Chapter 1: The Changing Mountain Snowpack

1.1 Mountain Weather Resources

Mountain weather and terrain combine to form the layered mountain snowpack. To forecast where and when avalanches are likely to occur, the backcountry traveler must have basic understanding of mountain weather—and experience with *how the weather interacts with* the local terrain. For avalanche forecasters, reading and interpreting current weather data and weather forecasts and projecting how the weather interacts with the local mountains becomes a daily routine. This is not a meteorology lesson. The session provides an introduction to local weather resources and tools and provides motivation to learn more about the important relationship between mountain weather and avalanches.

Learning Outcomes

Access the following resources:

- Local weather station information.
- Web-accessed local weather and snow stations.
- Local or Web sources' ridge top winds and temperatures.
- Weather forecasts for mountain regions.
- Local interpretations that include a description of how weather interacts with mountain terrain (avalanche bulletin or other sources).
- Be introduced to the weather information useful in daily hazard evaluation and forecast.

Key Concepts

- air masses
- high pressure
- low pressure
- fronts
- orographic lift
- upper level winds
- ridge top winds
- lapse rate
- precipitation type, rate, and duration
- forecasts
- weather resources

During the lesson presented in class, each student is introduced to various online resources for monitoring and anticipating weather conditions. The instructors recommend that participants establish a daily routine of monitoring these websites to develop skill at acquiring weather observations in a systematic way. This concept, along with the notion of manual weather observations, will be discussed further in Chapter 2.

It is important that the backcountry traveler understands the distinction between weather data and weather forecasts. It is also important to note the difference between a weather forecast for mountain towns (example: evening TV forecast) and a forecast for how the weather will affect the avalanche conditions (example: weather forecasts in the avalanche bulletin).

Observations and recordings of recent weather history are combined with current data to observe *trends*. The better an avalanche observer understands the local trends and patterns in each geographic region, the better is their understanding of why the mountain snowpack varies so dramatically over terrain.

AIARE encourages enrollment in a course on mountain weather to improve knowledge of this phenomenon.

Notes

Online Weather Resources

Each of these sites is a home page for a site that has a vast number of specific products. To explore these sites thoroughly will take a long time. It is helpful to choose a few weather products, stick with them and watch them daily to learn to recognize trends. The list below represents a few of many websites available.

National Weather Service: http://www.weather.gov/

Colorado Avalanche Info Center weather model forecasts (Western US domain): https://avalanche.state.co.us/pub_model_wx.php

Unisys Weather: http://weather.unisys.com/

San Francisco State University: http://squall.sfsu.edu/

University of Washington: http://www.atmos.washington.edu/weather.html

Colorado State University GOES satellite imagery: http://rammb.cira.colostate.edu/ramsdis/online/goes-west_goes-east.asp

National Center for Atmospheric Research real-time weather data: http://weather.rap.ucar.edu/

Snotel Data from NRCS: http://www.wcc.nrcs.usda.gov/partnerships/links_wsfs.html

Mesowest Wx Stations: http://mesowest.utah.edu/index.html

MetEd Comet Mountain Weather Distance Learning Course (estimate learning time 9-12 hrs) http://www.meted.ucar.edu/dl_courses/mtnwx/index.htm

Recommended Reading

The Avalanche Handbook – Selections from Chapter 2

Mountain Weather and Snow-Climate Types & Mountain Wind and Precipitation, p.21-26
Convergence: Upward Motion around a Low-Pressure Area; Frontal Lifting; Orographic Lifting & Convection, p.26-28
Quantitative Precipitation Forecasts & Orographic Precipitation Forecasts, p.28-29
Local Wind Flow Over Mountain Terrain & Blowing and Drifting Snow, p.29-34

Questions

Describe the general upper level weather pattern (example: SW flow) that provides the most precipitation for the local region?

Why are ridge top or valley winds often different from the prevailing upper level winds?

List local online weather resources where you can observe ridge-top wind speed, direction, and temperature. List an online snow resource where one can find local precipitation amounts.

Describe the Web weather forecast that describes and interprets how the weather is forecast to affect local avalanche terrain.

1.2 The Layered Snowpack

This lesson is an initial discussion of processes that combine to form layers in the snowpack and change the characteristics of those layers over time. It begins with the formation of snow in the atmosphere and introduces changes that begin to affect the shape of the snow grain and the surface layers. The mechanisms of heat exchange are covered, which lays the framework for discussing the processes that are responsible for snowpack metamorphism, including the creation of weak layers.

1.2.1 Formation and Classification of New Snow and Rimed Snow

The knowledge of how snow crystals form and change in the atmosphere is an important building block toward understanding the effects that crystal form can ultimately have on new snow instability and how well new snow will bond to the old snow surface.

Learning Outcomes

- Identify new snow types including dendrites, plates, riming, graupel.
- Explain how variations in precipitation type, rate, and intensity create different snow layers.

Key Concepts

- Condensation deposition
- super-saturated air
- water droplet
- water vapor
- snow crystal/snow grain: snowflake, new snow, precipitation particle, riming, graupel, snowpack

The Formation of New Snow

When the environment is right, *snow crystals* form in the atmosphere. These crystals are created when water vapor *condenses (deposits)* as ice on a crystalline *nucleus* (or dust molecule). Depending on the temperature and humidity in the regions where snow is forming, new snow crystals take a variety of shapes and fall to earth in a variety of sizes.

The classic six-sided "Dendrite or Stellar" crystal is what most people visualize when we talk about a new snow crystal. In reality, atmospheric (new) snow comes in a variety of shapes and sizes. We recognize a number of sub-classes that reflect the main types of new snow. Large irregular snow grains including plates, needles, or columns may form weak layers if covered by storm snow.

Each of the sub-classes in turn has numerous variations. More than one sub-class and/or variation can form in a single storm as the temperature and humidity regimes change. It is not uncommon to see several different types of new snow during a single storm, sometimes changing back and forth over relatively short periods of time (a few minutes or hours).

When a new snow crystal gains enough mass to overcome gravity and escape any updrafts that might exist in the air mass, the crystal falls from the atmosphere and eventually lands on the ground. The build-up of snow crystals on the ground from successive snowfalls creates what we refer to as the *snowpack,* which is really just the total accumulation of snow that has fallen to the ground to date in a given winter.

Recording New Snow

In avalanche work, we refer to most atmospheric snow simply as *new snow (also precipitation particles)* and often use one symbol (+) as the basic grain classification for all types when making field notes. Notable exceptions include plates, needles, or graupel. Advanced practitioners often identify sub-classes when they are able to clearly identify the grain type and when a sub-class is significant in terms of stability.

Observers are interested in observing and recording precipitation type, rate, and intensity. Even when the snowpack is stable avalanches can result when precipitation rates exceed 2cm/hr and deposit 30cm or more on the mountain slope. Varying types of snow falling during a storm cycle can result in a buried weak layer (example: large, well-shaped dendrites forming a thin layer under 30cm of small, more densely packed precipitation particles).

Additional specialized symbols for new snow sub-classes are in the SWAG, Table 2.3, and pg. 30.

Riming, Graupel, and Hail

Under some conditions, tiny water droplets form in the atmosphere and remain in a liquid state at temperatures below 0° C due to a lack of a freezing nucleus. These water droplets are described as *super-cooled*. When a super-cooled water droplet comes into contact with any surface or object, it immediately adheres to the surface or object and freezes, forming a small spherical piece of ice. This process is called *riming*. The tiny ice spheres are referred to as *rime*.

The most visible form of rime is when super-cooled water is driven against a surface by wind. Under these conditions, rime accretes on the windward side of the surface and creates a kind of icy stalactite formation that grows larger as additional rime is added. These rime formations are often seen on rocks, trees, communication towers, etc., in wind-exposed areas, especially in maritime climates.

If a snow crystal comes into contact with super-cooled water droplets, riming occurs and the rime accretes on the crystal. When this happens, we refer to the new snow crystal as being *rimed*. When only a few of these ice spheres exist, they are almost invisible to the naked eye; however, they can usually be observed using a simple hand lens magnifier. As the amount of riming increases, rime becomes visible to the naked eye.

Under heavy riming, new snow crystals can accumulate so much rime that their original form becomes completely obscured, eventually forming a roughly spherical (seldom a perfect ball) pellet. Sometimes referred to as "pellet snow," this is what we call *graupel*. Graupel particles that ride atmospheric updrafts and accrete multiple layers of rime can eventually form *hail.*

Riming may occur to individual snow crystals, or it can be deposited directly onto the snowpack if conditions are right. For example, if super-cooled water is present and the wind blows directly onto a slope where rime can be deposited and accumulate, a *rime crust* may form on the surface of the snowpack. While not a new snow crystal, rime added to the snowpack in this way becomes a layer that is part of the *snowpack*. Rime crusts are generally white and opaque, rough, and feel crunchy underfoot or to the touch.

Conclusion

This section presents a simplified discussion of how new snow forms and riming takes place. The actual processes are complex meteorological subjects. The previous paragraphs have limited the discussion to observable characteristics relevant to snowpack stability.

Since different sub-classes and variations of new snow often fall during a storm and since each of these may have significantly different characteristics, it is not unusual to see a number of layers form in the snow that accumulates during a storm (the *storm snow*).

Even if the storm snow is homogeneous, in most cases it differs from the surface of the snowpack it falls onto. This often forms the first of what may be many layers in the mountain snowpack, with the interface between the storm snow and the old snowpack surface being the boundary. In addition, riming may occur to individual snow crystals or on the snowpack itself.

The snow climate has an influence on the type of snow that forms, weather conditions under which it is deposited, and the likelihood that surface hoar will form (discussed in 1.2.5).

Due to all these factors (and more to be discussed later), it is unusual to see a snowpack composed of a single homogeneous layer with consistent characteristics throughout its height. Successive storm snow deposits, the weather conditions present during and between storms, riming, surface hoar deposits (discussed later), and the snow climate combine to create a succession of layers in the snowpack as it develops over the winter. These layers are often significantly different from one another. Even if they are initially similar, they may become different over time due to snow metamorphism processes. Since there are layers in the snowpack, and if they are different from one another, the layers may not bond to each other. It is this layering that is the basis for the formation and release of avalanches.

It is important to have this foundation prior to understanding the processes that drive snow metamorphism over time. Observers of the mountain snowpack require a solid grasp of the metamorphic processes. This knowledge provides essential clues to know where and what to look for when making field observations, recording findings, and eventually analyzing and forecasting snow stability.

Recommended Reading

The Avalanche Handbook - Selections from Chapters 2 & 3

Mountain Weather and Snow Climate Types, p.21

Snow Formation and Growth in the Atmosphere & Classification of Newly Fallen Snow Crystals, p.43-50

Snow, Weather, and Avalanches - Selections from Chapter 2

Table 2.3, p.30

Questions

List three factors that affect the shape and character of snow crystals as they form in the atmosphere.

Describe the differences between rimed snow, graupel, and hail.

Briefly explain how a layered snowpack develops.

1.2.2 Snowpack Structure

To understand how snow deposited from the atmosphere changes over time, it is helpful to begin with a mental framework of the physical structure of the snowpack and forces acting upon it.

Learning Outcomes

- Describe the physical makeup of a snowpack.
- Compare and contrast layers and interfaces.
- Explain how the various forces constantly exerted upon the snowpack by gravity change the snow through time.

Key Concepts

- ice lattice
- grain to grain contact
- pore space
- layers
- interfaces
- settlement
- snowpack creep
- snow gliding
- glide cracks

The Ice Lattice

The snowpack is a structure comprised of two basic components, the *grains* and the *pore space*. These parts may be apparent even to the casual observer. It is important to understand the physical nature of each component and its respective role in the transfer of heat and the movement of vapor (discussed in section 1.2.3).

The snow grains are ice particles comprised mostly of solid water and a smaller proportion of water vapor. The mass contained in these particles is not constant, and neither is their shape. Instead, the surface of these solid particles actually gives off water vapor to the air immediately surrounding the grains within the snowpack, also known as the pore space. Additionally, water vapor in the pore space migrates back onto the surface of the snow grains. The interplay of this movement of water vapor will determine the shapes that these snow grains will take in the near future. We call this process *metamorphism*. The actual process of snow metamorphism will be discussed more in section 1.2.4.

To the observer, it is important to understand that in low-density snow, where the grains are widely spaced, water vapor can move more readily. In contrast, with high-density snow, water vapor movement through the pore space is inhibited.

The transfer of heat is also determined by the structure of the snow grains and pore space. Solid ice conducts heat better than air, so dense snow or ice layers will transmit heat better than less dense snow. This concept will come into play in the upcoming section on heat exchange (section 1.2.3).

Layers and Interfaces

Each time snow falls from the sky, the snowpack gains a new layer. In some cases, where the nature of the storm changes, a single storm may produce multiple layers. As snow changes over time, multiple adjacent snowpack layers may become quite similar in their grain size and form. In practice these layers may be considered a single layer. Other times a single buried layer may be exposed to different conditions at various heights within that layer, becoming multiple layers over time. In short, avalanche practitioners consider a snowpack layer to be a band of snow grains with similar characteristics.

The boundary between two adjacent layers is referred to as the *interface*. This distinction between layers and interfaces will play an important role for the snowpack observer.

Settlement, Creep, & Glide

Over time, individual snow grains will move under the influence of gravity. This movement can be categorized in three basic categories—settlement, creep, and glide (see Avalanche Handbook p. 75 & 78). Ultimately, the impact of these processes causes snow grains to move both down slope and to settle into place closer to the ground. All of these processes tend to happen more quickly and play a more significant role in analyzing snowpack instability at warmer temperatures—particularly in relation to a dry snowpack.

Settlement involves the snow grains fitting together tighter like pieces of a puzzle. This process results from snow grains rearranging as they change shape over time and settling under the weight of overlying layers. Settlement tends to happen on the order of hours to days and can play a role in both weak layers stabilizing as well as slabs forming.

Snowpack creep is settlement occurring on a slope, where gravity acts to pull snow grains slowly downhill. On an incline the grains in the snowpack rearrange and move down slope at a faster rate near the snow surface than near the ground.

Snow gliding involves the entire snowpack slipping down slope. When the snowpack is dry, glide is small or negligible. Glide in late spring can occur on certain slopes at a fast enough rate to produce a full-depth avalanche, called a glide avalanche. In this case the snowpack glides along a warm, (0°C), smooth, lubricated surface such as a smooth grassy slope, a smooth rock slab, or occasionally an ice layer. Glide cracks in the snowpack are often visible.

Snowpack creep is a continuous process and glide features can often be observed over multiple days.

Conclusion

A basic understanding of the physical structure of the snowpack is essential to understanding snowpack processes. In general terms, the snow grains interconnect to form a solid lattice of ice. In a dry snow layer, every pore space not filled with ice is filled with varying amounts of water vapor. The mountain snowpack is not a complete solid but a porous material that changes structure, deforms, and very slowly creeps downhill under the influence of gravity. The knowledge of how layers form, how grains change shape, and how the snowpack deforms as it lies over terrain is the foundation for anticipating and observing where and why avalanches occur.

Recommended Reading

The Avalanche Handbook - Selections from Chapter 4
Snowpack Creep & Snow Gliding, p.75-79

1.2.3 Snowpack Interaction with the Environment

Now that snow crystal and snowpack formation have been introduced (section 1.2.1), and the basic conceptual model of snowpack structure has been reviewed (section 1.2.2), the next step is to review how the snowpack interacts with the environment. This lesson introduces how energy (heat) is transferred to, from, and within the snowpack. It addresses the mechanisms for heat transfer, the importance of energy exchanges at the snow surface, and how air temperatures and precipitation can influence these heat exchanges to, from, and within the snowpack. This lesson illustrates the importance and usefulness of quality weather and snowpack observations in assessing how the snowpack changes over time.

Learning Outcomes

- Relate why energy exchange at the snow surface and within the snowpack is important to the snow observer.
- List the mechanisms for energy (heat) exchange.
- Describe the components of radiation balance at/near the surface (short-wave radiation and long-wave radiation).

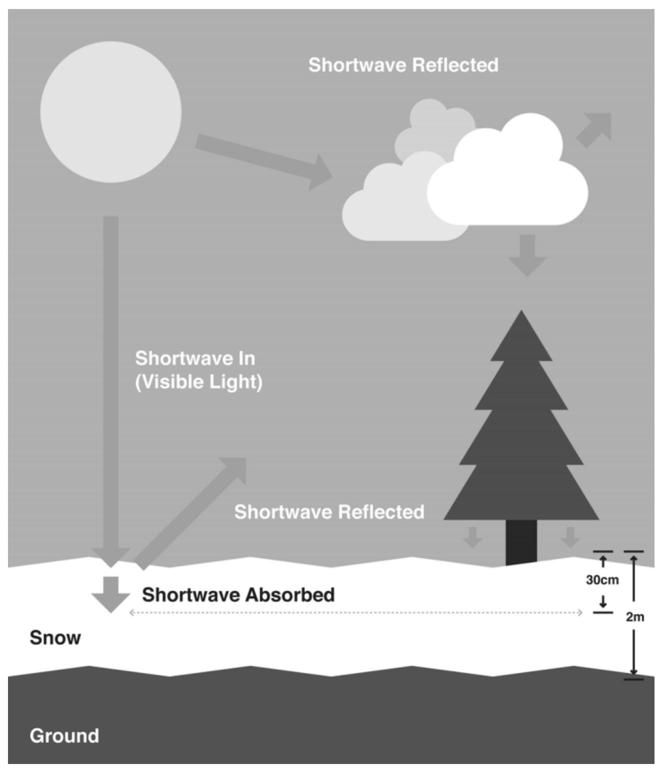
Key Concepts

Methods for Heat to Enter, Leave, and Transfer within the Snowpack

- Heat transfer: warm to cold, grain to grain, through pore space, rain and melt water
- Heat source: sun, earth, precipitation
- Terms: long-wave radiation, short-wave radiation, surface reflectivity

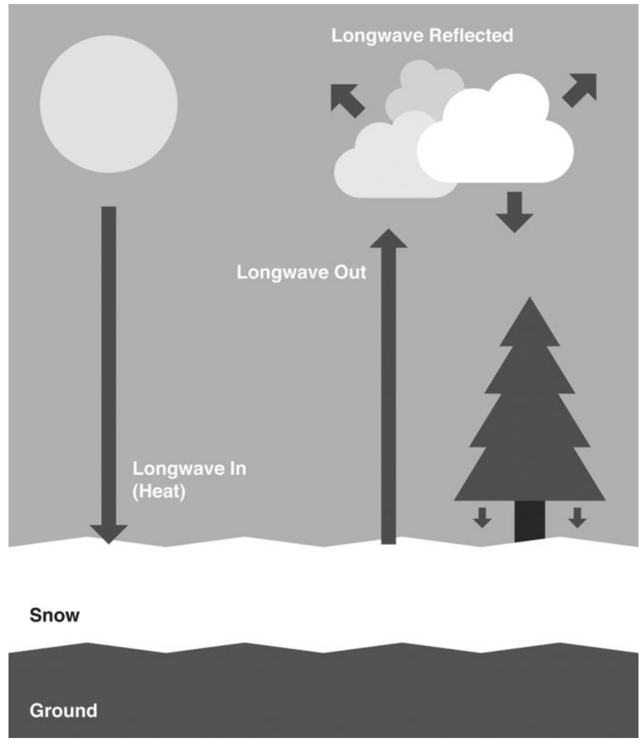
Solar Components: short-wave radiation, penetration into alpine snow, reflecting, warming of the snow surface

Energy (heat) exchanges at the snow surface play a major role in determining many properties of snow on the ground, including: snowpack stratigraphy, temperature, grain size and type, and snow density and depth. By examining energy exchanges at the snow surface, we can interpret and estimate metamorphism, and thereby make our weather observations more useful. This section describes how short-wave (sunlight) radiation factors into this overall energy balance at and near the surface.



Terrestrial Components: radiation into space, from clouds, heat flux through snow cover, conduction grain-to-grain

Long-wave radiation (heat) exiting or entering the snowpack is a primary component in estimating the overall energy balance at the snow surface and within the snowpack. This section describes how heat exchanges between the snowpack and the overlying atmosphere, between the snowpack and the ground, and within the snowpack factor into metamorphic processes.



Near-Surface Temperature Inversions

Temperature inversions are common occurrences in the mountains. Inversions can result in wind patterns that may transport snow and can influence spatial variability in temperature gradients and surface hoar formation. In addition, inversions affect the heat exchange between the snowpack and the overlying atmosphere.

Precipitation, Melting, and Freezing

Sensible heat (the heat you can feel) is exchanged if new precipitation is a different temperature than the temperature of the snow surface on which it falls. Rain contains more heat energy than snowfall. The warmer the rain, the more heat energy it has, and vice versa. If rain percolates into the snowpack and freezes*, latent heat* (heat released or absorbed from water changing phases) is released. Similarly, latent heat is also exchanged through melting, refreezing, sublimation, and condensation of snow grains. *Latent heat exchange* is a process that can warm or cool certain areas of the snowpack and alter temperature gradients. This can have an effect on metamorphic processes

There is heat exchange between the three distinct layers of the atmosphere (air), the snowpack, and the ground. Heat is also transferred within the snowpack itself. The ground releases stored heat into the atmosphere, and the snowpack acts like an insulating layer that "slows down" the transfer of heat from the ground to the overlying atmosphere. It may be easiest to think of the snowpack as insulating the ground from cold winter air like a down jacket. Conditions at the ground-snow interface remain fairly constant, while conditions at the snow-atmosphere interface can vary considerably throughout the course of the day.

Heat exchanges are responsible for many of the changes snow goes through, from the time it crystallizes in the atmosphere, to how it changes while exposed to atmospheric weather conditions, to how it changes once within the snowpack and, ultimately, to how and when snow melts.

By examining heat exchange at the surface and within the snowpack, the observer can interpret and estimate metamorphism, and thereby make weather observations more relevant.

This is a simplified discussion of energy (heat) exchange at and near the snow surface and within the snowpack. Energy exchange drives the metamorphic processes we consider relevant to avalanche analysis (covered in section 1.2.4). The actual processes are complex physical processes beyond the scope of this course.

Notes

Recommended Reading

The Avalanche Handbook - Selections from Chapter 2

Heat Exchange at the Snow Surface; Penetration of Heat into Alpine Snow; Interaction of Radiation with the Snow Cover & Temperature Inversions, p.36-41

Questions

What are the primary components of radiation balance at/near the snow surface and how do they "add up"?

Why is energy (heat) exchange important?

How does precipitation onto the snow surface impact the snowpack?

1.2.4 Metamorphism: Rounding, Faceting, and Sintering

This lesson discusses the processes that drive snowpack metamorphism. It begins with a review of snow grain decomposition and fragmentation. It covers how heat exchange (section 1.2.3) drives metamorphic processes and the importance of the relationship between temperature and vapor pressure. The concepts of temperature gradients and regimes, conditions that promote rounding and faceting, and snow grain sintering are covered. The topics covered in this lesson further emphasize how quality field observations are instrumental in assessing how the snowpack changes over time.

Learning Outcomes

- Explain why we measure snow temperatures.
- Relate temperature observations to vapor movement in the snowpack.
- Observe temperature gradients and their influence on metamorphism.
- Describe melt-freeze metamorphism and its effect on the snowpack.
- Observe faceting, rounding, and sintering and relate this observation to snowpack layering.

Key Concepts

- Decomposition
- Fragmentation
- Temperature gradient
- Temperature regime
- Rounding
- Faceting
- Sintering
- Melt-freeze

Decomposition and Fragmentation

Snow crystals are constantly trying to achieve a state of equilibrium and are undergoing constant change through vapor transport within the snowpack. In addition, as wind redistributes the snow, it mechanically changes the crystals; they tend to break up into smaller fragments and pack together more tightly. This forms a harder, denser layer (a wind slab or wind crust) on the surface of the snowpack. Snow grains that have been broken into small pieces and packed by wind are properly referred to as “broken” grains, but field practitioners tend to refer to them simply as wind-affected, wind crust, or wind slab depending on the extent of the effect.

Changing wind speeds and/or duration of wind transport of snow from the “fetch,” or windward, slope to the lee slope results in stiffer and less stiff layers being formed on the leeward (deposition) slope. Strong layers (slabs) over weak layers on steep lee slopes may be conducive to avalanching. Temperature and humidity play a role in drifting snow and slab formation. Drier, colder snow favors more drifting and redistribution. Higher humidity favors bonding and sintering that may inhibit wind redistribution, but may favor slab formation.

Observing Temperature Gradients in the Snowpack

In this context, a temperature gradient is simply a change in snowpack temperature over height. Temperature gradients and vapor pressure gradients are related in a predictable way, and vapor pressure gradients drive the movement of water vapor in the snowpack.

Water vapor pressure is not practical to measure for most field practitioners and backcountry travelers, so we estimate vapor pressure by measuring snow temperatures. Because relative humidity in the snowpack pore space is always near 100%, as temperature increases in the pore space, so does vapor pressure. This is because warm air can “hold” more water vapor than cold air, so warmer pore spaces in the snowpack will have higher vapor pressures than similarly sized cooler pore spaces. This relationship between temperature and vapor pressure is non-linear, implying that a small change in temperature can cause a large change in vapor pressure.

Heat transfers from warmer areas of the snowpack to cooler areas by conduction of heat through the ice skeleton (or through liquid water if present) and convection of water vapor across the pore space. The rate of the vapor movement across the pore spaces dictates what type of metamorphic process likely will dominate. By measuring or estimating snowpack temperature gradients, it is possible to estimate where, and at what rate, vapor is diffusing through the pore spaces. The observer can therefore infer from careful field observations how the snowpack is changing (for example, estimating the dominant metamorphic process that is changing the grain shape).

Conditions that Promote Rounding and Faceting

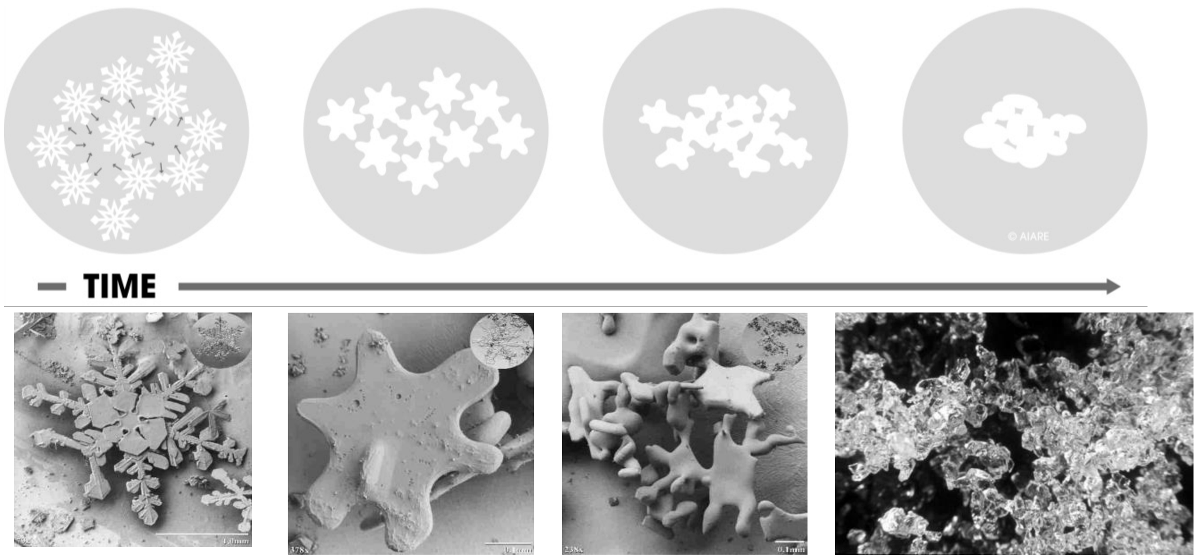
In avalanche work, temperature gradients are measured in degrees centigrade per 10 centimeters. This can be done for the layers of concern or for the entire depth of the snowpack. Taking temperatures throughout the entire depth of the snowpack is, of course, a time consuming and tedious process and often not practical. It may be worthwhile, however, to have a general idea of what the gradient is; this allows us to infer what metamorphic processes might be occurring in the snowpack so we can assess what the effect of those processes might be. Then we can decide whether it might be worthwhile for us to take a closer look at certain places to make a more detailed assessment.

Temperature gradients are described in this avalanche course as being either “low” or “high.” A low temperature gradient is less than a $1^{o}C$ changing over 10cm of snowpack height, and promotes rounding in the snowpack. Rounding is also promoted by high-density snow and warm temperature regimes. A high gradient is more than a $1^{o}C$ change over 10cm of snowpack height, and promotes faceting in the snowpack. Faceting is further promoted by low-density snow and warm temperature regimes. Note that warm temperature regimes promote enhanced rates of metamorphism for both rounding and faceting.

The characterizations of general snowpack temperatures are often referred to as temperature regimes. Simply put, “things happen” more quickly when the snowpack temperature is closer to 0°C (i.e., at -20° given a “high” gradient and a cold snowpack temperature regime, faceting would occur more slowly than at -5°C given a high gradient and warm temperature regime).

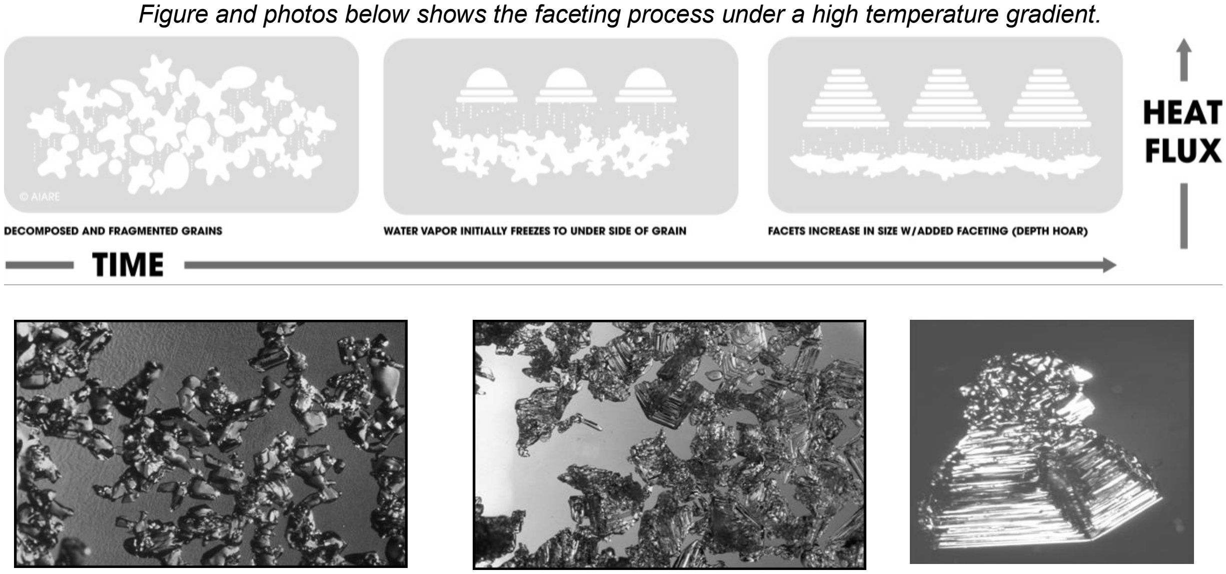
Rounding

Figure and photos below shows rounding process under a low temperature gradient.



Faceting

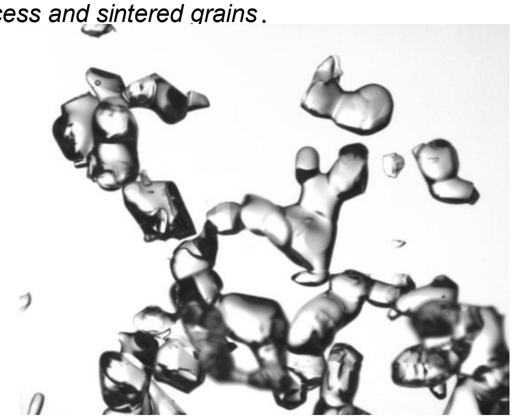
Figure and photos below shows the faceting process under a high temperature gradient.



Sintering

Ultimately, it is the degree to which snow grains bond to one another that determines the strength of any given layer in the snowpack, and how well each layer bonds to the layers above and below it. The strength of bonds within and between layers plays a critical role in assessing overall snowpack stability. Understanding conditions that promote sintering/bonding in the snowpack, and being able to recognize these factors with quality field observations, is a key element in developing stability evaluations.

Figure and photo below shows sintering process and sintered grains.



Melt-Freeze Metamorphism

The effect of melt-freeze metamorphism is obvious and relatively easy to assess, as it is due to weather effects (primarily sun and warm temperatures) and occurs at or near the surface. It creates very strong snow in the frozen phase. When melted, the snow is very weak. One needs little in the way of experience, skills, or tools to assess the effects of melt-freeze metamorphism.

Despite the ease of observing melt-freeze, it's important to recognize melting and refreezing can happen in different parts of the snowpack due to differences in slope aspect and angle, vegetative cover, elevation, snowpack characteristics, and spatial differences in air temperature and cloud cover. Melting does not only occur in the spring, and occurs in mid-winter to varying degrees in different climates. The surface may melt and refreeze as crust and then become buried by snowfall. Alternatively, the surface may melt, become buried as a wet layer, and *then* slowly refreeze into a buried crust. Either of these successive events can create a melt-freeze crust that is a distinct layer in the snowpack. The presence of crusts within the snowpack has implications for snow metamorphism and snowpack stability (discussed in section 1.2.4).

There are various degrees to which melting can occur, which is observable by the liquid water content of the snowpack. Melting may be confined to near the surface layers, or the entire snowpack may be experiencing some degree of melt. Similarly, the entire snowpack may refreeze if melting has occurred throughout, or only a portion of the snowpack may refreeze. If temperatures at night do not become cold enough, or stay cold enough for long enough, or if cloud or vegetative cover cause long-wave radiation inputs to the snowpack, only the surface of the snowpack may refreeze. Observers may notice a wet snowpack with only a thin melt-freeze crust at surface. This frequently occurs in spring conditions. It is not an uncommon occurrence to ski out early in the morning on a spring day, and have the surface freeze provide support in most places. Once the surface warms, the melt-freeze softens and one begins to "punch through" the surface crust to the wet snow layer below.

The melting and refreezing usually occurs many times in a cycle driven by the diurnal temperature and radiation fluctuations. This is what avalanche practitioners refer to as the melt-freeze cycle.

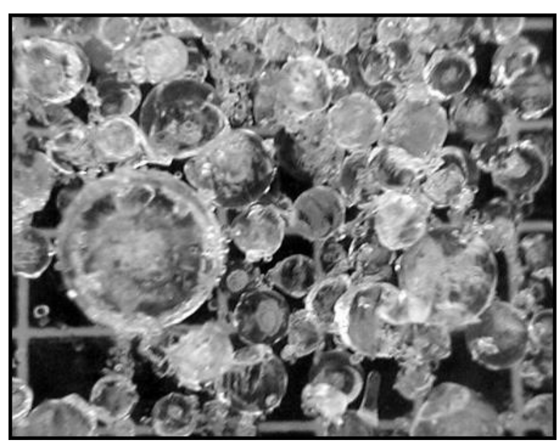


Photo shows melt freeze grains.

Conclusion

Snow crystals constantly change as they grow, fragment, and metamorphose. The precipitation particles seen on the snow surface are recorded as a form identified “at the time of observation.” Snow has already undergone substantial change before it hits the ground. When snow is on the ground, it continues to undergo change. This change is driven by heat exchanges, and the influence of atmospheric weather conditions such as air temperature, solar radiation, and wind. Once snow is buried, the changes are driven by heat exchange within the snowpack, pressure from overlying layers of snow, and/or the addition of liquid water through rain-on-snow events.

While a calculated temperature gradient may be useful (to determine the “direction” of faceting or rounding), determining what the temperature gradient might be and what processes are dominant quickly becomes intuitive and practical: if one is in a continental climate and it is early season, it’s usually a no-brainer to figure out that the temperature gradient is probably high much of the time, and it’s easy to tell that the snowpack is largely faceted when your skis are penetrating to the ground and the entire snowpack has a sugary texture. To the contrary, in maritime climates in the late winter where there are several meters of settled snow, you are skiing in a t-shirt, and ski penetrations are zero, you have a pretty good idea of what is going on in the metamorphic picture.

Despite this, it is valuable—one might say essential—to go through the exercise and a few examples to provide a thorough grounding in what temperature gradient is and how we measure it. Many people who have taken courses in the past will be stuck with the assumption that a high temperature gradient is “bad” because it creates “TG” snow. The instructors want to correct this “misperception.” While facets are often associated with weak snow layers, and persistent grain types, old facets may be well sintered and relatively strong.

The important point is that snow metamorphism occurs as a result of vapor moving within the snowpack. How vapor moves around, and hence, what metamorphic process(es) is observable, can be estimated by considering several primary drivers:

- Snow temperatures
- Radiation balance near and at the surface
- Effects of precipitation and melting/refreezing
- The heat exchanges between the ground and snowpack, between the snowpack and the overlying atmosphere, and within the snowpack itself

In addition to these discussed drivers, physical preconditions such as grain size, type, and available pore space (or porosity of the grain lattice) affect the rounding and faceting process. Wind-blown snow has small equal-sized particles that settle close together, providing low porosity and high grain contact. In this case, rounding and sintering is often the dominant process even given a relatively high temperature gradient. Stiffer wind slabs may result from rapidly sintering grains. Loose new snow recently exposed to clearing skies can rapidly facet even in conditions where the snow surface is relatively warm and a high gradient isn’t measurable (though radiation cooling can produce high gradients over a few millimeters or centimeters).

The discussion of rounding and faceting is not intended to delve into engineering or physics. The actual processes that cause rounding and faceting are complex and not fully understood. A good understanding of the factors that promote and influence the processes makes it easier to recognize which processes are likely dominating. The bottom line is: in stability analysis the observer needs to be able to recognize the difference between a rounded grain and a faceted grain and needs to know when rounding is likely occurring and when the factors favor faceting. *A look at the bonds between the grains as well as the grains themselves is encouraged.*

During faceting and rounding (or any other process), the resulting grains, and strong/strengthening or weak/weakening snow in and of themselves are not necessarily good or bad. Snow stability analysis requires us to take into account a much larger picture and look at not only individual factors but also combinations of factors. Yes, generally speaking, in the long term, weak or weakening snow is not desirable—but in certain combinations and over certain time spans, it may not be bad and, in fact, it may have a positive effect on stability (in the short term anyway). Conversely, strong/strengthening snow is usually preferred in the long run but it may not necessarily be good for stability in the short term. These concepts will be discussed further below.

Recommended Reading

The Avalanche Handbook – Selections from chapters 2 & 3

Snowpack Temperatures and Temperature Gradients, p.52
Disappearance of Branches: Initial Changes in Dry, Newly Fallen Snow, p.53
Dry Snow Metamorphism in the Seasonal Snow Cover & Crystal Forms in Dry, Seasonal Alpine Snow, p.55-63
Growth of Crystals Around Crusts in Dry Snow & Bond Formation in Dry Alpine Snow, p.63-67
Metamorphism of Wet Snow, p.68
Snow with High Water Content & Snow with Low Water Content, p.68-70
Bond Melting and Formation in Wet Snow, p.71

Questions

Why do we measure snow temperatures?

Define low and high temperature gradients.

Low

High

Which conditions promote rounding and which promote faceting?

Which conditions are conducive to sintering in the snowpack?

What influence does melt-freeze metamorphism have on the snowpack?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1.2.5 Facets: Near-Surface Facets, Near-Crust Facets and Depth Hoar

We know that faceting can occur when there is a *high* temperature gradient observed in the layered snowpack. While it is common for facets to occur at or near the bottom of a shallow snowpack, especially early in the season, facets can and do develop in other parts of the snowpack—sometimes in very localized regions of the snowpack.

In this lesson we will discuss two specialized circumstances in which facets might occur where they may not be suspected: 1) on or near the surface of the snowpack, and 2) near buried crusts in the snowpack where the surrounding temperature gradients are observed to be *low*. The facetted crystals produced in these circumstances are examples of persistent weak layers (persistence discussed in section 1.2.7) that are responsible for a large percentage of avalanches. Being able to recognize the existence of the problematic weak layers, and the conditions in which they are likely to form, is very important in assessing overall snowpack stability.

Learning Outcomes

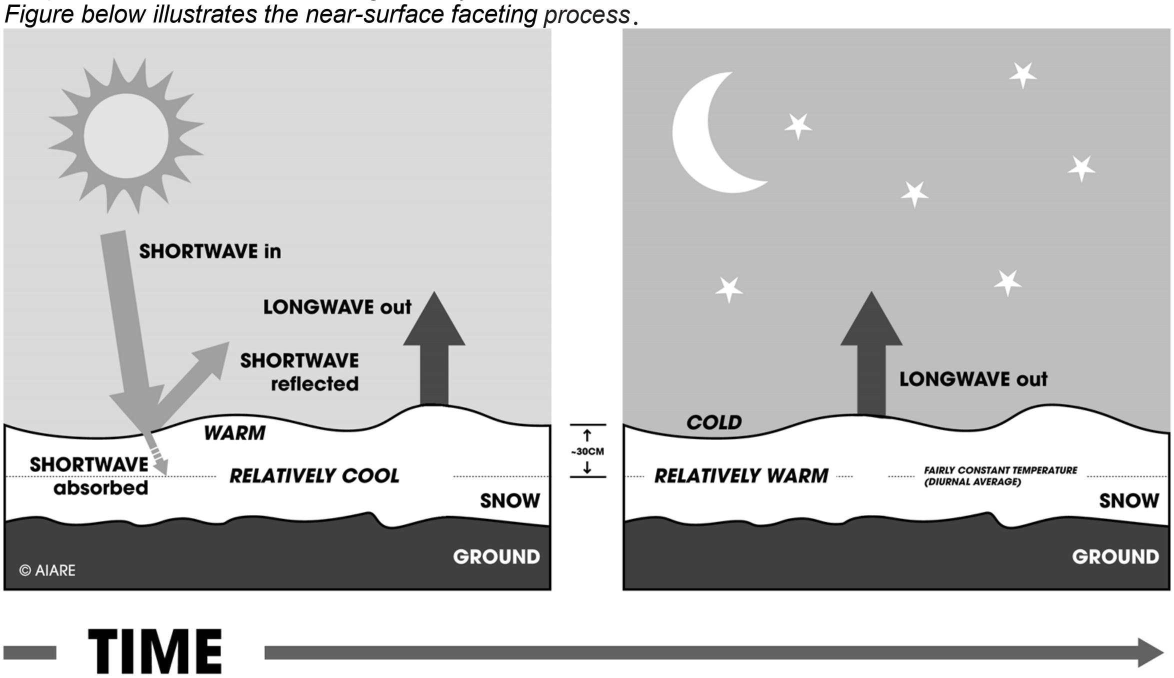
- Anticipate the weather and snow conditions that commonly lead to the formation of persistent facet layers.
- Describe why facets form around crusts in various places in the snowpack: near-surface faceting; dry snow over wet layer faceting, under-crust faceting.
- Observe how depth hoar forms and varies with terrain configuration and ground cover.

Key Concepts

- Near-surface energy balance
- Conditions that promote faceting
- Conditions that promote persistence
- Crust-facet interfaces

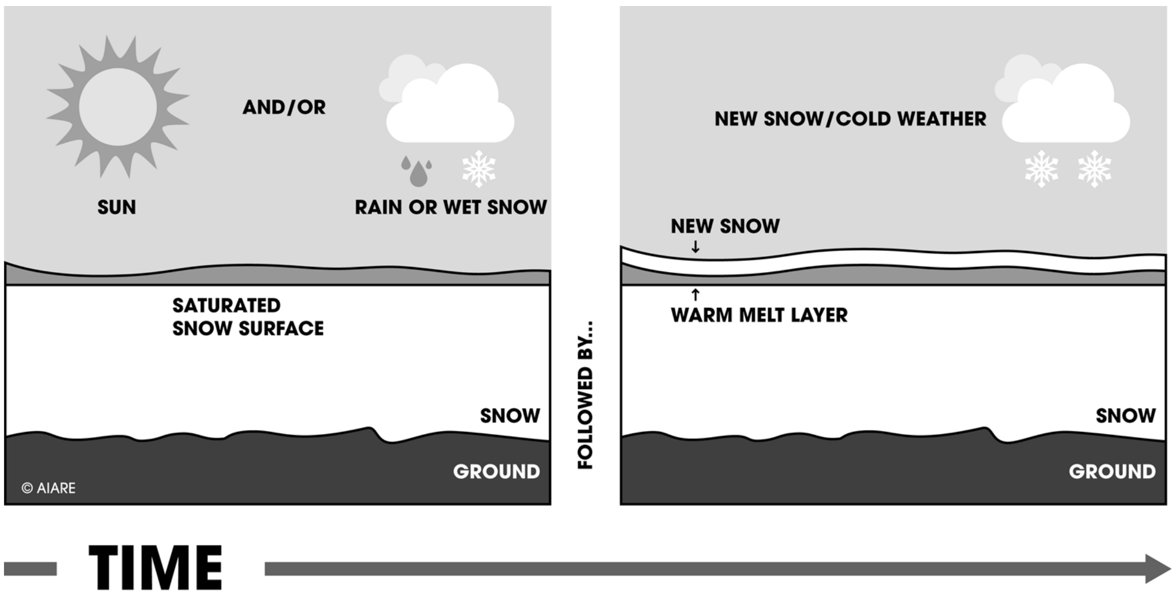
When surface or near-surface faceting is occurring, the surface of the snowpack will commonly change texture and appearance. Skiers often say the snow is “drying out” and skiing quality sometimes improves as moist or even wet snow which was sticky and well bonded loosens due to the breakdown in bonds with the development of faceted grains. Surface crusts and even soft slabs can soften or disappear altogether if surface faceting persists. Surface and near-surface facets often play a major role in skier-triggered avalanches. Understanding and recognizing when these layers are present, and when the conditions that promote the formation of these facets are present, is crucial in assessing stability.

Figure below illustrates the near-surface faceting process.



Field practitioners have noted near-crust faceting for years. Yet, new theories and recent published research are cautioning practitioners to look more carefully at crusts. We are now better aware of how problems can develop over time regardless of the crust's initial characteristics, associated temperature gradients, and whether there was a bonding problem of some sort when the crust originally formed. Crust formation can also occur in conjunction with near-surface faceting. When dry snow over wet-layer faceting occurs, the wet layer that provides the heat and moisture source to drive the faceting process will end up refreezing as a crust, with the newly formed facets above (and likely below) it.

Figure below illustrates the dry-snow over wet-layer faceting process.



With more careful observations, near-crust faceting has been noted in a variety of scenarios. For example, in Crested Butte, Colorado, near-crust faceting was observed in a fracture line profile where the snowpack was completely faceted over its entire depth. An old, weak sun crust that was almost completely eroded had notably larger facets just above and below it. Another notable case occurred in conjunction with the famous "ice storm" of January 1998 that occurred in eastern Canada and New England. When the snowpack at Pinkham Notch in the White Mountains of New Hampshire was observed in March, the entire snowpack was moist or wet. Facets were observed on the bottom of a very strong, 10cm thick freezing rain crust. Near- crust faceting created a very persistent problem in the Columbia Mountains of Western Canada during the '96/97 season when facets that formed in conjunction with a November rain crust caused large avalanches for several months.

These examples, while extreme, indicate that near-crust faceting can be a significant factor in the metamorphism of the snowpack and that practitioners should be aware of its potential and know what to look for.

Both surface/near-surface and near-crust faceting are important processes to recognize, since they can create problematic and persistent weak layers relevant to snowpack stability. The good news is the conditions that promote these processes are easy to observe in the field. Conditions that promote surface/near-surface faceting can be ascertained by considering the radiation balance at the surface, the amplitude of diurnal temperature swings, and the presence of wet layers. Conditions that promote near-crust faceting can be ascertained by looking for crusts in the snowpack, and when dry snow is falling on a crust or wet snow surface.

Recommended Reading

The Avalanche Handbook – Covered in reading list for section 1.2.4

Questions

Describe the conditions that promote near-surface facets.

Describe how and why facets form both above and below crusts in the snowpack.

1.2.6 Surface Hoar

Learning Outcomes

- Describe how surface hoar forms and under what weather conditions.
- Apply the process of surface hoar formation to terrain features where it is and is not likely to grow.
- Explain why surface hoar can be persistent and difficult to observe.

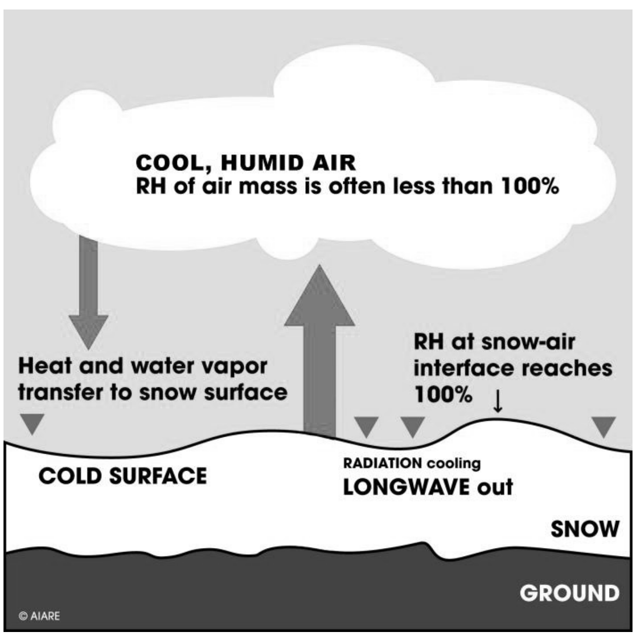
Surface hoar is the winter equivalent of dew.

Under certain conditions, the surface of the snow cools a thin layer of air at the snow/air interface to the dew point. The surface hoar visible on the snowpack in winter comes from the air that was in contact with the snowpack. Surface hoar crystals grow when the moisture in the air condenses on the snow surface. This process is analogous to the moisture in the air condensing on a beer mug removed from the freezer. Surface hoar is not limited to forming on snow; it is often seen on trees, bushes, rocks, etc., and sometimes referred to as "hoar frost" in non-technical circles.

Surface hoar crystals have a characteristic "icy" looking "V" shape, but they can also form as needle, plate, and hollow six-sided cuplike varieties. Generally, striations are visible on the crystals. The number of ice crystals formed on the snow surface and the size and shape of the crystals depends primarily on how much water vapor was in the air, what the air temperatures were, and the temperature of snowpack surface while the surface hoar was forming.

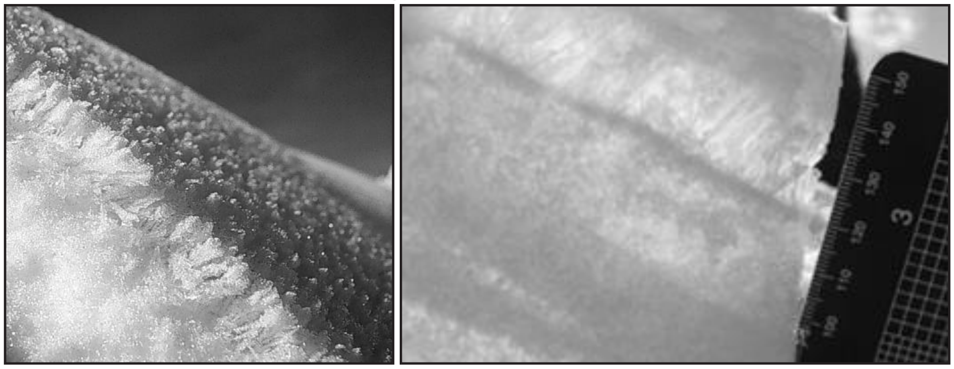
Surface hoar is an example of *a persistent weak layer* that is a major factor in many avalanches, especially in inter-mountain and continental climates.

Figure below illustrates the process by which surface hoar forms.



Surface hoar is quick to form (hours to overnight), hard to find once it is buried, and slow to decompose. Surface hoar can be easy to see when on the surface of the snow, but is often more difficult to find once it is buried. With an understanding of energy balance at the surface of the snow—and daily observations of radiation, cloud and vegetative cover, and wind patterns—inferring where and when surface hoar is likely to form becomes easier. For example, surface hoar is more likely to form in clearings and less likely to form in a dense forest because the tree cover interferes with radiation cooling. Additionally, surface hoar tends to form on clear nights, not on cloudy nights, again because clouds interfere with radiation cooling.

Photos below show surface hoar deposited on snow surface and buried surface hoar.



Notes

Recommended Reading:

<u>The Avalanche Handbook</u> – Selection from Chapter 3

Surface Hoar: Formation and Growth Conditions, p.49-52

Persistent and Non-persistent Weak-layer Forms, p.67

1.2.7 Weak Layer Characteristics

For a slab avalanche to occur, a weak layer that prevents the slab from bonding to the bed surface is required. It is in this layer that shear (and perhaps compression) fractures occur and propagate. The Avalanche Handbook distinguishes between weak layers (the Avalanche Handbook refers to these as “non-persistent” weak layers) and persistent weak layers.

Learning Outcomes

- Know the difference between persistent and non-persistent weak layers.
- Understand the conditions that promote persistence of weak layers.

Weak Layers

Non-persistent weak layers consist of snow grains that (while creating a weak layer after forming) strengthen quickly and bond to the slab and bed surface readily. These weak layers commonly consist of new snow grains, decomposing and fragmented grains, rounds, and perhaps wet grains. These types of grains metamorphose readily into stronger forms that bond well to each other and surrounding layers. Generally speaking, non-persistent weak layers will show observable strength gain and improvement in bonding in a matter of hours or days.

If a weak layer is related to new or recent snow (new snow or DF grains), note the depth of the fracture lines and watch the trend of avalanche activity. If avalanches are running in the layer of storm snow and activity tapers off in the first 24 - 36 hours after the storm ends, instability is almost certainly related to a non-persistent weak layer and stability will likely improve dramatically by the time 48 hours has elapsed.

If a weak layer is related to wet grains, watch (measure) air and snow temperatures above and below the wet layer. As air and snow temperatures fall to well below freezing, the problem will likely resolve itself quickly as the wet grains freeze. A wet layer may persist if temperatures are very warm and the grains do not freeze on an interface between grain types, as exemplified by density changes in storm snow.

Persistent Weak Layers

Persistent weak layers strengthen slowly (or continue to weaken) and do not bond readily to the bed surface or slab. Persistent weak layers usually consist of facets, either near-surface facets, depth hoar, or surface hoar. These grains do not metamorphose readily into stronger forms and do not bond well to each other or adjacent layers. Persistent weak layers may get weaker over time--even when strengthening persistent weak layers take many days, weeks, and sometimes months to show significant increases in strength or improvement in bonding. Persistent grain types forming above or below stiff layers and crusts can be durable and last for weeks, months, or even throughout the season in a mountain snowpack.

Persistent weak layers are often associated with mountain climates where extended periods of cold, dry weather are common, and where there are fewer precipitation events and accumulations are moderate or light.

Persistent weak layers are much harder to assess and forecast. Avalanches associated with these layers may occur sporadically when the layer first forms. Sometimes no avalanches occur until some time after the layer has formed and some combination of seemingly minor events triggers failure. Persistent weak layers are difficult to assess as they may go through cycles where strength decreases, increases, and then decreases again. In conjunction with these strength fluctuations, persistent weak layers often go into extended dormant periods before becoming sensitive to triggering.

Persistent weak layers require ongoing, long-term monitoring using a variety of observation, testing, and recording methods to ensure one does not lose track of their locations and characteristics (observation and testing methods are discussed later when we talk about observing and recording instability factors). Typically, persistent weak layers also call for a more conservative approach to terrain selection and hazard forecasting.

Notes

Questions

Describe the factors and conditions that lead to the development of surface hoar.

Describe conditions that promote the persistence of weak layers.

List three persistent weak layers that factor into a large percentage of avalanches, and describe conditions that would lead to the disappearance of these layers.

T. Carter

1.3 Avalanche Formation and Release

Learning Outcomes

- Relate key characteristics of avalanche formation to avalanche release; including the characteristics of loose snow avalanches, slab avalanches and cornices.
- Describe conditions that promote triggering of loose snow and slab avalanches, and cornice fall.

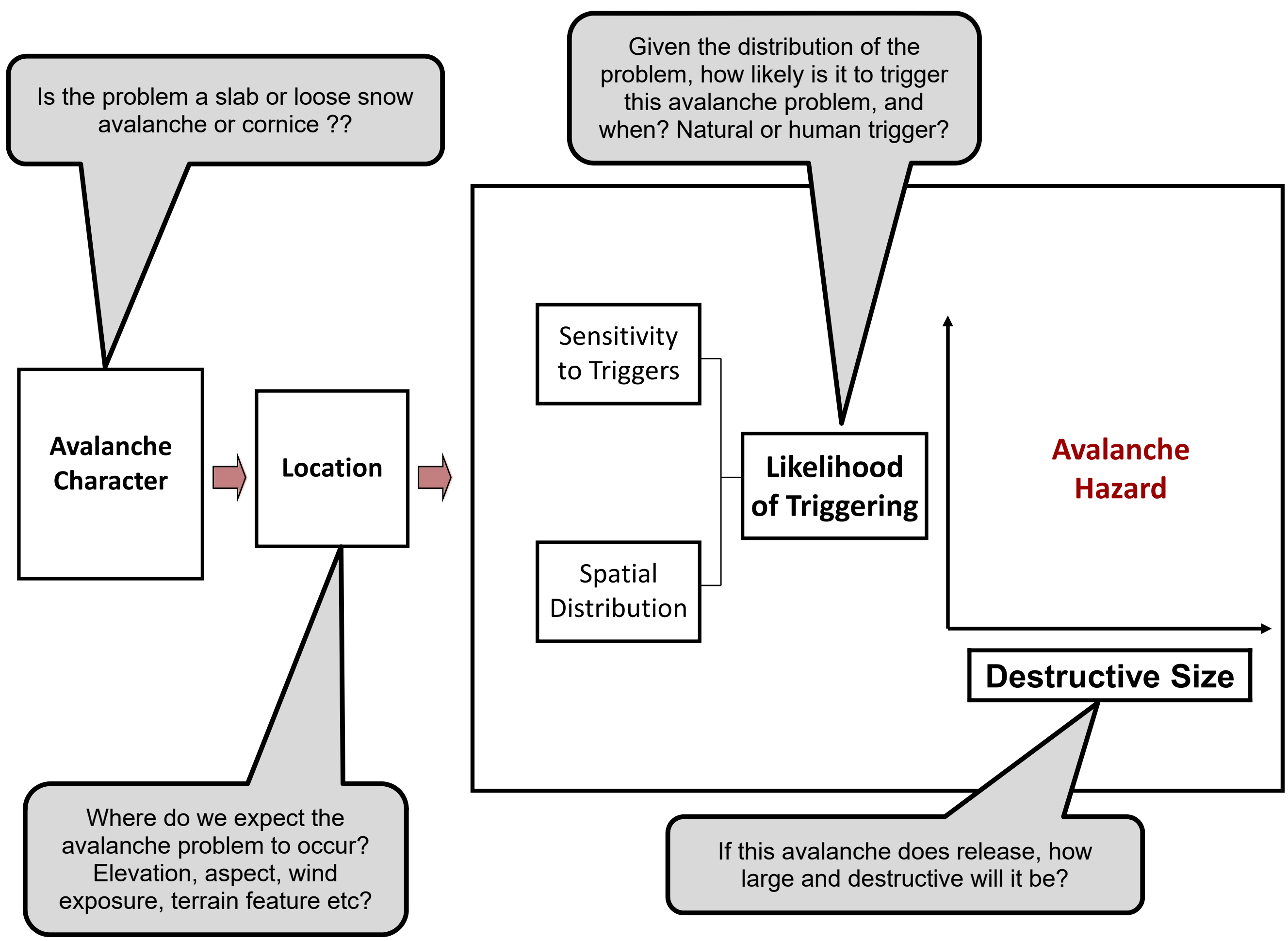
Key Concepts

- Loose snow avalanches (dry and wet)
- Dry slab avalanches (storm slab, wind slab, persistent slab, deep slab)
- Cornice hazard
- Glide avalanches
- Likelihood of triggering x destructive size = avalanche hazard
- Avalanche release
- Settlement
- Creep
- Glide
- Propagating crack
- Tensile fracture
- Crown, flank, stauchwall

Understanding "The Problem"

As an important component of evaluating avalanche risk, experts assess the avalanche hazard. The following diagram illustrates a commonly used approach when assessing avalanche hazard:

Chart from ADFAR2 Project: Parks Canada, CAC, G.Statham et al. Comments, AIARE



Our ability to evaluate the avalanche hazard relies on our understanding of how the mountain snowpack develops over terrain. This includes understanding how snow layers become relatively strong or weak, and it includes relating snowpack instability to a loss of cohesion of near surface snow or to propagating cracks through weak layers. This is knowledge of how avalanches form and how avalanches release.

Understanding the mechanism of *avalanche release* improves our ability to:

- Determine where (distribution) and when (timing) avalanches could occur.
- Determine the probable extent and consequence resulting from avalanche release.
- Better understand which field observations and tests provide valuable clues that describe the avalanche problem.

Students are advised to bookmark the AIARE Avalanches and Observations reference (Section 3.1, p.74) and refer to the chart while reading the following section. It supplements this chapter's information on "how avalanches release" by targeting the important field observations and tests specific to each avalanche type and characteristic.

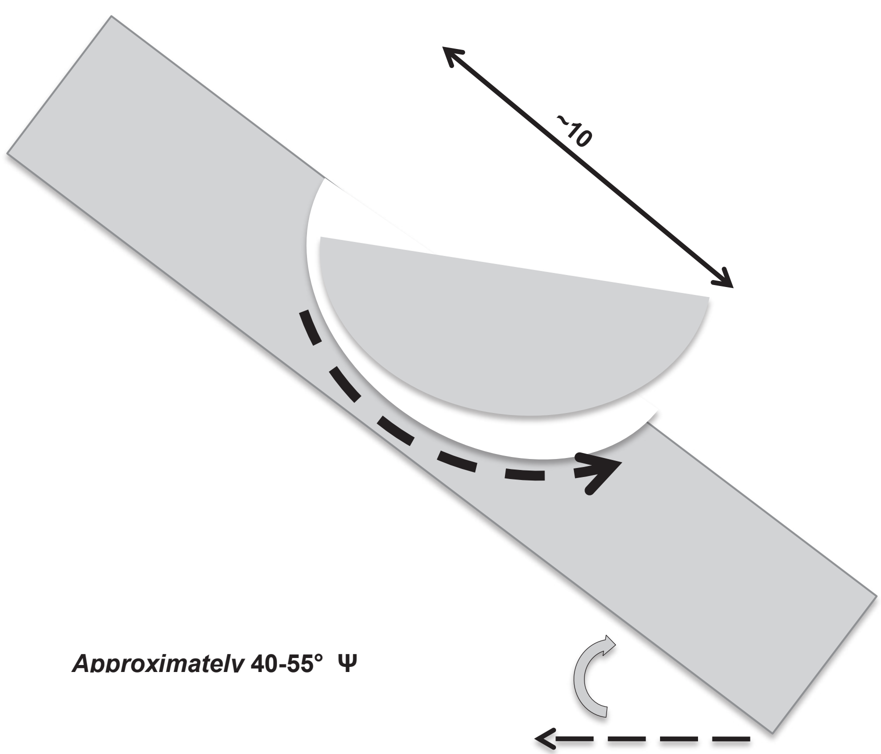
Loose Snow Avalanches

Loose new snow has low cohesion. Loose snow avalanches begin when a localized area of cohesion-less surface snow begins to move downhill; setting into motion additional subsurface loose snow (entrainment). The result is a fan-shaped avalanche initiating from a point in steep terrain (approximately ≥40 degrees) and widening as it proceeds downhill. (AHB: Chapter 4).

Loose *dry snow* avalanches are also referred to as point release avalanches and sluffs. Larger avalanches of this type tend to entrain subsurface loose snow or gain mass and speed on longer, larger slopes. The loss of cohesion occurs in both loose new snow and loose faceted old snow on steep slopes.

Loose dry snow avalanches tend to be small (size 1-2) though destructive potential increases with slope size or the exposure of those at risk to cliffs or terrain traps. Loose dry snow avalanches can trigger larger destructive slab avalanches.

Figure: Loss of cohesion at the snow surface, AIARE



A brief summary of factors that promote triggering loose dry snow avalanches includes:

- Steep terrain with a start zone incline approximately ≥40º.
- Loose *new* snow.
- Rapid snowfall rates (>4cm/hr) and slow settlement (cool temperatures).
- Mechanical action that can also trigger the initial loss of cohesion includes rockfall, rolling snow chunks, and skier/snowboarders.

R1 D1, loose wet snow avalanche.

Loose *wet snow* avalanches also release as a result of localized loss of cohesion at the snow surface. Wet snow is defined as snow at 0ªC. This avalanche type can be more destructive than loose *dry snow* avalanches, as the release can entrain denser, wetter snow with more destructive potential. Loose wet snow avalanches may be the trigger for larger, more destructive, slab avalanches.

Observers note that it may be hazardous to travel on steep slopes subject to a wet snow avalanche condition. Timing is critical when forecasting the problem and avoiding the hazard.

The factors that promote triggering of wet loose snow avalanches include:

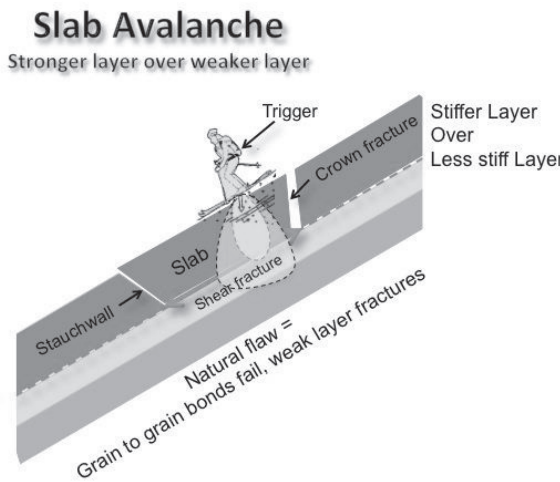
- Rapid warming of the snow surface, rocks, or trees, from radiation (sunny aspects during a diurnal cycle) or rainfall.
- Continued temperatures (day and night) of above 0ªC (cloud cover at night) resulting in surface snow temperatures reaching 0ªC.

Notes

Dry Slab Avalanches

Slab avalanches form when a cohesive snow layer forms over a less cohesive and weaker snow layer.

Under the influence of gravity a snow slope settles in a vertical (settlement) and down slope (creep) direction. Larger, angular grains (facets, depth hoar) settle and creep at a different rate than smaller, uniform grain types (fragments and rounds). Natural flaws develop between grains at the interface of layers with different *grain type, size*, *stiffness*, and *mass*.

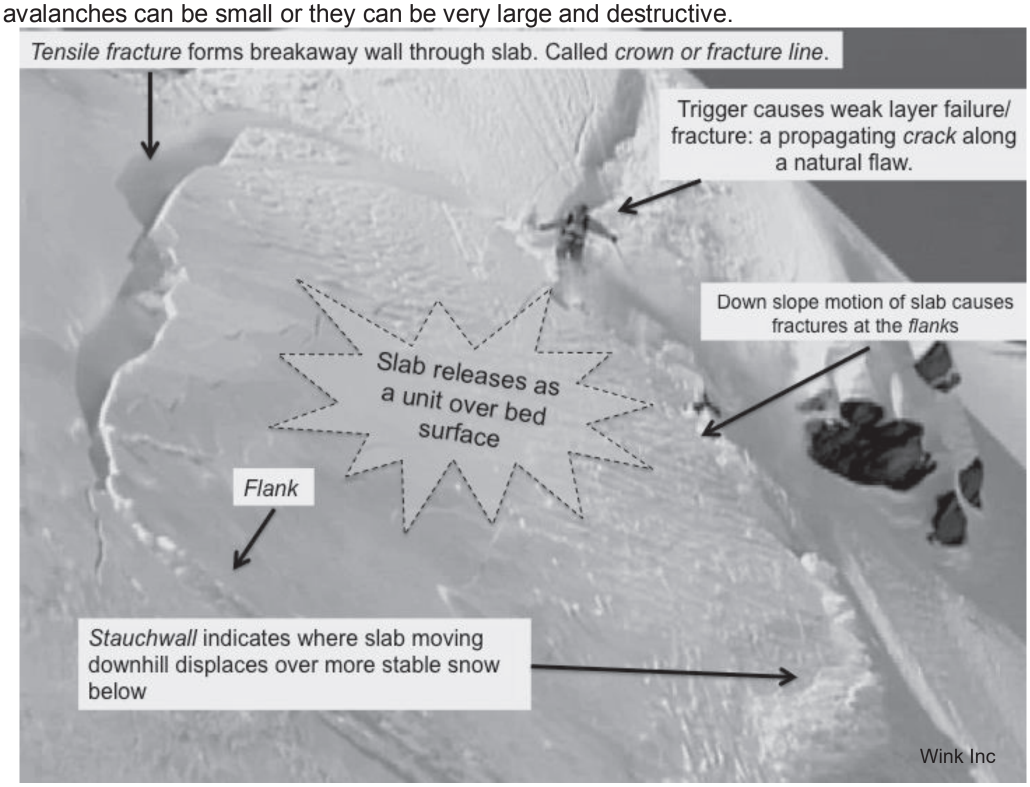


When avalanches are *not* occurring, the snowpack deforms slowly and reduces the strain rate at the weak layer interface. In other words, the snowpack adapts well to *slow* change.

However, when a trigger is introduced*,* a rapid loading of the weak layer occurs. Grain-to-grain bonds fail in rapid succession at the weak layer interface and a crack propagates along this natural flaw (shear fracture) displacing the slab downslope over the *bed surface*.

On the snow surface *shooting cracks* are visible to the observer as the cohesive slab displaces as a unit from the mountain slope. The shooting cracks are also called *tensile fractures* that fracture through the thickness of the slab as it breaks away and moves downslope. The displaced slab leaves behind identifiable features including the *crown fracture* indicated by the breakaway wall at the top of slope. The *flanks* mark the left and right fracture line on each side of the slab, formed as the slab moves downhill. The lowest feature is called the *stauchwall*, where the toe of the slab fractures and is displaced over the more stable snow below. Often the stauchwall fracture is obliterated by slab material moving downhill. (*AH. Chapter 4: Characteristics of Dry Slab Avalanches)*

Slab avalanches can be small or they can be very large and destructive.



Persistent slab avalanche

Public avalanche bulletins refer to different types of avalanches (described as "the avalanche problem") by their forming characteristics. **Storm slab avalanches** are defined as a release of a soft cohesive layer (a slab) of *new* snow that breaks within the storm snow, or on the old snow surface. Storm slab problems typically last between a few hours and few days. Storm slabs that form over a persistent weak layer (surface hoar, depth hoar, or near-surface facets) may be termed persistent slabs, or may develop into persistent slabs. **Wind slab avalanches** differ in that the cohesive layer of snow (a slab) is formed by the wind. Wind typically transports snow from the upwind sides of terrain features and deposits snow on the downwind side. Wind slabs may have a smooth or wavy snow surface, and may sound hollow under a skier's weight, and can range from soft to hard. Wind slabs that form over a persistent weak layer (surface hoar, depth hoar, or near-surface facets) may develop into persistent slabs, and may be termed a **Persistent slab avalanche**,**.** Persistent layers include: surface hoar, depth hoar, near-surface facets, or faceted snow. Persistent weak layers can continue to produce avalanches for days, weeks or even months, making them especially dangerous and tricky. As additional snow and wind events build a thicker slab on top of the persistent weak layer, this avalanche problem may develop into a persistent deep slab**.**

Therefore, a **Deep slab avalanche** involves an underlying persistent weak layer, deep in the snowpack or near the ground. The most common persistent weak layers involved in deep slabs are depth hoar, deeply buried surface hoar, or facets surrounding a deeply buried crust. Deep slabs are typically hard to trigger but may be remotely triggered where the weak layer is less deep. Deep slabs are very destructive and dangerous due to the large mass of snow involved, and can persist for months once developed (from CAIC, CAC, Parks Canada and others).

Each avalanche problem can be identified by specific field observations and specific tests. Refer to the AIARE Avalanches and Observations reference (AIARE Fieldbook p. 4) to assist to help target, and manage the hazards associated with slab avalanches.

Factors to Consider With Regards To Dry Slab Avalanche Release

Naturally occurring slab avalanches
Observing natural slab avalanches is always an indicator that conditions are unstable and prone to natural or human triggers. Unfortunately persistent and slab avalanches can be sensitive to triggering for long periods of time, and, *may not release naturally*.

Timing and sensitivity to triggering
Storm slab and wind slab avalanches commonly have a "window of opportunity" where they are more reactive to triggers. Avalanche control teams take advantage of this knowledge and attempt to control the problem soon after it forms. The storm slabs and wind slabs are formed by either deposition of new snow or wind deposit. Once the weak layer (often decomposed or fragmented grains or graupel) is buried roughly 25cm deep, the slab becomes reactive to a trigger. As the slab thickens with additional snow or wind deposit, it remains sensitive to triggering for anywhere from a few hours to 48 hrs, though in certain conditions up to a week (*TAR* article in press, Lazar et al). Weight from overburden and time encourages the weak layer to decompose, settle, bond and stabilize. In contrast, *persistent weak layers*, however, can stay unstable for days, weeks and even months.

Relating the depth of the weak layer and character of the slab to avalanche release
Studies *(Jamieson)* and the Avalanche Handbook *(Schaerer, McLung)* suggest that the majority of skier triggered avalanches are 50cm deep or less. However a significant portion of "unexpected" avalanches reported by avalanche professionals (Jamieson '99) were 50-100cm deep. This suggested that *unexpected* slab avalanches were thicker than most *skier triggered* avalanches. Consider two compelling factors when triggering slabs: 1) A deeper weak layer (>1m) is less likely to be triggered by a "skier", and 2) Slightly stiffer, thicker slabs, while harder to initiate, *favor propagation* and result in larger, more destructive avalanches. When observing deeper weak layers, observers recognize that the weak layer may be remotely triggered, or triggered from a shallow area.

Most "skier" triggered slabs are 4F (and 4F+) stiffness, and increasing in stiffness adjacent to the weak layer interface. These are recorded as "soft" slabs. Yet, many (less than half in a survey of professionals by Jamieson) "unexpected" events were described as "hard" slabs (1F or stiffer). It has been suggested (S. Thumlert, ASARC, University of Calgary) that the presence of stiff crust layers on the snow surface or "mid pack" reduces the likelihood of skier/snowboard triggering.

Preliminary work by Thomas Exner (ASARC, University of Calgary) suggests that as the slab warms (sun or heat) the stress applied by a human trigger doesn't penetrate any deeper into the snowpack. However his studies suggest the human applied stress affects a “wider” area of the weak layer, and given the penetration of the stress to the depth of the weak layer, can increase the likelihood of initiating the weak layer failure/fracture.

Chapter 1 briefly introduces the concept of relating snowpack observations to the possibility of avalanche release. Chapter 2: Making Quality Observations relates in detail the importance of craftsmanship/technique, site selection, experience with interpretation and application, and verification when assessing snowpack observations in the context of hazard and risk forecasting.

Relating the weak layer / interface characteristics to potential for avalanche release
The Snowprofile Checklist helps to identify the weak layer and interface characteristics most often associated (67-75%) with skier triggered slab avalanches. (*Using a Checklist to Assess Manual Profiles, Schweizer, Jamieson 2005*). If the underlying weak layer and interface has five or six of the following properties, the weak layer is more likely to be human triggered.

Weak layer properties:
- Persistent grain type (V, DH, FC)
- Grain size >1mm
- Weak layer <1F

Interface Properties:
- Grain size difference >0.5mm
- Hardness difference >1
- Depth of the interface 25-85cm

Relating fracture character in column tests to the possibility of avalanche release
Sudden fractures in compression tests and deep tap tests (and whole block fractures in Rutschblock tests) have been correlated to increased likelihood of skier triggering (Jamieson, Campbell, Cameron and others).

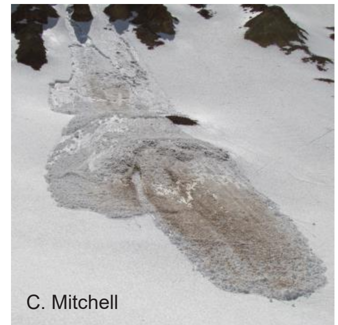
Observing propagating cracks while testing the weak layer, and shooting cracks on the snow surface
Extended Column Tests and Propagation Saw Tests that produce results for propagation have also been correlated to skier triggering of slab avalanches (Birkland, Simonhoise, Gauthier, Cameron, Jamieson, and others).

Whumping under a rider’s weight indicates the presence of a large, persistent grain types (DH, SH), and propagating fractures in the weak layer. *Shooting cracks* visible on the snow surface, and initiated by a rider’s weight, are tensile fractures indicative of slab fracturing and displacement without slab release (low angled slope or a localized area of unstable snow).

Relating localized loading to the potential for avalanche release
Scott Thumlert (ASARC, University of Calgary) has compared localized dynamic loading on a mountain snowpack. His measurements suggest that snowmobiles exert considerably more stress to the snowpack (3 to 5x) than skiers increasing the probability of a slab release. In addition, the sled penetrates stress 3x deeper into the snowpack. There was a significant decrease in stress with increased depth (this agreed with previous studies), and an observed “bridging effect” from supportive snow layers (stiff crusts) that reduced the measured depth of the applied stress.

Mr. Thumlert’s findings importantly suggest that, understanding the transmission of stress due to localized dynamic loads may help people avoid situations in which they can trigger avalanches”. (Source: http://www.sciencedirect.com/science/article/pii/S0165232X1200167X)

Wet Slab Avalanches



Wet slab avalanches occur from the release of a cohesive layer of snow (a slab) that is generally moist or wet from a rain on snow event or a prolonged period of sun and warm air temperature. Wet slabs release when liquid water weakens the bond between the slab and the bed surface. Wet slabs can be very destructive. This problem may be difficult to forecast and observe. It is dangerous to cross or conduct tests on steep slopes suspected to be prone to wet slab conditions. Timing is critical as wet slabs can quickly stabilize during cooling trends, and quickly become unstable when subject to additional heat and/or rain.

Factors that contribute to triggering:

- Rain on snow provides the most common trigger. Rain simultaneously weakens surface snow, provides additional load, and rapidly transmits heat into the snowpack (via latent heat exchange). Continued rainfall can percolate through the snowpack to a weak layer.
- Often loose wet snow avalanches precede and/or trigger wet slab releases.
- Prolonged periods of above freezing temperatures. During spring months, there is longer and more intense daytime solar radiation. Nighttime cloud cover can keep air temperatures above freezing and cause a portion of the snowpack to become *isothermal* (at zero degrees Celsius) and lose cohesion and strength.
- Nearby exposed rock and vegetation. Dark objects absorb radiation. Exposed rock and vegetation also inhibit snowpack settlement and provide channels for water percolation to the ground or lower snowpack layers.

Glide Avalanches

A glide avalanche is defined as the release of the entire snow cover as result of gliding over the ground. Glide avalanches can be composed of wet, moist, or almost entirely dry snow. They typically occur in very specific paths, where the slope is steep enough and the ground surface is relatively smooth. They are often preceded by full depth cracks (glide cracks), though the time between the appearance of a crack and an avalanche can vary between seconds and months (*TAR* article in press, Lazar et al).

Factors that contribute to triggering:

- Glide avalanches are unlikely to be triggered by a person, are nearly impossible to forecast, and thus pose a hazard that is extremely difficult to manage.
- Rain on snow, and rapid warming can increase glide rates and contribute to a full depth release

Glide avalanche at Alpental, WA

Cornice Hazard

Cornice fall is described as a release of an overhanging mass of snow that forms as the wind moves snow over a sharp terrain feature, such as a ridge, and deposits snow on the down-wind side. Cornices range from small wind lips of soft snow to large overhangs of hard snow that are 30 feet (~10 meters) or taller. They can break off the terrain suddenly and pull back onto the ridge top and catch people by surprise even on the flat ground above the slope. Even small cornices can have enough mass to be destructive and deadly. Cornice fall can entrain loose surface snow or trigger slab and deep slab avalanches (*TAR* article in press, Lazar et al).

Factors that contribute to triggering:

- More common triggers include rain or heat (daytime warming) on the cornice top.
- Less common triggers include new snow or wind deposited snow load.
- Other factors include weakening of the cornice "root" or cornice attachment point on the windward side from scouring or radiation. "Reversed" winds effect can scour and undermine the scarp and face below the cornice and create an unstable overhanging mass of snow.

Conclusion

In the conclusion of section 1.2.7 The Layered Snowpack, it was stated that in order to predict, anticipate, and make terrain choices, the observer must understand how snowpack layering occurs and how these layers combine (weak and strong layers) to form unstable snow.

Section 1.3 Avalanche Release described how near surface unstable snow forms loose dry or loose wet snow avalanches. Additionally, if the unstable snow is buried underneath a slab of more cohesive stronger snow, slab conditions were described in terms of how dry and wet slabs form and release. Also key are factors that promote triggering of either loose or slab avalanche problems.

Importantly, these concepts link to the forecasting of the avalanche problem. The understanding of 'how avalanches form and release' is inextricably linked to being able to name and describe the problem, including matching field observations to avalanche characteristics.

An understanding of how layering changes over time and varies over terrain is crucial to understand the notion of snowpack instability. Chapter 3, the Snow, Weather and Avalanche Recording and Observation Guidelines (SWAG, 2010), and the AIARE 2 field exercises are all tools employed on the AIARE 2 course to introduce observation techniques and recording methods that help the forecaster and guide to observe snowpack characteristics and apply this information in a hazard and stability forecast. Weather, snow and avalanche observations should begin with an objective that is created from the forecaster's knowledge of the history of the weather, snowpack and terrain.

The relevancy of weather, snow and avalanche observations depends on the site selection, craftsmanship, and interpretation of the observation. Chapter 3 and much of the AIARE 2 program introduces the importance of quality observations in the process of evaluating snow stability and avalanche hazard.

Introducing snowpack characteristics into the hazard evaluation process shouldn't distract from the most important tool: historical and current avalanche observations. Snowpack characteristics are merely one more piece of the puzzle. Carefully observed and recorded observations as to *where in the terrain avalanches are likely to occur*—especially relating to seasonal weather patterns and seasonal snowpack development—assist the observers with making prudent and sensible terrain choices and creating terrain options. Field exercises during the AIARE 2 Course will link the theory, the techniques, and the observations into terrain choices as part of the decision-making process.

By the end of this course each student may ask themselves the following questions, each time they travel in the backcountry:

"Given the conditions, what types of avalanches are likely to occur?"

"What are the observations that help me understand whether the snow is unstable?"

'Where in the terrain are avalanches likely to occur? Where in the terrain are avalanches likely to be triggered?

"If avalanches occur, what could be the consequence?"

Recommended Reading

The Avalanche Handbook – Sections from Chapter 4

Deformation in the Alpine Snowpack, Snowpack Creep, Snow Gliding, p. 73-79
Loose Snow Avalanche Formation, p. 87-90
Characteristics of Dry Slab Avalanches & Dry Slab Avalanche Formation, p. 91-98
Wet Slab Avalanche Formation, p. 100-103

Questions

Why is it challenging to assess the potential size and destructive potential of a wet loose snow avalanche?

You are investigating a particular slope. Five riders have descended the slope with no problems. You observe a persistent weak layer is buried 80cm deep under a stiff 1F slab. Is this *Persistent Slab* a problem? If not, why? If so, why?

What characteristics would indicate that a *Storm Slab* is less likely to be rider triggered?

Why refer to the AIARE Avalanches and Observations reference?

1.4 Chapter 1 Summary

The Chapter 1 reviews how terrain and mountain weather interact to create the mountain snowpack, and discusses how this can evolve into an avalanche problem. The mechanics of how loose and slab avalanches form and release were reviewed, as were the factors that contribute to the triggering of avalanches.

In order to understand the avalanche phenomena and estimate where and why avalanches could occur, the forecaster must have a data set of daily field observations. Chapter 2 deals with the integration of quality data into the decision making process. This includes international standards and guidelines for weather, snow, and avalanche observations. It also discusses the need for craftsmanship and a process for verifying the data set. It is important to manage human factors in the integration of these observations into the decision making process (outlined in chapter 3).

Notes