

THE MOUNTAIN SNOWPACK

by Richard L. Armstrong
CIRES Campus Box 449
University of Colorado
Boulder, CO 80309

Snow is one of the most variable substances found in nature and consequently one of the most complex. A high degree of compressibility and thermodynamic instability are two of its dominant characteristics. Examples of these and other characteristics are available from a variety of field and laboratory measurements. New snow crystals begin to change as soon as they collect on the ground or the old snow surface. The type and rate of change depends primarily on temperature conditions. The development of several snowpack types will be presented with emphasis on their respective layered structure. How the layers are formed and why they possess their particular physical properties will be discussed. Layering is the combined effect of the particular meteorological conditions at the time of new snow accumulation and changes (metamorphism) which occur within the snow cover due to variation in overburden pressure and temperature. Processes involved in three distinct types of metamorphism will be described. The concept of the layered structure as the basis for slab avalanche formation will be introduced.

Mechanically, snow exhibits visco-elastic properties. The viscous qualities of snow allow it to deform slowly, in some cases, without fracture. The elastic properties of snow allow energy to be stored (as in a stretched rubber band) and this sets the stage for the brittle type fracture (as a pane of glass would break) associated with slab avalanche release. While many materials have well defined failure criteria (e.g., a definite fracture stress can be determined), snow does not. How snow reacts to the application of stress is determined by its complex and interrelated physical properties as well as the rate of stress application. When snow lies on a slope the relationship between strength and stress becomes important. In general, the stress condition is simply related to the mass of snow on the slope and the slope angle, but strength is controlled by the complex properties of numerous individual layers.

SNOW METAMORPHISM AND INTERGRANULAR BONDS

The International Classification for Seasonal Snow on the Ground has been developed by the International Commission on Snow and Ice (IAHS) and its use is generally accepted. The features used to classify snow include: density, temperature, grain size, hardness (strength), and free water content which in one way or another can be determined in a reasonably quantitative fashion; and, finally, grain shape or type, which must be determined by means of an accepted morphological classification scheme. While the international classification of grain types is generally understood and accepted by experienced field workers, the physical processes responsible for the development of these respective stages of snow metamorphism are often unclear or confusing. In the following discussion the intent is to combine the international classification of grain type or morphology with a description of the possible processes which may lead from one identifiable form to another.

Snow is a porous, permeable aggregate of ice grains with its pores filled with air and water vapor and sometimes, liquid water. Many of the unique properties of snow are due to the fact that, unlike most other solid materials found in nature, the ice contained in snow is normally encountered at temperatures close to its melting point. Because of this fact, the water molecules making up the ice particles are relatively free to move around on the ice surface or to actually leave the ice structure and sublime into the vapor phase. As a result of this mobility, water molecules will eventually be redistributed within a given volume of snow such that the original shapes disappear and distinct new forms are created. This process is called snow metamorphism and it begins as soon as the snow reaches the ground or the old snow surface. The term "metamorphism" means the same as it does in geology, the changes in texture which occur as a result of temperature and pressure.

The rate of metamorphism depends primarily on temperature; the closer the temperature is to 0 degrees C, the faster the change. The process behind these changes involves sublimation at certain locations on the snow grains and deposition at others. Within a given subfreezing snow layer, once the new snow crystals have lost their original shape, the individual grains will tend toward one of two general forms. They may become smooth, rounded grains with average diameters of about 1.0 mm or they may become coarse, angular, or faceted grains with average diameters between 2 and 6 mm or larger. Which path of metamorphism a given snow layer takes is of importance in avalanche hazard evaluation because the rounded, smooth grains tend to create a snow texture which

gains strength with time, while the coarse, angular grains show little or no gain in strength with time. What then are the conditions which determine the specific metamorphism of a given layer?

Let us first have a look at how the original shape of the new snow crystal is lost. In order to describe this process in detail we will begin with the well accepted assumption that the air within the pore space of the snow is nearly saturated with water vapor with respect to ice at the prevailing temperature. This means that the same number of water molecules are leaving the ice surface as are arriving back at the ice surface (100% relative humidity). When viewed on a large scale, the system is in balance. This is not the case at the microscale. This is because the total number of water vapor molecules (vapor pressure) which can be supported in a saturated condition just above the ice surface is influenced by the shape of the surface. More molecules can be supported above a surface with a high positive curvature, (convexities, sharp corners, small grains) than over a flat surface, and more molecules can be supported over a flat surface than over a surface with a high negative curvature, (concavities and grain contacts). This difference in vapor concentration causes a net flow of molecules from the locations of higher concentration to those of lower concentration resulting in the loss of sharp angles on the crystal faces and the gradual development of a more rounded or isometric shape. However, it is currently believed that this process is of importance only when radii of curvature (positive or negative) are very small, e.g., 1.0 to 100.0 microns.¹ Such radii would be typical of the angles on the arms and branches of new unrimed stellar crystals.

About the time the original shapes of the new snow crystals are no longer recognizable and the sharpest angles (smallest radii of curvature) have been lost, the influence of surface curvature begins to diminish. At this point the specific course of metamorphism to be followed by a given snow layer will be primarily determined by the temperature gradient. A *temperature gradient* is the variation in temperature with distance measured up or down in the snow cover. In a natural snow cover, the temperature gradient usually varies from warmer near the ground to colder near the snow-air interface. As was shown in the section on meteorology, warm air can hold more water vapor than cooler air. Therefore, the air which fills the pore space within snow cover near the ground contains more water vapor than is contained within the colder layers above. In terms of conditions at the surfaces of the individual ice grains, this means that the concentration of vapor is greater adjacent to

¹(0.001 to 0.1 mm)

the grains in the warmer layers than it is adjacent to the cooler grains. This difference in vapor concentration results in a vapor pressure gradient. Because this vapor pressure gradient is produced by the temperature gradient, the greater the temperature difference the greater the vapor pressure gradient. In the presence of a strong temperature gradient (10 to 20 degrees C/m or more), a relatively rapid transport of water vapor occurs due to this imbalance in water vapor concentration. As the water vapor moves from warmer to colder locations in the snow cover, it comes in contact with colder grain surfaces resulting in a condition of high supersaturation. Consequently, some of the vapor is deposited as solid ice on the face of the colder grain. A series of sublimation and deposition processes between grains takes place with the relatively warmer ice surfaces losing mass to the colder surfaces. This is generally understood to occur on a rather small scale, with the transfer taking place from one adjacent grain to another, i.e., the upper surface of one grain is the location with the slightly higher temperature and the lower surface of the grain just above it is the cooler surface. In the presence of a strong temperature gradient, grain growth occurs by the evolution of visible steps across the crystalline faces. This process produces specific shapes characterized by facets, steps, and eventually hollow cup crystals. Grain growth may be quite rapid and the smaller grains disappear creating fewer but larger grains. This process used to be referred to as "Temperature-Gradient (TG) Metamorphism," because the bulk of the vapor transfer results from temperature gradients in the snow cover. However, this term is somewhat misleading since all snow metamorphism outside the laboratory takes place in the presence of at least a small temperature gradient. Thus, we now simply refer to this process by the crystal forms associated with it: "Faceting". A sustained strong temperature gradient (20-40 degrees C/m) in new low density snow can create grains 3 to 6 mm in diameter in approximately 10 to 20 days.

The rate of crystal growth is, however, not only controlled by temperature gradient, but also by the average temperature of the gradient. The closer the temperature is to 0 degrees C, the more water vapor that is available for transport within the pore space. In fact, the rate of crystal growth is actually controlled by the vapor pressure gradient, which is itself determined by the overall temperature conditions. The relationship between temperature and vapor pressure is non-linear and is shown in Figure 1. Steep temperature gradients alone do not always provide adequate vapor pressure gradients. For example, a temperature gradient of 10 degrees C/m may result in moderately rapid crystal growth if the average temperature of the snow layer is very close to 0 degrees C. At mid-latitude sites, this would commonly occur in those layers at the base of the snow cover near the warm ground.

However, as the average temperature of the snow layer decreases, the temperature gradient must increase to provide the same vapor pressure gradient and associated crystal growth rate. If, for example, the average temperature of the snow layer decreases from near 0 degrees C to -20 degrees C, the temperature gradient must be increased nearly five times in order to provide the same vapor pressure gradient, (See Figure 1).

When the temperature-gradient is less than about 10 degrees C/m, the resulting grains have a shape totally different from those produced by faceting. Under these conditions, water vapor is still moving from the warmer to the colder portions of the snow cover but at a much slower rate. This causes grain growth to be much slower. In this case, each site on the grain surface is more or less equivalent and the water vapor is deposited uniformly over the surface. The result of this slow growth rate is a grain with smooth surface features and a rounded shape is approached. This is in contrast to the process just described where strong temperature gradients and rapid growth rates produce highly preferential vapor deposition at specific locations on the grain surface, and distinctive coarse, angular grains result. This slow growth process was previously known as "Equitemperature (ET) Metamorphism". However, it does occur in the presence of a weak temperature gradient (in fact, when there is no temperature gradient the process is slowed significantly), so we now refer to this process simply as "Rounding". In the presence of a weak temperature gradient, another process known to occur is sintering. *Sintering* is the growth of bonds between the grains producing an increase in intergranular strength. When the concavities at the grain contacts are in the form of sharp, negative angles, the sintering process will be driven by differences in curvature, as described above. In this case, molecules migrate from the flat or slightly convex surfaces to the sharp, negative angles of the grain contacts. As the vapor deposits at these locations, the bonds or necks between the grains grow and strength increases. This process will take place in the absence of a temperature gradient, but it is understood to take place at a slightly accelerated rate in the presence of a weak temperature gradient, (less than 10 degrees C/m). In the presence of a strong temperature gradient, the rapid movement of vapor apparently overrides the sintering process and little or no bond growth occurs.

In summary, the average temperature of the snow layer determines the *rate* of metamorphism, being faster the closer the temperature is to 0 degrees C, while the temperature gradient determines the *type* of metamorphism. Strong temperature gradients eventually produce large, faceted, and poorly bonded grains while weak temperature gradients result in relatively small, smooth, rounded grains with some degree of intergranular bonding.

2 At 4 degrees C each gram of rain would contain 4 calories of heat. Eighty calories are required to melt one gram of ice. Therefore, 20 grams of 4 degrees rain are required to melt one gram of ice. One gram of ice is equal to 1.1 cm³ of ice or approximately 4 cm³ of snow with a density of 250 kg/m³. With a moderate rainfall rate of 3 mm/hour, which is equal to 0.3 grams of water per hour, it would have to rain for more than 66 hours to melt the 4 cm³ of snow, (20 grams - 0.3 = 66.7). In summary, it is safe to say that more than 12 hours of steady rain at 4 degrees C would be required to melt even 1 cm of snow with a density of 250 kg/m³.

Rain can be a significant source of free water, but it is not often important in producing melt. In winter, at a high altitude site, rain is rarely more than a few degrees above freezing. Under these conditions, rain is not a significant heat source with respect to melt. For example, with rainfall at +4 degrees C, approximately 12 hours of rain would be required to melt one centimeter of snow. 2 Rain falling on a subfreezing snow cover will refreeze and the associated release of latent heat will warm the surface layers. When free water, produced by rain and/or melting, percolates downward through 0 degrees C surface layers and encounters colder layers, the free water will refreeze, again releasing latent heat. This process allows that portion of the snow cover still below 0 degrees C to be warmed in a very efficient manner. For each

The processes described above may occur as long as the temperature of the snow remains below 0 degrees C. If the snow temperature reaches 0 degrees C, wet snow or "Melt-Freeze (MF) Metamorphism" will result. A thorough description of the warming of the snow cover to 0 degrees C and the subsequent production of liquid water (free water) is presented in other parts of this notebook dealing specifically with wet snow, so only a brief summary and a few additional details will be presented here. Wet snow metamorphism is a more complex process due to the fact that it involves a three-phase system: ice, vapor, and now, liquid water. Nevertheless, the same physical principles drive the metamorphic processes and again, due to curvature differences, large grains will grow at the expense of smaller grains. The continuation of a diurnal melt-freeze cycle tends to diminish the number of grains while increasing the average size of the grains. This results from the fact that smaller grains have a slightly lower melting temperature and, therefore, will melt first. However, at night the liquid water resulting from these melted grains refreezes onto adjacent ice grains. After several melt-freeze cycles, clusters of large, coarse grains develop, and these are called melt-freeze grains.

cm³ of water that refreezes, 80 calories are released. This amount of heat has the capacity to increase the temperature of more than 400 cm³ of snow by 1.0 degrees C.³ In addition, the glaze or crust formed by rain falling on cold snow will decrease the albedo of the snow, thus increasing the amount of solar radiation which can be absorbed at the snow surface.

With respect to avalanche release, the primary significance of rain on snow is the addition of weight to a slope. A moderate to heavy rainfall often provides additional mass to a slope much more rapidly than typical snowfall rates. In addition, the added weight of the rain does not provide the additional tensile strength that would accompany a layer of new snow.

³When one gram of water refreezes, 80 calories of latent heat are released. The specific heat of ice is 0.5 calorie/degree C which means that only 0.5 calorie is required to raise the temperature of one gram of ice 1 degree C. Therefore, the refreezing of one gram of water (which is equivalent to 1 cm³ of water) releases enough heat to raise the temperature of 160 grams of ice 1 degree C, (80 calories - 0.5 calories). One hundred sixty grams of ice are equal to 174 cm³ of solid ice in terms of snow with a density of 400 kg/m³ would be 435 cm³. Therefore, the refreezing on only 1 gram of water would have the capacity to warm a volume of snow about 7.6 cm on a side (=435 cm³) by 1 degree C.

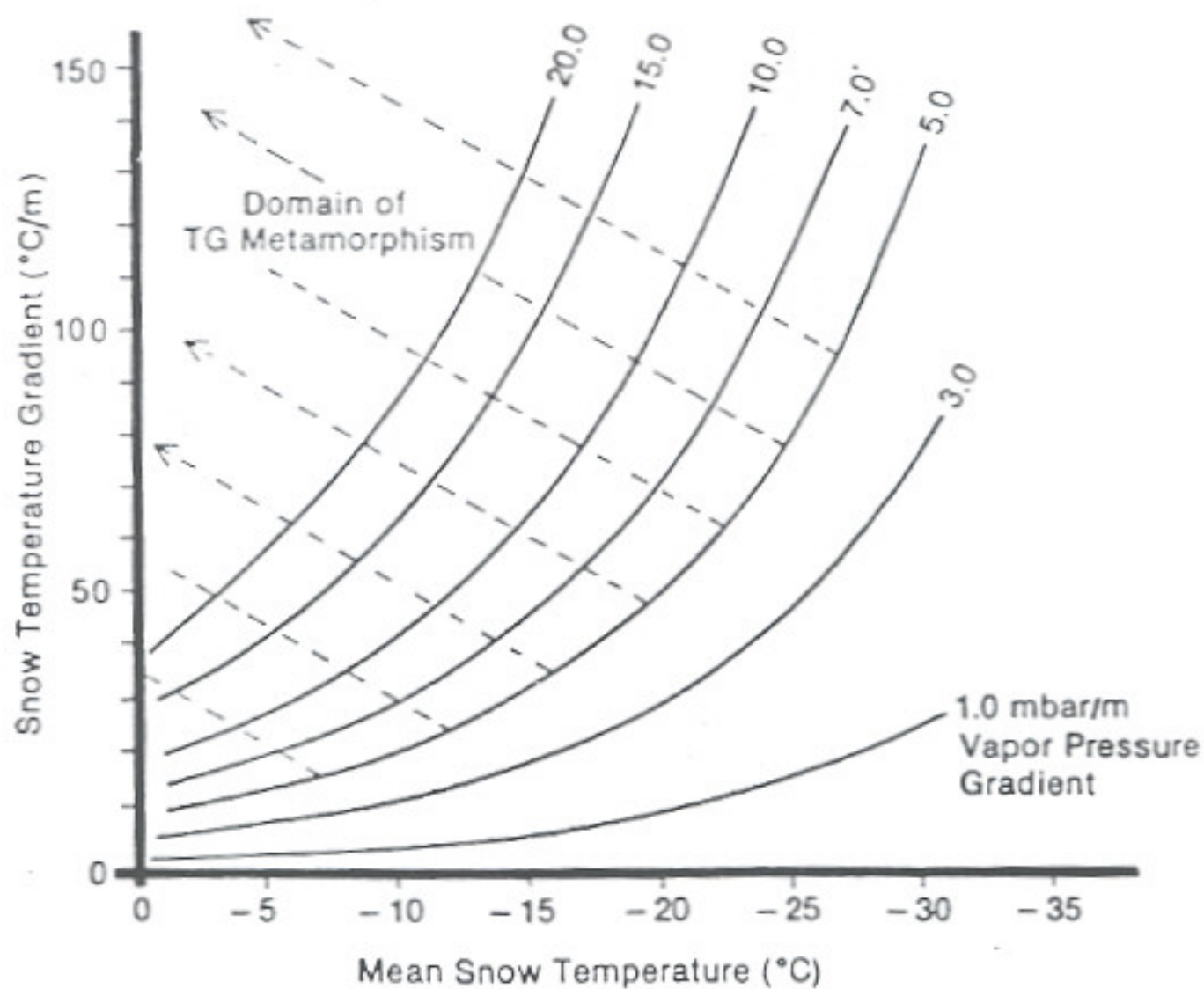


Figure 1.

The relationship of vapor pressure gradient (in millibars per meter) to temperature gradient and average temperature within the pore space of a snowcover. The value 5.0 mbar/m is considered by this author to be the lower limit for rapid TG metamorphism in low density new snow.

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Glossary

Crystal: A substance which has solidified with its molecules or atoms arranged in an orderly array. An example is the new snow crystal which is a single crystal of ice which grew by vapor deposition in the atmosphere. As metamorphism proceeds in snow on the ground, special techniques are often required to identify single crystals. Various influences may alter the external morphology of a crystal but the internal form remains unchanged.

Deposition: The process by which a vapor changes from its gaseous state directly to the solid state without having passed through the liquid state. In the case of snow, this process allows the mass transfer associated with metamorphism to occur in a subfreezing snow cover.

Elastic Deformation: Behavior characteristic of a solid, resistance to change in shape. Deformation is recoverable, i.e., the material will resume its original form and dimensions when the forces acting on it are removed.

Failure Criteria: For many materials, a failure criteria has been established which indicates the amount of loading which is required to initiate failure. However, with snow this relationship is highly dependent on snow density, grain type, temperature, as well as rate of loading. Consequently, no conventional failure criteria for snow has been established.

Force: Any action that alters, or tends to alter, the state of a body at rest or its uniform motion in a straight line. The Newton (N) is the unit of force and is defined as the force that provides a mass of one kilogram with an acceleration of one meter per second.

Fracture: In terms of an avalanche release, an initial fracture will occur within a localized portion of the snow cover at that moment when stress equals strength. Because the location at which this initial fracture has taken place can no longer accept any further stress, the load experienced by the adjacent snow structure increases. If this additional stress cannot be sustained by adjacent snow layers, crack propagation begins. Thus, stress redistribution resulting from the initial fracture may produce crack propagation and secondary fracture which in turn may lead to an avalanche release.

Grain: The visually obvious subunit or particle in snow on the ground. Strictly speaking, grain and crystal cannot be used interchangeably. A grain may consist of one crystal or several. In poorly bonded snow, disaggregation occurs at grain boundaries and thus the identification of separate grains can be easy and precise. However, when the snow becomes bonded into a complex three-dimensional network, the location of grain boundaries becomes much more difficult to determine. When referring to individual particles in the snow cover, the term grain is used in preference to crystal which has more specific meaning.

Strain: The change of volume and/or shape of a body due to applied forces. Strain is expressed as a ratio of dimensional change compared to the original or unstrained dimension. Typical strain rates in a snow cover resulting from snowfall (settlement) are 10^{-6} /sec (approximately 0.1/day), from explosives 10^{-3} /sec, and from crack propagation 1/sec.

Stress: Force per unit area expressed as Newtons per square meter (N/m^2), which is equivalent to Pascals (Pa). With respect to avalanche release, it is the localized stress concentrations in a release zone which are important rather than the average stress across the entire snow slope.

Structure: In terms of a snow cover, it is intended to refer to the layering or stratigraphy.

Sublimation: The opposite of deposition, the process by which a solid changes directly into the vapor without passing through the liquid state. In the case of the subfreezing snow cover, this is the process which allows change directly from solid ice to water vapor.

Texture: The shapes and the relationships among snow grains or crystals in a snow cover; for example, crystal type and the presence or lack of bonds.

Thermodynamic Instability: The tendency to shift to a lower energy state.

Vapor: A substance in the gaseous state which may be liquified by increasing the pressure and/or decreasing the temperature. (Technically, such a gas must be below its "critical" temperature if it is to be liquified by increase in pressure alone.)

Viscous Deformation: Flowing as a fluid-like material, ability to change shape readily. Deformation is continuous and remains when the forces are removed. A viscous material will undergo irreversible shape changes under any stress.

THE BASIC IDEAS BEHIND SNOW METAMORPHISM

by S. C. Colbeck

CRRRL
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.

1. 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 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.

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

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

IV. MEASURABLE INFLUENCES

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.

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 combination of near-surface solar heating and a strong temperature gradient of near-surface solar heating and a strong 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 outgoing 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.

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