THE ROLE OF SLABS AND WEAK LAYERS IN FRACTURE ARREST

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ABSTRACT: Though recent work on fracture has provided us with new stability tests and improved our knowledge of avalanche release, our understanding of fracture arrest is still limited. We studied fracture arrest by making modifications to weak layers and slabs in a series of propagation saw tests (PSTs). We conducted more than 100 tests at a single study plot over eight weeks during which cracks along a surface hoar weak layer consistently propagated. Slab characteristics changed dramatically over time, with increasing slab depth, density, and hardness. High speed videos of more than 70 tests allow the analysis of fracture arrest dynamics. Our results show that removing the weak layer had no effect on propagation. Fracture arrest only occurred when we replaced a 30 cm long section of the weak layer with a non-collapsible structure. Modifying the slab by introducing slope normal cracks (either from the surface down or from the weak layer up) showed that sometimes small changes to soft (F hardness) parts of a slab were sufficient to arrest fractures through slab fracture, while other times only a strong thin portion of a thick slab was capable of communicating fracture farther down the beam. Our results suggest that the tensile strength of the upper layers of the slab is a key component for crack propagation. This work demonstrates the importance of the slab in slope stability, and it also suggests avenues for developing tests capable of assessing slab characteristics conducive to fracture propagation.

KEYWORDS: fracture, fracture arrest, slab, weak layer, stability tests

1. INTRODUCTION

There are four criteria necessary for slab avalanche release: 1) crack initiation, 2) slow crack growth to a critical size, 3) rapid crack propagation (or fracture) along the weak layer, and 4) slab detachment. While past work and many snowpack tests looked at crack initiation, more recent practical work and stability tests have focused on the propagation part of the puzzle (e.g., Sigrist and Schweizer, 2007; Gauthier and Jamieson, 2008; Simenhois and Birkeland, 2009).

Slab avalanches require both a slab and a weak layer or interface. The combination of the slab and the weak layer is critically important for propagation. However, a great deal of past research focused on weak layers and paid little attention to slabs. Indeed, the widely used shear frame test requires the complete removal of the slab (Perla et al., 1982; Jamieson and Johnston, 2001).

The exact role that changes in slab and weak layer properties have on fracture arrest is unclear, but recent research is starting to address this topic. Gauthier and Jamieson (2010) discuss the role of the slab and weak layer, and the importance of the slab for "communicating" the fracture outward as part of propagation. In essence, they argue that fractures arrest where "the energy transfer required for propagation exceeds the energy transfer capacity of the slab" (Gauthier and Jamieson, 2010, p. 226). van Herwijnen (2005) discusses the importance of an intact slab for propagation and notes that cracks in the slab may effectively arrest fracture. Simenhois and Birkeland (2008) found that changes in slab thickness could arrest fractures in extended column tests, and Simenhois and Birkeland (2014) made measurements at slab boundaries to investigate possible fracture arrest mechanisms. Other recent work by Gaume et al. (2014) and Schweizer et al. (2014) discuss the importance of

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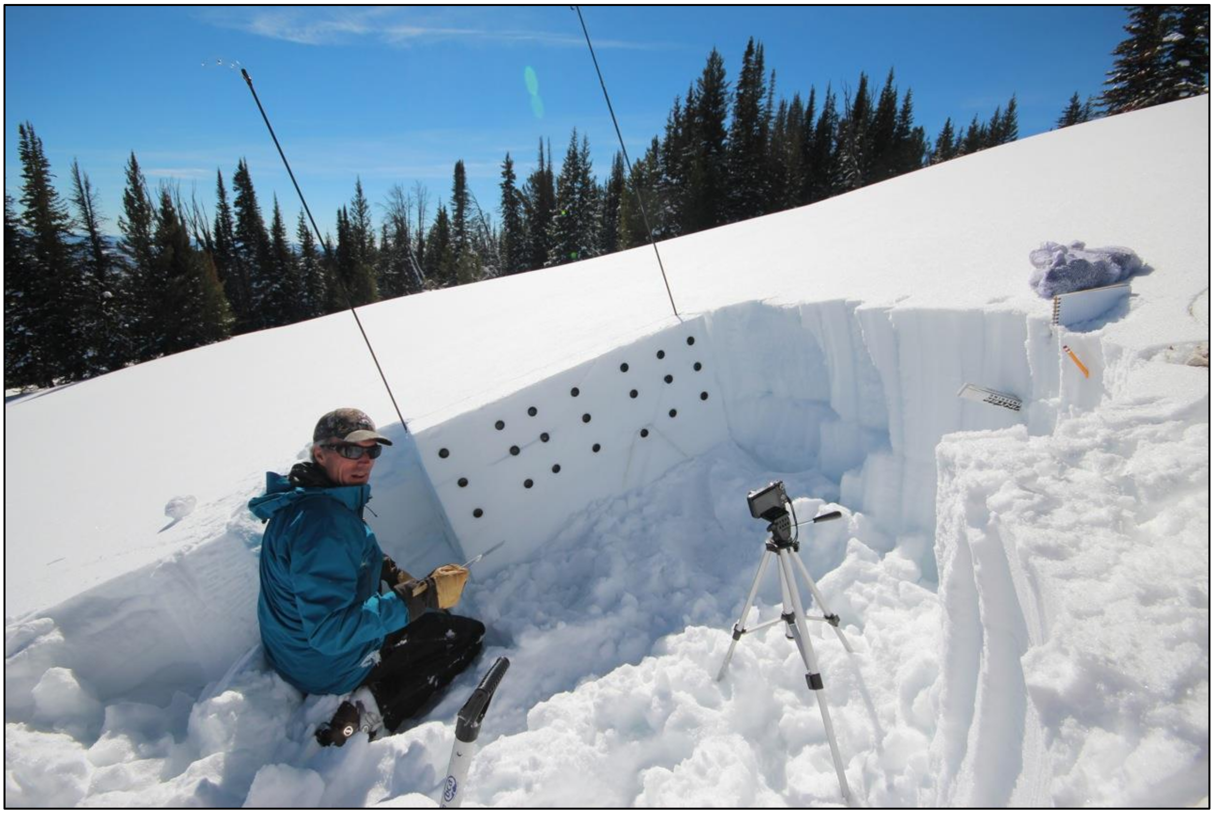

Figure 1: Our experimental setup involved taking high-speed video of our tests for particle tracking velocimetry. This picture also shows the relatively uniform, gently sloping meadow where we conducted our experiments.

slab properties such as density and tensile strength for crack propagation and fracture arrest.

In terms of weak layers, we decided to test whether or not introducing voids to the weak layer could arrest fracture. Though this seems counterintuitive since snow is porous and weak layers can be viewed as a series of voids, the fracture mechanics literature establishes that crack tips are "atomically sharp" and that voids effectively arrest classic fractures (e.g., a hole arresting fracture in glass) (Lawn, 1993). For snow, Chiaia and Frigo (2010) use a modeling approach to show the effectiveness of voids in arrest fractures in homogeneous slab layers.

Another way to potentially arrest fractures is by eliminating weak layer collapse. The mixed-mode anticrack model presented by Heierli et al. (2008) requires collapse to drive propagation, and Heierli (2005) suggests a large area of weak layer that is not "appropriately collapsible" can arrest fracture.

The purpose of this paper is to conduct field experiments to qualitatively test the effect of changes in slabs and weak layers on fracture arrest. We conducted long propagation saw tests (PSTs) during conditions favorable for crack propagation, and we modified slabs and weak layers to see the effect of those changes. Our results demonstrate the critical importance of an intact slab and a collapsible weak layer for propagation, and therefore for slope stability.

2. FIELD AREA AND METHODS

2.1 Field area

We conducted our fieldwork in southwest Montana's Madison Range near Bacon Rind Creek (44º58'13"N, 111º5'50"W). The site is an open, wind-protected, easterly-facing meadow at 2700 m (9000 ft) that offers ample sampling terrain with slope angles ranging from 19º to 25º (Figure 1).

2.2 Field data

We visited our field site eight times over a seven week period from 8 February to 1 April 2014. Each field day we collected a manual snow profile, including measuring density for each significant layer in the slab (Greene et al., 2010). Our targeted weak layer was a layer of surface hoar buried in late January. Over the course of our sampling, slab thickness increased from 39 to 125 cm, average slab density increased from 124 to 298 kg/m^3, and the maximum density measured in the profile increased from 160 to 385 kg/m^3.

On each sampling day we conducted PSTs (Greene et al., 2010) with some slight modifications. First, in order to facilitate particle tracking, we cut the back and sides perpendicular to the slope rather than vertically. Second, we made the columns as long as possible while still ensuring that unmodified columns would consistently propagate to the end of the column. Our column length started at 1.0 m, but increased to 2.5 m by the end of our sampling. By that time we may have been able to utilize even longer columns, but conducting multiple tests > 2.5 m was too time-consuming.

2.3 Slab and weak layer modifications

On each field day the sampling team conducted a few PSTs to confirm consistent propagation to the end of the column. We then did additional tests after modifying either the weak layer or the slab. On all but the first sampling day, we placed plastic markers in the snowpack and filmed our tests with a high speed (120 frames per second at 640X480 resolution) video camera for particle tracking velocimetry (PTV) (Figure 1). Those results are the subject of another paper (Birkeland and van Herwijnen, In preparation) and are also being used to validate a propagation model (Gaume et al., 2014), while this paper focuses qualitatively on the effect of weak layer and slab modifications on fracture arrest.

Weak layer modifications included: 1) removing the weak layer to simulate crack-tip blunting using a 5.5 cm diameter density tube (Figure 2a and 2b), 2) interrupting the weak layer by placing a piece of cardboard or a three-ring binder through the weak layer (Figure 2c), and 3) supporting the slab over a 30 cm section of the weak layer to eliminate collapse (Figure 2e and 2f).

Slab modifications included making slope normal cuts from the surface down into the slab (Figure 2d), and making slope normal cuts from the weak layer up into the slab (not shown). Except for our last day, we made surface down cuts each field day and varied the cuts until we ascertained within about 5 cm how much slab was necessary for continued propagation and how deep a cut caused fracture arrest. We cut up from the weak layer to compare how cuts up from the weak layer compared with cuts down from the surface.

3. RESULTS AND DISCUSSION

3.1 Weak layer modifications

3.1.1 Removing the weak layer

Using a 5.5 cm diameter density tube we removed anywhere from 5.5 to 68.0 cm of the weak layer (Figure 2a and 2b). In every case the crack propagated through the gaps and continued to the end of the column. Fractures did not arrest in any of these cases.

Clearly, gaps at this scale are not sufficient to arrest fracture. Indeed, they may have facilitated fracture since the PTV analysis shows that the fracture speeds were greater for these modified tests than in our unmodified tests (Birkeland and van Herwijnen, In preparation). The gaps may not arrest fracture due to the scale of the gaps in relation to the scale of the weak layer crystal size. Alternatively, this could be because cohesive slab above the weak layer caused all the stress to be immediately transferred across the gap and to the start of the weak layer on the other side, which is clearly an existing flaw in the material.

3.1.2 Interrupting the weak layer

Interrupting 10 to 20 cm of the weak layer with a three ring binder pushed about 5 cm up into the slab did not affect propagation (Figure 2c). We did observe fracture arrest when the binder was pushed far into the slab, but this was due to modifications to the slab and not to the weak layer.

These results confirm that propagation does not proceed like dominoes through the weak layer: the slab drives the crack. In our experiments propagation continued even when the weak layer was interrupted for up to 30 cm. Fractures did not arrest as long as the slab's integrity was not compromised and there was sufficient collapse for the slab to bend and "communicate" the fracture.

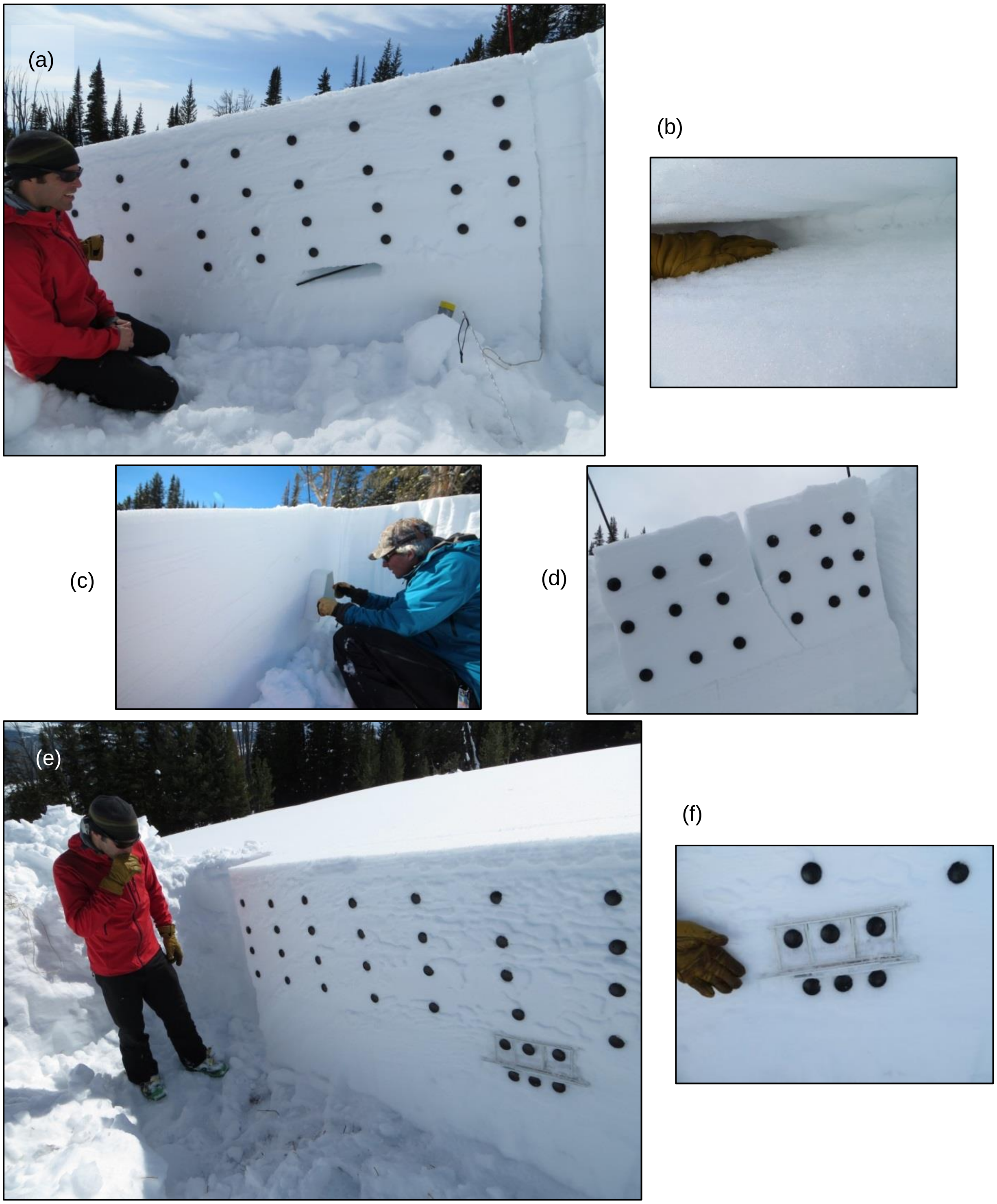

Figure 2: Weak layer and slab modifications included: a) removing a portion of the weak layer , b) close up of (a), c) interrupting the weak layer with a three ring binder with the rings removed, d) slope normal cuts into the slab from the surface down (this particular case resulted in weak layer fracture arrest due to slab fracture) and from the weak layer up (not shown), e) supporting the slab over a 30 cm distance using binder pieces placed up into the slab and down into the layer below the weak layer, and f) close up of (e) with weak layer visible through the middle of the structure.

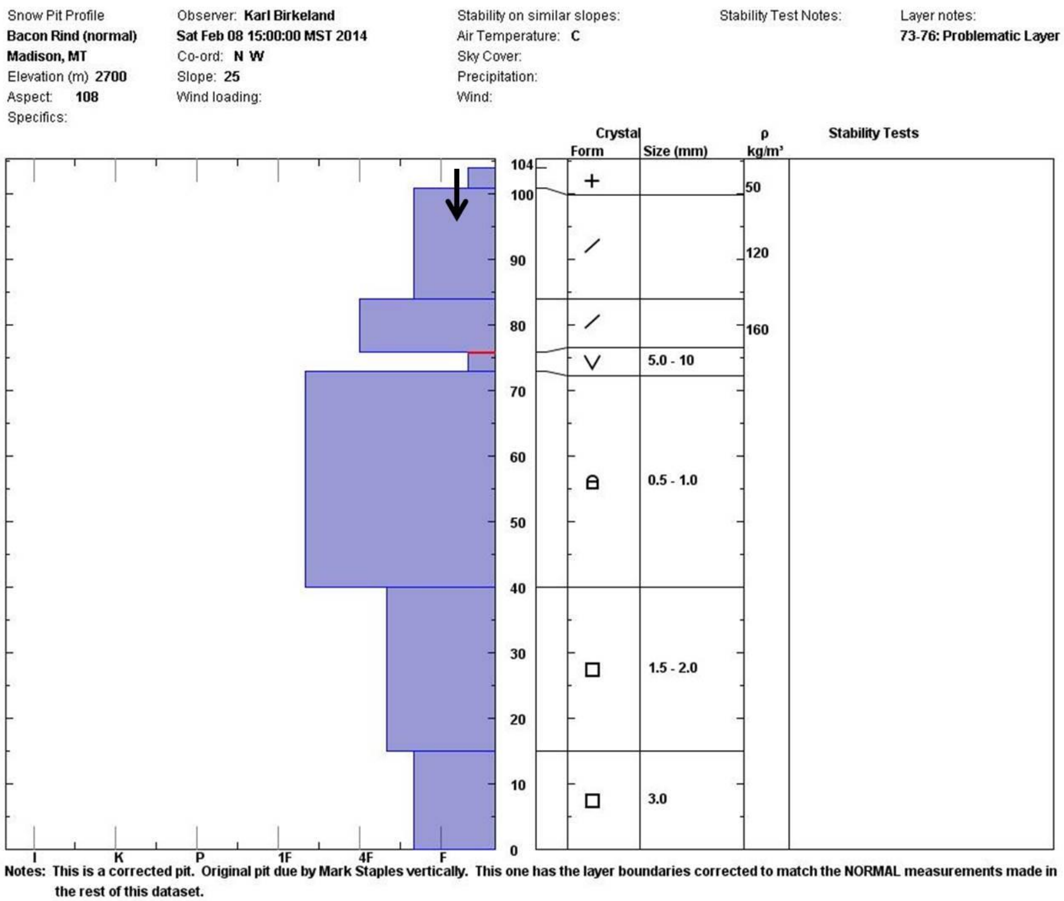

Figure 3: Snow profile from our first sampling day, nine days after weak layer burial. On this day a cut of only 7 cm into the extremely soft slab (shown by the arrow) was sufficient to arrest fracture.

3.1.3 Supporting the slab

In order to eliminate weak layer collapse, we constructed a structure with several pieces of cut up three ring binder (Figure 2e and 2f). This structure extended up into the slab, down into the snow underneath the weak layer, and across the entire beam. We found that lesser structures allowed a small amount of collapse and did not arrest fractures. However, this particular structure eliminated collapse over a 30 cm length of the column, arresting the fracture at or close to the position of the support. We confirmed the slab was well supported when we removed the structure after the test. During removal the undisturbed section of the weak layer collapsed, and the crack propagated to the end of the column.

Fracture arrest occurred when we eliminated collapse in our tests, consistent with Heierli's (2005) contention that fractures will arrest when the weak layers are not "appropriately collapsible".

3.2 <u>Slab modifications</u>

3.2.1 Cuts into the slab from the snow surface down

On every sampling day besides our final field day we made cuts down into the slab and identified the cut length necessary to cause fracture arrest (Figure 2d). In all cases, disturbing a certain portion of the slab effectively arrested fracture, which is consistent with past work (Simenhois and Birkeland, 2008). A few results were surprising. For example, our first sampling day had a 38 cm thick soft slab. A cut of only 7 cm into the soft (F-hardness) surface snow was sufficient to arrest the fracture (Figure 3). On other days we cut through significant layering, but the harder snow layers immediately above the weak layer provided

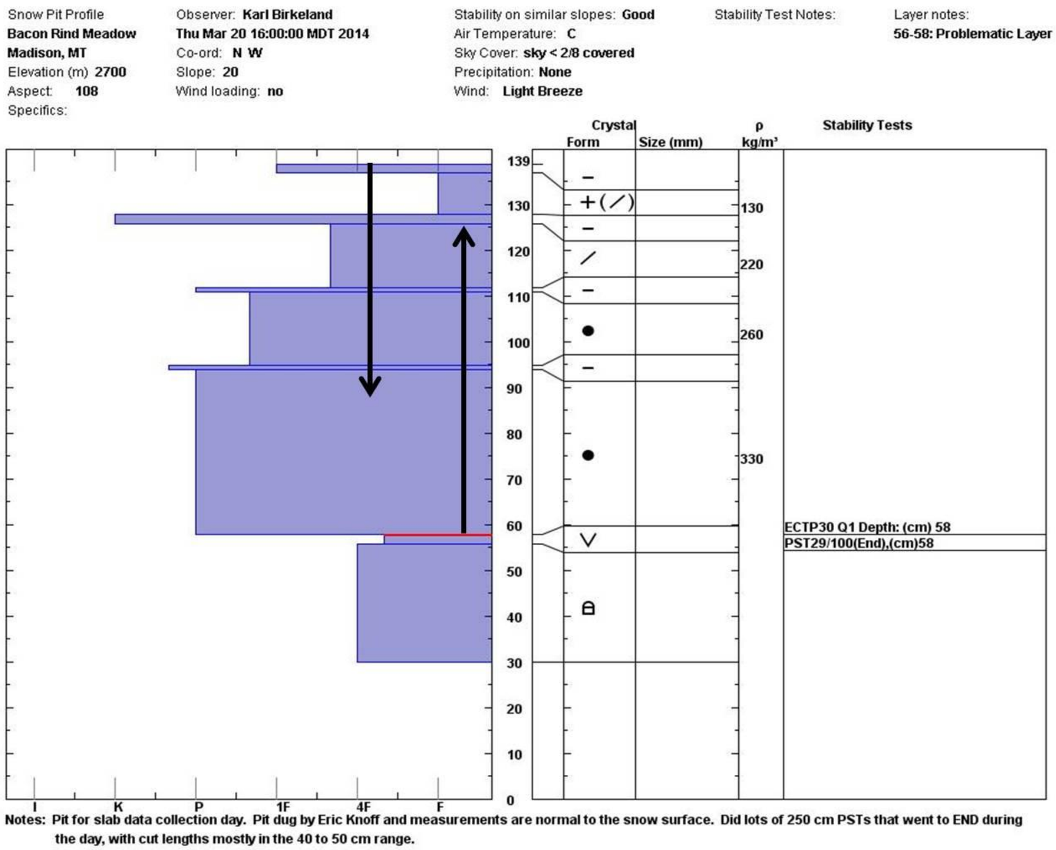

Figure 4: Snow profile from March 20th, 49 days after weak layer burial. The arrows show how far we could cut the slab from the surface down and from the weak layer up and still get propagation. The ice crust immediately above our upward cut from the weak layer was only 2 cm thick, but it had sufficient tensile strength to keep the crack propagating along the weak layer.

enough integrity to communicate the fracture farther along the column, which propagated to the end (Figure 4).

Over the 45 day period that we made these cuts, the proportion of the existing slab necessary for propagation decreased sharply, from around 85% on our first sampling days, to between 50 and 60% by the end (Figure 5a). This change occurred as the average slab density increased from 135 to 325 kg/m^3 (Figure 5b). Thus, as the density (and associated tensile strength) of the slab increases, a smaller percentage of the original slab is necessary to continue weak layer crack propagation.

This part of our work clearly showed the importance of the slab for propagation. If the integrity of the slab is compromised past a certain point, weak layer fractures will arrest. In some cases, disturbing a relatively small and soft portion of a soft slab is sufficient to arrest fracture

3.2.2 Cuts from the weak layer up into the slab

As with the cuts down from the surface, cuts up from the weak layer also affected the slab integrity and arrested fractures. Since the lower part of the slab is in compression during the slab bending that accompanies fracture, we hypothesized that smaller cuts would be needed from the surface down than from the weak layer up to arrest fracture. Unfortunately, we could not adequately test this hypothesis because of the differing physical characteristics between the layers at the surface (generally softer and less dense) and those just above the weak layer (generally harder and denser).

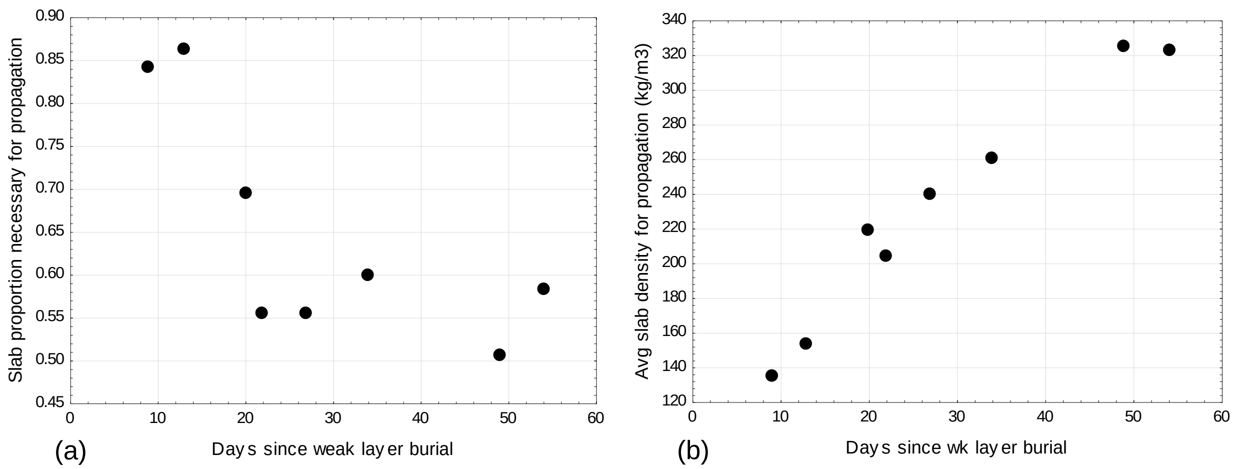

Figure 5: Over the sampling period, (a) the proportion of the slab necessary for propagation decreased, while (b) the average density of the minimum slab required to maintain propagation increased.

Still, cutting from the weak layer up provided some unexpected results. In one case with an 82 cm deep slab, we could cut all but the top 13 cm of the slab and still get propagation. In this case, the upper part of the slab consisted of a 2 cm ice crust that was K hard, as well as softer snow and another slightly softer crust (Figure 4). Amazingly, all it took was the stiff and thin upper snowpack layer to communicate the fracture even when the thicker lower part of the slab (which was P hard and had a density of 330 kg/m^3) was disrupted.

4. CONCLUSIONS

This paper qualitatively examines how changes in slabs and weak layers affect fracture arrest. Our field experiments utilizing long PSTs suggest the following:

- Voids in the weak layer do not arrest fracture. This helps explain why weak layer voids in talus fields, for example, do not arrest fracture.
- Collapse is necessary for propagation. Eliminating collapse causes fractures to arrest. This result is consistent with past work on mixed-mode anticracks (Heierli, 2005; Heierli et al., 2008).
- Since an intact slab is required for propagation, compromising the integrity of the slab will arrest fractures. Thus, when conducting propagation tests, especially with new soft slabs, keeping surface snow undisturbed is important.
- Conversely, sometimes only a small part of slab is required to communicate the fracture. In these cases, if that part is intact then the fracture will not arrest.

Our results provide experimental evidence of mechanisms for fracture arrest. Since a great deal of variability of both slabs and weak layers are found on avalanche slopes (Schweizer et al., 2008), changes in their properties may explain slab boundaries. Indeed, measurements by Simenhois and Birkeland (2014) on the crowns and flanks of avalanches suggested that many slab boundaries were associated either with decreases in weak layer collapse amplitude or decreases in slab depth.

This work emphasizes the importance of both the slab and the weak layer in crack propagation. Though much past work focused only on the weak layer, our experiments demonstrate that both a collapsible layer and an intact cohesive slab are necessary for propagation and therefore for avalanche release. Our work is consistent with other ongoing research emphasizing the importance of slab tensile strength – which relates to both density and hardness – in crack propagation (Gaume et al., 2014; Schweizer et al., 2014). Future experimental and modelling work may help us to better understand the nature of the slab/weak layer relationship that is so critical for understanding slope stability.

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