

ON THE METAMORPHISM, MORPHOLOGY AND MICROSTRUCTURE OF SNOW¹

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Abstract -- The tendency for snow microstructure to reduce surface energy via sintering and crystal growth (ET-metamorphism) is discussed using solutions to a simple rate equation. ET-metamorphism is contrasted with temperature gradient (TG-) metamorphism whereby the microstructure attempts to remove the gradient via a positive feedback mechanism which causes exaggerated growth. Metamorphism in the presence of the liquid phase (melt-freeze metamorphism) is discussed briefly.

INTRODUCTION

Metamorphism is driven by Nature's attempt to equalize temperature and stress gradients in the snowpack, and to minimize the surface energy of the interconnected ice crystals. Temperature gradients arise due to energy fluxes at the snowpack boundaries, -- the ground surface and the snow surface. In accordance with Le Chatelier's principle, the microstructure must evolve to remove the temperature gradient (often impossible given the strength of the energy fluxes). Stress gradients are due to gravitational body forces, and are removed by deformation and fracture. Unless overwhelmed by these temperature and stress gradients, the microstructure will all the while metamorphose spontaneously toward lower and lower surface energy, as do all multiphase materials close to their melting temperatures.

The type and rate of metamorphism is determined by the magnitude of the gradients, the temperature, microstructure geometry, very strongly by the amount of liquid water if that phase is present, and by impurities although we will not discuss that complication in this paper. Metamorphism induces remarkable changes in the microstructure, as well as in the size and morphology of the crystals that form the microstructure.

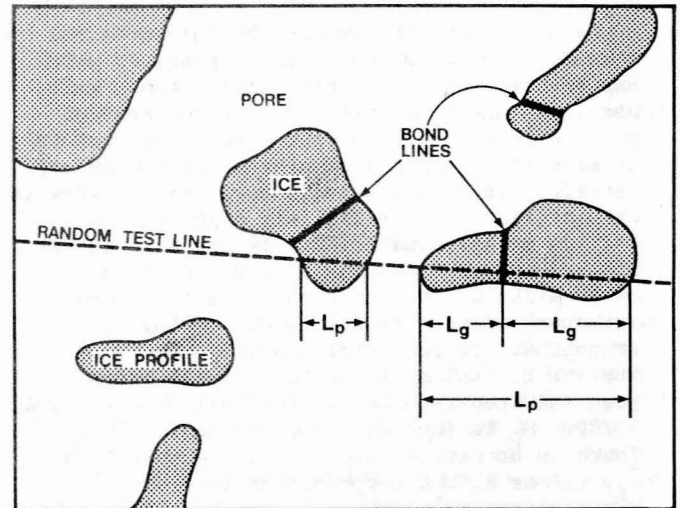


Figure 1.--Definition of stereological intercepts on a snow section or thin-slice.

MICROSTRUCTURE PARAMETERS

We first restrict our discussion to dry snow which consists of sintered ice crystals and pore. The crystals are bounded by curved or plane ice-pore interfaces, and by grain-boundaries to neighboring crystals. The latter may also be idealized as interfaces, but with an associated surface-energy of about half the ice-pore value. Crystals can be observed within disaggregated specimens. The "profiles" of crystals (see fig. 1) can be observed on thin slices or on sections (Perla et al. 1985). Crystal size can be indexed by a maximum dimension, or by some mean diameter \bar{D} which involves averaging of lines that intersect the crystal interior. High density

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perennial snow ($>500 \text{ kg/m}^3$) usually consists of equant polyhedral crystals separated by well defined grain boundaries, in which case \bar{D} can be measured with reasonable objectivity. Lower density seasonal snow consists, in general, of more complex and assorted morphologies (plates, prisms, tubes, cups), in which case \bar{D} is not easily measured.

An objective index of \bar{D} can be based on stereological parameters (Underwood 1970). One easily accessible parameter is the mean intercept length of the ice profiles on the section or thin slice. We designate this parameter \bar{L}_p , where the subscript p emphasizes that the intercepts cross the entire profile from pore to pore, irrespective of any bond lines that are contained within the profile. As illustrated in fig. 1, we also define an \bar{L}_g as the mean of intercepts that end at pore or bond interfaces. Note that $\bar{L}_p > \bar{L}_g$, and that it is \bar{L}_g not \bar{L}_p which is an index of \bar{D} . The problem is that \bar{L}_g is not as accessible as \bar{L}_p because the former requires that bond lines are located on sections or thin slices.

A snow specimen may also be characterized by stereological measures of surface areas, which may be normalized per unit volume or per unit mass. We use S_p to mean the surface area of the ice-pore interface (per unit mass), and S_g to mean the surface area of the grain boundary interface (per unit mass). Newly fallen snow is characterized by a relatively high S_p ($\sim 100 \text{ m}^2/\text{kg}$), and relatively low S_g . In an older seasonal snowpack, S_p may reduce to $\sim 10 \text{ m}^2/\text{kg}$ while S_g increases as the microstructure sinters to increased bonding strengths. In perennial snow, S_p may reduce further to $\sim 1 \text{ m}^2/\text{kg}$ while S_g reaches its peak and then reduces (Narita 1971, Narita et al 1978). S_p is inversely proportional to \bar{L}_p . There is no direct relationship between S_g and \bar{L}_g , unless $S_p \approx 0$ (approaching polycrystalline ice), in which case S_g and \bar{L}_g are inversely proportional.

The above discussion pertains to dry snow. More generally, liquid water could be present in measurable quantities ($\approx 1 \text{ gm}/100 \text{ sample grams}$). Its distribution is somewhat speculative since no one has demonstrated a method for preparing sections or thin slices through wet snow specimens and measuring the intercept of the liquid phase. It is believed that a liquid-like film appears on the ice-pore interface even at temperatures below 0°C , and that the film thickens as the temperatures rise toward 0°C , eventually converting into a true melt film of variable thickness depending on crystal curvature and orientation. With rising temperatures it is believed that the grain boundaries also become more liquid-like.

Temperature gradients come and go in both seasonal and perennial snowpacks. When they are present they tend to be the dominant driving force for metamorphism. However, the tendency for the microstructure to lower its surface energy proceeds slowly, even if temporarily offset by a transient temperature gradient. Sommerfeld and LaChapelle (1970) refer to these processes as temperature-gradient metamorphism (TG-metamorphism), and equitemperature metamorphism (ET-metamorphism). They could just as well have used "surface-energy" in place of "equitemperature", but they preferred to emphasize what could be measured in the field, rather than emphasize the theory. They could have used "isothermal" since this would be more in keeping with crystal growth literature, however snow studies have traditionally reserved "isothermal" for the specific case where the entire snowpack is at 0°C during snowmelt.

The resulting crystal morphologies are sometimes called ET- and TG- crystals. The former are simpler and often rounded in shape. The latter, characterized by facets, steps and layers, and hollowed morphologies, are usually more complicated. Colbeck (1986a) proposes that ET and TG should be replaced by "equilibrium" and "kinetic" growth forms. However, these terms are misleading in the present context. In the crystal growth literature an "equilibrium form" refers to the shape of a microscopic ($< 0.1 \text{ mm}$) crystal that has minimized its surface energy as an isolated unit. The equilibrium form of an ice crystal may be found shortly after birth in a cloud or supercooled solution. It will not be found at $\bar{D} > 0.1 \text{ mm}$ in a sintered microstructure. Gubler (1985) has recently proposed the terms "low gradient" and "high gradient", but within the present dichotomy we believe it is obvious enough that dT/dz need not precisely vanish in an ET-process. There are many other name-calling possibilities such as "slow" vs "fast" metamorphism, or "stable" vs "unstable" metamorphism. It should be noted that models of dry snow metamorphism (including those of Colbeck and Gubler) seek with varied success that line of demarcation where dT/dz is strong enough to drive fast or unstable growth, for it is dT/dz that is accessible to measurement. It must be emphasized this is not meant to imply that other variables included in the state of the current microstructure (density, temperature, S_g , S_p) are not important.

When temperature fluctuates with small amplitude around 0°C , metamorphism largely involves advancing and falling back of a liquid-solid interface in the melt film. Sommerfeld and LaChapelle (1970) call this "melt-freeze metamorphism". Here, the temperature gradients are highly transient since the liquid-solid interface responds rather quickly to small super- or under-

coolings; that is, quickly compared to the response of the solid-vapor interface to small positive or negative supersaturations.

ET-METAMORPHISM

If dT/dz is small, a low density snowpack will metamorphose to reduce S_p at a decelerating rate which depends on the current value of S_p . The simplest differential equation is therefore

$$\frac{dS_p}{dt} = -K \frac{S_p^{n+1}}{S_p} \quad (1)$$

where K is a function of T , and the exponent n depends on the process (viscous flow, vapor deposition, surface diffusion, volume diffusion, grain boundary migration). We need $n > 0$ because the solutions corresponding to $n = 0$, namely

$$S_p = S_0 \exp(-Kt) \quad (2)$$

$$\bar{L}_p = \bar{L}_0 \exp(Kt) \quad (3)$$

are asymptotic limits given the initial values S_0 and \bar{L}_0 . For $n > 0$, the solutions to (1) take the form

$$\frac{1}{S_p^n} - \frac{1}{S_0^n} = K_1 t \quad (4)$$

$$\bar{L}_p^n - \bar{L}_0^n = K_2 t \quad (5)$$

For example, with $n = 1$, and with S_p reducing from $100 \text{ m}^2/\text{kg}$ to $50 \text{ m}^2/\text{kg}$ in 100 days, from (4) we force K_1 to be $0.0005 \text{ kg/m}^2\text{-day}$, and predict a further drop to $1 \text{ m}^2/\text{kg}$ in about 5000 days. This appears to be a reasonable deceleration of S_p as the microstructure converts to high density firm where (1) must ultimately fail since surface energy is further reduced by a decelerating S_g and S_p . However, at high enough density, when S_p is approximately constant, S_g may be substituted for S_p in (1) and its solutions. Similarly, \bar{L}_g may be substituted in (5).

The morphological consequence of the reduction in S_p and ultimately in S_g is that large crystals are favored to grow and sinter at the

expense of their smaller neighbors. Material scientists (Lay 1973) have for some time modeled crystal growth during isothermal sintering with expressions of the form

$$\bar{D}^n - \bar{D}_0^n = F(T)t \quad (6)$$

which is analogous to (5) using the more general concept of mean crystal diameter \bar{D} in place of the stereological parameters. For the perennial snow of Antarctica, Gow (1975) has modeled growth of \bar{D} (over centuries) setting $n = 2$ and using an Arrhenius relationship for $F(T)$. To the best of our knowledge no one yet has applied (5) or (6) to dry seasonal snow.

The relative importance of the possible transport paths in ET-metamorphism is controversial. Vapor deposition (Colbeck 1980) is usually considered the dominant pathway in seasonal snow, although Kuroiwa (1975) presents evidence of significant transport on the ice-pore interface via mobility of the liquid-like film. Diffusion along grain-boundaries, migration of grain-boundaries, and diffusion through the bulk ice phase must play an increasingly important role with density increase. The influence of viscous flow and microfracture/healing induced by gravity needs clarification.

TG-METAMORPHISM

The microstructure will also rearrange in an attempt to reduce an imposed dT/dz . Although surface, grain-boundary, and bulk ice diffusion paths cannot be excluded, it is believed that the rearrangement is largely carried out by vapor diffusion across the gradient. Recent models (Armstrong 1985, Gubler 1985) provide reasonable predictions for mass transfer, but do not model the exaggerated morphologies (hollow cups, elongated prisms, sheet-like fins) described by Akitaya (1974), and known to develop rather quickly in the presence of a strong dT/dz . Gubler (1985) suggests enhancement shape factors based on the electrostatic analogy to the diffusion equation in an attempt to explain why crystal sizes are larger than the mass rates calculated on the basis of diffusion theory would predict. However, this theory is essentially a steady-state approach, whereas exaggerated morphologies are intrinsically due to moving boundary instability.

A plausible mechanism for exaggerated growth is the positive feedback that occurs when a few preferential growth sites begin protruding toward the vapor source. The temperature and vapor-pressure gradients intensify around the protrusion which in turn intensifies the growth, which in turn intensifies the local gradient, and so on.

The positive feedback is eventually stabilized by a limited supply of vapor from the source crystals, by limitations in heat conductivity, by interfacial kinetics, and by the tendency of the crystal to lower its surface energy by eliminating protrusions. If dT/dz is high enough ($\approx 10^\circ\text{C/m}$ is often quoted) there will be a tendency toward complex morphology which offsets the usual tendency to reduce surface energy, and in fact S_p could increase with time. Note this means that \bar{L}_p may decrease, perhaps contrary to what is expected. Actually, neither \bar{L}_p nor \bar{D} need change more in TG-metamorphism than in ET-metamorphism. However, increases are observed in the maximum value of the stereological intercepts (Perla 1985).

As illustration of the power of the mechanism, Kuroiwa (1975) has observed protrusions growing at rates of $\sim 1 \mu\text{m/min}$ with $dT/dz \approx 20^\circ\text{C/m}$, which is a strong but possible gradient in a natural snowpack. At that rate a crystal could grow at about $\sim 1 \text{ mm/day}$ along a preferred direction. Kuroiwa started with a collection of dendrites and observed dramatic shrinkage of the source branches simultaneous with the above growth at the sink branches. However, it is expected that the situation would not be that symmetrical if the initial morphology consisted of more equant shapes (solid prisms and ellipsoids). Here one envisions protrusions advancing from the corners and edges of the sink crystals while the source crystals tend to erode uniformly. At low porosity the protrusions could short circuit the pore and catch the source crystals. The net effect of that situation could be a strengthening of the layer. By contrast, at high porosity the advancing protrusions have room to wander about the pore (scooping up the excess vapor) with the net effect of weakening the microstructure by producing the classic depth hoar crystals with their nefarious ability to collapse unpredictably and cause slab avalanches.

MELT-FREEZE METAMORPHISM

Wakahama (1968) identified two types of melt-freeze processes. One type occurs below the snow surface in a wet snowpack where perturbations due to surface energy fluxes are minimum, and where the ice crystal and water phases remain close to equilibrium. In this situation, surface energy gradients are quite effective drivers of diffusional transport through the liquid phase, with the result that surface energy drops rather quickly (compared to dry snow processes), and large crystals grow quickly at the expense of their smaller neighbors. The other process occurs near the surface where strong energy fluxes may perturb the ice-water mixture away from equilibrium through transient supercooling and undercooling. Whereas in the first process a slowly advancing freezing front will tend to remain rounded with any protrusional instability (positive feedback) damping out quickly, in the second

case an advancing interface may be more generally rounded or faceted, or conceivably dendritic if the energy perturbations are extreme and the positive feedback mechanism comes into play.

Without the advantage of sections or thin-slices we cannot be certain how these processes influence the microstructure. However, we know from laboratory studies (Colbeck 1986b) and field measurements on disaggregated specimens (Marsh in press) that in the first process \bar{D} increases rapidly with time and amount of liquid water.

Equation (1) and its solutions remain applicable to the first process, except that K is no longer a function of temperature, but some increasing function of liquid water. It is also expected that the exponent n in (6) could decrease below 2, and in fact Marsh (in press) provides some evidence for n as low as 1 in a wet arctic snowpack.

DISCUSSION

The objective measurement of microstructure parameters that describe snow metamorphism is a wide open and exciting field of research. For progress we need to show how S_p , S_g , \bar{L}_p , \bar{L}_g and their distributions vary in the metamorphic processes. In the past, too much emphasis has been placed on matching theory and subjective estimates of crystal "size". Even for a simple two-parameter model of crystal growth such as (1) we know very little about how the parameters vary as a function of temperature, liquid-water, and microstructure.

On the theoretical side, an exciting topic is to model the positive feedback instability which causes the exaggerated morphologies in temperature gradient metamorphism.

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