ANATOMY OF A POST CONTROL RELEASE: THE LIBERTY BOWL EVENT AT BIG SKY RESORT

Scott Savage*
Friends of the Gallatin National Forest Avalanche Center, Bozeman, MT
Formerly Snow Safety Director, Big Sky Resort, Big Sky, MT

ABSTRACT: An impressive early season avalanche cycle occurred during the 2007/2008 winter season at Big Sky Resort in southwestern Montana, culminating in a significant in-bounds post control release on 26-December in Liberty Bowl. This remotely ski triggered avalanche involved a heavily compacted snowpack on a 32-34 degree slope with soft moguls on the snow surface. The deposition covered approximately 1.6 hectares (four acres) with one to over four meters of debris, but fortunately no one was caught or injured. This paper discusses the weather and snowpack conditions that produced the persistent instability and associated avalanche cycle, the avalanche hazard forecasting and mitigation efforts and techniques used in Liberty Bowl and surrounding paths, and observations and accounts of the post-control release. Additionally, I discuss what I feel the forecasting team and ski patrol did "right" and what I would consider doing differently in the future; this discussion includes sizing explosive charges, charge placement, stability and propagation test interpretation, evaluating the effects of ski compaction on stability, and other topics. This paper does not aim to answer complex snow and avalanche questions. Rather, it poses questions to stimulate discussion and possible future research within the avalanche community

KEYWORDS: post control release, deep slab instability, explosives, avalanche forecasting

1. INTRODUCTION

Lone Mountain, the dominant peak at Big Sky Resort, is located in the Madison Range of the Rocky Mountains about 80 km (50 miles) north of West Yellowstone, MT and 80 km (50 miles) southwest of Bozeman, MT. In 1995, Big Sky installed the Lone Peak Tram to take skiers to the top of Lone Mountain. The tram accesses over 130 hectares (320 acres) of avalanche terrain in an area known as the South Face. Stutzman's Bowl (named in honor of David Stutzman, a Big Sky ski patroller killed in an avalanche near Lone Mountain in 1982) was part of this expansion (Figure 1). The ski area changed the name of the ski run to Liberty Bowl in 1995, but the avalanche path is still referred to as Stutzman's Bowl.

Stutzman's is a south facing, alpine path over 150m (500') wide with a maximum vertical runout of approximately 500m (1650'). Big Sky snow safety personnel had observed no avalanche activity in Stutzman's between the ski area's opening in 1974 and 1995 (Ueland, pers com). However, flag trees in the runout zone are obvious indicators of significant avalanche activity prior to 1974.

Stutzman's Bowl is the easiest ski route off of the 3400m (11,166') summit and sees a lot of ski traffic. Being a concave bowl reaching only 32-4 degrees in the primary starting zone, the path is excellent advanced intermediate to expert ski

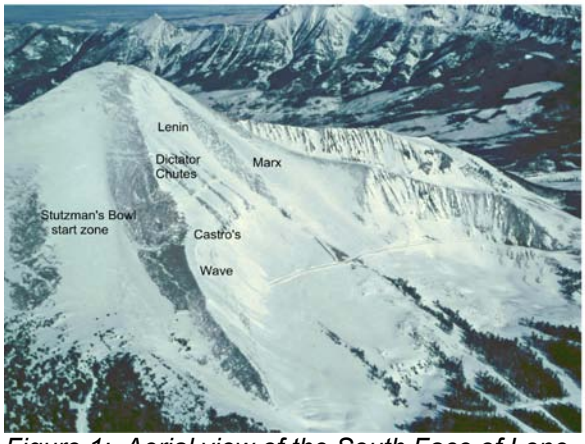

Figure 1: Aerial view of the South Face of Lone Mountain. Photo by K. Birkeland.

* *Corresponding author address:* Scott Savage, 301 N Valley Dr, Bozeman, MT 59718; tel: 406.580.8142; email: pasoirrigation@msn.com

terrain, depending on weather and snow conditions. The Stutzman's Bowl region receives approximately 11m (430") of snow annually and is frequently cross loaded by prevailing winds (Savage, 2006). While frequent avalanche activity can keep most starting zones and tracks of the steeper South Face avalanche paths/ski runs thin during the early season, Stutzman's Bowl's more gentle slope angle leads to fairly dependable early season snow coverage. Stutzman's Bowl is usually the initial South Face ski terrain to open for the season and often times is the only December skiing available off of the summit of Lone Mountain.

2. 2007/2008 SEASON

2.1 Early Season Weather

The 2007/2008 winter began with several October storms bookended by extended periods of high pressure. The last hot, sunny spell lasted nearly three weeks and ended on 9-November after forming a stout ice crust. This ice layer covered much of Stutzman's Bowl and created an excellent bed surface approximately 30-60 cm above the ground. This early season ice crust scenario has been responsible for several deep slab avalanche cycles on the South Face since 1995 (Savage, 2006). Mid-November saw intermittent snow showers, depositing low density snow with light winds and cool clear spells between snow events – excellent near surface faceting conditions (Birkeland, 1998). November 20-25 brought light snowfall with 30-80 km/hr (20-50 mph) winds, burying the small facets on top of the ice crust underneath a thin but stiff wind slab. November ended with three days of much colder temperatures (-17 to -13C, zero to eight degrees F), likely further faceting the layer sitting above the ice crust.

2.2 December 3-4 Storm

December 1-2 saw continued cold temperatures with light snowfall followed by a warm coastal system on 3-December. The upside down storm deposited 25cm (10") of snow and 26mm (1.02") of snow water equivalent (SWE) by the time the rain ended on 4-December. Temperatures rose from -10 to +1C (14-34 degrees F) during the storm, and prevailing W/SW winds blew from 50-80 km/hr (30-50 mph).

This load produced a widespread avalanche cycle below tree line, keeping the ski patrol busy with a .3-1.2m (one to four feet) deep instability. One notable slide (Madwolf slide path) was remotely triggered from over 30m (100') away and ran much wider than it had in the ski area's 33 year operational memory. Above tree line, two larger natural events occurred on the steeper South Face near Stutzman's Bowl (Wave and Hanging Valley paths, 1.2-2m [four to six feet] crowns, over 60m [200'] wide).

Big Sky personnel were not yet regularly visiting the South Face terrain due to lingering mechanical issues with the Lone Peak Tram. Without uphill transportation, South Face access and rescue required a time consuming 200 vertical meter (700') hike on scree. On 5-Dec, Big Sky personnel hiked to the Marx path on the South face and deployed a 1 kg shot that released a significant avalanche (HS-AE-R3-D3).

2.3 December 7th Meeting

After spending 6-December finishing lower mountain routes and opening new terrain, a small group met on 7-December to develop a hazard mitigation plan for the South Face. Big Sky forecasters have preferred to let early season instabilities passively stabilize when the terrain in question is not ready to open to the public (e.g. shallow snow cover, lift issues). Aggressively releasing avalanches during the early season in Big Sky's alpine terrain often times lead to shallower and more faceted snowpacks and resulted in persistent instabilities lingering later into the year (Ueland, pers com). However, some seasons brought instabilities that failed to stabilize in a reasonable period, causing the ski patrol to "hit the reset button" and aggressively attempt to clean out all paths containing the given instability. On 7-December, the small group compared early season photos showing prominent crusts to photos of the South Face avalanches from the previous three days. The photos provided evidence that the crust/facet instability was widespread enough on the South Face paths to warrant "hitting the reset button."

2.4 South Face Avalanche Observations

The Tram was not operational, so five ski patrollers hiked to the summit on 7-December with several explosive charges. The second 1kg charge thrown into the Lenin avalanche path produced a large slide (HS-AE-R3.5/D3.5) that ran on the November crust/facets, involved several

2007 December

Date	Snow(cm)	H20(mm)	South Face Large Avalanches	Stutzman's explosives
1	2.5	2.5		
2	2.5	1.3		
3	20	18.0	Wave/Rodeo, Hanging Valley	
4	5	7.5	Madwolf remote triggered slide	
5	0	0	Marx	
6	5	3.0		
7	0	0	Lenin, Dictators, Castro's, Wave	
8	Trace	0.1		
9	0	0		Two 1kg, two 2kg
10	10	6.0		
11	0	0		1kg, 2kg
12	Trace	0.1		
13	5	3.0		
14	2.5	1.5		
15	2.5	1.0	***Stutzman's Bowl opens***	
16	Trace	0.1		
17	0	0		
18	Trace	0.1		
19	Trace	0.1		
20	5	3.0		
21	12.5	7.5		
22	Trace	0.1		
23	2.5	1.0		
24	25	15.0		1kg, 2kg
25	7.5	3.0		2kg
26	1	0.7	Stutzman's Bowl	

Figure 2: 2007 December snowfall, avalanche activity, and Stutzman's Bowl mitigation missions.

paths, and was over 300m wide. A 2kg charge released another large slide in the last remaining major path (Castro's Face) on the South Face (excluding Stutzman's Bowl).

2.5 Stutzman's Bowl Pre-event

At this point, Stutzman's Bowl became a much bigger concern. Performing mitigation routes in this remote area without the Tram to support a potential rescue decreases safety margins, so the ski patrol did not access Stutzman's until the Tram was available on 9-December. Two 1kg shots and two 2kg surface shots were detonated in the Stutzman's Bowl starting zone with no results. After 10cm (four inches) of low density snow with very light winds on 10-December, 1kg and 2kg surface shots were deployed on 11-December with no results. Signs of a stabilizing trend within the ski area and surrounding backcountry included no avalanche activity, decreased cracking and collapsing, and no explosives results. Snowpit and stability test data in Stutzman's Bowl indicated neither a very stable nor a very unstable slope; the data depicted a conditionally stable situation. At this point, Big Sky personnel felt comfortable moving around on the path but assumed the snowpack would become unstable if loaded significantly in the near future.

Following 10cm (four inches) of low density snow with light winds over a four day period, the ski patrol opened Stutzman's Bowl to the public on 15-December. December 16-19 saw a trace of new snow. Intermittent showers from December 20-3 deposited 20cm (eight inches) of very low density snow with moderate winds; 1kg and 2kg surface shots were deployed on 24-December with no results. 25cm (10") of low density snow (15mm/.60" SWE) fell during the day on 24-December while Stutzman's Bowl was open, and 7cm (three inches) of very low density snow (3.0mm/.12" SWE) fell that night. On 25-December, the author deployed a 2 kg explosive

just above the snow surface, telling his route partner “this isn’t going to do anything with this fluff out here, but what the hell, we’re here” before igniting the shot. That shot did not produce any results either.

3 STUTZMAN’S BOWL AVALANCHE

3.1 Hazard Evaluation and Mitigation 26-December 2007

The upper mountain received a trace of new snow and winds transported some snow over Lone Mountain’s highest ridge tops on the night of 25-December. On the morning of 26-December, we released hard, new snow slabs with explosives in some upper South Face starting zones (Upper Lenin region, Dictator Chutes). Based on this activity, I asked an avalanche technician who would soon be done with his route to rearm and become our third team member, heading to Stutzman’s to assess conditions and “drop off a double or triple” (a 2kg or 3kg shot). With a ridgeline in my line of sight, I could not see the Stutzman’s Bowl starting zone. However, my route partner and I would soon be low enough to see our third team member when he reached the starting zone. As we worked our way down a ridge and neared the elevation of the Stutzman’s starting zone, the wind decreased dramatically and visibility cleared. The slabs became softer as we dropped in elevation and disappeared altogether when we reached the starting zones on the paths adjacent to Stutzman’s Bowl (the Castro’s Shoulder and Wave area on the Lenin High route).

At this point, our extra team member reported “nothing going on here in Liberty” as he skied through soft bumps and cut-up powder with six 1kg shots and two sticks of bamboo in his pack. I looked over to Stutzman’s Bowl to watch him ski down to a safe place and vividly remember staring at the black powder mark on the surface from the shot I deployed the previous day. At the time, I felt a little bit silly for asking him to “arm up” to ski through a ski run that looked exactly as it did during the previous afternoon’s closing sweep, thinking “oh well” to myself. He deployed a 2kg air blast in a closed area below and adjacent to Stutzman’s Bowl (Runout Ridge Face), triggering a small pocket immediately around the charge. We completed our route and opened the South Face, including Stutzman’s Bowl, with no reservations.

3.2 Stutzman’s Bowl Weather and Avalanche

26-December was partly cloudy with 15-30 km/hour (10-20 mph) ridge top winds and cool -15 to -13 C (four to eight degrees F) temperatures. Recent loading was minimal. The Stutzman’s Bowl starting zone was dusted with a trace-1cm of new snow in the previous 24 hours. The avalanche technician who assessed the path that morning reported “a little bit of thick snow between the bumps and not a breath of wind.” Several patrollers skied Stutzman’s Bowl on 26-December and noted the prominent black explosives residue and soft moguls/cut up powder in the starting zone but reported nothing remarkable. At approximately 13:30hrs, a lift mechanic on a road next to the runout zone of Stutzman’s Bowl radioed “there’s a big slide in Liberty Bowl happening right now.” She did not see anyone in the avalanche, but she was unable to see the crown due to deteriorating visibility.

3.3 Response

Nine skiers were on the slope at the time of the avalanche, including a Big Sky volunteer ski patroller. All nine were above the crown and reported not seeing anyone in the avalanche, but they were unable to see the entire debris field. Based on ten corroborating witness reports, ski patrol management felt that it was unlikely that anyone was buried. However, burials were a possibility and a full rescue response ensued. After multiple beacon and Recco searches, four dog teams working the debris once or twice, and two organized probe line passes over all of the debris deeper than 1m, we called the search at dusk.

Figure 3: Stutzman’s Bowl debris field.

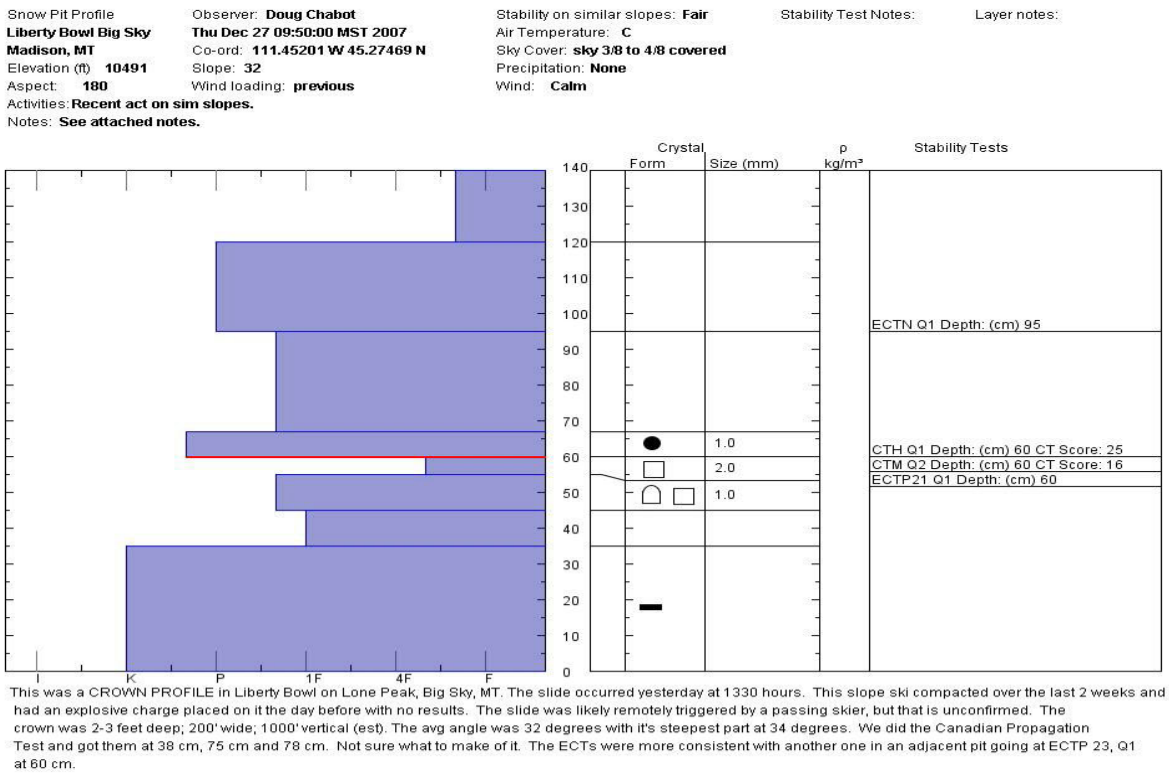

Figure 4: Stutzman's Bowl crown profile, courtesy of Doug Chabot

3.4 Avalanche Observations

The avalanche was initially classified as HS-U-R4/D3. It was 75m (250') wide, ran 330 vertical m (1100'), and produced 1.6 hectares (four acres) of one to four meter deep (3-13') debris. The avalanche failed on a layer of 1-2mm facets, forming a .6-1m deep crown. The failure layer contained all five of McCammon and Schweizer's (2002) structural "lemons". Much of the slab that failed was significantly deeper than the crown. The slope angle at the crown averaged 32 degrees with a maximum of 34 degrees. Explosive residue was evident through out the debris and on the bed surface. Multiple explosives craters were observed in the bed surface approximately 15m (50') below the crown face. The snow surface near the crown and track was soft moguls. The crown face was the most jagged and uneven one that the author has ever observed, presumably due to the significant ski compaction in the slab. This was the third recorded avalanche in the Stutzman's Bowl path and was similar in size and scope to the previous events in the 1997/1998 and 2003/2004 winter seasons.

4 INVESTIGATION

So what happened out there? Witness accounts were helpful in determining skier positions at the time of fracture, but poor visibility prevented detailed, accurate descriptions of exact locations and the event. Three skiers were right and just below or near the crown, three skiers were above the crown near the right flank, two skiers were just above the center of the crown, and one skier was just above the crown left of the other skiers. One skier reported triggering a slough that triggered the slab; this was deemed an unlikely explanation on a 30-34 degree slope with soft moguls.

The slope received some sun during the hour prior to the event, but the relatively low angle of incidence on 26-December in Montana and cold air temperatures (-14C) probably minimized the effect of the solar input and kept the snow surface cold. No rescuers noted heavy or wet snow while accessing or leaving the avalanche site. While there was minor seismic activity in Western Montana a couple days prior to the event, there was no significant seismic activity nearby within the previous 48 hours (Lageson, pers com). The avalanche may have been a true natural event, but this is unlikely with nine potential ski triggers

near the crown. The most likely explanation is that one or some of the skiers triggered the slope. The event has since been tentatively reclassified as a remotely triggered ski release (ASr).

5 DISCUSSION

5.1 Compaction

Stutzman's/Liberty Bowl was open for 11 days before the event. Being the most popular run from the summit and the only one open for several of those 11 days, a conservative estimate is at least 2000 skiers and snowboarders descended Stutzman's Bowl before it slid. This estimate includes at least 150 people on the day of the avalanche and at least 350 since the last measurable snowfall. This volume of ski traffic affected the snowpack; however, a hard slab buried the faceted weak layer weeks before skiers were in the area. While the slab was heavily compacted, the weak layer was likely never or rarely touched by skis or snowboards. The author's experience is that, in situations where an overlying slab is significantly ski compacted but a persistent weak layer is not directly affected, avalanches are less likely to be triggered but are still possible. Chabot and others (Chabot et al, in press) describe a frequently and often times heavily skied slope failing in 2010 February in a sidecountry area adjacent to the Bridger Bowl ski area. Heavily compacted slabs may inhibit fracture initiation by preventing skiers from directly affecting the weak layer in the majority of a starting zone; however, ski area forecasters must assume that the public will find a spot on a slope where fracture initiation is possible if such a spot exists. A plausible explanation for the Stutzman's Bowl avalanche is that one, or some, of the nine skiers on the slope found a thinner spot where they were able to affect the weak layer and initiate a fracture that then propagated across the slope.

5.2 Stability and Propagation Tests

Taken individually, many widely used stability tests do not correlate very strongly with deep slab stability evaluations. As slab depth exceeds 1m, Compression Test (McClung and Schaerer, 1993) and Stuffblock Test (Johnson and Birkeland, 1994) scores' correlation with stability decreases; in order to initiate failure, thicker hard slabs can require impacting the column beyond the upper limits of the tests. Shear quality (Birkeland and Johnson, 1999) and fracture character (van Herwijnen and Jamieson, 2004) can be useful when evaluating deep slab stability. Even when unable to cause the column to fail while performing the standard number of taps or bag drops, sufficient force should be applied to observe fracture character/shear quality. The Extended Column Test (Simenhois and Birkeland, 2006 and 2009) and Propagation Saw Test (Gauthier, 2008) show great promise for evaluating deep slab instabilities, but more data and research is needed. When performing the ECT on thicker hard slabs, it may be necessary to apply more than 30 taps to obtain a valid result. In 2007 December, both propagation tests did a fairly good job predicting deep slab stability or instability in both pits and crown profiles on Big Sky Resort paths.

5.3 Explosives

Why didn't any of the numerous explosives applied to Stutzman's Bowl trigger the slope? Unfortunately, the avalanche community as a whole is not able to definitively answer this question. Explosives and their interaction with the snowpack are poorly understood topics, and a plethora of explanations are possible.

Explosives craters in the bed surface indicated that at least some shots directly affected the weak layer. The shots that created these craters may have been detonated during a period when the snowpack had already adjusted to any recent loading and was generally stable (e.g. possibly in mid-December). Maybe when the initial explosives affected the snowpack on 9-December, the slope was stable; then future shots were placed in the same locations when the path was potentially unstable but detonated in areas already affected/hardened/collapsed by explosives. It is possible that areas affected by explosives are rendered incapable of initiating or propagating fractures in the near term.

Another possible explanation is that, when the slope was unstable, the explosive was placed where the snowpack was much deeper and an insufficient amount of energy reached the weak layer. In this hypothetical situation, the explosive may fail to initiate a fracture or the affected area may be too small for the fracture process to continue.

Maybe slab thickness differences inhibited fracture propagation; Simenhois and Birkeland (2008) showed in ECT tests that fractures preferentially propagate from thin areas to thick areas and not

from deep to shallow areas, and some case studies have supported this concept. On the morning of the Stutzman's event, what would the 2kg shot on a stick of bamboo have done, especially if it was located over a thin area near the slab boundaries? Would air blasts, which affect the snowpack more forcefully than same-sized shots detonating on or within the snow (Gubler, 1977; Ueland, 1994), have triggered the avalanche on other dates if used in lieu of surface shots?

Some Big Sky patrollers discussed deploying a larger shot (e.g. 10-20 kg of ANFO) during the first mitigation mission on 9-December; would this have triggered the path or was the slope very stable at that point? The last measurable loading event preceding the avalanche occurred on 24-December; would a larger shot have triggered the slope on 25-December when a 2 kg surface shot did not?

Did the 2 kg explosive detonated on 25-December fracture some of the slab boundaries and leave the slope more susceptible to avalanching? The timing of the avalanche (28 hours after explosives work) makes this explanation unlikely; field researchers observed fractured weak layers sinter and regain or exceed their original strength within hours rather than days (Birkeland et al, 2006). However, they stressed that their limited data is insufficient to confidently predict strengthening rates or timetables. While explosives are currently a ski area forecaster's best friend when evaluating and mitigating persistent dry deep slab instabilities, we must accept them for what they are: an excellent but poorly understood and, most importantly, imperfect stability test.

6 CONCLUSIONS AND IMPLICATIONS

What did we, as a forecasting operation and ski patrol, do right?

- We opened the slope during a good weather window with a minimal 7-14 day new load following extensive observation, stratigraphy analysis, stability and propagation testing, and explosive testing.
- We paid close attention to cumulative loading.
- We had workers with years of experience who had triggered or investigated previous slides there leading most of the explosives testing missions before and after Stutzman's Bowl was opened.
- We noted and respected multi-path and "wider than previously seen" activity, sympathetic releases, and remote triggering, performing more evaluation and explosives mitigation missions in Stutzman's than in any previous year.
- We weren't afraid to tell management "we need to do a bunch of blasting and keep Liberty closed today", but we never got the large rapid load or bad gut feeling that would have prompted this action.
- After 11 days and thousands of tracks, we remained suspect and did not become complacent.

Ultimately, we were very fortunate.

What would I do differently, both in this case and going forward? I would probably try additional explosive sizes, placements, and positions in relation to the snow surface; I would use at least one large shot, I would ensure we got several shots near the thinner areas on the slab boundaries, and I would use air blasts in addition to surface shots. I would continue to use several 1-2kg shots as well; testing several different spots in large starting zones should increase the likelihood of stressing a deficit zone or weaker area that is capable of propagating a fracture, and I cannot discount the success we've had triggering deep slab avalanches with smaller shots detonated on the surface of hard slabs.

In my opinion, a holistic approach is best suited to dealing with persistent deep slab instabilities. This approach considers snow stratigraphy, the spatial extent and variability of different layers, stability and propagation test results, settling and cracking, natural occurrences and mitigation results in nearby paths, and the instincts and intuition of experienced professionals when evaluating these dangerous conditions. Also, it is important to note that the operational memory of North American forecasting operations is not extensive enough to conclude that "since we have never seen that happen here it's not going to happen"; the probability of experiencing a 100 year return period event in any 100 year period is only 63.4%. Pay attention to the clues that present themselves and are discovered, and heed the wise words of a longtime Big Sky deep slab hunter…"I'll never control avalanches, but avalanches will always control me."

7 ACKNOWLEDGEMENTS

Ron Simenhois and Mark Staples reviewed this paper and provided useful comments and discussions. Numerous individuals discussed this incident and shared valuable experiences and insights with me including Jon Ueland, Mike Buotte, Karl Birkeland, and Liam Fitzgerald.

8 REFERENCES

Birkeland, K.W., 1998: Terminology and predominant processes associated with the formation of weak layers of near-surface faceted crystals in the mountain snowpack. Arctic and Alpine Research, 30, 199-204.

Birkeland, K. W., K. Kronholm, S. Logan, and J. Schweizer, 2006: Field measurements of sintering after fracture of snowpack weak layers, Geophys. Res. Lett., 33, doi:10.1029/2005GL025104.

Canadian Avalanche Association, 2002: Observation guidelines and recording standards for weather, snowpack and avalanches. Canadian Avalanche Association, Revelstoke, BC, Canada.

Chabot, D., M. Staples, K.W. Birkeland, and E. Knoff, 2010: 2010 Saddle Peak Avalanche: Sidecountry challenges, misconceptions, and lessons learned. *Proceedings of the 2010 International Snow Science Workshop,* Squaw Valley, California.

Gauthier, D., 2007: A Practical Field Test for Fracture Propagation and Arrest in Weak Snowpack Layers in Relation to Slab Avalanche Release. PhD Thesis, 302pp. Department of Civil Engineering, University of Calgary, Alberta.

Greene, E.M., K.W. Birkeland, K. Elder, G. Johnson, C.C. Landry, I. McCammon, M. Moore, D. Sharaf, C. Sterbenz, B. Tremper, and K. Williams, 2004: Snow, Weather, and Avalanches: Observational guidelines for avalanche programs in the United States, 136 pp., American Avalanche Association, Pagosa Springs, Colorado.

Gubler, H., 1977: Artificial release of avalanches by explosives. Journal of Glaciology 19(81): 419-429.

Johnson, R., and K.W. Birkeland, 1994: The stuffblock: a simple and effective snow stability test. Proceedings of the 1994 International Snow Science Workshop, Snowbird, Utah, 518-26.

Johnson, R., and K.W. Birkeland, 1998: Effectively using and interpreting stability tests. Proceedings of the 1998 International Snow Science Workshop, Sun River, Oregon, September 1998, 562-73.

Lageson, D.R., 2008: Montana State University Department of Earth Sciences. Personal communication.

McCammon, I. and J. Schweizer, 2002: A field method for identifying structural weaknesses in the snowpack. Proceedings of the 2002 International Snow Science Workshop, Penticton, British Columbia, September 2002.

McClung, D.M., and P. Schaerer, 1993: The Avalanche Handbook, The Mountaineers, Seattle, 253 pp.

Savage, S, 2006: Deep slab avalanche hazard forecasting and mitigation: the South Face at Big Sky ski area. Proceedings of the 2006 International Snow Science Workshop, Telluride, Colorado, September 2006.

Simenhois, R. and K.W. Birkeland. 2006. The extended column test: A field test for fracture initiation and propagation. Proceedings of the 2006 International Snow Science Workshop, Telluride, Colorado, September 2006.

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. and K.W. Birkeland. 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.

Ueland, J., Big Sky Snow Safety Department, 1991-2010. Personal communication.

van Herwijnen, A., and J.B. Jamieson, 2004: Fracture character in compression tests. Proceedings of the 2004 International Snow Science Workshop, Jackson Hole, Wyoming, September 2004, 182-191.