STABILITY CHANGES AFTER WEAK LAYER COLLAPSE: INSIGHTS FROM AN UNEXPECTED DATASET

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ABSTRACT: While conducting avalanche mitigation or traveling through the backcountry, avalanche professionals sometimes experience a “whumpf”: a collapse-mode crack accompanied by surface cracking that does not produce an avalanche. These whumpfs are a clear warning sign of instability in the surrounding terrain. But assessing the collapsed slope itself, if it is steep enough to avalanche, carries much more uncertainty. Can slopes that whumpf and are steep enough to slide still avalanche? The answer to this question supports avalanche mitigators and ski guides in assessing whether to open such slopes. Previous research on collapsed slopes is limited to one study conducted before tests that estimate crack propagation propensity, such as the Propagation Saw Test (PST), were developed. This work showed that weak layer shear strength decreased immediately after collapsing and then increased over time. However, no research has examined crack propagation propensity after a whumpf. Studying propagation propensity is key for assessing how whumpfs immediately affect slope stability. To improve our understanding of changes in propagation propensity following weak layer collapse, we conducted PSTs on a test slope in the hours and days after an unexpected collapse occurred on a layer of surface hoar. Two PSTs at our study site three days prior to this collapse provided an estimate of weak layer propagation propensity. PST cut lengths decreased immediately following the collapse, suggesting that the collapse increased the propagation propensity. However, over the next 4-5 hours, PST cut lengths steadily increased at our site, likely due to ongoing sintering and strengthening in the collapsed weak layer. By the end of day two, we were no longer able to initiate propagation, suggesting substantial stabilization of the weak layer. Our results support prior findings and observations suggesting that slopes may remain capable of producing avalanches immediately after a collapse but likely stabilize over the next day or two. Although this research does not provide answers about precisely when a slope becomes stable after a collapse, it does highlight uncertainties in our understanding and interpretation of the stability of slopes that have whumpfed.

KEYWORDS: whumpf, crack propagation, Propagation Saw Test (PST), snowpack stability, avalanche release

1. INTRODUCTION

Many avalanche professionals and backcountry recreationists have experienced a ”whumpf” while traveling through snowy mountains. The term ”whumpf” refers to a propagating collapse of a weak snow layer under a slab, often accompanied by surface cracking (Figure 1). Whumpfs are a clear sign of snowpack instability and depending on the terrain and the extent of crack propagation, may trigger slab avalanches (American Avalanche Association 2022; Konigsberg et al. 2023; Birkeland 2025). In some cases, whumpfs in flat terrain may propagate into steeper terrain, and release a remotely triggered avalanche (Konigsberg et al. 2023). The terms whumpf and collapse are often used interchangeably, so we use ”collapse” for consistency in the rest of this paper (American Avalanche Association 2022).

When a slope steep enough to avalanche collapses, but does not avalanche, it leaves the observer with two key questions: 1) Why did the slope collapse but not avalanche? and 2) Could the collapsed slope still avalanche? Research on this topic is limited. One paper reports two cases where a slope collapsed after mitigation efforts with explosives, and then avalanched when patrollers placed additional explosives on the slope (Birkeland et al. 2006b). More recently, at a 2026 workshop attended by about 60 experienced ski patrollers, about 25% of them reported a similar experience at some point during their career

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(Trautman 2026). Although uncommon, these experiences raise an important question and its answers can inform avalanche professionals who make decisions about opening terrain to the public or their clients: How should we treat collapsed slopes that did not avalanche?

Interpreting these events requires an understanding of avalanche release. When a slope steep enough to slide collapses but does not avalanche, crack initiation and propagation occur, but the crack arrests before the slope releases. This can occur if the weak layer and/or slab are not continuous enough to support slope-scale crack propagation (Birkeland 2025).

Previous research on the stability of collapsed slopes describes two case studies from the 2005-06 season at Big Sky and Moonlight Basin, Montana, USA, where notable avalanches released immediately after a slope had collapsed during avalanche mitigation (Birkeland et al. 2006b). In both cases, an initial explosive resulted in a collapse with visible surface cracking, and a second explosive applied shortly afterward, within a few minutes on the same mitigation mission, triggered a large avalanche. During the season, there were other instances where slopes collapsed with an initial explosive but did not avalanche with subsequent explosives or were not tested with explosives, and did not avalanche, following the collapse. Snow safety personnel noted that, of the slopes that collapsed but did not slide, none avalanched later in the season on the suspected weak layer. This pattern suggests that the collapse may have ultimately made these slopes more stable over time, but also that they may have been quite unstable immediately after they collapsed. These occurrences emphasize the uncertainty associated with interpreting slope stability after a collapse, and underscore the importance of treating collapsed slopes with caution.

Two datasets that include stability tests from before and after a collapse support these observations. Researchers in Montana and Switzerland documented changes in shear strength before and after unintentionally collapsing the weak layer of interest (Birkeland et al. 2006b; Birkeland et al. 2006a). They found that weak layer shear strength decreased immediately following weak layer collapse, but then increased over time. They hypothesized that shear strength initially decreased due to many of the bonds in the weak layer being broken by the collapse. Subsequent increases in shear strength likely resulted from increased sintering in the collapsed weak layer. When a weak layer collapses, grains are rearranged into closer contact. This increases the number of contact points, and sintering at these contacts points then strengthens the layer over time (Szabo and Schneebeli 2007; Van Herwijnen and Miller 2013). This prior research on collapsed slopes occurred before the development of field tests that better estimate crack propagation propensity, such as the Propagation Saw Test (PST) (Gauthier and Jamieson 2008). Crack propagation is a necessary step in slab avalanche release; thus, understanding crack propagation propensity is central to assessing slope stability. Weak layer shear strength offers insight into changing weak layer characteristics, but it does not fully capture how a collapse might affect crack propagation propensity. PST results, in contrast, provide direct insight into crack propagation propensity and changes in critical crack length (Birkeland 2025). Understanding whether cracks can propagate through a previously collapsed weak layer, and how critical crack lengths change with time, is therefore key to understanding how collapses affect slope stability.

In March 2026, while preparing to collect data for an unrelated project, we unintentionally collapsed a layer of buried surface hoar across the entire test slope at our study site. Three days before the collapse, we collected a small data sample that consisted of two PSTs. This provided a unique opportunity for us to examine changes in propagation propensity over time following a collapse.

2. METHODS

2.1. Field site

We selected a field site along the ridge between Beehive Basin and Bear Basin (45.32638, -111.38200), Montana, USA, at an elevation of 2800 m, in an area unaffected by skier traffic. The slope is east facing with an average inclination of 25°. To check for snow depth consistency, we measured depths across the study slope.

2.2. Field data

Three days prior to the collapse, we collected a snow profile on our study slope. We conducted a 1 m and a 1.2 m long, 0.3 m wide, PST with the upper and lower column walls vertically oriented. Our observations confirmed the existence of a surface hoar layer that we targeted for sampling. Our original project goal was to make measurements on the slope during an upcoming period of forecasted warming.

Three days later, on day one of our data collection,



Figure 1: Occasionally, slopes steep enough to slide will collapse, but not avalanche. In this case a skier triggered a collapse from above that propagated down onto the slope, resulting in this crack. The slope did not avalanche, but it is unclear if the slope is more or less stable immediately following the collapse (photo used with permission from the Forest Service National Avalanche Center, December 20, 2002).

we triggered a large collapse across the entire slope when we arrived at our site. We then conducted five PSTs and collected a snow profile for each PST. We recorded videos of our tests so we could analyze the crack propagation. The first PST propagated during isolation, before filming began. We filmed all subsequent PSTs. We made our PST columns 2 m long and 0.3 m wide to minimize edge effects. We cut the columns upslope and aligned edge walls at the bottom and the top of the column in a slope-normal angle (Bergfeld et al. 2025). We returned to the field site on the next two days for additional testing.
Over the course of three days, we conducted a total of 14 PSTs: five on day one, five on day two, and four on day three (Bruckmeier et al. 2026).

2.3. Video analysis

We measured slab collapse from side-view video of each PST. We used the Good Features to Track method (Shi and Tomasi 1994) to select up to 240 locations on the PST block, and tracked these locations on the slab frame-to-frame with sparse optical flow (Lucas and Kanade 1981; Bouguet 2001), recording at up to 240 frames per second (fps) to resolve the fast propagation. We set the image scale (mm px^{-1}) from the known column length by marking the two column ends, which makes it independent of the column's tilt in the frame. We fit the column's long axis to the initial marker positions by principal-component analysis. Along-column position is the projection onto that axis and collapses the displacement normal to it (downward-positive), so the measurement is insensitive to the column's orientation in the image. For each marker, we took the collapse height as the total vertical displacement of the snowpack. This meant that we captured the full drop, whether the slab collapsed abruptly or gradually. We excluded markers within the saw-cut length and rejected optical-flow tracks that appear as outliers relative to their neighbors. We then summarized collapse as the median collapse of the moving markers in bins along the column.

3. RESULTS

3.1. Pre-collapse

On March 14, 2026, three days prior to our more intensive field campaign, both PSTs resulted in full propagation to the end of the column (PST 35/100 END and PST 32/120 END), confirming the buried surface hoar layer as our weak layer of concern and also confirming the high crack

propagation propensity of the slab and weak layer.

Between the pre-collapse data collection and the time of collapse, the weather at our study site was somewhat unsettled. Two weather stations located 8 km to the south of our study site at a similar elevation reported 10 to 14 cm of new snow with 15 to 18 mm of snow water equivalent (SWE) between our pre-collapse data collection and the time of collapse (Gallatin National Forest Avalanche Center n.d.). A comparison of our pre- and post-collapse snow profiles reveals that our field site likely received less precipitation than these weather stations. On March 17 at 1030, we noted an additional 6 cm of new snow and graupel in comparison to our snow profile on March 14 at 1300 (Figure 2). Thus, the snowpack changed only slightly between the pre- and post-collapse data collection.

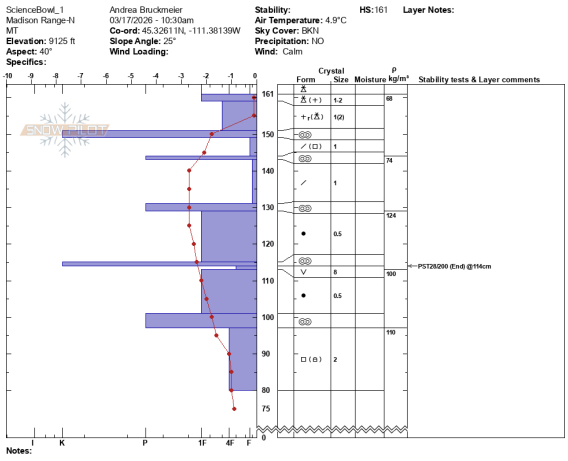


Figure 2: Snow profile on March 17, 2026 displaying the snowpack for the PST 50 min after the slope-collapse.

3.2. *The unexpected collapse*

On March 17, 2026, we triggered a collapse as we approached the site. When we examined the surface cracking associated with the collapse, we saw that it had propagated diagonally across the entire field site. An inspection of the buried surface hoar revealed the crystals were lying flat instead of standing upright as they had been prior to the collapse. Although the collapse prevented us from collecting our planned data, it also presented a unique opportunity to collect a post-collapse PST time series.

3.3. *Snow structure*

We measured the total snow depth across our study site and found relatively consistent depths of about 1.60 m. We dug a snow profile (see Figure 2) and identified that the upper portion of the snowpack consisted of 12 cm of new snow mixed with graupel overlying a well-developed melt-freeze crust. Below this melt-freeze crust, we observed alternating thin melt-freeze crusts and layers of decomposing particles that together formed a cohesive slab. The layer of concern beneath the slab was a 1 cm thick surface hoar layer located approximately 50 cm below the snow surface.

3.4. *Changes in PST cut lengths, propagation, and collapse height following collapse*

After the collapse, our PST cut lengths immediately decreased in comparison to those conducted before the collapse, and then began increasing quickly. Our first PST, about 20 minutes after the collapse, propagated during isolation (PST 0/200 END). Fifty minutes after the collapse, our second test propagated with a cut length of 28 cm (PST 28/200 END). By our third test, 130 minutes after the collapse, the cut length had already increased to 70% of the column length (PST 140/200 END), suggesting a rapidly stabilizing snowpack. The other two tests that day had cut lengths between 124 and 156 cm. PSTs over the next two days showed a stable snowpack with very low propagation propensity (Day two: all cut lengths > 160 cm, no propagation (PST 200/200 X) in one of five tests; Day three: all cut lengths > 198 cm, no propagation (PST 200/200 X) in four of five tests) (Figure 3).

In summary, the PST cut length decreased immediately following the collapse, but then increased substantially within 24 hours, reaching at least 75% of the column length. PSTs propagated to END the first day and began transitioning to no propagation the second day. PST cut lengths were so long on the second day that the short propagation distances were likely due to edge effects (Bergfeld et al. 2025) (Figure 3). Over the course of our first sampling day, we observed decreases in the PST collapse height. We could both hear and see the collapse in our first two PSTs. In subsequent PSTs, crack propagation became increasingly difficult to discern. A video analysis of our tests confirmed our observations. The vertical displacement for a pre-collapse PST was about 2 mm. The collapse height decreased to about 1.5 mm for our second post-collapse PST about one

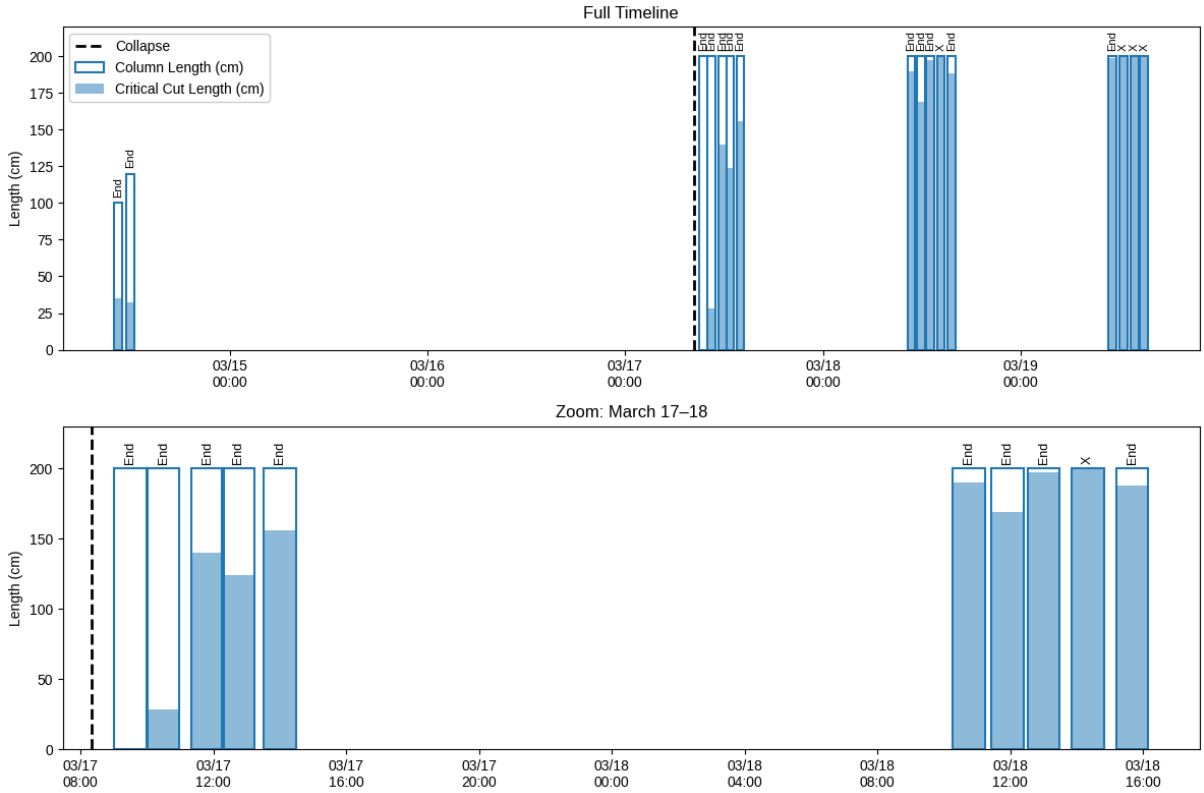


Figure 3: PST time series (a) with a close up on the first two days (b). Bird's-eye view of PST columns, blue filling represents the critical cut length. Dashed line indicates the collapse.

hour after the collapse. By the time we conducted our third PST, about two hours after the collapse, the height further decreased to 0.5 mm. The last two PSTs of that day had vertical displacements in the range of 0.5 to 0.7 mm (see Figure 4).

4. DISCUSSION

Our study examines how crack propagation propensity changes after a weak layer collapses. Immediately following a collapse, PST cut lengths decreased, before increasing rapidly over the next several hours. Our results show that collapse-mode crack propagation is still possible in some weak layers immediately after an initial collapse. Further, in some cases, it may occur more readily than before the collapse. In two to three hours, the collapse height decreased by more than 50% at the same time PST cut lengths increased by more than a factor of five (see Figure 3). Our results suggest that, for our particular slab/weak layer combination, crack propagation propensity initially increased following a collapse, but then rapidly decreased over the next several hours. The time it takes a slope to stabilize is likely to be different with other slab and weak layer combinations.

The collapse of our weak layer raises a fundamental question: How can we observe collapse-mode crack propagation, as demonstrated by our PSTs, in a surface hoar layer that has already collapsed? Repeated collapse events seem more likely in depth hoar weak layers because multiple grains are stacked on top of each other. For surface hoar layers, conceptualizing a second collapse is less straightforward. A famous photograph of a collapsed surface hoar layer published by Jamieson and Schweizer (2000) provides visual evidence of how a collapsed surface hoar might collapse a second time (see Figure 5). This photo documents how a collapse breaks some bonds and grains, decreasing the void space in the layer. Despite these changes, some void space still exists in the collapsed surface hoar layer, which implies it could collapse again. Our results are consistent with these observations and emphasize that surface hoar layers may be capable of collapsing a second time, particularly right after the first collapse.

Our results also show that collapse height decreases after the initial collapse. In our measurements, collapse height dropped from 2.1 mm before the collapse to 1.4 mm about an hour and a half after the collapse. The collapse height decreased even more in the following hours, to

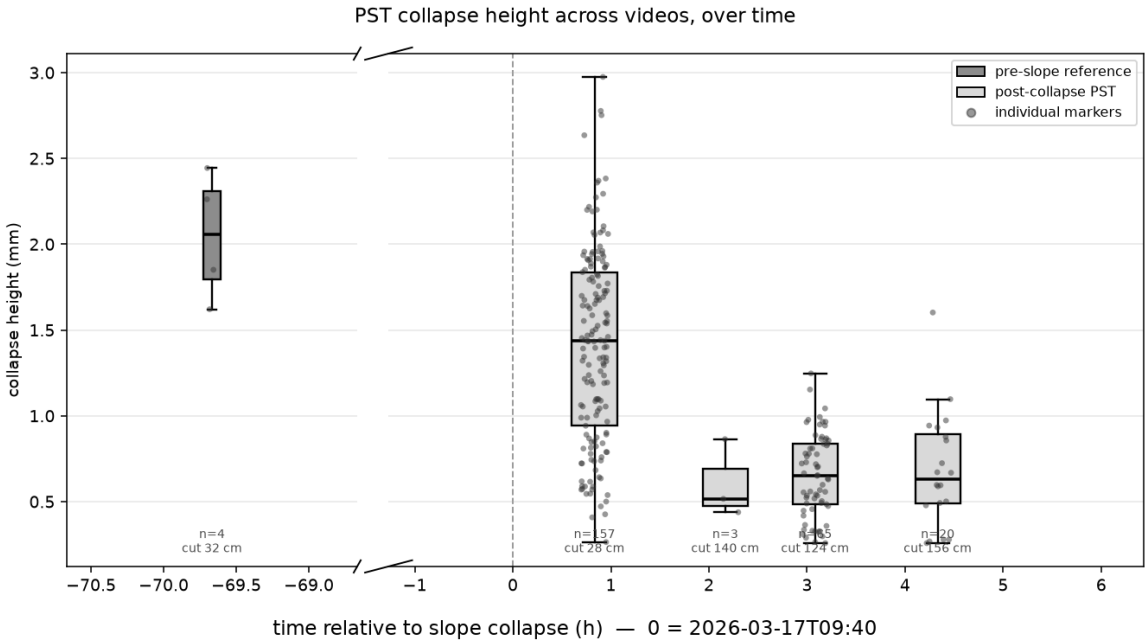


Figure 4: PST collapse height over time relative to a slope collapse (0 h = 2026-03-17 09:40). The leftmost box is a pre-collapse reference (7̃0 h prior); the remaining four boxes show post-collapse measurements. Boxes show interquartile range and median, whiskers show min/max, and dots show individual measurements. Sample sizes (n) and cut heights are labeled below each box.

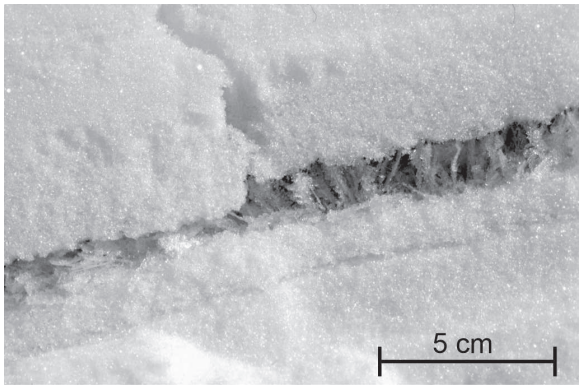


Figure 5: This photo shows the changes in a surface hoar weak layer following collapse. On the left side the weak layer has collapsed, and on the right side the weak layer is still intact. The collapse decreases the weak layer thickness and reduces the void space in the weak layer. However, void space still exists in the collapsed weak layer. We hypothesize that this remaining void space is why we observed crack propagation in our collapsed weak layer immediately following the collapse (photo used with permission from Bruce Jamiesion and ASARC, February 1994).

around 0.5 mm. We hypothesize that the initial decrease in collapse height is due to the decrease in void space in the weak layer following the initial collapse. In our final three tests, the collapse height was even less, potentially due to continued sintering leading to weak layer strengthening.

Our dataset provides insight to the strengthening of one particular weak layer after a collapse. During a collapse, bonds between grains break and some larger grains break into smaller ones. This process first destabilizes the strength of the weak layer. However, over time it provides more grain-to-grain contact points for sintering and strengthening (Van Herwijnen and Miller 2013; Szabo and Schneebeli 2007).

At the same time that the collapse height is decreasing, PST cut lengths increase from 28 cm in our first filmed PST (50 minutes after collapse) to 140 cm (130 minutes after collapse). These results suggest that the reduced collapse height lowered the crack propagation propensity, thereby increasing the PST cut length. Our observations are consistent with fracture mechanical models showing that the collapse height is an important factor to consider when analyzing propagation propensity (Trottet et al. 2022; Bergfeld et al. 2023).

The remaining question is why the PST cut lengths decreased relative to the pre-collapse data. We

cannot directly compare pre- and post-collapse cut lengths because the slope angle, column geometry (vertical versus slope-normal), and column lengths (120 cm versus 200 cm) differed. Longer column lengths generally reduce edge effects and therefore increase PST cut lengths whereas slope-normal orientated PSTs may result in more than 50% shorter critical cut lengths (Bergfeld et al. 2025). Due to these discrepancies between the tests we treat the pre-collapse data as a general baseline and we focus our analysis of the critical cut lengths primarily on the temporal evolution of the post-collapse data.

We accounted for spatial variability by recording snow profiles before each PST, ensuring that the surface hoar layer had collapsed, and that the slab structure and depths were similar. Although we cannot fully eliminate its potential impact on our results, the dramatic changes in PST cut lengths over time are unlikely to have been substantially affected by snowpack spatial variability (Birkeland 2025).

Though our results demonstrate post-collapse stabilization, we cannot provide guidance on how long it takes a snowpack to stabilize following collapse. In this study, PST results changed rapidly from unstable at 20 and 50 minutes after the collapse (PST 0/200 END and PST 28/200 END) to stable at 130 minutes after the collapse (PST 160/200), and subsequent tests remained stable. This suggests the snow became more stable a little over 2 hours after the collapse. Previous work similarly documented strengthening after collapse, but over widely varying timeframes: one weak layer exceeded its original shear strength within 2.5 hours, while another remained below 50% of its pre-collapse strength after 3 hours and did not fully strengthen until the following day (Birkeland et al. 2006b). Several factors likely contribute to this variability. Sintering occurs more quickly at warmer temperatures (Van Herwijnen and Miller 2013; Szabo and Schneebeli 2007), and our relatively warm weak layer (temperature of -2.2°C) may have sintered faster than a collapsed weak layer in a colder, mid-winter snowpack. Also, weak layer and slab properties differ between cases. For example, deeper and higher-density slabs may more completely compress a weak layer during collapse than relatively thinner and lower density slabs. Clearly, snowpack temperatures, as well as the weak layer and slab properties, are unique for each collapse measured. With only a small number of documented cases, we cannot provide general guidance for how long it might take for a particular slope to stabilize after a collapse. Instead, the previous work and our study show that there is considerable uncertainty about exactly when a slope may become more stable following a collapse.

5. CONCLUSIONS

Our results demonstrate a substantial decrease in PST cut length immediately following a collapse. This implies that propagation propensity increases immediately after a collapse, indicating a decrease in slope stability. This is a key takeaway that can be used to inform avalanche professionals who are tasked with assessing avalanche terrain to make decisions that impact client and public safety. It emphasizes that slopes that have collapsed once may be able to collapse again and produce an avalanche. This implies that these collapsed slopes may not be safe immediately after the collapse. In the hours and days following the collapse, we observed increasing PST cut lengths and decreasing crack propagation propensity, implying that stability on the slope eventually increased. However, we cannot provide a specific time it takes for a slope to stabilize following a collapse. Each collapsed weak layer and associated slab is different, so the rates of strengthening are likely to differ as well. Ultimately, there is a great deal of uncertainty about the stability of slopes that have collapsed and are steep enough to avalanche. These slopes should be treated with appropriate care and caution.

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DISCLAIMER

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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