interfaces have been previously investigated. Jamieson et al. (2001) assessed the predictive merit of weather and snowpack parameters for over 700 natural dry slab avalanches in the Columbia Mountains of southwestern Canada. They found factors such as accumulated snowfall over 3 or more days, changes in air temperature over 4 – 5 days, shear frame stability index, and the difference in hand hardness between the facet layer and the crust are potential predictors.

3 Weather and avalanche observations

Meteorological conditions were recorded by automated weather stations in Little Cottonwood Canyon at Alta Ski Lifts' Collins (2945 m) and Mt. Baldy (3370 m) study plots. At the Collins study plot, air temperature, water equivalent of precipitation, and snow depth were recorded. The Mt. Baldy weather station provided air temperature as well as wind speed and direction. Hourly averages from both weather stations were converted to 24-hour averages and are shown in Figures 2 and 3. In Big Cottonwood Canyon, manual observations of snow depth and water equivalent precipitation were recorded at the Utah Department of Transportation's Silver Lake Study Plot (2600 m). Observations

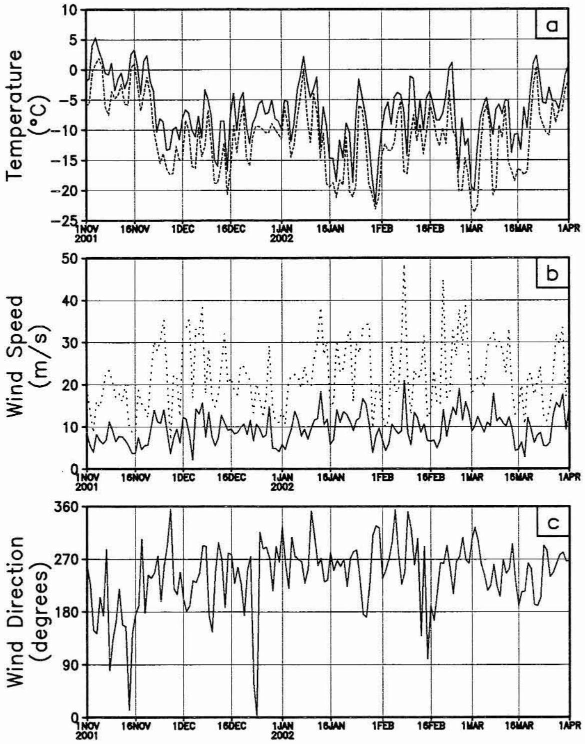

Figure 2: Daily averaged meteorological conditions from November 1, 2001 through April 1, 2002 at the Mt. Baldy weather station (3370 m). a) maximum and minimum air temperature, b) wind speed and maximum gust, c) wind direction.

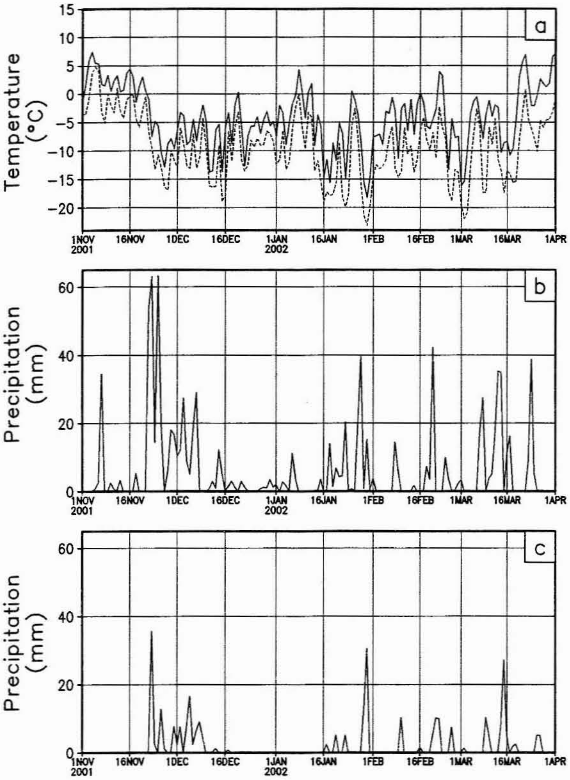

Figure 3: Daily averaged air temperature and precipitation from November 1, 2001 through April 1, 2002. a) maximum and minimum air temperature at the Collins study site (2945 m ASL), b) precipitation at the Collins study site, c) precipitation at the Silver Lake study site (2600 m ASL).

were recorded every 12 hours, but 24 hour averages were calculated for use in this study (Figure 3).

Avalanche occurrence was recorded at the Forest Service Utah Avalanche Center (FSUAC) in Salt Lake City. These records are the combined observations of the FSUAC staff, numerous avalanche professionals that work and recreate in the Wasatch Range, and backcountry travelers. Within the Utah avalanche community several avalanche classification systems are used. These include the United States Avalanche Size Classification (McClung and Schaerer, 1993), the Canadian Avalanche Size Classification (McClung and Schaerer, 1993), and modified scales used for specific applications. Each classification system uses a scale from one to five. The Canadian classification is based on the estimated destructive effects of the avalanche, while the U.S. system is based on the volume of snow transported down the avalanche path relative to the path size. While all of the systems used have their advantages the numerical categories are not comparable. For this study we used avalanche observations that were recorded in the U.S. or Canadian systems. Human triggered avalanches size 2.0 (both scales) or larger were used as well as natural and explosive released avalanches size 3.0 (both scales) or larger. This selection method generated a data set containing 211 avalanches. Of those avalanches 125 were triggered by explosives, 28 were triggered by skiers or snowboarders, 3 were triggered by snowmobilers, 54 were natural avalanches, and 1 was triggered by a cornice fall. Because of the inconsistent classification systems, discussions involving avalanche size are not possible.

The data set used in this study is comprised of avalanches that released on the January 6 layer and occurred in the Big Cottonwood Canyon and Little Cottonwood Canyon areas (Figure 1). Avalanches that occurred on either side of the bounding ridgelines were also included in the data set. Thus the data set includes some of the avalanche activity that occurred in Mill Creek Canyon, American Fork Canyon, and along the Park City Ridgeline.

4 Weak layer formation

In mid-November the Wasatch Mountains were nearly devoid of snow. A pair of strong storms moved through in late November dropping over 200 mm of water (250 cm of snow) at the Collins site in a 100-hour period (Figure 3). The beginning of December remained relatively wet with regular snow events. By the middle of the month the snowpack was generally stable and nearly homogenous throughout the range. The third week in December was marked by the return of high pressure and no significant snowfall occurred through the end of the month (Figure 3).

During the first week of January the amplitude of the high pressure ridge decreased allowing a moist northwesterly flow to move over the state. On the morning of January 6, 2002 the snow surface consisted of a shallow layer of recrystallized snow. A relatively warm and moist air mass moved into northern Utah. Air temperatures warmed during the day and precipitation began about midmorning (Figure 4) falling as rain below approximately 2500 m and rime above. Above 2500 m a thin layer of rime ice immediately formed on the snow surface. By nightfall air temperatures dropped below 0°C, freezing the near saturated snow surface below 2500 m (Figure 4).

Overnight and early in the morning on January 7, 2002, 5 cm of snow fell at the Alta Ski Lifts' Collins study plot (2945 m ASL). Air temperatures warmed through January 8 with daytime temperatures rising above freezing at 3,300 m (Figure 2). Over the next six days the dominant weather feature over northern Utah was a low amplitude ridge of high pressure. This feature produced mostly stable weather and nocturnal temperatures in the -4°C to -10°C range (Figure 4). A cold front moved through northern Utah on January 15 dropping another 10 cm of snow. Only trace amounts of precipitation fell over the next three days and nighttime temperatures were in the -12°C to -19° C range (Figure 4). On January 18, a strong Pacific Storm moved through the Great Basin dropping 14 mm of precipitation (45 cm of snow) at the Collins study plot (Figure 4).

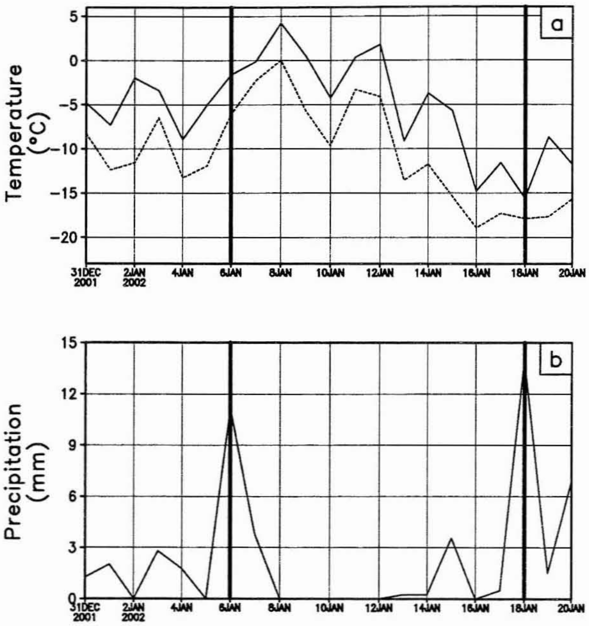

Figure 4: Daily averaged air temperature and precipitation at the Collins study site (2850 m ASL) from December 31, 2001 through January 20, 2002.

Without detailed snowpack measurements it is impossible to determine exactly what processes formed the layers of facets around the January 6 ice crust (subsequently referred to as the January 6 layer). However, by examining the meteorological conditions and the theory discussed above we can suggest a likely scenario.

During the rain/rime event of January 6 latent heat was added to the snowpack. Due to the large time duration and prevalent turbulent mixing of the depositional event (wind speeds at the Mt. Baldy weather station averaged over 10 m/s on January 6), latent heating of the snow surface was probably minor in areas where riming was dominant (Brownscombe and Hallett, 1967; Seinfeld and Pandis, 1998). In areas below about 2500 m faceting due to latent heat release is more likely. Once the ice crust was formed it remained on or near the surface for nearly 12 days. During this period there were large diurnal temperature fluctuations with nocturnal temperatures in the -4°C to -19°C range. The ridge of high pressure allowed periods of cloud cover with observations ranging from clear to overcast. These conditions (cold clear nights) were favorable for diurnal recrystallization and this process may have been enhanced by the presence of the crust. By January 11 there were faceted snow grains under the crust 1 mm in size.

5 Spatial and temporal patterns

The spatial patterns of avalanche cycles in the Wasatch Mountains are heavily influenced by the characteristics of the range (Bruce Tremper, personal communication). Although the wind direction fluctuates due to the combined affects of local orography and weather systems, the predominant upper level wind direction in the Wasatch Range is westerly (Figure 2). Winter precipitation events that favor Big and Little Cottonwood Canyons typically occur during periods of northwest flow at the 700 mb level (Dunn, 1983). As a result, avalanche activity is most prevalent (although not confined to) easterly aspects.

Natural and skier or snowboarder triggered avalanches that released on the January 6 layer are displayed in Figure 5 by aspect. Over 60% of both natural and human triggered avalanches occurred on aspects with an easterly component, while less than 20% occurred on westerly aspects. There were no natural or human triggered aspects on south facing slopes and no natural activity on northwest facing slopes.

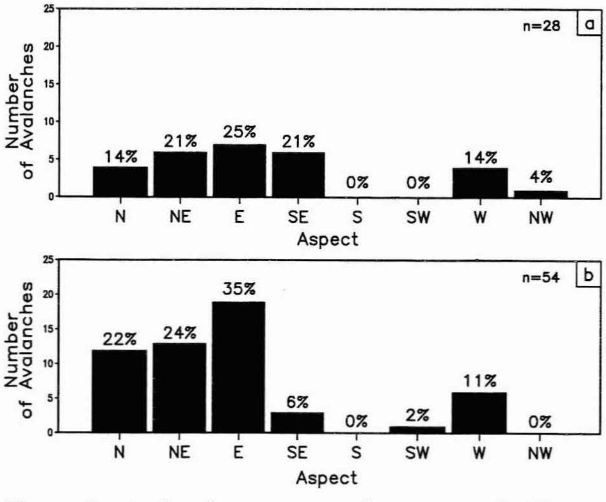

Figure 5: Avalanche occurrence by aspect. a) skier and snowboarder triggered avalanches b) natural avalanches

Table 1: Avalanches on the January 6 layer by elevation band.
** Rounded to the nearest whole percent.*

Elevation Band		Number of Avalanches	Proportion of Total* n = 211
11,000-11,500 ft	3354-3506 m	9	4%
10,000-10,999 ft	3049-3353 m	120	57%
9,000-9,999 ft	2744-3048 m	71	34%
8,000-8,999 ft	2440-2743 m	8	4%
7,000-7,999 ft	2134-2439 m	3	1%

The majority (91%) of the avalanche activity occurred within the 2744 m to 3353 m (9,000 ft to 10,999 ft) elevation band (Table. 1). All of the natural and human triggered activity occurred above 2440 m (8,000 ft). These patterns are also greatly affected by the characteristics of the Wasatch Range. Precipitation patterns in the Wasatch Mountains are heavily affected by orographic forcing, increasing by a factor of five or more from Salt Lake City (1288 m) to Alta (2945 m) depending on the dynamics of the event (Dunn, 1983). This causes more rapid loading rates to occur at higher elevations. In addition, the 2001/2002 winter featured uncharacteristically long periods without precipitation causing the low elevation snowpack to remain relatively thin.

A timeline of the avalanche cycle is shown in Figure 6. In general the greatest number of natural and explosive triggered avalanches occurred either during or directly after a major precipitation event. Precipitation events that triggered widespread activity occurred at the end of January, end of February, and middle of March (Figure 6). The only exception to this pattern occurred during the first week of April. This was the first wet avalanche cycle of the spring and occurred after several days with strong daytime heating and nocturnal lows near 0°C.

An interesting aspect of this event was the duration of the avalanche cycle. Although the most widespread avalanche activity occurred during or directly after the first major loading event, significant avalanche activity continued throughout the winter (Figure 6). Explosive testing in backcountry areas produced several slides with crowns greater than 3 meters in depth and 100 meters wide. Backcountry travelers were able to trigger very large avalanches (2+ m deep and 100+ m wide with one over 600 m wide) after the January 6 crust had

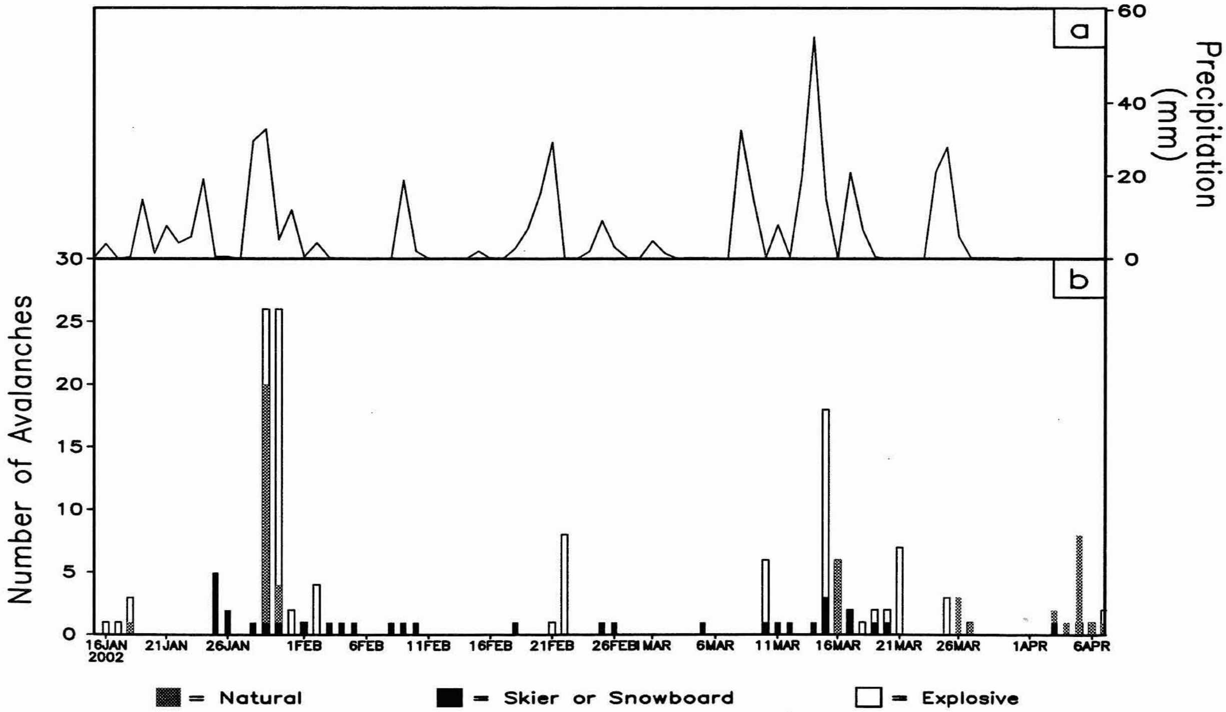

Figure 6: Timeline of avalanche cycle from January 16, 2002 through April 7, 2002. a) precipitation at the Collins study site (2850 m ASL), b) number of avalanches separated by trigger

been buried in excess of 50 days and human triggered avalanches continued into early April over 70 days after the layer was first buried.

6 Deep slab avalanches and the avalanche danger scale

Backcountry avalanche advisories or bulletins rate the avalanche danger using a five level rating system or Avalanche Danger Scale (Table 2). This scale takes into consideration both the probability of triggering an avalanche and the spatial extent of the instability. The scale has been proven effective for many different scenarios, however in practice the increments tend to be more representative of snow stability than danger to people. The Canadian Avalanche Association defines avalanche danger as the potential for an avalanche to cause injury or death to a person (CAA, 2002). When a deep slab instability is present, the Avalanche Danger Scale does not adequately communicate the danger to the public because the rating system does not consider avalanche size.

Deep slab instabilities often attain a moderate or considerable rating on the Avalanche Danger Scale. This rating arises from a combination of factors. First, deep slab instabilities often affect a small percentage of the terrain described in an avalanche advisory. Second, in the absence of loading events, natural avalanches are often unlikely but human triggered avalanches are possible and sometimes probable. Since deep slab instabilities are infrequent, the public often associates a moderate or considerable danger rating with a more widespread instability that produces avalanches with a lesser destructive force. During a deep slab instability it may be possible to travel safely in many areas, but if an avalanche is triggered it is likely to be a very large and destructive event. This presents a confusing situation for the public and a difficult situation for the forecaster. The public struggles to determine which type of moderate danger is occurring on a particular day, while the forecaster struggles over using the same danger rating for two very different situations.

The Forest Service Utah Avalanche Center (FSUAC) was presented with communicating the danger of the January 6 layer from the end of January through early April. While none of the staff felt the avalanche danger was adequately described as moderate, the majority agreed that the definitions dictated this rating. The forecasting staff generally used a moderate or considerable danger rating and attempted to describe the complex nature of the conditions in their advisory. This approach is probably adequate for users that both read and understand the entire advisory. However, users that rely heavily on the danger rating may not get enough information to travel safely in the backcountry.

We do not have a solution to this deficit in the Avalanche Danger Scale. One method would be to use a danger scale that weighed instability, spatial extent, and size equally. Over the past few years the FSUAC has attempted to add a factor into internal avalanche danger

Table 2: The United States Avalanche Danger Scale. Modified from Dennis and Moore, 1996.

Danger Level (color) **...What...**	**Avalanche Probability and Avalanche Trigger** **...Why...**	**Degree and Distribution of Avalanche Danger** **...Where...**	**Recommended Action in the backcountry** **...What to do...**
LOW (green)	Natural avalanches very unlikely. Human triggered avalanches unlikely.	Generally stable snow. Isolated areas of instability.	Travel is generally safe. Normal caution advised.
MODERATE (yellow)	Natural avalanches unlikely. Human triggered avalanches possible.	Unstable slabs possible on steep terrain.	Use caution in steep terrain on certain aspects (defined in accompanying statement).
CONSIDERABLE (orange)	Natural avalanches possible. Human triggered avalanches probable.	Unstable slabs probable on steep terrain.	Be increasingly cautious in steep terrain.
HIGH (red)	Natural and human triggered avalanches likely.	Unstable slabs likely on a variety of aspects and slope angles.	Travel in avalanche terrain is not recommended. Safest travel on windward ridges of lower angle slopes without steeper terrain above.
EXTREME (red with black border)	Widespread natural or human triggered avalanches certain.	Extremely unstable slabs certain on most aspects and slope angles. Large and destructive avalanches possible.	Travel in avalanche terrain should be avoided and travel confined to low angle terrain well away from avalanche path run-outs.

worksheets that accounts for danger to humans. This so called "pucker factor" represents the level of danger the avalanche conditions present to an individual backcountry traveler. While this is not an explicit representation of avalanche size it does represent destructive force.

7 Concluding remarks

The avalanche cycle that occurred around the January 6 layer contained several unusual aspects. During the twelve days between the formation of the crust and the next major snow event, facets grew on adjacent snow grains both above and below the ice crust. During the first period of avalanche activity (in the end of January), avalanches released on faceted layers both above and below the ice crust. As the season progressed the faceted snow below the ice crust became the dominant failing layer. This indicates that while both layers were gaining in strength, the snow under the crust gained strength slower. If this observation is correct it would support some of the theoretical work presented above.

Although the most widespread avalanche activity occurred during and after the first major loading event, avalanches released near the January 6 layer for the duration of the winter. Large explosive triggered avalanches occurred after every major loading event and human triggered avalanches occurred over 70 days after the facet-crust layer was completely buried. During the first spring warming event large natural avalanches occurred.

The January 6 layer posed a serious forecasting problem for all of the avalanche safety programs that operate in northern Utah. The Forest Service Utah Avalanche Center approached this problem by both using an Avalanche Danger Scale rating and describing the complex nature of the avalanche cycle in the advisory. It is our belief that the Avalanche Danger Scale alone does not adequately communicate the avalanche danger to the public and that a danger scale rating should be augmented with a more detailed discussion of snowpack conditions.

8 Acknowledgements

We would like to thank the snow safety programs at Alta Lifts Ski Area, Snowbird Ski Resort, Solitude Ski Area, Brighton Ski Area, Park City Ski Resort, The Canyons Ski Resort, Utah Department of Transportation, and Wasatch Powderbird Guides for sharing the data they collected during their daily operations. In addition Dan Howlett (Howie), Jim Collinson, Sam Davis, Eric Wright, and Greg Dollhausen went above and beyond the call of duty to help us get the data for this paper. We had many useful discussions with Bruce Tremper, Evelyn Lees, Tom Kimbrough, Drew Hardesty, Robert Athey, Karl Birkeland, and Alan Jones. Jim Steenburgh provided portions of Figure 1.

9 References

Birkeland, K.W., 1998: Terminology and predominant processes associated with the formation of weak layers of near-surface faceted crystals in the mountain snowpack. *Arctic and Alpine Research*, **2**, 193-199.

Birkeland, K.W., R.F. Johnson, and D.S. Schmidt, 1998: Near-surface faceted crystals formed by diurnal recrystallization: A case study of weak layer formation in the mountain snowpack and its contribution to avalanche formation. *Arctic and Alpine Research*, **30**, 199-204.

Brownscombe, J.L., and J. Hallett, 1967: Experimental and field studies of precipitation particles formed by freezing of supercooled water. *Quarterly Journal of the Royal Meteorological Society*, **93**, 455-473.

Canadian Avalanche Association, 2002: *Observation guidelines and recording standards for weather, snowpack and avalanches*. Canadian Avalanche Association, Revelstoke, BC, Canada.

Colbeck, S.C., 1983a: Ice crystal morphology and growth rates at low super saturations and high temperatures. *Journal of Applied Physics*, **54**, 2677-2682.

Colbeck, S.C., 1983b: Theory of metamorphism of dry snow. *Journal of Geophysical Research*, **88**, 5475-5482.

Colbeck, S.C., 1991: The layered character of snow covers. *Reviews of Geophysics*, **29**, 81-96.

Colbeck, S.C., and J.B. Jamieson, 2001: The formation of faceted layers above crusts. *Cold Regions Science and Technology*, **33**, 247-252.

Dennis, A., and M. Moore, 1996: Evolution of public avalanche information: The North American experience with avalanche danger rating lev els. Proceedings from the International Snow Science Workshop, Banff, British Columbia, October, 1996, 60-72.

Dunn, L. B., 1983: Quantitative and spacial distribution of winter precipitation along Utah's Wasatch Front. NOAA Tech. Memo. NWS WR-181, [Available from NOAA NWS Western Region Headquarters, 125 S. State St., Rm. 1311, Salt Lake City, UT 84138-1102].

Fierz, C., 1998: Field observation and modeling of weak-layer evolution. *Annals of Glaciology*, **26**, 7-13.

Fukuzawa, T. and E. Akitaya, 1993. Depth-hoar crystal growth in the surface layer under high temperature gradient. *Annals of Glaciology*, **18**, 39-45.

Jamieson, J.B., T. Geldsetzer., and C. Stethem, 2001: Forecasting for deep slab avalanches. *Cold Regions Science and Technology*, **33**, 275-290.

Jamieson, J.B., and A. van Herwinjin, 2002: Preliminary results from controlled experiments on the growth of faceted crystals above a wet snow layer. Proceedings of the International Snow Science Workshop, Penticton, British Columbia, October 2002.

McClung, D.M., and P. Schaerer, 1993: *The Avalanche Handbook*, The Mountaineers, Seattle, 253 pp.

Moore, M.B., 1982: Temperature gradient weakening of snowpacks near rain crusts or melt-freeze layers, unpublished paper, abstract appears in the Proceedings of the International Snow Science Workshop, Bozeman, Montana, October 1982.

Seinfeld, J.H., and S.N. Pandis., 1998: *Atmospheric Chemistry and Physics*, John Wilely and Sons, New York, 847-848 pp.

Seligman, G., 1936: *Snow Structure and Ski Fields.* International Glaciological Society, Cambridge, 555 pp.