MEASUREMENTS OF ECT SCORES AND CRACK-FACE FRICTION IN NON-PERSISTENT WEAK LAYERS: WHAT ARE THE IMPLICATIONS FOR PRACTITIONERS?

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ABSTRACT: Field observations suggest that avalanches releasing on non-persistent weak layers tend to slide on steeper slopes than other dry slab avalanches. Recent research indicates that the initiation of fracture in a weak snowpack layer is almost unaffected by slope angle. However, this field research included only persistent weak layers. Thus, the question remains: Why are avalanches involving non-persistent weak layers slope angle sensitive? Our paper investigates the following for non-persistent weak layers: 1) the effect of slope angle on fracture initiation and 2) the friction coefficient. We performed Extended Column Tests (ECTs) on slopes where we could track the number of taps needed for weak layer fracturing on a variety of slope angles (from 8° to 46°) with minimal snow structure change. Our results show that the number of taps required to initiate a fracture that crosses the entire column (ECTP) was mostly independent of slope angle. In addition, we measured the friction coefficient of two different non-persistent weak layers types (PPsd and DFdc) within minutes after avalanches were triggered and in the following days. Our results show that the friction coefficient of non-persistent weak layers was higher than published values for persistent weak layers. From a theoretical perspective, our results are in line with the mixed-mode anticrack model for fracture in a weak snowpack layer. From a practical perspective, our results can contribute to safer pit site selection, terrain and snowpack analysis, and they give us insight into the value of observing downslope block movement after fracturing in stability tests.

1. INTRODUCTION

Two imperative, independent stages leading to dry slab avalanche formation are the extended propagation of fracture in a weak snowpack layer and overcoming the frictional force resisting the slab's down-slope movement. Previous research has shown that fractures leading to slab release involve collapse of the weak snowpack layer [Heierli and Zaiser, 2006, van Herwijnen et al., 2008].

A large body of field work utilizes Extended Column Tests (ECT) [Simenhois and Birkeland 2009] and Propagation Saw Tests (PST) [Gauthier and Jamieson, 2008] to investigate fracture propagation. One seemingly counter-intuitive finding is that both PST and ECT test results are independent of slope angle [Gauthier and Jamieson. 2008, Birkeland et al., 2010, Heierli et al., 2011]. While these experimental results cannot be explained by the traditional simple shear models for slab avalanche release [e.g. McClung, 1979, Bazant et al., 2003], they are in good accordance with the mixed-mode anticracking as the main process for

extended fracture propagation in snow [Heierli et al., 2008].

Many field observations show that weak snowpack layer fractures can propagate over low-angle terrain as well as over steep terrain. The fracture process is accompanied by a sudden subsidence of the slab that produces a characteristic 'whumpf' sound. Therefore, slab avalanches may be remotely released on steep slopes after being triggered by a person traveling on horizontal terrain [e.g., Johnson and Jamieson, 2001]. These observations confirm the existence of a minimum slope angle for slab avalanche release and none for fracture propagation. These findings with persistent weak layers have significant practical implications, as they allow practitioners the ability to dig pits in safer, less steep areas without sacrificing crucial information. Bair et al. [2012] examined non-persistent weak layers collapse using PSTs. He found that critical crack lengths were mostly independent of slope angle. In this respect, persistent and non-persistent weak layers exhibit the same behavior.

On the other hand, field observations suggest that slab avalanches releasing on different weak layer types have different "preferred" slope angles that depend on the type

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of weak layer in which fracture takes place. In particular, slab avalanches running on non-persistent weak layers (NPWLs) tend to release on steeper slopes than avalanches running on PWLs. The median slope angles for avalanche involving NPWLs were in the low 40's, but for PWLs they were in the mid to upper 30's [McCammon 2009]. The weak dependence between slope angle and fracture initiation

raises the question: why do avalanches involving NPWLs tend to occur on steeper slopes? The reasons behind these observations are investigated in this paper.

2. METHOD

2.1 ECT on different slope angle
Field area:

We conducted our testing on three small slopes in the Kukahan Mountain Range, Southeast Alaska (Figure 1). The test sites were slightly below tree line and somewhat protected from the wind at the time of testing. The slopes were selected because there were large changes in slope angle change within a short distance. On our test sites, slope angles ranged from 14° to 38°, 8° to 43° and 14° to 46° (Table 1).

Snowpack structure:

The snowpack at all three sites was unstable at time of testing as evidenced by shooting cracks and small avalanches (Figure 2). We performed our tests on unstable days because non persistent weak layers stabilize very rapidly. In all three cases we returned to the same site the next day, but by that time fractures did not cross the entire ECT column anymore, i.e. ECTN test scores. The snowpack structure was reasonably similar for all three datasets. The weak layers consisted of 1 – 2 mm stellar dendrites (PPsd) under a somewhat harder wind slab consisting of broken precipitation particles (DFdc). We dug one pit for each field day following the guidelines outlined by Greene et al. [2010].

Test procedure:

To measure the effect of slope angle on the number of ECTP taps, we followed the procedure described in Birkeland et al. [2010]. We conducted a series of ECT tests immediately upslope from one another. We followed standard
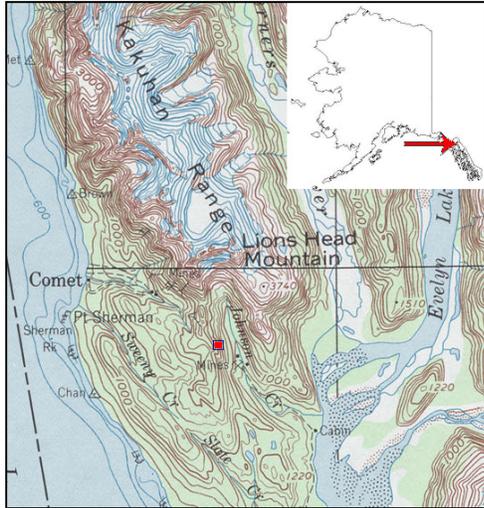

Figure 1: Overview of the geographical location of the field site in Southeastern Alaska.

Figure 2: Dataset 1 test area. Obvious signs of instability are visible in the background. When we tried to sample a day later, weak snowpack layer fractures arrested before crossing our ECT columns (ECTN).

Table 1: Snowpack characteristics at our field sites. N: number of tests, θ: slope angle at sample, h: average slope normal thickness of the slab for all the experiments, σ_h: standard deviation of h for all experiments, ρ: average density of the slab measured at the site of the snow profile, F: weak layer crystal type, E: weak layer grain size.

Dataset	N	θ [deg]	h [m]	σ_h [m]	ρ [kg/m^{-3}]	F	E [mm]
1	11	14 - 38	0.19	0.03	70	PP	3
2	14	8 – 43	0.26	0.031	95	PP	2
3	15	14 - 46	0.26	0.027	NA	PP	2

Table 2: Snowpack characteristics, related avalanche activity and friction coefficient.

Date	Slab hardness	Slab Type	Weak layer	Friction coefficient [µ]	Sliding angle [deg]	Avalanche activity
19 Dec. 2011	1F -	RGwp	DF	0.65	33	High
14 Feb. 2012	P	RGwp	PP	0.57	30	None
14 Feb. 2012	P	RGwp	PP	0.60	31	None
21 Feb. 2012	4F+	DFbk	PP	0.80	39	High
21 Feb. 2012	4F+	DFbk	PP	0.79	38	High
22 Feb. 2012	4F	RGwp	DF	0.79	38	None
22 Feb. 2012	4F	RGwp	DF	0.75	37	None

procedure for the ECT [Simenhois and Birkeland, 2009] with one exception. To minimize the influence of the free boundaries, we cut the cross-slope width of the column to be the maximum between twice the slab depths plus the width of the shovel (0.25 m) and the standard 0.90 m. Prior to each test, we measured the slab depth and sighted up the snow surface with a Suunto clinometer, measuring the slope angle to an estimated accuracy of ±1°.

2.2 Friction coefficient measurements:
Field area:

We measured weak layer friction coefficients in the same area where we measured the effect of slope angle on ECT results. In days with avalanche activity, we performed our measurements around crown walls of recent avalanches. On days after avalanche activity, when the snowpack was stable, we measured friction coefficient on typical avalanche slopes or at a flank of a day old avalanche.

Snowpack:

The weak layers for our friction measurements were either one day old decomposed fragments (DF) or newly fallen snow (PP). Three of the tests were recorded on two different days with high avalanche activity. On these days, avalanches were easily triggered with explosives, ski cutting, and in some cases avalanches were remotely triggered. The remaining four measurements were carried out the day after high avalanche activity days (Table 2).

Deriving the coefficient of friction:

In order to measure the coefficient of crack-face friction across the freshly formed fracture plane, we used the simple method proposed by van Herwijnen and Heierli [2009]. This method is

based on measuring the displacement of markers placed in the snow slab by using a particle tracking algorithm [Crocker and Grier, 1996]. We recorded videos of PSTs at 20 and 120 frames per second to measure the down-slope velocity of the slab over the bed surface after fracture. We modified the standard PST procedure [Gauthier and Jamieson 2008] in two ways: (i) by shortening the specimen length to less than 1 m, but no less than twice the slab thickness to save digging time under precarious conditions, and (ii) by using a 0.06 m thick saw to prevent contact between the cut faces before fracture sets in. Bair et al. [2012] also used a thicker saw for this same reason when testing the fracture behavior of non-persistent weak layers.

3. RESULTS AND DISCUSSION

3.1 The effect of slope angle on number of ECTP taps:

In all three datasets the number of taps required to initiate fractures along a weak snowpack layer was essentially independent of slope angle (Figure 3). The number of ECTP taps in the first dataset varied between ECTP3 and ECTP9 on slope angle between 14° and 38°, but no trend with slope angle was found. We attribute the variation in the test scores to changes in slab thickness. Indeed, the highest test scores were obtained for the thickest slabs. Identical scores of ECTP4 were obtained on the steepest and least steep locations of the slope. The second dataset had the largest number of tests (N=14) and covered the largest range of slope angles (8° to 43°). Again the test results were almost independent of slope angle, varying between ECTP11 and ECTP14. In the third dataset slope angles ranged from 14° to 46°. Again, test results fell between ECTP12 and ECTP15, without a visible trend in slope angle.

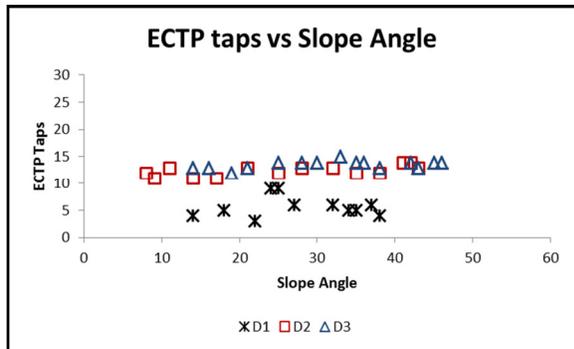Our results provide further evidence that the ECTP scores needed to initiate fractures across

Figure 3: Number of ECTP taps versus slope angle for each of our three datasets. D1, D2 and D3 are

non-persistent weak layers is independent of slope angle. The results show that persistent and non-persistent weak layers behave in the same way since both Birkeland et al. [2010] and Heierli, et al. [2011] found similar results using ECT and ECT-like tests on persistent weak layers. Furthermore, similar experimental results have also been obtained using PST and PST-like tests [Gauthier and Jamieson, 2008; McClung, 2009]. Altogether, the field work is consistent with the mixed mode anticrack model [Heierli et al., 2008].*datasets 1, 2 and 3.*

3.2 Friction results:

Our friction measurements indicate that the frictional force between crack-faces of the freshly collapsed weak layer is substantially higher in non-persistent than in persistent weak layers (Figure 4). The friction coefficients we measured on non-persistent weak layers ranged from 0.57 to 0.80 with a median of 0.75 (Table 2). In comparison, the values found by van Herwijnen and Heierli [2009] for persistent weak layers ranged between 0.52 and 0.68 with a median of 0.57 (Figure 4).Our limited data set do not show any correlation between avalanche activity and friction coefficient. In fact, the highest friction coefficient was recorded during a time of high avalanche activity at the test site, whereas the lowest friction coefficients were all associated with a stable snowpack at the test site (Table 2). These results however, are not consolidated due to the relatively small sample size. On the other hand, we did find some correlation between slab hardness and friction coefficient. Our limited dataset indicates that harder slabs tend to produce less friction across the crack faces than softer slabs (Figure 5).
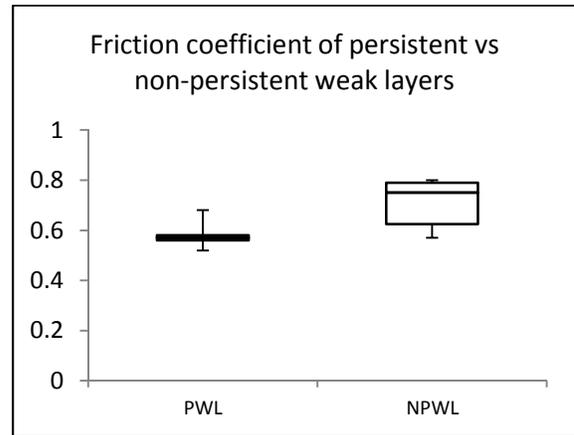

Figure 4: Box-whisker plot comparing PWL friction coefficients from [van Herwijnen and Heierli 2009] (N=34) with NPWL friction coefficients from this study (N=7). The median friction values correspond to sliding angles of 38° and 30° for non-persistent and persistent weak layers, respectively.
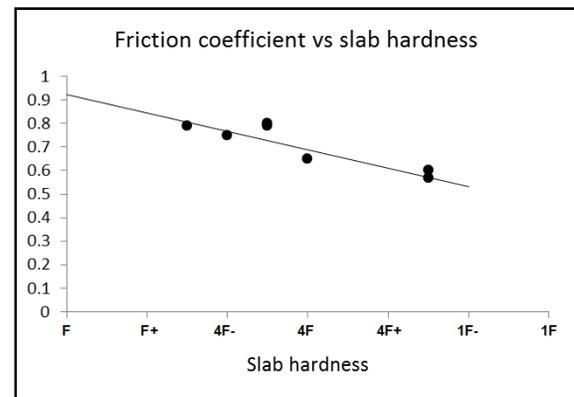

Figure 5: Friction coefficient versus slab hardness. The line represents a linear fit to the data.

4   CASE STUDY

Two of the days we measured weak layer friction were days with high avalanche activity. On both days we performed our measurements around an avalanche crown wall that was triggered minutes before measurements. The differences in the slope angle of the crown walls correlated well with our friction measurements. On 19 December 2011 we measured a weak layer friction coefficient of 0.65 (corresponding to a sliding angle of 33°) and slab hardness of 1F-. The crown wall in the area where we performed our measurements was located in a 34° steep section of the slope. On that day avalanches were running on slope angles in the low 30°s.

On 21 February 2012 we measured higher weak layer friction coefficients of 0.79 and 0.80 (corresponding to sliding angles between 38° and 39°) and a slab hardness of 4F+. The crown wall near our measurement location was on a 37° steep section of the slope. On that day, avalanches only released on slopes steeper than 38°. Furthermore, on both days, we placed a 5 lb. cast booster in the same location on a flat slope (about 20°) above the crown wall. On both days, the weak layer fractured over a distance of 150 m across a flat area and subsequently triggered avalanches on steeper slopes. While on 19 December 2011 these avalanches continued through the low angle terrain above the crown wall and into slopes that already avalanched, on 21 February 2012 these avalanches stopped shortly after reaching the measurements were in line with the steepness These results suggests that weak layer friction (and possibly slab hardness) plays a fundamental role in terms of terrain associated with avalanche release on a given day of the

release areas on these particular days. flat slope (Figure 6). Crack-face friction certainly is not the only factor that determines the release area of slab avalanches. However, our friction

5   CONCLUSIONS

Our field data show that ECTP scores on non-persistent weak layers are independent of slope angle. These results are consistent with previous measurements on persistent weak snowpack layers. Bair et al. [2012] independently arrived at the same conclusion using PSTs. The ECT data and measured friction coefficients presented in this work suggest that slab avalanches releasing on non-persistent weak layers release on steeper slopes than slab avalanches releasing on persistent weak layers due to higher crack face friction within the freshly formed fracture plane rather than the supposedly easier fracture
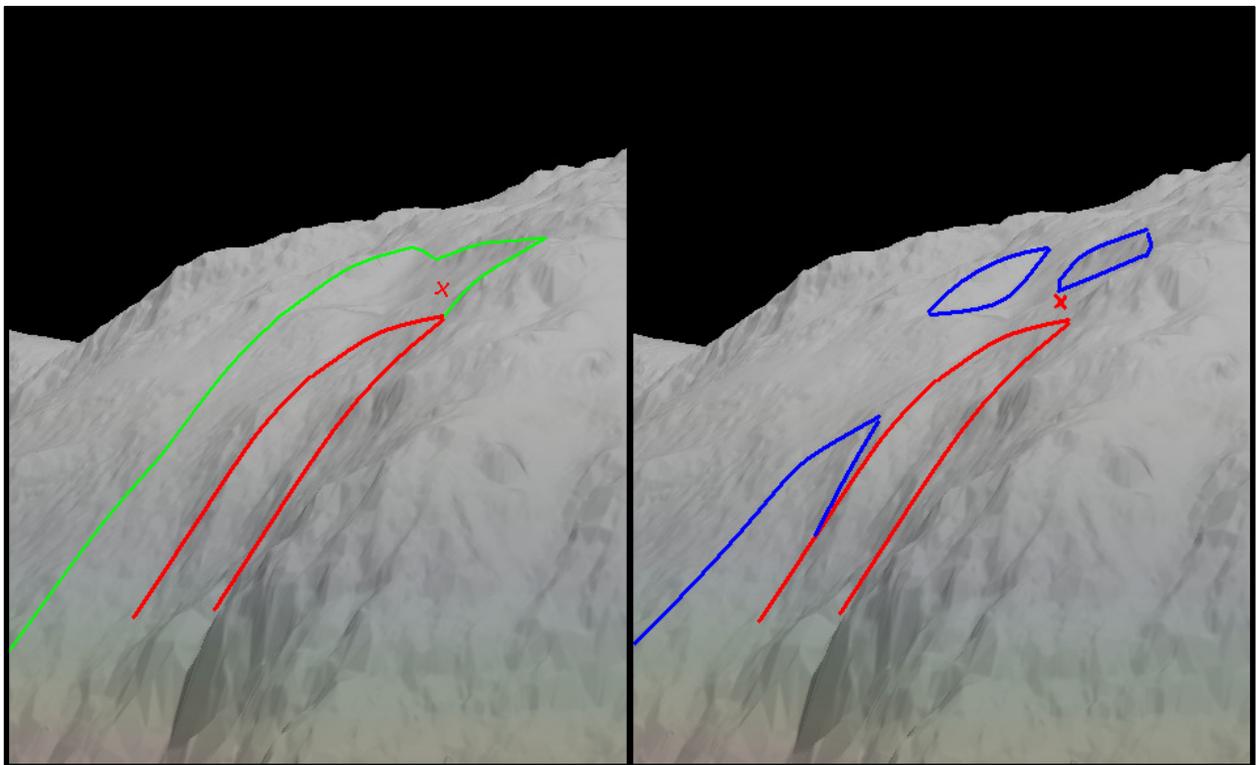

Figure 6: Avalanche distributions for 19 December 2011 (on the left) and 21 February, 2012 (on the right). The outline of the initial avalanche is marked in red. The location of the explosive charge that triggered the secondary avalanches from the flat area is marked with the red X. The outline of the secondary avalanches are marked in green for 19 December, 2011 and blue for 21 February 2012

initiation on steeper slopes. From a practical perspective, this result confirms that observers can conduct reliable tests on gentler, safer terrain before committing themselves to exposed areas, regardless of whether the weak layer of interest is persistent or non-persistent. Of course, extrapolating test results to steeper terrain requires a spatially consistent snowpack structure. From a conceptual perspective, the field data confirms the validity of the mixed mode anticrack model for slab avalanche release.

Deriving friction angles from observations on the down-slope sliding of the block in small column tests is problematic. Clearly when all other things are equal, a sliding block after weak layer fracture indicates less friction than a block that does not slide. However, we found that obtaining reliable measurements requires a sliding area longer than a small block test to allow the snow block to accelerate or decelerate. In addition, we found in our field work that changes in tapping force and the shovel angle in relation to the slope may sometimes have a larger effect on the snow block's down-slope movement than crack face friction. In any case, at this point relying on crack face friction for stability evaluation is impractical since measuring friction requires the observer to commit to increasingly steep and more dangerous slopes. Further, since our limited data showed similar friction coefficients on stable and unstable snowpacks, we do not yet know the value of such measurements for assessing stability. We further caution the reader that even though sliding angle may be obtained in the field, we have no data on the spatial variability of crack face friction or the ability of different slab strengths to pull (or push) an avalanche over flatter terrain.

6 ACKNOWLEDGMENTS:

7. REFERENCES

Bair, E. H., R. Simenhois, K. W. Birkeland and J. Dozier. 2012. A field study on failure of storm snow slab avalanches *Cold Regions Science and Technology* 79-80 (2012) 20–28.

Bazant, Z. P., G. Zi, and D. McClung, 2003. Size effect law and fracture mechanics of the triggering of dry snow slab avalanches, J. Geophys. Res., 108(B2), 2119.

Birkeland, K. W, R. Simenhois and J. Heierli. 2010**.** The Effect Of Changing Slope Angle On Extended Column Test Results: Can We Dig Pits In Safer Locations? *Proceedings of the 2010 International Snow Science Workshop*, Squaw Valley, California.

Crocker, J., and D. Grier (1996), Methods of digital video microscopy for colloidal studies, J. Colloid Interface Sci., 179, 298– 310.

Gauthier, D., and J. B. Jamieson. 2008. Evaluation of a prototype field test for fracture and failure progagation propensity in weak snowpack layers. *Cold Regions Science and Technology* 51 (2-3):87-97.

Greene, E. M., D. Atkins, K. W. Birkeland, K. Elder, C. C. Landry, B. Lazar, I. McCammon, M. Moore, D. Sharaf, C. Sterbenz, B. Tremper, and K. Williams. 2010. *Snow, Weather and Avalanches: Observation guidelines for avalanche programs in the United States*. 2nd ed. Pagosa Springs, Colorado: American Avalanche Association.

Heierli, J., Birkeland, K.W., Simenhois, R., Gumbsch, P., 2011. Anticrack model for skier triggering of slab avalanches. Cold Regions Science and Technology 65 (3), 372–381. doi:10.1016/j.coldregions.2010.10.008.

Heierli, J., P. Gumbsch, and M. Zaiser. 2008. Anticrack nucleation as triggering mechanism for snow slab avalanches. *Science* 321:240-243.

Heierli, J., and M. Zaiser, 2006. An analytical model for fracture nucleation in collapsible stratifications, Geophys. Res. Lett., 33, L06501, doi:10.1029/2005GL025311.

Heierli, J., K. W. Birkeland, R. Simenhois, and P. Gumbsch. 2010. New insights into skier-triggering of slab avalanches. *Proceedings of the 2010 International Snow Science Workshop*, Squaw Valley, California.

Johnson, B., and B. Jamieson (2001), Field data and theory for human triggered ''whumpfs'' and remote avalanches, paper presented at the 2000 International Snow Science Workshop, Am. Avalanche Assoc., Big Sky, Montana.

McCammon I., 2009. 38° Revisited: A Closer Look at Avalanche Types & Slope Angle. *The Avalanche Review, Vol. 27, NO 4, April 2009.*

McClung, D.M., 1979. Shear fracture precipitated by strain softening as a mechanism of dry slab avalanche release. J. Geophys. Res. 84, 3519–3526.

McClung, D.M. (2009). *Dry snow slab quasi-brittle fracture initiation and verification from field tests.* Journal of Geophysical Research 114 (F01022), doi:10.1029/2007JF000913.

McClung, D. M. and P. Shaerer. 2006. *The Avalanche Handbook.* Seattle, WA: The Mountaineers Books.

Schweizer, J., and J. Jamieson (2001), Snow cover properties for skier triggering of avalanches, Cold Reg. Sci. Technol., 33, 207– 221.

Simenhois, R., Birkeland, K., 2009. The extended column test: test effectiveness, spatial variability, and comparison with the propagation saw test. Cold Regions Science and Technology 59 (2–3), 210–216.
doi:10.1016/j.coldregions.2009.04.001.

van Herwijnen, A., J. Heierli, and J. Schweizer (2008), Field study on fracture propagation in weak snowpack layers, paper presented at the 2008 International Snow Science Workshop, Whistler, B. C., Canada.

van Herwijnen and Heierli 2009. Measurements of Weak Snowpack Layer Friction. *Proceedings of the 2009 International Snow Science Workshop*, Davos, Switzerland.