# Morphology of crystal growth and grain bonding in snow

E. E. Adams* and D. A. Miller
Montana State University, Bozeman, Montana

**Abstract:** Microstructure is of paramount importance to the structural stability of a snowpack. We have scrutinized microstructure at the grain and bond scale with the aid of optical and scanning electron microscopes (SEM). SEM images of fractured samples of equilibrium growth form snow distinctly demonstrate that failure occurs at the grain boundary bonds in this type of snow. Earlier laboratory studies of large flat ice crystals placed in a supersaturated vapor environment have demonstrated that numerous crystals developed across the surface and all displayed the same crystallographic orientation as the parent crystal. This led to a dominant grain growth theory for a kinetic growth snow layer. In this study, SEM images of depth hoar crystals grown in a snowpack expose a very complex geometry near the kinetic crystal bond sites, which smoothly transition to the large striated crystal. It is suggested that these bond areas are comprised of less optimally oriented crystals, which nucleated on the parent grains, but have had their growth truncated by the dominant growth grains. Stress concentrations and potentially small bond to grain ratios imply a weaker structure when compared to SEM images of an equilibrium morphology snowpack. Primary nucleation sites in snow are conjectured to be at high-energy areas associated with grain boundaries.

**Keywords:** snow and ice, snow crystal, snow crystal growth, snow crystal structure, snow metamorphism

## 1 Introduction

In the case of dry snow, it has been well established that in the presence of a significant temperature gradient (nominally taken as ~10 to 25 °C/m (Akitaya,, 1974, Armstrong, 1980; Marbouty,1980;Colbeck, 1983a, 1983b) a snowcover will metamorphose on the microstructural scale into what is termed the kinetic growth form. The outcome is a snow layer usually of low structural integrity composed of highly faceted crystals. In the absence of such a gradient the microstructure tends toward a configuration of rounded sintered grains and a macroscopic strengthening of the snowcover (Colbeck, 1983a). In dry snow, vapor diffusion is an important driving mechanism in either of these processes.

In a recent study Adams and Miller (accepted) have demonstrated that kinetic growth crystals deposited onto an ice substrate will adopt the orientation of the parent crystal. In that study, the substrate used was obtained from Antarctic lake ice, since it is composed of very large crystals, which were needed for the experiment. Figure 1 shows examples of kinetic growth crystals that developed on parent crystals with c-axis parallel to the growth direction (hexagonal face) and with c-axis normal to the growth direction (rectangular face). Note that numerous individual crystals have formed on the single large crystal substrate. Kinetic growth crystals that form deep in a snow pack, often called depth hoar, are frequently described as striated cup shaped crystals (Akitaya, 1974). It is apparent from the study on crystals grown on an oriented ice substrate (figure 2) that the hollow face of these hopper type crystals (Lock, 1990) may occur on either the basal (hexagonal) or prism (rectangular) face (Adams and Miller, accepted).

In the present investigation we observe the structure of intergranular bonding in snow by comparing the equilibrium and kinetic growth bond morphologies. Bonding is very important to the macroscopic mechanical and thermodynamic properties of snow. Sintering processes, which take place in equilibrium metamorphism (Colbeck, 1980, Colbeck 1998, Adams and Miller, 2001), have received considerably more attention than the intergranular connections that occur during kinetic development, perhaps due to the difficulty of observation. Kinetic growth morphology is considered in light of the oriented crystal growth studies since it pertains to metamorphism and the macroscopic physical properties of depth hoar. The initial crystal morphology during nucleation may influence how the intergranular connections between facets develop.

## 2 Methodology

Conditions required for depth hoar crystal growth have been studied extensively (Trabant and Benson, 1972; Akitaya, 1974; Marbouty, 1980; Sturm and Benson, 1997), however, the crystal interconnections or bonds have not been comprehensively considered or observed in detail. In the present study, natural snowpack samples were removed intact from the field. Dry natural snow that had not been subjected to melt-freeze cycling was collected from the Bridger Range near Bozeman, MT, USA. One sample was subjected to a near "equi-temperature" condition by storing it in an insulated container inside a -12°C cold room. Minimizing temperature gradients encouraged the equilibrium growth form. Another sample was subjected to a controlled temperature gradient (35°C/m) to produce the kinetic form. To gain additional insight to the grain connections, these morphologies were examined in a JEOL 6100 scanning electron microscope (SEM) with a cryogenic chamber (-170 °C, using no surface coating). The SEM allows for the detailed imaging of the surface features of the ice, which are often obscured by the transmitted and scattered light encountered when using optical techniques.

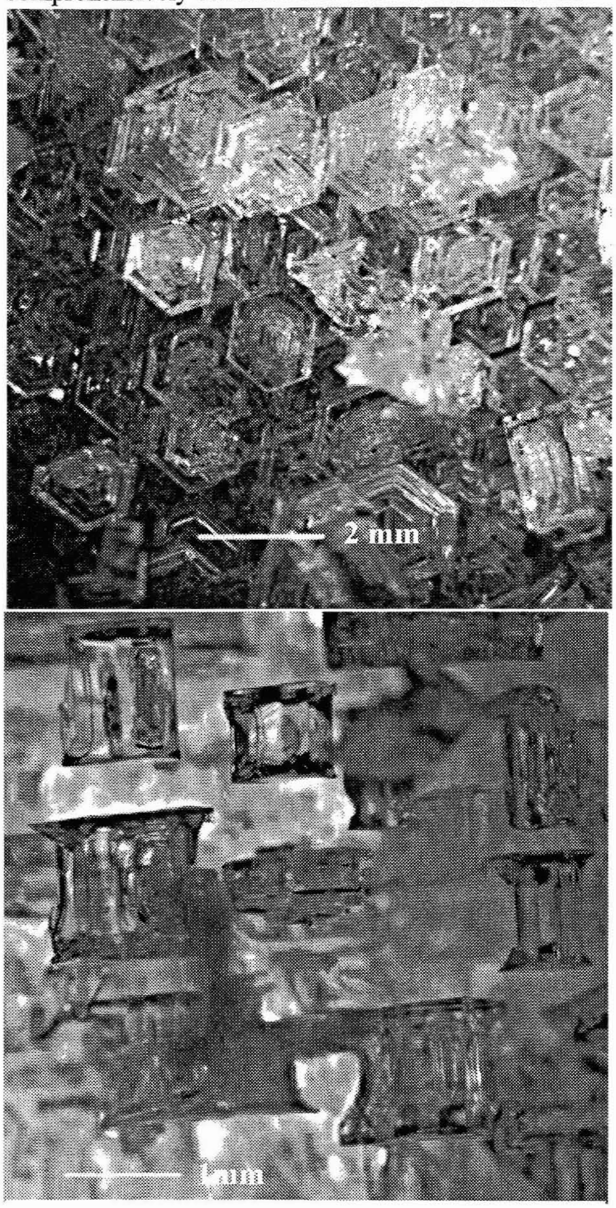


*Figure 1 Multiple crystals nucleated and developed from supersaturated vapor onto large flat, oriented crystals. New crystals take on the orientation of the parent. The upper figure shows the hexagonal shape of the crystallographic basal face, where the c-axis is normal to the page. In the bottom image the c-axis lies in the plane of the page (From Adams and Miller (accepted))*

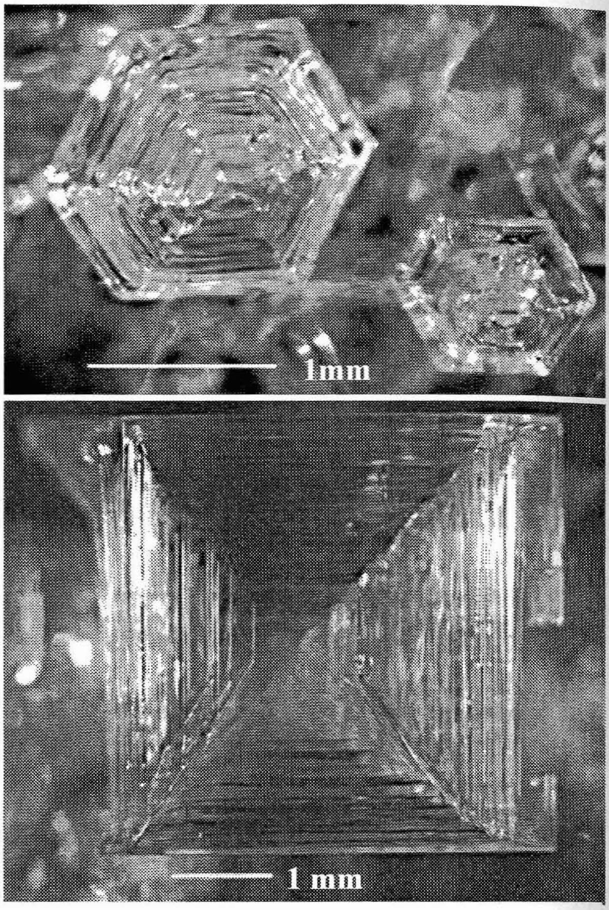


*Figure 2 Striated kinetic growth hopper crystals may develop with a hollow basal or prism face as they grow on a substrate crystal. (From Adams and Miller (accepted))*

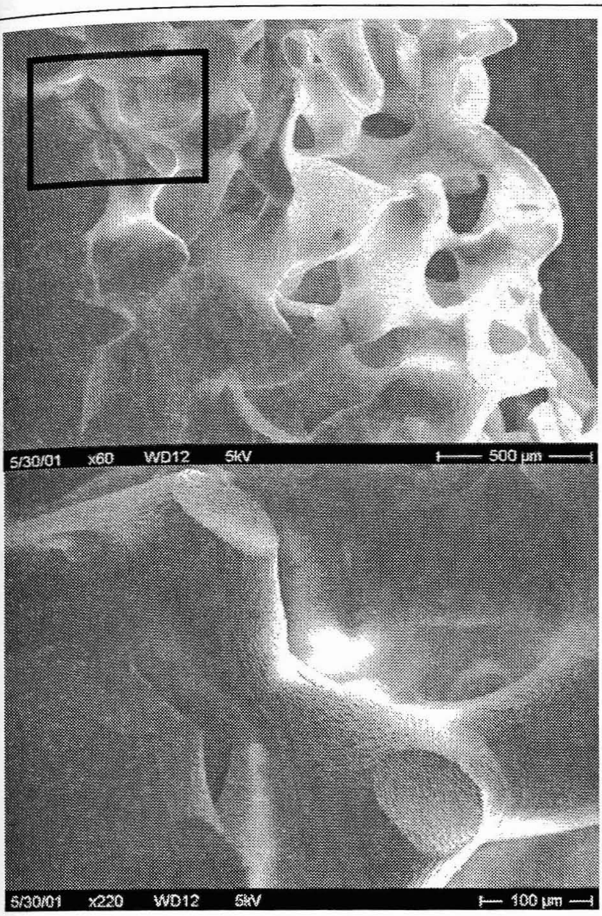


*Figure 3 Scanning electron microscope (SEM) image of a typical equilibrium form snow. Enlargement of the box in the upper image, displayed in the lower, shows the cleanly fractured bonds*

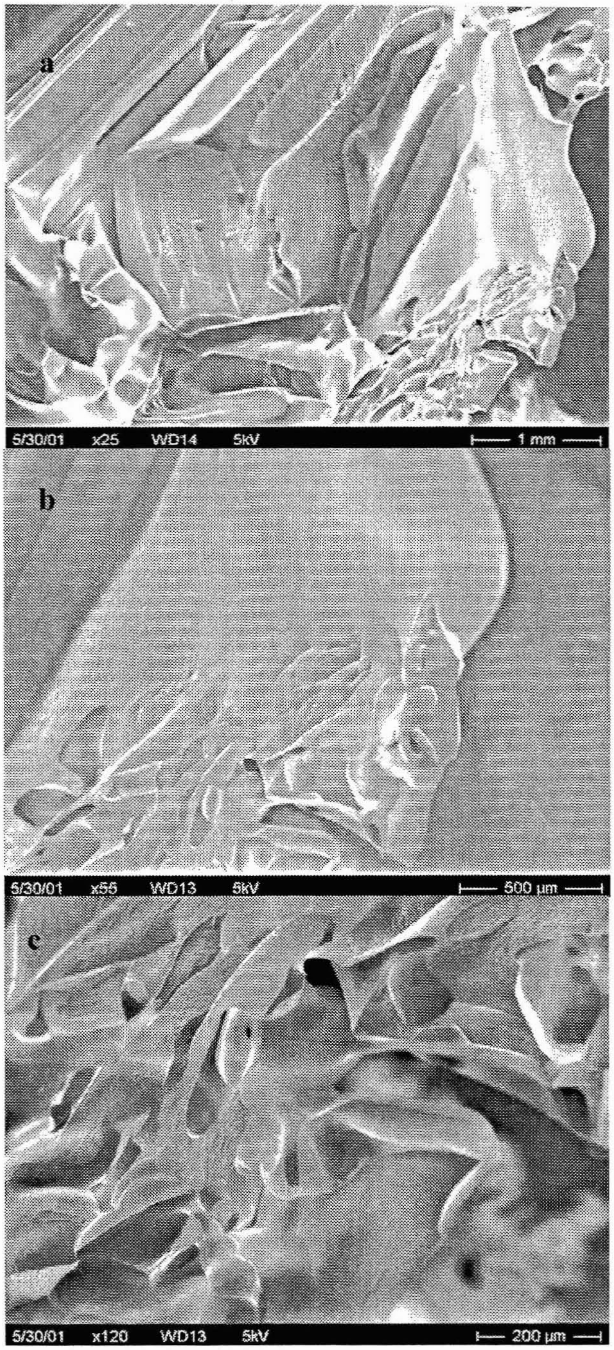


*Figure 4 Scanning electron microscope (SEM) images of the connections between large depth hoar crystals. In (a) the striations of the larger depth hoar crystal is apparent starting in the upper left. Progressing to (b) and (c) with increasing magnification features what may be truncated kinetic growth crystals that had nucleated but were at a disadvantage to the larger crystals that eventually dominated.*

## 3 Results

Observations on the bonding between grains using the SEM are presented. The equilibrium form in Figure 3 exhibits the characteristic smooth grains with convex bond connections. Grain boundaries are clearly visible. An enlargement of the broken bonds is also presented in the figure to emphasize the importance of considering not only crystal growth, but also grain interconnections. Figure 4 presents images of the bond or transition region of the kinetic growth depth hoar crystals. Geometrically complex bonds that transition to relatively smooth striated facets, such as in this figure, were persistently present in this snow.

## 4 Discussion

In earlier work Adams and Miller (accepted) hypothesized that when the temperature gradient becomes sufficient to initiate kinetic growth, numerous crystals would nucleate on the existing grains taking on the orientation of that grain. Depending on conditions, crystals of a particular orientation will be at an advantage, thus crowding out less optimally oriented ones, resulting in a dominant crystal type and orientation within a snow layer. We extend the hypothesis here to conjecture that many of the original grains likely remain, ensconced under the conglomeration of truncated kinetic growth crystals. Multiple abridged crystals may manifest themselves at the "attachment" locations or bonds of depth hoar crystals, as seen in Figure 4.

Figure 3 clearly reveals several cleanly fractured bonds of equilibrium form snow. Snow strength should be a strong function of the relative bond to grain size ratio and grain coordination number. Similarly, the interconnections between depth hoar grains may provide insight into the strength and stability of snow composed of these faceted crystals.

The images in Figure 4 display the intricate bond region of kinetic growth crystals. Note that these kinetic growth bonds are not small relative to the bonds of the equilibrium form. The transition from the faceted grain to these attachments or bonds is clearly visible in Figure 4 where the striated grain is contrasted to the geometrically complex bonds. Even though these connections are relatively large, they may be weak since they are not continuous and the irregular structure will induce stress concentrations. In addition, the bond to grain size ratio may be much less than for the equilibrium form and the grain coordination number will also likely be smaller as the structure will tend to metamorphose into a transversely isotropic arrangement composed of ice crystal chains and channeled pores (Trabant and Benson, 1972; Akitaya, 1974; Adams et al, 1996).

In the recrystallization of metamorphic rocks, there is a higher potential for heterogeneous nucleation at sites of high energy such as grain boundaries, dislocations and strained areas and it is favored at corners, triple points or high angle boundaries (Spry, 1969). High energy sites in an equilibrium snowpack would include grain boundaries, grain boundary grooves (Colbeck,1998) and grain boundary ridges (Adams and Miller, 2001). Furthermore, strain is likely high in these regions, which may be inferred from the failure planes demonstrated in Figure 3. Consider also that mass flux near negative radius of curvature regions associated with bonds is locally high due to the vapor pressure gradient, which would enhance the mass supply to these potential nucleation sites. This leads to the conclusion that the kinetic growth may be preferential near the necks and bonds in a sintered snowpack.

# 5 Conclusion

Microscopic observations of the regions near the attachment points of depth hoar crystals reveal a geometrically complicated region and may provide evidence of numerous truncated kinetic growth crystals, which nucleated on the original grains. These highly irregular bonds are prone to stress concentrations and may provide a relatively small bond to grain ratio when compared to microscopic observations of the smooth bonds apparent in the equilibrium metamorphic form. This provides some insight to the relative strengths of these snow types. However, these detailed images of bonds present in kinetic growth snow reveal an exceedingly complex geometry that offers significant scientific challenges before we can confidently comprehend the physics of formation and the implications of these features.

**Acknowledgements:** The research reported here was supported by the Geosciences Program of the Army Research Office under grant DAAG55-98-1-0018 and National Science Foundation grant OPP-9815512.

## References

Adams, E.E., Vandervoort, D.C., Edens, M.Q. and Lang, R.M., 1996. Ice grain orientation in processed snow. *Snowsymp-94 Proceedings - International Symposium on Snow & Related Manifestations*, Snow & Avalanche Study Establishment, Manali (H.P.) India, pg 96-102.

Adams, E.E., D. A. Miller and R.L. Brown, 2001. Grain boundary ridge on sintered bonds between ice crystals. *Journal of Applied Physics*, **90**(11), 5782-5785.

Adams, E.E and Miller, D.A.,(accepted). Ice crystals grown from vapor onto an oriented substrate: Application to snow depth hoar development and gas inclusions in lake ice. *Journal of Glaciology*.

Akitaya, E., 1974. Studies on depth hoar. *Contributions from the Institute of Low Temperature Science.* **26**(Series A), 1-67.

Armstrong, R.L., 1980. An analysis of compressive strain in adjacent temperature-gradient and equi-temperature layers in a natural snow cover. *Journal of Glaciology*, **26**(94), 283-289.

Colbeck, S.C., 1980. Thermodynamics of snow metamorphism due to variations in curvature. *Journal of Glaciology*. **54**(94), 291-301.

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

Colbeck, S.C., 1983(b). Ice crystal morphology and growth rates at low supersaturations and high temperatures. *Journal of Applied Physics*, **54**(5), 2677-2682.

Colbeck, S.C., 1998. Sintering in a dry snow cover. *Journal of Applied Physics*, **84**(8), 4585-4589.

Gow, A.J. and D. Langston, 1977. Growth history of lake ice in relation to its stratigraphic, crystalline and mechanical structure. *CRREL Report 77-1*. Cold Region Research and Engineering Laboratory.

Lock, G.S.H., 1990. *Growth and decay of ice*, Cambridge University Press.

Marbouty, D., 1980. An experimental study of temperature-gradient metamorphism. *Journal of Glaciology*, **26**(94), 303-312.

Spry, A., 1969. *Metamorphic Textures*, Pergamon Press Ltd., Oxford.

Sturm, M. and C.S. Benson, 1997. Vapor transport, grain growth and depth-hoar development in the subarctic snow. *Journal of Glaciology*, **43**(143), 42-59.

Trabant, D. and C. Benson, 1972. Field experiments on the development of depth hoar. *Geological Society of America Memoir,* **135**, 309-322.