

## A review of the metamorphism and classification of seasonal snow cover crystals

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**ABSTRACT** Knowledge of the growth of ice crystals in both wet and dry snow has evolved steadily over many years. Dry snow is characterized by rounded crystals growing slowly at low temperature gradients. Wet snow is characterized by clusters of grains at low liquid contents and poorly bonded slush at high liquid contents. Melt-freeze cycles greatly influence wet snow as well.

Information was first gained through field observations, then laboratory tests, and then physical modeling. Advances have been made through application of phase-equilibrium thermodynamics and knowledge of ice crystal growth although much remains to be learned about the slow growth of ice crystals over a range of temperatures. The grain-to-grain nature of vapor flow in dry snow is complicated by the geometry of snow and this topic is being studied through stereology. Given recent advances in our understanding of snow metamorphism, a reclassification of snow seems necessary.

"Une Revision de la Métamorphose des Cristaux de neige et de leur classification."

**RESUME** La connaissance de la croissance des cristaux de glace dans la neige sèche ou humide a régulièrement progressé pendant de nombreuses années. La neige sèche se caractérise par des cristaux ronds dont la croissance est lente à de faibles gradients de température. Par contre la neige humide peut présenter: soit des amas de grains reliés entre eux, lorsque sa contenance en liquide est faible; soit elle devient malle et perd sa cohérence intergranulaire lorsque la contenance en liquide devient importante. Les cycles de gel et dégel agissant aussi sur la neige humide. Des observations sur le terrain ont fourni les premières données sur les cristaux de neige, par la suite se sont développés les essais en laboratoire, ainsi que la modélisation physique. L'analyse thermodynamique permet d'avancer dans la compréhension du phénomène. Cependant de nombreux aspects sur la croissance lente des cristaux, dans large domaine de température reste à analyser. Dans la neige, la nature des échanges de vapeur entre les grains est

influencée par leur géométrie. Les études sont alors effectuées à l'aide de la stéréologie. La compréhension de certains mécanismes contrariant les métamorphoses de la neige ayant avancé, il nous semble nécessaire de proposer ou redassement des cristaux de neige et de leur évolution.

## INTRODUCTION

Snow is a highly variable material both as it falls and after it has formed a cover over the ground. The variation in snow on the ground arises not so much from its variable origins as from the fact that snow covers are generally subjected to varying conditions and that snow is a finely dispensed aggregate of ice, water vapor, and/or water at, or close to, its melting temperature. Accordingly, snow is constantly moving to reduce its surface free energy by densifying and eliminating smaller grains. At the same time it responds to different stimuli produced by its environment - melt-water and temperature gradients being the most important.

The wide range of grain sizes, shapes and assemblies found in snow inevitably leads to a wide range in all of the material properties of snow. Besides our basic interest in snow metamorphism as one of nature's more interesting phenomena, through an understanding of snow metamorphism we hope to provide some insight into the physical properties of snow, all of which depend on the snow type.

This review is divided into three parts. The metamorphism of dry snow and wet snow are necessarily described separately because they are rather different materials governed by very different processes. Only after we have described the characteristics and relevant physical processes of these two types of snow can we classify snow into meaningful groups with meaningful words.

### Metamorphism of Dry Snow

#### A. Perspective

The earliest reported observations of the crystalline form of falling snow (about 1550 according to Hellmann, 1893) were made centuries before systematic observations of fallen snow. Once the microscope was developed in the last half of the 17th century, observations of many natural phenomena followed. Systematic observations of fallen snow, however, were not reported until the 19th century (e.g. Ladame, 1846) and attempts to categorize the observed crystals waited until the 20th century (Paulcke, 1933). During that time relationships were developed describing capillarity (Young, 1805), vapor pressure and temperature (Clausius, 1850), and curvature and vapor pressure (Thompson, 1871). These relationships allowed a better understanding of the physical nature of snow metamorphism (Koch, 1895) although the applications of these ideas were very qualitative.

The quality and availability of observations of fallen snow improved dramatically in the 1930's, at least in part because of interest in skiing and avalanches (Paulcke, 1933; Seligman, 1936). Earlier work had partly provided the background necessary for Seligman's book on snow (e.g., Ratzel, 1889; Brun, 1900; Ferrara, 1916). All of these were largely field observations and physical speculations which led to the need for more detailed and controlled observations of the behavior of crystals in fallen snow.

A new era of investigations began with the founding of the laboratory in Davos in 1936 and the onset of systematic laboratory investigations of the changes occurring in the snow cover (Bader, 1939). The behavior of snow in the laboratory away from the ever changing temperatures and the temperature gradients in nature provided new insights into such phenomena as the "destructive metamorphism" of a snowflake. These efforts were continued by de Quervain (1945, 1958) and eventually various groups around the world became involved (e.g., Yosida and Colleagues, 1955; Giddings and LaChapelle, 1962).

The metamorphism of dry snow continued to be a topic of some interest after that period but advancements were generally limited to laboratory and field observations. Interpretation of the field results and the design of more meaningful laboratory experiments were constrained because of limited knowledge of thermodynamics and ice crystal growth.

At the present time considerable effort is being made to increase our understanding of snow metamorphism through increased knowledge of how heat and vapor flows interact with the complicated geometry of crystals in deposited snow. Certain principles of phase-equilibrium thermodynamics and crystal growth must be used to understand snow metamorphism so these topics are reviewed too. The most difficult part of this task, developing an understanding of the interactions among the particles, is approached through stereology, the study of three-dimensional compacts from two-dimensional sections. The study of snow metamorphism would seem to be poised for a major step forward if stereology can, in fact, provide us with the necessary insights into the geometrical relationships among the particles in snow.

#### B. Phase-Equilibrium Thermodynamics

In dry snow we deal with the solid and vapor forms of water while considering the air as an inert gas (Defay and Prigogine, 1966, p. 274). This simplifies the relationships to two basic forms. By minimizing the Gibbs Function we get

$$v_g dp_g - S_g dT = v_s dp_s - S_s dT \quad (1)$$

and from Laplace's Equation

$$p_s - p_g = \frac{2\sigma}{r_m} \quad (2)$$

where  $v$  is specific volume,  $p$  is pressure,  $S$  is entropy,  $T$  is temperature,  $\sigma$  is surface free energy,  $r_m$  is the mean radius of

curvature,  $g$  is for gas, and  $s$  is for solid. We also need

$$\frac{2}{r_m} = \frac{1}{r_1} + \frac{1}{r_2} \quad (3)$$

where  $r_1$  and  $r_2$  are the radii of curvature of the surface in any two mutually perpendicular planes and

$$S_g - S_s = L_s / T \quad (4)$$

where  $L_s$  is the heat of sublimation.

In snow we usually observe the geometry and wish to explain the shape and growth rate. Thus we know  $r_m$  and therefore  $p_s - p_g$  but need  $p_g$  as a function of temperature and/or size. Since our system is divariant, we must assign a value to one variable in order to get a relationship between the other two. Accordingly, we can derive a form of Kelvin's equation,

$$p_g = p_o \exp \left( - \frac{v_s}{RT_o} \frac{2\sigma_{sg}}{r_m} \right) \quad (5)$$

where  $p_o$  and  $T_o$  are reference values for a flat surface and  $R$  is the gas constant for water vapor. Alternately, we derive

$$T = - \frac{v_s T_o}{L_s} \frac{2\sigma_{sg}}{r_m} \quad (6)$$

or, for a given geometry, we can show how vapor pressure varies with temperature:

$$L_s \left( \frac{1}{T} - \frac{1}{T_o} \right) = R \ln (p_g / p_o) \quad (7)$$

where the reference values can be for any curvature desired (for details of these derivations see Colbeck, 1980).

Although limited by the assumed values of  $T$ ,  $p_g$  and  $r_m$  respectively, Equations (5) to (7) are very powerful in that they can be used to explain many of the observed features of snow metamorphism at low temperature gradients. To understand the limitation to low temperature gradients, or alternately, low growth rates, we first introduce another achievement of phase-equilibrium thermodynamics, the equilibrium shape of a crystal.

When crystals grow slowly their shapes are determined by the variation of surface free energy with direction in the crystal in a manner that was first described by Wulff (1901). As is described later in the case of depth hoar, when crystals grow rapidly their shapes are determined by the surface kinetics of their growth and have nothing to do with phase equilibrium (see Figure 1 where rapid growth is represented by a high temperature gradient). At high growth rates it may follow that the supersaturation is high enough to negate the phase equilibrium assumption behind Equations (5) to (7) but that is not clear. It is clear that at low growth rates where rounded crystals develop in snow, that shape arises because it minimizes the surface free energy. The shape is called the equilibrium form although growth still occurs.

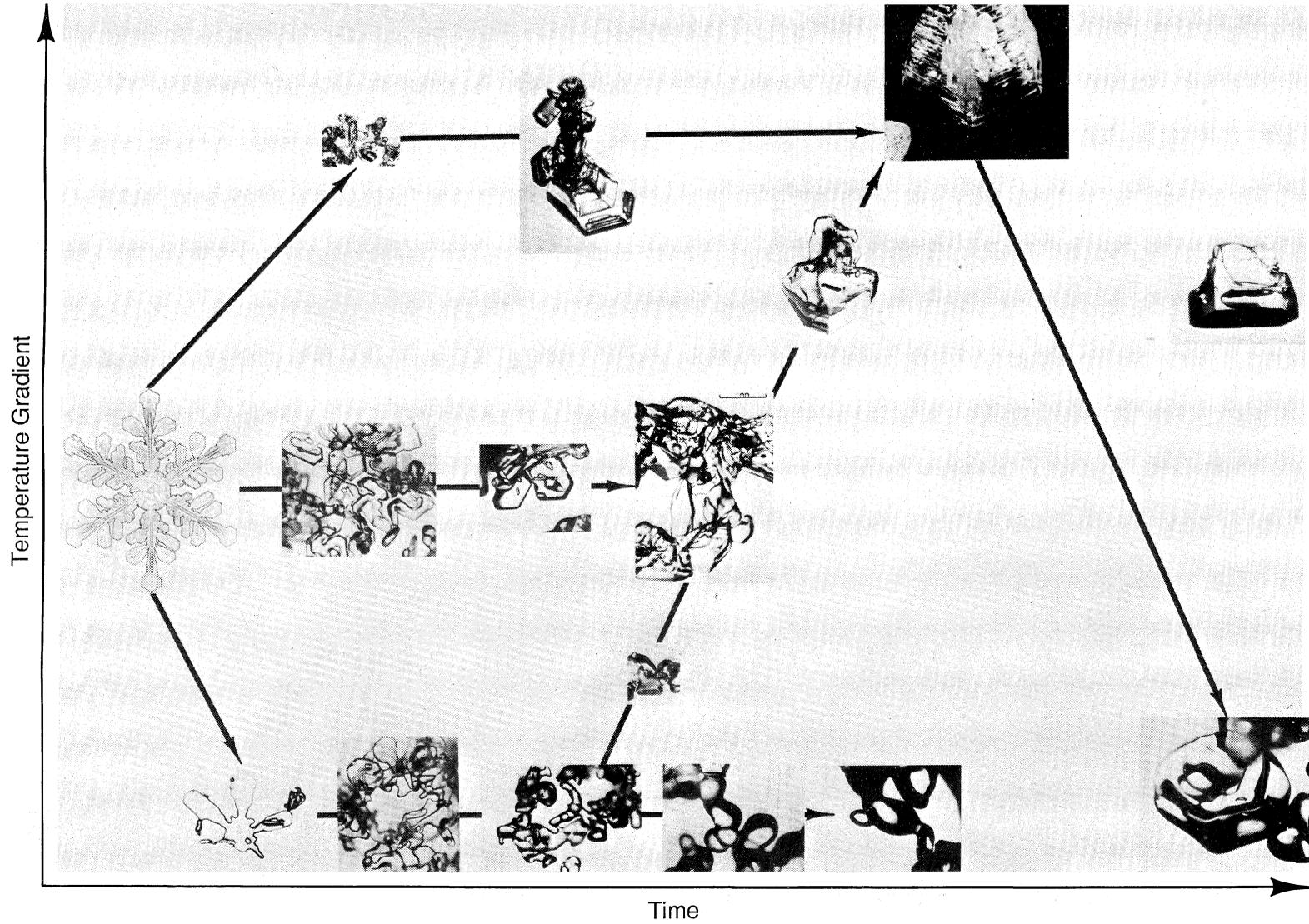


FIG. 1 Photographs of crystals that develop by different paths are shown on a map of temperature gradient and time.

Krastanow (1941) showed that the equilibrium shape of an ice crystal should be a hexagonal prism whereas well-rounded crystals are normally observed in snow. There are two apparent explanations for this discrepancy. First, the growth of single crystals at low supersaturations shows a transition from well rounded to highly faceted crystals at  $-10^{\circ}$  to  $-11^{\circ}\text{C}$  (Colbeck, 1985). The apparent explanation for this transition is the development of surface roughening at higher temperatures (Nenow, 1984). Once this layer achieves a sufficient thickness, the dependence of surface free energy on direction in the crystal is greatly reduced and the equilibrium form is well rounded. This explanation itself suggests that only faceted crystals should be observed below  $-11^{\circ}\text{C}$ ; however, there is a second consideration. When two slowly growing, faceted crystals are in contact, the surface area adjacent to the crystal boundary must be rounded (Nelson, Mazey and Barnes, 1965). Therefore we would expect to see at least partly rounded crystals in snow even at low growth rates and low temperatures. While partly rounded and faceted crystals have been observed in snow (Fig. 1), I know of no observations of faceted crystals with rounded portions at grain boundaries at low growth rates and low temperatures. Because of the very long time that it takes for these forms to develop, they may only occur in special situations, such as polar ice sheets.

#### C. Heat and Vapor Flows

Crystal growth in dry snow is a process of continuous sublimation-evaporation from warmer and/or more curved surfaces and condensation on colder and/or less curved surfaces. Since evaporation necessarily requires a supply of heat and since condensation necessarily releases heat, heat flow produced by temperature differences must accompany all crystal growth. Ice is about one hundred times more conductive than air so, if we are considering evaporation off of one side of a grain with the same amount of condensation on the other side, the heat required can readily be conducted through the grain. In general, vapor diffusion is the rate limiting process and heat flow is a lesser consideration in the metamorphism of dry snow. However, to fully appreciate why some grains grow while others shrink and disappear, it is necessary to understand why some grains are in more favorable while others are in less favorable situations. This kind of analysis would necessarily involve heat flow through the ice grains, heat conduction through the air, and latent heat transfer among a complicated geometrical distribution of ice grains. A good place to start such an analysis would be with downward facing grains on which rapid growth is occurring (see drawings of Perla and Martinelli, 1976, p. 46), possibly the branch grains as suggested by Sommerfeld (1983). Analyses of interparticle vapor flux are described later.

Water vapor diffusion through air occurs in response to vapor density gradients according to Fick's law (Dorsey, 1940, p. 72),

$$j = -D\partial\rho/\partial z \quad (8)$$

where  $D$  is the diffusion coefficient for water vapor through the medium. Since a temperature gradient is imposed on snow, we could consider thermal diffusion as well. However, this effect is small

(Bird, Stewart and Lightfoot, 1960, p. 567) and would greatly complicate our problem for very little benefit. The vapor density ( $\rho$ ) depends on temperature according to the ideal gas law and, using Equation (7), vapor flux can be expressed as

$$j = - \frac{D_p}{RT^2} \left( \frac{L_s}{RT} - 1 \right) \frac{dT}{dz} \quad (9)$$

The flux can be expressed more completely by letting  $\rho$  vary with both temperature and curvature (Colbeck, 1982a). Although Gubler (1985) has used this more complete formulation, curvature effects are generally dominated by temperature effects so only the temperature dependence is used here. Equation (9) is often approximated by taking temperature as a constant, in which case Equation (8) immediately reduces to

$$j = - \frac{D}{RT_0} \frac{dp}{dz} \quad (10)$$

where  $T_0$  is some average temperature. While Equation (10) is a good approximation, working in terms of vapor pressure offers no particular advantage over vapor density and, since neither one of them can be directly measured, it is best to work with temperature. To simplify Equation (9) we note that  $L_s \gg RT$  and that  $p_g$  can be approximated as a simple function of temperature, although the equation is easily used in the form given.

The rate limiting process in crystal growth in snow is the slow diffusion of water vapor among surfaces of different temperatures and curvatures. Thus, if air flow were to occur through the pores of snow, there would be a substantial effect on the transfer rate of vapor and possibly on the rate of metamorphism. Perhaps the forced motion of air and not just the reduction in particle size is one reason for the rapid sintering of wind-blown snow.

Attempts have been made in the past to observe natural convection in snow but the critical Rayleigh number for the onset of convection was not exceeded in experiments such as Akitaya's (1974). The appropriate form of the Rayleigh number in a porous medium is (Combarous and Bories, 1975)

$$R_a = \rho \beta g H K \Delta T / \mu K_D \quad (11)$$

where  $\beta$  is the coefficient of thermal expansion of the fluid,  $g$  the acceleration of gravity,  $H$  the depth of the porous layer,  $K$  the intrinsic permeability,  $\Delta T$  the temperature difference across the porous layer,  $\mu$  the fluid viscosity, and  $K_D$  an apparent thermal diffusivity given by  $k/\rho C_p$  where  $k$  is the thermal conductivity of the entire porous medium whereas  $C_p$  is the volumetric heat capacity of the fluid above. In this case  $\rho$  is the air density. Natural convection has been directly observed in snow in the laboratory (Powers, Colbeck and O'Neill, 1985) and examined in numerical

models (Klever, 1985; Powers, O'Neill and Colbeck, 1985). It has recently been observed in the field in interior Alaska (Johnson et al., in press) where Trabant and Benson (1972) suggested that convection was necessary to account for some of their observations.

Although the existence of natural convection in snow is well established, particularly on slopes where Rayleigh convection would occur for any temperature gradient (Powers, O'Neill and Colbeck, 1985), its effect on snow metamorphism is still a matter of speculation. There is greatly increased heat flow above the critical Rayleigh number because Bernard convection occurs and vapor transfer would be enhanced as well. However, at small air velocities the effects of creeping flow severely limit the mass transfer by convection to a single sphere (Acrivos and Taylor, 1962) and thus there may not be a significant increase in crystal growth rate associated with thermal convection. This conclusion is supported by the crystal growth experiments of Keller and Hallet (1982) who found that the forced movement of air affected crystal shape, even when the change in growth rate was small. Their results suggest that the effect of natural convection in snow is not so much to overcome the diffusional limitation and to increase the growth rate as it is to shift the dominant crystal type towards the more spectacular hollow, striated and scrolled forms of depth hoar. At this time much observational evidence is needed to test this suggestion.

#### D. Ice Crystal Growth

The metamorphism of dry snow, which is essentially a phenomenon of ice crystal growth from the vapor, cannot be fully appreciated from considerations of vapor flow alone. de Quervain (1945) recognized this many years ago but not much was known about crystal growth at that time. Many of the observations in snow could have been explained as the science of crystal growth evolved (e.g. Burton, Cabrera and Frank, 1951) but application of information from another field usually lags by a generation or more. Furthermore, most of the information about ice crystal growth could only have been useful qualitatively since the early work on ice crystal growth was done at growth rates and supersaturations relevant to the atmosphere (e.g., Kobayashi, 1961; Lamb and Scott, 1972; Rottner and Vali, 1974). In the snow cover the supersaturations and growth rates are limited by the large surface area available for condensation and the absence of finely dispersed water droplets. Nevertheless, there are three essential areas of ice crystal growth that we must draw from if we wish to understand snow metamorphism. We need to explain the transition from rounded to faceted morphologies with increasing temperature gradient, the dependence of growth rate on temperature, and the relationship between temperature and shape.

The fact that crystals make a sudden transition from their equilibrium form to a kinetic growth form at a critical growth rate has been known for a long time. Ideas about this transition were quantified by Burton, Cabrera and Frank (1951), were reviewed by Hirth and Pound (1963), and were recently updated by Bennema (1984). This transition is manifested in snow by the critical temperature gradient for the rapid growth of faceted crystals which has been reported to be around  $10^{\circ}\text{C m}^{-1}$  (LaChapelle and Armstrong, 1977) but is apparently somewhat greater in high density

snow. As described later, the crystal growth rate in snow increases directly as the temperature gradient so the transition from rounded to faceted crystals with increasing temperature gradient is expected. To quantify the critical supersaturation (or at a given temperature, the critical growth rate) at which the morphological transition takes place, I did a set of crystal growth experiments similar to the ones done by atmospheric physicists but at lower growth rates (Colbeck, 1983a). The results, shown in Figure 2, exhibit a clear transition from rounded to faceted crystals with increasing vapor density difference (which drives the growth) at temperatures above  $-10^{\circ}\text{C}$ . Some of the more rapidly growing crystals at these higher temperatures even had the hollow and striated features of depth hoar.

The problem with using these results is that the vapor density difference, the difference between the actual vapor density of the air surrounding the crystal and the equilibrium vapor density at the crystal surface, is not equivalent to the supersaturation that drives the growth. Supersaturation is by definition the fractional, excess vapor pressure at the crystal surface, excess meaning above the vapor pressure required for phase equilibrium at the surface temperature. Here we use both vapor density difference ( $\Delta\rho$ ) and excess vapor density ( $\rho'$ ) which is the vapor density equivalent of supersaturation although  $\rho'$  is not expressed in fractional form.

To convert the data shown in Figure 1 into a useful format, a model of crystal growth is required. Based on the known influences on ice crystal growth, we take the mass growth rate as

$$\dot{m} = c \tau (T) A (\rho')^2 \quad (12)$$

where  $c$  is a constant found from the experiments,  $A$  is the crystal area, and  $\tau(T)$  is a function of temperature. The temperature dependence of growth rate was determined in a general way by Lamb and Hobbs (1971). The quadratic dependence on excess vapor density was suggested for low growth rates by Burton, Cabrera and Frank (1951) and was observed by Beckmann and Lacmann (1982). Using this formula and the experimental data, the critical excess vapor density for the onset of faceted crystal growth is shown to be 5 to  $6 \times 10^{-4} \text{ g m}^{-3}$  and to vary rather little with temperature. Thus while the critical growth rate strongly increases with temperature over the primary range of interest in snow studies, the critical excess vapor density does not. This suggests that faceted crystal growth should occur more readily in the upper portions of a snow cover consisting of a regular distribution of equal spheres with a linear temperature gradient. However, the growth actually occurs very much more rapidly near the bottom where the temperatures are higher. Thus Seligman (1936) suggested "depth hoar" because the crystals develop first in a warmer layer at the bottom and then sweep upward into colder portions where crystals take more time to develop. This discrepancy is discussed later.

The other effect of temperature on ice crystal growth has already been mentioned. At temperatures below  $-10^{\circ}$  to  $-11^{\circ}\text{C}$ , all single

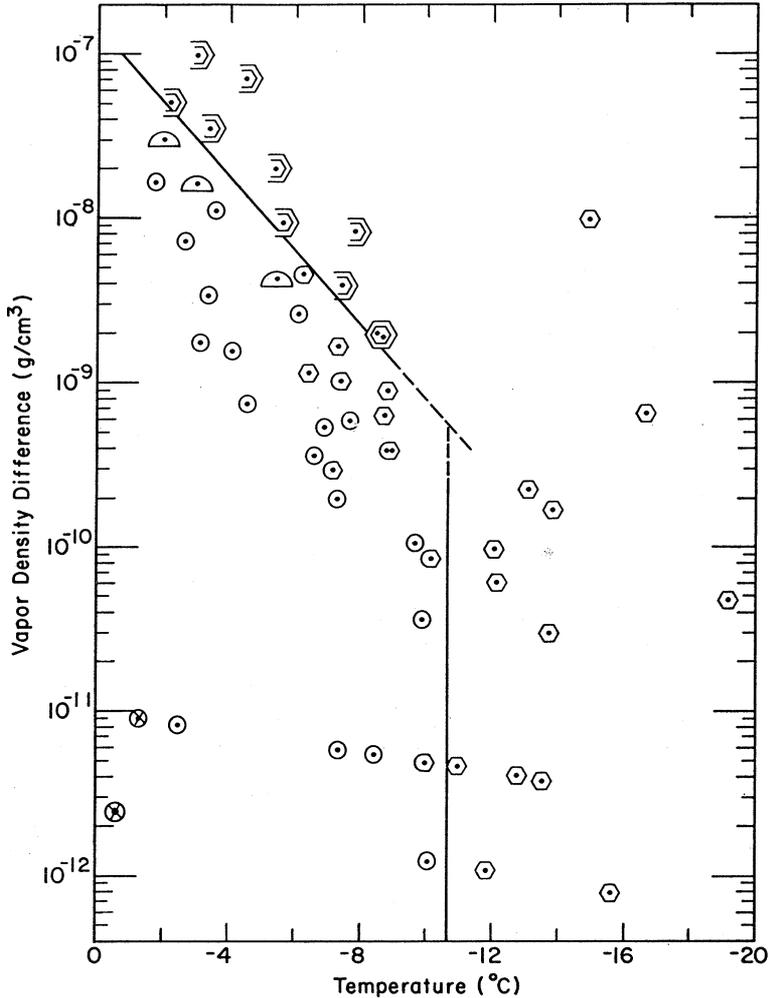


FIG. 2 Crystals grown at various vapor density differences and temperatures (from Colbeck, 1985). The rounded and faceted symbols indicate the degree of rounding of the crystals. Hollow and striated crystals are also indicated.

crystals are faceted. It is clear that a transition occurs between the faceted, equilibrium form at low temperatures and the kinetic growth form of high growth rates because surface hoar grows at these low temperatures at very high growth rates. Also, Akitaya (1974, p. 28) shows a transition from solid to sector crystals with increasing temperature gradient below  $-10^{\circ}\text{C}$ . However, the position of the transition from equilibrium to kinetic-growth form is not clear from either the data shown on Figure 1 or Akitaya's results. Thus additional work needs to be done at these lower temperatures. It is also unclear what shape multiple-crystalline aggregates will have at low temperatures since the surfaces adjacent to the grain boundaries must be curved.

There is a great deal of work now being done on the growth of ice crystals although most of it continues to be done at supersatura-

tions which are too high for direct application of the results to our problem. However, the work must be closely monitored (e.g., Gonda and Namba, 1981; Kuroda, 1983; Wang, Chuang and Miller, 1985).

#### E. Observations of Metamorphism

Reports of observations of snow cover crystals first appeared in the middle of the 19th century (e.g., Ladame, 1846; Wolley, 1858). These were supplemented by laboratory observations much later (e.g., Bader, 1939) and a steady production of both field and laboratory observations has occurred ever since.

Bader (1939) isolated single snowflakes and watched their "destruction" with time. Once the rapid growth of any crystal ceases, the morphology changes toward the equilibrium form. In Bader's experiments this happens very slowly because the isolated crystals had no warmer neighbors from which to draw vapor as suggested by Yosida's (1955) "hand-to-hand delivery of water vapor." Nevertheless, it is misleading to think of Bader's isolated snowflake as undergoing "equitemperature" metamorphism as labeled by Sommerfeld and LaChapelle (1970); temperature variations around the snowflake drove its destruction. It is evident from Bader's data that the rate of metamorphism decreases very rapidly with temperature, at least in the range of  $-2.5$  to  $-11.5^{\circ}\text{C}$ . This drop is mostly due to the effect of temperature on crystal growth rates, although temperature also affects the vapor pressure dependence on curvature (Eq. 5). This temperature dependence can also be seen in the results of Yosida and Colleagues (1955).

Yosida's (1955) observation of snow metamorphism under the influence of an imposed temperature gradient shows faceted crystals growing under high temperature gradients ( $15^{\circ}$  to  $70^{\circ}\text{C m}^{-1}$ ) and rounded crystals growing under a lower temperature gradient ( $6^{\circ}\text{C m}^{-1}$ ). These experiments nicely illustrate the growth forms at high and low growth rates although some caution must be exercised in interpreting such experiments because the distance between coupled crystals as well as the temperature gradient influence the growth rate of any individual crystal. Yosida found similar behavior in the snow cover, observing the rapid destruction of dendrites and the general growth of crystals thereafter. de Quervain (1958) found more rapid growth of depth hoar at  $70^{\circ}\text{C m}^{-1}$  than at  $18^{\circ}\text{C m}^{-1}$  and, of course, a complete lack of faceting when he removed the temperature gradient. His results show no particular effect of overburden pressure on the development of the crystals although these experiments can be difficult to interpret because overburden pressure increases the snow density and reduces the spacing among the crystals, a condition which favors the growth of rounded, rather than faceted crystals. The overburden pressure *per se* should have little effect on crystal growth since, for crystals which are visible with a microscope, stress has rather little effect on chemical potential (Cabrera, 1964). Nevertheless, Yosida (1955) felt that elastic stresses could affect very thin and highly stressed ice crystals, such as where fresh snow overhangs the edge of a roof.

Trabant and Benson (1972) showed that mass is removed from the lower portion of a snow cover subjected to a large temperature gradient. Thus the normal density profile of the snow is disrupted by the continuous upward transport of vapor at rates which, for very

high temperature gradients (e.g.,  $60^{\circ}\text{C m}^{-1}$ ), suggest natural convection. Akitaya (1974) found that hollow crystals develop only at the higher growth rates represented by temperature gradients above about  $20^{\circ}\text{C m}^{-1}$  and that solid faceted crystals develop at  $17^{\circ}\text{C m}^{-1}$ . Akitaya (1974) found that at a temperature gradient of  $50^{\circ}\text{C m}^{-1}$  solid prisms instead of open cups grew below  $-10^{\circ}\text{C}$ , just as Colbeck (1985) observed in single crystal growth. In open cavities where the most spectacular crystals should grow because of the large separation between source and sink (Colbeck, 1983b), Akitaya (1974) found a variety of forms, including needles. Since then Marbouty (1980) has suggested that these forms correspond to the forms seen in the atmosphere at corresponding temperatures. Marbouty also found that the growth rate increased with the applied temperature gradient and with temperature itself. The crystal growth rate decreased with increasing density and depth hoar disappeared altogether above  $350\text{ kg m}^{-3}$ . Marbouty's (1980) work has helped to quantify a number of important things about crystal growth in snow. More work is needed to quantify such things as the effects of density on the critical temperature gradient that divides rounded and faceted crystal growth in snow. Unfortunately, not much experimental work has been done at low temperature gradients because of the long time periods necessary to achieve results, but much of the work done at higher temperature gradients does not reflect the situation in nature.

One of the original motivations for studying the growth of faceted crystals in snow was to understand the role of weak layers in the release of avalanches. At low temperature gradients snow gains strength by sintering, the process by which the ice grains are welded together by the movement of water molecules to the intergranular contacts. Using concepts from equilibrium thermodynamics, which are clearly applicable at low growth rates, the equilibrium vapor pressure is lower over the concave surface at a grain bond and hence water molecules migrate there by vapor diffusion. Thus at low growth rates, snow develops a "slab" strength. At large growth rates where the supersaturation over the surface is high enough that the shape of a crystal is no longer dictated by phase equilibrium principles, there is no reason to think that bonds should form by sintering. If they do form between two of the more slowly growing grains, they would probably be eliminated when these grains are consumed by the faster growing grains. The fastest growing grains, the most highly faceted ones, probably grow into large pores (Sommerfeld, 1983; Gubler, 1985) where they fail to form contacts with other grains. Bradley, Brown and Williams (1977) have shown that the strength of snow does not weaken continuously as faceted grains grow but that there is an apparent minimum in the strength associated with an intermediate stage in the development of hollow, striated crystals.

These and other gaps in our knowledge about crystal growth in snow over the full range temperature gradients can only be understood by detailed examination of the crystals in conjunction with the property measurements. To facilitate this kind of work, snow scientists are using stereology, which can provide insights into the structure but is difficult to do and has very definite limitations

(discussed by Kry, 1975a; 1975b). Nevertheless, Kry (1975a; 1975b) was able to conclude a variety of things about the mechanical properties, snow structure, and the nature of chains of grains in snow that point the way to a better understanding of how the structure affects the complicated heat and vapor flows that determine crystal growth. For example, Perla (1985) was able to suggest that the surface area per unit mass decreases with time even under the influence of a temperature gradient of  $1000^{\circ}\text{C m}^{-1}$ . Thus the system moves towards a lower energy state by growing larger grains even though the new grains are hollow and striated.

#### F. Models of Metamorphism

A satisfactory understanding of the ever changing crystals in snow and the effect of these changes on the properties of snow could not be achieved without quantitative application of the thermodynamics discussed in the early work on metamorphism. The first attempt at modeling may have been Bader's (1939) description of the flow between parallel ice plates. This geometry nicely illustrates the principle of vapor flow between two surfaces at different temperatures, but grossly misrepresents the shape and the magnitude of the flow field. Snow consists of particles, not parallel plates, and flow between two particles depends on their size, shape and separation as well as on their temperature difference. Nevertheless, de Quervain (1963) successfully extended this approach to illustrate qualitatively favorable positions for evaporation and deposition, and Adams and Brown (1983) used a parallel plate model to suggest levels of rapid growth due to the effects of layering. According to Gubler (1985), an expanded version of the latter model confused supersaturation with vapor density difference and compared ice crystals grown at relatively large supersaturations with those grown in the snow cover (Adams and Brown, 1982).

Sommerfeld (1983) started with one-dimensional vapor flux, which can only apply to infinite, parallel plates, and then arbitrarily added factors to construct a model which probably has no physical meaning. Further complicating acceptance of this model is that it relies on data taken from wedge-shaped thin sections of snow. The data were analyzed on a system developed by Good (1980), which requires an arbitrarily chosen discrimination level, a feature which presents no special problems as long as the sections are prepared carefully (Perla, 1985). Other objections to Sommerfeld's model are given by Gubler (1985).

Another approach to understanding snow metamorphism, the continuity model, was largely doomed from the start. Taking diffusion as

$$j = -D \partial \rho / \partial z \quad (8)$$

and the conservation of mass as

$$\frac{\partial j}{\partial z} + \frac{\partial \rho_s}{\partial t} = 0 \quad (13)$$

where  $D$  depends on porosity and  $\rho_s$  is snow density, we find

$$\frac{D}{RT_0} \frac{\partial^2 \rho}{\partial z^2} = \frac{\partial \rho_s}{\partial t} \quad (14)$$

Taking vapor pressure from the Clausius-Clapeyron Equation and using the ideal gas law, the left hand side of this equation can be expanded to give a value for the rate of increase of snow density in a medium with no boundaries. However, for a linear temperature gradient of  $20^{\circ}\text{C m}^{-1}$ , de Quervain (1963) has shown that the rate of increase in density is only micrograms per  $\text{mm}^3$  per year and Yosida (1955) measured a similar amount. Therefore, an average particle sees very little mass gain from the forced condensation associated with a normal temperature gradient. It has been repeatedly shown that snow is not strongly densified by temperature gradients (e.g., Armstrong, 1980) and so the dimensionless accumulation rates derived by Palm and Tveitereid (1979) are unlikely to be relevant to metamorphism.

Giddings and LaChapelle (1962) developed a version of the continuity approach but actually constructed a model directly from an expanded version of Equation (10). As Sommerfeld (1983) states, Giddings and LaChapelle made the unrealistic assumption that the water vapor diffusing upward all stops at one level. This would be true and use of the one-dimensional diffusion equation would be valid if snow consisted of parallel plates of ice. Since this is clearly not the case, both the models of Giddings and LaChapelle (1962) and Sommerfeld (1983) have a limited physical basis.

Yosida (1955) clearly showed an understanding of the role of particle-to-particle interactions in snow and Perla (1978) was the first to really model snow as consisting of particles. While Perla's equations must be used carefully because the thermodynamics is not always expressed correctly, the conclusions do provide some important insights into the metamorphism of dry snow. In particular, beyond contributing to the elimination of the initial dendrites in fresh snow, the effect of curvature can largely be ignored compared to the effect of temperature differences arising from the imposed temperature gradient. Colbeck (1980) refined this conclusion by comparing the role of heat flow to that of vapor flow in the destruction of a snowflake held in isolation as in Bader's (1939) experiment. As stated before, this process requires heat flow and temperature differences and should not be called "equi-temperature." The suggestion has also been made that nothing need be considered in the elimination of small particles except the reduction in surface free energy associated with the increase in the average grain size. This assertion can be easily disproved by comparing the surface free energy liberated with the latent heat of sublimation required to eliminate a sphere, or  $4\pi R^2\sigma_{gs}$  versus  $4/3\pi R^3\rho_i L_s$ , where  $R$  is radius and  $\rho_i$  is ice density. The energy available is only greater than the energy consumed for spheres of less than  $1.2 \text{ \AA}$ , or about the size of a water molecule! Thus metamorphism is always driven by heat flow resulting from temperature differences, even when only rounded crystals result.

The first treatment of metamorphism under an applied temperature gradient drew from Yosida's (1955) description of "the hand-to-hand delivery of water vapor" and Marshall and Langleben's (1954) model of crystal growth in the atmosphere. Colbeck (1983b) constructed a model of crystal growth in snow where the interparticle vapor flow could be calculated from the capacitance of two particles. Since

capacitance ( $4\pi C$ ) is available from well-known formulae which include the effects of spacing, shape and size, the mass growth rate of two isolated particles can be readily calculated from

$$\dot{m} = 4\pi CD(\Delta\rho - \rho') \quad (15)$$

where  $\Delta\rho$  is the vapor density difference between two particles at different temperatures and  $\rho'$  is the excess vapor density, or the supersaturation just over the ice surface.

Although  $\Delta\rho$  is only slightly greater than  $\rho'$  in most crystal growth experiments,  $\Delta\rho$  is much greater than  $\rho'$  in snow because the growth rate is limited by vapor diffusion between crystals rather than the kinetics of growth on the crystal surface. Accordingly, in snow the mass growth rate of a grain can be determined from temperature differences and geometry. Unfortunately, this calculation is greatly complicated by two problems - finding the temperatures of individual grains and having to approximate grains in chains as isolated units. The first problem is treated by assuming that ice is infinitely more conductive than air (actually about 100 to 1) and that the temperature of an ice grain is set by the average temperature in the snow at the height of the middle of the grain. Clearly more realistic treatments could be made if more were known about grain chains, especially end grains. Gubler (1985) develops this approach in more detail. The second problem also requires more information about snow structure although a series of calculations (Colbeck, 1983b) did show that there is a very strong tendency for particles to couple with one or a few particles directly beneath them. Thus if branch grains or end grains are preferential sites for rapid growth, the simple coupling among two or a few particles can be described reasonably well by the capacitance model. The capacitance approach treats the snow compact as discrete grains and construction of a complete model would require some arbitrary choices which should be improved through a better understanding of the structure of snow.

In addition to crystal growth rate, we are interested in crystal shape. The transition between rounded and faceted ice crystals occurs at an excess vapor density of  $5$  to  $6 \times 10^{-4} \text{ g m}^{-3}$  (i.e., supersaturation of about  $2 \times 10^{-4}$ ) as described earlier. The excess vapor density can be calculated for any matched source and sink by combining Equations (12) and (15) to eliminate  $\dot{m}$ . This model, an equation for  $\dot{m}$  and one for  $\rho'$ , shows that  $\dot{m}$  increases as  $\Delta\rho$ , which in turn increases as the temperature gradient since  $\Delta\rho$  equals  $(d\rho/dt)\Delta T$ , for any given geometry. Thus the crystal growth rate should increase as the temperature gradient whereas the excess vapor density increases at  $T^{1/2}$  (Colbeck, 1983b). These relationships would seem to explain much of what has been observed in snow although calculations of mass growth rate and critical supersaturation underestimate the measured values by about 50 percent. What is worse, application of these relationships to a simple geometrical model indicates that faceted crystals should grow at lower temperatures rather than at higher temperatures as observed. These discrepancies can be easily eliminated by allowing the separation of particles in snow to be represented by a statistical distribution

(Colbeck, 1983b). Clearly the sources and sinks in snow are distributed since examination of a sample of snow with predominantly rounded grains will usually reveal the existence of isolated faceted grains. Presumably these are the grains most favorably situated for rapid growth. Unfortunately, Colbeck (1983b) chose a distribution arbitrarily so the results cannot be quantitatively significant until that arbitrariness is removed. The model does, however, explain the more rapid growth of faceted crystals in the lower portions of the snowcover because of the higher temperatures, the lack of depth hoar in high density snow because of the small interparticle distances, and the increase in mass growth rate and faceting with increasing temperature gradient because of the higher temperature differences.

Gubler (1985) extended the capacitance approach by developing a model that can be related to measurable stereological parameters. As shown in Figure 3, Gubler considered source and sink grains in coupled pairs but made the structure more sophisticated by stressing the lack of growth of inert grains in the clusters to which source and sink are attached. In developing his ideas about interparticle relationships, he suggested that net growth diminishes once the grains are large enough to serve as source and sink simultaneously. This and other ideas lend themselves to testing in controlled laboratory experiments.

Gubler (1985) convolutes the size distribution function of growing and shrinking grains while keeping track of the fractions of growing, shrinking and inert grains. From this model he shows how

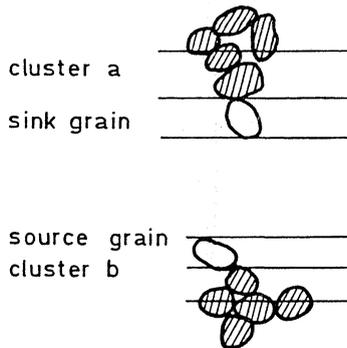


FIG. 3 A possible arrangement of source and sink grains from Gubler (1985).

the grain size distributions could evolve with time at very high and very low temperature gradients. Unfortunately the model does not fully consider the dependence of the growth rate on the sink-source particle geometry, which also evolves with time. He does show, however, that at large temperature gradients the fraction of growing particles is only a few percent, which is compatible with the need for only a small percentage of the initial grains to survive a large increase in average grain size. At low temperature gradients, on

the other hand, several tens of a percent of the grains may be slowly growing. This difference causes significant differences in the predicted size distributions. At large temperature gradients the size distribution initially develops a tail towards large sizes but much later becomes nearly symmetric as all particles get involved.

Whether or not these detailed predictions of size distributions prove to be true, the modeling of snow metamorphism has definitely grown beyond the stage of the one-dimensional diffusion equation describing vapor flow between parallel ice plates. Diffusion among multiple particles in other systems is now handled in more sophisticated ways (e.g., Jagannathan and Wey, 1981) but in snow, where the process is driven by an imposed temperature gradient, the approach of coupled pairs of grains is more attractive. The challenge at this point is to make the geometrical basis more realistic and to do the laboratory testing of the model predictions.

#### G. Surface Processes

Many things happen on the surface of the snow cover which are peculiar to the surface - solar melting, wind breakage, surface hoar growth and condensation. These were described earlier (Colbeck, 1982b) and, while these phenomena are very important to snow slope stability because former surfaces often become buried planes of weakness, rather little work has been done on metamorphism in these layers. It would be very important, for example, to observe the metamorphism in a buried layer of surface hoar. Surface hoar grows as highly faceted crystals and bonds rather poorly once buried, perhaps because large particles sinter very slowly. Whatever the reason, direct observations of this and other surface phenomena are needed. Perhaps more studies of surface phenomena have not been made because of the need to understand all of the things discussed in this paper plus the micrometeorology close to the surface. It is clear, for example, that the growth of surface hoar is not diffusion-limited but must involve slight air currents, the surface energy and mass balances, and rapid crystal growth.

### Metamorphism of Wet Snow

#### A. Perspective

Interest in wet snow has long lagged that of dry snow although wet snow is, if anything, of more importance to some topics (e.g., hydrology) than dry snow. Early observations of wet snow often centered around its compaction into ice on glaciers (Ladame, 1846). Seligman (1936) observed wet snow and speculated about its structure but not to the extent that he observed the spectacular depth hoar crystals. The establishment of the snow laboratories in the western United States in the 1940's intensified observations of wet snow (e.g., Gerdel, 1945). Its layering and drains were observed but still not much was said about its crystallographic development. This changed when the Japanese, who have enormous problems with wet snow, began (e.g. Wakahama, 1963) an intensive series of observations which continue today. In the 1970's much of the basic physics of wet snow was developed so that wet snow could be described in a more quantitative way.

### B. Role of Equilibrium Thermodynamics

Metamorphism happens more quickly as the melting temperature is approached. However, the large temperature variations of dry snow are impossible in wet snow so the largest crystals actually grow below the melting temperature. To understand this enigma, we must understand the nature of three-phase equilibrium with curvature. When the Gibbs Function is minimized there are three equations,

$$v_g dp_g - S_g dT = v_l dp_l - S_l dT = v_s dp_s - S_s dT \quad (16)$$

and three Laplace Equations,

$$p_s - p_g = \frac{2\sigma_{sg}}{r_{sg}} \quad (17)$$

$$p_s - p_l = \frac{2\sigma_{sl}}{r_{sl}} \quad (18)$$

and

$$p_g - p_l = \frac{2\sigma_{gl}}{r_{gl}} \quad (19)$$

Each mean radius is defined as in Equation (3).

Not as much use has been made of these relationships as their counterparts in dry snow. Several derived relationships are particularly useful, however, and are used below. Details of these derivations are given elsewhere (Colbeck, 1973, 1979). At high liquid contents where air occurs in isolated bubbles, the melting temperature is given by

$$T_m = \frac{2T_o}{L} \left( \frac{1}{\rho_s} - \frac{1}{\rho_l} \right) \frac{\sigma_{gl}}{r_{gl}} - \frac{2T_o}{L\rho_s} \frac{\sigma_{sl}}{r_{sl}} \quad (20)$$

where  $L$  is the latent heat of fusion,  $r_{gl}$  is the mean curvature of the air bubbles, and  $r_{sl}$  is the mean curvature of the ice particles. When no air is present in the snow, this reduces to the well-known relation which accounts for rapid grain growth in water-saturated snow (Wakahama, 1968).

In freely draining snow where the liquid content is typically five percent by volume, the air is continuous throughout the pore space. The liquid content is directly related to its pressure which is commonly reported as capillary pressure, where

$$p_c = p_g - p_l \quad (21)$$

The air pressure is atmospheric pressure but the liquid pressure is less because of the convex curvature of the liquid inclusions. The melting temperature is determined by the liquid content and ice particle size according to

$$T_m = -\frac{T_o}{\rho_1 L} p_c - \frac{2T_o}{\rho_s L} \frac{\sigma_{gs}}{r_{sg}} \quad (22)$$

and the geometry of the three phases is constrained to

$$\frac{\sigma_{sg}}{r_{sg}} + \frac{\sigma_{gl}}{r_{gl}} = \frac{\sigma_{sl}}{r_{sl}} \quad (23)$$

The geometry of wet snow at low liquid contents is particularly important because the ice crystals cluster together to form well-bonded units (see Fig. 4) which have very different mechanical properties than the individual crystals in water-saturated snow (see Fig. 5). In the latter case the grain boundaries are unstable and melt out easily, whereas in the unsaturated case the system of bonded crystals has some strength. This difference is often thought to account for the release of wet snow avalanches by failure of water-saturated layers in the snow cover.

The geometrical details of the clustering of ice crystals surrounded by small amounts of liquid water are given by Colbeck (1979). The geometry is dictated by the pressure-curvature relationship for each of the three kinds of surfaces, the contact angle

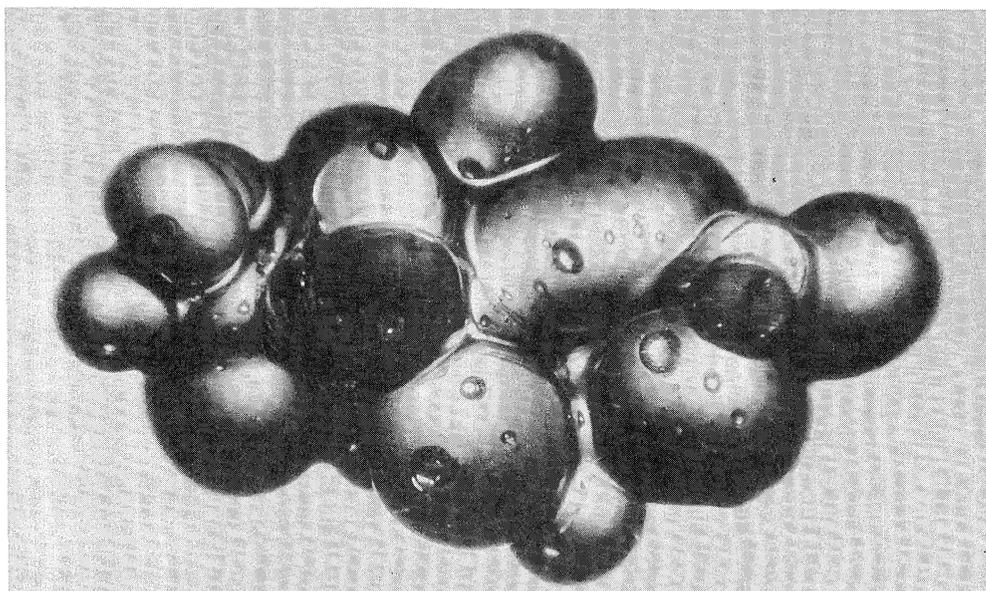


FIG. 4 A cluster of ice crystals with attached liquid water in freely draining, wet snow. These clusters do not arise from melt-freeze cycles but because they minimize surface free energy.

of ice on water, the dihedral angle in a liquid-filled grain boundary groove, and the need to match the three phases at triple junctions. The geometries dictated by these requirements are shown by

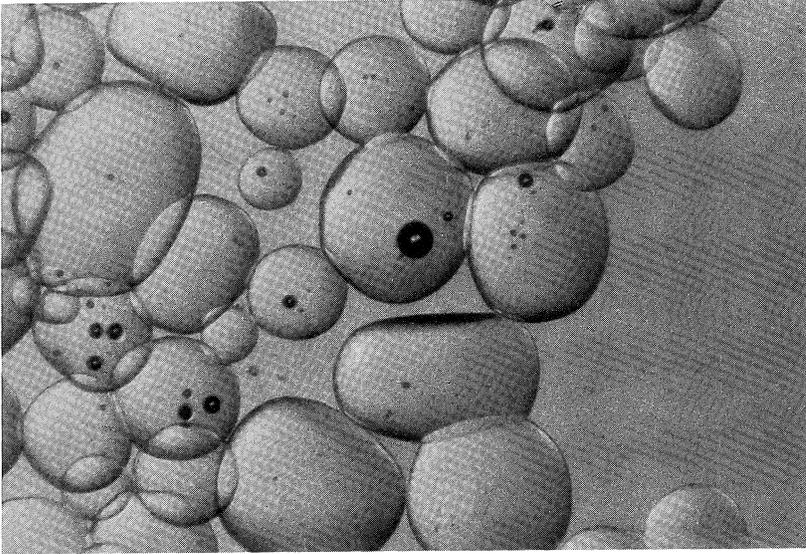


FIG. 5 Slush is a collection of poorly bonded ice crystals soaked with water.

the tightly packed clusters of grains that are common in wet snow. At least since the days of Ladame (1846), these clusters of grains have been associated with melt-freeze cycles but they actually arise to minimize the surface free energy. The role of melt-freeze cycles is described later.

#### C. Grain Growth

Wakahama (1965, 1968) made the first quantitative observations of grain growth in wet snow. He found more rapid growth at higher liquid contents showing not only the mean, but the distribution of sizes as well (which still has not been done in dry snow!). Unaware that such modeling of coarsening in similar systems had already been done (e.g., Lifshitz and Slyozov, 1961; Wagner, 1961), Colbeck (1973) constructed a simple model of two particle interactions in order to explain such behavior as the accelerating shrinkage rate as the smaller particles disappear. While much agreement exists between the models and observations, it is very important that the distributions of particle sizes predicted by these models (commonly known as LSW theory) and more recent versions of those models are widely different than the observed distributions. Thus interest in grain coarsening in water-saturated snow arises in part because data from snow provide a test of ideas developed in other fields. Besides applying results from wet snow to other fields, the study of grain growth in water-saturated snow tests our ability to understand the simplest case of snow metamorphism. In snow saturated with pure water, the grains have the simplest shape, the porosity is constant, and we do not have to worry about mass diffusion since the "medium is the message."

Raymond and Tusima (1979) extended Wakahama's observations to include the effect of soluble impurities on grain growth. These reduce the growth rate by reducing the temperature differences among particles of varying curvature. Since the impurities must diffuse

away from a growing particle and to a shrinking particle, each particle has an impurity field around it which reduces its melting temperature by some amount depending on its size and rate of change of size. The particle size distributions for coarsening in solutions are also different than the prediction of the LSW theory, thus suggesting that the classic theory is in error for both diffusion-controlled and interface-controlled coarsening in compacts.

Raymond and Tusima observed a linear dependence of growth rate on time as predicted by LSW theory, and Colbeck (1986a) has shown that this dependence is quasi-linear over more than one thousand hours. Also as predicted by LSW theory, Raymond and Tusima (1979) found that the distribution established a steady shape. Although Raymond and Tusima used another distribution, Colbeck (1986a) found that the log-normal distribution fit his data very well as shown in Figure 6. The data from coarsening at nine times between 1 min and 1028 hours are shown after normalizing to the mean value at each time. The fact that the normalized distribution can be characterized as

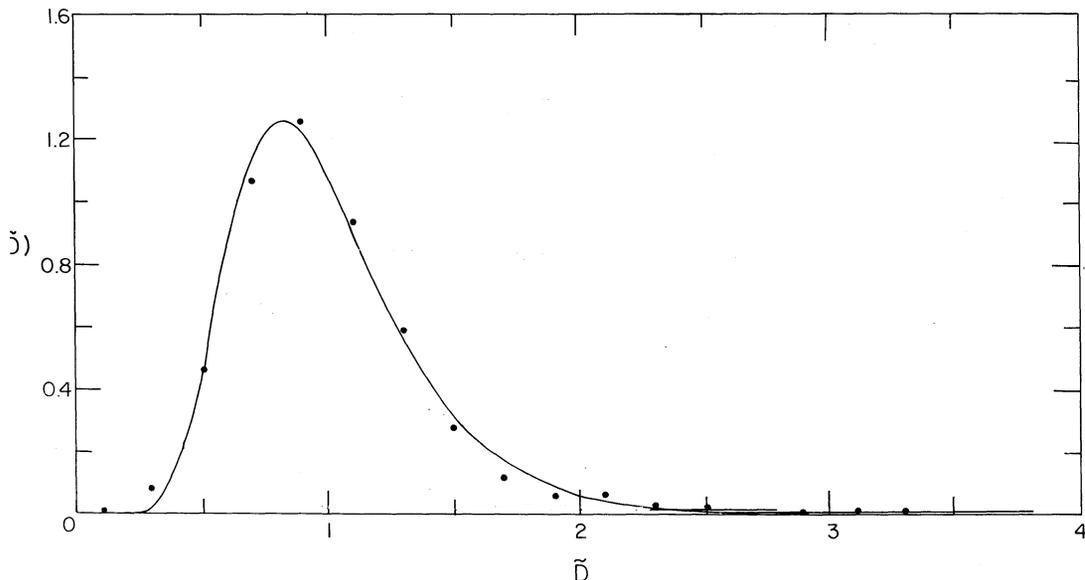


FIG. 6 Coarsening data from Colbeck (1986a) normalized to the mean value at each time. The data are compiled from nine time steps.

stationary in time gives a very powerful assist to analyzing the metamorphism of water-saturated snow because the log-normal distribution has well-known moments and the invariance makes the mathematics much easier. It would certainly be convenient if the same thing could be shown for dry snow metamorphism.

The normalized distribution for water-saturated snow is

$$f(\ln \tilde{D}) = \frac{1}{\sqrt{2\pi}} \frac{1}{\ln \sigma} e^{-\frac{1}{2} \left( \frac{\ln \tilde{D}/\tilde{D}_g}{\ln \sigma} \right)^2} \quad (24)$$

where  $\bar{D}$  is  $D/\sigma$ ,  $\sigma$  is the geometric standard deviation equal to 1.460,  $D_g$  is the geometric mean value of 0.931, and  $\bar{D}$  is the mean value which increases according to

$$\bar{D} = \bar{D}_0 + 0.132 t^{0.362} \quad (25)$$

where  $D_0$  was about 0.2 mm and  $t$  is in hours. Mass is conserved in the stationary distribution when

$$\frac{\partial n}{\partial t} + \frac{\partial q}{\partial \ln D} = 0 \quad (26)$$

where  $n$  is the number density equal to  $fN$ , and  $q$  is the flux of particles through the distribution, or  $nV$  where  $V$  is the rate of change of size of particles of a certain size.  $N$ , the total number of particles, is always decreasing so  $n$  decreases steadily even though  $f$  is fixed. By combining Equations (24) and (26), it is possible to show that in real dimensions,

$$\frac{\dot{\bar{D}}}{\dot{D}_g} = \frac{D}{D_g} (1 - 3(1 - F)/f) \quad (27)$$

where  $F$  is the fraction of particles below  $D$  in size. This relationship between growth rate and size shows that  $\dot{D}$  goes to negative infinity as the particles vanish and that  $\dot{D}$  passes through zero just above  $\bar{D}$ . The first conclusion was shown by LSW theory and Wakahama's experiments but the second conclusion was not so obvious. It was usually assumed that  $\dot{D}$  vanished at some convenient value such as  $\bar{D}$  or  $\bar{D}^2/\bar{D}$ . However, the major difference between Equation (27) and LSW theory is that the theory requires the growth rate to vanish at great size whereas Equation (27) suggests that growth rate increases linearly above a size of  $1.5 \bar{D}$ . This difference largely accounts for the difference between the observed and the LSW predicted size distributions.

Even the more recent versions of the LSW theory (e.g., Brown, 1985) do not allow for contacting particles, which is clearly the case in compacts. Until this deficiency is corrected, the models cannot hope to duplicate the processes in a compact. In the water-saturated case this will be difficult because of the lack of information about how the number of contacting and near contacting neighbors varies with particle size, particle size distribution and porosity. In the case of freely draining snow the problems are even more difficult because the pore space is not filled with liquid water through which the heat can readily diffuse and the crystals cluster together in groups whose configuration is well known but whose size is highly variable. In fact the only thing we do know about grain growth at a low liquid content is that the growth rate in snow is much less at the lower liquid values (Wakahama, 1968). This is not surprising because of the disruption of the liquid path although the temperature dependence on size is higher at low

liquid contents. Whereas in water-saturated snow the melting temperature decreases with crystal size as  $2T_{0sl}/L\rho_s$ , at low liquid contents the melting temperature decreases as  $2T_{0gs}/L\rho_s$ , so temperature difference between similar sized pairs is three times greater in unsaturated snow. Clearly the lack of a continuous liquid path is more important than the larger temperature differences.

Raymond and Tusima (1979) quantified the dependence of growth rate on impurity levels and the dependence on size is given by Equation (27). There is not a great deal more we need to know about grain growth in water-saturated snow, but certainly more effort on unsaturated snow would be nice. Wakahama (1968) observed the growth rate at low liquid contents but application of Equation (22) to understand the heat and mass flow is necessary. Further progress on either the saturated or unsaturated cases depends on getting more information about intergranular contacts.

#### D. Melt-Freeze versus Surface Free Energy

There is a longstanding myth in snow studies that melt-freeze cycles are necessary for development of the grain clusters commonly observed in wet snow (Ladame, 1846). As stated above, the distinctive clusters like the one shown in Figure 4 arise from the minimization of surface free energy and can be grown in the laboratory without melt-freeze cycles (Colbeck, 1979). Clusters of two-to-many crystals form in configurations which are the equilibrium form for that number of crystals of the specified sizes and have an arrangement which is similar to soap bubbles except that crystals have liquid-filled veins at triple junctions (Smith, 1948) and liquid fillets along crystal boundaries. These internal veins and external fillets are quickly frozen when the temperature drops and are not necessarily completely re-formed when the melting temperature returns. Since the distinctive shape shown in Figure 4 is the equilibrium form for that particular collection of crystals, that shape

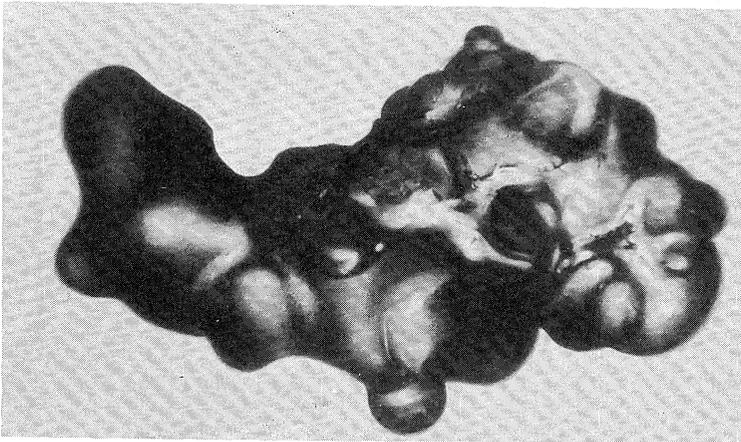


FIG. 7 A grain cluster after several melt-freeze cycles. The individual single crystals are not distinguishable in this particle.

will return with internal liquid veins and external fillets if given enough time at the melting temperature. The absorption of solar radiation greatly speeds the process of internal melting (Langham, 1975) but, if melt-freeze cycles occur too quickly for the equilibrium form to redevelop, the cluster will lose its distinctive shape and adopt the amorphous appearance shown in Figure 7. Besides the absence of internal veins in the melt-freeze particle shown on Figure 7, the most notable feature is the lack of visible single crystals as shown in Figure 4. A sequence of photographs of the conversion of a grain cluster (like the one in Figure 4) into a melt-freeze particle (like the one in Figure 7) can be seen in Colbeck (1982b).

In a snow cover experiencing repeated melt-freeze cycles, there is generally a mixture of these two types of grains (see Fig. 8). This mixture, like mixtures of rounded and faceted grains in dry snow, makes classification difficult.

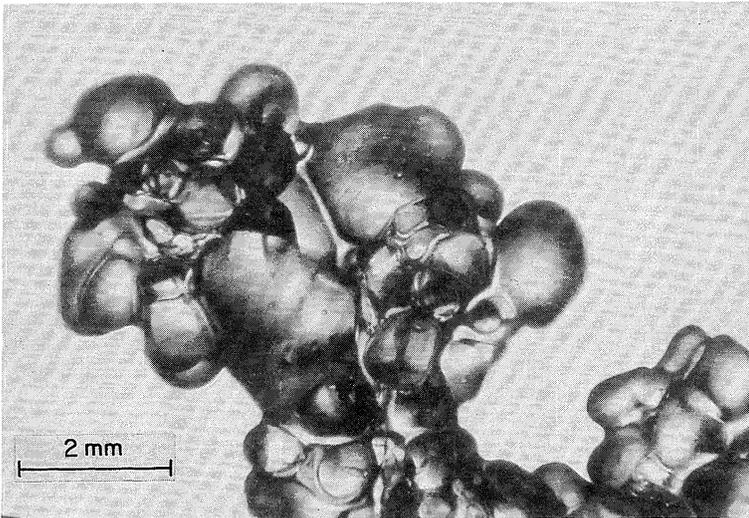


FIG. 8 A mixture of melt-freeze and pure grain clusters are commonly seen in wet snow.

### Classification of Seasonal Snow

#### A. Perspective

The classification of snow is necessary for a wide variety of snow studies but has been pursued mostly by the avalanche community. Nevertheless, we should remember that a classification system must be based on fundamental principles in such a way that it accurately represents both the appearances and the processes, regardless of the application.

Various researchers have classified snow (e.g., Paulcke, 1933; Eugster, 1950; TCSI, 1954; Sommerfeld and LaChapelle, 1970) but older terms must be occasionally examined in view of current thinking. Most of the material given in this review was developed and/or

applied to snow after 1970 so it is not surprising that I would classify snow differently today than Sommerfeld and LaChapelle did in 1970. A further reason to reclassify snow is that use of such terms as equitemperature metamorphism (ET) to describe rounded crystals in dry snow has led to the widespread misconception that depth hoar should develop at any temperature gradient. Since this is clearly not true (e.g., Yosida and Colleagues, 1955), Colbeck (1986b) proposed a new set of terms to describe snow and those terms are reviewed here.

#### B. Dry Snow Terms

In the simplest sense, dry snow can be divided into rounded and faceted crystals. Rounded crystals develop at lower growth rates and faceted crystals develop at higher growth rates, which are themselves driven by lower and higher temperature gradients. LaChapelle and Armstrong (1977) suggest that the critical temperature gradient for the onset of predominantly faceted crystal growth is  $10^{\circ}\text{C m}^{-1}$  but this value probably increases with snow density.

The division of dry snow into rounded and faceted crystals is adequate for most purposes but many mixed forms of crystals also occur. Unfortunately, surfaces which are partly rounded and partly faceted greatly complicate classification because similar looking crystals can arise for different reasons. Some of the multiple paths that give rise to similar-looking crystals are shown in Figure 1.

One possible way of classifying these crystals is shown in Table 1. Following precipitation, the crystals usually round off (IIA1) and form fully rounded and well-bonded compacts (IIA2). If colder weather arrives and the temperature gradient increases, some faceting appears. At intermediate growth rates the crystals will have flat faces with rounded corners (IIB1) but mixed crystals also appear as a transitional form (IIB2) during a major recrystallization from predominantly well-rounded to predominantly highly faceted grains. If the large temperature gradient persists long enough, fully developed, faceted crystals will predominate. Either the solid form (IIC2) will develop if the temperature gradient is not too strong or the hollow form (IIC3) will develop at the highest temperature gradients. Once the temperature gradient is reduced below the critical value, the rounded form will return (IIB3).

#### C. Wet Snow Terms

If the weather warms sufficiently to cause melting, an entirely new set of shapes will occur. Freely draining wet snow develops clusters of grains (Fig. 4) to minimize surface free energy (IIIA) but these clusters are often consolidated by freeze-thaw cycles so that they lose their distinctive shapes (IIIB). At large liquid contents, grain boundaries are unstable and individual crystals predominate (IIIC).

Since melting and other processes take place only on the surface, unique features develop there and are incorporated into the snow cover by subsequent burial. These features are very different but all generate layers in the snow cover that greatly affect the snow cover behavior.

Table 1 Snow Classification System

- 
- I. Precipitation
  - II. Dry Snow
    - A. Equilibrium (rounded) Form
      - 1. Initial rounding of precipitate.
      - 2. Fully rounded (may be faceted at low temperatures).
    - B. Mixed Rounded and Faceted
      - 1. Intermediate growth rate.
      - 2. Transitional as temperature gradient increases.
      - 3. Transitional as temperature gradient decreases.
    - C. Kinetic Growth (faceted) Form
      - 1. Faceted growth on precipitate.
      - 2. Solid crystals, usually hexagonal prisms.
      - 3. Hollow crystals called depth hoar.
  - III. Wet Snow
    - A. Pure Grain Clusters
    - B. Melt-Freeze Particles
    - C. Slush
  - IV. Surface Generated Features
    - A. Surface Hoar
    - B. Wind Crust
    - C. Melt-Freeze Layers
    - D. Sun Crust
    - E. Freezing Rain Crust
-

## CONCLUSION

Snow metamorphism has attracted much interest for many years because of its curious nature and fundamental importance to snow studies. Through a combination of field, laboratory and theoretical investigations, our understanding of snow metamorphism has evolved steadily. The thermodynamics is well understood although the complicated pattern of heat and mass flows among ice particles is not so well understood. Stereology is being used to gain information about the structural nature of snow in order to allow better modeling of these flows.

The simplest case of snow metamorphism, water-saturated snow, has been studied to the point where the growth rates are well known and the frequency distribution of grain size established. When normalized to the mean this distribution is invariant in time, thus allowing mathematical manipulation and conclusions about the nature of the growth process itself. It is important that this kind of data be produced for grain growth in dry snow so that the ideas produced through recent model studies can be tested.

The model studies themselves were made possible in part by experiments on ice crystal growth. These experiments should be expanded to investigate the effect of temperature on the growth rate and growth shape of ice crystals over the complete range of supersaturations of interest in the snow cover. In spite of the lack of a full understanding of all aspects of grain growth in wet and dry snow, enough has been learned to develop a more appropriate classification system for snow cover crystals and such a system is outlined.

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## DISCUSSION

### J. Dozier

In a refrozen wet snow cluster, why does the penetration of solar radiation restore the original cluster form along the original grain boundaries? Is this due to preferential absorption?

### S.C. Colbeck

The original shape of a "grain cluster" is restored spontaneously but slowly because the grain cluster is the equilibrium shape in wet snow at low liquid contents. Solar radiation penetration provides an energy source to speed the restoration of the grain clusters but not necessarily by preferential absorption at the grain boundaries.

### Ch. Mätzler

Recent snow dielectric studies at microwave frequencies indicate that in wet snow the liquid water has a strongly elongated shape. In terms of an ellipsoid the length - to - diameter ratio is at least 20:1. Is this result in agreement with the size of the liquid veins you observed geometrically?

### S.C. Colbeck

A few years ago I found that the dielectric constant could be modeled with mixing theory assuming elongated spheroids. The water inclusions are not ellipsoids but are triangular in cross-section. Nevertheless, they are elongated. An interior vein has an elongation much less than 20:1 but the fillets running around the grain boundaries may well have that ratio.

**M. de Quervain**

1. Remark: Special attention should be given to snow surface metamorphism. There the highest temperature gradients are encountered due to outgoing radiation. This results in:
  - Surface hoar formation (leaf like crystals)
  - Gradient metamorphism to a considerable depth (more important for avalanche formation than bottom metamorphism).
2. Remark to convection in snow: In an old experiment a snow block was heated in the middle plane, producing an upward and downward gradient (distorted by convection?). On both sides of the heating plane strong constructive metamorphism was observed. In the upper part it was slightly more advanced. This was interpreted as an effect of convection.
3. Would you think that we should adjust the old snow classification of grainshape being
  - + new snow of original shape and snow in transformation (destructive and constructive), first stage. Original shape still visible.
  - o rounded crystals (except melt metamorphism)
  - o faceted grains (full crystals, completely or partially faceted)
  - o depth hoar (faceted, hollow crystals and parts of them)
  - o rounded (melt metamorphism).

**S.C. Colbeck**

2. Without knowing the details of your experiment, I don't know if thermal convection should have been expected. If thermal convection does occur, we would expect some accelerated metamorphism but we don't know how much.
3. I am trying to get people to use words to describe metamorphism which I consider to be physically meaningful but I have not yet considered the symbols used to represent the various snow crystals. My impression is that the symbols you show are reasonable.

**E. LaChapelle**

My own laboratory experiments confirm the experience of M. de Quervain in finding asymmetry of snow metamorphism around a heat source in the center of a cold snow sample. If you exclude the role of convection in visibly affecting kinetic growth forms, can you offer an explanation for the asymmetry?

**S.C. Colbeck**

I do not exclude thermal convection from either experiment. I cannot say if I would expect thermal convection without having more information about these particular tests. It is possible that the differences reported were either do to density or temperature differences, so thermal convection is not the only possible explanation.