THE BASIC IDEAS BEHIND SNOW METAMORPHISM

by **S. C. Colbeck**
CRREL
72 Lyme Road
Hanover NH 03755-1290 USA

ABSTRACT

The basis for thinking about snow metamorphism has evolved from a combination of field observations, laboratory experiments and theory. The results are synthesized here in a qualitative manner to provide a basic understanding of how and why different snow grains evolve in the seasonal snow cover. The basic shapes can be understood readily but there are many transitional steps among the basic shapes that complicate identification and understanding. When a high energy input occurs it drives the grains away from the simplest shapes and towards more complicated shapes. This accounts for the progressively more complicated shapes that occur in dry snow as the temperature gradient increases.

I. INTRODUCTION

Snow is a highly variable material which has so many different grain shapes that we can think of it as being many different materials. Unfortunately, there are not just distinct classes of snow grains, but there are often intermediate shapes between the basic classes. Thus the fundamental forms or shapes can be simply characterized or classified, but other shapes occur frequently.

Figure 1 is a representation of the "snow-ice-water cycle" and includes two basic concepts about snow. First, snow is either wet or dry, that is it either contains liquid water in its pores, or it is too cold to contain liquid water. Second, each category, wet and dry, can be divided into subcategories depending on grain shape, and therefore can be divided into the different conditions or processes which give rise to the different shapes.

The many basic shapes of snow grains arise from the great variety of thermal conditions experienced by snow covers. The simplest way to think about these shapes is the fourth row in Figure 1: two boxes for wet, a shared box between wet and dry, and two boxes for dry snow. However, there are transitional shapes between the two basic boxes in dry snow and, the basic shape of a melt-freeze particle changes each time it goes through a melt-freeze cycle.

The purpose here is to give qualitative explanations of the various shapes found in the seasonal snow cover, since the shapes affect the important material properties. Properties of dry snow like density or strength span the spectrum between those of ice and air. However, for properties like albedo which are controlled by grain size and shape, the spectrum is shifted because both ice and water have much lower albedos than snow. For the mechanical properties we mostly care about the bond strength which is predominately controlled by bond size and number density. Bond size, in turn, is controlled by the conditions of growth described below. In particular, we want to know when bonds develop, when they disappear, and what factors control the rate and extent of their development.

First the basic shapes are described, then the mixed shapes, then the environmental influences on metamorphism, and finally the physical processes that are involved. Thus we will first describe the shapes we see, then what the outside forces are, and finally what processes are driven by those forces to give the observed shapes. While bonds are not described because less is known about them, they are products of the same processes.

II. BASIC SHAPES

We have to consider the complete spectrum of both shapes and properties which is not easy because they are so varied. In fact, to understand the behavior of snow we must recognize that the shapes are determined by many different factors. If we were to show the shape of snow grains on a multi-dimensional map, the axes of the map could, for example, be represented by temperature, temperature gradient, liquid-water content, density, grain size and bond size. This idea is shown by the simple example in Figure 2 where dry snow was chosen, only easily measurable variables were used on the axes, the matrix was limited to three dimensions so it could be drawn as a figure, and the example could be constructed from common field experience. This example attempts to show qualitatively the relationship among temperature, temperature gradient, density and basic crystal shape in dry snow. The boundaries between shapes, like faceted and mixed shapes, are in reality much more diffuse than shown. Likewise, within the faceted shape there is a spectrum from simple, solid particles with facets to very ornate, hollow hoar crystals. However, at a given growth rate the rounded shape changes only slightly with temperature and probably not at all with density or temperature gradient.

In spite of all of the complications of thermodynamics, crystal growth physics and geometry, there are only a few basic shapes of snow grains that characterize seasonal snow. These must be separated into wet and dry classes since the presence of liquid water greatly changes the appearance of, and most of the properties of snow. I further divide all snow grains into "Basic" or "Mixed" which is arbitrary since all of these shapes are on their way to becoming something else. However, I consider the Basic Shapes to form the basis for understanding what we usually observe in snow. The other group, Mixed Shapes, I think of as less stable, and more likely to change into one of the Basic Shapes as soon as conditions permit. These Basic Shapes often survive for a long time in this form:

1. ***Buried Graupel***: Layers of buried graupel can persist for a long time in the snow cover because the particles are fairly large when they fall and therefore are slow to metamorphose into something else. Because of their large size, graupel particles are also slow to bond to their neighbors. The particle itself consists of well-bonded, frozen water droplets.
2. ***Surface Hoar***: This grows on the surface of the snow cover (Fig. 3) during episodes of rapid vapor deposition from the overlying air mass. These are planar crystals, sometimes rather large, and, if left standing upright, do not sinter readily even once they are buried. This appears to be a result of both their large size and the fact that they can retain their orientation and separation once buried. These and cavity hoar are the only crystals that grow two-dimensionally in or on the snow cover.
3. ***Rounded Grains***: These grow in dry snow (Fig. 4) at low growth rates as determined predominantly by a small temperature gradient and secondarily by a high density. This is the stable or the "equilibrium form" of the ice crystal which minimizes the surface free energy and sinters spontaneously.
4. ***Faceted Grains***: These grow in dry snow (Fig. 5) at higher growth rates as determined predominately by a larger temperature gradient and secondarily by a lower density. This is the "kinetic growth form" whose shape is dictated by the kinetics of growth, and not by phase equilibrium. These grains grow above a critical temperature gradient while they consume the existing grains; thus the snow layer loses its strength. The faceted grains do not readily sinter during their growth phase and are often too large to sinter rapidly after the rapid growth ceases. While there may only be one rounded shape, there are many different shapes of faceted crystals since the exact shape depends on the growth rate and probably on the density, history and temperature too. For a given set of conditions, there appears to be a faceted shape which corresponds to those conditions, but we cannot yet relate each shape to a set of conditions with great

certainty. One such shape is only partly faceted because the growth rate is not quite strong enough to produce the fully faceted shape.

5. *Wind Crusts*: Initially, these consist of small fragments (Fig. 6a) which, at higher temperatures, quickly become small, well-rounded and well-sintered grains (Fig. 6b). The rounded grains are stable in spite of their small sizes because faceted growth does not occur readily in dense layers where the grains are well connected.
6. *Ice Layers*: These form when water infiltrates the snow cover, is absorbed by a fine-grained layer such as a wind crust, and then refreezes. Ice layers are persistent since they are very dense and not readily subject to change. They can disappear in dry snow if the temperature gradient is strong enough for long enough, and in wet snow they can lose strength by absorbing solar radiation. They are discontinuous horizontally and may occur at various heights if there are many layers and freeze-thaw events.
7. *Grain Clusters*: At low liquid contents which correspond to high liquid tensions, grain clusters (Fig. 7) form spontaneously to minimize the surface free energy. These are clusters of single crystals of ice, each crystal being identifiable by its rounded shape, connected to its neighbors by ice-to-ice bonds of considerable strength and separated from neighboring grains by boundary grooves filled with water.
8. *Slush*: As liquid content increases there is a transition from a continuous air path to a continuous water path through the pore space. Then ice bonding in grain clusters disappears as a cohesionless collection of single crystals of ice evolves (Fig. 8). The grains tend to grow rapidly to about 1 mm in size where the driving force for growth, the effect of size on melting temperature, is reduced.

III. MIXED SHAPES

Although the average size is probably always increasing, the shapes described above are relatively stable. I think of all other shapes found in snow as transitional shapes, shapes which only exist temporarily while the grains are on their way to becoming something else relatively quickly:

1. *Precipitation Fragments*: These are remnants of the precipitation (Fig. 9) that fell to form the snow cover. Since the shapes which form in the atmosphere develop under conditions which are very different than the conditions in the snow cover, it is not surprising that most of these shapes disappear once they reach the ground. They tend to have too much curvature to survive under their new conditions.

2. ***Wind-Blown Shards***: Wind action on the surface of snow often breaks the particles into fine, glass-like shards (Fig. 6a) which are quite unstable because of both their small sizes and angularity. If warm enough, they quickly reform into small but well-rounded and well-sintered grains which form strong, sintered crusts (Fig 6b).
3. ***Partly Faceted, Partly Rounded***: This category (Fig. 5a) leads to confusion because similar looking grains arise from different conditions. It is not usually possible to tell which conditions are responsible for producing a grain of this mixed shape simply by looking at the grain. One must also know the history of recent snow conditions or at least recent weather conditions. These grains can form at intermediate growth rates which are too fast for purely rounded grains, but not fast enough for purely faceted grains. They can also form from the partial decay of fully faceted grains after the growth rate has slowed, probably due to an increase in the thickness of the snow cover, or to the moderation of very cold weather.
4. ***Melt-Freeze Particles***: These (Fig. 10) are common during the Spring when the surface freezes at night, but melts during the day. They are not stable since they require continued melt-freeze cycles to sustain them, but these melt-freeze cycles will soon melt them. In their extreme form, they are called "corn" which are large, solid particles formed on the surface when the day-to-night changes are extreme.

IV. MEASURABLE INFLUENCES

The factors listed below affect the way grains in snow develop into particular shapes. Some of these factors have obvious consequences but many effects are subtle. All of these parameters are measurable although not always with the required precision. Nevertheless, we cannot apply the basic principles described later without knowing the conditions of the snow during the time when the shapes developed. These are the dominant influences on the development of different shapes:

1. ***Temperature Gradient***: The temperature gradient is of fundamental importance because the rate of vapor diffusion is proportional to it. Thus the rate of grain growth in dry snow increases with it. In general, the temperature gradient is higher when the ground is warmer, the air is colder, the snow cover is thinner, and/or the snow is less dense. There is a familiar rule-of-thumb which states that, in low density snow, depth hoar forms at temperature gradients above 10 ^{0}C/m. This high energy input drives the grain shapes away from their equilibrium forms and, the higher the energy input, the more elaborate the grains (Fig. 5).

2. ***Temperature***: Temperature is of fundamental importance because, if the temperature is between 0 and -10 °C, ice is within 4 % of its melting temperature on the absolute scale and is therefore active thermodynamically. It is especially active at 0 °C and activity decays noticeably at -10 °C. The difference between these two temperatures is large only because one is the melting temperature and activity decays rapidly below it. For example, the difference between thermodynamic activity at -100 and -110 °C is negligible. One profound consequence of this large dependence on temperature, when nothing but temperature varies with depth, is that depth hoar grows at depth in the snow cover where it is warmer and the crystal growth rate is higher. This occurs for two basic reasons: First, for a given supersaturation over a growing crystal, the crystal growth rate increases markedly with temperature. Second, for a given temperature gradient, the vapor density gradient and therefore the vapor flux increase rapidly with temperature. The net result is that crystals grow faster at higher temperatures and thus faceting is more likely to occur.
3. ***History***: The history of the growth rate is important because, if the growth rate increases and then decreases again, the predominant growth shape may shift from rounded to faceted and back to rounded again due to changes in the temperature gradient. Thus we may see changing weather conditions cause changing temperature profiles and mixed growth forms resulting from changing growth conditions. A mixed growth shape can look like the partly faceted growth shown in Figure 5a or the melt-freeze particle in Figure 10.
4. ***Density***: Snow density affects the growth shape because it directly affects the growth rate. There are two reasons why faceted shapes are more common in low density snow (Fig. 2). First, low density snow has a lower thermal conductivity and therefore has a higher temperature gradient for a given heat flux. More rapid growth and thus more faceting occurs with a higher temperature gradient. Second, in lower density snow the ice grains are further apart, on average, so a matched pair of grains forming a vapor source-sink have a greater temperature difference between them. This leads to higher growth rates because the higher temperature difference causes higher vapor density differences between the source-sink pairs. This also explains why large faceted crystals are often seen in cavities in snow.
5. *Grain size*: Things tend to happen more rapidly when the grains are small so the results of metamorphism become apparent more quickly. For example, sintering occurs much more readily in fine-grained snow, fresh snow rounds off more rapidly because of high curvature,

but old depth hoar grains round off and sinters slowly because of their large size.

6. ***Liquid-water content***: Liquid-water content is a fundamental variable in wet snow just like temperature gradient is a fundamental variable in dry snow. At high temperature gradients in dry snow, we find cohesionless depth hoar and at high liquid-water contents in wet snow we find cohesionless slush. At low temperature gradients in dry snow we find well-bonded, round grains and at low liquid contents in wet snow we find well-bonded grain clusters (Fig. 7).
7. ***Humidity***: It is not possible to measure humidity, or water vapor pressure, in snow with enough resolution to tell if a particular grain is growing or shrinking, although atmospheric humidity measurements are used by avalanche forecasters as a factor in assessing snow stability. Since vapor pressure over the ice surface directly determines growth rate, we would like to know it in great detail throughout the pore space. However, if we cannot measure it in snow, we can only theorize about its role in grain growth. Thus we calculate vapor pressure by measuring temperature, assuming the phases are in equilibrium at each point, and using the theory of thermodynamics.
8. ***Solar radiation***: Solar input can be a big factor in determining the properties of snow close to the surface. Most solar energy is reflected but some is absorbed close to the surface. When the conditions are right, a near-surface hoar layer can form by the combination of near-surface solar heating and a strong temperature gradient.

   In dry snow the growth rate increases with the temperature gradient which is partly determined by the upper surface conditions and these are partly determined by the absorption of solar radiation. Absorption can warm the surface and reduce the temperature difference between the top and bottom of the snow cover. In wet snow there is no temperature gradient but the upper surface can still be heated very strongly by penetrating solar radiation. In this case strong radiation absorption causes melting which raises the liquid content of the surface and leads to a slushy snow surface. With a lot of incoming solar radiation, the top one to three centimeters can be so weak that it can be easily removed by one finger. Below this slushy layer the snow can still be weakened by sunshine, but the strength is much greater than that of the top layer.
9. ***Radiational cooling***: On clear nights the surface is cooled by out going radiation as the snow surface radiates energy back to space. The cool surface then draws water vapor from the warmer air above it. When the cooling is strong enough and the vapor source is plentiful enough, the rapid deposition of vapor on the surface causes

rapid growth leading to hoar shapes. At lower elevations water vapor is more plentiful but snow surfaces do not cool as much because of the overlying atmosphere. At higher elevations the surface cools more, but there is not much water vapor available for deposition. Thus surface hoar formation requires special circumstances to produce just the right combination of strong cooling with an ample vapor supply, probably brought in by a light wind. These restrictions on the conditions for surface hoar formation are fortunate since buried surface hoar forms a persistent weak layer which reduces snow slope stability.

10. ***Microstructure***: We are still learning how to quantify microstructure and how to think about its influence on the physical properties of snow. It is clear that the interconnectedness of the grains and the existence of chains of grains are important. However, it is less clear what observations to make, how to get quantitative information from those observations, and how to apply this information to describe the forces that shape the grains.

V. BASIC PRINCIPLES

The basic principles which must be understood come from studies of the thermodynamics of equilibrium among two or three phases and from studies of crystal growth. While the details of these fields are difficult to understand, application of the general principles should be easy because we already understand what actually happens in snow. However, we still need a formal way of thinking about it. The basic principles can be separated into these parts:

1. ***Phase equilibrium***: There are two phases of water in dry snow - ice and water vapor - and three phases of water in wet snow - ice, water vapor and liquid water. Because snow is always changing, i.e., the grains are always growing and/or changing shape, the phases are never quite in equilibrium and, in that sense, snow is always thermodynamically unstable. However, the rate at which the grains grow is so slow that we can apply the principles of thermodynamics at phase-equilibrium to help understand why snow grains change the way they do. However, we recognize that this is only an approximation. This approach has led to the use of two relationships among measurable variables which snow scientists have employed to explain dry snow's behavior. In particular, these are the dependence of vapor pressure on temperature and the dependence of vapor pressure on curvature. For example, the vapor pressure at equilibrium over ice increases in a well-known way as temperature increases. The application of this result to snow subjected to a temperature gradient is fundamental to understanding why dry snow

recrystallizes from rounded to faceted crystals. In a constant attempt to achieve the equilibrium condition, water vapor migrates from warm snow layers to cold snow layers. Thus the system moves towards equilibrium, but it never gets there.

2. ***Minimum Surface-Free Energy***: The effect of temperature on vapor pressure is greater than the effect of curvature on vapor pressure, but both are of fundamental importance to the metamorphism of dry snow. At a given temperature, the vapor pressure is higher over areas of high curvature than over areas of low curvature and is higher over grains than over bonds. Since vapor diffuses from areas of high vapor density to areas of low vapor density, small grains are less stable than large grains and bonds spontaneously develop as the whole snow pack moves towards equilibrium. Energetically, snow is like a ball which spontaneously rolls downhill looking for a valley to come to rest, except snow never reaches a valley: snow is always on its way to becoming something else. However, the rounded grains in either dry snow or slush minimize the surface-free energy by minimizing the surface energy over the entire rounded grain. While the grains are not spherical because of the crystalline structure of ice, rounded shapes do minimize the surface-free energy. In freely draining wet snow the minimum is harder to achieve because the surface energy must be minimized as the sum of the energies of the liquid-ice, liquid-vapor and vapor-ice interfaces. Thus the minimum is for the whole cluster (Fig. 7). This requires a complicated geometry which actually has a fairly large surface area, but a minimum surface-free energy.

   In wet snow there is an analogy with the effect of temperature on vapor pressure in dry snow; in wet snow, on the scale of the grains, there is also one overriding thermodynamic dependency. The melting temperature in wet snow is strongly dependent on size such that smaller grains have lower melting temperatures. Therefore, heat flow from larger to smaller grains causes the smaller ones to melt by consuming heat and the larger ones to grow by releasing heat. This process also drives the population of grains to larger sizes without ever achieving the final equilibrium, in part because the process slows greatly once the grains exceed about 1 mm in size. It is not a thermodynamic accident that we use 5 to 10 power hand lens to look at these well-rounded grains.

3. ***Dry Grain Shapes***: The major driving force for change in dry snow is the temperature gradient since the vapor pressure varies strongly with temperature, some with curvature, and very slightly with stress and impurity content of the ice. That is why the temperature gradient is the critical parameter in determining the growth rate, and therefore the shape, of the grains. Grains of any size or shape will

recrystallize if the temperature gradient is strong enough. The reason for this is clear: ice grains in dry snow grow by vapor diffusion from warmer regions to colder regions of the snow cover and the mechanism for this vapor transport is the grain-to-grain delivery of water vapor. At higher temperature gradients, the temperature differences among snow grains are greater so the driving force for grain-to-grain vapor flow is larger. Thus the growth rate of the colder grains, the vapor sinks, is higher and faceted grains grow preferentially at higher growth rates. If the growth rate is high enough, the faceted grains grow as hollow grains with striations and other adornments (Fig. 5c).

There are two basic shapes that crystallographers use to characterize growing crystals - the "equilibrium form" and the "kinetic growth form" (Figs. 4 and 5) The equilibrium form does not mean that the crystal has reached thermodynamic equilibrium, but it does mean that the shape minimizes the surface free energy. The shape of a water droplet that achieves the minimum surface free energy is a sphere. The surface energy is the same everywhere on the surface of a water droplet and thus the sphere minimizes both the surface-free energy and the surface area. However, the surface energy varies with the direction in ice so the shape that minimizes the overall surface-free energy of an ice crystal is not a sphere, but the shape is sphere-like. When two ice grains are brought together the shape that minimizes the surface-free energy is a dumbbell; thus two grains bond together to reduce surface free energy and move a little closer to the elusive condition of thermodynamic equilibrium. In a snow cover, minimizing surface free energy determines the shape if, and only if, the growth rate is slow enough. The growth rate will be slow enough as long as the energy input, as measured by the temperature gradient, is not too high. There is one other complication: if the temperature is low enough, the equilibrium form appears to be a simple, faceted crystal that could be mistaken for the kinetic-growth form. However, we generally ignore this possibility and assume that all faceted crystals are due to kinetic growth.

The other form of dry snow, the kinetic-growth form, dominates the shape when the vapor pressure over the growing surfaces is high due to large temperature differences among the grains. When the growth rate exceeds a critical value, the growth mechanism changes at the molecular scale and faceting appears.

4. *Growth Mechanisms*: More powerful processes control weaker processes and thus the growth of faceted crystals can move the system away from achieving the minimum surface free energy per unit mass. It requires a lot of energy input to replace the equilibrium

form, the rounded crystals, and move the system toward higher states of disequilibrium. The driving force is provided by the temperature gradient which powers both vapor diffusion and rapid crystal growth. The extreme case of the growth of faceted crystals is the growth of dendrites in the atmosphere. These crystals have very large surface areas per unit mass which are necessary for their rapid growth from vapor supplied by water droplets in clouds, the ideal source of large amounts of water vapor. Something similar happens when hoar grows on the snow surface, due to a large temperature difference between the surface and the overlying air, and when depth hoar forms at large temperature gradients.

There is a fundamental difference in the way the two forms look - rounded and faceted - because there is a fundamental difference in the way the two forms grow at the molecular level. The equilibrium form grows by the inclusion of water molecules into vacant spaces in the crystal lattice whereas the kinetic growth form grows by the movement of steps across a crystal face. When vacancy filling takes place, the growth rate is slow enough to allow the equilibrium form to develop. However, when steps sweep across the crystallographic faces, the growth rates are much higher and the shape is dictated by the mechanics of step motion without time to achieve the shape that thermodynamic equilibrium requires.

In wet snow there is no analogy to the kinetic-growth form although kinetic growth forms do occur in water with large supercoolings, e.g., frazil ice. There are two features of growth in wet snow that distinguish it from dry snow. First, the pore space contains liquid water which is the ideal medium for transporting water molecules from one spot on a grain to another. Diffusion of mass is not always necessary. Second, wet snow is at the highest possible temperature and everything happens at the maximum possible rate allowed by the small, local temperature differences that cause phase change.

5. ***Wet Grain Shapes***: Given that the shape of the well rounded grain in dry snow is not exactly a sphere, it is no surprise that the shape of the single ice crystal in water is only close to being a sphere. That is the case of slush (Fig. 8): water-saturated wet snow with a liquid-water content that is high enough that the only air left in the system is in isolated bubbles trapped among the grains. Slush is cohesionless because the equilibrium form at high water contents is the single, isolated crystal with no ice-to-ice bonds to its neighbors. Slush minimizes surface-free energy in two ways. First, the sphere-like grains have individually achieved their own minimum and, second, the population of grains continuously reduces its overall

energy by consuming the smaller grains which have a higher specific surface area.

The other form of wet snow occurs at low liquid-water contents where the air is continuous through the pore space and the minimum surface-free energy is achieved by the individual crystals moving together to form ice-to-ice bonded clusters (Fig. 7). Unlike slush, these clusters have considerable strength because of their ice bonds. They have no ideal shape except that the geometrical relationships among the three phases of water are fixed when the number and size of crystals and the liquid-water content is given. Thus clusters of any size can occur but they are larger in higher density snow where they move closer together and have more contacts. By their very nature they form in a way that minimizes the total surface-free energy of the solid-liquid, solid-vapor and liquid-vapor surfaces. It is commonly assumed that these are bonded by capillarity or encased in a liquid film, but they are actually ice bonded.

6. ***Capillarity***: The water in an unsaturated porous medium is in a state tension, meaning that its pressure is less than air pressure. This pressure difference gives rise to capillary suction. As the liquid-water content increases, the "tension" in the liquid decreases as water displaces air in the pore space.
7. ***Stress***: "Pressure metamorphism" due to the stress carried through the ice lattice is often thought to be a major factor in controlling snow metamorphism. However, from thermodynamics we know that the effect of stress on vapor pressure is small, much smaller than the effect of temperature or curvature. Thus it seems likely that the effects of stress are simply to rearrange the grains and to increase the density and the number of intergranular contacts. These geometrical changes will affect grain growth, but there is no published evidence that stress has any other influence.

VI. SUMMARY

Snow is variable due to many different grain shapes with intermediate shapes between the basic classes. Snow is either wet or dry and these categories can be subdivided depending on grain shape. The many basic shapes of snow grains arise from the great variety of thermal conditions experienced by snow covers. Qualitative explanations of the various shapes found in the seasonal snow cover are given here since the shapes affect the important material properties. I consider certain basic shapes to form the basis for understanding what we usually observe in snow. Another group of mixed shapes, I think of as less stable, and more likely to change into one of the basic shapes as soon as conditions permit. These basic shapes, which often survive for a long time in this form, include buried graupel, surface hoar, rounded grains, faceted grains, wind crusts, ice layers, grain clusters, and slush. Although the average size is probably always increasing, these shapes are relatively stable. I think of all other shapes found in snow as transitional shapes, shapes which only exist temporarily while the grains are on their way to becoming something else relatively quickly. These include precipitation fragments, wind-blown shards, partly faceted-partly rounded grains, and melt-freeze particles.

These factors affect the way grains in snow develop into particular shapes: temperature gradient, temperature, history of growth rate, density, grain size, liquid-water content, humidity, solar input, radiational cooling, and microstructure. These basic principles must be understood and applied to what we already know about what happens in snow: phase equilibrium, minimum surface-free energy, growth mechanisms, dry grain shapes, wet grain shapes and capillarity.

VII. ACKNOWLEDGEMENTS

Very useful comments on this manuscript were made by Dr. Ted Arons and Dr. Bert Davis. Dr. Mathew Sturm provided an especially thorough and useful review. My work on snow metamorphism was supported at CRREL by work units like Physical Properties of Snow Covers, AT24-SC-S01.

VIII. READING LIST

This is a list of the references to other peoples work which I have cited most frequently in my own published work:

Akitaya, E., Studies on depth hoar, *Low Temperature Science, Series A*, *26*, 1-67, 1974.

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

Bader, H., R. Haefeli, E. Bucker *et al.*, Der Schnee und seine metamorphose, *Beitrage zur Geologie der Schweiz, Geotechnische Serie, Hydrologie Report*, Number of Pages, Bern, 1939.

Bradley, C. C., R. L. Brown, and T. R. Williams, Gradient metamorphism, zonal weakening of the snow-pack and avalanche initiation, *Journal of Glaciology*, *19*, 335-342, 1977.

Colbeck, S. C., E. Akitaya, R. Armystrong *et al.*, The International Snow Classification for Seasonal Snow on the Ground, *International Commission for Snow and Ice (IAHS) Report*, Number of Pages, World Data Center A for Glaciology, University of Colorado, Boulder CO, 1990.

Davis, R. E., B. Jamieson, J. Hughes *et al.*, Observations of buried surface hoar-persistent failure planes for slab avalanches in British Columbia, Canada, International Snow Science Workshop, 1996.

de Quervain, M., Schnee als kristallines aggregat, *Experientia*, *1*, 207-212, 1945.

de Quervain, M. R., On metamorphism and hardening of snow under constant pressure and temperature gradient, in *International Association of Scientific Hydrology*, edited by Secondary de Quervain, M. R., Publication 46, 225-239, 1958.

de Quervain, M. R., On the metamorphism of snow, in *Ice and Snow*, edited by Secondary de Quervain, M. R., 377-390, MIT Press, Cambridge, Mass., 1963.

Defay, R. and I. Prigogine, *Surface Tension and Adsorption*, 432, Longmans, London, 1966.

Dufour, L. and R. Defay, *Thermodynamics of Clouds*, 255, Academic Press, New York, 1963.

Frank, F. C., Snow crystals, *Contempary Physics*, *23*, 3-22, 1982.

Gerdel, R. W., The transmission of water through snow, *EOS, Transactions of the American Geophysical Union*, *35*, 475-485, 1954.

Giddings, J. C. and E. LaChapelle, The formation rate of depth hoar, *Journal of Geophysical Research*, *67*, 2377-2383, 1962.

Gubler, H., Determination of the mean number of bonds per snow grain and of the dependence of the tensile strength of snow on stereological parameters., *Journal of Glaciology*, *20*, 329-341, 1978.

Gubler, H., Model of dry snow metamorphism by interparticle vapor fluxs, *Journal of Geophysical Research*, *90*, 8081-8092, 1985.

Hirth, J. P. and G. M. Pound, *Condensation and Evaporation. Nucleation and Growth Kinetics*, 190, Macmillian, New York, 1963.

Hobbs, P. V., *Ice Physics*, 837, Clarendon Press, Oxford, 1974.

Keller, V. W. and J. Hallet, Influence of air velocity on the habit of ice crystal growth from the vapor, *Journal of Crystal Growth*, *60*, 91-106, 1982.

Kobayashi, T., The growth of snow crystals at low supersaturations, *Philosophical Magazine*, *6*, 1363-1370, 1961.

Kuroda, T., Recent developments in theory and experiment of growth kinetics of ice crystals form the vapour phase and their growth forms, *Journal of Crystal Growth*, *65*, 27-35, 1983.

Lamb, D. and P. V. Hobbs, Growth rates and habits of ice crystals grown from the vapor phase, *Journal of Atmospheric Sciences*, *28*, 1506-1509, 1971.

Lamb, D. and W. D. Scott, Linear growth rates of ice crystals grown from the vapor phase, *Journal of Crystal Growth*, *12*, 21-31, 1972.

Lang, R., B. R. Leo, and R. L. Brown, Observations on the growth processes and strength characteristics of surface hoar, International Snow Science Workshop, 188-195, Mountain-Rescue Aspen, 1984.

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

Marshall, J. S. and M. P. Langleben, A theory of crystal habit and growth, *Journal of Meteorology*, *11*, 104-120, 1954.

Nenow, D. and V. Stoyanova, Appearance of non-singular surfaces on vapor grown ice crystals, *Journal of Crystal Growth*, *46*, 779-782, 1979.

Pahaut, E. and D. Marbouty, Les cristaux de neige, 2, Evolution, *Neige Avalanches*, *25*, 3-42, 1981.

Perla, R., Temperature-gradient and equi-temperature metamorphism of dry snow, International Meeting on Snow and Avalanches, 43-48, Association Nationale pour l'Etude de la Neige et des Avalanches, 1978.

Perla, R., Snow in strong or weak temperature gradients, Part II: Section-plane analysis, 1985.

Powers, D., K. O'Neill, and S. C. Colbeck, Theory of natural convection in snow, *Journal of Geophysical Research*, *90*, 10,641-10,649, 1985.

Raymond, C. F. and K. Tusima, Grain coarsening of water-saturated snow, *Journal of Glaciology*, *22*, 83-105, 1979.

Seligman, G., *Snow Structure and Ski Fields*, 555, Macmillian, London, 1936.

Sturm, M., The Role of Thermal Convection in Heat and Mass Transport in the Subarctic Snow Cover, *CRREL Report Report*, Number of Pages, U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, N. H., 1991.

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

Wakahama, G., Metamorphisms of wet snow, *Low Temperature Science, Series A*, *23*, 51-66, 1965.

Wakahama, G., The metamorphism of wet snow, IUGG General Assembly of Bern, Sept.-Oct. 1967, 370-379, Int. Assoc. Sci. Hydrol., 1968.

Yosida, Z. and Colleagues, Physical studies on deposited snow. I. Thermal Properties, *Low Temperature Science*, *7*, 19-74, 1955.

2. Of my own publications these should be most useful:

Colbeck, S. C., Theory of metamorphism of wet snow, *Research Report Report*, Number of Pages, U. S. Army Cold Regions Research and Engineering Laboratory, Hanover NH, 1973.

Colbeck, S. C., Grain clusters in wet snow, *Journal of Colloid and Interface Science*, *72*, 371-384, 1979.

Colbeck, S. C., Thermodynamics of snow metamorphism due to variations in curvature, *Journal of Glaciology*, *26*, 291-301, 1980.

Colbeck, S. C., Growth of faceted crystals in a snow cover, *CRREL Report*, Number of Pages, U. S. Army Cold Regions Research and Engineering Laboratory, Hanover NH, 1982.

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

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

Colbeck, S. C., Temperature dependence of the equilibrium form of ice, *Journal of Crystal Growth*, *72*, 726-732, 1985.

Colbeck, S. C., Statistics of coarsening in water-saturated snow, *Acta Metallurgica*, *34*, 347-352, 1986.

Colbeck, S. C., A review of the metamorphism and classification of seasonal snow cover crystals, in *Avalanche Formation, Movement and Effects*, edited by Secondary Colbeck, S. C., 162, 1-34, Int. Assoc. Hydrol. Sci., 1987.

Colbeck, S. C., Ideas on the micrometeorology of surface hoar growth on snow, *Boundary-Layer Meteorology*, *44*, 1-12, 1988.

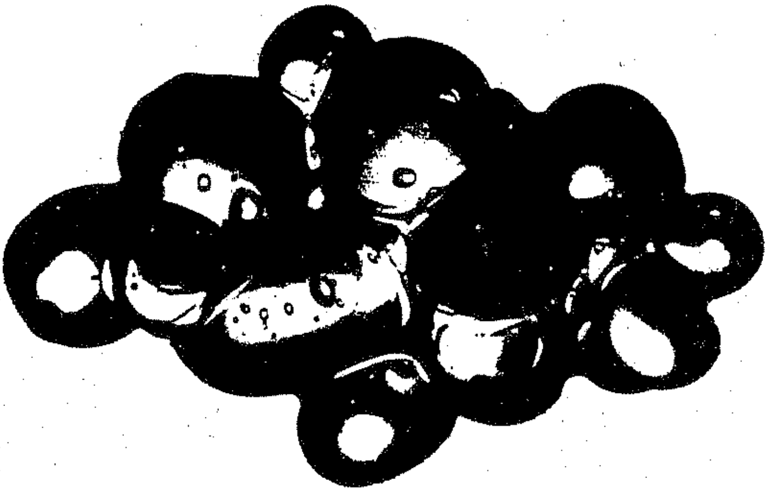
Colbeck, S. C., Snow crystal growth with varying surface temperatures and radiation penetration, *Journal of Glaciology*, *35*, 23-29, 1989.

FIGURE CAPTIONS

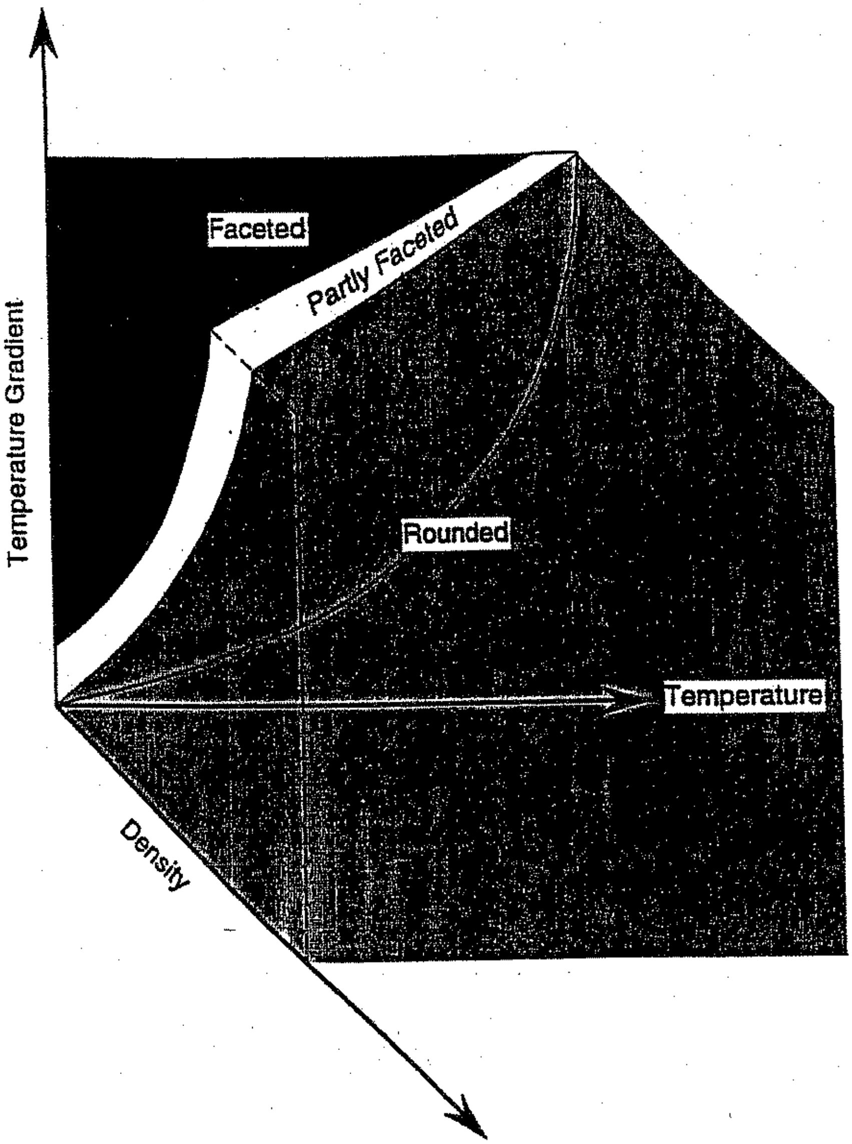
1. A simple representation of the snow-ice-water cycle.
2. Growth shapes of crystals in dry snow as determined by temperature, temperature gradient and density (no scale or origin).
3. Surface hoar. These planar crystals grow on the surface on clear, cold nights.
4. Rounded or equilibrium form of dry snow.
5. Three forms of faceted grains: a. A grain from dry snow which shows some rounded and some faceted areas. This can result from either an intermediate growth rate or from a change to a slower growth rate; b. A solid, facet crystal resulting from faster growth; c. A hollow, faceted crystal resulting from the fastest growth.
6. a. Wind-blown shards; b. Small, rounded, well-sintered grains from a wind crust.
7. Ice-bonded, grain clusters form spontaneously in wet snow at low liquid contents. This shape minimizes the surface-free energy, not the surface area.
8. Slush. These are well-rounded, cohesionless ice crystals immersed in water.
9. A fragment of precipitation. These are unstable because of their high curvature.
10. A melt-freeze particle.

1. Grains from dry snow which show some rounded and some faceted areas. This can result from either an intermediate growth rate or from a reduction in growth rate.

2. A melt-freeze particle. These arise from melting during the day and freezing at night.



4. Ice-bonded, grain clusters form spontaneously in wet snow at low liquid contents. This form minimizes the surface-free energy of the cluster as a whole.



3. Growth forms of crystals in dry snow as determined by temperature, temperature gradient and density (no scale or origin).

Acknowledgements

I have had helpful conversations about near-surface faceting with many avalanche workers, especially R. Johnson. L. McKittrick helped with the figures. Insightful reviews by R. Armstrong and M. Sturm on the paper that appeared in *Arctic and Alpine Research* helped to improve this paper.

References

Armstrong, R.L., 1985: Metamorphism in a subfreezing, seasonal snow cover: The role of thermal and vapor pressure conditions. PhD Dissertation, Department 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.

Birkeland, K.W., Johnson, R.F., and Schmidt, D.S., 1998: Near-surface faceted crystals formed by diurnal recrystallization: A case study of weak layer formation in the mountain snowpack and its contribution to snow avalanches. *Arctic and Alpine Research*, 30(2): 200-204.

Birkeland, K.W., Johnson, R.F., and Schmidt, D.S., 1996: Near-surface faceted crystals: Conditions necessary for growth and contribution to avalanche formation, southwest Montana, U.S.A. *Proceedings of the 1996 International Snow Science Workshop*, Banff, Canada: 75-79.

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

Fierz, C., in press: Field observation and modelling of weak layer evolution. *Annals of Glaciology*, 26.

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

Jamieson, J.B., 1997: The facet layer of November 1996 in western Canada. *Canadian Avalanche Association Avalanche News*, 52: 10-15.

LaChapelle, E.R., 1969: *Field Guide to Snow Crystals*. University of Washington Press, Seattle, Washington, 101 pp.

LaChapelle, E.R., 1970: Principles of avalanche forecasting. *In: Engineering and Avalanche Forecasting and Control*. Tech. Memo. No. 98. National Research Council, Canada, 106-113.

LaChapelle, E.R. and Armstrong, R.L., 1977: Temperature patterns in an alpine snow cover and their influence on snow metamorphism. U.S. Army Research Office, Institute of Arctic and Alpine Research Technical Report, University of Colorado, 33 pp.

Stratton, J. 1977. "Development of upper level temperature gradient crystals" and "Upper level temperature gradient avalanche cycle - February 1-2, 1977". Short, unpublished papers that were circulated among Utah avalanche workers in the late-1970s and early 1980s by John Stratton, Snowbird Snow Safety.