How Surface Warming Affects Dry-Snow Instability

Temperature Effects
WARMING

Story by Jürg Schweizer, Bruce Jamieson, and Benjamin Reuter

Warming is believed to be one of the most prominent causes of snow instability – although experimental evidence is rare. We know that due to the low thermal conductivity of snow, warming at the snow surface rarely affects the weak layer temperature. In the case of dry-snow slab avalanches, instability is not due to weakening of the weak layer, but is believed to be due to increased deformation within the near-surface layers of the slab. Solar radiation can penetrate the surface and effectively reduce the stiffness of the upper layers. Changing slab properties directly affect snow instability in many ways. Recent field measurements provide insight into the processes believed to promote dry-snow instability. But still, field evidence is rare, which is also because the effects of surface warming are subtle and likely only promote instability during certain slab/weak layer conditions.

Dry-snow slab avalanche triggered on February 24, 2008, 2500m a.s.l., ENE; Avalanche danger level: "Low" (since eight days); Air temperature = +5°C, Temperature change = +6°C, warm southerly wind ("Föhn"): Surface warming – or freak avalanche? *Photo courtesy Jürg Schweizer*

INTRODUCTION

Apart from precipitation and loading by wind, a rapid increase in air temperature and/or in solar radiation is commonly considered a meteorological factor contributing to snow instability under dry-snow conditions. Despite the fact that the rule of thumb, "A rapid significant increase in air temperature leads to instability," is widely stated in avalanche education *(e.g., Munter, 2003)*, data to support this rule are rather sparse.

After an avalanche release often no other obvious external factor can be found. Harvey and Signorell *(2002)* reported that in 20% of the recreational accidents in the Swiss Alps an increase in air temperature (from the day before the accident) was the only indicator of instability. On the other hand, in many of the statistical avalanche forecasting models, temperature – but also the temperature change – ranks consistently low among the meteorological forecasting parameters *(e.g., Davis, et al., 1999; Schirmer et al., 2009; Schweizer and Föhn, 1996)*. In fact, in some of the leading textbooks *(McClung and Schaerer, 2006; Tremper, 2008)* suggest that the effect of warming on dry-snow stability is probably relatively small or only prominent under very special circumstances. Still, temperature (and radiation) is listed as one of the five main contributing factors (terrain, precipitation, wind, temperature/radiation, and snow stratigraphy) in Schweizer, et al. *(2003)*. They suggested that instability would be due to changing slab rather than weak layer properties, and that radiation would be more efficient than increasing air temperature in causing instability.

In the following we will briefly review some key elements on surface warming and its effects on snow instability – this is not a comprehensive review of the temperature effect.

DEFINITIONS, PROPERTIES, AND PROCESSES

To set the stage we first define the relevant terms and conditions. First of all, we focus on dry-snow conditions and dry-snow slab avalanches. With surface warming we mean that in the surface layers of the snowpack (i.e., in the upper layers of the slab) snow temperature increases. The temperature increase is due to a net energy flux directed into the snowpack which indicates an energy gain *(King, et al., 2008)*. The net surface flux is the sum of surface fluxes (shortwave radiation, longwave radiation, and turbulent fluxes of sensible and latent heat) neglecting latent or sensible heat added by precipitation or blowing snow and ground heat fluxes. Describing conditions by which the snowpack gains energy is complex, but occur mostly with intense solar radiation and/or an air temperature significantly warmer than the snow surface temperature accompanied by wind (wind is a necessary condition). Still, the snowpack only gains energy if these fluxes, the net solar radiation and the sensible heat flux, are not compensated by the energy loss due to the net longwave radiation flux.

Since the thermal conductivity of snow is low, the energy added to the snowpack by sensible heat travels slowly from the snow surface to the layer beneath *(e.g., Fierz, et al., 2008)*. In contrast, the energy input by shortwave solar radiation more efficiently warms the surface layers as the radiation penetrates into the near-surface layers (so that the energy is released within the snowpack). However, shortwave radiation penetration strongly decreases with depth below the snow surface. Compared to solar radiation, an increase in air temperature by 10°C from one day to the next will affect the snowpack to a depth of, say, 20cm much later and in attenuated form. Diurnal changes in air temperature over snow-covered surfaces are mostly not significant for surface warming, but diurnal changes in snow temperature in near-surface layers are predominantly due to absorbed solar radiation. Figure 1 *(on page 30)* shows an example of measured snow temperatures. In the course of the day, snow temperatures rose most remarkably in upper layers due to solar radiation on a southwest-facing slope. During the last time step, the snow already started to cool down due to the decrease in incoming shortwave radiation. Typically, significant surface warming takes place in the uppermost 20-30cm *(Fierz, 2011)*. A temperature increase of 10°C 10cm below the snow surface is common on south-facing slopes on sunny days *(Bakermans and Jamieson, 2008)*.

By the way, cooling – the opposite effect – is mainly due to heat loss by outgoing longwave radiation. The low thermal conductivity will cause cooling to take more time than warming by penetrating shortwave radiation.

Having identified the sources, conditions, and magnitude for surface warming we move on to the effect of changing snow temperatures on the mechanical properties of snow, and ultimately to stability. With snow being within a few degrees of its melting point, there is no doubt that changes in snow temperature strongly affect the mechanical properties, especially as the melting point is approached. Based on strength measurements in the cold laboratory, McClung and Schweizer *(1999)* concluded that the stiffness (effective modulus) of snow would be the property most sensitive to temperature, with strength being much less influenced. With increasing temperature the stiffness decreases – in other words, deformation in the near-surface layers increases, both in slope parallel as well as vertical direction (settlement). In fact, Exner and Jamieson *(2009)* have observed the increased deformation. If the temperature change in the near-surface layers is primarily due to the instantaneous release of energy from absorption of shortwave radiation, the change in mechanical properties is rapid as well. The change of the modulus in the near-surface layers has recently been determined from Snow Micro Penetrometer (SMP) measurements *(see Figure 2 on page 30)*. Over a few hours of solar radiation on a suitably inclined slope, cumulative energy inputs at the snow surface exceeded 300 kJ/m2 and caused the effective modulus of the surface layers to decrease by almost a factor of two on average *(Reuter and Schweizer, 2012)*.

Warming of near-surface layers affects mechanical slab properties resulting in increased deformation.

POTENTIAL MECHANISMS FOR PROMOTING INSTABILITY

For a dry-snow slab avalanche to release, a weak layer below a cohesive slab is required. An initial failure in the weak layer has to be initiated and needs to develop into a self-propagating crack below the slab. Surface warming is an external perturbation (trigger) that acts

Continued on page 31

Temperature Effects
COOLING

Treble Cone ski area in New Zealand: Saddle Basin was closed during the day due to creep and glide concerns. At 5pm the surface was starting to refreeze, so the forecaster gave the OK for groomer operators to go into the basin to work. The avalanche occurred sometime during the night, failing on depth hoar at ground. It damaged the lift bull wheel.

Cooling & Avalanches

Cool-Down Avalanches during periods of rapid refreezing can catch forecasters by surprise

Story by Penny Goddard

Avalanches that occur during periods of cooling are important because they can surprise people.

The subject first piqued my interest several years ago. I was sitting outside a ski lodge at the end of a hot spring day, watching the sun leave a steep slope on the opposite side of the valley. A few minutes later, a large slab released from the slope. It seemed incongruous, as no obvious trigger was present: no recent loading by wind, snow or rain; no person; and no bomb. The only change I could perceive was a rapid drop in temperature as the slope moved from full sunshine to shade and into its associated early evening chill. A few days later, I saw the exact same thing on the exact same slope.

In 2005, I took on the role of avalanche forecaster at Broken River Ski Club. Lingering in the shadows of my mind was an avalanche that had occurred there 13 years before. The week preceding the avalanche had been stormy, with 142mm of precipitation. Fluctuating freezing levels eventually led to a rain-soaked snowpack. On the day of the avalanche, the weather cleared, temperatures dropped, and the snow surface became slick and icy. Staff decided to open the area based on conventional wisdom: cooling and surface refreezing promote stability. At lunchtime, a size D4 avalanche failed near the ground on depth hoar, pulling out the entire Broken River basin with a crown up to 2.2m deep, which propagated 800m wide into low-angle terrain, leaving a deposit 20-30m deep. A snow groomer and skiers were in parts of the basin and may have been the trigger, but they were far from the fracture line. Amazingly, only one person (the ski area manager) was killed, as almost all the other skiers were inside having lunch. A photo of the avalanche hung on the wall in the forecasting office, leaving me chilled and uncertain. Doesn't an icy, frozen surface mean the snowpack's locked up? Why did the avalanche fail then and not during the warm storm? Why did it propagate so widely?

So began my investigation. I started by turning to the books to read up on this phenomenon and learn about the mechanisms behind such events. Beyond some passing references to rapid temperature changes, the standard volley of avalanche reference books left me empty-handed. I tried scientific journals, asked academics, and searched online. Very little came to light. So I began to ask my colleagues. A few people had experienced something like that. Many hadn't.

A more formal questionnaire followed. In the end, 40 avalanche professionals from around the world responded. The questionnaire focussed specifically on "refreeze" type events (where the snow surface goes from 0°C to below 0°C). I called this a "Cool-Down Avalanche" or CDA for short. The responses alerted me to the prevalence of surprising, large avalanches during periods of rapid cooling, not just when the snow surface goes from melt to freeze, but also at overall lower temperatures (e.g., a drop from -5°C to -15°C).

This article firstly summarizes the results of the questionnaire, then highlights a round of cooling-related avalanches in Western Canada during the 2010/11 winter season.

PART 1: CDA QUESTIONNAIRE RESULTS

In order of descending quantity, observations came from New Zealand, North America, Europe, Asia, and Antarctica.

- 15 of the 40 respondents had never experienced a CDA. (Many more people elected not to answer the questionnaire at all, due to having never experienced a CDA.)
- About 360 CDA were observed (this number is approximate, as the bulk of observations were poorly recorded, based instead on observers' memories).
- 98% of observed CDA were described as slab avalanches, 2% as loose.
- The bulk of the observed avalanches were size D2-D3. 14 were size D4, and three were size D5.
- 61% were described as "glide" releases.
- 20 CDA events occurred within 15-60 minutes of the sun leaving the slope. Another seven occurred less than 15 minutes after the sun left the slope.
- 21% of respondents had experienced a close call involving a CDA. These included very large avalanches hitting an open highway, burying a ski lift in an area that was open to staff and fully burying people in guided groups.
- 38% of respondents factor CDA into their decision-making while managing the exposure of people and infrastructure to avalanches. 44% said they do not.
- Seven people who have never had a close call involving a CDA factor the possibility of CDAs into their decision-making. Interestingly, three people do not factor CDAs into their decision-making, in spite of having had a close call involving a CDA (including involvement in fatal incidents).

The following comments made by respondents address some of the reasons why CDAs are rarely factored into operational forecasting:

- "[This is] much too speculative a theory to apply in an operational forecast."
- "I see 'cool-down' as the more stable end of the curve."
- "I don't factor CDAs into management due to a lack of understanding and observations."
- "I don't factor CDAs in, as it seems a very rare event."
- "I don't factor CDAs in, as there's no knowledge base, therefore they are hard to estimate."
- "The funny thing is, I probably still guide and operate considering cooling down as a good tick for stability."

CDA CONCLUSIONS

- CDAs (surface refreezing avalanches) were observed around the world.
- Accidents and near-misses have occurred when operators have re-opened previously closed terrain assuming that cooling means dramatically improved stability.

Ski patroller Ed Nepia at the crown wall of the Treble Cone avalanche. Hard refrozen snow jutted out like a diving board above soft, moist snow below. Similarly shaped crown walls were reported from various CDA events.
Treble Cone photos by Dean Staples

- Some operators actively manage the CDA hazard through closures or explosives control, timed to coincide with rapid cooling or surface refreezing.
- They were rarely observed overall; many experienced practitioners have never experienced a CDA.
- There's a feeling that they are too difficult to predict, so there's a tendency to ignore them when making decisions.

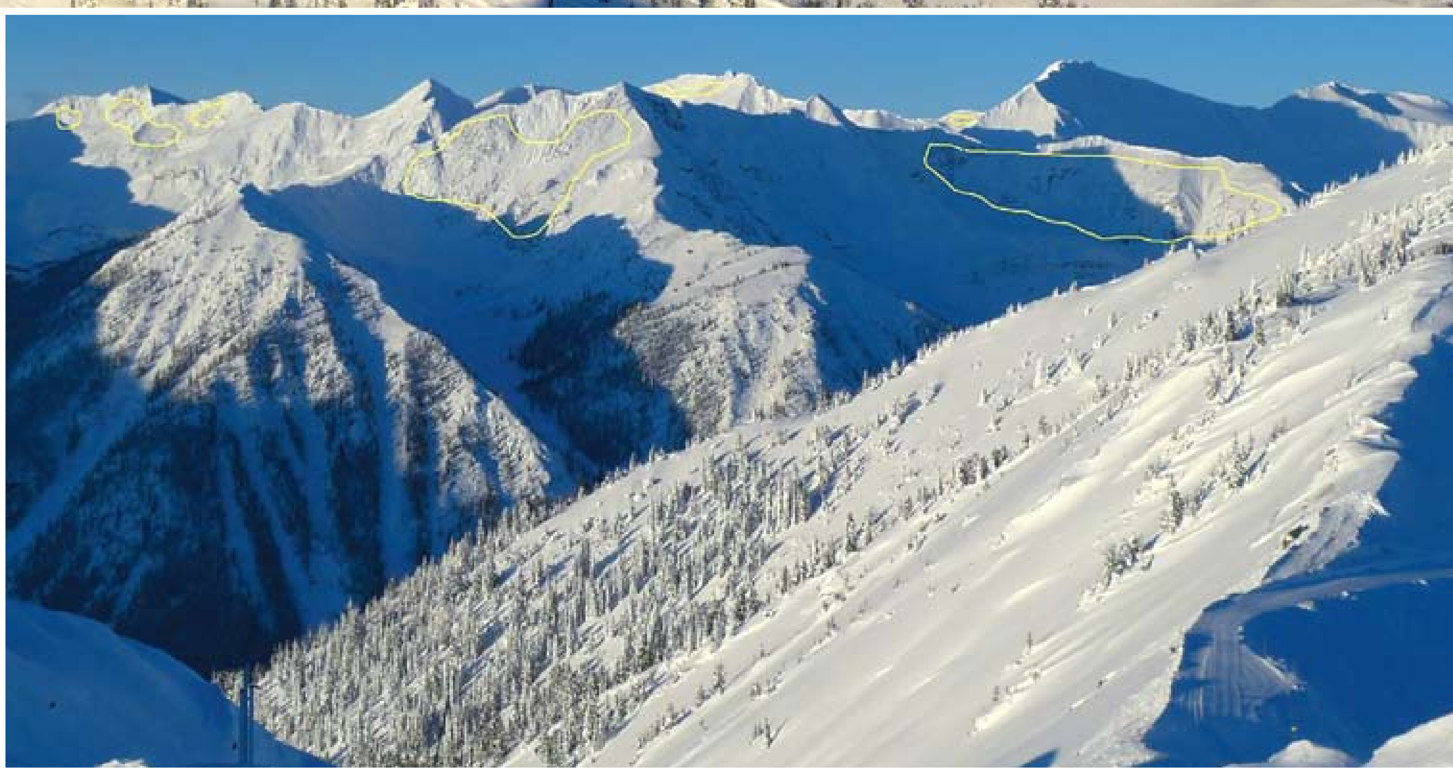
PART 2: COOLING EVENTS IN WESTERN CANADA DURING WINTER 2010/11

Before I launch into Part 2, it's important to distinguish a key difference between Part 1 and Part 2. The questionnaire in Part 1 asked specifically about "refreeze" CDA events (snow surface going from 0°C to below 0°C). The events listed in Part 2 occurred during periods of rapid cooling within an overall colder temperature regime and did not involve a clear melt-freeze process at the surface.

The photos show a succession of large avalanches which occurred during periods of rapid cooling in western Canada. Operators described these events as very surprising, eye-opening, historic, and unusual.

Continued on page 32 ➡

Monashee Powder Snowcats, Southern Cross Path, January 8-9, 2011. Overnight there was no appreciable new snow, no sign of wind, skies were clear most of the night, and temperatures dropped from -8.5°C to -15°C by morning. This was a size-D4, step-down slab, with very wide propagation. The trigger was a small cornice or small slope above. The lead forecaster said, "I'm busy rethinking my assumptions/intuition." (The guides were considering expanding their scope of terrain use that day). *Photo by Fiona Coupland*

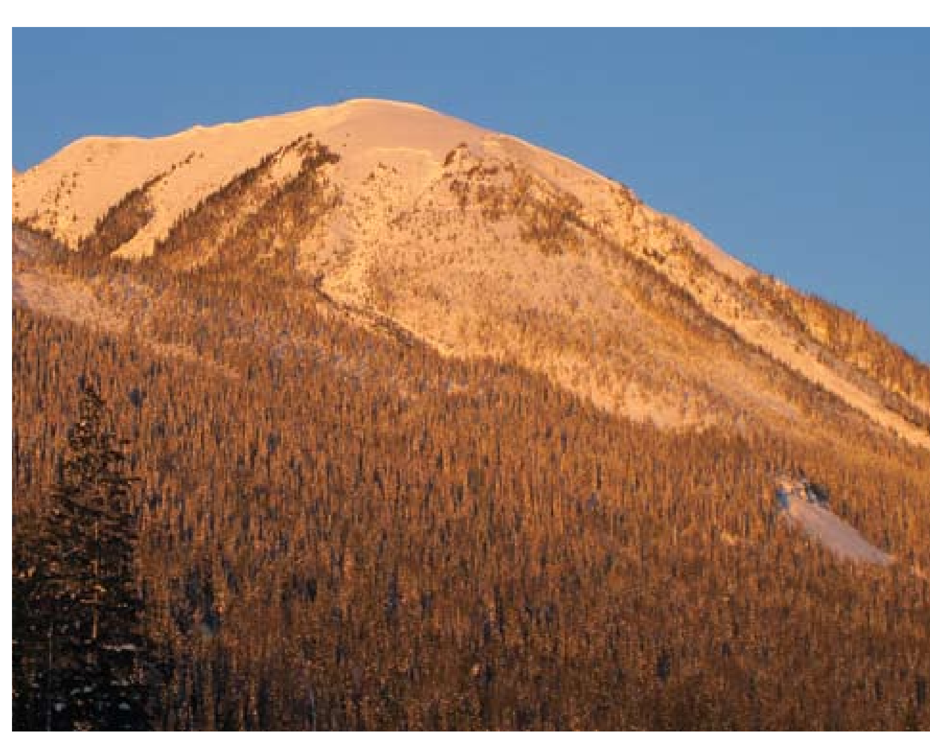


Above and right: Kicking Horse Mountain Resort backcountry, January 18, 2011. These paths did not avalanche during the preceding prolonged warm storm. They occurred overnight 17/18 Jan during rapid cooling and strong winds. The air temperature dropped overnight from -5.6° C to -16.4° C at he ski resort's nearby weather station.
Photos by Nicholas Rapaich

Mistaya Lodge, western Rockies: Overnight January 17-18, 2011, after a storm that had deposited 1m+ snow. There was overnight air temperature cooling from -3°C to -13°C and wind (however, many of these slopes were not lee to the wind). More than 20 avalanches released, size D1 to D3.5 (many D2-2.5) with crowns 100-150cm; some up to 200cm deep. Several avalanches were observed in unusual locations. *Photo by David Birne*

Lanark path, Rogers Pass: 8am, January 18, 2011. The avalanche was size D4.5 and damaged 10 acres of forest. It failed on facets/crust at ground. The air temperature dropped from -3°C to -17°C overnight prior to the event. The avalanche cycle was considered to be over. This one failed near the time that sun first hit the slope. *Photo by MOT, Canada*

Castor Peak, Glacier National Park, 8am, January 18, 2011. Under the same weather conditions affecting the Lanark Path (below left), this widely-propagating avalanche occurred. A second, historic avalanche occurred around the same time on nearby Crawford Peak, destroying mature timber in the runout. The surprising nature of these events led the Canadian Avalanche Centre to issue this warning message to operators on January 18: "Notable avalanche activity: We have received a couple of reports of large, unusual avalanches that occurred this morning as the temperatures were cooling…" *Photo by Kevin Boekholt*



Golden backcountry: Dogtooth Range, overnight February 7-8, 2011. There had been no avalanche activity during warming on February 7. Overnight, the air temperature dropped from -10°C to -17°C, and these and other large slabs released. *Photo by Thomas Exner*

A powder cloud across the glacier from Latok 1 Pakistan dusts camp.

Temperature-Induced Dry-Snow Avalanches

Story & Photos by Doug Chabot

Statements of "warming-triggered" dry-snow avalanches have become common in the last few years. The public mentions it frequently, and it is increasingly referred to in avalanche advisories and classes. The evidence presented includes increased creep rates, wild swings in net solar radiation, and avalanche activity occurring naturally and with human triggers due to warming temperatures. These statements occur with certainty and regularity but with scant data. In order to witness temperature-induced avalanches a perfect lab would be one where large temperature swings occur consistently along with year-round snowfall. One of the best places on Earth to witness the effect of diurnal temperature changes on a snowpack are in the highest mountains of the world, where I've been lucky enough to spend my spring or summer over the last 20 years. While alpine climbing in the Karakorum, Himalaya, and Alaska ranges I've experienced the uncomfortable effects of rapid and dramatic temperature swings: t-shirt to down parka in minutes. These ranges are natural labs. If cooling or warming are big factors in triggering avalanches it would be witnessed here.

High mountains are an extreme radiation environment, with large amounts of incoming solar radiation during sunny days, and huge losses in longwave radiation at night. I've routinely seen evidence of this daily flip-flopping through the formation of diurnal recrystallization facets, formed faster at high altitudes than I've ever seen in Montana. Although cooling or warming air temperatures are parts of the energy balance, the energy balance for the snow is driven largely by the radiation balance. I don't carry scientific gear with me into the mountains. I do not have a robust data set, nor do I pretend to know exactly what happens to the snow with large air temperature changes. But I have never seen what I would interpret as a temperature-induced, dry-snow avalanche. That's to not say I can't or won't see it, but it's certainly not a primary or even secondary avalanche concern.

Since the 1990s I've spent more than two years living on glaciers: climbing, watching, and doing my best to not get caught in avalanches. In this time I've seen a hundred or more dry-snow avalanches and even triggered a few. All of them were due to at least one of these big three factors: it snowed, the wind blew, or there was poor snow structure, matching what I've seen for 15 years as an avalanche specialist on the Gallatin National Forest. These three things are a recurring problem the world over, and it's what I concentrate on.

Diurnal recrystallization at high altitudes creates facets quickly. These were formed in India at 19,000' within 24 hours and were buried the next day. Three climbers died in an avalanche on a nearby peak when the new snow slid.

Temperature changes are real, but the best available information we have indicates that their effect on triggering dry-snow avalanches only exists if the snowpack is already very close to instability. Every day the sun sets and the temperature plummets; the next day it rises and warms. Yet avalanches don't happen daily. It's an extremely rare event when multiple factors with weather and snowpack line up to be influenced by a temperature swing. Consequently, I've relegated warming to a low-level concern, something that may increase instability at a very minor level as a secondary contributor to the big three. Schweitzer and Jamieson said as much in their 2010 ISSW poster, *On Surface Warming and Snow Stability*.

An avalanche releases down an unnamed ridge near Latok 2.

Weird, unexplainable, head-scratching avalanche cycles will always happen and challenge our thinking. As avalanche professionals it's our duty to look into these cycles, but as professionals it's our duty to speak with clarity and not confuse the public. It's dangerous to pretend to know something we don't. Avalanches scare me because I can never understand them as well as I'd like. Pretending otherwise can kill me as a climber and skier. Pretending otherwise can kill others in my job as an avalanche specialist. Let's keep our eyes on the obvious red flags. People die in avalanches because of new snow, wind, and poor snow structure, not because they were out at 1pm on a sunny mid-winter day. Focusing on the nuances of temperature-induced avalanches can muddle our message as avalanche forecasters and is a dangerous distraction for those with a less complete understanding of avalanches.

Doug Chabot balances a career as director of the Gallatin National Forest Avalanche Center with a drive for mountaineering and exploration in the remote and high ranges of the world.

Temperature Effects OVERVIEW

A Look Under the Hood

The effect of surface warming on snow stability

Story by Ron Simenhois

After the Utah Snow and Avalanche Workshop, Lynne asked if I'd be interested in writing a short article about the mechanics behind the processes that led to the March 4 Utah avalanche cycle. The reasons behind my positive answer may be a good decision-making case study and clearly didn't include what Alec van Herwijnen kindly reminded me about a week later: large parts of the mechanics leading to natural avalanche release are still unknown. In addition, there is very little snowpack data available from the March 4 avalanche cycle in the Wasatch. Hence, in this article I will try to give a general explanation of the effect of surface warming on crack propagation. I will also underline the areas where our knowledge falls short and will bring a few possible scenarios that may lead to natural avalanche release due to surface warming.

The idea that surface warming can contribute to snowpack instability is not new. With regard to skier-triggering, McClung and Schweizer *(1999)* concluded that the most important effect is the decrease of slab hardness (stiffness) with warming. More recent studies have shown that surface warming can increase the propensity for crack propagation. Simenhois and Birkeland *(2008)* presented two datasets where side-by-side ECT test results changed from ECTN to ECTP with surface warming, suggesting that the critical crack length decreased with surface warming. They also backed their results with case studies where slopes avalanched later in the afternoon when the snow surface was warm even though they had been tested in the morning when the snow surface was cold and didn't avalanche. It is important to note that in this work the warming was much more than simply warming up the snow a few degrees.

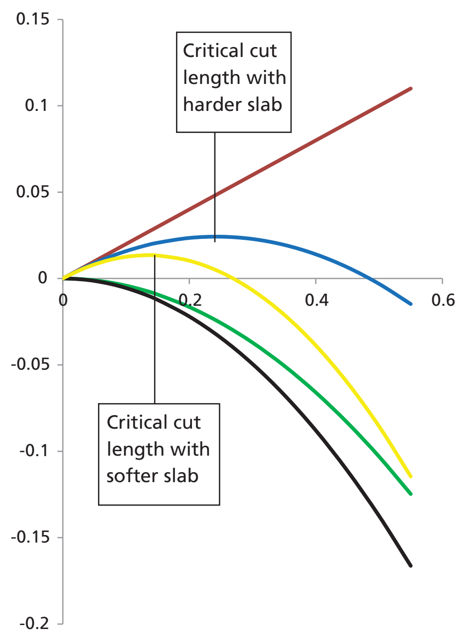


Figure 1: The fracture energy balance of the example cited in the text. Surface energy is in red, the mechanical energy when the slab elastic modulus is 1.2MPa is in blue, and the sum of the two energies is in green. The critical crack length is the value where the combined energy function reaches its saddle. In yellow and black are the total energy of the system and the mechanical energy, respectively, for the case the elastic modulus is reduced to 0.9MPa.

In all cases, the snow surface was melting. This is certainly the extreme case since changes in the snowpack accelerate rapidly as we approach the melting point. Thus, these preliminary and limited data really only apply to situations with snow-surface temperatures at the melting point and not to cold, dry slabs that are warmed up a few degrees.

Reuter and Schweizer *(2012)* measured changes in crack propagation in relation to the energy input at the snow surface (this is the overall energy changing the snowpack's temperature. Long-wave radiation and turbulent energy fluxes are also included). They measured and modeled changes in slab hardness (effective modulus), weak layer fracture energy and critical cut lengths of

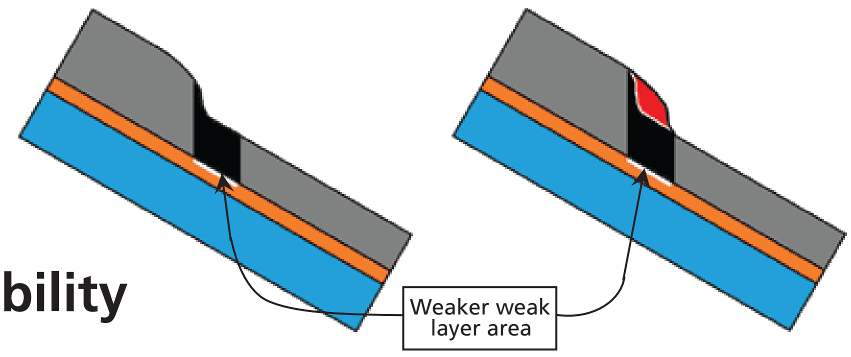


Figure 2: Graphic illustration of possible load increase on weaker weak layer areas due to surface creep. On the left is a possible scenario prior to surface creep – the load on the weak area is in black. The diagram at right shows a load increase after surface creep occurs – the red area indicates the additional load on the weak area.

Propagation Saw Tests on nine days with high incoming solar radiation. Their data showed that a cumulative energy input of above 400 KJm-2 coincided with decreases in slab hardness and shorter PST cut lengths. Furthermore, they did not observe any change in weak layer fracture energy. They therefore concluded that the increase in crack propagation propensity, as suggested by in the decrease of PST's critical cut lengths, was caused by an increase in energy release rate due to increased slab bending. Overall, changes in critical cut length were very subtle, strongly suggesting that both a preexisting weakness and significant energy input are required for surface warming to promote instability. Also, even in their carefully controlled data there is a great deal of scatter, pointing out the challenges of using these relationships in a forecasting context.

What is the energy release rate, how does surface warming affect it, and what does that mean for avalanche release?

Griffith's energy-balance approach shows that conditions are favorable for crack propagation when the mechanical energy release rate (rate per area, not time) of the slab exceeds the energy that must be expended for a crack to propagate over the same area. When a crack grows in the weak layer, a region of the slab above the crack subsides, and its strain energy is released. The total strain energy released is negative when the work it takes to bend the slab over the crack to the same depth it subsides and is given by:

$$\text{strain energy} \sim \frac{(\text{load})^2 \times (\text{crack length})^2}{\text{slab elastic modulus}}$$

The elastic modulus is a material property of hardness. More strain energy is released by increasing the crack length. But in creating a longer crack, bonds must be broken, and the fracturing energy is in effect absorbed by the weak layer. The energy that is needed to break the weak layer is related to the crack length. The total energy associated with the crack is the sum of the (positive) energy absorbed to create the new surfaces (surface energy), plus the strain energy that released by allowing the regions above the crack to subside. As the crack grows longer, the quadratic dependence of strain energy on crack length eventually dominates the surface energy, and beyond a critical crack length the system can lower its energy by letting the crack grow still longer. Beyond that point, crack growth is spontaneous and catastrophic. The value of the critical crack length can be found by setting the derivative of the total energy to zero *(see figure 1)*. This critical crack length is given by:

$$\text{critical crack length} \sim \frac{\text{weak layer fracture energy} \times \text{slab's elastic modulus}}{(\text{load})^2}$$

It is easy to see that both additional loading and reducing slab stiffness decrease the critical crack length. ***However, additional load has a far more pronounced effect on critical crack length than surface warming.*** That is one reason why additional loading is a much more frequent contributor to instability.

Estimating the critical cut lengths during the March 4 cycle is challenging due to lack of detailed snowpack data. However, to get an idea of typical critical crack lengths for an unstable snowpack, let's consider a 4F hard 50cm thick slab with density of 162kgm-3 and elastic modulus of 1.2MPa over a SH layer with fracture energy of 0.1Jm-2 and a hard bed surface. For such a slab/weak layer combination, the critical crack length would be 24cm. If for some reason the slab becomes softer, for instance due to surface warming, and the elastic modulus reduces to 0.9MPa, the critical cut length will be about 18cm. It is hard to estimate how much input energy is needed to reduce the overall slab's elastic modulus from 1.2MPa to 0.9MPa *(figure 1)*. However, to give you an idea, on March 23, 2011, Reuter and Schweizer measured the decrease of slab's effective modulus from 1.2MPa to 0.9MPa. This change occurred after input energy of 430kJm-2. The snow temperature at 10cm below the surface on that day changed from -4.9°C to -0.2°C.

Continued on next page

Temperature Effects HISTORY

Workshop discussion notes from Banff, Alberta, November, 1976:

Avalanche Control, Forecasting, and Safety

While researching for his article, "Playing with Fire" (see page 22), Drew Hardesty stumbled across the following notes from a discussion after a paper by Norm Wilson:

Ron Perla, the conference organizer, remembers the discussion: "Norm Wilson's presentation managed to stir up the pot; it was a small group in those days, just over 100 in a small classroom where anybody could get to the mike quickly.

"Based on Ned Bair's research, I might not have made that comment about 'inverted storm' depositing lower density snow, and I wished I had said that the cold, initial deposition could be a weak, potential failure surface (irrespective of its density)."

Newcomb: I hope no one objects if we move on to another question. Why does a rise in temperature reduce stability?

Bradley: Snow becomes very weak as it approaches the melt point (O°C). This is quite evident in the spring.

Perla: A temperature rise during a storm could produce an inverted density profile, with a heavy dense slab resting on a loose sliding layer. A temperature rise may also correlate with an increase in precipitation intensity during a storm.

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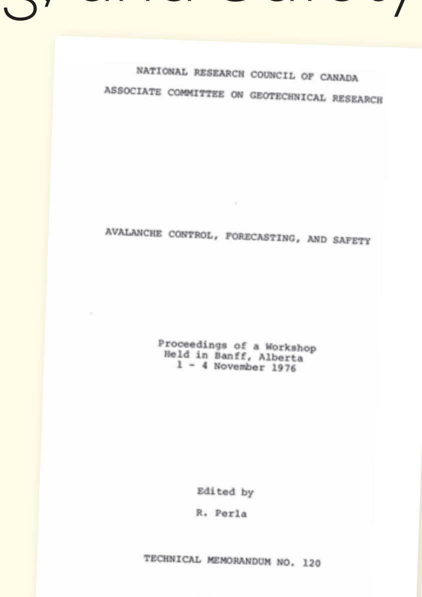
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ASSOCIATE COMMITTEE ON GEOTECHNICAL RESEARCH

AVALANCHE CONTROL, FORECASTING, AND SAFETY

Proceedings of a Workshop
Held in Banff, Alberta
1 - 4 November 1976

Edited by
R. Perla

TECHNICAL MEMORANDUM NO. 120

Ottawa

TEMPERATURE OVERVIEW

continued from previous page

The missing step

Studies using fracture mechanics to model crack propagation rely on the underlying assumption that there are preexisting sub-critical flaws (cracks) where the slab is unsupported. We assume that these unsupported slab areas exist shortly before slab release occurs because the mix mode anticrack successfully predicts field observations. However, to my knowledge, there are no field observations that confirm the existence of these areas. Further, the data from Reuter and Schweizer *(2012)* suggest that if such areas exist, they have to be very close to the critical size for surface warming to cause spontaneous slab avalanche release. The critical crack length formula in combination with the results from Reuter and Schweizer *(2012)* show that under spatially consistent slabs, surface warming by itself cannot cause sub-critical cracks to expand without additional load.

However, things are different on slopes with a spatially variable slab or slopes with rocks poking above the snow surface. In such cases, free water from surface melting can percolate down to the weak layer in areas where the slab is thin or around rocks. The water can then break weak layer bonds over an area large enough for spontaneous slab release.

Another scenario may be when the load on the weak layer is unevenly distributed throughout the slope due to spatially variable slab thickness. In this case, surface creep can redistribute the load over the weak layer and potentially increase the load over areas of weaker weak layer *(see figure 2 on page 29)*. In this scenario, the increase in load might reduce the critical crack length to where a small crack can start propagating spontaneously.

Clearly, these are only two possible scenarios (and there are certainly others) and not an attempt to explain what happened under the slab in the Wasatch on March 4, 2012.

Conclusion

Regardless of the mechanisms that lead to surface warming-induced dry-slab avalanches, it is important to remember that conditions must be on the verge of instability in the first place for surface warming to make a difference. In reality, our best data and models all predict that surface warming has a real, but very small, effect on dry-snow avalanching. In other words: if you are worried that a slope will become unstable (with dry-slab avalanches) in the afternoon due to surface warming, you probably shouldn't ski or ride it in the morning! Further, if you skied a slope in the morning and it avalanched (dry slab) in the afternoon due to surface warming, you probably had a lucky morning and not a set of fine-tuned forecasting skills.

Acknowledgments

I would like to thank Alec van Herwijnen, Benjamin Reuter, Karl Birkland, and Doug Chabot for the insightful discussions over this topic and for taking the time to make sure the content of this article is, for most part, in par with current knowledge and understanding rather than the author's vivid imagination.

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Ron Simenhois has been a consistent and gracious contributor to TAR since he was a ski patroller at Copper Mountain.

PNW BOUNDARY POLICIES

continued from page 20

First of all, to leave or re-enter the ski area, everyone is required to have the following: beacon, shovel, partner, and knowledge of 1) the current Northwest Weather and Avalanche Center forecast, 2) that season's snowpack profile, 3) avalanche phenomena, 4) the current weather forecast, and 5) the most recent snowfall amount and type. At times Baker requires these things just to ride certain chairs!

Baker uses rope lines, signage, and access gates to manage its boundary. There are closed areas, "Extreme Danger Zones," and "Hazard Advisory Rope Lines." The result is that there are some areas you must access through gates, which may be open or closed, some areas that are roped off but it's acceptable to duck the rope, and some areas that are roped off but the ropes can't be ducked. Undoubtedly the rope lines have prevented many opportunities for the Mt Baker Ski Patrol to practice their high-angle rescue skills.

Mt Baker: this sign seems pretty straightforward.

THE FOREST SERVICE PERSPECTIVE

Every ski area in this survey, and many of the other ones in the Pacific Northwest, operates almost entirely on Forest Service (FS) land. This fact makes the FS a very important entity in the discussion of how access to the backcountry will be managed. The official documents that outline policy for the FS are the FS Manual and the FS Handbook. These are documents that outline national policy, with some regions creating their own supplements that further define policy in their region.

The Pacific Northwest (region 6) does not have a specific boundary management policy to supplement the more generic national policy. The requirement outlined by the FS Manual/Handbook is that ski areas address boundary management in their annual operating plan. The example that is often cited of a region where policy has been more rigorously defined is that of Region 2, which includes Colorado. A review of Region 2's supplement shows a number of additional guidelines including: location and nature of backcountry access gates (they must be positioned so that users must physically stop and/or climb uphill for backcountry access), positioning of signage at all ingress and egress points, verbiage to be used on signs, and allowing for FS-enacted closures to restrict access into extreme avalanche hazard zones. Ski areas in Colorado are further supported in closing their boundaries by the Colorado Skier Safety Act, which allows for monetary penalties and/or jail time if closures are violated. Washington state recently (in 2011) passed similar legislation that made skiing into "closed areas" (as defined by the ski-area operator) a misdemeanor punishable by a fine up to $1000 and/or 90 days in jail.

For those who desire less government interference in our lives, this issue is a bright spot. There does not appear to be any desire by the FS to restrict access to public lands. The supplements that have been created in various regions generally encourage ski-area operators to allow access to the backcountry. The points they stress are primarily concerned with clear signage in appropriate locations. While the national policy and the supplements allow for FS supervisors to close areas of National Forest due to extreme avalanche hazard, it is generally discouraged because enforcement would necessitate qualified FS personnel who are seldom available to stand at a boundary line during a storm.

SO NOW WHAT?

When I initially began to research this issue, I thought that at the end I would come to a grand conclusion about the best way for everyone in Washington and Oregon to consistently manage backcountry access. However, after many conversations and careful consideration of the unique characteristics of all the ski areas in this part of the world, I'm not sure it would be the best idea to treat them all the same. Topography, snowfall patterns, and proximity to traditional backcountry runs are all factors that vary widely across this region. The policies in place at the various ski areas are what they are because that's what works best for them. Fortunately ski-area operators have been allowed to adapt and evolve because of the absence of a unilateral policy.

The issue that I described in the first paragraph still remains. If all the policies are different, how do we communicate that? First and foremost, it is absolutely the responsibility of the user to know the law of the land. If we're going to assume that they are savvy enough to check the avalanche-hazard forecast before they go into the backcountry, we should also assume they are able to look up the policy wherever they are riding.

Okay, well, we all know that doesn't always happen. As much as I'd like to be a hard ass and say, "Screw 'em, if they want to go die that's their prerogative," I would prefer not to have people get in trouble in the first place. If one thing we can do is make it easier for the backcountry users to get the information, then maybe that's something we should do.

A common theme that emerged while discussing this issue with industry leaders has been the concept of consistent signage in the Pacific Northwest. One thing that all the ski areas have in common is that those who do allow access have signage at the common access points. The verbiage and appearance of signage is a topic addressed in many of the FS supplemental boundary management plans. Perhaps coming up with a message we want to convey to all backcountry users in the Pacific Northwest, maybe even that day's hazard forecast, would become recognizable and useful to users who travel to different areas.

I have no delusions that there is a single solution to avalanche accidents in lift- accessed backcountry. They will continue to happen. Airbags, beacons that do your trig homework, and helmet-mounted cameras can't stop that. Something that we as a community do believe is that education and intentional decision-making do help. So if there is a way to make that process front and center, I think we should do it.

A Pacific Northwest native, Dan grew up skiing and climbing in the Cascades. His love of being in the mountains has taken him on expeditions all over the world. Dan has worked as a professional ski patroller at Stevens Pass for the past six years, and as an National Park Service climbing ranger at Mt Rainier National Park. Dan is an EMT and an AIARE 1 instructor.

SURFACE WARMING

continued from page 25

over a much wider area than, say, a skier. However, for the perturbation to have an effect, the existence of a critical slab/weak layer combination is probably essential *(e.g., Exner, 2013)*.

We now look at the two processes of failure initiation and crack propagation. In the case of natural release, failure initiation from damage accumulation (i.e., sub-critical crack growth) is due to the increased deformation in the topmost slab layers. This will increase the strain rate even down at the depth of the weak layer, though warming has not reached the weak layer. This can be shown, for instance, by finite-element (FE) modeling *(Habermann, et al., 2008)*. As snow strength is rate-sensitive, it seems plausible that surface warming may – where snow conditions are critical – lead to an initial failure.

In the case of human triggering, failure initiation is due to the localized dynamic load by the over-snow traveler. Measurements of the person's impact indicate that the stress at the depth of the weak layer increases when the surface layers are relatively warm and cohesive *(Camponovo and Schweizer, 1997; Exner and Jamieson, 2008; Schweizer, et al., 1995)*, which is in agreement with FE modeling *(Wilson, et al., 1999)*. Again, failure initiation is thought to become more likely due to changes in slab properties.

For crack propagation, the question is how surface warming affects the energy release rate. Reuter and Schweizer *(2012)* have recently conducted series of field measurements on days when surface warming was anticipated. They performed propagation saw test measurements *(Gauthier and Jamieson, 2006)* and were able to show by means of FE modeling that the specific fracture energy – a material property that is a measure of toughness (resistance to crack propagation) – remained unaffected. Measurements on the fracture toughness in tension with cantilever-beam experiments in the cold lab indicated that the fracture toughness decreases with increasing temperature up to about 8°C (with increased scatter suggesting an increase of toughness toward the melting point) *(Schweizer, et al., 2004)*.

As the slab stiffness decreases, the energy release rate should increase so that shorter critical crack lengths result (assuming that the specific fracture energy of the weak layer remains unaffected) – equivalent to higher crack propagation propensity. In their field study Reuter and Schweizer *(2012)* observed a slight but significant trend toward shorter cut lengths when the effective modulus of near-surface slab layers had decreased *(see Figure 3)*.

Furthermore, FE modeling indicates that the energy release rate depends strongly on the properties of the lower slab layers, which are rarely affected by daytime warming. For example, if the weak layer is overlain by a crust, the effect on the energy release rate is small when surface warming softens the upper layers. This finding suggests that surface warming is most efficient in the case of relatively thin new snow slabs (usually less than 50cm) *(McClung and Schaerer, 2006, p. 97)* – in agreement with observations by experienced practitioners.

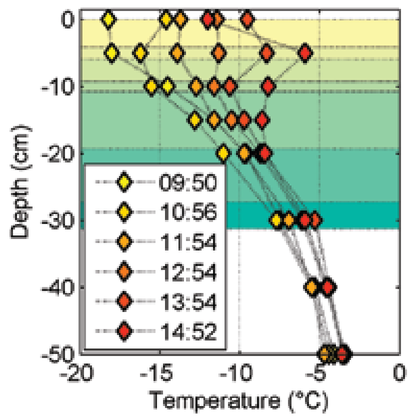

Figure 1: Snow temperature profiles (diamonds) measured on a southwest-facing slope on March 8, 2010. Yellow to green areas denote slab layers.

While there are fascinating examples of deep-slab natural avalanches during warming, a causal effect cannot be explained by current theory. Even in hindsight, not all avalanches have an identifiable trigger.

CONCLUSIONS

We have revisited the effect of surface warming on dry-snow slab release. Whereas the effect of warming to 0°C (surface becomes moist or wet) on loose-snow avalanching is strong, the effects we discuss on dry-snow slab release seem subtle. Without certain preconditioning, e.g., specific stratigraphy of the snowpack, surface warming will probably not cause instability.

Instability always stems from changes in slab properties. Increased deformation due to reduced stiffness of the surface layers increases the strain rate in the weak layer, increases the energy release rate, or increases the skier stress at depth. All these effects are immediate and promote instability (whereas delayed warming effects tend to promote stability) *(McClung and Schweizer, 1999)*. Surface warming is most efficient with warming by solar radiation as radiation penetrates the surface layers where the energy is released. Surface warming due to warm (relative to the snow surface) air temperatures is a secondary effect – except in the case when a moderate or strong wind blows.

When doing field tests such as the PST, shorter crack lengths were observed with surface warming. So far, evidence is rare; Reuter and Schweizer *(2012)* provide the first field study physically linking surface warming to dry-snow instability.

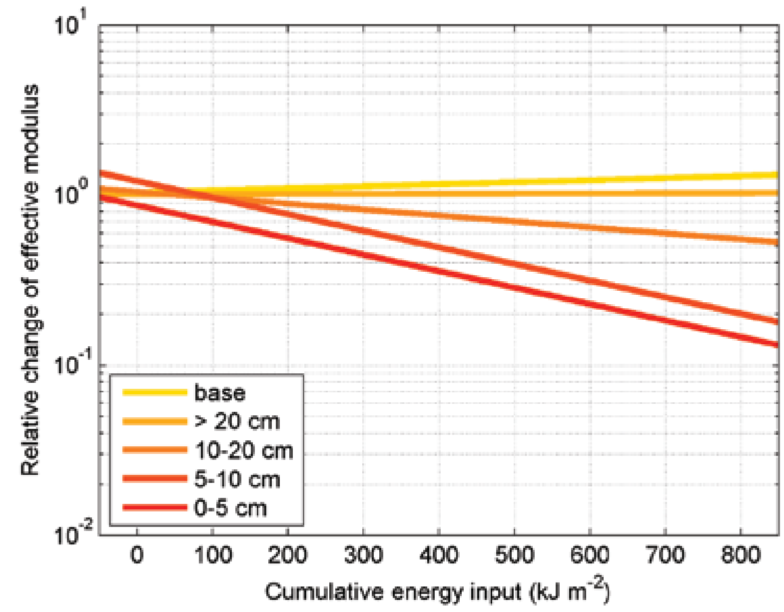

Figure 2: Trend lines for the relative change of effective modulus in a given range of depth vs. cumulative energy input at the snow surface. The closer a layer is to the surface the more pronounced is the change in slab stiffness with increasing energy input into the snowpack.

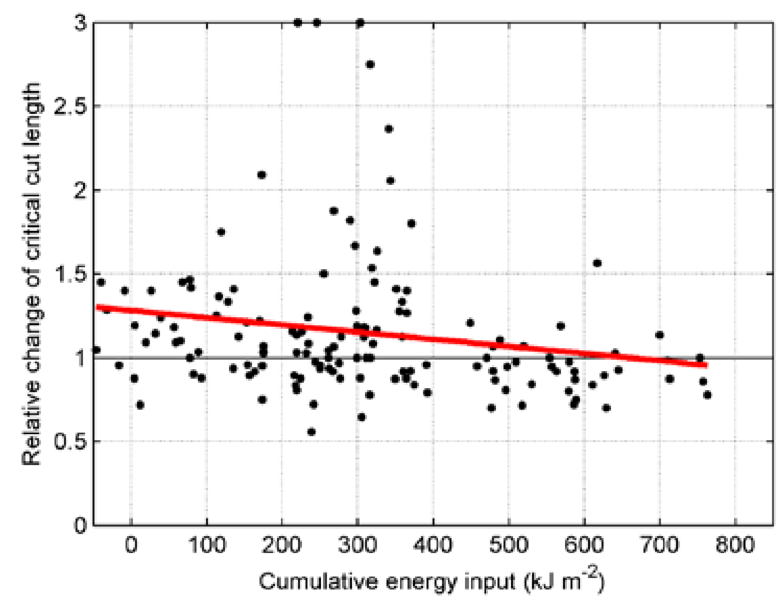

Figure 3: Relative change of critical cut length vs. cumulative energy input at the snow surface: There was a slight but statistically significant trend to shorter cut lengths with increasing energy input into the snowpack. *Figs 2 & 3 reproduced from Reuter & Schweizer (2012) with permission from Elsevier*

Field measurements on the fracture behavior of snow: performing series of PST in the course of a day and concurrently measuring slab stiffness with the SMP.
Photo courtesy Jürg Schweizer

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Jürg Schweizer and Benjamin Reuter both work at the WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland. Bruce Jamieson teaches in the departments of geoscience and civil engineering at the University of Calgary, where he runs the ASARC program.