THE MICROSTRUCTUAL EFFECTS OF KINETIC GROWTH METAMORPHISM IN A LAYERED SNOW STRUCTURE

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Abstract

Faceted snow near a hard crust often poses a dangerous problem for avalanche forecasters. producing a persistent weakness where the avalanches are difficult to predict and the avalanche cycle lasts for months rather than days or weeks. We conducted a series of laboratory experiments designed to investigate the structure of faceted snow near an ice crust. We created an artificial ice layer between two samples of natural snow. Then we subjected the samples to a large temperature gradient for five days. Serial sectioning and three-dimensional reconstruction of the samples showed drastic changes in bonding above and below the ice layer. The results of this study may help to explain patterns in avalanche activity that have been observed in the field and have implications for local and regional avalanche forecasting.

KEYWORDS: snow microstructure, kinetic growth metamorphism, facets near crusts

1. Introduction

Ice crusts and associated weak layers create dangerous conditions in the mountain snowpack. For example, on January 6th, 2002 in the Wasatch Mountains of Utah, a combination of rain and rime plastered the snow surface with a thin layer of ice. This widespread ice crust sat undisturbed for a week before being buried by a series of small snowstorms. On January 27th it started snowing again, but this time it didn't stop until more than 100 cm (40 in) of snow and 75 mm (3 in) of water had fallen in a 36-hour period. This storm triggered an impressive natural avalanche cycle with numerous northeast aspects above 2700 m ASL (9,000 ft) releasing during the storm. These avalanches generally broke 1.2 m (4 ft) deep and, in extreme cases, 400 m (1300 ft) wide. Most slides released on faceted snow grains directly above or below the January 6th ice crust. At least 23 human triggered avalanche incidents occurred in the three weeks that followed the storm, and many of these avalanches broke 30 -100 m (100 -300 ft) above the victims, or did not release until several people had already crossed the slope. As an indication of the difficulty in forecasting this layer, three of the people caught in these slides were experienced avalanche workers, and one of these people was buried and killed.

The presence of a crust or large density change in a seasonal snowpack significantly affects heat and mass transfer through the ice lattice. While it has been noted that faceted growth or kinetic metamorphism can be prevalent above or below a buried crust layer (McClung and Schaerer, 1993), little is known about how crust layers influence the adjacent morphology or what conditions enhance faceting above, rather than below a dramatic density change. Previous researchers have proposed theoretical explanations (Colbeck and Jamieson, 2000; Colbeck, 1991) and used models to investigate the influences of snow density and in turn thermal conductivity gradients (Adams and Brown 1982; Adams and Brown 1988; Adams and Brown 1990; Sato et. al 1994). However, a detailed observational study of processes occurring near these crust layers has not yet been undertaken. Faceted snow grains near a buried ice crust are of particular interest to avalanche workers because avalanches release on both faceted snow layers and near large density changes.

2. Methods

We performed a series of laboratory experiments to observe the change in thermal properties and microstructure of snow during kinetic metamorphism. We collected blocks of

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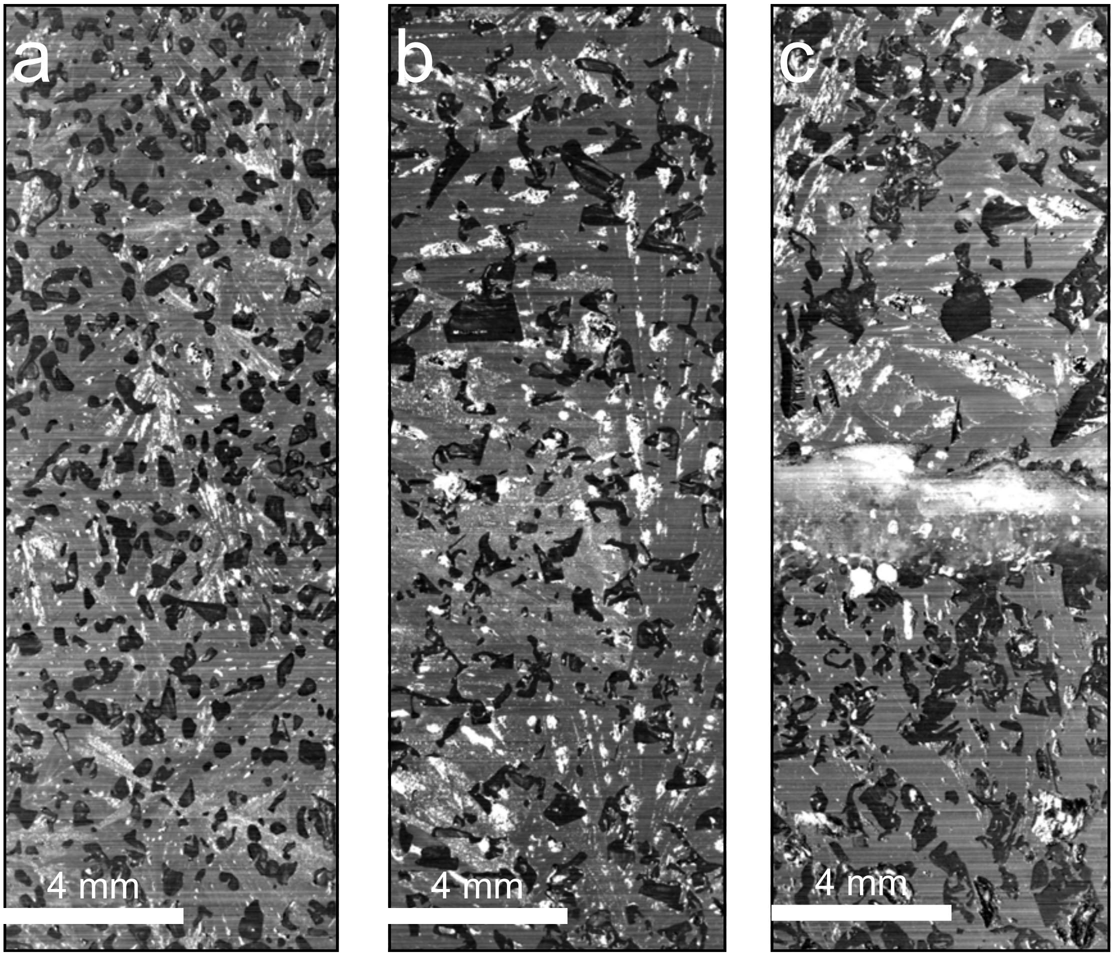

Figure 1: Surface sections of the Initial (a), Control (b) and Treatment (c) samples from one laboratory experiment. a) Initial snow with faceted crystals (class 4c) several structures show and eroding top and a growing (faceted) bottom. b) Depth hoar crystals (class 5a). Due to the hollow nature of most structures, many are only partially visible. Again, many of the tops are sublimating, while the bottoms are faceted and growing. c) Typical depth hoar columns (class 5a) have formed on the bottom of the ice layer. They seem to grow out of the ice layer, but in fact condense on the ice layer. Fewer structures are attached to the upper surface of the ice layer because the surface is generally sublimating

natural snow from sites in the northern Colorado Rocky Mountains and transported them to the cold laboratory in the USDA-Rocky Mountain Research Station in Fort Collins, Colorado. The snow blocks generally consisted of mixed faceted grains (4c) or broken new snow particles (2a) (Colbeck et al., 1990). The density of the blocks ranged from 150 to 300 kg/m^3. Each experiment consisted of two snow samples, a *Control* and *Treatment* sample. The *Control* sample was an unaltered block of snow from the field (11 cm x 11 cm x 11 cm). The *Treatment* sample contained a thin layer of ice (2 – 4 mm) sandwiched between two smaller blocks of snow (total dimensions 11cm x 11 cm x 11 cm). We placed heat flux sensors (TNO-43PU) on the top and bottom and inserted a vertically oriented array of thermocouples (Type T AWG 30) into each sample. Inside a cold laboratory (-17±4ºC), we placed both samples onto a heat exchange system (-1±0.5ºC) to induce a unidirectional vertically oriented temperature gradient (70 – 110 ºC/m). We also cast a sample of snow from the same block with dimethyl phthalate to record the initial microstructure (Perla, 1982).

The sample remained in a steady-state thermal environment for five days. At the end of this period we cast both the *Treatment* and *Control* samples in dimethyl phthalate and measured the exact location of the ice layer and each thermocouple. We shipped the cast samples to the Swiss Federal Institute for Snow and Avalanche Research (SLF) in Davos, Switzerland. We used serial sectioning techniques to collect vertical surface sections from each sample. From these surface sections we were able to measure the density and specific surface area of each sample (Howard and Reed, 1998) as well as create three dimensional models of the microstructure. These methods allowed us to observe the initial and final microstructure of the snow samples and the thermal environment during metamorphism.

3. Results and Discussion

During this series of experiments we collected a large amount of quantitative data including over 300 GB of image data. In addition we made some interesting qualitative observations. We were able to maintain steady-state thermal conditions, within a reasonable tolerance, throughout each experiment. The heat flux and temperature gradient quickly reached constant values. Although we observed a net loss in heat flux in each sample (5-20%), the loss remained constant during each experiment. In most cases we did not observe a consistent perturbation of the temperature field from the ice layer. An ice layer is highly conductive compared to the surrounding snow. However, our layer was probably too thin and our temperature measurements too coarse to observe any disturbance.

We observed an increase in the thermal conductivity of the snow during each experiment. This observation is consistent with other observations of the temporal evolution of thermal conductivity during metamorphism (Schneebeli and Sakratov, 2004). The increase was approximately 20% over the course of five days. This change is likely due to the reorganization of the structure as it adjusts to the applied temperature gradient. Many of the bonds between ice particles sublimate and new bonds grow, oriented in a direction that allows heat to move more efficiently through the snow structure.

Analysis of the quantitative data is ongoing; here we present a few interesting qualitative results. Figure 1 shows the initial and final microstructure from one experiment. The density of the snow in this experiment was 246 kg/m^3, and remained near this value throughout the experiment. The original snow sample was composed of mixed faceted and rounded grains (4c) (Figure 1a). By the end of the experiment the particles developed large facets with many hollow structures (Figure 1b and 1c). Although the structure in the *Control* sample is quite anisotropic, the size and shape of the particles are quite similar in the surface section (Figure 1b). In the *Treatment* sample, faceted formations grew on the bottom of the ice layer forming a branch-like structure. In this example the ice layer is composed of mostly clear ice. The upper surface of the ice layer is smooth and very few of the structures are attached to the layer (Figures 1c and 2). The particles above the ice layer have large facets and there are "holes" or areas with very little ice directly above the ice layer. We observed "holes" in nearly every sample. Examination of the three-dimensional reconstruction of the ice matrix showed that the holes or voids were discrete and repetitive across the surface above the ice layer. Figure 2 shows a *Treatment* sample from an experiment with an

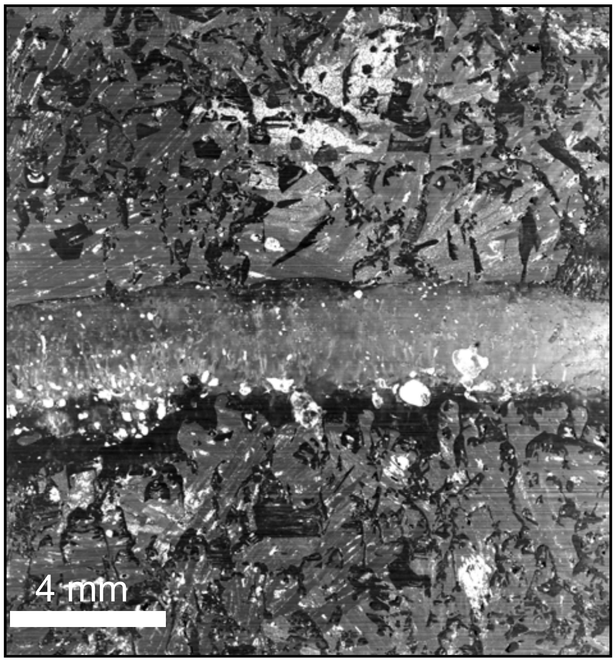

Figure 2: A vertical surface section imaged through a Treatment sample. Each side of the image is 20 mm in length. In this image the ice is black, the ice layer is gray and shiny and the pore filler material is also gray. Bubbles of air in the ice layer and areas that did not completely fill with the pore filler are white. Below the ice layer many cupped structures are growing. On top of the ice layer very few cups touch the ice layer, but hole-like structures have formed. These cavities are up to 4 mm wide and about 1-2 mm high. They form a microstructure which is very fragile and prone to fracture propagation on the microscale.

especially thick ice layer. In this sample the largest facets formed directly above the ice layer and the particles quickly become smaller with increased distance away from the ice layer. The length of the large gradient in particle size was less than a few millimeters.

In nature it is unlikely that a constant unidirectional temperature gradient would persist in a snow layer for multiple days. The weak layers that produce avalanches often from near the snow surface where the direction of the temperature gradient may switch during day and night cycles. This could cause the cavities we observed to form on either the upper or lower side of an ice crust. Thus the most likely fracture surface could be on the top or bottom of the crust, depending on the orientation of the temperature gradient, and switch positions over the course of weeks or months.

4. Conclusion

The results of these experiments emphasize the importance of microstructure on the physical properties of snow. The ice layer did not affect the bulk temperature profile of the snow samples. However, it had a large effect on the microstructure that developed during metamorphism. This effect occurred on and near the interface of the two layers and was limited to within one or two grains of the interface. A microstructural change of this magnitude is relatively easy to observe in the laboratory, but could be very difficult to detect in the field.

Along the lower surface of the ice layer, preferential areas grew from round bumps into large angular facets by vapor deposition. The upper surface of the ice layer became smooth and water mass sublimated into the pore space above. This indicates a net deposition below the ice layer and net erosion above. This process produced a well-bonded and probably strong connection below the ice layer and an area with much fewer bonds (and therefore mechanically weak) above. This indicates that in the presence of a large temperature gradient, increased bonding and greater mechanical strength will occur on the warm side of an ice lens, while the cold side will stay or become weak. The effect of the ice layer may be compounded by the size difference of the particles in adjacent layers of snow (Colbeck, 2001). This is consistent with some field observations (Greene and Johnson, 2002). Although this conceptual model may be difficult to confirm in the field, it can benefit avalanche forecasting efforts. By using this conceptual model, measuring the bulk temperature gradient and conducting mechanical strength tests, avalanche workers may be better equipped to explain their observations and anticipate the onset and decline of avalanche cycles.

5. References

Adams, E.E., and R.L. Brown, 1982: Further results on studies of temperature-gradient metamorphism. *Journal of Glaciology*, **98**, p.205-210.

Adams, E.E., and R.L. Brown, 1988: On the effect of strong density layering on Metamorphism of seasonal snowcover. *Proceedings of the International Snow Science Workshop*, Whistler, Canada, October 12-15, 1988, p.37-40.

Adams, E.E., and R.L. Brown, 1990: A mixture theory for evaluation heat and mass transport processes in nonhomogeneous snow. *Continuum Mechanics and Thermodynamics,* **2**, 31-63.

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

Colbeck, S. C., 2001: Sintering of unequal grains. *Journal of Applied Physics*, **89**, 4612–4618.

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

Colbeck, S. C., E. Akitaya, R. Armstrong, H. Gubler, J. Lafeuille, K. Lied, D. McClung, and E. Morris 1990:The International Classification for Seasonal Snow on the Ground. Intentional Commission on Snow and Ice. International Association of Science and Hydrology, Wallingford, U.K. pp.23.

Greene, E., and G. Johnson (2002), Characterization of a deep instability. *Proceedings of the International Snow Science Workshop*, Penticton, British Columbia, Canada, 491–498.

Howard, C.V., and M.G. Reed, 1998: *Unbiased Stereology: Three-dimensional measurement in microscopy*. Springer, New York, pp. 246.

McClung, D., and P. Schaerer, 1993: *The Avalanche Handbook.* The Mountaineers, Seattle, p.59.

Perla, R., 1982: Preparation of section planes in snow specimens. *Journal of Glaciology*, **28**, 199-203.

Sato, A., E.E. Adams and R.L. Brown. 1994: Effect of microstructure on heat and vapor transport in snow composed of uniform fine ice spheres. *Proceedings of the International Snow Science Workshop*, Snowbird, USA, October 1994, p.176-184.

Schneebeli M., Sokratov S.A., 2004:Tomography of temperature gradient metamorphism of snow and associated changes in heat conductivity. *Hydrological Processes* **18**, 3655-3665.