OBSERVATIONS OF FRACTURE ARREST AT SLAB AVALANCHE BOUNDARIES

Ron Simenhois[1] and Karl W. Birkeland[2]

[1]Coeur Alaska, Juneau, Alaska, USA
[2]USDA Forest Service National Avalanche Center, Bozeman, Montana, USA

ABSTRACT: Dry slab avalanches start when a catastrophic failure along a weak snowpack layer separates the slab from the underlying snowpack over a large section of the slope. Most research and papers focus on crack propagation, but little work has been done on fracture arrest, which is critically important for understanding slab boundary locations. This study investigates some of the factors contributing to fracture arrest at boundaries of actual avalanches. We targeted these areas by conducting a series of 2m ECTs (ECT200s) along crown walls, and working toward the flanks of 15 Storm-Slab and seven Persistent-Slab avalanches with maximum crown depth between of 45 and 80 cm. At 16 of our avalanches we recorded snowpack and terrain changes in 32 locations where fractures arrested as evidenced by our tests transitioning from ECT200Ps to ECT200Ns. In four ECT200Ns (13%), we observed a sharp increase in slab density down column from fracture arrest, in 21 ECT200Ns (65%) there was a decrease in slab thickness, density or both, and in seven ECT200Ns (22%) the weak layer disappeared within the scope of the column. The slab boundaries in the other six of our 22 avalanches were dictated by the slab and weak layer friction rather than weak layer fracture arrest. In these avalanches, slab fractures appeared beyond the release areas, but slope steepness around these fractures wasn't sufficient to overcome friction. Our work helps improve terrain management strategies and suggests terrain-related safety margins for different dry slab avalanche problems.

KEYWORDS: avalanche, avalanche boundaries, fracture, fracture arrest, slab, weak layer, friction

1. INTRODUCTION:

Two imperative, independent events lead to dry slab avalanche formation, the extended crack propagation along a weak snowpack layer and overcoming the frictional force resisting the slab's down-slope movement. On the contrary, dry slab avalanches will not extend into parts of the slope where the bonds between the slab and the weak layer remain intact (Gauthier and Jamieson 2010) or the gravitational down-slope forces fall below the slab and bed surface friction (van Herwijnen and Heierli 2009).

In theory, cracks arrest when the driving force behind crack extension falls below the material resistance for any finite length of time (Anderson, 2005). In the case of an avalanche, if the released energy from slab bending falls below the weak layer fracture resistance, the fracture will arrest. Reasons for fracture arrest can be a decrease in slab pressure (or stress intensity) on the weak layer, a decrease in collapse magnitude, or a spatial change in weak layer properties.

Simenhois and Birkeland (2008) showed that a decrease in slab thickness can lead to weak layer fracture arrest. Gauthier and Jamieson (2010) found evidence that slab fracture can also lead to weak layer crack arrest by cutting the slab load above the weak layer crack tip. On the other hand, a recent study (Birkeland et al. 2014) and field observations have also shown that spatial variability within the weak layer can arrest cracks along the weak layer.

Several studies have shown that weak layer fracturing is slope independent (Gauthier and Jamieson, 2008, Birkeland et al, 2010, Heierli et al, 2011, Bair et al 2012). On the other hand, avalanches are slope dependent events (van Herwijnen and Heierli 2009). Simenhois et al. (2012) showed that storm snow avalanches typically run on steeper terrains than persistent avalanches due to variations in weak layer friction. They also suggest hard slabs have less friction against the bed surface than soft slabs. Thus, slab-bed surface friction and the slab's tensile strength may also dictate the location of avalanche boundaries.

**Corresponding author:*

Ron Simenhois, email: ron_si@yahoo.com

To investigate the conditions that may stop crack propagation across a slope, we tracked snowpack and terrain changes around avalanche crown walls and flank intersections. In this paper we report on 22 such avalanches where we found obvious changes in snowpack or slope angle at these locations.

2. METHODS:

2.1 Field area:

We collected data from 22 avalanches on seven different slopes in the Coastal Mountain Range of southeast Alaska just north of Juneau.

2.2 Snowpack structure and avalanche characteristics:

We collected our data at the intersection of crown walls and flanks (Figure 1) on avalanches we triggered between 10 and 120 minutes earlier. Avalanche width ranged between nine and 27m with a median of 21m and standard deviation of 4.8m. Crown wall thickness ranged between 0.40 and 0.79m with median of 0.59m and standard deviation of 0.12. The slab hardness was equal or greater than 1F in at least one location of 11 out of the 22 avalanches we investigated.

The failure layer of seven of the 22 avalanches was faceted crystals (FC). The rest of the avalanches failed on precipitation particles (PP) and decomposed fragments (DF). Weak layers hardness varied between F and 4F (Table 1).

2.3 Test procedure:

We investigated the conditions associated avalanche slab boundaries using a series of 200 cm ECTs along avalanche crown walls, starting three to five meters from the flank and advancing toward the edges of the avalanche until test results changed from ECT200P to ECT200N (Figure 1). We recorded weak layer and slab stratigraphy along the ECT200N at 50 cm before and after fracture arrest. The data includes slab density, weak layer and slab thickness, and grain type and size (Greene et al. 2010). To ensure cracks were self-propagating before coming to arrest, we made sure that in those ECT200Ns where we collected our data, fracture arrest occurred at least 1 m from the tapping end.

Around avalanches where ECT200s kept propagating (ECT200P) well outside the avalanche boundary, we recorded other possible causes that may have created the observed slab boundary. Results from areas where we did not observe ECT200P along the crown walls are not included in this study.

Figure 1: Test layout shows a series of ECT200 along an avalanche crown wall. We started from the center side of the avalanche and toward the flank until ECT200 result changed from ECT200P to ECT200N.

3. RESULTS AND DISCUSSION:

Our data includes observations of snowpack and terrain from where the crown wall intersects the flank in 22 avalanches. In 11 of the locations (six

Table 1: Slab hand hardness and weak layer type of the 43 test locations. The snowpack properties in this table are from the avalanches crown, less than 2 m from the crown – flank interface.

		Weak layer type	
		Persistent (n=14)	Non - persistent (n=29)
Slab's hand hardness	F, F+ (n = 2)	0%	5%
	4F -, 4F, 4F+ (n=25)	11.50%	47%
	1F -, 1F, 1F+ (n=15)	11.50%	23%
	P (n = 1)	2%	0%

avalanches) we investigated, fractures kept propagating across our ECT200 columns and we found clear indications that weak layer fractures propagated beyond the boundaries of the avalanches (Figure 2). Out of the other 32 crown wall – flank intersections we sampled, we found a sharp change in slab properties in 25 locations and seven locations where the weak layer disappeared at approximately the same place where fractures arrested in our ECT200Ns.

3.1 Changes in terrain and slab-bed surface friction:

In 11 crown wall – flank intersections (six storm snow avalanches) our ECT200 results remained ECT200P beyond the avalanche boundaries. Four of the six avalanches (66%) were remotely triggered and cracks in the slab were visible in slope sections that did not avalanche (Figure 2). These cracks indicate that weak layer fractures advanced beyond the slab boundaries of the avalanche. We did not find an obvious change in the weak layer or slab stratigraphy in these locations. The only obvious change we noticed was a decrease in slope angle in relation to the release areas. The slope angle in these areas changed from an average of 42° two meters into the release area, to an average of 38° at the crown wall – flank interface and 36° at the furthest slab crack into the unreleased area. The sharp change in slope angle and the relatively steep minimum slope angle of the crown walls that day lead us to believe that slab – bed surface friction dictated the location of these avalanches' boundaries.

3.2 Changes in slab properties:

The other 32 locations (16 avalanches) we investigated where the avalanche crown intersected the flank, the slab boundaries were associated with fracture arrest. In four out of the 32 locations (12%), the fracture arrest was in proximity of a sharp increase in slab hardness and density. We use an equation from Scapozza (2004) to calculate the changes in the slab's elastic modulus *E* from the measured density:

$$E = 0.2 \cdot \exp\left[\frac{\rho}{67}\right] \qquad (1)$$

The calculated increase in the slab's elastic modulus between sections where the weak layer fractured and beyond the avalanche boundaries in these locations averaged over 300% (3.3 times). We are not entirely clear why an increase in slab density might cause weak layer fracture arrest. Reasons may be that the sharp increase in the slab's elastic modulus resulted in decrease in slab bending and therefore less fracturing energy input from the slab to the weak layer or the wave length under the lighter snow becomes insufficient as it reaches the denser / stiffer slab.

Figure 2: An example of weak layer fractures advancing beyond the avalanche boundaries. In this avalanche, the slab boundary location was dictated by slope angle, slab-weak layer friction and the slab's tensional strength rather than weak layer fracture arrest.

In 21 of our 32 sampling locations (66%) we found a decrease in slab density, thickness or both. The average decrease in slab thickness around these crown – flank locations was from 40.5 cm at the tapping end to 35.4 cm where the fracture arrested in our ECT200Ns (Figure 3). The slab load decreased an average of 191 Pa from 50 cm before the fracture arrested to the arrest point (Figure 4). In 17 of the 21 ECT200Ns in this group, the fracture arrest was associated with slab fracture. However we cannot know if the slab fracture caused the weak layer fracture arrest or the other way

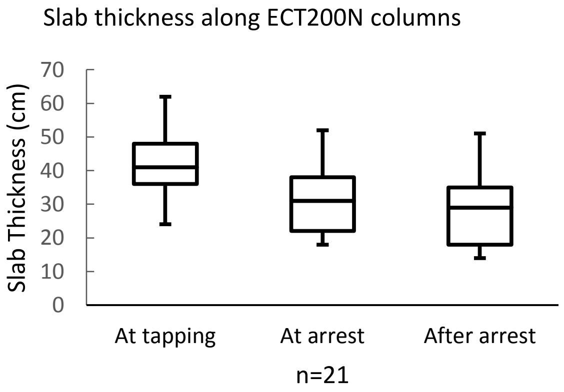

Figure 3: Box plot of slab thickness along ECT200N at the tapping end, where the weak layer fracture arrested and 30 - 50 cm down fracture from where the weak layer fracture arrested. The line represents the median, the box is the interquartile range, and the whiskers show the range of our data.

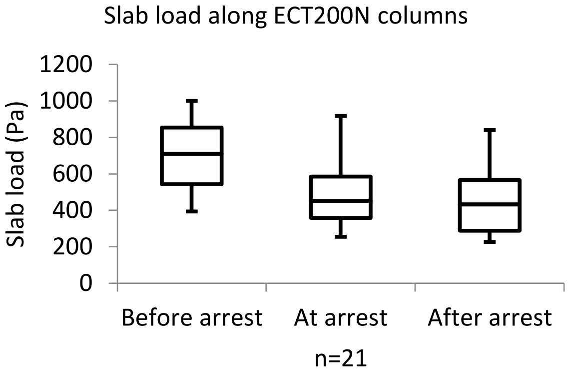

Figure 4: Box plot of slab load (thickness x density) along ECT200N at the tapping end, where the weak layer fracture arrested and 30 - 50 cm down fracture from where the weak layer fracture arrested. The lines, boxes and whiskers represent the same values in our data as in Figure 3.

In seven of our 32 locations (22%), the weak layer disappeared within the 200 cm column. In three of these locations, the weak layer changed from 4F hard faceted crystals (FC) to 4F+ and 1F hard decomposing fragments (DF). In the other four locations, the weak layer changes from F and 4F- hard precipitation particles (PP) to 4F+ to 1F hard decomposed fragments. These results are in line with Birkeland et al. (2014) and with Heierli (2005) that suggested that fractures will arrest when weak layers are not “appropriately collapsible”.

3.4 Slab density, hardness and slope angle at crown wall:

In addition to changes in slope angle at the crown wall – flank interfaces, we also compared the slope angle at crown walls to slab density (Figure 5) and hand hardness (Figure 6). Although our data is rather scattered (R^2=0.44 for density and 0.55 for hand hardness), it shows an overall trend of decreasing crown walls’ slope angle with increasing slab density (p-value < 0.01) and hardness. In our dataset, there is an average crown wall slope angle decrease of 5.4° for an increase of 100kg/m^3 in slab density (or three degrees per one hand

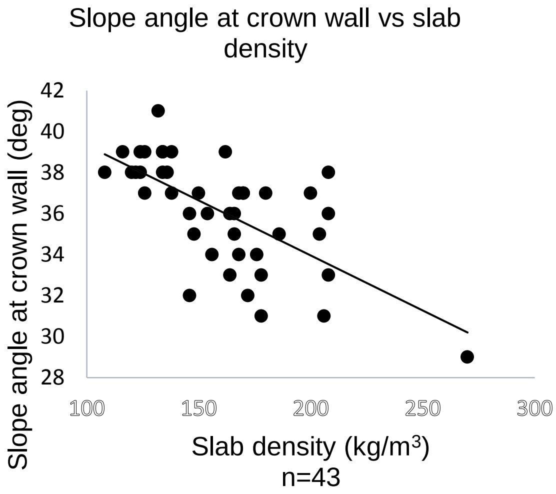

Figure 5: Slope angle at avalanches crown walls vs slab density. The decrease in slope angle with increasing slab density suggests that denser slab avalanches are more likely to propagate into flatter terrain than soft slab avalanches

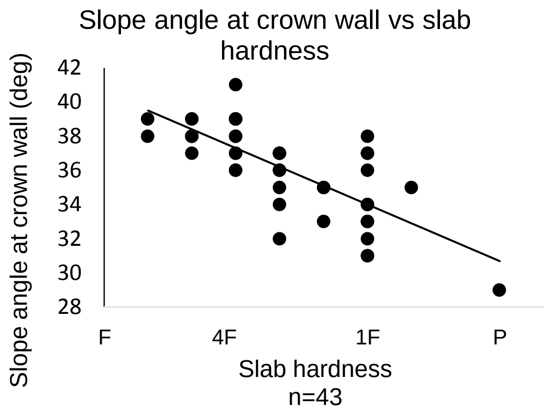

Figure 6: Hand hardness vs slope angle at avalanches crown walls. The negative correlation suggest that hard slab avalanches are more likely to propagate into flatter terrain than soft slab avalanches

hardness unit). This suggests that a hard slab avalanches are more likely to propagate farther upslope and into flatter areas in comparison to softer slab avalanches.

4. CONCLUSION AND PRACTICAL IMPLICATIONS:

We investigated changes in snowpack and terrain at 43 locations where crowns intersected the flanks of 22 dry slab avalanches. Our measurements suggest six potential mechanisms for arresting dry slab fractures (Figure 7). Five of the six mechanisms (decrease in slab load, slab fracture, increase in the slab's elastic modulus, and decrease in collapse amplitude and increase in weak layer fracturing resistance) involve changes in snowpack properties. The sixth mechanism involves a decrease of slope angle below that needed to overcome bed surface friction.

In addition, we also encountered avalanches where ECT200 never propagated along the crown, or where we didn't observe changes in the snowpack or slope angle around the avalanche boundaries. Therefore, there may be other mechanisms we did not identify.
Our data suggest that in some avalanches, slope angle rather than weak layer fracture

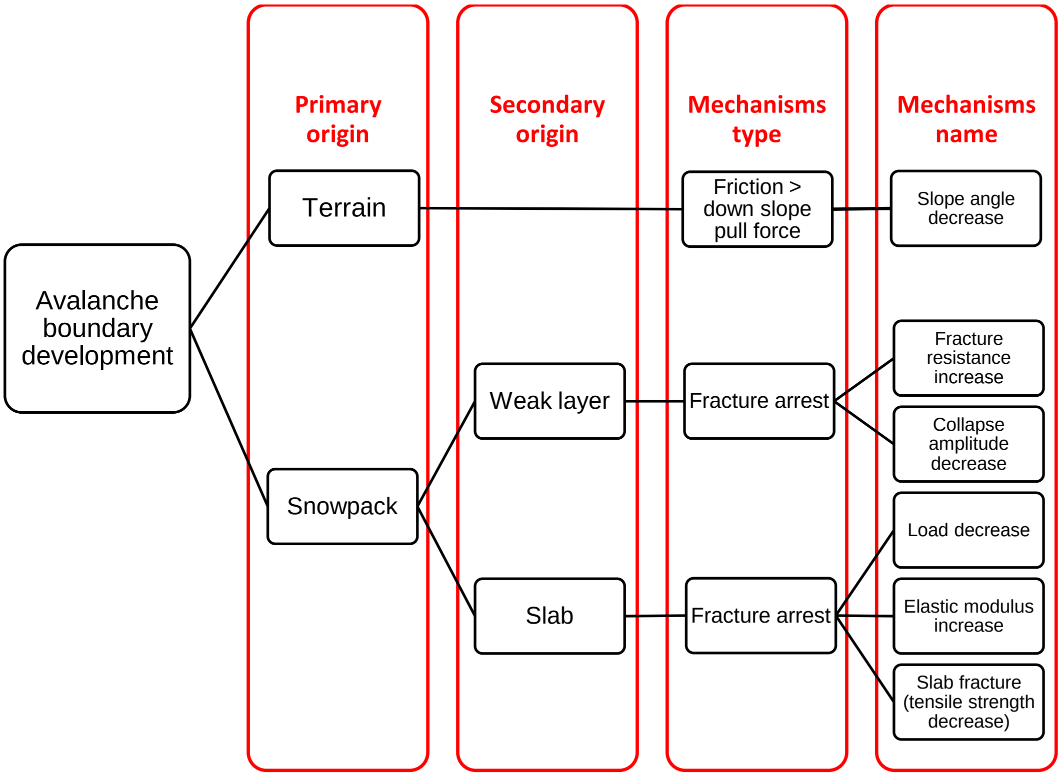

Figure 7: The six observed mechanisms and their origins for the 43 avalanche boundaries we investigated.

arrest determines slab boundaries. These slope dependent effects typically occur under storm snow and soft slab conditions. On the other hand, our data shows that hard slab conditions can help an avalanche to advance into flatter terrain than might be expected with softer slabs. Thus, backcountry travelers in soft slab conditions should be wary about being lured into steeper slopes without ski cutting the slope above. On the other hand, in hard slab conditions, back country travelers and avalanche professionals should be cautious of trusting flat slope sections that are in close proximity to steeper slopes.

5. ACKNOWLEDGMENTS:

Discussions with Alec van Herwijnen and Ned Bair contributed to this paper. Alan Gordon and Brian Baily helped with some of the field work. Jenny Sheleg supported the writing process.

6. REFERENCES:

Anderson, T. L.: Fracture Mechanics: Fundamentals and Applications, Taylor and Francis, Boca Raton, FL, 610 pp., 2005.

Bair, E.H., R. Simenhois, A. van Herwijnen, K.W. Birkeland, and J. Dozier. 2012. Storm snow avalanches: Characteristics and forecasting. *Proceedings of the 2012 International Snow Science Workshop*, Anchorage, Alaska.

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.

Birkeland K. W., A. vanHerwijnen E. Knoff, M. Staples, E. Bair, R. Simenhois. The role of slabs and weak layers in fracture arrest. *Proceedings of the 2014 International Snow Science Workshop*, Bunff, Canada.

Gauthier, D, Jamieson, B, 2010. On the sustainability and arrest of weak layer fracture in whumpfs and avalanches, *Proceedings of the International Snow Science Workshop 2010, Squaw Valley, USA, pp. 224-231.*

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., Atkins, D., Birkeland, K. W., Elder, K., Landry, C., Lazar, B., McCammon, I., Moore, M., Sharaf, D., Sterbenz, C., Tremper, B., and Williams, K.: Snow, Weather, and Avalanches: Observational Guidelines for Avalanche Programs in the United States, 136, 39–56, 2010.

Heierli, J., 2005. Solitary fracture waves in metastable snow stratifications. Journal of Geophysical Research, 110: doi: 10.1029/2004JF000178.

Heierli, J., K.W. Birkeland, R. Simenhois, and P. Gumbsch. 2011. Anticrack model for skier triggering of slab avalanches. *Cold Regions Science and Technology* 65(3), 372-381.

Scapozza, C.: Entwicklung eines dichte- und temperaturabhängigen Stoffgesetzes zur Beschreibung des visko-elastischen Verhaltens von Schnee, 10.3929/ethz-a-00468, 2004.

Simenhois, R. and K.W. Birkeland. 2008. The effect of changing slab thickness on fracture propagation. *Proceedings of the 2008 International Snow Science Workshop*, *Whistler, British Columbia, Canada.*

Simenhois, R., K.W. Birkeland, and A. van Herwijnen. 2012. Measurements of ECT scores and crack-face friction in non-persistent weak layers: What are the implications for practitioners? *Proceedings of the 2012 International Snow Science Workshop*, Anchorage, Alaska.

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