Fracture propagation and resistance in weak snowpack layers

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Introduction

As part of snowpack studies on 24 February 1994, Thierry Cardon, Roddy McGowan and I skied down a glacier in Hume Creek in the Purcell Mountains (Figure 1). We stopped near a small rock outcrop at the skier's right side of the glacier. As the third skier arrived, we all heard and felt a whumpf. Moments later, the heli-ski guide two runs to the north called on the radio to say the slope between his position and ours was avalanching. The guide and his group were able to watch the Class 4 avalanche (Figure 2).

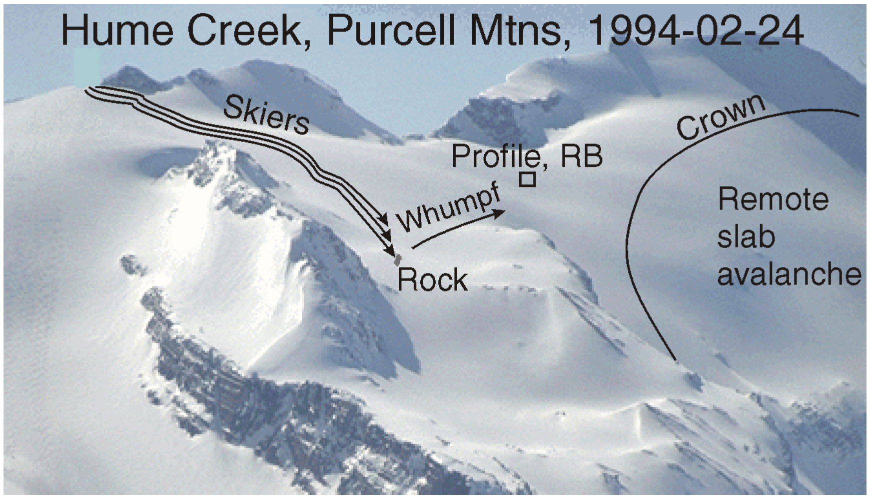

Figure 1. Photo of the glacier in Hume Creek in Purcell Mountains where the whumpf and remote slab avalanche occurred on 1994-02-24.

Figure 2. Photo of the remotely triggered Class 4 slab avalanche taken from the rock outcrop below the profile site.

Poking with our ski poles revealed that we had stopped where a thin slab was overlying depth hoar and rocks. We had started a fracture in depth hoar that had, presumably, extended into a surface hoar layer in which it propagated about 400 m across the glacier to the slope that avalanched (Figure 3). We chose to observe a profile and rutschblock test on a 28° slope about 150 m from the crown because we were concerned about the potential for the slab above the crown to release. The snow profile revealed that the February 6 surface hoar layer was down about 165 cm. We were unable to get it to slide in a rutschblock test, even when all three of us jumped together on the block. In this case, the snowpack where the fracture started (depth hoar under a thin slab) was very different from the snowpack at the profile site, which was likely typical of the snowpack where most of fracture propagation occurred and at the crown.

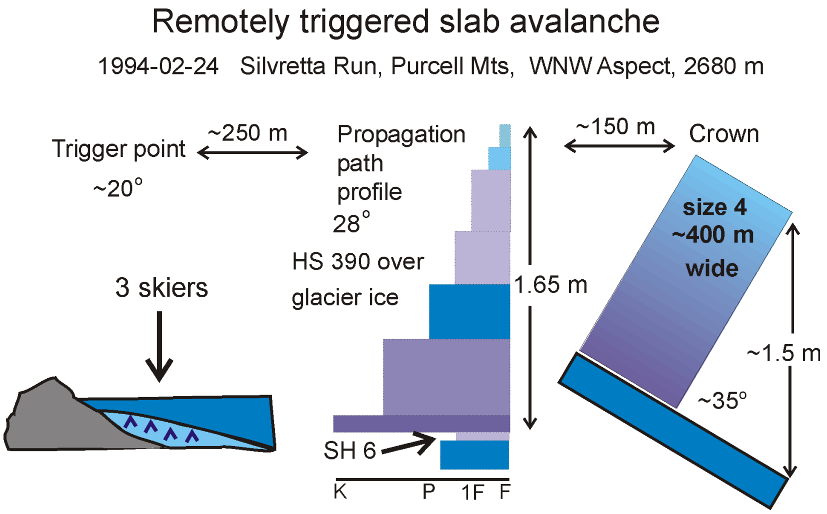

Figure 3. Diagrams of snowpack at the trigger point, the profile site near propagation path, and expected profile at the crown.

In his 1999 review of slab avalanche release, Jürg Schweizer clearly distinguished between fracture initiation and fracture propagation. Schweizer's distinction and this case study raise the question: When using snowpack tests to help assess avalanche risk, should we focus on whether fractures are likely to start in weak layers, or on whether they are likely to propagate far enough to release avalanches?

Observations of fracture resistance in crown fractures

The shape of crown fractures may be indicative of the *resistance* to fracture propagation along the weak layer. The weak layer fracture that released the slab in Figure 4 ran up to the top of the slope and a short distance over the ridge crest. The fracture appears to have propagated with ease, suggesting low fracture resistance in the weak layer of surface hoar. This is in contrast to Figure 5 where irregular parts of the crown fracture suggest areas of high fracture resistance. I have no profile for this slab avalanche or snowpack tests along the crown but one can imagine the propagating fracture in the weak layer stopping at areas of high fracture resistance.

In terms of fracture mechanics, we expect the fracture to propagate when the driving energy exceeds the fracture resistance. The energy driving the front of the fracture (crack tip) is difficult to observe or measure, so I'll focus on the fracture resistance of the weak layer, keeping in mind that we are only looking at one side of the propagation equation.

Figure 4. Crown fracture of slab avalanche in Cariboo Mountains in which the fracture in the weak layer propagated over the ridge crest.

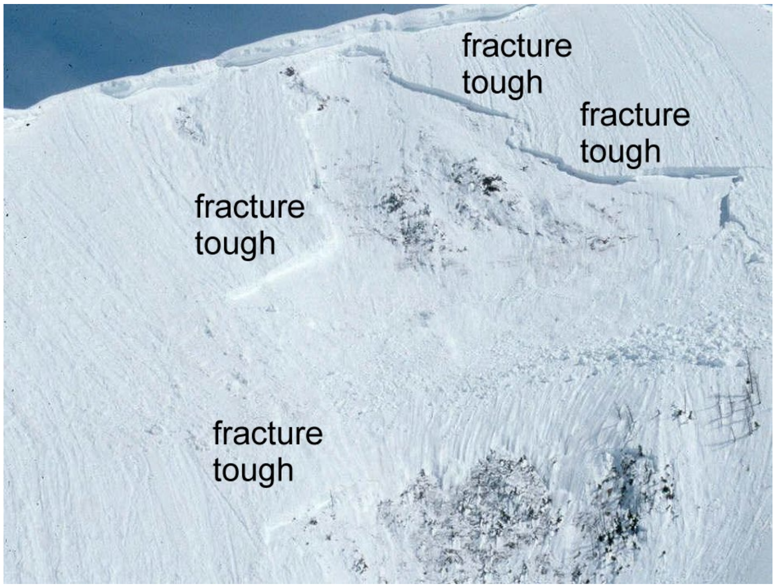

Figure 5. Crown fracture on Mt. Fernie. Irregular shape of crown fracture suggests areas of high fracture resistance (toughness).

One obvious cause of locally increased fracture resistance would be the lateral boundary of a weak layer. If a fracture starts in a weak layer of, say, surface hoar, the propagation may stop where the surface hoar ends. As multiple profiles or snowpack tests in start zones illustrate, some weak layers are not continuous. Other weak layers are interrupted at trees or rock outcrops.

Observations of fracture resistance in rutschblock tests

When doing rutschblock tests in the early 1990s, either Mark Shubin or I would often get into the trench beside the rutschblock while the other person loaded the block in the usual sequence: stepping onto the block, pushing down with the legs, jumping, etc. We sometimes noticed that one loading stage would start a fracture (crack) that would not propagate to the front wall. The next more energetic loading stage would cause the fracture to advance farther, sometimes to the front wall (Figure 6). This phenomenon was rare for persistent weak layers (consisting of surface hoar, depth hoar or faceted crystals) and more common for non-persistent weak layers (consisting of new snow forms, decomposing and fragmented particles or rounded grains), some of which seemed more *resistant* to fracture propagation. So the loading required to crack a weak layer was sometimes not enough to propagate the crack far enough to release the block. Clearly, skiers on rutschblocks can crack weak layers without sufficient propagation to release the block.

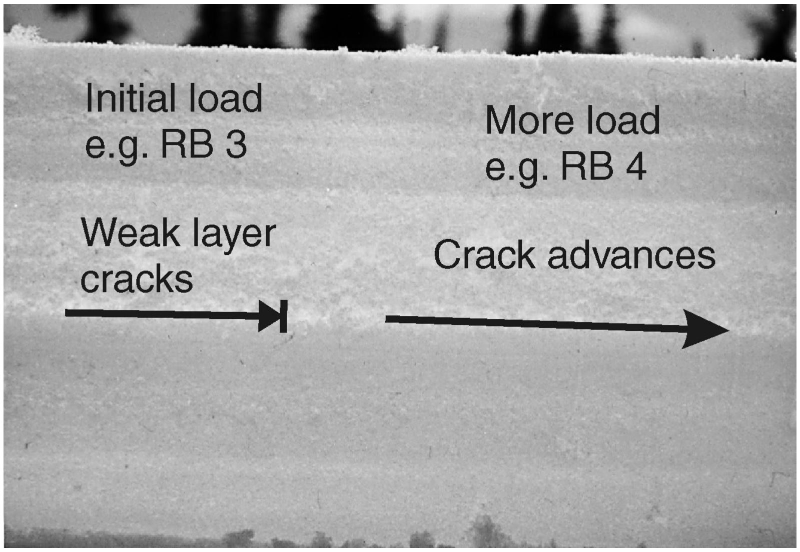

Figure 6. Although this photo does not show the sidewall of a rutschblock, it illustrates the staged growth of a fracture (crack) that can sometimes be observed in the sidewall of a rutschblock.

For rutschblock scores of 3 or higher, Figure 7 shows that skier triggering is more likely if the weak layer is persistent than if it is non-persistent. Most avalanche workers have come to interpret rutschblock scores of 4 to 7 on surface hoar layers with more caution than a similar score on a layer of DF particles because the rutschblock test is a better indicator of skier-triggering for non-persistent layers (less uncertainty) than for persistent layers. Years ago when looking at an earlier version of this graph, Alison Andrews asked "*But why do persistent weak layers release more human-triggered slabs than non-persistent weak layers with the same rutschblock score?*" Since thin slabs are triggered more often than thicker slabs, it might be tempting to conclude that the slabs over the non-persistent weak layers were thicker. However, the slabs over the persistent weak layers were about the same thickness or slightly thicker (Jamieson, 1995, p. 173). It could be that the persistent layers offered less resistance to fracture propagation, or that the thicker (often denser and stiffer) slabs transferred the driving energy more efficiently to the front of the fracture (crack tip).

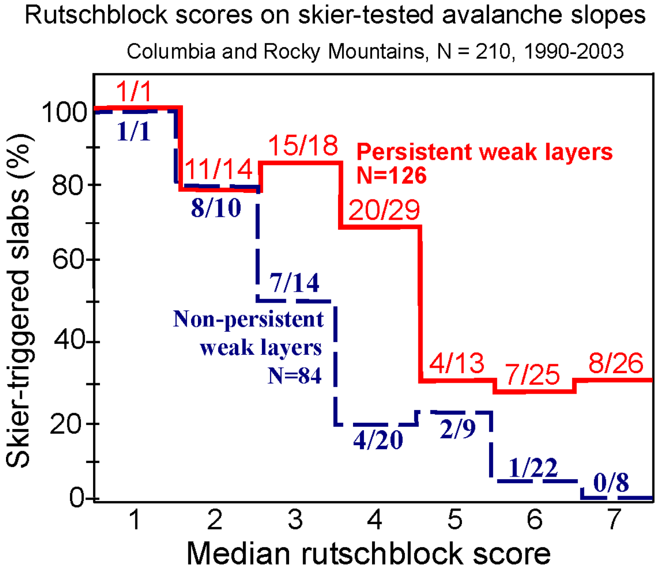

Figure 7. For non-persistent weak layers, higher rutschblock scores are better indications of skier triggering than for persistent weak layers. The percentage of triggered slopes for persistent weak layers and rutschblock scores of 5, 6 and 7 may be biased upwards because University of Calgary avalanche researchers seek unexpected slab avalanches on persistent weak layers.

For rutschblock tests, Swiss researchers classify the release type (whole block, part of block, or only an edge) and fracture type (smooth, not smooth) (Schweizer, 2002). These classifications correlated with human triggering, and release type was more significant than fracture type (Schweizer and Jamieson, 2003). With attention to how much of the block released and perhaps whether the fracture is smooth or not, the interpretation of higher rutschblock scores can likely be improved.

Are some weak layers more brittle than others?

Glass is brittle: when a crack starts it propagates farther and faster than a crack in a less brittle (more ductile) material like iron, the plastic in many modern kayaks, or putty. Brittle materials have lower fracture resistance than ductile materials. Is there an analogy for weak snowpack layers? Based on fracture toughness tests in a cold laboratory, Kirchner and others (2002) conclude that snow is one of the most brittle materials known. Fukuzawa and Narita (1993) found depth hoar (180 kg/m^3) to be brittle over a wider range of strain rates than denser snow (300 kg/m^3) of rounded grains (Narita and others, 1992). However, such tests have not yet been conducted on weak snow layers of similar density. Both Figure 7, and observations in rutschblock trenches mentioned above, suggest that non-persistent weak layers can offer more *fracture resistance* than persistent weak layers. Are persistent weak layers often the forecasting challenge because of their persistence, or because of their brittleness (low fracture resistance)? Both, I suspect. Certainly, it sounds like a great research topic!

By the way, *fracture toughness* is a quantity related to *fracture resistance*. A material (including a weak snowpack layer) with high fracture resistance has high fracture toughness, and visa versa. In Europe, Jürg Schweizer and colleagues (in press) and Failletaz and others (2002) are measuring the fracture toughness of homogeneous snow. Expect to hear more about fracture toughness and resistance in the future because these properties are likely better than weak layer strength for assessing slab instability (McClung, 2002).

Observations of fracture resistance in compression tests

In the previous edition of the *Avalanche News*, Alec van Herwijnen summarized one winter's experience with a scheme for classifying fracture character in compression tests. This five-class scheme includes two types of *sudden* fractures: Sudden Planar (SP) and Sudden Collapse (SC). In both these types of fractures, the fracture suddenly crosses the test column (small column for a compression test, large column for a rutschblock). Sudden fracturing suggests brittleness and – no surprise – most (95%) of the fractures in surface hoar and faceted layers were either Sudden Planar or Sudden Collapse. Not all planar fractures were sudden, some were classified as Resistant Planar (RP) because the fracture required more than one loading stage to cross the column, or the block would not slide easily after the fracture. Only about 26% of new snow and DF layers exhibited sudden fractures (SP or SC). The other fractures in these non-persistent weak layers were Resistant Planar, Progressive Compression (PC) or non-planar Breaks (B).

This link between fracture resistance (or its alter ego, propagation propensity) with fracture character in snowpack tests is not new. At the 2002 ISSW in Penticton, Ron Johnson and Karl Birkeland proposed that *shear quality*, which is an alternative scheme for characterizing fractures, provides a qualitative indication of how well a fracture will propagate through a weak layer.

The fracture characterization scheme in the last issue of Avalanche News does distinguish between sudden fractures with noticeable collapse (SC) and those without noticeable collapse (SP). The Sudden Collapses are more often associated with whumpfs (propagation on low-angle terrain) than are planar fractures (van Herwijnen and Jamieson, 2002), perhaps because the downward movement of the slab provides additional energy to drive the fracture across low angle terrain (BC Johnson and others, 2001)

Ron Johnson and Karl Birkeland also suggested that the character or quality of fractures may be more spatially homogeneous than test scores. In the last issue of *Avalanche News*, Cam Campbell showed that the results of fracture resistance tests in start zones were less variable than similarly sized and spaced stability tests. Figure 8 offers an explanation. As the thickness of the slab decreases from left to right, the scores from stability tests such as rutschblock and compression tests are likely to decrease (Jamieson, 1995, p. 173; Jamieson, 1999). However, the fracture character and scores from a hypothetical test for propagation propensity (see below) might change less as the slab thins.

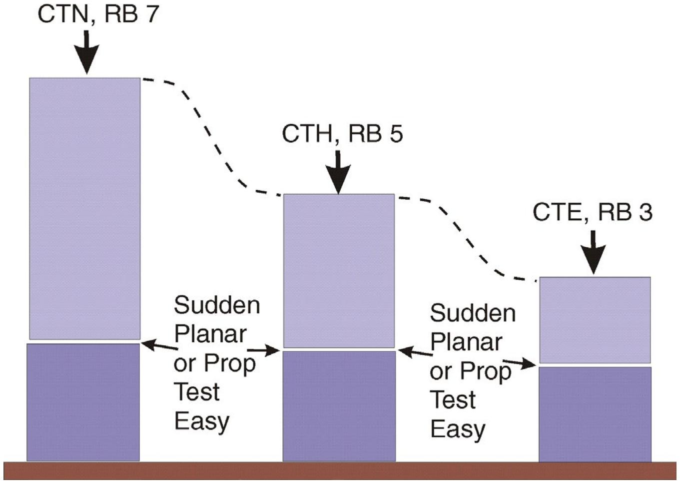

Figure 8. The results of rutschblock and compression stability tests may be more variable than observations of fracture character or experimental tests of propagation propensity because rutschblock and compression test scores are more affected by slab thickness.

On avalanche courses, students sometimes ask if the results of non-standard tests such as a dropped column (Figure 9) should be recorded. This varies from operation to operation, but in my opinion, sudden fractures (SP and SC, or clean fast fractures) that are *consistent* are often worth communicating. In field notes, this might read: "dropped column, SP 2/2, down 65 cm in □● 1" where the "2/2" indicates the Sudden Planar fractures occurred in two of two dropped columns.

Figure 9. A snowpack column dropped in a snow pit showing two planar fractures. Are such results worth recording and communicating?

Observations of fracture resistance in ski testing

In shallow layers of new snow and DF particles, progressive compression (PC) fractures are common in compression tests. Skiers, snowboarders and snowmobilers frequently crush these layers, starting fractures that often do not propagate far enough to release slab avalanches. Apparently, the relatively soft slabs usually associated with these layers do not transfer sufficient energy to the crack tip to overcome the fracture resistance of the layers.

At the Canadian Avalanche Association Technical Meeting in May 2003, Alec van Herwijnen showed a dramatic high-speed video (250 frames per second) of a skier starting a fracture in a weak layer, but the fracture only propagated about a metre and no slab avalanche released. Clearly, skiers, snowboarders and snowmobilers can crack weak layers without sufficient propagation for slab release. Hence, determining the propagation propensity of a combined slab and weak layer is relevant to assessing slab avalanche risk.

Towards a field test for propagation propensity

In the mid 1990s, when the compression test was gaining popularity and we were learning its limitation for deep weak layers, a guide showed me a variation. For years he had been removing the upper column, leaving only about 25 centimeters above a deep weak layer. I felt this deep or modified compression test should not be called the compression test since, without the upper column, the scores would be substantially reduced. With the upper slab removed, the test would not be indicative of whether skier triggering was likely where snowpack conditions were similar. But the guide felt this modified compression test could help determine if the deep weak layer being targeted was “still a problem”. In other words, was a fracture – perhaps initiated where the slab was thin – likely to propagate in the layer being tested? I now believe he was interested in a test of propagation propensity, in determining whether the resistance to fracture propagation was low or high. Some guides continue to use this deep variation of the compression test.

Since researchers are interested in how much energy is required to get an existing crack to propagate, last winter we altered the test by introducing a crack in the weak layer and making other minor changes. This *Deep Tap Test* (DTT) involves a 30 cm x 30 cm column, with only 15 cm of consolidated snow above the weak layer at the back wall, and a 5 cm notch (initial crack) cut into the weak layer along one of the sidewalls with a straight snow saw (Figures 10, 11). We tap on a shovel blade placed on top of the short column using the same loading steps as for compression tests (10 easy taps, 10 moderate and 10 hard taps). When shown the test, Jürg Schweizer and Kalle Kronholm from Switzerland were quick to ask whether cutting a 5-cm notch yields the same results as a 25 cm wide column. The short answer is that we don’t yet have sufficient data, but more comparisons are planned to answer the question in the coming winter. Certainly, the stress wave from tapping the shovel blade should concentrate at the notch, but it is too soon to be sure whether the results of Deep Tap Tests indicate whether or not deep slab avalanches or remote triggering are likely.

Figure 10. For this Deep Tap Test, the upper column has been removed to test a deep weak layer. Along the sidewall, the deep weak layer has been notched 5 cm with a straight snow saw. The tapping is the same as for a compression test.

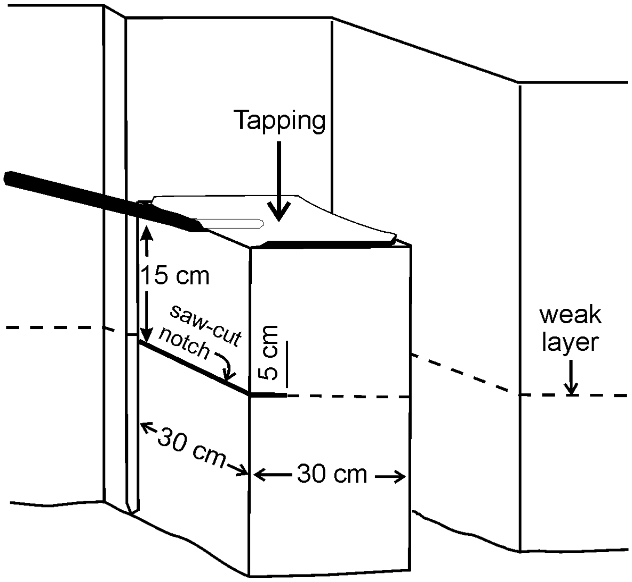

Figure 11. Diagram of Deep Tap Test showing the dimensions and the saw cut notch.

There are concerns that the Deep Tap Test may not be a good indication of fracture resistance. One issue is that the downward stress wave in the column from tapping on the shovel blade is quite different from the mostly slope-parallel shear stress applied to a weak layer during slab avalanche release. This is true; however, the Deep Tap Test is only intended to provide an index of the resistance to fracture propagation. Also, the fracture toughness of snow in tension (Mode 1 in fracture mechanics jargon) is roughly similar to fracture toughness in shear (in-plane shear, Mode II) (Kirchner and others, 2002; Schweizer and others, in press). Since snow with low fracture toughness will also have relatively low fracture resistance, the downward stress wave at the notch may not compromise the Deep Tap Test, especially since it is only intended to provide an index of fracture resistance.

The radius at the end of the saw-cut notch for these experimental tests is substantially greater than the radius at the tip of a propagating fracture in a weak layer or interface; this is a relevant concern that may not be resolved until we determine if the results of these tests correlate with deep slab avalanches and remotely triggered avalanches.

Another concern about the Deep Tap Test is that it is qualitative (resulting in a number of taps) and not quantitative (measuring the energy required to advance the fracture). For this reason, we are also studying a quantitative test, that we call the Fracture Resistance Test (FRT) (Figure 12). The technique for the Fracture Resistance Test loads a column with the same dimensions as for the Deep Tap Test. The difference is that the load is applied to a 30 cm x 30 cm stiff plate by a donut-shaped brass weight (hammer) dropped down a rod from 5 cm, 10 cm and so on, until the crack (notch) fractures across the column in the weak layer. We use mostly 0.3 and 1 kg hammers. In the last issue of the *Avalanche News*, Cam Campbell showed that, in side-by-side tests, the results of the Deep Tap Test correlated with results of the Fracture Resistance Test.

Figure 12. Cam Campbell demonstrates a drop hammer tester, consisting of a rigid 30 cm x 30 cm plate with a perpendicular guide rod. A brass weight (hammer) is dropped along the guide rod from 5 cm, 10 cm, etc. until the weak layer fractures across the column. From the weight of the hammer, 300 g in this photo, and the drop height, the energy delivered to the top of the snow column can be calculated. For these deep tests, the snow in the column is consolidated and no crushing is observed. Since much of the energy from the tester probably arrives at the weak layer, the energy required to fracture the weak layer can be calculated.

Using a drop hammer tester to apply dynamics stress through a column to a weak layer is not new. Martin Schneebeli called his drop hammer tester the *Rammrutsch* (Schweizer and others, 1995). Kalle Kronholm, Kyle Stewart and Cam Campbell have used drop hammer tests extensively to study spatial variability in Switzerland and Canada (Kronholm and others, 2002, in press; Stewart, 2002; Stewart and Jamieson, 2002; Campbell and Jamieson, 2003). But before you add a drop hammer tester to your pack, realize the equipment is heavy and specialized. Also, while drop hammer tests have yielded important results for spatial variability, neither the Fracture Resistance Test nor its lightweight cousin, the Deep Tap Test, have yet been correlated with fractures in deep slab avalanches, remote triggering or whumpfs. Field studies will determine if these tests prove valuable. It is encouraging that these techniques are variations of a test technique some guides have used for about 10 years.

Anticipating deep slab avalanches

Since the compression test as described in the CAA observation guidelines (CAA OGRS, 2002, p. 33-34) is not well suited to testing weak layers deeper than a metre or so, what tools do we have to assess the potential for deep slab avalanches? Existing techniques include: shovel tests, paying attention to persistent weak layers and slab properties in snow profiles; avalanche observations and test results from neighbouring operations; whumpfs and remote triggering, and triggering from thin areas. Some newer techniques include recording and communicating the propagation distance for whumpfs and remotes as well as the character of fractures in snowpack tests. In time, experimental snowpack tests of fracture resistance or toughness may also prove useful as indications of propagation propensity.

Summary

Snowpack conditions where a fracture initiates may be different, e.g. shallower, from conditions where much of the propagation occurs or where a slab avalanche releases.

A dynamic near surface load such as a skier or tapping a shovel blade can crack (start a fracture in) a weak snowpack layer. Additional dynamic loading can cause the fracture to advance. More propagation is required to release a slab avalanche than a rutschblock, either of which require more propagation than a test on a smaller column.

The fracture toughness or resistance of weak snowpack layers varies spatially. Irregular crown fractures may indicate areas of increased fracture resistance (and toughness).

Observations of fractures in rutschblock tests and compression tests suggest that many non-persistent weak layers may be more resistant to fracture propagation than many persistent weak snowpack layers.

Weak layer fractures in snowpack tests that are sudden and planar (SP, Q1, “pops”, clean and fast) may indicate less fracture resistance than most fractures without these characteristics. Weak layer fractures in compression tests, stuffblock tests and some other snowpack tests can be classified according to schemes developed in Canada and the US. Fractures in rutschblock tests can be classified according to a Swiss scheme. For higher scores, the interpretation of rutschblock, compression and stuffblock tests can likely be improved by considering the character of the fracture.

Stability tests such as the compression test or rutschblock test are not well suited to determining the fracture propagation propensity of a thick slab (e.g. > 1 m) over a deep weak snowpack layer. Tests for propagation propensity in deep weak layers are under development.

The anticipation of fracture propagation in deep weak snowpack layers may be improved by observing and communicating the propagation distance for whumpfs and remote avalanches as well as the fracture character (or shear quality or fracture/release type) in snowpack tests.

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