Untangling **Slab Avalanche Release**

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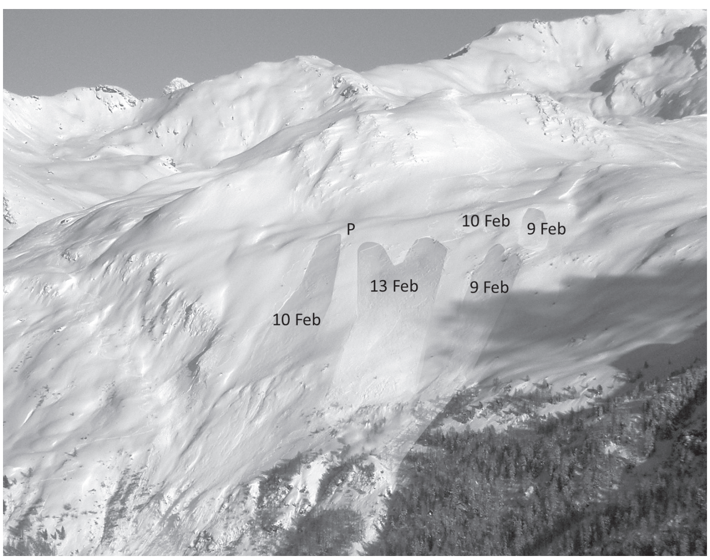
Between February 10-13, 2013, several slab avalanches were triggered by skiers on the west flank of Hüreli, a popular freeride spot above Davos, Switzerland. Cracks easily propagated in a weak layer below a wind slab. Four cold days later, we returned to the scene and dug a snow pit. Highly motivated to capture propagating cracks on tape we were very disappointed to see that our PSTs were not propagating. Signs of instability were lacking too. What was going on? Nothing seemed to have changed—at least in the weather plots.

Canadian research has shown that weak layer strength only slowly changes with time when no additional load is applied. So is it the changes in the slab that made the difference? We know that layering is vital for avalanching. In a Black Forest cake, the chocolate and whipped cream layers are very different. If the cake is fresh, the whipped cream is pushed out under your spoon, but when the cake is stored in the fridge for a few days, hardness differences vanish and your spoon runs through the cake smoothly. The same can happen to the snowpack when it is cooled: surface layers start to facet and lose strength and skiing can become really fun with fast snow and lots of sluffing in steep terrain. This is exactly what happened to the snow around Davos in mid-February 2013.

The start of a snow slab avalanche is commonly interpreted as a sequence of fractures. After an initial failure is created, crack propagation through the weak layer occurs before a tensile crack at the crown arrests this process and the slab is detached. The two most important processes are called failure initiation and crack propagation. In the field it is very difficult to observe both processes independently, but in fracture models we can do exactly that. Looking at the processes separately allows us to investigate the influence of snow cover properties, understand how the processes interact and finally control snow instability.

Failure initiation is best described by the balance of stress (force per unit area) and strength. Crack propagation is best described by the balance of the fracture energy required to break the weak layer and the deformation energy supplied by the slab to advance the crack. Clearly, both slab and weak layer properties are



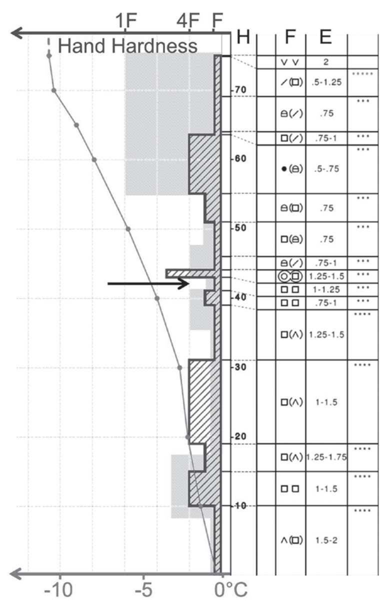


FIG. 1: THE WEST FLANK OF HÜRELI. THE SLAB AVALANCHES RELEASED BETWEEN FEBRUARY 10 AND 13, 2013 AND ARE HIGHLIGHTED. SNOW PIT LOCATION INDICATED WITH "P". THE SNOW PROFILE WAS RECORDED ON FEBRUARY 17. SINCE FEBRUARY 11 (ORANGE HARDNESS PROFILE) THE SLAB HAS BECOME SOFT DUE TO NEAR-SURFACE FACETING, AND PST RESULTS WERE ALL SLAB FRACTURES.

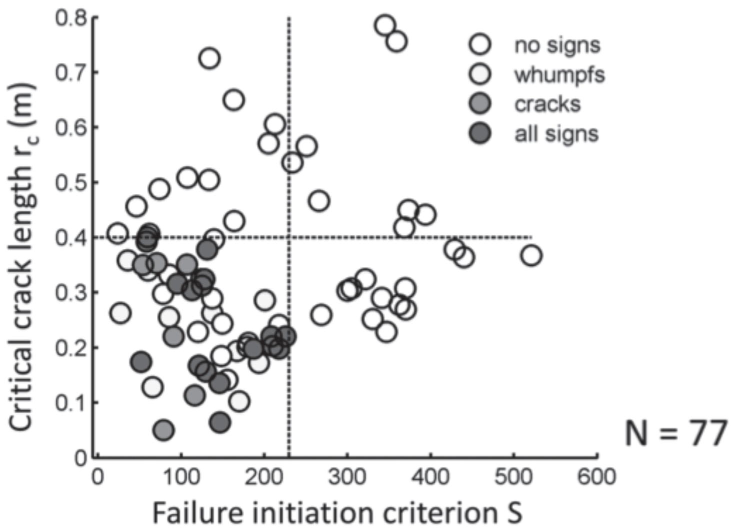


FIG. 2: THE FAILURE INITIATION CRITERION AND THE CRITICAL CRACK LENGTH, AS MEASURES FOR THE PROPENSITY OF FAILURE INITIATION AND CRACK PROPAGATION, CONTRASTED WITH THE PRESENCE OF SIGNS OF INSTABILITY IN THE AREA FOR 77 CASES WITH VARYING STRATIGRAPHY. DASHED LINES INDICATE THRESHOLD VALUES (REUTER ET AL. 2015).

of fundamental importance if we want to describe failure initiation and crack propagation in a quantitative manner. Unfortunately, manual snow profiles often do not provide us with the necessary physical snow properties, such as the effective elastic modulus of the slab or the specific fracture energy of the weak layer. Luckily, there is an alternative. With the snow micro-penetrometer (SMP) it is possible to derive all the necessary quantities to develop criteria for failure initiation (S) and crack propagation (r_c).

Over the past few seasons, we have collected several hundreds SMP profiles with one major goal: derive snow instability. Press a button, measure an SMP profile and get the answer to the question: What would a rutschblock, a CT, an ECT or a PST tell me if we had dug one here? A noble goal indeed, but we still have a little way to go. Thanks to recent developments, the micro-mechanical properties of snow can be derived from the SMP signal and after some calculations and computer simulations, the rutschblock or CT score and critical crack length can be derived. While there are still countless buttons to push and numbers to crunch, we are now able to derive criteria for failure initiation and crack propagation from SMP signals.

Contrasting signs of instability in the area, such as whumpfs, shooting cracks and recent avalanches, with the propensity of failure initiation and crack propagation we calculated from the SMP signals brought some interesting insights (Fig. 2). The first thing that strikes us in Fig. 2 is that all the coloured circles (snow pits with signs of instabilities)

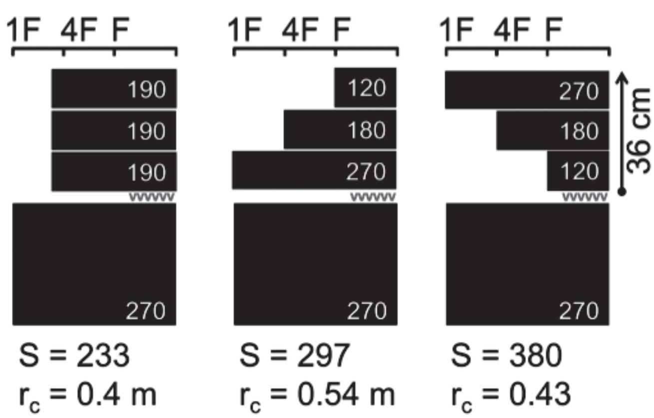


FIG. 3: EXEMPLARY SNOW STRATIGRAPHY REPRESENTED BY SLAB AND BASAL LAYERS (BLACK BARS) DISRUPTED BY A CRITICAL WEAKNESS (TRIANGLES). BELOW VALUES OF FAILURE INITIATION (S) AND CRACK PROPAGATION (r_C) ARE SHOWN FOR THREE LAYERINGS DIFFERING BY HAND HARDNESS (SCALE AT THE TOP), AND DENSITY (WHITE NUMBERS IN KG/M^3). THE PROFILES HAVE THE SAME MEAN DENSITY AND HARDNESS.

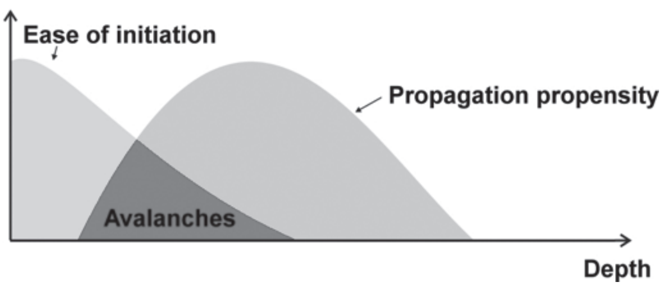


FIG. 4: SCHEMATIC REPRESENTATION OF THE INFLUENCE OF WEAK LAYER DEPTH ON FRACTURE INITIATION AND CRACK PROPAGATION. IN OVERLAPPING AREA, CONDITIONS FOR AVALANCHING ARE FAVORABLEM (VAN HERWIJNEN AND JAMIESON, 2007).

are located in the lower left corner. Obviously, both the critical crack length and the failure initiation criterion were low when signs of instability were present. In other words, signs of instability were mainly observed when it was relatively easy to initiate a failure and relatively short cracks would already propagate. Based on the data shown in Fig. 2 we can derive two instability thresholds. Unstable snow conditions were typically present for a failure initiation criterion of S≤230, which translates approximately to the split between rutschblock scores 3 and 4, and for a critical crack length r_c≤40 cm in PSTs. When both criteria were fulfilled, the chances of observing signs of instability were highest. One criterion is not sufficient to adequately separate situations with and without signs of instability, confirming the importance of both criteria for snow instability evaluation.

The variations observed in Fig. 2 are in large part due to differences in the layering, (e.g., thickness, density, stiffness, and strength). Accounting for the sequence of the layers in the slab is crucial to obtain realistic estimates of snow instability criteria. Using average values for the slab, for instance a mean density or hardness, can result in poor estimates, since the mechanical behavior of the slab is not adequately reproduced. To highlight this fact, we calculated S and r_c for three idealized slabs (Fig. 3).

The three exemplary slabs all have the same mean properties with respect to density, hardness and stiffness. However, the two cases on the right, with more pronounced layering in the slab, have higher values of the instability criteria than the homogeneous case on the left. Actually, the layering has some positive aspects to it, too. We know that hard layers spread the force exerted by a skier—the so-called bridging effect—and there is less stress at the depth of the weak layer. Also, harder layers tend to be stiffer, which decreases the amount of deformation during the onset of crack propagation, and hence less energy is available and the initial crack has to be longer for it to start spreading. Comparing the profile in the centre with the one on the right, we find opposite effects on the failure initiation and the crack propagation propensity. The configuration with easier failure initiation in the centre is more resistant to crack propagation. Conditions favorable for failure initiation do not necessarily support crack propagation—and vice versa. For example, a thick and dense slab provides a lot of energy for propagation and tends to support crack propagation, whereas it is hard to initiate a failure in a deeply buried weak layer (Fig. 4). As the depth of the weak layer increases, stiffness and density of the slab generally increase as well. Hence, from a failure initiation point of view, snowpack conditions are becoming less favourable, but from a crack propagation point of view snowpack conditions are becoming more favourable. At the overlap of the two curves in Fig. 4, when the weak layer is not buried too deep, snowpack conditions are best suited for avalanche release.

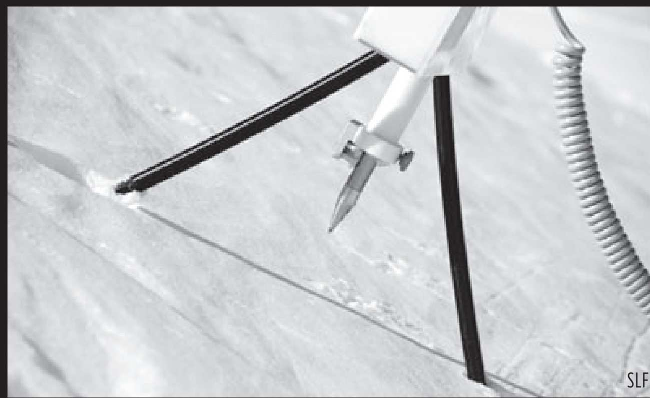
Untangling snow instability means to focus on the avalanche release processes, the most prominent of which are failure initiation and crack propagation. They are closely tied together and both eventually control the avalanche release probability. Returning to the Hüreli, it is obvious now that "low temperatures did not preserve the danger"—near-surface faceting took away the slab's energy needed for crack propagation. Thus, whenever we evaluate snow instability, we must keep in mind avalanche release mechanisms: is there a weak layer, how is the slab above it, can we initiate a failure and will the crack propagate?

REFERENCES

Reuter, B., Schweizer, J. and Alec van Herwijnen. 2015. "A process-based approach to estimate point snow instability." The Cryosphere 9: 837-847.

van Herwijnen, A. and J. B. Jamieson. 2007. "Snowpack properties associated with fracture initiation and propagation resulting in skier-triggered dry snow slab avalanches." Cold Regions Science and Technology 50(1-3): 13-22.

THE SNOW MICRO-PENETROMETER



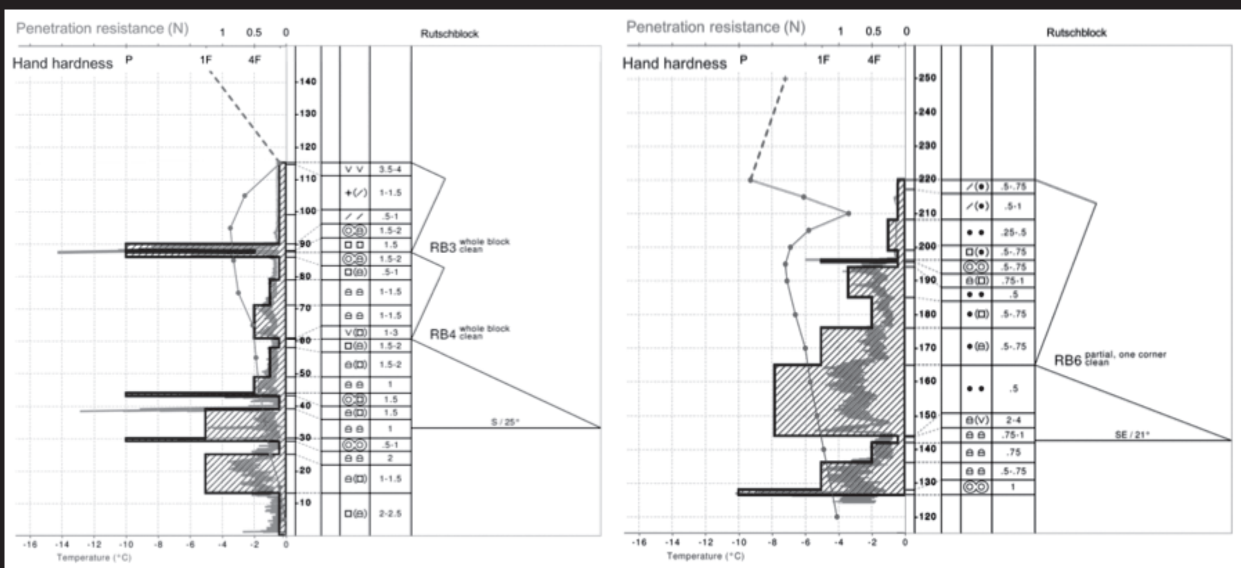


FIG. 5A: SNOW PROFILE FROM FEBRUARY 26, 2015 AT STEINTÄLLI, DAVOS, 2320M, S, 25°. FIG. 5B: SNOW PROFILE FROM THE SAME DAY, BUT AT CHILCHERBERG, DAVOS, 2480M, SE, 21°. BOTH CONTAIN TRADITIONAL PARAMETERS, SUCH AS HAND HARDNESS, GRAIN TYPES AND SIZES, AND SNOW TEMPERATURE, BUT ALSO CONTAIN THE PENETRATION RESISTANCE MEASURED WITH THE SMP.

Despite well-defined observation standards, snow hardness remains observer dependent. Clearly, hand hardness index depends on the size of your fingers, your strength and perhaps your pain tolerance. The oldest and best known objective measurement device is the Swiss ramsonde, which was developed during the 1930s, and the most recent example is the SP1 from Avatech (Lutz and Marshall 2014). For research purposes, the most precise instrument is the snow micro-penetrometer (SMP), which has been developed and improved since the mid-1990s. The SMP can be used to obtain an incredibly detailed hardness profile of the snow cover, with 250 hardness measurements per mm. It can therefore easily be used to compare human fingers to objective snow measurements.

In Fig. 5 we present last year's winners of the "man against machine contest" during the 2015 International Advanced Training Course on Snow and Avalanches in Davos. As in chess the machine is not only faster but also more accurate. Still, humans are quite good at identifying hardness differences, but with our tactile senses we often overestimate the absolute value of the hardness of snow layers.

The SMP was not just developed to calibrate fingers of snow nerds. Snow researchers were primarily interested in obtaining objective measurements of the microstructure of snow, because, let's admit it, our fingers are a bit rough to carefully sense the fragile ice structures which make up the snow cover. The SMP has kept many snow scientists off the street, both sides of the Atlantic. Endless nights counting signal peaks, head scratching and the occasional cursing have provided us with increasingly reliable methods to interpret SMP signals. This provided the community with a more thorough understanding of what we measure in terms of microstructure. After all this preparatory work, the road was paved to derive snow instability.

REFERENCES

Lutz, E.R. and H.P. Marshall. 2014. "Validation study of AvaTech's rapid snow penetrometer, SP1." In: P. Haegeli (Editor), Proceedings of the 2014 International Snow Science Workshop. Banff, Alberta, Canada: pp. 843-846.