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Snow Metamorphism:
The Force Behind Our Ever-Changing Snowpack

The mountain snowpack is in a constant state of change. From its creation in the Fall to its demise by Summer, avalanche forecasters study its mood swings and monitor influences that cause it to transform throughout the Winter. You know that many rocks go through geologic changes, or metamorphose, from the influence of tremendous heat and pressure. The term metamorphism, borrowed from geology, is also used to describe changes that take place within the snowpack. Like the earth's crust, the snowpack is comprised of different layers, each having its own unique characteristics in hardness and density. Some layers are formed by diverse snow crystals falling from the sky; some develop from drifting. Sometimes the snow melts on the surface and then re-freezes to form an ice crust that later becomes buried. Each layer, regardless of origin, is ultimately influenced by metamorphism. But unlike rock, snow exists very close to its melting point. Thus, it takes only subtle differences in pressure and temperature to bring about change.

Soon after a snow crystal lands from the sky, it begins to change. It continues to change, or metamorphose, along with its neighbors until it finally melts in the Spring. There are three types of snow metamorphism—equilibrium, kinetic and melt-freeze—that take place in the snowpack. Equilibrium metamorphism simplifies the original crystal, making it more round. Thus, we refer to the resulting snow grains as "rounds," and the process as "rounding." Kinetic metamorphism turns the snow grains (new or old) into angular shapes with sharp corners and flat faces, or facets like on a diamond. We typically refer to these as "squares," or "faceted grains," or simply "facets." In the Spring melt-freeze metamorphism builds large, round grains on the snow surface called "corn snow."

Before we examine the three types of metamorphism in moredetail, here's some background information that will help you understand how these processes work in snow.

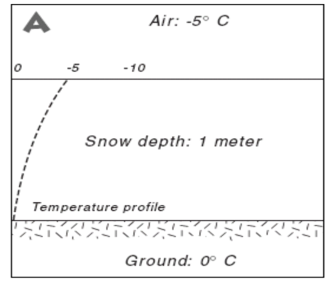
1. Snowpack properties commonly found in our continental climate zone:
- Snow depth varies greatly, even over short distances.
- Snow density varies from layer to layer—fresh powder is about 70kg/m3 (7% water, 93% air); a hard layer created by drifting is about 400kg/m3 (40% water, 60% air).
- Snow grains from different layers vary in size and shape.
- Air in the pore space between grains is saturated (100% relative humidity).
- Warmer pore spaces hold more water vapor than colder pore spaces.
- Snow temperature is generally warmer close to the ground, near 0°C, because porous snow is a good insulator (only 1/10,000 as efficient as copper for heat conduction).
- Snow is colder near the surface because of cold air temperatures and from longwave radiation heat loss to the atmosphere.
- The snowpack temperature gradient is usually non-linear as it varies from the warmer ground to the colder top surface.

2. The driving force behind the type of metamorphism that will take place, equilibrium or kinetic, is the temperature gradient in the snowpack. A small gradient of $<10°C/m$ ($<1°C/10$ cm) leads to equilibrium metamorphism (rounded grains). A large gradient of $\geq 10°C/m$ ($\geq 1°C/10$ cm) leads to kinetic metamorphism (faceted grains). Influences that control the temperature gradient include:
- Snow depth—highly variable.
- Terrain—aspect, elevation, or geothermal areas.
- Weather—warm or cold, clear or cloudy, dry or snowyperiods all affect the snow differently.

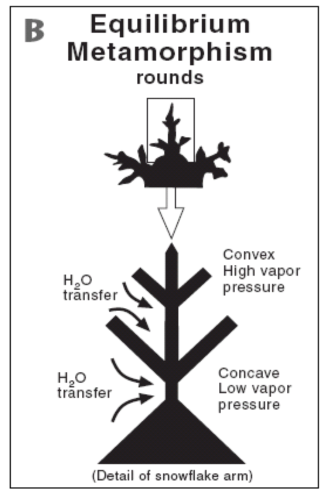
3. Another key player is vapor pressure. This is the pressure of confined vapor, such as found in the air spaces of the snowpack. Some important concepts to remember:
- Vapor pressure is lower over a colder ice grain than over warmer ice grain.
- If an ice grain warms, water molecules sublimate into the pore space.
- If the ice grain cools, water molecules redeposit onto the ice.

- If the pore space becomes supersaturated (>100% relative humidity), water molecules are attracted to the colder grains with a lower vapor pressure where they deposit onto the ice.
- Vapor pressure is greater over a convex ice shape (points) than over a concave ice shape (cups).
- Vapor flows more freely when the layer density is lower.

4. Snow temperature of a layer helps to determine the rate of metamorphism. If the snow is warm (e.g., -1°C to -5°C), the process occurs faster than if the snow is cold (e.g., -10°C to -15°C). Metamorphism comes to a virtual standstill at -40°C. But Colorado's snowpack rarely dips below -20°C, and then only near the surface. Now let's venture out into the field, dig some holes in the snow and gather data. We'll apply the concepts above to scenarios that can be found in Colorado's snow pack.



A small temperature gradient promotes equilibrium metamorphism



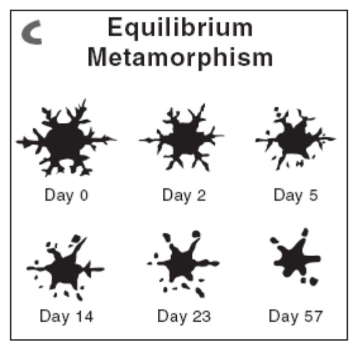
Original crystals lose their sharp points

Snowpit No. 1

This snowpit is dug on flat ground on a mild, -5°C day (see A). The measurements taken are:

- Snow depth = 100 cm
- Snow temperature near the ground = 0°C
- Snow temperature near the surface = -5°C

What can we determine about this snowpack? The temperature gradient is 5°C/m (0.5°C/10 cm). Since the gradient is weak, rounding will dominate. The snow is relatively "warm" so there is sufficient water vapor for transport. There will be a transfer of mass (water molecules) from areas of high vapor pressure (convexities) to areas of low vapor pressure (concavities), through sublimation (see B and C). As this happens, necks will grow between the grains—a process called sintering (see D). This process strengthens the snowpack. Rounded grains with strong bonds between grains form strong snow layers.



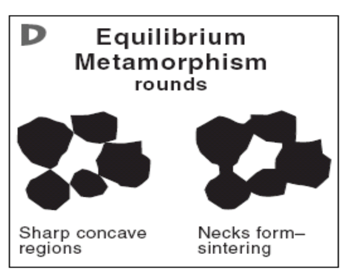
Rounds develop from equilibrium metamorphism

Snowpit No. 2

We've dug this snowpit several days after cold weather has set in (see E). Here are our measurements:

- Snow depth = 100 cm
- Snow temperature near the ground = 0°C
- Snow temperature near the surface = -10°C

What do we know about this snowpack? The temperature gradient is 10°C/m (1°C/10 cm), which is twice the gradient we found in our earlier snowpit. The snowpack is still relatively warm so any metamorphism that takes place will progress at a "normal" rate. And with the strong temperature gradient, kinetic metamorphism has taken over. Therefore, we can expect squares (facets) to grow, and this will weaken that snow layer over time. And the lower the snow density, the faster the growth of facets. In this case the water vapor doesn't slowly migrate and deposit in the concave areas of lower vapor pressure. The strong gradient forces the molecules to leave the warmer ice grains and reattach directly onto a colder grain nearby (see diagram F, above). This occurs progressively up through the snowpack as long as a sufficient temperature gradient is sustained. If this process were to continue for a few weeks, the resulting snow grains would look similar to those in photo G at right. These are large, angular grains called depth hoar, which is the result of advanced kinetic metamorphism. Note the weak bonds between the grains. This is an exceptionally weak layer (see photo H). The thin bonds between the large grains can be easily broken when stress is added, such as the weight of a



Strong bonds form between grains

person or snowmobile. This is the bane of avalanche forecasters in Colorado. This type of snow, whether in a thick or thin layer, cannot support much weight. Since these layers are subject to collapsing and causing an avalanche, they are monitored closely by avalanche forecasters.

Snowpit No. 3

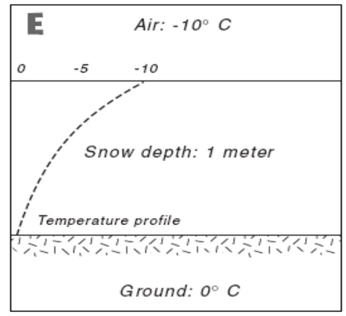
Now let's dig a snowpit on a typical day in the springtime (diagramI, above). The measurements taken are:

- Snow depth = 100 cm
- Snow temperature near the ground = 0°C
- Snow temperature mid-pack = -1°C
- Snow temperature near the surface = 0°C
- Average snow density = 300kg/m3 (30% water, 70% air)

What do we see in this snowpack? It is now much warmer at the surface. There is only a negligible temperature gradient in the mid layers as the snow approaches isothermal conditions (near 0°C throughout). And the surface snow is starting to melt. This is the end stage of the snowpack's life. Density has increased because the snow has settled over time and the pore space has decreased. Layers that developed early or mid-winter are losing their identity because of prolonged equilibrium metamorphism. All of the grains are rounding and the snowpack is gaining strength. Thus, spring snow conditions are less risky for avalanches. When the snow surface melts during the day and refreezes at night (regardless of the time of year), melt-freeze metamorphism takes over. During the melt stage the smaller grains melt first, providing free water in the snow, and the bonds are destroyed between the grains. Wet snow avalanches become likely on steep slopes, especially around rocky areas that soak up the heat on sunny aspects. When the snowpack refreezes, free water freezes onto the remaining ice grains, making them even larger than before (diagram J). This is how "corn snow" develops for good spring skiing. The snow is very strong in the frozen stage and very weak in the melt stage. Avalanche forecasts often call for different danger ratings from morning to afternoon.

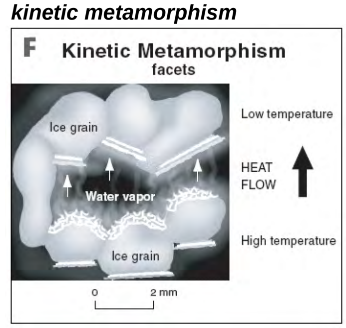
Summary

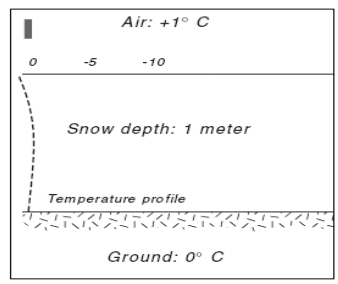
These simplified snowpits are good examples of how the three basic types of snow metamorphism work. But combinations of the contributory factors explored here are almost endless, making the Colorado snowpack a complex structure that develops and metamorphoses throughout the Winter. Its many layers, and the constantly changing forces acting on them, pose a formidable challenge to the forecasters at the Colorado Avalanche Information Center.



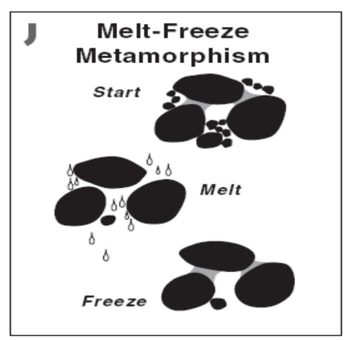
A large temperature gradient promotes kinetic metamorphism

Squares developing from kinetic metamorphism

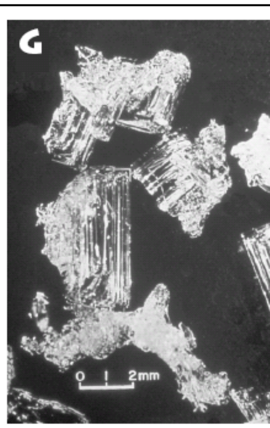




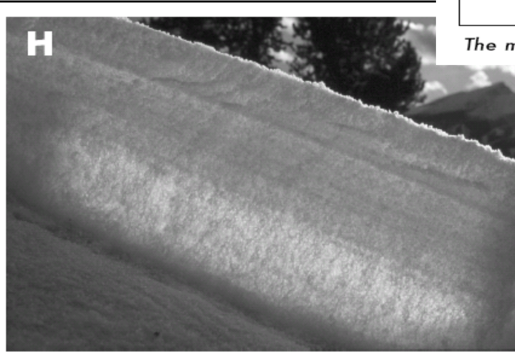
A typical spring snow temperature profile



The melt-freeze cycle



Depth hoar grains with weak bonds



A snow profile that is back lit. The lighter layer near the bottom is a weak layer of faceted grains (depth hoar).