UNCERTAINTIES IN ASSESSING THE STABILITY OF FRACTURED SLOPES

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ABSTRACT: While doing avalanche mitigation work or traveling in the backcountry, occasionally a sizable part of a slope fractures without triggering an avalanche. An example is when a weak layer fractures with a characteristic “whumpf” sound and tensile cracks open up, but no avalanche releases. Disagreement exists among avalanche professionals about the immediate safety of these slopes. Many assume that if the slope does not slide during initial fracture propagation then it is unlikely to slide and is probably safe. Others treat the slopes with extra caution, especially immediately following the event. This paper provides a synopsis of recent research and two case studies that provide insight into this problem. Research shows that shear strength decreases immediately after a collapse, followed by differing strengthening rates. In both case studies, avalanche mitigation work with explosives resulted in the fracturing of some slab boundaries, as evidenced by tensile cracks visible on the surface. Additional explosives applied to the slopes shortly following the initial fractures resulted in sizable avalanches, casting doubt on the idea that fractured slopes are necessarily safe. Over many years and a handful of such experiences, an unofficial policy at Big Sky Ski Area has evolved whereby the snow safety group typically will not open slopes that have deep fractures until the following day. Our paper does not provide definitive answers about the safety of fractured slopes. However, it does point out uncertainties in our knowledge and, as a result, suggests taking a cautious approach toward such slopes.

KEYWORDS: snow stability, fracture, whumpf, avalanche release, avalanche forecasting

1. INTRODUCTION

Avalanche workers and backcountry riders are familiar with the characteristic “whumpf” sound made as weak snowpack layers collapse and fracture [*Johnson, et al.*, 2001; *Johnson, et al.*, 2004]. When this happens in relatively flat terrain well away from avalanche slopes it makes for fun and dramatic observations of fracture propagation, but in steeper terrain these collapses often result in avalanches that are sometimes triggered from great distances [*Lundy*, 2005]. Occasionally people or explosives trigger fractures in steeper terrain, but for some reason no avalanche releases. The evidence for the fracture is the tensile cracks that typically open up from the surface to the weak layer, though it is often uncertain exactly how far the fractures may have propagated along the bed surface.

When collapses occur in the course of avalanche mitigation or guiding work, it is unclear how to treat those slopes after the fracture. We discussed this problem with groups of experienced ski patrollers, avalanche forecasters, and helicopter guides over the past two years and found no consensus exists. Some people believe that post-collapse slopes are safer, having had their chance to release. However, others treat the slopes with more caution, noting that some of the slab boundaries have already fractured, thereby causing a decrease in the peripheral strength of the slab.

This paper does not provide a definitive answer to the question of whether collapsed slopes are more or less stable than before the collapse. However, we present a synopsis of recent research that gives insights into changes in snow stability on slopes where some slab boundaries have fractured. In addition, we present two case studies of fractured slopes from

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ski areas in southwest Montana. The bottom line is that while some avalanche workers may treat fractured slopes as stable, enough unknowns exist to suggest using additional caution around these slopes, especially immediately following the initial fracture and possibly up to 24 hours after the initial fracture occurs.

2. RECENT RESEARCH

Recent research by *Birkeland, et al.* [2006] provides information about changes in shear strength on slopes with fractured weak layers. During the course of recent spatial variability studies [*Kronholm*, 2004; *Logan*, 2005], two slopes being sampled collapsed with audible "whumpfs" and tensile cracks opened up. Neither slope avalanched, and the field teams continued sampling through the day. Here we provide a synopsis of the work; interested readers are encouraged to refer to *Birkeland, et al.* [2006] for a more complete description of the study slopes, methods, sampling schemes, and results.

One of our sampling areas was a cross shaped pattern on a relatively uniform 31 m by 31 m slope just west of West Yellowstone, Montana, USA (Figure 1). We used a 250 cm^2 shear frame to measure the shear strength of a buried surface hoar layer located 55 cm below the surface. Weak layer temperature was -5° C. The weak layer was complicated, consisting of two layers of surface hoar stacked on top of each other. After completing 14 tests the slope collapsed with an audible "whumpf", and tensile cracks opened up. Luckily, the slope angle averaged 28° and it did not avalanche. Our observations indicated that the upper surface hoar layer was the one involved in the collapse (Figure 2). The sampling team then conducted another 34 tests.

Our second sampling area was an 18 by 18 m area on a north-facing slope near Davos, Switzerland (Figure 3). Slope angles varied from 25° to 34°, with the steeper angles toward the top of the slope. Here we used a rammrutsch [*Schweizer, et al.*, 1995] to collect stability data and converted the data into approximate shear strength [*Jamieson*, 1995, 1999; *Stewart*, 2002] to calculate a strengthening rate. The snowpack consisted of a 50 cm thick slab layer of small (0.25 - 0.75 mm) primarily rounded and partly faceted crystals overlying a weak layer of larger rounded facets and cup shaped crystals (1.5 - 2.5 mm) sitting on top of a melt-freeze crust and the weak layer temperature was -3° C. The slope collapsed between the 4th and 5th measurement. Of 24 tests, 10 did not fracture in

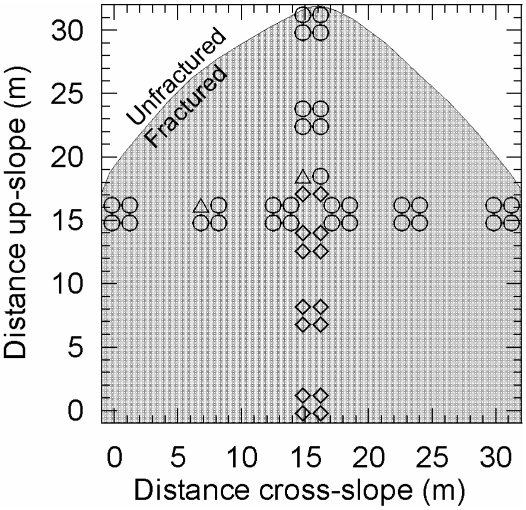

Figure 1: Shear frame test locations at our Montana site. Gray area indicates the assumed extent of the fracture within the study area. Diamonds indicate samples taken before the collapse, circles show the post-collapse measurements, and the two triangles represent outliers not considered in the calculation of the sintering rate (see Figure 4). Figure is from Birkeland, et al. [2006].

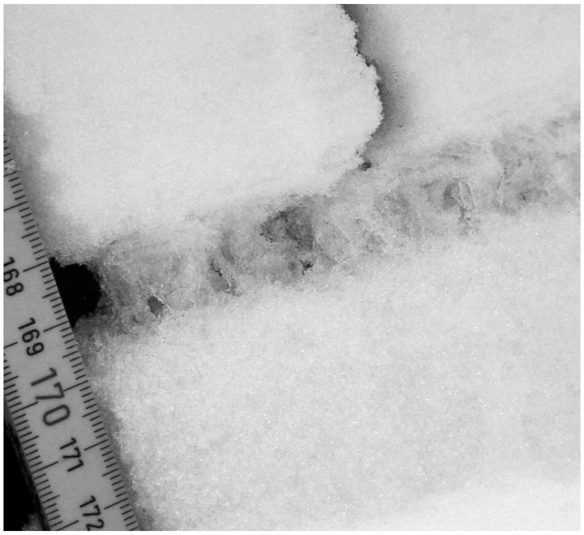

Figure 2: The Montana weak layer consisted of two layers of surface hoar stacked on top of one another. The slope collapsed on the upper of the two layers. This photo was taken at the tensile fracture, showing the collapsed layer (left of the fracture) and the uncollapsed layer (right of the fracture). Ruler is marked in cm. Photo by E. Lutz.

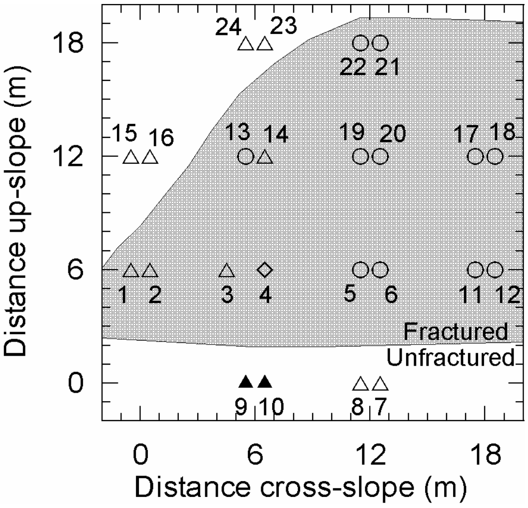

Figure 3: Rammrutsch sampling locations at the Swiss site, with the numbers indicating the test order. Gray area indicates the assumed extent of the fracture within the study area. Open triangles represent points not used in the analysis because they did not fracture on the targeted weak layer. Filled triangles represent points where the fracture occurred in the targeted weak layer, but are located outside our assumed weak layer collapse area. The diamond represents the test prior to the collapse, and the circles are post-collapse data points. Figure is from Birkeland, et al. [2006].

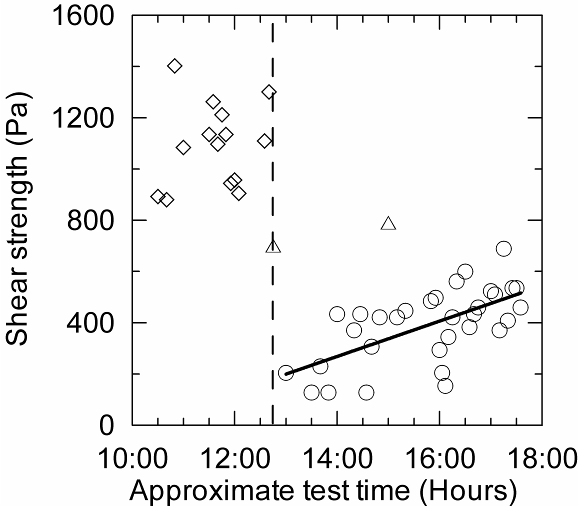

Figure 4: Plotting shear strength versus the approximate time of the test at the Montana site shows: 1) a significant decrease following the collapse (indicated by the dashed line), and 2) a roughly linear increase in shear strength through time following the collapse, with a rate of about 70 Pa h^{-1}. The triangles represent outliers removed from the analysis before calculating the strengthening rate. Figure is from Birkeland, et al. [2006].

the specific weak layer, either because the maximum drop height of 1 m was reached or because a fracture occurred in a lower weak layer. Therefore we had 14 test results for our analysis of this slope.

In both cases the shear strength of fractured areas decreased dramatically immediately following the collapse, and then increased through time (Figures 4 and 5) [*Birkeland, et al.*, 2006]. Shear strength increased relatively slowly at the Montana site (approximately 70 Pa hr^{-1}); at that rate collapsed areas would regain their pre-fracture strength in about 10 hours. Measurements one day after the collapse indicated no significant difference in shear strength between collapsed and uncollapsed parts of the slope ($p = 0.88$). At the Swiss site shear strength increased more rapidly (approximately 300 Pa hr^{-1}), perhaps due to the weak layer structure or warmer weak layer temperature. Here the fractured areas regained their pre-fracture shear strength in about 1.5 hours. Our results make physical sense since the weak layer collapse fractured the bonds holding the snow in place, thereby decreasing the shear strength. Strength subsequently increased as the

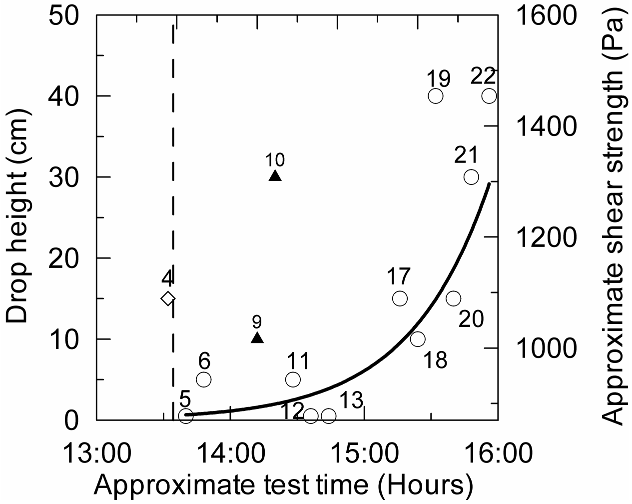

Figure 5: Rammrutsch drop height plotted versus approximate test time shows an increasing rate of strengthening in the weak layer. The collapse occurred at the vertical dashed line. Same symbols as in Figure 2. Figure is from Birkeland, et al. [2006].

layers sintered. There are many factors involved in the sintering of fractured weak layers, and many more of these unique datasets will be necessary to establish guidelines for strengthening rates for different fractured weak layers.

From a practical perspective, these data are interesting because they suggest that fractured slopes may be more unstable immediately after the fracture if one considers only basal shear strength. In fact, on the Montana slope the stability ratio (slab shear stress divided by shear strength) of seven of the ten tests immediately following the collapse was less than one. This may be counterintuitive to many avalanche professionals who feel that fractured slopes may be somewhat safer than before they fractured. However, point stability measurements such as shear frames do not always tell us about slope stability. Clearly many other factors besides shear strength and calculated stability ratios, such as the energy necessary to drive fracture propagation or stress relaxation, affect overall slope stability. Our work emphasizes that avalanche workers should continue to use extra caution around fractured slopes, especially immediately following the fracture.

3. CASE STUDIES OF FRACTURED SLOPES

In the course of the research described above, we discussed the results with a number of long-time avalanche professionals. While many felt that collapsed slopes were probably safer after the fracture, some were not so sure and most had at least one story of a fractured slope that had surprised them during their career. Two particularly interesting examples occurred during the 2005-06 season at Big Sky and Moonlight Basin ski areas, which are both situated on southwest Montana's Lone Peak, located about 50 km (30 miles) southwest of Bozeman. Though physically located in the intermountain snow avalanche climate of the western United States, Lone Peak has one of the most continental snow climates of the intermountain zone [*Mock and Birkeland*, 2000]. Conditions on the peak are alpine, with cold temperatures, depth hoar, strong winds, and a large number of hard slab avalanches [*Savage*, 2006]. The remainder of this section of our paper will describe the particular avalanche events at the two ski areas.

3.1 Big Sky Ski Area

A series of relatively warm and wet storms in October and early-November of 2005 resulted in a snowpack depth (HS) of 30-60 cm (12 to 24 in) on most avalanche paths on Lone Peak's South Face. Subsequent warm and sunny weather with strong inversions (maximum temperatures of 2-10°C (35-50°F) in alpine areas) in mid- to late-November resulted in a hard melt-freeze crust at the snow surface. A week of cool, snowy weather followed this warm spell, with temperatures ranging from about -23 to -9°C (-10 to 15°F) and new snow totals of 85 cm (34 in) at mid-mountain. Temperatures subsequently warmed and snow continued until the event on 2 January 2006. The weather conditions produced a weak layer across the South Face consisting of a layer of small grained facets possibly formed by diurnal recrystallization [*Birkeland*, 1998] that was sitting on top of the hard melt-freeze crust. Significant avalanche activity on this weak layer began by late-December. On the morning of the 28th, 8 cm (3 in) of new snow fell accompanied by winds of 9 to 16 m/s (20 to 35 mph), and avalanche activity was limited. Snowfall increased by the morning of the 29th with 38 cm (15 in) of new snow falling accompanied by 13 to 22 m/s (30 to 50 mph) westerly winds. These conditions resulted in the Lenin and 1st Dictator Chute avalanche paths producing large avalanches (classified as HS-AE-R3-D3 in the U.S. classification [*Greene, et al.*, 2004]) fracturing 1.8 to 2.4 m (6 to 8 ft) deep on the weak layer/crust interface. Neither path released the day before despite being tested with a total of four 1-kg shots and one 2-kg shot.

The avalanche of interest for this study occurred on 2 January 2006 in the 2nd Dictator Chute avalanche path, a 40 degree southeasterly facing slope at 3,250 m (10,700 ft) in elevation. By the morning of 1 January an additional 15 cm (6 in) of new snow fell with mostly light southwesterly winds. The next morning winds increased to about 9 to 18 m/s (20 to 40 mph) from the south-southwest and an additional 3 cm (1 in) of new snow fell. The first control team in the area threw a double shot (two 1-kg pentolite cast primers) into the 2nd Dictator Chute A, and had only new snow results (SS-AE-R1-D1.5) (Figure 6). Due to blowing snow and extremely poor visibility, they left 2nd Dictator Chute B for the next team and moved on with their route. The second team threw a 1-kg shot from the ridge into the 2nd Dictator Chute B starting zone. When one of the team members went onto the slope, they discovered a large crack had opened up across it. Retreating to a safe location, they deployed a second 1-kg shot on the slope, triggering the large avalanche. The resulting slide fractured at the initial crack, broke 1.2 to 2.1 m (4 to 7 ft) deep down to the crust/facet interface, ran 500 m (1600

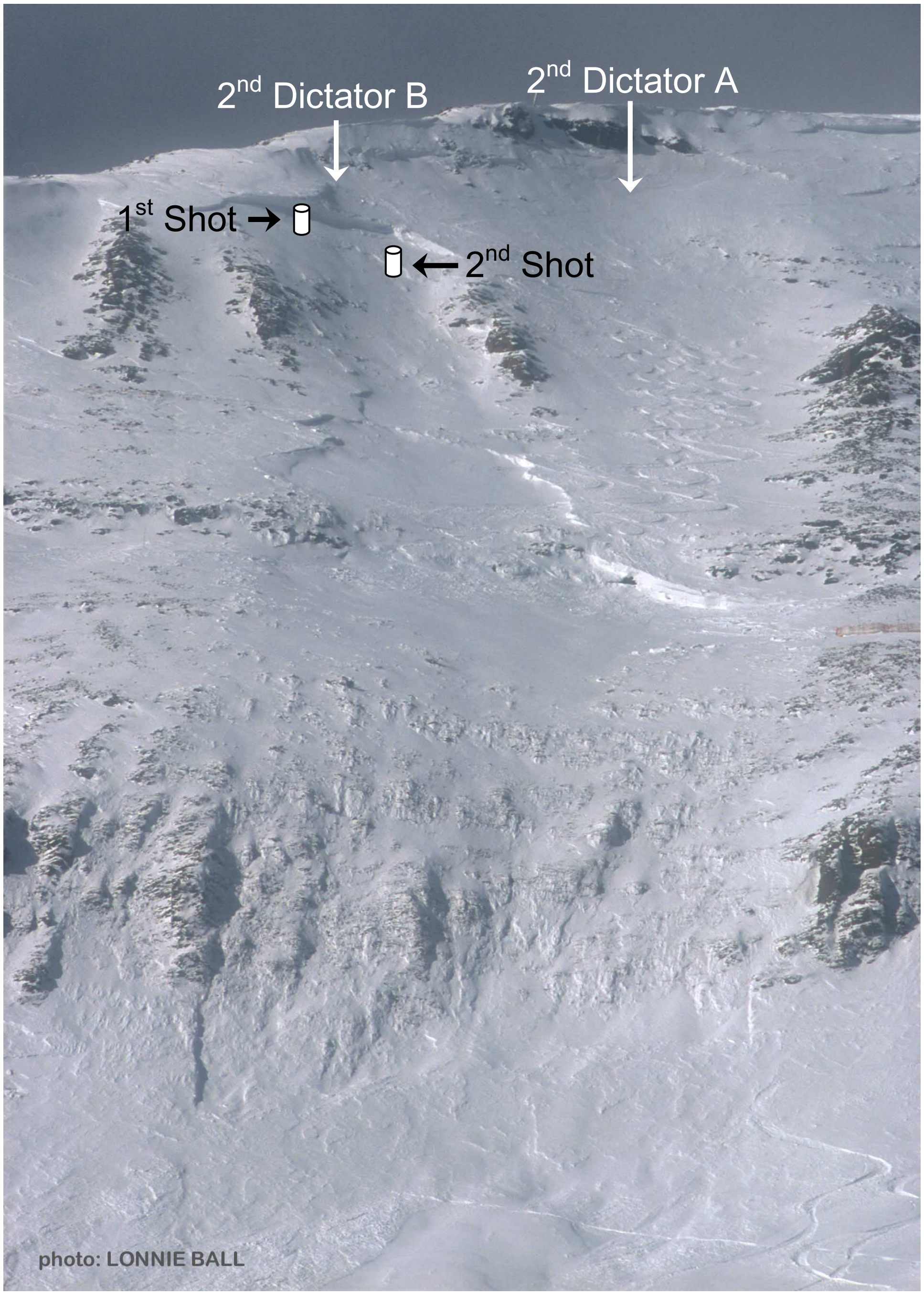

Figure 6: Photo of the avalanche in Big Sky's 2nd Dictator Chute. The initial 1-kg explosive opened up a large tensile fracture. When the control team went onto the slope they saw the fracture, retreated to a safe location, and put another explosive on the slope. The second explosive triggered the avalanche. Photo by L. Ball.

Figure 7: The Big Sky avalanche. A tensile crack opened up when the slope was tested with the first 1 kg shot. Noting the crack, the control team applied a second 1 kg shot and released this avalanche. The HS-AE-R3-D3 slide released 1.2 to 2.1 m (4 to 7 ft) deep on faceted snow overlying a crust.

ft) vertically, and was classified HS-AE-R3-D3 (Figure 7).

This example clearly shows that slopes that have fractured with visible tensile cracks are still capable of producing significant avalanches. Of course, in such cases we know only the location of the visible tensile cracks; we do not know how far the fractures extend throughout the bed surface. Further, conditions such as these may not be typical in many areas since the thick, strong slabs involved might help arrest the fracture, leaving the slope in a potentially precarious balance.

Though not common, several slopes have partially fractured and developed deep tensile cracks during avalanche hazard reduction work in the 10 years that Big Sky has opened the south face of Lone Peak regularly for skiing. Only in the case discussed above did the application of additional explosives result in an avalanche. In approximately three other cases control teams immediately applied additional explosives to the slopes (in one case they applied 11 kg (25 lb) of ANFO) with no additional results. In about three or four other cases the control team decided not to immediately apply explosives to the slope. Interestingly, of the limited sample of Big Sky slopes that have fractured and not slid, none of those slopes released later in the season on the suspect weak layer despite avalanche cycles that affected nearby, and sometimes adjacent, slopes. This suggests that weak layers or interfaces that fracture and subsequently sinter are stronger than the original snow structure.

Due to the uncertainty associated with slope stability on fractured slopes, and the potentially severe consequences to the skiing public of making a mistake, the snow safety group takes a conservative approach and typically will not open such slopes until the next day. Though each situation is unique, now when slopes fracture without releasing avalanches control teams generally do not immediately apply additional explosives. The aim is to let the slope sinter and strengthen, thereby keeping the snow on the slope rather than avalanching it to the runout zone. After waiting overnight, they conduct additional explosive testing before opening the slope to the public.

3.2 Moonlight Basin Ski Area

Moonlight Basin first opened its terrain on the North Face of Lone Peak during the 2005-06 season. On 5 January 2006, a few days after the Big Sky event discussed above, a similar event occurred in the Ahab's Whale area of the North Summit snowfield, a 40 degree northwesterly facing slope at an elevation of 3060 m (10,100 ft) (Figure 8). A snow profile dug on 1 January revealed a layer of 1 mm facets buried about 50 cm (20 in) below the surface, but on Moonlight Basin's more northerly exposures these facets were not sitting on top of the melt-freeze crust found on Big Sky's South Face. In the five days leading up to the slide, temperatures remained below freezing, winds blew moderate to strong out of the southwest, and 46 cm (18 in) of new snow fell. On the day of the avalanche only a trace of new snow fell, but winds were strong and the control team found moderate to hard 20 to 38 cm (8 to 15 in) deep wind slabs that were difficult to ski cut and released locally and slowly when triggered by explosives. Before working on the slope in question, the team released four small avalanches (HS-AE-R1-D1) in difficult conditions with low visibility.

Arriving at the top of the Ahab's Whale slope, the team dangled a 1-kg shot about 8 m (25 ft) down the slope over an area with considerable amounts of wind deposited snow. The explosive released a small avalanche (HS-AE-R1-D1) about 25 to 38 cm (10 to 15 in) deep and 23 m (75 ft) across (Figure 8). Visibility was limited and the true size of the slide could not be determined. One patroller skied onto the bed surface of the slide and noticed a clean 4 cm (1.5 in) wide crack in the bed surface that extended to an indefinite depth and to either side for an unknown distance.

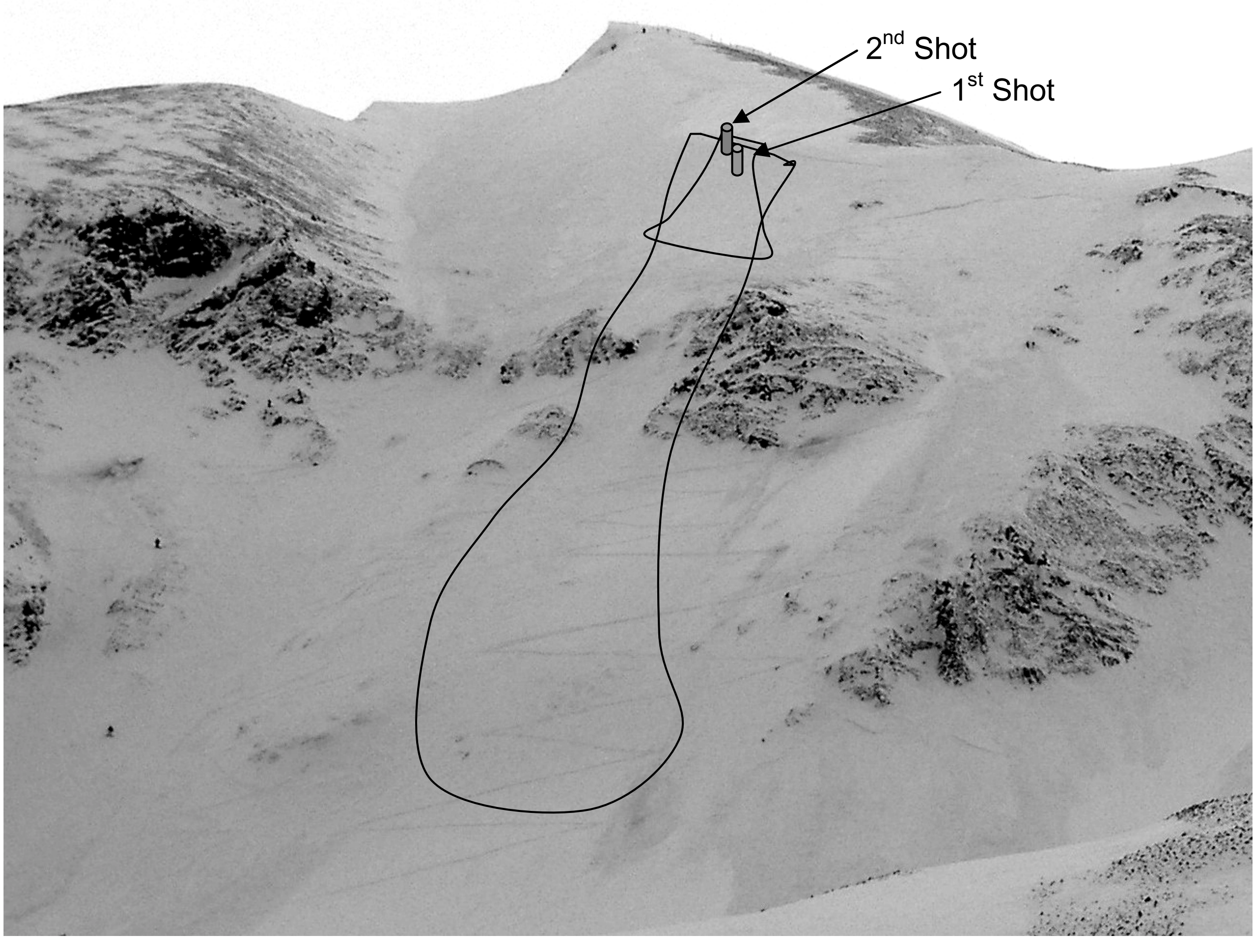

Figure 8: Photograph of Lone Peak's north face. The outlines show the two avalanches and the shot placements for the Moonlight Basin case study. This photo was taken on a different day than the avalanches, and is simply used to illustrate their location. The first 1 kg shot trigged the smaller avalanche, and resulted in a deep tensile crack in the bed surface of that avalanche that extended beyond the flanks of the slide. A second 1 kg shot placed on the crack resulted in the larger avalanche.

The crack was located about 1 to 2 m (3 to 7 ft) down from the crown wall of the explosive-triggered avalanche. A lower portion of this slope had produced a large avalanche four days prior, so the control team agreed that the slope warranted another 1-kg shot on the crack. The second shot resulted in a much larger avalanche (HS-AE-R2-D2.5). The crown followed the existing crack described above and extended past the flank of the smaller slide in both directions. The crown was 0.5 to 0.9 m (20 to 36 in) deep, approximately 45 m (150 ft) wide, and the debris ran approximately 260 m (850 ft) to the bottom of the slope (Figure 8).

This slide is notable and has the same unsettling implications for avalanche workers as the Big Sky slide discussed above. First, an explosive and subsequent avalanche significantly stressed the slope, but it did not immediately release. Second, despite not avalanching, it certainly was not stable. In fact, the slope did not need much to release since the application of a relatively small explosive placed on the crack was sufficient to trigger a large avalanche. It is impossible to know exactly what was happening at the slab boundaries throughout the sequence of events leading up to this slide. However, this case clearly shows an example of where a slope that has fractured is not safe, and emphasizes the need for careful evaluation and testing of such fractured slopes before trusting them.

4. IMPLICATIONS OF RESEARCH AND CASE STUDIES OF FRACTURED SLOPES

The research and case studies discussed in this paper emphasize the importance of a conservative approach when dealing with slopes that have recently fractured. Over the short term, shear strength decreases where the slope collapsed. Further, visible tensile cracks are clear evidence of decreased peripheral slab strength. However, whether the slope becomes more or less stable immediately following a fracture is an open question, and the answer probably varies from case to case. In a decade of experience at Big Sky, three or four fractured slopes did not avalanche when immediately tested with additional explosives, while the one fractured slope discussed in detail in this paper did avalanche on a deep weak layer with the addition of only a small explosive. Clearly, the relationship between the area of the fracture and the area of the starting zone is important. For fractures that propagate throughout entire slopes it may not be immediately possible for another fracture to propagate across the fractured area. However, for the most part we do not know how far fractures may have propagated. If the fracture arrests – perhaps due to changes in the weak layer and/or slab across the slope – our two case studies show the slope might only need a small additional load to avalanche.

There are still many unanswered questions about collapsed slopes. For example, how does shear quality [*Johnson and Birkeland*, 2002] or fracture character [*van Herwijnen and Jamieson*, 2004] change before and after a collapse? Does shear quality drop from a Q1 to a Q2 and does fracture character change from sudden to resistant? Is there a way to better assess how far fractures have propagated along the different slab boundaries? How fast does the sintering process take place for fractured weak layers for different situations in terms of the weak layer temperature, the load on the weak layer, the weak layer type, etc.? What role do hard, deep slabs play in arresting fractures on collapsed slopes that do not avalanche? What factors are involved when we get seemingly slope-wide collapses on slopes steeper than 30 degrees, but no avalanche releases?

Given the difficulty in collecting these unique datasets, coming up with answers to the above questions will take time. In the meantime, taking a little extra care around these slopes seems like a good idea. We would welcome hearing any and all stories avalanche workers might have about collapsed slopes. In addition, we encourage others to collect data on these slopes when it is possible, and safe, to do so.

Acknowledgements

Numerous colleagues provided useful comments and shared their practical experience on this subject with us, including R. Elliot, L. Fitzgerald, T. Leonard, B. Jamieson, I. McCammon, E. Lutz, and E. Greene. The U.S. National Science Foundation (Grant BCS-024310, K. Hansen, PI) and the Swiss National Science Foundation (Project 2000-066643.01) provided partial support for this work. KB, KK, SL, and JS greatly appreciate the field help of E. Lutz in Montana and J. Hendriks and A. Heilig in Switzerland. SS thanks Bart Mitchell, Ryan Ayres, Nate Opp, and Alan McClain for assisting with the Big Sky case study explosives placement details and Big Sky Resort for supporting this paper. ST thanks John Milich for guidance and experience in the field, and Moonlight Basin for providing a job with enough latitude to allow thought and some work on this subject.

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