WET SLAB INSTABILITY AT THE ARAPAHOE BASIN SKI AREA

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ABSTRACT: Empirical evidence gathered at the onset of ablation on a ski slope where a wet slab avalanche claimed the life of a skier indicates a chance of snowpack fracture. Wetting fronts which fully penetrate the basal layer of depth hoar in response to the first episode of excessive diurnal melt result in a softening of ice-to-ice contact points and a significant change in cup-shaped ice particle geometry. The authors believe that wet slab instability reaches a maximum within this transient period. Quantitative studies consist of dielectric measurements that show wetting front speeds of 1.5 millimeters per second in the vertical direction and integrated ram penetrometer scores of 66 ± 22 Joules. Finally, probable indicators of wet slab instability including air temperatures that effect rapid melt rates, snowpack characteristics conducive to brisk water transmission and stream discharge trends are identified.

Key Words: Wet slab instability, volumetric water content

1. INTRODUCTION

Wet slab instability is of importance to decision makers at ski areas that offer recreational activities in avalanche terrain during sustained snowmelt. In a continental alpine climate, a layer of fine grained ski compacted snow accumulates over a layer of depth hoar during winter. By spring, intermittent periods of superficial melting at the ski surface result in meltwater penetration of the ski compacted snow layer and subsequent refreezing due to contact with colder underlying snow. Successive episodes of diurnal meltwater further penetrate the layer of ski compacted snow and warm it due to a release of heat of fusion by the meltwater. When the layer of ski compacted snow approaches the melting temperature, meltwater enters the upper region of the depth hoar layer. Meltwater then penetrates the depth hoar layer in response to warmer weather conditions and vigorous snowmelt at the ski surface. Once meltwater arrives at the soil and snow interface, dry snow is replaced by wet snow.

Colbeck (1987), based on laboratory tests and physical modeling, reports that dry and wet snow are two different materials. Structural dissimilarities arise from the presence and quantity of liquid water as the melting temperature is approached. For example, wet snow at low liquid water content encourages the rapid formation of multigrain clusters held together by strong ice to ice bonds while snow at high liquid water content gives rise to individual grains of weak cohesionless slush (Colbeck 1997).

Quantitative studies conducted by researchers in the field support Colbeck's findings. For example, Brun and Rey (1986) applied shear frame, penetrometer and dielectric probes to layers of snow found in the European Alps. They determined that for a significant decrease in snow cohesion to occur, liquid water content must exceed 7% to 8% by volume. Bhutiyani (1994) evaluated the effects of meltwater on the shear strength of wet snow in the Himalayas. He not only concurred with the earlier findings of Brun and Rey, but demonstrated that shear strength drops by over half at water content in excess of 7% by volume.

Waldner *et al.* (2004) described the effects of snow structure on water flow in fine and coarse grained samples of packed snow in containers. In their laboratory experiments, tracers permitted visualization of liquid water flow paths, liquid water content was determined by permittivity measurements and high resolution photographs of surface sections revealed pore and grain size distributions. Their results confirm capillary barriers at textural discontinuities between fine and coarse grained snow similar to that described by Colbeck and Davidson (1973), Jordan (1994) and Wankiewicz (1979). Furthermore, they identified two water flow regimes: matrix and preferential. For instance, initial conditions necessary for matrix flow required a relatively uniform distribution of liquid water at low water content in snow samples without textural discontinuities. In contrast, preferential flow, the

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development of well defined flow fingers at high liquid water content, occurred in snow samples with textural discontinuities.

Empirical evidence recovered from a broad range of snow climates by McClung and Schaerer (1996) indicates three principle causes of wet slab avalanches, one of which is a loss of strength in a buried weak layer as liquid water content increases. However, they mentioned that the strength of wet snow depends on structure as cases of avalanche release demonstrate that the failure layer liquid water content was less than that of overlying layers. Reardon and Lundy (2004) cite field observations in Montana which show that wet snow avalanches occurred when the drainage capacity of the snowpack was exceeded. Moreover, their practical experience indicated that climax wet slab avalanches required broad regions of persistent weak layers (Jamieson, 1995) located near the ground.

Trautman *et al.* (2006) related changing surficial shear strength to wet loose avalanche activity during melt periods at a ski area. In addition, they provided quantitative evidence that rapidly changing wet loose instability required avalanche workers to make operational decisions at fifteen minute intervals. However, to our knowledge, quantitative field studies of factors linked to wet slab avalanches on ski slopes in a continental alpine climate and methods of integrating findings in daily avalanche risk assessments have yet to be documented.

Following a wet slab avalanche fatality on a ski run at the Arapahoe Basin Ski Area, we formulated the following problem statement: Although rare, crack propagation or wet slab avalanches which involve the entire snowpack are most likely to occur at the onset of sustained snowmelt. The purpose of our investigation was to augment practical avalanche forecasting skills with quantitative measures of wet slab instability. Consequently, over the past three annual snowmelt periods, our inquiry focused on indicators of wet slab instability such as air temperature trends conducive to rapid snowmelt, snowpack resistance to penetration, morphological trends in underlying layers of depth hoar and the effects of sustained snowmelt such as stream discharge rates.

2. METHODS

The Arapahoe Basin Ski Area is located on the spine of the northern Colorado Rockies. Assessing avalanche risk to users of the ski area is justified given terrain, weather and snowpack characteristics. For instance, above tree limit 5.2 kilometers of ridgeline defines the upper boundaries of some 62 avalanche start zones. Despite ski compaction of recent snowfall which results in the formation of a cohesive layer of snow in the upper snowpack, the continental climate (Armstrong & Armstrong, 1986) stimulates the formation of persistent weak layers in the lower snowpack.

Within the operational ski area boundary two study sites were selected. First, the mid-mountain weather and snow reporting study site known as ABS (39° 37' 56.64" N., 105° 52' 08.70" W) provided a base line assessment of a snowpack evolving in absence of ski compaction. A second study site referred to as ABP (39° 38' 04.18" N., 105° 52' 42.08" W) was located on a ski run and in the start zone of a north facing avalanche path where the fatality occurred in May of 2005. Loamy soil is found at both study sites, which are located in a subalpine zone (Kersha *et al.* 1998) at an elevation of 3,550 meters (m).

At ABS, in addition to manual and automated snow and weather observations (American Avalanche Association, 2004), the dielectric permittivity of snow was measured with Campbell Scientific, Inc CS616-L water content reflectometers. A base layer reflectometer was inserted in the early season snowpack at 0.4 m above the soil and snow interface. A second reflectometer was maintained at approximately 0.2 m below the air and snow interface during the snowmelt period. Also, snow temperatures adjacent to the reflectometers were measured with Campbell Scientific, Inc. T107-L temperature sensors.

At ABP, following commencement of the ski season, a pair of reflectometers was separated by a horizontal distance of 8 m and inserted in the depth hoar immediately below the ski compacted snow layer. When the height of snowpack had increased by approximately three-fold, a second pair of reflectometers was inserted in the ski compacted snow layer above those which were place earlier in the ski season. T107-L sensors measured snow temperatures near the reflectometers. Snow surface temperature was acquired with an IRR-P Apogee infrared radiometer. ABP remained open to skiing throughout winter and into the snowmelt period.

Volumetric water content was determined by first correcting reflectometer output to the melting point due to a nonlinear dependence on temperature (Bilskie, 2008). Next, the relative apparent permittivity of snow was calculated given methods found in Kelleners *et al.* (2005). Liquid water content was derived (Waldner, *et al*. 2004) for each reflectometer based on apparent permittivity values 24 hours prior to the first indicator of diurnal meltwater reaching the reflectometer. Data summary included illustrative analysis of volumetric water content at 1, 5, 15 and 60 minute intervals and descriptive statistics.

Snowpack resistance to penetration at ABS and ABP was determined with a standard penetrometer. At ABS a transect consisting of 3 penetrometer tests, each separated by a distance of 1.5 meters, was recovered twice monthly during winter and then generally every day during the snowmelt period. At ABP, the same sampling scheme was adopted with the exception that each transect was aligned across the fall line and consisted of 15 penetrometer tests. For each penetrometer test the total work performed during penetration, the average force (total work divided by snowpack height), the height of snowpack and the maximum penetration distance was either calculated or noted. In addition to descriptive statistical summary, illustrative analysis included box-whisker diagrams showing scores within the inner quartile (boxes) and the minimum and the maximum scores (whiskers).

Additional activities were periodically conducted during the snowmelt period at both study sites. First, snow density and snow temperature at 0.1 m increments above the soil and snow interface were recovered. Average snowpack densities as well as the density trend at specific locations within the snowpack were analyzed graphically. Second, in order to quantify daily snowmelt, snow surveys (U.S.D.A. 1973) were obtained and plotted over time. Third, during the snowmelt period, microphotography permitted visual scrutiny of the morphological trend of ice grains at 0.1 m increments above the snow and soil interface.

3. FINDINGS

Snowpit observations on May 12, 2008 at ABP revealed a stiff layer of fine grained ski compacted snow overlying a brittle layer of depth hoar at a layer ratio of 6:4. Snow temperatures ranged from - 1° C at the ski surface to - 3° C at the soil and snow interface. Also, illustrative analysis of penetrometer sampling showed that snowpack resistance to penetration had reached a maximum for the 2007/08 ski season.

On May 20th, coincident with the first seasonal episode of air temperatures approaching 15° C, the depth hoar at ABP reached the melting point (Figure 1). By the morning of the 21st, the fractional liquid water content in the depth hoar was measured at 0.01 (Figure 2). In the depth hoar later that day, the largest increase in liquid water content during the spring 2008 snowmelt period was measured over a 3-h period. Concurrent with the surge in liquid water content, snow surveys showed a loss of 2.5 cm of snow water equivalent due to snowmelt at the ski surface.

Snowpack resistance to penetration at ABP shows a local minimum on May 21st (Figure 3).

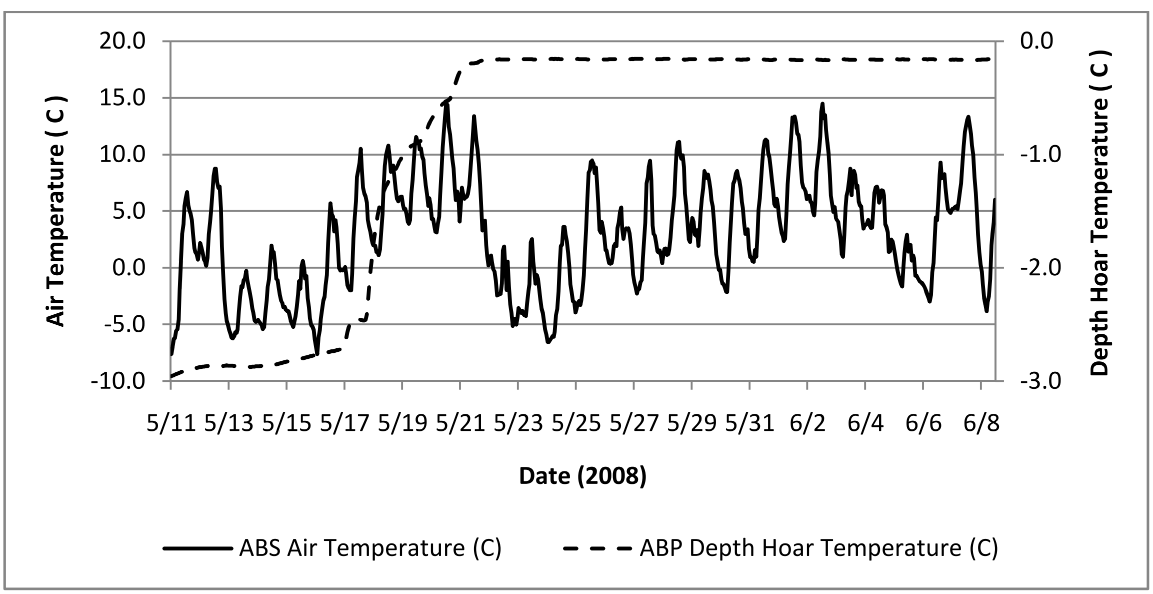

Figure 1. The air temperature trend at ABS is compared to the depth hoar temperature trend at ABP during the 2008 spring snowmelt period (note air and snow temperature trends on the 20th and 21st).

Furthermore, striking a straight line through the sequence of box plots leading up to the 21st underscores the observation that snowpack resistance to penetration was reduced by about 60 percent over the 4 day period. Increasing resistance to penetration following the 21st was in response to a winter storm. This increase was exclusively due to a rapid hardening of the ski compacted snow in response to snow temperatures that fell to - 7° Celsius. Following storm conditions, rising air temperatures prompted a return to snowmelt and a decrease in snowpack resistance to penetration.

Although the presence of liquid water in the depth hoar at ABP could not be visually confirmed with a 20x stereoscope on May 17th, reflectometer data indicated that the first wetting front had reached the soil and snow interface. One day later image 1 (Figure 4) captured snow grain structure in the ABP snowpack at 40 cm above the soil and snow interface. At the same height, 3 days later, image 2 confirmed that striated features and sharp edges had deteriorated. Once snowmelt at the ski surface had reduced snowpack water equivalent by approximately 10 cm, image 4 illustrates the dominating presence of multigrain clusters held together by ice to ice bonds.

4. DISCUSSION

At the onset of sustained snowmelt, small (≈ 5 cm^3) vertically aligned ice bodies form in the upper regions of the ski compacted snow. As additional episodes of meltwater penetrate the ski compacted snow, the number of ice bodies increase. For example, 3 days prior to the 21st of May, 2008 we estimated their abundance at 650 m^{-3}. When the ski compacted snow reaches the melting point and the ice bodies become a common feature throughout, their growth cycle ends. Although flow fingers have yet to be visually confirmed in close proximity to individual ice bodies, we suspect that preferential flow is an effect of the structure of ski compacted snow (Waldner *et al*, 2004), (Colbeck, 2008).

Visual evidence of capillary barriers or slope parallel ice layers at the ski compaction and depth hoar interface are nonexistent. Here, textural characteristics trend from small abraded snow grains, an effect of forces imparted on the snow grain by the ski edge, to facets and then to depth hoar over a few centimeters. Furthermore, Wankiewicz (1979) demonstrates that the intrinsic permeability of snow increases approximately ten-fold from fine grained old snow to depth hoar. Consequently, liquid water pressure differentials across the ski compaction and depth hoar interface are balanced by increased flow velocity into the depth hoar. Although our field observations are not supported by laboratory experiments, we speculate that matrix-like flow develops across this interface.

Visual analyses of the data recovered from the pair of reflectometers located in the

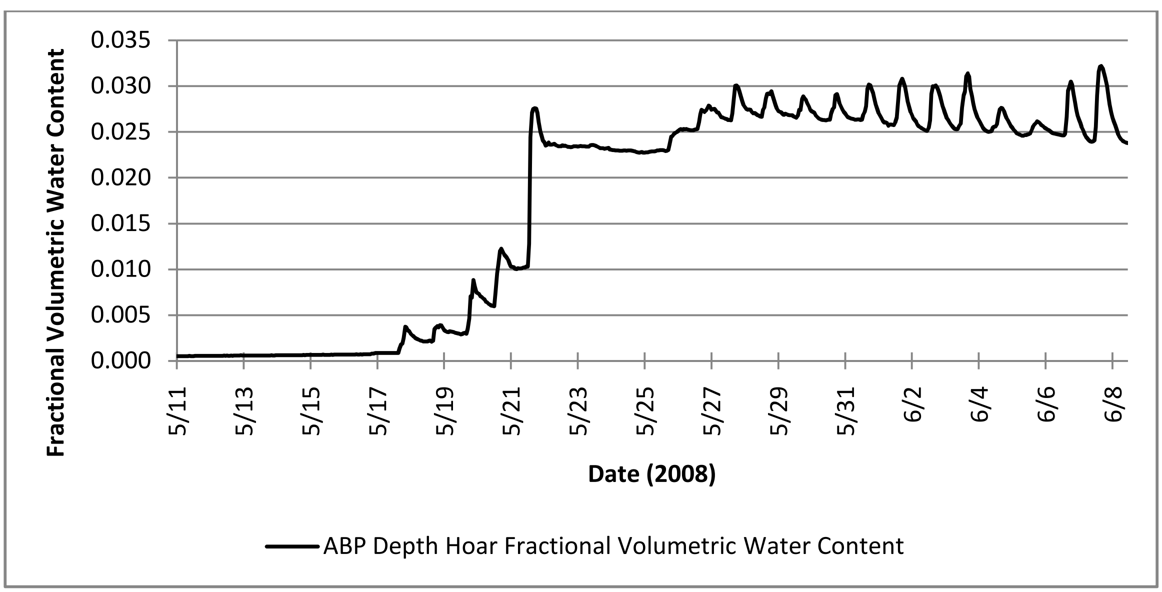

Figure 2. Liquid water content flux in the depth hoar at ABP during the spring 2008 snowmelt period (note the spike in liquid water content on the 21st).

depth hoar at ABP show similar volumetric water contents and trends. Moreover, visual evidence of flow fingers, vertical or horizontal ice bodies in the depth hoar is absent. Thus, we hypothesize that the structure of depth hoar favors matrix-like flow behavior.

Visual analyses of the data showing timing and effects of air temperatures near 15° C indicate a chain of events that result in a sudden softening of the snowpack. They are: (1) snow temperatures rapidly approaching the melting point (2) a sudden increase in liquid water content and (3) abrupt changes in snowpack structure.

McClung and Schweizer (1999) emphasize the effects of snow temperature on dry slab hardness, failure toughness and strength with respect to skier triggering. They say that in dry snow there are “two competing effects”: metamorphism and mechanical properties. Although they exclude the effects of metamorphism due to time scale constraints, the concept of competing effects seem to apply to wet slab instability. For instance, in the presence of liquid water, the rapid reconfiguration of grains and bonds shown in Figure 4 plus spatial rearrangement of grains throughout the snowpack leads to a stable configuration (Agrawal & Mittal, 1994). Thus, following the initial snowmelt period, metamorphic and structural changes lead to a snowpack increasingly resistant to skier triggering.

Practical experience indicates that the chance of wet slab avalanche release increases when a thin layer of ski compacted snow overlies a layer of depth hoar. Comparing layer ratios of ski compaction to depth hoar at fracture lines at the onset of sustained snowmelt underscores the following observations. Williams (2005) showed ratios as large as 1:9 at the fracture line of the 2005 wet slab avalanche whereas a ratio of 3:7 was observed one day prior to the explosive triggered wet slab avalanche in 2006. In comparison, an absence of crack or fracture propagation was noted in 2007 and 2008 where ratios were both 6:4 at the onset of sustained snowmelt. McClung and Schweizer (1999), show the importance of skiers imparting sufficient deformation energy through a dry slab to the weak layer. In a similar fashion, we believe that when wet ski compacted snow dominates the layer ratio, skier induced deformation forces are unlikely to incite fracture at the depth hoar horizon.

When shear fracture occurs below the ski compacted wet slab, dishpan shaped fracture lines result. Writing about dry slab avalanches McClung and Schaerer (2006) suggest “that when a slab releases from failure above the depth hoar, it provides a jolt to sweep out material beneath it all the way to the ground”. Our observations show that this is the case for wet slab avalanches at ABP.

The briefest episode of pre-snowmelt to

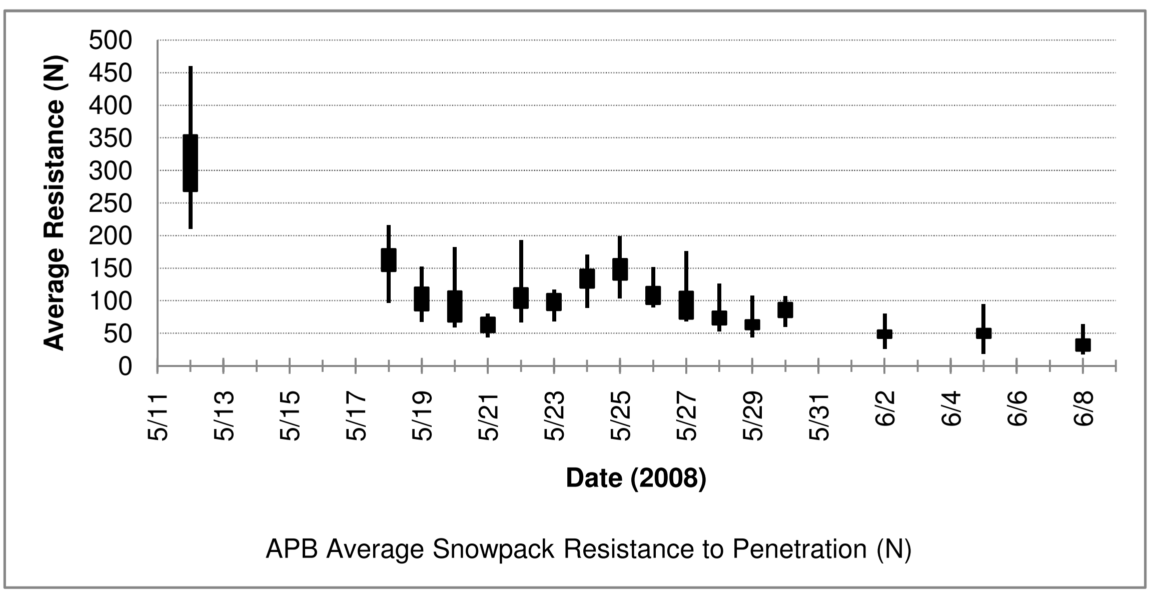

Figure 3. From penetrometer transects at ABP, box plots showing the maximum, minimum and the inner quartile average snowpack resistance to penetration during the spring 2008 snowmelt period (note trend and spread prior to and on the 21st).

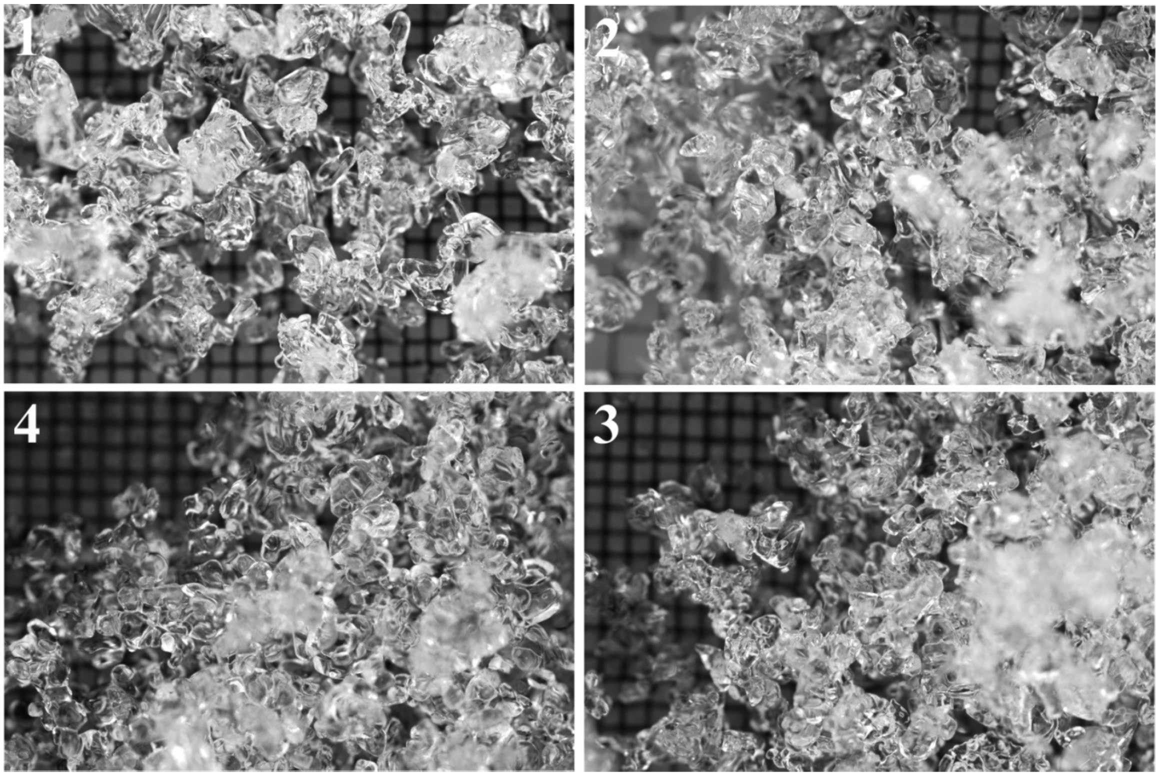

Figure 4. Microphotographs of snow grains at 40 centimeters above the soil and snow interface show the morphological trend during the spring 2008 snowmelt period at ABP. Grid size is 1 mm. (Image dates, 1: May 18th, 2: May 21st, 3: May 25th, and 4: June 8th).

peak stream discharge in the 62 year Snake River record occurred in May 2005. In response to what Williams (2005) notes as an “extraordinary warm-up,” that began on the 18th, stream discharge climbed above the winter time flow rate for the first time. Two days later, May 20th, a wet slab avalanche which originated in the ABP study site claimed the life of a skier. The peak seasonal discharge rate was reached 4 days afterward. We don’t believe that this is coincidence, rather as supporting evidence that wet slab avalanches which remove the entire snowpack at ABP are more likely to occur during the initial phase of aggressive and sustained snowmelt.

To review, the salient quantitative findings at ABP during the 2008 snowmelt period were: (1) The migration of small ice bodies through the ski compacted snow layer began when maximum daily air temperatures approached 10° Celsius (2) Snowpack resistance to penetration declined as snowpack temperatures trended from winter time values to - 2° C or warmer (3) A surge in volumetric water content in the ski compacted layer and the depth hoar coincided with the first onset of maximum daily air temperatures near 15° C (4) Coincident with the initial increases in the irreducible water content (Colbeck, 1979) of the ski compacted snow and the depth hoar, snowpack resistance to penetration decreased by 60 percent over a 4 day period and finally (5) the inner quartile of average snowpack resistance to penetration concurrent to the surge in volumetric water content was 51 – 74 N.

In conclusion, the problem statement mentioned earlier in this paper reads: Although rare, crack propagation or wet slab avalanches which involve the entire snowpack are most likely to occur at the onset of sustained snowmelt. Based on findings presented here, we fail to reject this statement.

5. ACKNOWLEDGEMENTS

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