HOW GROUND TEMPERATURE AFFECTS TEMPERATURE GRADIENT METAMORPHISM--AN EMPIRICAL STUDY.

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Abstract.--The temperature at the snow/ground interface was sampled at 285 points in the common avalanche starting zones at Big Sky Ski Area, Montana in March of 1983. The temperatures, when plotted on a map, show a definite pattern of warm and cold areas ranging from +0.4°C to -5.6°C. An examination of past snowpit and avalanche records show that: (1) Temperature gradient (TG) metamorphism occurs more rapidly and later comprises a greater percentage of the vertical profile of the snowpack on warm areas as opposed to cold areas. (2) In the early season (usually from October through December) full-depth avalanche cycles running on TG snow tend to begin first on warm areas. Also, once a path runs to the ground on a warm area, it tends to run to the ground again--often several times--throughout the season. (3) Early season ski and/or boot compaction of snow in avalanche starting zones before the snow metamorphoses to TG significantly reduces the number and extent of full-depth avalanches runing to the ground on TG snow.

INTRODUCTION

Big Sky Ski Area in southwestern Montana is one of the major "Class A" avalanche areas in the United States usually ranking between third and fifth in the country for the number of avalanches per season (U.S. Forest Service 1982-1986). The avalanche starting zones exist between 9,000 and 11,000 feet elevation with the snowpack characteristically dry, cold, between 100 and 300 centimeters settled depth and usually about 50 percent of the vertical profile of the snowpack is composed of temperature gradient (TG) or faceted snow. The great majority of all avalanches, other than new snow avalanches, release on TG snow--either on TG near the ground (depth hoar) or mid snowpack TG layers. The rock substratum in all the avalanche areas is permafrost and throughout the winter remains at or below 0°C--sufficiently cold to support three major rock glaciers in the runout areas of several avalanche paths. However, the Big Sky area also has several areas of low-level geothermal activity with some located in avalanche starting zones. This creates a rather marked difference in ground temperature between the cold permafrost areas and the warm geothermal areas that is perhaps not unusual in high elevation terrain in the Rocky Mountains.

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Previous researchers have found that the speed and/or the amount of development of TG snow correlates with higher temperature gradient as well as a higher ambient temperature within the snowpack (Akitaya, 1974; Adams and Brown 1982; Adams 1982; Perla, 1985). One would expect, then, that a higher ground temperature would increase both ambient temperature as well as the temperature gradient within the snowpack--therefore promoting TG crystal growth in warm areas more than cold areas. This study attempts to answer the question: how does elevated ground temperature affect TG metamorphism and subsequent avalanche activity?

METHODS

In order to answer this question, I sampled the ambient snow temperature at the snow/ground interface in 285 locations throughout the common avalanche starting zones within the ski area boundry. I used a thermister with a low thermal mass (0.1 grams) coupled to a digital recorder acurate to 0.1 degrees centigrade and mounted on the end of a probe pole. I sampled the snow within a 3 day period during March 1983 after more than a week of relativly constant temperature.

I assumed that this temperature reading would show differences in normal wintertime ground temperature based on the assumptions that: (1) Any difference in ground temperature from summer solar heating had dissipated. This assumption is suported by the fact that many of the warm areas are located on north or northeasterly exposures which would normally be cold areas if latent solar heat was the heat source. (2) the snowpack was deep enough to insulate the snow near the ground from atmospheric influences; I did not sample temperatures in snow shallower than 100 cm. Also, a plot of ground temperature versus snow depths shows no significant statistical correlation.

In order to see how differences in ground temperature influence snowpack structure (namely the extent and timing of TG development) as well as the characteristics and timing of avalanche activity, I examined the records of both avalanche occurrence and snowpit data routinely taken by ski patrolers doing avalanche control work from 1972 through 1986. I also used my own observations during three seasons 1983-1985 while I was Director of Snow Safety at Big Sky as well as interviewing previous patrolers.

RESULTS

When the temperatures are plotted on a map, definite patterns of warm and cold areas show up (Fig. 1). The temperatures range between -5.6 ^{0}C and +0.4^0 C. One can see that this difference is significant because, a typical early season condition of a 100 cm snowpack with a surface temperature of -10^{0}C, would have double the

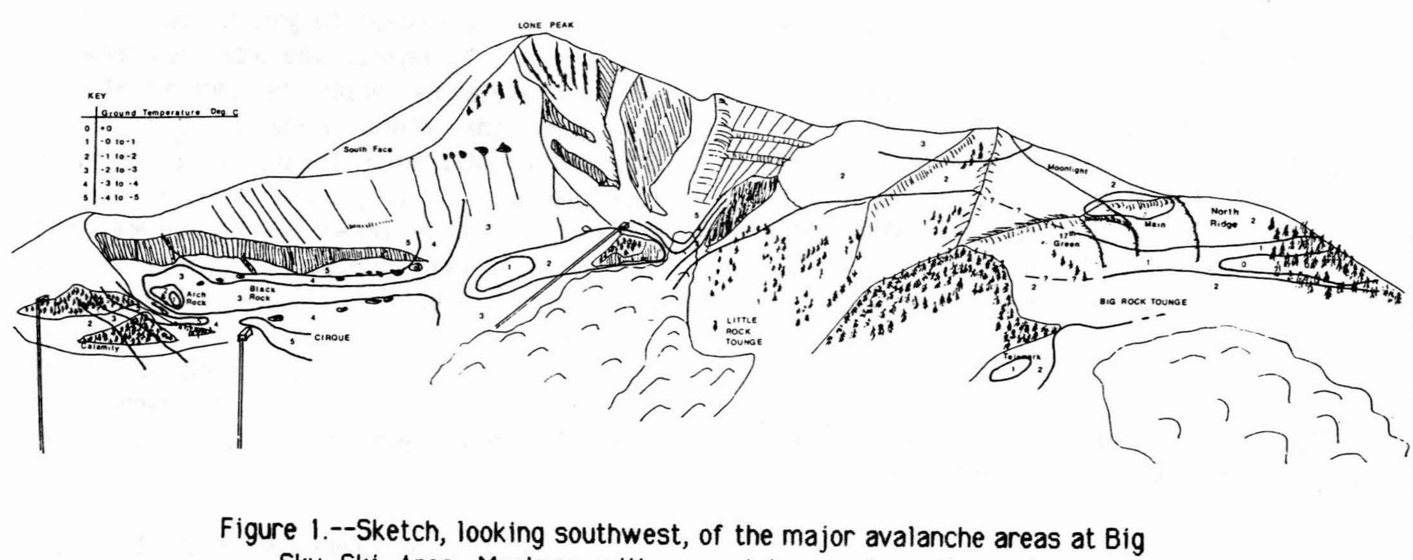


Figure 1.--Sketch, looking southwest, of the major avalanche areas at Big Sky Ski Area, Montana with ground temperature lines plotted. Andesite Mountain which contains the Snake Pit area is not pictured.

temperature gradient if the ground temperature were $0^{o}C$ instead of $-5^{o}C$.

I found several differences in the snowpack structure between warm and cold areas. In the early season--usually from October through December--the snowpack in the warm areas tends to undergo TG metamorphism faster and consequently a greater percentage of the vertical profile is composed of TG snow. In many warm areas, especially in lower elevation northerly facing ones, almost the entire snowpack is composed of TG snow whereas colder areas are usually around 50 percent TG (fig 2).

Perhaps the most important difference between warm and cold areas is in avalanche activity. This difference does not show up every season, but instead, it becomes more apparent during what is commonly referred to as a "bad depth hoar year", characterized by a thin early season snowpack--generally 100 cm or less--combined with cold temperatures--generally sub zero (deg. F) temperatures for about two weeks or longer. During these seasons, much of the snowpack is metamorphosed into TG snow which begins near the ground and progresses upward through the snowpack through time with the leading upper boundary composed of the weakest and most fragile crystal structure--the early or intermediate stage crystals as opposed to the advanced stage depth hoar near the ground (Adams and Brown, 1982). The snowpack becomes progressivly weaker as long as temperatures remain cold, eventually culminating in a cycle of full-depth avalanches. The cycle often begins in response to the added weight of new or windblown snow, although it can also, yet less often, begin without new loading as the snowpack weakens to the point to where it can no longer support its load.

The records show that when these depth hoar cycles begin, the first avalanche of the cycle usually begins on one of the warm areas. Also, once a full depth avalanche runs--especially on the warm areas--they tend to repeat this performance later in the season, sometimes more than once since the snow remains thin and a high temperature gradient occurs again and repeats the old cycle.

The 1985-86 season is a classic example of a depth hoar season and I present the interesting part of the seasonal history chart in figure 3. Notice several things: The first significant snows came in early November followed by a week of cold temperatures. A significant storm occurred on Novermber 22-23 but did not initiate an avalanche cycle. Several more days of cold temperatures followed and weakened the snowpack enough to finally begin a depth hoar cycle. With only an incremental addition of new snow, the cycle began with a small path, Calamaty Road, sliding to the ground with a ski release (a moderately warm area). Then the next three days witnesed major full depth slides in the three areas which commonly run first in depth hoar cycles--all warm areas. For the following week, many other slide paths ran with full depth avalanches, most of them on warm or moderately warm areas.

Also notice that several areas slid multiple times throughout the season. Arch Rock and Little Tree, both warm areas slid twice to the ground. BRT North Ridge, a very warm area slid three times to the ground and 17 Green, a moderately warm area also slid three times to the ground.

Finally, the warm areas tend to turn isothermal first during springtime warm weather (fig 4). Because most of the warm areas exist on north facing slopes, wet slides seldom occur there and consequently, I do not know how warm areas affect wet slide cycles.

DISCUSSION AND GENERAL OBSERVATIONS

In this section, I discuss several topics and observations--some do not directly relate to the study but pertain to temperature gradient metamorphism in general.

Three Seasons of Avalanches

In the northern Rocky Mountains, in regard to avalanche forecasting and avalanche control, there are really three seasons of avalanches. First is what I call the depth hoar season--usually from October through December--characterized by a thin snowpack combined with long nights and cold temperatures, steep temperature gradients within the snowpack, subsequent rapid depth hoar

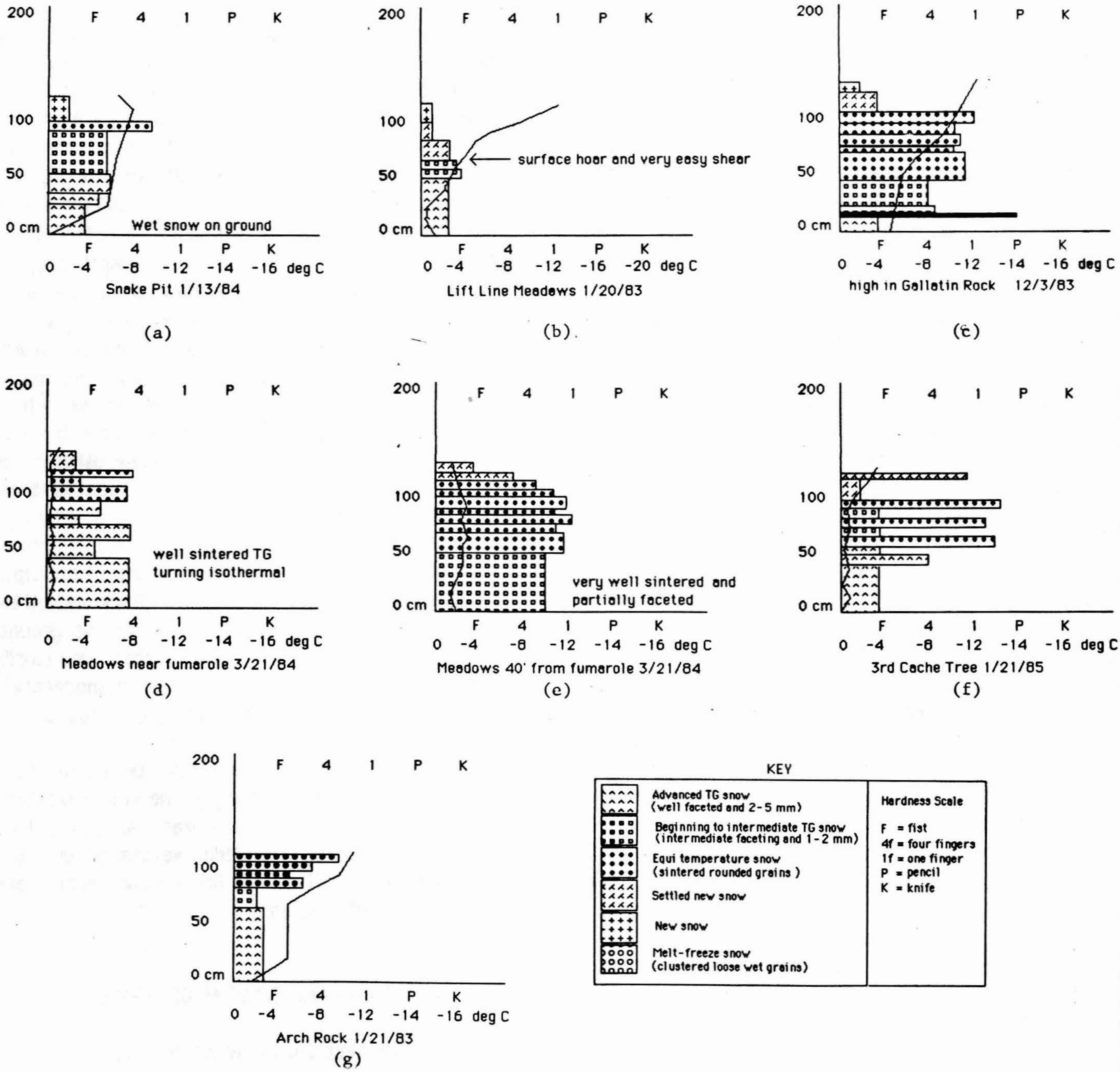
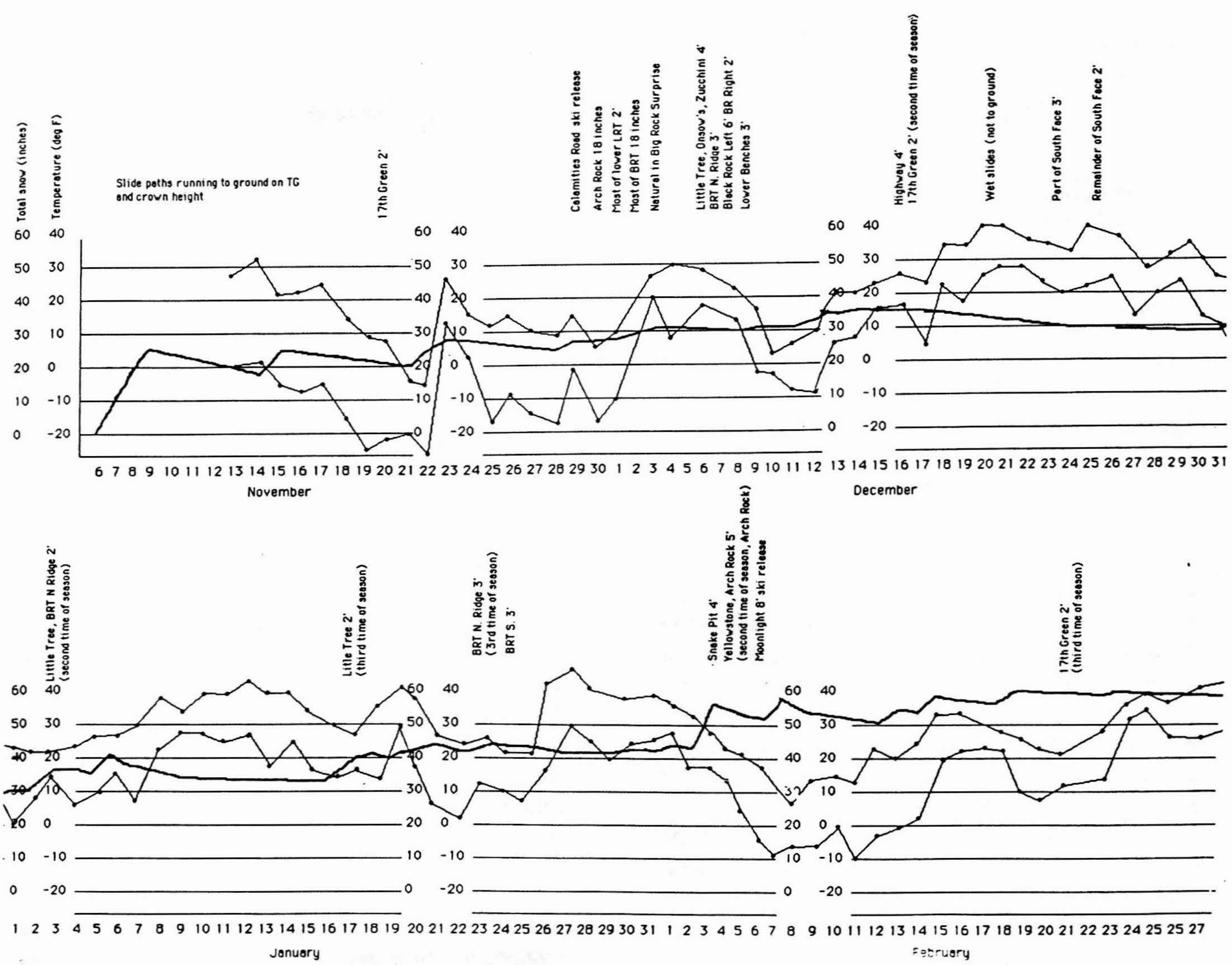


Figure 2.--Snow pit profiles of various areas at Big Sky Ski Area. (a) and (b), two profiles on Andesite Mountain--a very warm area (0°C or above) on well developed talus where 70 to 90 percent of the vertical profile is typically TG throughout the season. (c) A cold area (-4 to -5°C). (d) and (e) Two profiles, one near a warm area (0°C and above) and the other 40 feet from the other pit on a colder area (-2 to -3°C). (f), (g) typical profiles on warm areas which commonly release first during a depth hoar cycle. Profiles (c) and (g) are in the same area of the Cirque and at the same aspect and elevation; the only major difference is ground temperature.



Avalanche Path running to the ground	Average ground temperature in starting zone (deg. C).
Big Rock Tongue area (BRT)	
- BRT North Ridge	0-1
- Lower BRT in general	0-2
- 17th Green	unknown but extrapolated to 1
- Moonlight Bowl	2
- Big Rock Surprise	unknown
Little Rock Tongue area (LRT)	
- Highway	2
- Little Tree	1
- Onslow's	1
- Zuchini Patch	1
- Lower LRT in general	1
Cirque area	
- Calamity Road	2
- Arch Rock	1
- Black Rock Left	3
- Black Rock Right	3
- Lower Benches	3
Miscelaneous areas	
- Snake Pit	0-1
- South Face	unknown

Figure 3.--Seasonal history chart for Big Sky Ski Area, 1985-86. Temperatures and total snow readings taken from a protected climate station on a ridge lower in elevation than the avalanche areas. Most avalanche areas will have somewhat deeper snow and colder temperatures.

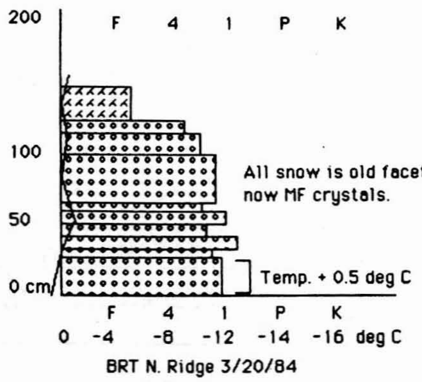


Figure 4.--Snow profile from a very warm area ($0^{o}C$ or above). This area often turns isothermal first in spring.

formation, and persistent instability. This instability is usually much more hair-trigger than the direct action avalanches common later in the season and it is also very sensitive to loading by new snow or human triggers. Not surprisingly, most avalanche accidents occur in early season and it is always the most anxious season for avalanche forecasters and snow safety directors. As Clair Isrealson, an avalanche forecaster for the Canadian National Park Service at Lake Louise, says, "Its like living with a crazy aunt--you never know when she's going to snap".

To compound problems, avalanches often release in areas where slides are rare in mid winter or spring. Specifically, they tend to occur much lower on avalanche slopes as well as on slopes in the bottoms of basins. I feel this occurs for several reasons: (1) The snowpack is usually thinner at lower elevations. (2) Cold air pools in basins especially in the early season long cold nights. (3) Ground temperature is often warmer because groundwater will tend to discharge lower on a slope or basin. (4) At Big Sky, there seems to be greater TG development on talus slopes as opposed to bedrock, presumably because water vapor can travel easily through talus blocks from the warm ground below, and often talus slopes exist lower in avalanche paths.

The second season of avalanches is the mid winter season. It occurrs normally from January through March as the snowpack becomes deeper, increasing the distance between the cold air and the warm ground, thereby decreasing the temperature gradient within the snowpack. Also, the increased load of snow compresses some of the pore space out of the depth hoar increasing the density which promotes strong depth hoar rather than the more fragile skeleton type (Akitaya, 1974; Marbouty, 1980; Adams, 1982; Perla, 1985). This season is characterized by much more predictable "direct action" avalanches composed of new or wind transported snow with deeper slab avalanches becoming much less frequent. During a bad depth hoar year, however, large loads of new snow during the mid winter occasionally initiate deep slides breaking to depth hoar. But most releases into old snow break on surface hoar or mid-snowpack TG layers. Most often, depth hoar becomes quite well bonded although the crystals are persistently large and keep much of their faceted morphology.

The third season af avalanches is, of course, the wet slide season, usually from April through June. Avalanches become even more predictable as they run almost always during hot sunny afternoons or in response to rain. During this season, avalanches breaking to the ground on depth hoar become common once again.

Snowpit Techniques

It seems that each snow researcher or avalanche forecaster has their own favorite snowpit techniques possibly because each is accustomed to working with different types of snowpacks. I too, have found certain techniques better than others and I use the following techniques with depth hoar snowpacks.

First, isolate a column of snow. Then cut another block of snow the same size as the top of the column, about 6 inches thick, and set it on top of the column. Keep adding blocks until failure occurs within the column. The snow can fail either from collapse of a TG layer or, since the layers are oblique to the direction of load (assuming your snowpit is not on level ground), failure can occur from shear on another weak layer, for example a surface hoar layer.

This tells you not only which layer is most likely to fail but you get an idea of the amount of new snow load required to make it fail. For example, if you added one foot of 20 percent density snow before failure occurred, it would take about 2 feet of new 10 percent density snow to make the snowpack fail. This, of course, is not a precise index but with some experience, it yields a quantifiable index of the snow stability with a minimum of time and equipment.

Early Season Snow Compaction

As mentioned previously, densification of snow promotes the formation of strong depth hoar instead of the tender skeleton type depth hoar. Because of this, I have used early season ski and/or boot compaction of problem areas (especially warm areas) and have found that it significantly reduces full-depth avalanches running on TG snow. Compaction should occur as soon as possible after the first significant permanent snowfall of the season. The compaction should penetrate through the snow to the ground. Often, widely spaced Z-shaped ski tracks are enough to anchor a snowpack.

CONCLUSION

Differences in ground temperature affect the snowpack and the avalanche occurrence in several ways. (1) TG metamorphism occurs more quickly and later comprises a greater percentage of the snowpack in areas with elevated ground temperature, because higher ground temperature increases the temperature gradient as well as the ambient temperature within the snowpack. (2) Early season avalanches cycles running to the ground on depth hoar often begin first on a warm area. Once these warm areas have run to the ground, they tend to run to the ground again, often several times, during the season. (3) The snowpack in warm areas tends to turn isothermal first in spring.

Early season depth hoar avalanches tend to occur lower on avalanche slopes and on slopes lower in basins when compared to mid season avalanches. This may be because: (1) The snowpack tends to be thinner at lower elevations due to less snowfall from orographic precipitation. (2) Cold air tends to pool in basin bottom and lower on avalanche slopes. (3) Ground temperature is often warmer because groundwater tends to discharge lower on slopes and in basin bottoms. (4) Often, TG development is greater on talus slopes presumably because water vapor can travel easily through talus blocks from the warm ground below, and often talus slopes exist lower in avalanche paths.

Ski or boot compaction of the snow in the avalanche starting areas before it metamorphoses to TG, significantly reduces the number and extent of avalanches running to the ground on TG.

Other ski areas plagued by depth hoar avalanche cycles may also benefit from a similar investigation of ground temperature in order to isolate problem areas.

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