EXTENDED COLUMN TEST RESULTS DURING SURFACE WARMING: DOES SURFACE WARMING AFFECT FRACTURE PROPAGATION POTENTIAL?

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ABSTRACT: Dry slab avalanche stability typically increases over time in the absence of active loading from new snow or wind. However, field observations suggest that occasionally slopes showing no signs of instability in the morning avalanche later in the day when the snow surface is warmed by the sun. In this paper we present evidence that dry snowpack fracture propagation propensity may increase during sunny days as the snow surface warms up and becomes wet. During four warm, sunny days in the winters of 06/07 and 07/08, we tracked changes in results for both Extended Column and Propagation Saw tests. Our data suggest that snow surface temperature affects fracture propagation propensity on inclined slopes, with fractures more likely to propagate when the snow surface is wet. We support our test results with two case studies where explosives and ski cuts produced no avalanches when the snow surface was cold and dry, but when those same slopes were re-tested after the snow surface warmed to zero degrees they avalanched. In both cases the weak layer was dry and had a temperature below zero. We hypothesize that fracture propagation propensity may increase due to increased surface creep or due to changes in the mechanical properties of the slab.

KEYWORDS: ECT, extended column test, PST, propagation saw test, fracture propagation

1. INTRODUCTION

Some avalanche workers and backcountry travelers report increased dry slab avalanche activity as the snow surface warms. For example, springtime control work occasionally produces more dry slab avalanches in the afternoon than earlier in the day. Furthermore, in some cases those avalanches run on old weak layers that existed for the majority of the season and have been previously tested with explosives and heavy skier loads.

Harvey and others (2002) identified 128 days with four or more avalanche accidents in the Swiss Alps from 1970 to 1999. On 20% of those days, no significant snowfall or wind was reported and the only contributing factor identified for instability was daytime warming. Some of the avalanches probably fractured on persistent weaknesses and would have occurred regardless of daytime warming. However, the high number days suggests that a correlation may exist between daytime warming and increasing instability. Further, these days proved difficult for Swiss forecasters, having the lowest mean avalanche danger rating when compared to the other accident days (Harvey and others, 2002).

Those observations are not limited to the Swiss Alps. During the spring of 2007, the Colorado Avalanche Information Center reported two avalanche incidents illustrating increasing afternoon instability. One slide occurred in Deer Creek just south of Montezuma and the other one was in Ruby Jewel Bowl, north of Cameron Pass. In both cases, the groups skied the slope or similar slopes earlier in the day without observing signs of instability. Further, maximum air temperatures reached well above freezing at the nearest SNOTEL sites, with average temperatures at or slightly above freezing. Despite the warm temperatures, both of these avalanches released as dry slabs.

Given the above observations, the next logical question is why a warmer snow surface might increase the likelihood of avalanche release. Exner and Jamieson (2008) report on cases where warming facilitates the strengthening and stiffening of a low density surface layer into a reactive slab, but our observations are not like their cases since we are looking at slopes with existing stiff slabs overlying weak layers. Since avalanches require both fracture initiation and propagation, we need to understand how surface warming affects each

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of these processes. In terms of fracture initiation, studies show that surface warming reduces slab stiffness, allowing the stress underneath a skier to penetrate deeper into the snowpack (McClung and Schweizer 1999), and therefore increasing the potential for artificially triggered avalanches. In fact, at a depth of 50 cm the increase in stress can be 51% higher with a warm snow surface than with a cold one (Wilson et al. 1999). Thus, fracture initiation is facilitated through surface warming.

Recently, van Herwijnen and Jamieson (2005) showed that fractures are commonly initiated underneath skiers. This is interesting because skiers only occasionally trigger avalanches. Their research suggests that the fracture initiation process may not be the limiting factor in some cases in terms of producing avalanches. Rather, the fracture propagation potential of a particular weak layer/slab combination might be critically important.

The focus of this preliminary paper is to investigate the effect of surface warming on fracture propagation. We are not aware of previous research in this area. A likely reason for the lack of studies is until recently no field tests existed that attempted to determine the fracture propagation potential of a particular weak layer/slab combination. This changed in the last couple years as researchers introduced two new tests. Gauthier and Jamieson (2006) developed the Propagation Saw Test (PST), and Simenhois and Birkeland (2006) presented the Extended Column Test (ECT) and later used additional data to further evaluate its effectiveness and to update its reporting standards (Simenhois and Birkeland, 2007). Both the PST and the ECT show promise for enhancing avalanche forecasting and slope evaluation.

For this study, we hypothesize that surface warming increases fracture propagation potential. We are unsure of the mechanism for this change, though it might be due to changes in the material properties of the slab (McClung, 1996) or increases in near-surface creep. Since we observe changes in fracture propagation potential without warming a significant portion of the slab, we suggest that changes in near-surface creep are a more likely explanation. This creep is transmitted through the snowpack to the weak layer, thereby increasing the fracture propagation potential of that layer (Figure 1). We utilize the ECT (Simenhois and Birkeland, 2006) and the PST (Gauthier and Jamieson 2006, 2007) to test our hypothesis, conducting tests during warming conditions to show the effects of surface warming on test results on both inclined and flat slopes. Though our data are limited, results show surface warming: 1) increases the propensity of ECTs to fully fracture across the column, and 2) shortens the saw cut length of the PST on inclined slopes. On flat slopes, we did not observe differences in PST cut length during surface warming. We further support our test results with two case studies where slopes tested with ski cuts or explosives did not release in the morning, but did release as dry slabs within hours or a day once the snow surface had warmed to near freezing. Our results suggest that fracture propagation potential of buried dry weak layers may increase during surface warming events, thereby raising the probability of triggering an avalanche.

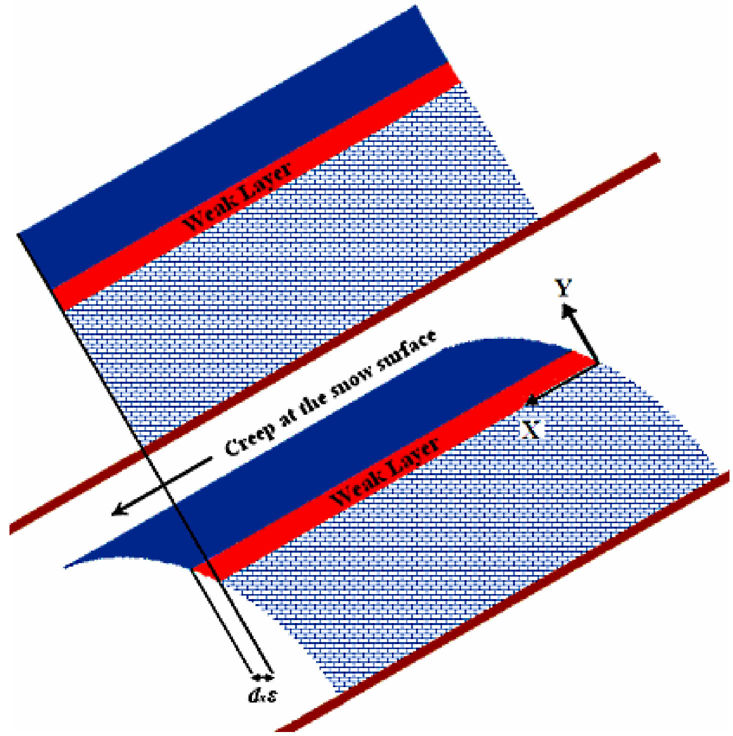

Figure 1: A conceptual illustration showing how surface creep might be transmitted to buried weak layers, thereby increasing the fracture propagation potential in those layers.

2. DATA AND METHODS

During four relatively warm days in spring of 2007 and winter of 2007-08 the senior author dug 37 pits in different locations around Copper Mountain, Colorado (Figure 2). He conducted a variety of fracture propagation tests, tracking changes in test results during the day.

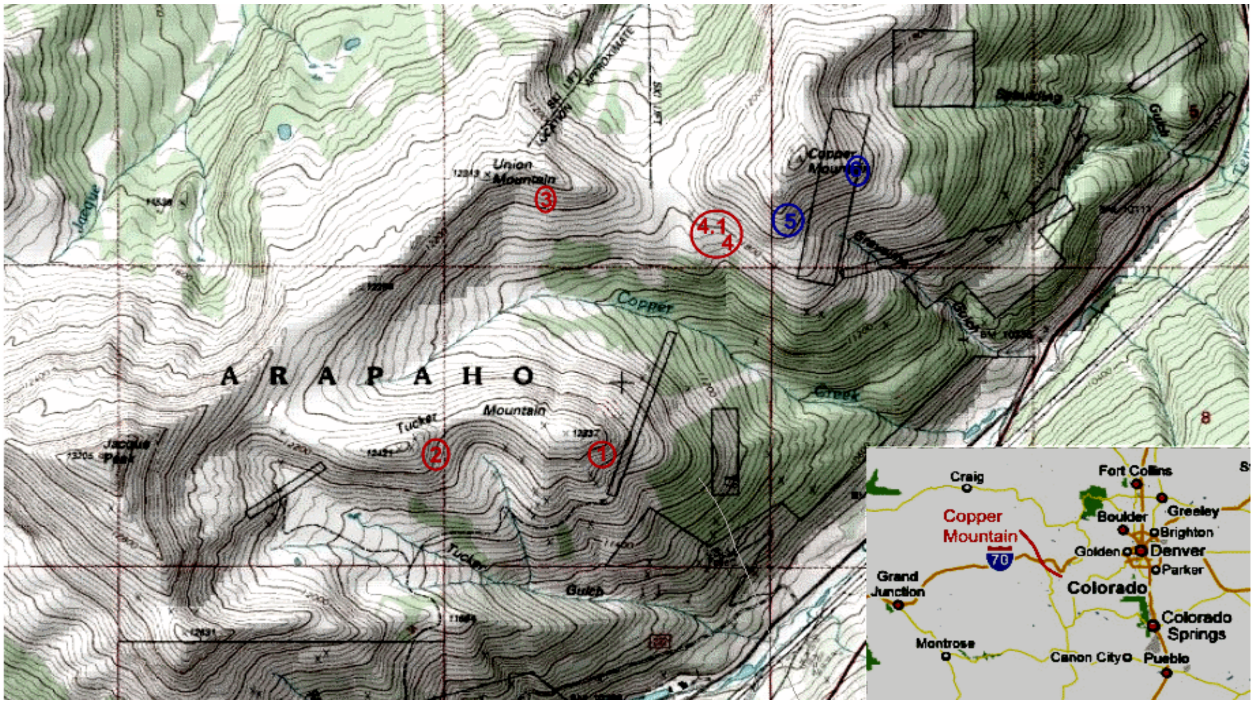

Figure 2: The location of the four study slopes investigated in this paper (in red) and the two case studies (in blue): 1) the site from 8 March 2007, 2) the site from 4 April 2007, 3), the site from 2 January 2008, 4) the site from 10 February 2008 showing the inclined (4) and flat (4.1) slopes, 5) the incident from 29 February, and 6), the incident from 2 April 2008.

The senior author dug the first two sets of pits in spring of 2007. He conducted both standard sized ECTs and ECTs with column width of 300 cm (ECT300), with two primary goals: 1) testing the spatial variability of snowpack propagation propensity, and 2) investigating fracture propagation under a slab with changing thickness and stiffness (see Simenhois and Birkeland, 2008 for more information on this work). Using a 300 cm column rather than a standard 90 cm ECT column allowed us to capture the thickness and stiffness changes within a single column. In both sampling areas the buried weak layer was sandwiched between two thin crust layers and consisted of a 2 cm thick layer of 1mm near-surface faceted crystals (crystal form 4b) that was consistent across the entire sample area. The slab above the top crust consisted of two main layers. The top layer consisted of highly broken particles (crystal form 2b) with average thickness of 12 cm and its hardness was 1F- on average. The bottom layer was a hard slab (1F+), 46 cm thick on average, and consisted of 0.2 mm of round grains (crystal form 3a) with density of 380 kg/m^3.

On 8 March 2007 we dug the first set of six pits on a southeast-facing, 36° slope between 3745 m and 3710 m (Figure 3). Two days prior other similar slopes in the area avalanched during

Figure 3: ECT300 results in the morning (with a frozen snow surface) show that all but three of our initial tests fully propagated across the 300 cm wide column (ECT300P). Interestingly, when we repeated those three tests in the afternoon (with a wet, melting snow surface), a fracture fully propagated across the entire 300cm column in all three tests. At this site we also conducted three standard sized ECTs in each of the six pits in the morning. All 18 of those ECT tests fully propagated across the column (ECTP).

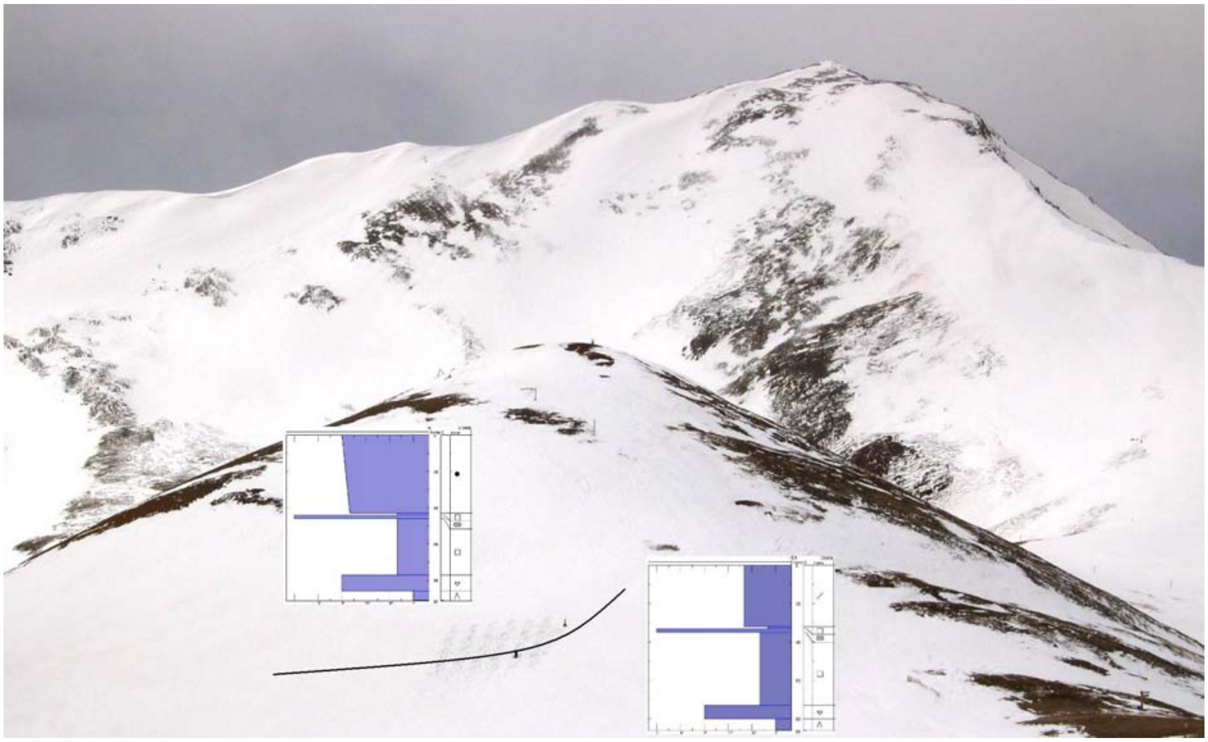

Figure 4: An overview of the pit set from 4 April 2007 The line marks the approximate lower edge of the reactive slab, and the pits shown are representative snow profiles from above and below the line.

control work with explosives, but not with ski cuts. On the morning of the sampling day the snow surface was cold, and we collected two ECT300s and three regular ECTs in each pit. In locations where no fractures propagated in the tests (ECT300N), an ECT300 was repeated later in the afternoon. Other data included the necessary information to assess structural weaknesses using lemons (McCammon and Schweizer, 2002). In the afternoon, creep cracks were observed on the same aspect about 1.5 km NE of the sampling area.

The second set of pits consisted of a six by four grid of standard ECTs dug on 4 April 2007 on an east-facing 27° slope at an elevation of 3765 m. Other slopes with the same aspect and elevation avalanched a day before with explosives, ski cuts and cornice fall. The slab in those avalanches was typically confined to the top 15 m of the slope. A similar slab existed only at the upper part our study slope, where 17 of the 24 pits were dug (Figure 4). This slab had a density of 390 kg/m^3, hardness of P-, and averaged 45 cm thick. Where the remaining seven pits were located, the top of the snowpack was a softer, 1F-slab with density of 270 kg/m^3 and was 34 cm thick on average. In each pit we collected ECT results early in the morning when the snow surface was frozen. In those pits where we got ECTN, we recollected an ECT result later in the afternoon when the snow surface was warm. Other pit data included the necessary information to assess structural weaknesses using lemons (McCammon and Schweizer, 2002).

During two relatively warm days during the winter of 2008, the senior author dug two sets of pits on avalanche crown walls and a pit on a flat slope. He conducted standard sized ECTs, ECTs with column width of 200 cm (ECT200), and PSTs, with three primary goals: 1) assessing the change in fracture propagation propensity over time, 2) assessing the change in fracture propagation propensity due to snow surface warm up and 3) investigating fracture propagation under a slab with changing thickness and stiffness.

On 2 January 2008 we dug three pits on the crown face of a hard slab avalanche that was triggered by a skier two days earlier. It was a south-facing 36° slope at an elevation of 3600m. The failure layer was 0.5 mm, near-surface faceted crystals (crystal form 4b) under a 30 to 55 cm thick P hard wind slab. In each pit we collected results from three ECTs, three ECT200s and three PSTs as well as surface and weak layer temperature both in the morning when the snow surface was cold and in the afternoon when the snow surface was warm. We also collected sufficient data to assess structural weaknesses using lemons (McCammon and Schweizer, 2002).

The second day we collected data was on 10 February 2008. That day we collected data from three pits on a crown face of a natural, hard slab avalanche. This avalanche slid three days earlier on a southeast-facing, 37° slope at an elevation of 3600m. In each pit we collected surface and weak layer temperature as well as two sets of ECT and PST when the snow surface was cold and later in the day when it was warm. We also collected data to assess structural weaknesses using lemons. In addition, we collected PST results from a pit in a flat area with similar snowpack, 50m northwest from where we dug the later three pits. In those pits the weak layer was 1-2mm mix-form faceted crystals (crystal form 4c), 50 to 82cm deep.

3. RESULTS

All four datasets demonstrate a temporal change, with propagation propensity increasing in the afternoon in comparison to the morning. In all cases, fracture propagation potential increased when the snow surface became wet in comparison to earlier in the day when the surface was frozen. These preliminary results suggest a warming snow surface affects ECT results, possibly because the increased near-surface creep of the warmer snow surface increases the fracture propagation potential of dry buried weak layers.

On 8 March 2007, the snow surface temperature was -8°C at 10:00. All 18 ECTs in the six pits fractured completely across the column (ECTP), suggesting relatively spatially uniform conditions (Figure 3; Table 1). The spatial variability of these ECT results is more fully discussed in Simenhois and Birkeland (2007). However, when we conducted two of the wider ECT300s in each of the six pits, fractures failed to propagate across the entire column (ECT300N) in three tests in two different pits where the overlaying slab was relatively thin. In those pits the average slab thickness on top of the 300 cm column was 25 cm in one pit and 36 cm in the other, in comparison to a slab thickness of 46 cm on average. By 14:00 warm temperatures melted the snow surface, wetting the snow to a depth of 10 cm. In the same pits where fractures did not fully propagate across the 300 cm column in the morning, all fractures propagated across the entire column at 14:00. Further, the force needed to initiate a fracture did not change between the morning and afternoon in those pits. Unfortunately, weak layer temperatures are unavailable for that day; however the weak layer remained cold and dry when we did the afternoon set of ECT300s.

On 4 April 2007, the snow surface temperature was -6°C at 9:05. ECT results in this set were mixed. In the 17 pits with a relatively hard overlying slab, the results were ECTP with the force required to initiate the fracture varying from 21 to 35 taps. Fractures only partially propagated across the column (ECTN) in the other 7 pits with a softer overlaying slab (Figure 5). However, we conducted ECTs in those seven pits at 14:30 when the top 4 cm of the snowpack was wet, and at that time fractures propagated across the whole column in five of the pits (ECTP). In all 24 pits the weak layer temperature was -5.3°C in the morning and -5.0°C at the time we did the second set of ECTs in the afternoon.

A notable observation from this latter dataset is that that during the initial set of ECTs, we found ECTP results in areas with a stiffer overlying slab, while ECTNs existed where the slab was softer (Figures 4 and 5). After warming, when the slab presumably softened further, results in five of the seven pits changed to ECTP. This suggests that fractures would be more likely to be initiated and also to propagate after warming at this site.

On 2 January 2008 at 10:00 the surface temperature was -11°C and weak layer temperature was -9°C. ECT results were ECTP in all six ECTs. However, fractures didn't cross the entire 200 cm column (ECT200N) in any of the six ECT200s. Further, minimum PST cut lengths along the weak layer needed to start a self propagating fracture (cut length) were between 63 and 70 cm out of 100 cm column length (PST 63-70/100 (end)). By 14:30 warm temperatures and sunshine melted the snow surface, wetting it to a depth of 5 cm, though weak layer temperature remained at -9°C. Under those conditions and in the same pits, all six ECT200 fractures crossed the entire 200 cm column on the same tap as they initiated (ECT200P) and with a similar number of taps as it took to initiate a fracture when the snow surface was cold. Further, PST cut lengths were on average 26% shorter with values between 40 and 51 cm on 100 cm column (PST 40-51/100 (end)).

On 10 February 2008, at 8:50 surface temperature was -6°C and weak layer temperature was -11°C. ECT results were ECTN on all six tests in all three pits. PST cut lengths were between 74 and 80 cm out of 100 cm column (PST 74-80/100 (end)). By 15:25 warm temperatures melted the

Table 1: Terrain and snowpack characteristics for snowpits where the morning and afternoon ECT results differed.

Date	8 March 2007	4 April 2007	2 January 2008	10 February 2008
Test results				
Number of morning ECTN results	3 ECT300N	7 ECTN	9 ECT200N	9 ECT200N
Number of ECTN results that changed to ECTP in the afternoon	3 ECT300P	5 ECTP	9 ECT200N	8 ECT200P
Percentage change, ECTN -> ECTP	100%	71%	100%	89%
Number of morning PST and average results on inclined slope	N/A	N/A	9 PST with average CutLen of 69 cm	6 PST average CutLen of 77cm
Number of afternoon PST and average results on inclined slope	N/A	N/A	9 PST with average CutLen of 44 cm	6, with average CutLen of 47 cm
Percentage change from morning to afternoon on inclined slope	N/A	N/A	34%	38 %
Number of morning PST and average results on flat slope	N/A	N/A	N/A	3 PST with avrg CutLen 79 cm
Number of afternoon PST and average results on flat slope	N/A	N/A	N/A	3 PST with avrg CutLen 79 cm
Snow temperatures, depth of wetting				
Morning surface temperature	-8.0°C	-6.0°C	-11 to -8°C	-6°C
Morning weak layer temperature	N/A (but dry)	-5.3°C	-9°C	-11°C
Afternoon surface temperature	0°C	0°C	0°C	0°C
Afternoon weak layer temperature	N/A (but dry)	-5.0°C	-9°C	-11°C
Depth of afternoon surface wetting	10 cm	4 cm	5 cm	10 cm
Snowpack characteristics				
Weak layer crystal type	4b	4b	4b	4c
Slab depth (range)	18 – 73 cm	31 – 53 cm	30 – 55 cm	50 – 82 cm
Slab density (range)	380 kg/m^3	270 – 390 kg/m^3	N/A (P – hard)	N/A (1F hard)
Terrain characteristics				
Aspect	SE	E	S	S
Elevation	3745 m	3765 m	3600 m	3600 m
Slope angle	36°	27°	36°	37& three PSTs on 0° slope

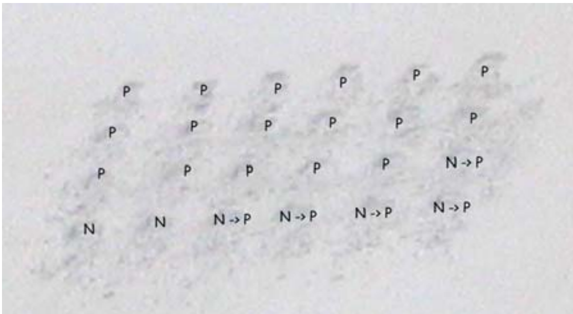

Figure 5: ECT results from 4 April. ECT results at the top 17 pits were ECTP (marked in P) when the snow surface was frozen, while the lower seven pits had a result of ECTN. Of those seven ECTN pits, five changed to ECTP when the snow surface was wet (those pits marked as N→P).

snow surface, wetting it to a depth of 10 cm, though weak layer temperature remained the same. Under those conditions all six ECT results in all three pits were ECTP. PST cut lengths were on average 39% shorter with cut lengths between 43 and 50 cm on 100 cm column (PST 43-50/100 (end)). In contrast, on the same day, the four PST's cut lengths where the slope was flat remained virtually the same through the day. PST's cut lengths were 78 cm (PST 78/100 (end)) on average both when the snow surface was -6°C and wet to depth of 10 cm. Hence, our limited data from February 10th suggest that surface warming induced propagating fractures may require inclined slopes.

4. CASE STUDIES

Our results suggest that propagation propensity, as measured by the ECT and PST, increases when the snow surface is wet on inclined slopes. However, we do not know how those changes in test results definitively relate to slope stability. Here we present two case studies to strengthen our conclusions from the stability test results. In the spring of 2008, around Copper Mountain, Colorado, we witnessed two cases where slopes did not slide when test loaded while the snow surface was frozen. Later in the day or on the next day when the snow surface warmed to 0°C, those slopes produced dry slab avalanche when loaded. In both cases, there was no additional loading from new snow or wind between the times those slopes were first tested and the time they avalanched. In addition, we are reasonably certain that in both cases fractures initiated in the weak layer, but did not propagate when the snow surface was below freezing.

Our first case study is from 29 February 2009 on a 39°, southeast-facing slope at an elevation of about 3500 m located south of Copper Mountain ski area. On the morning of 28 February, patrollers were conducting avalanche control work in the area. At that time snow surface temperature was well below freezing. A quick pit revealed a weak layer of 0.5 mm buried near-surface facets under 30 to 40 cm of 4F hard wind slab. Still, three charges on this slope yielded no results other than bomb craters (Figure 6). The depth of the craters

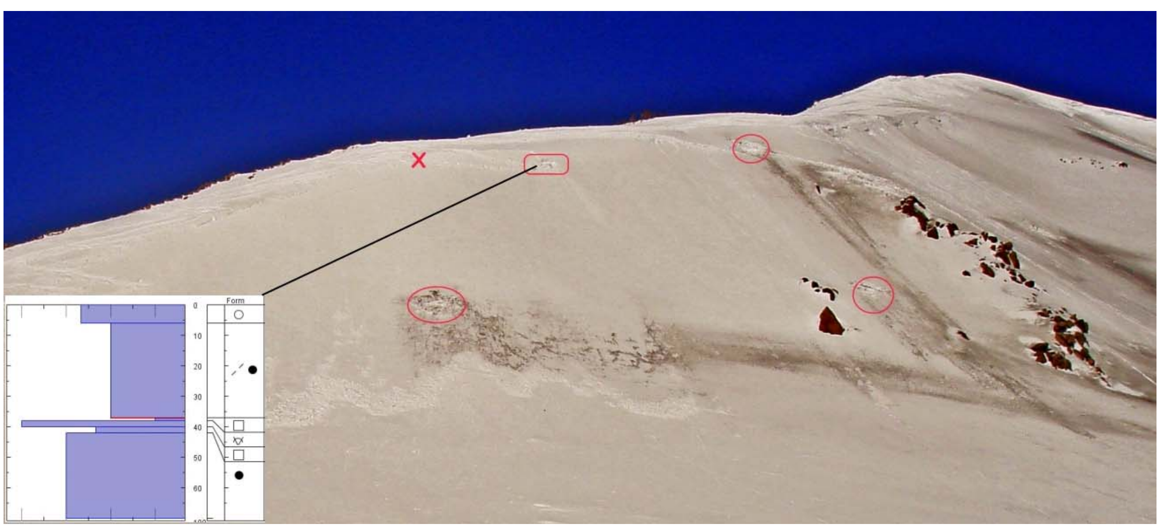

Figure 6: A photo of the case study from 29 February. The explosives placements from 28 February when the snow surface was frozen are marked with red ellipses, the pit is marked with a red square. The explosive placement on the 29th, when the snow surface was wet is marked with red X. This shot triggered the slide.

shows these charges must have initiated fractures in the weak layer, but those fracture did not propagate far enough for a slab to release. The next day the senior author returned to the same slope and triggered a soft slab avalanche with one more charge after the day's sun and high temperature wetted the top 6 cm of the snowpack.

Our second case study occurred on 2 April 2008 on a 38°, east-facing slope at an elevation of 3550 m. The snow surface temperature was -9° C, and the slope was tested in the morning with a ski cut. The ski cut penetrated through the 30 cm 4F hard wind slab all the way to the buried near-surface facet weak layer. However the slope did not slide. Three hours later that day the senior author returned to reassess the stability of this slope. At that time the snow surface had warmed up to 0° C and the slope avalanched on the approach to the steeper part of the slope (Figure 7).

5. DISCUSSION AND CONCLUSIONS

Research demonstrates that surface warming softens the overlying slab, thereby allowing stress from skiers to penetrate more deeply into the snowpack (McClung and Schweizer, 1999). This increases the likelihood of a skier-initiated fracture and therefore increases the potential for skier-triggered avalanches.

In addition, surface warming accelerates creep in the upper snowpack. This effect can clearly be shown by boring a vertical hole into the snowpack and tracking creep during a warm day (Trautman et al., 2004). We suggest that the rapidly creeping upper layers likely transfer some

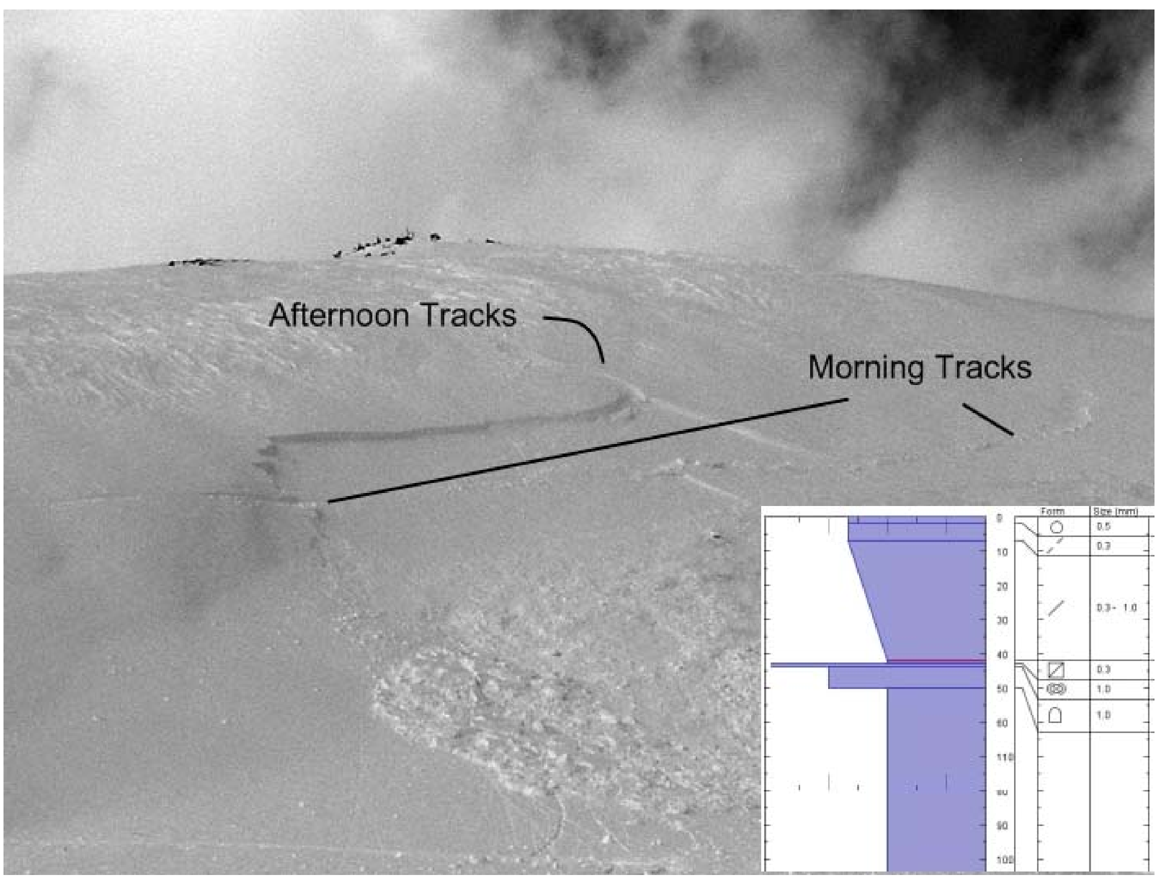

Figure 7: Case study from 2 April 2008. The morning ski tracks - when the snow surface was cold - cross the area that later slid. The tracks on the bed surface are still visible, suggesting that ski cut initiated a weak layer fracture that did not propagate. The afternoon ski cut triggered the avalanche.

of that creep to the weak layer, thereby increasing the fracture propagation potential (Figure 1) If the mechanism for our observations is increased surface creep then we would not expect to see changes in test results on flat slopes during periods of warming, and this is exactly what we observed in our limited data from 10 February 2008.

While a softening snow surface increases the probability of fracture initiation, prior to this study we know of no data on the effect of surface warming on fracture propagation potential. Our data are preliminary, only consisting of a handful of tests on four slopes. However, our results and the case studies mentioned above clearly suggest that fractures in dry, deep weak layers are more likely to propagate when free water is present near the snow surface. In our sets of pits, fractures in both ECTs and PSTs propagated across the column when the surface was warm and wet in locations where they did not fully propagate or needed longer saw cut length earlier in the day when the snow surface was frozen. In essence, these data suggest that warming leads to an increase in propagation propensity in buried, dry weak layers.

Our results have implications beyond the effect of surface warming on buried weak layers. For example, avalanche workers in some snow climates face significant problems from rain-on-snow events. In many cases avalanches may occur within minutes of when a heavy snowfall transitions to rain, even though the precipitation rate remains constant and the liquid water from the rain has not penetrated to the weak layer or interface. Perhaps the mechanism for this dramatic increase in instability is the same as for our test results, with the addition of liquid water increasing the near-surface creep rates and therefore increasing the fracture propagation potential of the buried weak layer.

Clearly, surface warming by itself will not suddenly transform a stable snowpack into an unstable one. If it did so, then surface warming would trigger widespread avalanching, and it typically does not. It is likely a second order effect. However, for snowpacks that are already close to the threshold for avalanching, surface warming can significantly affect the snow stability in two ways. First, as shown previously, the warming allows stress to penetrate more deeply into the snowpack, increasing the chances of initiating a fracture (McClung and Schweizer, 1999). Secondly, this work suggests that surface warming and increased surface creep may increase the fracture propagation potential of buried dry weak layers.

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