Field Data and Theory for Human Triggered "Whumpfs" and Remote Avalanches

Ben Johnson[a], Bruce Jamieson[a,b] and Colin Johnston[a]
[a]Dept. of Civil Engineering, University of Calgary, Calgary, Alberta, Canada
[b]Dept. of Geology and Geophysics, University of Calgary, Calgary, Alberta, Canada

Remotely triggered avalanches and whumpfs (sometimes called "settlements") are common occurrences in many mountains ranges, but have received little research attention in the past. These events are generally associated with persistent weak snowpack layers, consisting of surface hoar, depth hoar and facets.

Over the past four years, snowpack data have been collected at the sites of forty skier-triggered whumpfs and thirteen remotely skier triggered avalanches in the Columbia and Rocky Mountains of British Columbia. These data are compared to data for skier triggered avalanches that were not remotely triggered. Whumpfs and remotely triggered avalanches showed significant differences in the weak layer and slab properties. Additional measurements at five whumpf sites indicated a collapse of the weak layer and downward displacement of the snow surface. At one site during the winter of 1999-2000, the speed of the propagating fracture through a weak layer under a soft slab was measured at 19.9 m/s using geophysical equipment.

A theory is presented that explains propagation of a fracture in a weak layer on level terrain. This theory also explains the large difference in speeds observed for whumpfs.

KEYWORDS: Avalanche Release, Persistent Weak Layers, Fracture Propagation

1. INTRODUCTION

Whumpfs and remotely triggered avalanches have received very little attention by researchers, although they are frequently responsible for avalanche involvements. The lack of attention probably stems from the fact that they are difficult to study due to their infrequent and unexpected nature. In a recent survey by Jamieson and Geldsetzer (1999), when 153 avalanche professionals were each questioned about one unexpected avalanche that they recalled, a surprising 41 percent recalled a remotely triggered avalanche. This number seems high considering how infrequently they occur. One possible explanation is that often the propagation distances are great or the fracture travels through level terrain, both of which are unexpected and therefore remembered quite well. Whumpfs can be thought of as a remotely triggered avalanche in which the propagating weak layer fracture did not reach an avalanche start zone.

2. PREVIOUS WORK

Information about whumpfs and remotely triggered avalanches that do exist in the literature are mostly observational comments. One of the first references to remotely triggered avalanches was by Bader and others (1939) who noted that an explosion detonated in one valley was able to trigger multiple avalanches some distance away from the location of the explosion. Carl Benson (1960) documented the collapse of softer snow layers and the propagation of these collapses in Greenland. He estimated that the softer layers of snow collapsed approximately 2.5 cm. In 1973, Truman reported the observation of several whumpfs that occurred outside of his Midwest home in an isothermal snowpack. He observed a wave like pattern on the surface of the snow. The surface of the snow was displacement downward approximately 1-2 cm after the wave had passed. He visually estimated the speed of these waves to be around 6 m/s. He concluded that based on the speed of the wave, it could not have been a compression or shear wave. DenHartog (1982) documented an event triggered by a large explosion in Antarctica. Again, a layer in the snowpack compressed with the fracture traveling at least five miles. The collapse of a softer layer in the snowpack

---

**Corresponding author address:* Ben Johnson; 3875 Geist Road, Ste. E #276, Fairbanks, AK 99709-3549
Email: bcjjohn@ucalgary.ca

caused the surface to be displaced downward. This downward displacement traveled slightly slower than the speed of sound in air.

The reports of downward displacement of the snow surface and wave like behavior of the surface lead us to the following hypothesis.

3. HYPOTHESIS

One accepted theory for skier triggered avalanche release is that a skier first triggers a shear fracture in a weak layer of the snowpack (e.g. Föhn, 1987). This fracture propagates outwards from the trigger point. Fracture of the weak layer is followed by fracture of the crown, flanks and stauchwall, releasing an avalanche (e.g. McClung, 1987 and Schweizer 1999). The fact that whumpfs and remotely triggered avalanches can propagate across horizontal terrain questions whether propagation is strictly a shear fracture of the weak layer. Schweizer (1999) states that collapse of the weak layer (compressive failure) seems quite plausible as the initial failure in an avalanche. While fracture mechanics texts (e.g. Broeck, 1984) indicate that a component of shear is necessary for fracture propagation in the weak layer we hypothesize that propagating fractures on level terrain ***require*** a compressive component. This collapse of the weak layer should be associated with whumpfs and remotely-triggered avalanches, most of which involve propagation on low-angled terrain. Whumpfs and remotely triggered avalanche are most likely initiated with a compressive fracture of the weak layer.

4. METHODS

Our first step was to compare remotely triggered avalanches with avalanches that were not remotely triggered. Data were collected at the sites of whumpfs and remotely triggered avalanches and at avalanche sites that were not remotely triggered. To date we have collected data from forty whumpfs and thirteen remotely triggered avalanches. These data were then compared to data collected at fifty-one skier triggered avalanches that were not remotely triggered. All whumpfs and remote avalanches were triggered by either by a person on skis or snowshoes.

The second step was to develop and implement an experiment to measure the speed at which these failures traveled. This has never been measured and allowed us to compare the measured value to published theoretical values for shear fracture through the weak layer. If the speed was much greater than or less then the expected values for a shear fracture then it would support our hypothesis that it might not be strictly a shear fracture propagating through the weak layer.

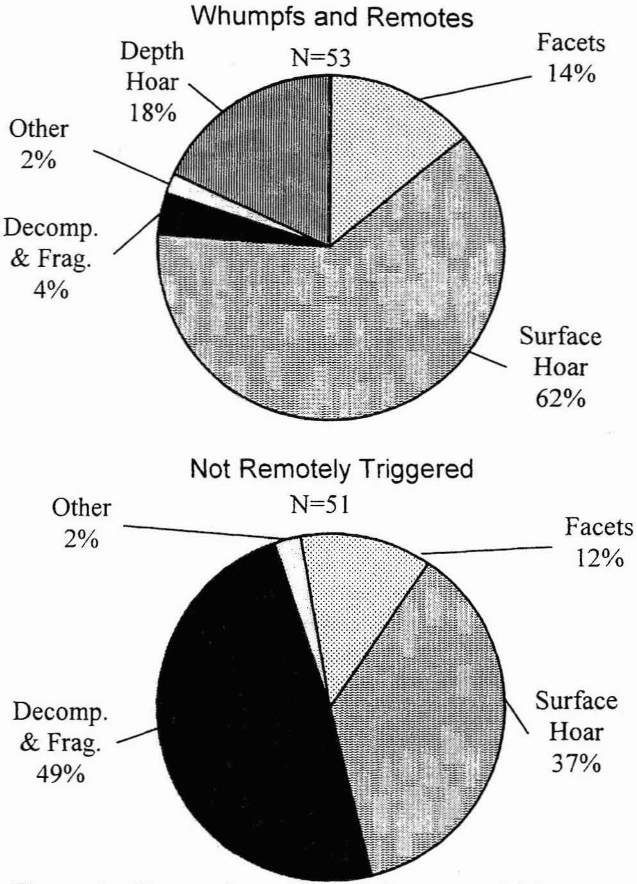

Figure 1. Comparison of weak layer crystal types.

5. COMPARISON OF REMOTE AND NON-REMOTELY TRIGGERED AVALANCHES

One of the most important pieces of information collected at investigated avalanche sites was the crystal type of the failure layer. Figure 1 shows the crystal types for remotely triggered avalanches and for the non-remotely triggered avalanches that we have investigated.

Whumpfs and remotely triggered avalanches involved persistent weak layers in all but two events investigated in the Columbia and Rocky Mountains of Western Canada. The two cases where the weak layer was reported as non-persistent, field notes show that a persistent weak layer at the base of the snowpack could have contributed to the failure. This distribution of crystal

Table 1: Comparison of remotely triggered avalanches with non-remotely triggered avalanches. Shaded values show statistically significant differences in the mean values.

	Remotely Triggered and Whumpfs		Not-Remotely Triggered		*t test*	
	N	Mean	N	Mean	t	p value
Age of weak layer (days)	44	19.4	22	10.9	-2.66	0.001
Weak layer thickness (cm)	45	3.6	40	0.9	-2.59	0.01
Shear strength of weak layer (kPa)	38	0.76	39	0.62	-1.48	0.14
Maximum crystal size of weak layer (mm)	49	10.1	46	4.3	-4.44	$< 10^{-5}$
Density of slab (kg/m^3)	48	148.	41	127	-2.54	0.01
Thickness of overlying slab (cm)	55	63	51	43	-3.83	0.0002
Compression test score	40	15.8	38	15.3	-0.241	0.81

types for remote avalanches is notably different than the weak layer crystal type for non-remotely triggered avalanches, which consisted of decomposed and fragmented crystals in forty eight percent of the cases. If we could have investigated all non-remote, skier triggered avalanches we would expect a larger percentage of failures occurring in decomposed and fragmented crystal layers; our research focuses on avalanches that have occurred on persistent weak layers. Although the data are biased towards persistent weak layers, it still clearly indicates that whumpfs and remotely triggered avalanches tend to only involve persistent weak layers.

One characteristic of persistent weak layers is that the layer has a measurable thickness usually between 2 and 30 mm, although some facet and depth hoar layers can be much thicker. Because these layers have thicknesses greater than their grain size there is potential for collapse of the layer. During the winter of 99/00 at five sites where a whumpf occurred, the thickness of the weak layer was measured in an area where the weak layer had fractured then again in an area where the weak layer had not fractured. Often a perimeter crack appears on the surface indicating where the fracture stopped (Figure 2). One whumpf showed a remarkable 10 mm of collapse between the un-fractured and fractured regions. The four other measurements showed a collapse of 3-7 mm, 3 mm, 2 mm and 1 mm respectively. We were only able to make these measurements at five sites where the extent of propagation could be determined from perimeter cracks.

While we did try to determine why propagation stopped, it was difficult to draw any specific conclusions about the stopping condition. In most cases, the perimeter fracture was at an abrupt change in slope incline or, in an area where vegetation was protruding through the surface of the snow.

In addition to comparing the weak layer crystal types we have also compared the following measured variables: age of the weak layer, shear strength of the weak layer, thickness of the weak layer, maximum crystal size of the weak layer, thickness of the overlying slab, density of the overlying slab and average compression test score. Table 1 shows the comparison of these characteristics. Out of these seven characteristics of the slab and the weak layer, five have statistically different means. The two variables that did not prove significantly different ($p<0.05$) were the shear strength and compression test scores.

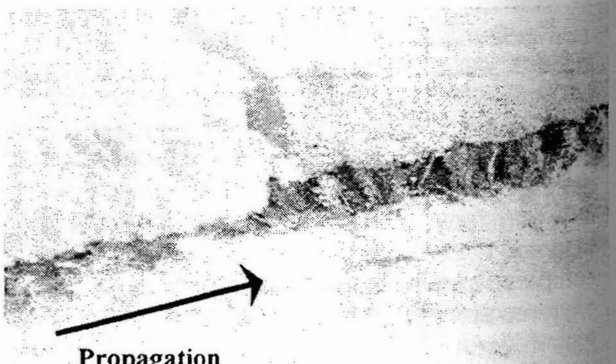

Figure 2. Collapse of a surface hoar layer, taken at the site of a whumpf. The vertical crack extends to the surface and indicates the perimeter of the failed area. This fracture was triggered 8 meters to the left of the area photographed.

Comparison of these remotely triggered avalanches with non-remotely triggered avalanches shows significant differences in both the weak layer and the overlying slab. Remotely triggered avalanches tend to have thicker, more dense slabs, and the weak layers for remotely triggered avalanches are much thicker and have larger crystals.

6. MEASUREMENT OF PROPAGATION SPEED

On February 19th of 2000, we set out to measure the propagation speed of a whumpf in Banff National Park, Alberta (whumpfs had been reported in this area several days prior to February 19th). We used six geophones connected to a Bison 12 channel recorder. The weak layer consisted of a surface hoar layer that had formed Jan 1st. The layer was approximately 14 mm thick and at a depth of 39 cm. The overlying slab was dry snow with an average density of 189 kg/m^3. The six geophones were placed in a line on the snow's surface and then a whumpf was triggered near one end of the geophone string (Figure 3). Sampling at 2000 Hz, we recorded the downward displacement of the snow surface as the failure traveled through the weak layer below each geophone. The weak layer collapsed approximately 1 mm in one snow profile. After measuring the geometry of the

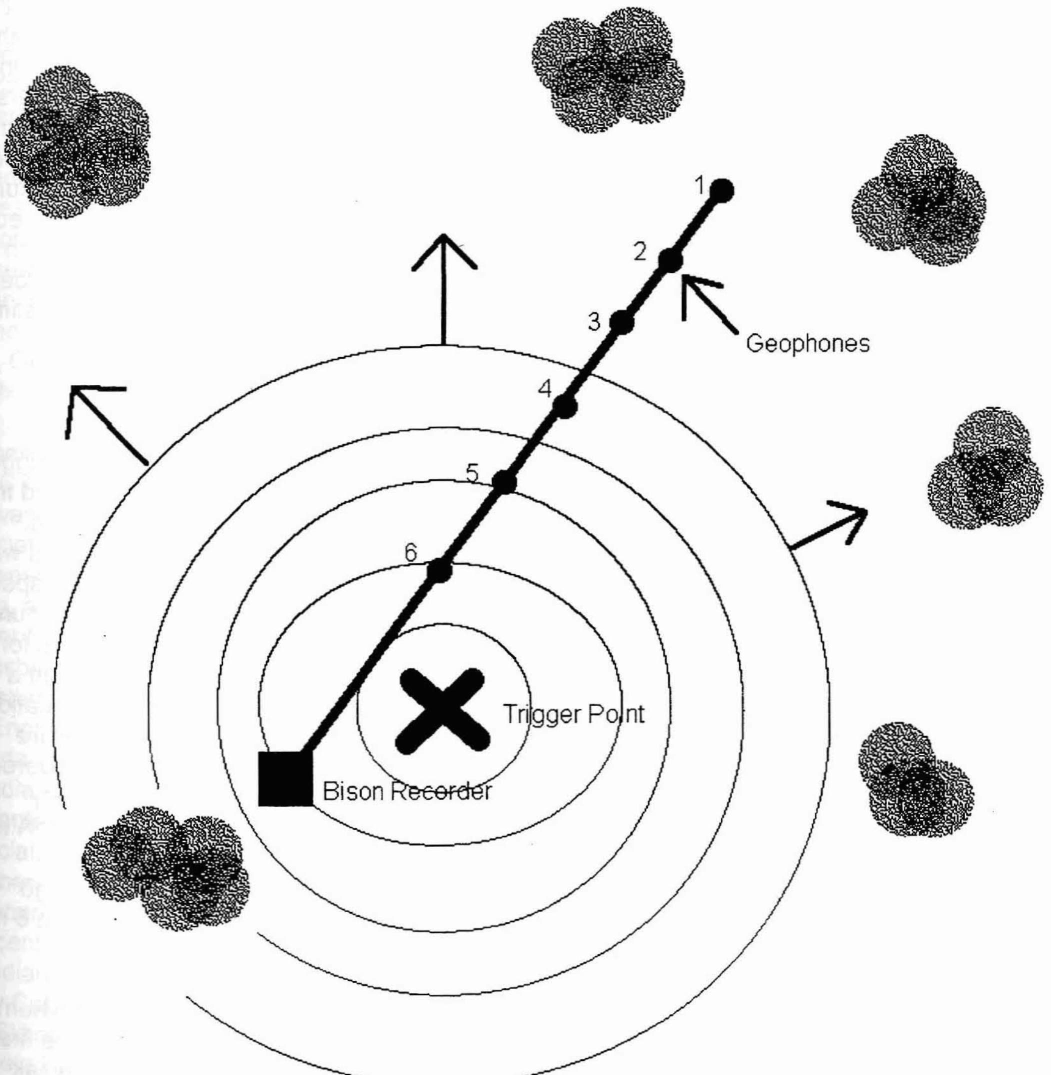

Figure 3. Schematic of the experimental setup used to measure the propagation speed of a whumpf. Concentric circles indicate propagation of the weak layer failure.

geophones in relationship to the trigger point we calculated the propagation speed of the whumpf at 19.9 m/s. Theoretical values for the propagation of shear fracture through weak layers was thought to be on the order of 100 to 1000 m/s (Bader and Salm, 1990). Our measured speed was an order of magnitude slower than expected.

7. DISCUSSION

In 1989 Lackinger, proposed that the failure of a weak layer in compression with an area of bending in the overlying slab widening outward could be one mechanism of avalanche initiation and fracture propagation. Our measurements of compression of the weak layer and the fact that geophones on the surface of the snow were able to record this collapse supports the argument that when a whumpf occurs the weak layer fractures and this includes a component of compression. As first noted by Bohren and Beschta in 1973, we believe that the overlying slab does exhibit a wave like behavior that is different from normal compression or shear waves. We believe that a flexural wave propagates in the overlying slab. Flexural waves are quite common in sheets of ice. Wilson (1955) states that any disturbance of a floating ice sheet generates flexural waves in the ice. As the flexural rigidity of the ice sheet increases so to does the flexural wave velocity. The length of theses waves in ice sheets range from 30 m to 300 m.

Our proposed theory is that a compressive fracture occurs in a persistent weak layer, which creates a flexural wave in the overlying slab (Figure 4). Energy is transferred through the overlying slab to progressively collapse the weak layer. This coupled process then spreads outward with the stiffness of the overlying slab controlling the speed of propagation. If we make several assumptions, we can calculate a simple estimate of what the speed a flexural wave should have traveled on Feb. 19th in the overlying slab. These assumptions are that the thickness contributing to the flexural rigidity of the slab is equal to the thickness of the layers four fingers in hardness or greater, the flexural wave length of the slab is 10 m and that the speed of shear waves through the overlying slab is 350 m/s (Smith, 1965) based on a density of 250 kg/m^3 for the snow layer just above the weak layer. Using an equation developed by Voyiadjis and Baluch (1981) for the speed of flexural waves in isotropic plates, we calculate an estimated speed of 23.5 m/s. While this value is close to our measured value, this calculation only shows that if our assumptions are correct a flexural wave would have traveled at this speed. This supports but does not prove our theory.

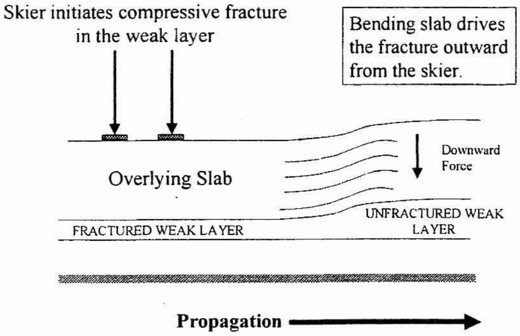

Figure 4. Diagram showing initial collapse of the weak layer. The overlying slab is bent, providing the downward force to progressively fracture the weak layer.

This flexural theory would also account for much greater speeds observed by researchers in Greenland and Antarctica. The weak layers, in those cases, were 2-3 m deep indicating a much stiffer overlying slab. This would result in flexural waves propagating much faster than the speed we measured on February 19th. Conversely, In an isothermal snowpack, slower speeds would be expected where the overlying slab has lost stiffness due to warming and free water content.

8. CONCLUSIONS

Data from whumpfs and remotely triggered avalanches were compared to data collected from avalanches that were not remotely triggered. Several important snow pack characteristics were found to be different. In addition to this the speed of a propagating fracture was measured and found significantly slower than previous estimates for the propagation speed of shear fracture through a weak layer. These two important pieces of information help to support our hypothesis that the failure mechanism for whumpfs and remotely triggered avalanches might be different than for many avalanches that are not remotely triggered. A theory was proposed that accounts for both the compression of the weak layer, and the large difference in observed speeds ranging from 6 m/s to over 300 m/s.

The theory presented here is for whumpfs and remotely triggered avalanches. It is the first theory to explain fracture propagation in weak layers through horizontal terrain.

9. WHAT DOES IT MEAN?

For the avalanche practitioner the most important piece of information in this paper is that whumpfs and remotely triggered avalanches are associated with weak layers consisting of surface hoar, depth hoar or facets. If a persistent weak layer exists in the snowpack, we must keep the danger of a remotely triggered avalanche in mind.

This paper has offered a theory for these events, but more importantly creates more questions that could be answered with careful experimentation. If the failure mechanism were correctly understood, then forecasting for these types of events would improve.

10. ACKNOWLEDGEMENTS

We would like to thank Mitcham Canada Ltd. for providing the geophysical equipment used in the fracture speed experiment.

For their careful field work we are grateful to Jill Hughes, Ken Black, Thomas Chalmers, Joe Filippone, Michelle Gagnon, Torsten Geldsetzer, Sue Gould, Brian Gould, Phil Hein, Nick Irving, Greg Johnson, Alan Jones, Kalle Kronholm, Paul Langevin, Steve Lovenuik, Bill Mark, Greg McAuley, Andrew Rippington, Jordy Shepherd, and Adrian Wilson.

For their assistance with field studies, we thank the BC Ministry of Transportation and Highways, the Canadian Avalanche Association, Canadian Mountain Holidays, Intrawest Corporation, Mike Wiegele Helicopter Skiing, and the avalanche control section of Glacier National Park including Dave Skjönsberg and Bruce McMahon.

This study was funded by the Natural Sciences and Engineering Research Council of Canada, Canada West Ski Areas Association, the Canadian Avalanche Association and the BC Helicopter and Snowcat Skiing Operators Association (BCHSSOA). The supporting members of the BCHSSOA include Canadian Mountain Holidays, Cat Powder Skiing, Crescent Spur Helicopter Holidays, Great Canadian Helicopter Skiing, Great Northern Snow Cat Skiing, Island Lake Lodge, Klondike Heli-Skiing, Last Frontier Heliskiing, Mike Wiegele Helicopter Skiing, Monashee Powder Adventures, Peace Reach Adventures, Purcell Helicopter Skiing, R.K. Heli-Skiing, Retallack Alpine Adventures, Robson Heli-Magic, Selkirk Tangiers Heli-Skiing, Selkirk Wilderness Skiing, Sno Much Fun Cat Skiing, TLH Heliskiing, Whistler Heli-Skiing and White Grizzly Adventures. The supporting members of Canada West Ski Areas Association include Apex Mountain Resort, Banff Mt. Norquay, Big White Ski Resort, Hemlock Ski Resort, Mt. Washington Alpine Resort, Silver Star Mountain Resorts, Ski Marmot Basin, Sun Peaks Resort, Sunshine Village, Whistler Blackcomb, Whitewater Ski Resort, and the Resorts of the Canadian Rockies including Skiing Louise, Nakiska, Kimberley Alpine Resort, Fortress Mountain and Fernie Alpine Resort.

11. REFERENCES

Bader, H.R., R. Haefeli, E. Bucher, J. Neher, O. Eckel and C. Thams. 1939. Snow and Its Metamorphism. SIPRE Translation 14, 1954.

Benson, C. 1960. PhD Thesis. California Institute of Technology.

Bohren, C.F. and R.L. Beschta. 1974. Comment on "Wave Propagation in Snow." American Journal of Physics, 69-70.

Broek, D. 1986. Elementary Engineering Fracture Mechanics, fourth revised edition. Kluwer Academic, Hingham, MA, 516 pp.

DenHartog, S.L. 1982. Firn Quake. Cold Regions Science and Technology, Vol. 6, 173-174.

Föhn, P.M.B. 1987. The stability index and various triggering mechanisms. IAHS Publication No. 162, 195-211.

Jamieson, B. and T. Geldsetzer. 1999. Patterns in unexpected skier-triggered avalanches. Submitted to Avalanche News.

Lackinger, B. 1989. Supporting forces and stability of snowslab avalanches: a perimeter study. Annals of Glaciology, 13, 140-145.

McClung, D.M. 1987. Mechanics of snow slab failure from a geotechnical perspective. IAHS Publication No.162, 475-508.

Scheizer, J. 1999. On the role of deficit zones in dry snow slab avalanche release. Cold Regions Science and Technology, Vol. 30, 43-56.

Smith, J.L. 1965. The elastic constants, strength and density of Greenland snow as determined from measurements of sonic wave velocity. U.S. Cold Regions Research and Engineering Laboratory, Technical Report 167.

Truman, J.C. 1973. Wave Propagation in Snow. American Journal of Physics, Vol. 41, 282-283.

Wilson, J.T. 1955. Coupling between moving loads and flexural waves in floating ice sheets. SIPRE report 34.

Voyiadjis, G.Z. and M.H. Baluch. 1981. Refined theory for flexural motions of isotropic plates. Journal of Sound and Vibration, 76(1), 57-64.