When the Cracks Begin to Show

Cutting-edge avalanche release research

Figure 1: A snowboarder gets a real-world lesson avalanche release in the backcountry near Cooke City, Montana. Luckily, he was only partially buried and uninjured. *Photo Chris Awe*

BY KARL BIRKELAND

Understanding avalanche release is critically important for our work, regardless of whether we are triggering avalanches during avalanche mitigation work, avoiding avalanches while guiding clients, or just going backcountry skiing, snowboarding, or snowmobiling (*Figure 1*). The Colorado Snow and Avalanche Workshop's Avalanche Release session brought together top field workers and modelers virtually to discuss and present recent cutting-edge research. Presenters prepared videos of their work so workshop participants could watch presentations prior to extensive live question and answer discussion sessions. Links to the freely available video presentations are listed in the references for this article. This area of research has seen some dramatic and exciting advances in the last two decades, with a mix of innovative field research and increasingly sophisticated numerical models. The live session was moderated by Bruce Jamieson and Ben Reuter, both of whom have contributed considerably to our understanding of avalanche release and other avalanche-related topics.

Slab avalanche release is a multi-scale process covering as many as six orders of magnitude ranging from snow microstructure (millimeters or less) to slope scale avalanches (up to hundreds of meters) (Schweizer et al., 2015; *Figure 2*). Natural avalanche release starts with failure initiation, consisting of progressive weak layer damage leading to the formation of an initial crack. If this initial crack reaches the so-called *critical crack length*, which appears to be on the order of decimeters or possibly up to a meter, we get the onset of crack propagation.

In the case of artificial triggering, the initial damage process is not required since skiers, snowmobilers, or explosives can create weak layer cracks large enough for crack propagation to begin. The onset of crack propagation is followed by dynamic crack propagation across the slope, which takes place at a scale of around 10 m up to 1000 m or more. The final step is the tensile failure of the slab, followed by avalanche release if the slab is on a steep enough slope to overcome friction. Of course, it may not be a perfect progression and some steps could overlap. The avalanche release session at CSAW covered all these relevant scales, and this summary will refer to the avalanche release sequence to connect the different presentations.

Basti Bergfeld, a PhD student at the WSL Institute for Snow and Avalanche Research (SLF) in Davos, kicked off the session with his presentation on multiscale field measurements of crack propagation in weak snowpack layers (Bergfeld et al., 2020). On one day Basti and colleagues measured crack speeds in a long Propagation Saw Test (PST) (5.5 m), a whumpf (up to 20 m), and an avalanche (up

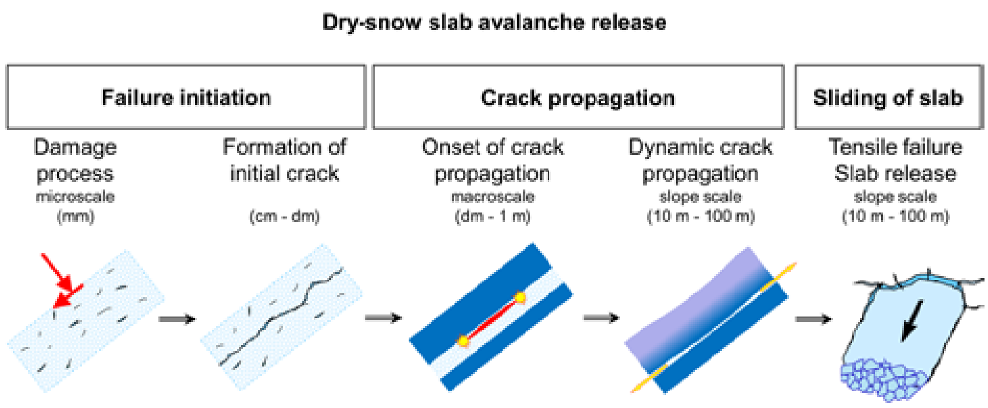

Figure 2: The avalanche release process covers multiple scales, from snow microstructure (millimeters) to large slope-scale avalanche release (kilometers) (from Schweizer et al., 2015).

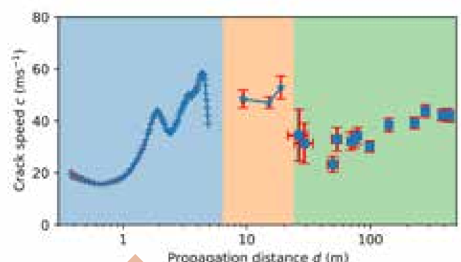

Figure 3 : Crack propagation speed in a long Propagation Saw Test (in blue), a whumpf (in light orange) and in an avalanche (in green) all measured on the same day by Bergfeld et al. (2020). Crack speeds are comparable across the different scales.

to 400 m). PST crack speeds were determined with digital image correlation, the whumpf crack speed was measured with a special set of accelerometers (more on these in the next presentation), while the crack speed for an avalanche was determined by analyzing the formation of surface cracks from a georeferenced video. The main question was whether crack speeds measured in PSTs are comparable to actual crack speeds in slope-scale avalanches. His measured crack speeds ranged from about 20 to 60 m/s, and were reasonably consistent between the different scales, suggesting that crack speeds of long PSTs can indeed be representative of avalanches (*Figure 3*). These measurements were the first to try to connect slope scale avalanche fractures to PSTs and they suggest that we can learn about avalanches by investigating PSTs.

Basti's long PST measurement was conducted on the roof of a concrete bunker just outside of Davos (*Figure 4*). These bunkers are near a creek and get frequent surface hoar layers, presenting an ideal research site. Part of Basti's PhD research focuses on long PSTs, some of which are up to 10 m long!

The second presentation featured Alec van Herwijnen and colleagues as they hunted for elusive whumpfs (van Herwijnen et al., 2020). Alec, a Research Scientist and leader of the Avalanche Formation research team at SLF, showed the slow progression of direct measurements of whumpf crack speeds starting with the initial measurement by Johnson et al. (2004). SLF recently developed portable wireless accelerometers that can be time-synchronized and tossed out in the snow to measure crack speeds associated with whumpfs (*Figure 5*). Basti and colleagues utilized these in their whumpf measurement in 2018/2019 (Bergfeld, 2020), but this past winter the conditions came together for measuring a series of multiple whumpfs in one day. The conditions also presented a unique opportunity for the researchers to wander through a creek with snowshoes on, something you'll have to tune in to the video to learn more about (van Herwijnen et al., 2020). Such "extreme snowshoeing", a common technique used by whumpf-hunting enthusiasts, may become a requirement for future avalanche researchers!

Alec summarized his results by showing that the whumpf crack speed measurements were consistent with past measurements, and that—from the quite limited direct measurements available—it appeared that crack speeds are higher for longer crack distances (*Figure 6*). He also noted that one of the whumpfs created an avalanche because it propagated onto a 40-degree slope, and the crack speed for that whumpf was consistent with the other whumpfs. These are topics we will re-visit in the last two talks in this session.

Figure 4: To better understand avalanche release, Basti Bergfeld and colleagues conducted extra-long Propagation Saw Tests (up to 10 m long) on top of a concrete bunker outside of Davos, Switzerland. *Photo Alec van Herwijnen*

Figure 5: (a) Alec van Herwijnen and Basti Bergfeld prepare custom-built accelerometers for measuring whumpf crack speeds in the field. (b) With the accelerometers thrown out in the snow in front of him, Basti triggers a whumpf. *Photos Karl Birkeland*

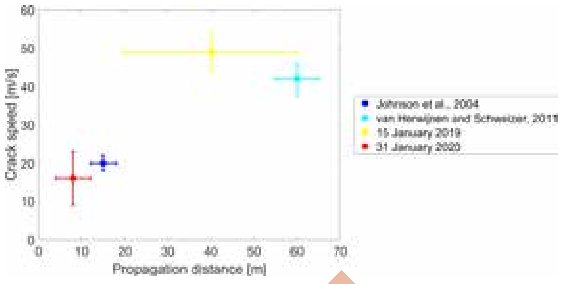

Figure 6: The limited available data of direct crack speed measurements and their propagation distances, including the measurements presented by van Herwijnen et al. (2020) in red and Bergfeld et al. (2020) in yellow.

Figure 7 : The third talk in the session investigated changes in PST critical crack lengths following loading. Karl Birkeland prepares to cut a PST while Basti Bergfeld films the test with a high-speed video camera at 3000 frames per second. *Photo Alec van Herwijnen*

I presented the third talk on some work I conducted with Basti and Alec while on a WSL Visiting Fellowship at SLF last winter (Birkeland et al., 2020). This work built on and refined some previous work we did with Ben Reuter (Birkeland et al., 2019). Here we added a slab by sieving 10 cm of snow into a cardboard frame on top of the existing snowpack, which had a shallowly buried surface hoar layer. We then conducted 15 PSTs (with a beam length of 120 cm) from 4 minutes to 7.5 hours after adding the slab, and we filmed our tests with a high-speed video camera capable of capturing 3000 frames per second (*Figure 7*). We also measured changes in slab properties directly with the SnowMicroPen (SMP). The results matched our previous work, with the PST critical crack length increasing from just 1.5 cm at 4 minutes out to 9 cm at 7.5 hours. Much of this increase in critical cut length is likely due to increasing slab stiffness (increasing effective elastic modulus), though some might also be due to increases in the weak layer specific fracture energy (which can be thought of as the resistance to crack extension) as well. In all this gives us more information about snowpack stabilization following loading. Further, our SMP measurements suggested that even artificial slabs carefully constructed with a sieve could be somewhat variable.

Ron Simenhois, a forecaster with the Colorado Avalanche Information Center, brought the conversation back to crack speed measurements in the next presentation (Simenhois, 2020). Ron is well-known for his innovative and practical approaches addressing relevant avalanche-related questions from the practitioner perspective. In this presentation he utilized a novel video magnification technique to detect subtle changes in pixel color and intensity related to slab deformation occurring prior to the opening of visible cracks in the snow surface (*Figure 8*). This is important because looking at videos of surface cracks in avalanche releases (such as done by Bergfeld et al. (2020) previously in this session and in more avalanches by Hamre et al. (2014)) only gives us a lower bound for crack speeds; the actual weak layer cracks may be traveling much faster. Ron assessed a video of a snowboarder triggering an avalanche, with quite interesting results. First, his analysis documented the progression of cracking in different directions. Weak layer cracks for this avalanche propagated in the downslope direction first, and then as larger sections of the weak layer broke the cracks started to propagate in the cross-slope direction (Figure 8). Second, Ron was able to document crack speeds at high spatial and temporal resolutions. Crack speeds started relatively slowly near the initiation point at 11 m/s before accelerating dramatically. Maximum cross slope crack speeds were 20 m/s, while downslope crack speeds reached about 100 m/s or 225 miles per hour! The final presentation of the session would shed additional light on Ron's findings.

Next up was Johan Gaume, Professor and the head of the SLAB Snow and Avalanche Simulation Laboratory at EPFL (École Polytechnique Fédérale de Lausanne) in Switzerland (Gaume et al., 2020). Since being hired at EPFL, Johan has gathered a strong group that works on modeling various parts of snow avalanches at all the relevant scales, from snow microstructure to slope-scale avalanche release and flow. Utilizing both Discrete Element Modeling (DEM) and the Material Point Method (MPM), Johan and his extensive team are addressing a wide array of relevant questions that aim help us to better understand snow and avalanches. These include:

- Modelling snow microstructure.
- Reproducing the crack speeds and processes of PST field experiments. These models also suggest a size for the fracture process zone, something that will be investigated further.
- Modeling slope scale avalanche release, including remote triggering from flat terrain and explosive triggering. This has allowed them to better understand failure modes and how crack speeds vary.
- Creating new models of avalanche flow, which allows them to calculate avalanche impact pressure, and avalanche flow through forested slopes and other complex terrain features (*Figure 9*).
- Modeling the effect of snow temperature on flowing avalanches, with a -1 degree C threshold change from granular flow to more of a plug flow (*Figure 10*).

Suffice to say there's enough here that I won't try to summarize it all, but rather I would encourage interested folks to watch Johan's video (Gaume et al., 2020) to better grasp the range of the work he and his group are doing.

However, some of the findings by Johan's team regarding crack speeds bear repeating because they dovetail nicely with several other talks in the session. At the scale of a long PST, modeled crack speeds are consistent with direct measurements made by Bergfeld et al. (2020). Further, modeled crack speeds on flat terrain are consistent with whumpf crack speed measurements presented earlier in the session (Bergfeld et al., 2020; van Herwijnen et al., 2020). However, an interesting thing happens when Johan's group extends their models from flat terrain onto steep avalanche slopes. Here they note that crack speeds initially start slowly, but after reaching a certain size (or length), termed the supercritical crack size, the crack speed jumps dramatically. Under some conditions, crack speeds jump from about 30 m/s up to around 100 m/s or more, which is consistent with some of the higher slope scale crack speeds reported by Hamre et al. (2014) and Simenhois (2020), but is about twice the crack speed directly measured prior to an avalanche release by van Herwijnen and Schweizer (2011). Johan's team observed in their model that on an avalanche slope the slab starts to move downhill and the downhill movement helps to drive a change in the fracture mode from a mixed mode anticrack to an almost pure shear mode. This shear mode is well-described by the original shear model proposed by McClung (1979). The supercritical crack size varies depending on several factors, but it was around 3 to 5 m in some of their simulations. They observed this crack speed transition in both their slope-scale models and their models of long PSTs.

Johan's presentation sheds light on a question that has been asked among avalanche researchers and practitioners for at least 50 years, but perhaps more often in the past 15 years: When thinking about avalanche release, do we need to think more about shear failure or mixed-mode anticrack (collapse) failure? His team's results suggest the answer to this question is nuanced, with both modes playing an important role. The models of Johan's team show mixed mode anticracking—and the associated bending of the slab—is important for avalanche triggering and is also key for remote triggering from flat terrain. Then, after cracks reach a certain supercritical size in steeper terrain, pure shear may become the dominant driver for crack propagation.

To summarize the session in a few points:

- Direct measurements and models of crack speeds in PSTs and in whumpfs in relatively flat terrain are reasonably consistent, ranging from around 15 to 30 m/s.
- Models of crack speed in steep avalanche terrain jump dramatically after the initial crack reaches a so-called supercritical size, and top out near 100 m/s.
- This latter finding is remarkably consistent with the analysis by Ron Simenhois (2020), who used video magnification to measure slab deformation speeds ahead of the appearance of cracks on the snow surface. This slab deformation speed in the downhill direction, which is presumably associated with the extension of the crack in the weak layer, was about 100 m/s.
- These values are also consistent with both the video analyses of multiple avalanches by Hamre et al. (2014), and the video analysis of cross-slope avalanche-scale crack speed measured by Basti Bergfeld and colleagues (2020).
- Direct measurements of crack speeds on avalanche slopes are rare. So far, only one such measurement exists, and the recorded crack speed was 42 m/s (van Herwijnen and Schweizer, 2011). Hopefully more direct measurements can be made to field-truth models and video measurement techniques.
- Crack speeds are important because our limited measurements suggest that high crack speeds may be associated with larger avalanches, though this is an area that will undoubtedly be studied further in the coming years.

Figure 8: A technique for magnifying video frame pixel intensity and brightness demonstrates slab deformation during a snowboarder-triggered avalanche (Simenhois, 2020). *Video provided by Red Bull Media House*

Figure 9: The work by Gaume et al. (2020) includes modeling avalanche flow through complex terrain, including through forests.

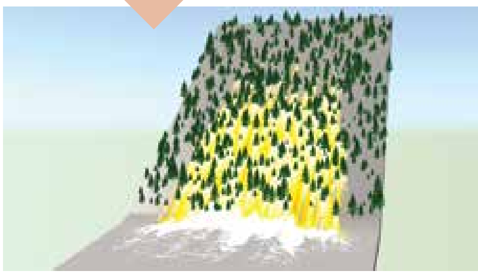

Figure 10: This debris field of a modelled avalanche looks remarkably realistic. Gaume et al.'s (2020) models showed a transition from granular flow to plug flow when the snow temperature in flowing avalanches reached -1 degree C.

This session at CSAW demonstrated our steady improvements in understanding avalanche release through both field work and modeling. These advances will aid in developing ever-more complete and sophisticated models that may one day provide tools to assist avalanche forecasters. The good news for those of us that love to go outside is that avalanches are exceedingly complex. Thus, the need for being in the field and having and having your feet and your shovel in the snow are not going to go away anytime soon. ⬢

ACKNOWLEDGMENTS

I am grateful to the session participants, Basti Bergfeld, Alec van Herwijnen, Ron Simenhois, Johan Gaume, Ben Reuter, and Bruce Jamieson, not only for their participation in the session, but also for reviewing a draft of this article. Thanks also to Jürg Schweizer for providing Figure 1 from one of his articles. Finally, thanks to all these folks, and many others in the avalanche community, for helping me to better understand the complexity of avalanche release.

REFERENCES

Bergfeld, B., A. van Herwijnen, J. Cathomen, and J. Schweizer. 2020. Measuring slope-scale crack propagation in weak snowpack layers. Talk presented at the 19th Annual Colorado Snow and Avalanche Workshop. Video posted at: https://www.youtube.com/watch?v=TZxUf3phTqI&list=PL8JNcWk4vjFuM4JkCKnTKfcmn8mHz0Hy_&index=1

Birkeland, K.W., A. van Herwijnen, B. Reuter, and B. Bergfeld. 2019. Temporal changes in the mechanical properties of snow related to crack propagation after loading. Cold Regions Science and Technology 159, 142-152. https://www.sciencedirect.com/science/article/pii/S0165232X18303306?via%3Dihub

Birkeland, K.W., B. Berfeld, and A. van Herwijnen. 2020. Changes in propagation saw test critical cut lengths in the minutes and hours following loading. Talk presented at the 19th Annual Colorado Snow and Avalanche Workshop. Video posted at: https://www.youtube.com/watch?v=wyNCyu661G8&list=PL8JNcWk4vjFuM4JkCKnTKfcmn8mHz0Hy_&index=2

Gaume, J., X. Li, L. Blatney, B. Trottet, G. Bobiller, M. Kyburz, C. Ligneau, and C. Jiang. 2020. Recent advances in snow and avalanche modeling. Talk presented at the 19th Annual Colorado Snow and Avalanche Workshop. Video posted at: https://www.youtube.com/watch?v=nGF9K82c1qg&list=PL8JNcWk4vjFuM4JkCKnTKfcmn8mHz0Hy_&index=6

Hamre, D., R. Simenhois, and K.W. Birkeland. 2014. Fracture speeds of triggered avalanches. Proceedings of the 2014 International Snow Science Workshop, Banff, Alberta. https://arc.lib.montana.edu/snow-science/item.php?id=2048

Johnson, B.C., B. Jamieson, and R.R. Stewart. 2004. Seismic measurement of fracture speed in a weak snowpack layer. Cold Regions Science and Technology 40(1-2), 41-45. https://schulich.ucalgary.ca/asarc/files/asarc/Seismic-FractureSpeed.pdf

McClung, D.M. (1979). Shear fracture precipitated by strain softening as a mechanism of dry avalanche release. Journal of Geophysical Research 84: doi: 10.1029/JB084iB07p03519.

Schweizer, J., P. Bartelt, and A. van Herwijnen. 2015. Snow avalanches. In: Snow and Ice-related Hazrds, Risks, and Disasters. Academic Press, https://www.sciencedirect.com/science/article/pii/B9780123948496000123?via%3Dihub

Simenhois, R. 2020. Using avalanche videos to track slope deformation during avalanche release. Talk presented at the 19th Annual Colorado Snow and Avalanche Workshop. Video posted at: https://www.youtube.com/watch?v=IeKD35D-S7U&list=PL8JNcWk4vjFuM4JkCKnTKfcmn-8mHz0Hy_&index=3

van Herwijnen, A., B. Bergfeld, J. Cathomen, and K.W. Birkeland. Hunting whumpfs. 2020. Talk presented at the 19th Annual Colorado Snow and Avalanche Workshop. Video posted at: https://www.youtube.com/watch?v=iKVGEInqsS4&list=PL8JNcWk4vjFuM4JkCKnTKfcmn8mHz0Hy_&index=27

van Herwijnen, A. and J. Schweizer. 2011. Seismic sensor array for monitoring an avalanche start zone: Design, deployment and preliminary results. Journal of Glaciology, 57(202), 267-276. doi:10.3189/002214311796405933