Preliminary results from controlled experiments on the growth of faceted crystals above a wet snow layer

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Abstract

Faceted crystals have been observed above melt-freeze crusts, and the layers of such crystals form the failure layer for some hard-to-predict dry slab avalanches. Previous work proposed that wet layers could provide the heat to promote faceting in overlying dry snow, resulting in a weak layer of faceted crystals above a crust.

A series of seven experiments was conducted in the Rogers Pass Cold Laboratory in February and March 2002. Each experiment involved three snow layers within a laterally insulated box: a lower layer, approximately 15 cm thick, of natural dry snow; a middle layer of artificially wetted snow; and an upper layer of dry snow that was sieved onto the wet layer. In different experiments, the wet layer was varied in thickness from 2 to 9 cm, and the overlying dry snow (slab) was varied in thickness from 6 to 14 cm. The temperature was monitored in the wet layer, in the overlying dry snow layer and in the air, which remained well below 0°C. The crystals from the interface and from the overlying dry snow were observed at 20x magnification and photographed through a microscope at least once per day.

Faceted crystals were observed above the wet layer in all seven experiments within two days, and in two of the experiments after only two hours. The elapsed time until the wet layer froze was longer in experiments in which more liquid water was added to the wet layer. The maximum temperature gradient near the base of the dry slab was greater in experiments in which the dry slab was thinner. Facets were observed sooner in experiments in which the wet layer was thicker.

Keywords: snow heat flux, snow metamorphism, snow stability, slab avalanche, avalanche formation

1. Introduction

In the mountain snowpack, faceted crystals are sometimes observed just above melt-freeze crusts and such facet-over-crust combinations sometimes release dry slab avalanches (Stethem and Perla, 1980; Schweizer and Jamieson, 2001). Some of these avalanches are unexpected because the conditions favouring the formation of facets above crusts are not well understood and vary over the terrain, resulting in spatially variable instability.

This study focused on the formation of facets in dry snow overlying a temporarily wet layer of snow. A range of these conditions was created in a series of experiments in the Rogers Pass Cold Laboratory during the winter of 2001-02. Our objective was to better determine the range of conditions favourable to the formation of facets just above freezing wet layers.

2. Literature review

In 1985, Richard Armstrong asked, "Could a melting or relatively warm, snow layer provide a heat source beneath a subsequent fall of cold snow sufficient to cause identifiable recrystallization?" Using simple boundary conditions, he calculated that a 1-m-thick layer of rain-soaked snow could take six days to freeze, during which time an overlying layer of dry snow would be subjected to a strong temperature gradient.

In field studies, Fukuzawa and Akitaya (1993) observed that the presence of a wet layer increased the rate of near surface faceting in an overlying thin layer of dry snow. In one night, a 6-cm-thick wet layer took six hours to freeze during which time the temperature gradient in the overlying 2-cm-thick layer of dry snow was sufficient to grow depth hoar crystals.

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Using tree-line weather data from the Columbia Mountains of western Canada in November 1996, Jamieson and others (2001a, b) proposed that a prominent layer of faceted crystals formed in a new layer of dry snow due to surface cooling combined with latent heat provided by the underlying rain-wetted layer. The faceted layer released many dry slab avalanches until March 1997, and wet avalanches in May 1997.

Birkeland (1998) named this process *melt layer recrystallization* although we prefer *near-wet-layer faceting*.

Using the latent heat in the wet layer as the heat source, Colbeck and Jamieson (2001) derived an equation for the temperature in overlying dry snow during the period in which the wet layer would freeze. Based on the grain growth model of Colbeck (1983), they showed that a high growth rate is likely at the wet-dry interface even though the wet layer might freeze within hours.

3. Methods

A series of seven experiments, each lasting two to nine days, was conducted in the Rogers Pass Cold Laboratory during the winter of 2001-02. Each experiment consisted of a three-layer snowpack placed inside a box with internal dimensions 50 cm x 50 cm x 42 cm high (Figures 1, 2). The box was laterally insulated with 7-cm-thick foam.

The lower layer consisted of a 10- to 21-cm-thick block of dry natural snow with a density of 200-300 kg/m^3 that was fitted into the base of the box. The middle layer consisted of a mixture of snow and liquid water that was manually spread onto the underlying dry snow base (Figure 3). (Initial attempts to sprinkle water like rain resulted in uneven wetting of the snow layer.) In different experiments, the wet layer varied in thickness from 1.5 cm to 9 cm. Six to 14 cm of dry snow was then sieved onto the wet layer (Figure 4), forming the top dry layer which is subsequently referred to as the slab.

A total of twelve thermistors were placed in the air a few centimetres above the snowpack, at or near the snow surface, at or near the dry-wet interface, in the wet layer and in the dry base (Figure 5). The thermistors were connected to a datalogger that recorded average temperature every 30 minutes based

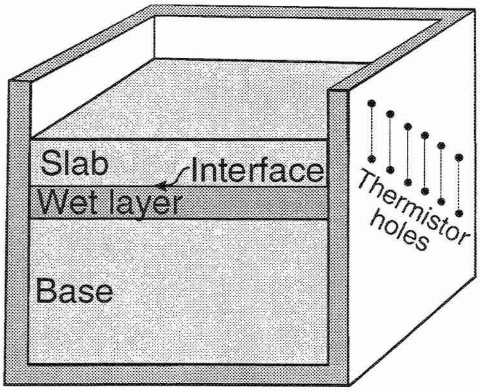

Figure 1. Section of laterally insulated box showing snow base, wet layer, overlying slab and interface between slab and wet layer. Six pairs of thermistors are placed in the holes on the right wall to monitor snow and air temperature.

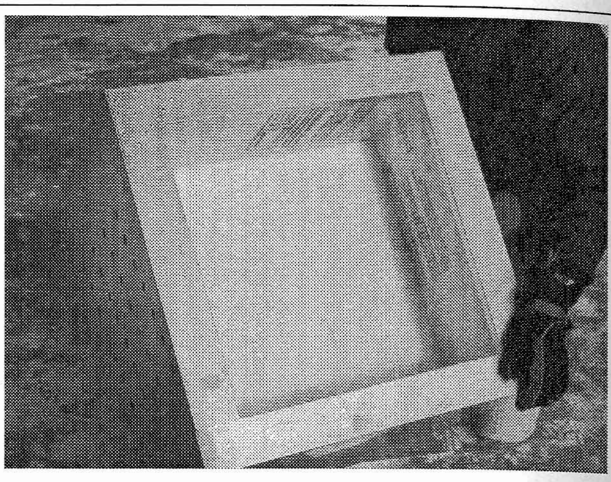

Figure 2. Laterally insulated box with base snow layer. The side of the box at the bottom of the photo is removable to facilitate crystal extraction.

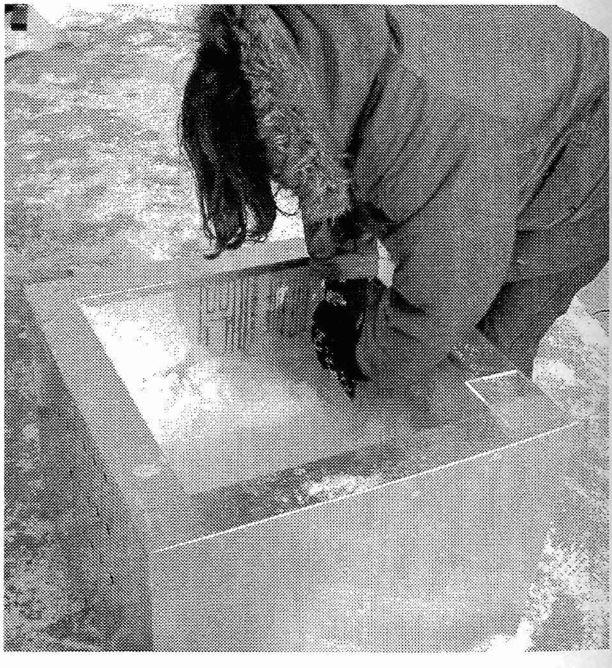

Figure 3. Spreading wet snow layer evenly onto dry snow base.

on readings every 30 seconds. The thermistors were calibrated to obtain an accuracy of 0.1°C.

The air temperature in the cold lab cycled between –7°C and –16°C every day to simulate a typical mid-winter diurnal cycle for the snow surface. The net radiant energy exchange at the snow surface was assumed to be minimal.

Crystals were extracted from the interface at the base of the slab and in the middle of the slab and were observed under 20x magnification and photographed with a microscope at 31x magnification. The most prominent and secondary grain types and sizes were classified according to Colbeck and others (1990).

There were some problems associated with the method. Forming the wet layer by spreading slush may have resulted in a wet layer with different characteristics than naturally occurring wet layers formed by rain, warm air and/or solar radiation. In the experiment started on 02-03-16, liquid water from the wet layer percolated down channels in the base layer and down the side of the box, reducing the latent heat in the wet layer. We experienced difficulty placing low-density dry snow onto the wet layer. After sieving, the density of the slabs varied from 138 to 339 kg/m^3 (mean 202 kg/m^3), which is approximately double that of many layers of fresh dry snow.

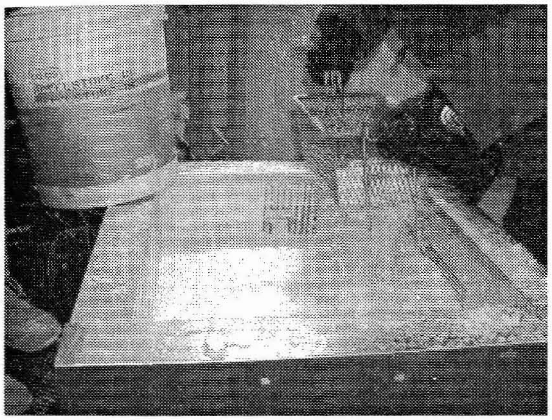

Figure 4. Sieving fresh snow onto the wet layer.

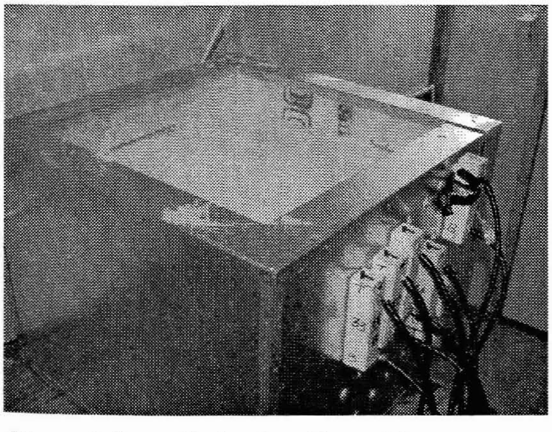

Figure 5. Laterally insulated box with thermistors placed to monitor temperature in air and in three-layer snow specimen.

4. Observations

For each of the seven experiments, Table 1 shows the length of the experiment, number of crystal observations during the experiment, selected properties of the wet layer and the slab, initial and final grain forms, elapsed time until the wet layer froze (i.e. until the last thermistor dropped below –0.5°C), maximum temperature gradient over a 30-minute period measured with thermistors placed 3 to 5 cm apart near the top of the wet layer, and the time to the observation in which facets were first recorded as the major grain type. For the wet layer, the water added is reported as the equivalent amount of rain in millimetres.

In each experiment, faceted crystals were observed at the interface and slab within 72 hours (Table 1). In two experiments, facets were observed at the interface and in the middle of the slab during the same observation. In the other five experiments, facets were first observed at the interface and then subsequently in the slab one or more observations later. For the experiment started on 2002-03-16, photographs of the crystals extracted from the interface show an increase in faceting over a period of 20 hours (Figure 6).

The maximum temperature gradient in all the experiments ranged from 11°C/10 cm to 23°C/10 cm, which is roughly 10 times the threshold usually associated with faceting (Colbeck, 1983).

5. Analysis

In Table 2, two properties of the wet layer (thickness and rain equivalent of added water) and two properties of the slab (thickness and density) are correlated with the time for the wet layer to freeze, the maximum temperature gradient and the time to observed faceting at the interface and in the slab.

Most of the correlations are not significant (significance level $p \geq 0.10$), in part because there were only seven experiments with a limited range of slab and wet layer properties. The time required for the wet layer to freeze positively correlated with the rain equivalent of the liquid water added to the wet layer (correlation coefficient $r = 0.82$, $p = 0.02$, Figure 7). The slab thickness negatively and weakly correlated with the maximum temperature gradient ($r = -0.70$, $p = 0.08$, Figure 8). Also, thickness of the wet layer negatively correlated with the time before facets were observed at the interface ($r = -0.71$, $p = 0.08$, Figure 9) and in the slab ($r = -0.78$, $p = 0.04$, Figure 9).

Table 1 Summary of cold laboratory experiments

Experiment			Wet layer			Slab		Grain form at interface (Colbeck and others, 1990)		Max TG[1]	Time to first obs. of facets[2]	
Start date 2002	Duration (days)	No. of obs.	Thickness (cm)	Equiv. rain (mm)	Time to freeze (h)	Thick-ness (cm)	Density (kg/m³)	Initial	Final	(°C/ 10 cm)	Interface (h)	Mid-slab (h)
02-14	6.9	6	1.5	4	4	6.5	203	/ 0.5-1, + 1-1.5	□ 0.5	16	24	72
02-21	8.7	7	3.5	7	11.5	14	143	+ 3-4, / 1-2	□ 0.5 / 0.5-1	11	25	40
03-11	4.8	3	2.5	8	9.5	6[3]	201	• 0.5-1	□ 0.5-0.8	20	51	51
03-16	4.8	6	7.5[4]	21	23	5.5	141	+ 1, / 0.5-1	□ Λ 1-1.5	21	7	20
03-21	3.7	6	9	11	8	12	248	/ 0.5-1, □ 0.5	□ 0.5-0.8	13	2	2
03-25	1.9	4	4	11	10	8	339	• 0.5-1	□ 0.5-0.8	23	5	2
03-27	3.8	8	6	15	9.5	6	138	/ 1, + 1-1.5	□ 0.3-1	15	2	20

[1] Maximum temperature gradient between a thermistor placed in the wet layer and one 3-5 cm above in the dry layer.

[2] Time to first observation of facets in dominant grain form.

[3] Snow was moist when sieved.

[4] Percolation channels observed below wet layer.

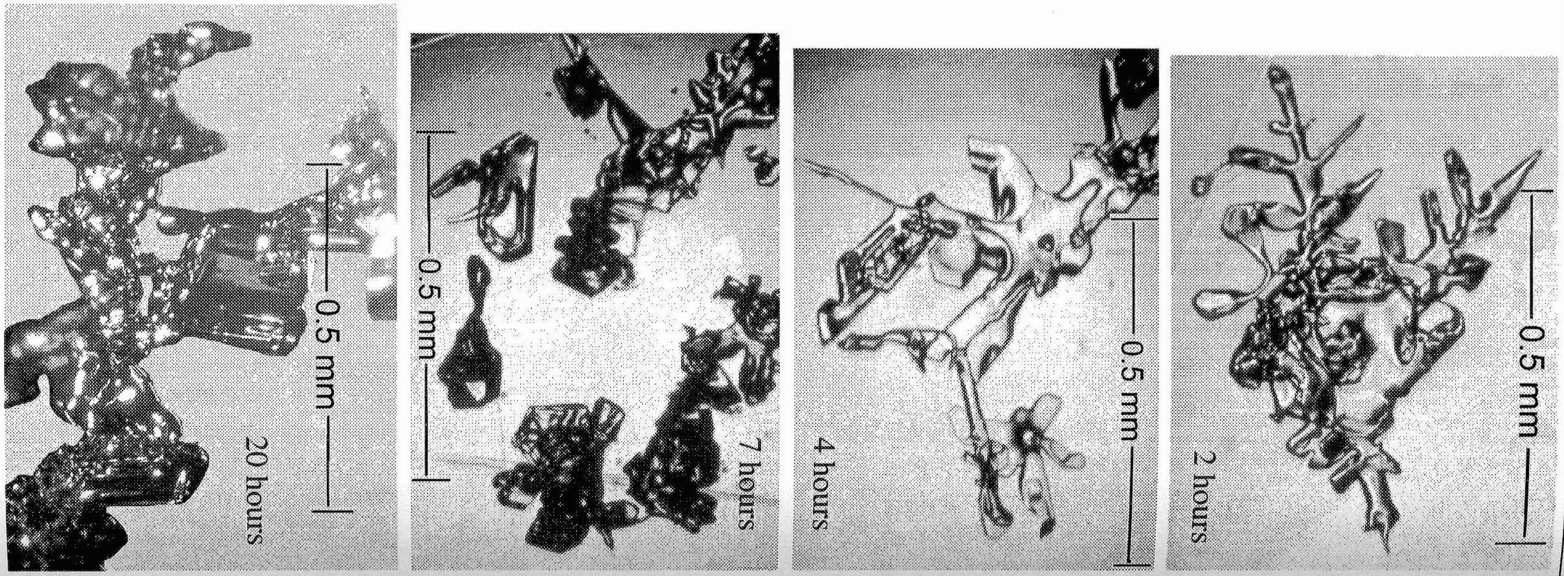

Figure 6. Photos of snow grains after 2 to 20 hours from interface of experiment started 2002-03-16. Faceting of grains over time is apparent.

Table 2 Coefficients for correlations between layer properties and effects

	Effects			
	Time for wet layer to freeze	Max. temp. grad.	Time to facet	
Layer properties			Interface	Slab
Wet layer				
Thickness	0.46	-0.12	*-0.71*	**-0.78**
Equiv. rain	**0.82**	0.35	-0.60	-0.64
Slab				
Thickness	-0.19	*-0.70*	-0.09	-0.21
Density	-0.37	0.45	-0.16	-0.39

Bolded correlation coefficients indicate significance level $p \leq 0.05$

Italicized correlation coefficients indicate significance level $0.05 < p \leq 0.10$

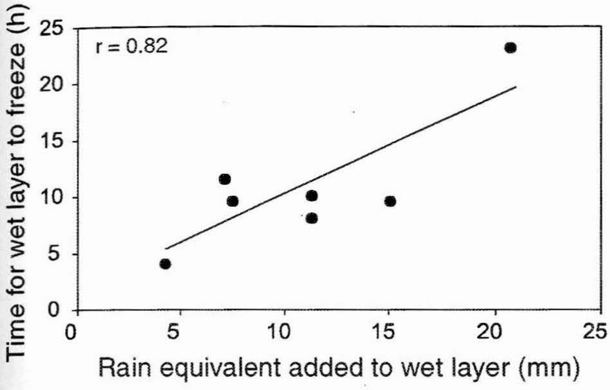

Figure 7. The time required for the wet layer to freeze increased with the amount of liquid water applied.

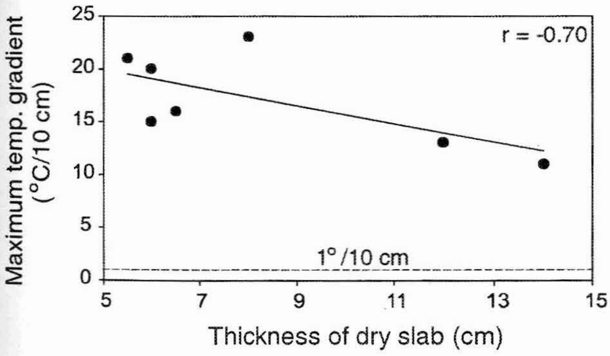

Figure 8. The maximum temperature gradient measured over a 30-minute period decreased with the thickness of the dry slab overlying the wet layer. The measured maximum temperature gradient greatly exceeded the commonly used threshold of 1°/10 cm.

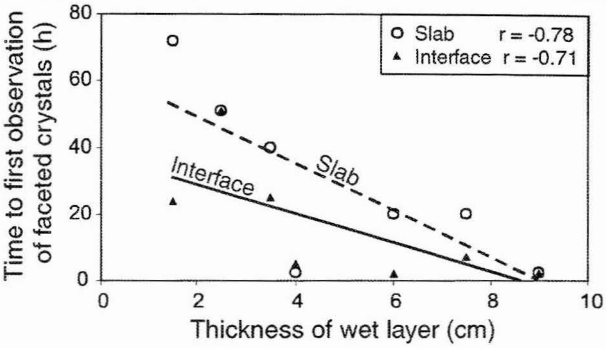

Figure 9. The elapsed time until faceted crystals were first observed at the interface and in the slab decreased with increased thickness of the wet layer.

6. Conclusions

When a cool thin layer of dry snow overlies a wet snow layer, there is a strong temperature gradient – often sufficient for faceting – in the lower part of the dry layer until the wet layer freezes.

In all seven experiments in which a thin layer of dry snow overlying a wet snow layer was subjected to subfreezing air temperature:

- The maximum magnitude of the temperature gradient near the base of the dry slab was temporarily 10 times the commonly accepted threshold for faceting.
- Facets formed at the interface within two to 51 hours, and in the thin overlying slab within two to 72 hours.

When comparing the experiments, the following trends were observed:

- The wet layer was slower to freeze in experiments in which more water was added to the wet layer.
- The maximum magnitude of the temperature gradient was greater in experiments in which the dry slab was thinner.
- Facets formed faster at the interface and in the overlying slab in experiments in which the wet layer was thicker.

We did not observe a significant effect of slab thickness or slab density on the time until facets were observed, but the range of these properties and the number of experiments were limited.

7. Application

The formation of major layers of faceted crystals that form in dry snow over a freezing wet layer can, in some cases, be predicted from a suitable located weather station (Jamieson and others, 2001b).

Areas of a mountain range, or of a start zone, that acquire more liquid water by rain (including wind-blown rain) or due to the exchange of radiant energy are, if overlain by cool dry snow, more likely to develop a weak layer of facets on a crust than areas that acquire less liquid water. Also, areas where the overlying dry snow was thinner while the underlying layer was wet may be more likely to develop a facet/crust combination than areas where a thicker dry layer overlaid a similar wet layer. The resulting spatial variability of stability can persist for weeks. An understanding of the conditions associated with near-wet-layer faceting may help site selection for profiles and snowpack tests, for explosive placement and intentional skier triggering (of small avalanches), as well as for routes to avoid. However, many other factors and observations are important for site and route selection.

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9. References

Armstrong, R.L. 1985. Metamorphism in a subfreezing, seasonal snowcover: The role of thermal and water vapor pressure conditions. PhD dissertation. Dept. of Geography, University of Colorado, 175 pp.

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* 30(2), 193-199.

Colbeck, S.C. 1983. Theory of metamorphism of dry snow. *Journal of Geophysical Research* 88(C9), 5475-5482.

Colbeck, S.C. and B. Jamieson. 2001. The formation of faceted layers above crusts. *Cold Regions Science and Technology* 33(2-3), 247-252.

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. 2001a. Case study of a deep instability and associated dry slab avalanches. Proceedings of the International Snow Science Workshop in Big Sky, Montana October 2000. American Avalanche Association, P.O. Box 1032, Bozeman, MT, USA, 101-108.

Jamieson, B., T. Geldsetzer and C. Stethem. 2001b. Forecasting for deep slab avalanches. *Cold Regions Science and Technology* 33(2-3), 275-290.

Schweizer, J. and B. Jamieson. 2001. Snow cover properties for skier-triggered avalanches. *Cold Regions Science and Technology* 33(2-3), 207-221.

Stethem, C. and R. Perla. 1980. Snow-slab studies at Whistler Mountain, British Columbia, Canada. *Journal of Glaciology* 26(94), 85-91.