Case study of a solar triggered persistent deep slab avalanche

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ABSTRACT
Persistent deep slab avalanches are one of the most dangerous types of snow avalanche because of their destructive potential from the release of an enormous amount of snow. They are usually difficult to forecast because the buried persistent weak layer is generally deep in the snowpack. A case study is evaluated where a natural deep slab avalanche was likely triggered from increased strain rates in the upper snowpack caused by reduced snow slab stiffness from solar warming. Fracture initiation likely occurred in a thin spot of the snowpack where the persistent weak layer was shallow. Clear skies were observed during the day of release, leading to an additional modelled upper snowpack warming of nearly 9 °C. Snowpack tests conducted near the avalanche crown after the release resulted in a Sudden Planar fracture character for eight Deep Tap tests. Eight Propagation Saw Tests all propagated to the end of the column after a critical cut length ranging between 47 and 61 %. Longer relative cut lengths were required for shallow areas of the snowpack compared to deeper areas. We argue that solar input was required to decrease stability, favouring avalanche release. This indicates the importance of analyzing snowpack test results on both the spatial and temporal scales.

RÉSUMÉ
Les avalanches de plaques de neige profondes et persistantes sont l'un des plus dangereux types au vu de leur potentiel de destruction du à la libération d'une quantité énorme de neige. Ils sont vraiment difficiles à prévoir parce que la fragile couche persistante est généralement enterrée profondément dans le manteau neigeux. Une étude de cas est évaluée où une avalanche de plaques de neiges profondes d’origine naturelle a probablement été déclenchée par une augmentation de la pression dans le manteau neigeux supérieur causées par la réduction de la rigidité de la plaque de neige du au réchauffement solaire. L’amorce de rupture s’est probablement produite dans une partie fragilisée du manteau neigeux ou la couche persistante était superficielle. Un ciel dégagé a été observé ce jour-là, entrainant un réchauffement supplémentaire du manteau neigeux supérieur simulé de presque 9 °C. Des analyses du manteau neigeux effectuées près de la couronne après la libération conduisent à un caractère de fracture Sudden Planar pour huit tests de Deep Tap. Huit Propagation Saw Tests tendent tous vers la fin de la colonne après une longueur de coupe critique allant de 47 à 61 %. Des coupures plus longues ont été nécessaires pour les zones peu profondes du manteau neigeux par rapport aux zones plus profondes. Nous soutenons que les chutes d’avalanche font suite à la réduction de la stabilité du manteau neigeux causé par le soleil. Cela indique l'importance d’analyser les résultats des analyses du manteau neigeux en utilisant autant une échelle spatiale que temporelle.

1 INTRODUCTION

One of the most dangerous types of snow avalanches is persistent deep slab avalanches because of their large destructive potential. Such avalanches have severely damaged infrastructure such as ski lifts (Savage 2006), buried roads, and killed humans in mountainous terrain (Jamieson and Geldsetzer 1996). Persistent deep slab avalanches are formed from the failure of a persistent weak layer with widespread propagation across an avalanche start zone. The failed persistent weak layers are generally a layer of surface hoar, facets, or depth hoar and all may be associated with an underlying or overlying stiffer melt-freeze crust (Jamieson et al. 2001). Deep slabs are generally greater than 80 cm in average thickness and can reach up to several metres, equating to 100 mm H_2O to over 400 mm H_2O of load (Conlan et al., 2014). Slab avalanches can either be triggered from the weather (from here on called natural releases) or from localized dynamic loads such as skiers, snowmobilers, or explosives (known as artificial releases). Both release types of deep slab avalanches are generally hard to forecast because of the depth to the persistent weak layer (failure layer). With greater depth, stresses induced from localized dynamic loads generally dissipate prior to reaching the persistent weak layer (Thumlert et al. 2013). Some weather parameters typically also play a lesser role in deep slab avalanche releases, such as warming from air temperature or incoming shortwave radiation, as they typically only affect the top 40 to 50 cm of the snowpack (Schweizer and Jamieson 2010).

The effect of the sun on the snowpack is well understood but it is sometimes overlooked during the middle of the winter in avalanche terrain. Solar warming of the snowpack occurs primarily from direct incoming shortwave radiation (0.15 to 4 µm) (Armstrong and Brun 2008). A small fraction, on the order of 10 %, penetrates the snow surface and warms the upper snowpack while the remainder is reflected back towards the atmosphere (Oke 1987). Shortwave radiation that penetrates the snow surface decreases with depth as explained by Beer’s Law. Although incoming shortwave radiation is lower during the mid-winter months than late season months, it can still increase temperatures near the surface of the snowpack by multiple degrees Celsius. Exner and Jamieson (2008) discuss stability changes that occur from daytime warming with air temperatures remaining below 0 °C. They state that the most frequent cause of near surface warming within a snowpack in western Canada is direct solar radiation.

Snowpack warming can be a cause of both stability and instability, largely dependent on the amount and timescale. Slow warming of a snowpack, such as a modest temperature increase over days, generally leads to equilibrium metamorphism, or rounding of the snow grains (McClung and Schaerer 2006). This process promotes bond growth between the grains and ultimately increased stability of the snowpack. Warming also causes elevated strain rates, also known as snowpack creep in the upper tens of centimetres of the snowpack. Densification of the snowpack and a higher grain bond to surface area ratio generally occurs from such conditions and a stable snowpack is the result. With rapid warming, such as direct sun exposure over hours, equilibrium metamorphism and the creation of new bonds is too slow to substantially increase stability but strain rates can dramatically increase and the destruction of bonds results. This generally leads to instability within the upper snowpack. Depending on the snow stratigraphy, the high strain rates may lead to strain softening and then direct brittle fracture of a weak layer that may be present in the upper snowpack (Exner and Jamieson 2009).

The results of common snowpack tests used by forecasters and recreationists can be influenced by surface warming. Simenhois and Birkeland (2008) found that stability scores tended to decrease with surface warming for the Extended Column Test (ECT) and the Propagation Saw Test (PST) for inclined snowpacks. They found that crack propagation occurred more frequently in the afternoon after surface warming compared to the morning when the overlying snow was stiffer. Similarly, Reuter and Schweizer (2012) found lower PST scores during days of high incoming shortwave radiation, associated with a decrease in slab stiffness as derived from snow micro-penetrometer measurements. They state that the decrease in PST scores was likely because of decreased slab stiffness and hence increased bending of the overlying slab rather than a change in the weak layer fracture energy.

Simenhois and Birkeland (2008) argue that the increased creep associated with warming of the upper snowpack increases the fracture propagation potential of a shallow buried weak layer. This was concluded from the findings that snowpack test results decreased on inclined snowpacks but remained constant on flat snowpacks over days that experienced high amounts of warming.

Solar warming is currently applied in snowpack stratigraphy simulation models because of its importance. Both the French model CROCUS (Brun et al. 1992) and the Swiss model SNOWPACK (Bartelt and Lehning 2002) use meteorological data to simulate the effects of incoming shortwave radiation on the snowpack. For simple every-day use and for areas without powerful simulation models, the solar warming model SWarm (Bakermans and Jamieson 2009) was developed to quantify temperature increases in the upper snowpack. It is a simple spreadsheet-based regression model solely used to estimate the amount of solar warming within the upper snowpack.

Avalanche forecasters are well aware of the impact shortwave radiation has during late winter and spring months, but sometimes overlook its importance during early and mid-winter months. The case study presented here shows an example of when solar warming can still be of importance during the middle of the winter for a large avalanche.

Figure 1. Deep Tap Test (DT). A block of 30 cm by 30 cm by 15 cm above the persistent weak layer is isolated. The test is completed by applying 10 taps moving the hand from the wrist, 10 taps moving the arm from the elbow, and 10 taps moving the arm from the shoulder. The number of taps and the fracture character are recorded.

Figure 2. Propagation Saw Test (PST). A column of 30 cm laterally by 100 cm upslope is completely isolated to below the persistent weak layer. The user passes the blunt edge of a snow saw along the persistent weak layer until the fracture propagates ahead of the saw. The cut length, total column length, and release type are recorded.

Figure 3. Deep slab avalanche start zone. Profile locations are visible above the crown on the right portion of the naturally triggered avalanche and labelled in Figure 4.

2 METHODS

We accessed a natural persistent deep slab avalanche that was reported by a helicopter skiing operation. The avalanche released during the first week of February and we performed our snowpack tests three days post-release. Four snowpack profile locations were chosen to analyze the persistent weak layer, the overlying slab, and to perform snowpack tests. The profile locations were judged to be representative of the majority of the start zone because of its uniform aspect and elevation. Two Deep Tap tests (DTs) (Figure 1) and two PSTs (Figure 2) were conducted at each profile to observe reproducibility. The DTs were performed as described in the Observation Guidelines and Recording Standards for Weather, Snowpack and Avalanches (OGRS) (CAA 2007). The PSTs were prepared and completed as described by Snow, Weather, and Avalanches Guidelines (SWAG) (Greene et al. 2010).

The weather preceding the avalanche was obtained from an automated weather station operated by the British Columbia Ministry of Transportation and Infrastructure (BCMOTI). This station reports hourly temperature, precipitation, wind speed, and wind direction data. The station is approximately 24 km from the release site. The weather station elevation is 1570 m above sea level and the start zone elevation is approximately 2400 m above sea level. Although there is a variation in location and elevation leading to different absolute weather values, it is expected that the weather station and start zone experience similar weather trends. Manual weather measurements from a nearby operation's lodge located 6.5 km from the start zone and at an elevation of 1110 m were also used in comparison. The operation reports daily values of minimum and maximum temperature, cumulative precipitation, wind, and sky cover.

The precipitation and sky cover data were used to estimate solar warming of the snowpack from incoming shortwave radiation using SWarm (Bakermans and Jamieson 2009). This model estimates the amount of warming 10 cm down from the snow surface, with a standard error of approximately 1.6 °C.

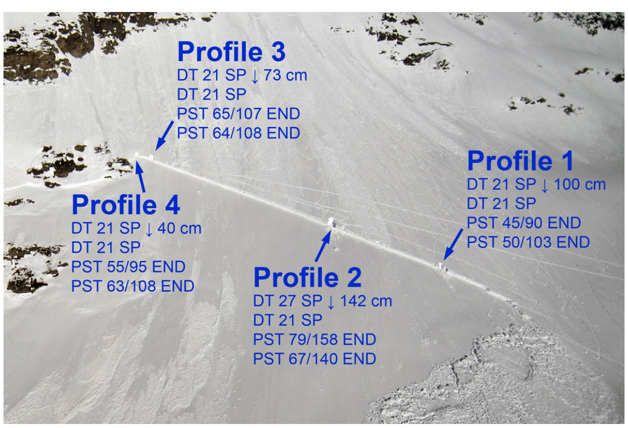

Figure 4. Profile locations with Deep Tap test (DT) and Propagation Saw Test (PST) results. The depth to the weak layer at each profile location is also displayed.

3 RESULTS

This avalanche was classified as a destructive size 3 based on the definitions provided in OGRS (CAA 2007). The start zone was inclined between 30° and 37° with an average angle of 34°. It had a consistent aspect of 235° and it was located at an elevation of 2400 m, in alpine terrain. The width of the avalanche was approximately 300 m (Figure 3). Two similar natural avalanches released on an adjacent mountain during the same day, with approximately the same aspect and incline.

The avalanche released on a persistent weak layer of rounded facets below a melt-freeze crust. The faceted layer likely dated from a prominent surface hoar growth period nearly 60 days prior to the day of release. There was a varying height of snow measured vertically above the weak layer, ranging from approximately 20 cm near rocky cliffs to 170 cm in areas where the snowpack was deep. The overlying snow had a slab density of approximately 280 kg m^{-3} and a bridging index of 3.5, as described by Conlan et al. (2014).

DTs conducted on the failed persistent weak layer all released between 21 and 27 taps (Figure 4). The fracture character was consistently Sudden Planar (CAA 2007). PSTs all propagated to the end of the column. The relative cut length varied from 48 % to 61 % of the column length (Figure 4) with the longest relative cut lengths observed where the slab was relatively thin.

Preceding weather is presented in Figure 5. Similar trends are observed for both the weather station and the operation's weather plot. The minimum daily air temperature decreased by approximately 1 °C each day at the weather station over the preceding five days. Relatively small diurnal fluctuations were observed at the two weather station locations and maximum air temperatures reached zero at the elevations of the weather stations. No precipitation was observed during the day of release or over the preceding two days at the weather stations. Wind speeds were generally light to moderate over the entirety of the preceding two weeks at the weather stations. Sky cover data from the operation's observations indicates a clearing trend over the preceding four days, with clear skies observed during the day of release. When applying snow surface conditions with sky cover for a southwest slope of 35^o steepness, SWarm indicates an additional warming of 8.7 °C at a depth of 10 cm within the snowpack during the day of release (Figure 5). This is the most amount of warming from incoming shortwave radiation observed over the fourteen days preceding the release.

Weather trends remained consistent between the day of release and the day that the avalanche was visited (Figure 5). Minimum daily air temperatures generally decreased by about 0.5 °C per day. No precipitation was observed, as clear skies were reported each day. Wind speeds increased slightly, but only to the moderate range.

4 DISCUSSION AND CONCLUSIONS

The reproducibility of the DT Sudden Planar fracture character was expected, as found at most start zones that released deep slab avalanches (Conlan et al. 2014). The fracture character provides insight into the likelihood of fracture initiation as well as fracture propagation. The results of Sudden Planar (i.e. high likelihood of fracture initiation if stresses are applied to the layer and high

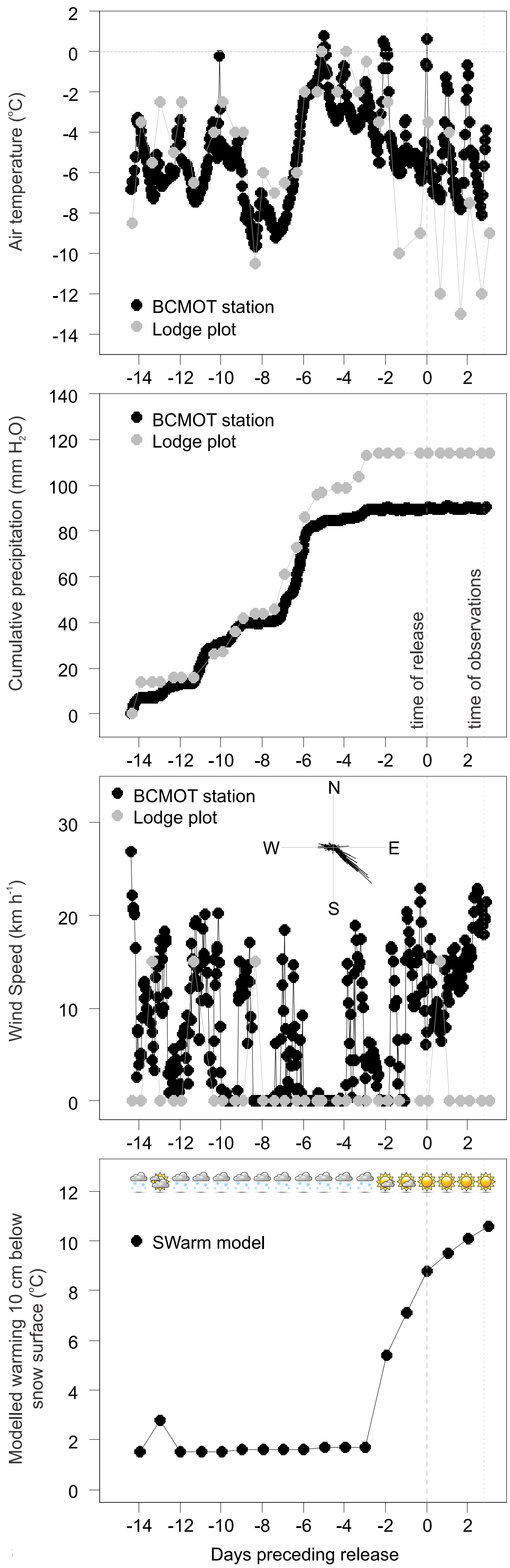

Figure 5. Air temperature, cumulative precipitation, and wind speed preceding and proceeding the time of the avalanche release as observed from the British Columbia Ministry of Transportation and Infrastructure (BCMOTI) weather station and the backcountry ski lodge's weather plot. Wind direction data are also displayed as a rose diagram for the two weeks preceding the release. The solar warming model SWarm was used to model solar warming 10 cm below the snow surface. It used sky cover data and snow surface conditions obtained from the backcountry ski operation. It was applied for a slope angle of 34° and aspect of 235° and a latitude and longitude of the start zone. Sky cover data obtained from the local operation is displayed above the SWarm model output. Both the time of the release and the time of observations are displayed as dashed lines.

fracture propagation potential) are expected across a slope that released a slab avalanche. The number of taps for the test was relatively consistent for all the tests, and this is probably because the hardness difference between the overlying layer, the persistent weak layer, and the underlying layer were similar for all profile sites.

Results from the PSTs were spatially variable. Both of the locations of thin snowpack produced relative cut lengths greater than the relative cut lengths in the regions with thicker snowpack. We speculate that snowpack warming from incoming shortwave radiation could have influenced the results of the tests performed in the shallow snowpack. The shallower PSTs conducted on this slope were approximately 40 and 70 cm deep. We suspect that the shallowest PST would have experienced some influence of the increased strain rates from warming of the upper snowpack during peak warming. This is in accordance with Reuter and Schweizer (2012) who noticed that PST cut lengths decreased as the day progressed and more incoming shortwave radiation warmed the snowpack for a weak layer buried approximately 40 cm. It is unlikely that the tests conducted at 70 cm had a substantial influence from snowpack warming, unless sustained warming occurred. Such conditions were not observed with air temperature data at the weather station. Although the potential solar warming amounts were high and even increased between the release day and observation day, it is unlikely that this alone would allow for warming this deep in the snowpack because of strong radiative cooling at the snow surface at night and because heat conduction is slow.

With this temporal variation of snowpack warming, it is possible that the PST cut length results at the shallowest profile (Profile 4, 40 cm slab thickness) would have decreased if the tests were conducted at the time of avalanche release (i.e. mid-afternoon), when upper snowpack warming was high. This highlights an important point, that test results should be analyzed and interpreted for not only spatial variations but also temporal variations. We speculate that the cut lengths of the PSTs conducted in the shallow profile might have been lower, possibly below the 50 % mark of *high propagation propensity* as discussed by Gauthier and Jamieson (2008) and Greene et al. (2010). This is in agreement with findings from finite element modeling performed by Schweizer et al. (2011) that larger critical cut lengths are observed with stiffer slabs. We believe that the tests would all have still propagated to the end of the column during maximum warming because of the relatively low weak layer specific fracture energy. Further testing at similar avalanches is required to assess this hypothesis.

The preceding weather trends of the parameters obtained at the weather stations do not show any substantial evidence of why this avalanche released. Often, a weather station may indicate high amounts of precipitation, high winds, or warm temperatures preceding the release of a deep slab avalanche (e.g. Jamieson et al. 2001; Föhn et al. 2002; Savage 2006; Tracz 2012; Conlan and Jamieson 2013). For this avalanche, sky cover also had to be analyzed to provide a probable cause for the release of a natural deep slab avalanche. Sky cover is not often available from weather stations, as expensive radiometers are required along with the upkeep of them. In this case, sky cover data obtained from backcountry ski guides was crucial in estimating additional snowpack warming from incoming shortwave radiation. Weather forecast models also predict sky cover and radiation amounts which can be used to predict potential solar warming. We suspect that the warming of the upper snowpack caused high enough strain rates to cause weak layer failure then brittle fracture in the shallow portions of the snowpack. This initiated fracture then propagated where the persistent weak layer was quite a bit deeper.

This case study highlights the importance of incoming shortwave radiation for avalanching during even the heart of the winter season. Often, solar warming is not routinely discussed within operations or by backcountry recreationists until the late winter and spring. As in this example, if the weather and the snowpack are suitably predisposed, deep slab avalanches from solar warming can occur much earlier than usually anticipated. Such a situation may be where a spatially continuous persistent weak layer exists in a sun-exposed start zone with some shallow areas, such as near rocks. Furthermore, a day of strong incoming shortwave radiation would be required to increase the strain rate in the upper snowpack.

However, it should be noted that such weather conditions that released this deep slab avalanche typically occur a handful of times over a winter season, but rarely deep slab avalanches are observed. This is because the ideal situation of a deep persistent weak layer with shallow spots near rocks or trees is required for the upper snowpack warming to affect the weak layer. In most cases where deep persistent weak layers are present within a start zone, shallow spots do not exist, the weak layers are still too deep to be largely affected, or the layers are spatially variable and differ in properties around the shallow spots. Snow profiles are often conducted in the most represented or *average* snowpack for a start zone and very few profiles are conducted to assess the vast spatial variability that can exist. Jamieson (2003) summarizes practical methods for assessing the spatially variable snowpack. We find that attention to solar radiation, optionally using the model SWarm, is helpful on a daily basis, even in the middle of the winter when solar input has traditionally received less attention.

ACKNOWLEDGEMENTS

The authors thank the members of the Applied Snow and Avalanche Research group at the University of Calgary (ASARC) for data collection and insightful discussions. We thank the Avalanche Control Service of Parks Canada at Rogers Pass, B.C. and Mike Wiegele Helicopter Skiing at Blue River, B.C. for research facilities and logistical help. The primary author further thanks the Natural Sciences and Engineering Research Council of Canada (NSERC) for scholarly funding. The authors recognize NSERC, Parks Canada, HeliCat Canada, the Canadian Avalanche Association, Mike Wiegele Helicopter Skiing, Canada West Ski Areas Association, Backcountry Lodges of British Columbia Association, the Association of Canadian Mountain Guides, Teck Mining Company, the

Canadian Ski Guide Association, Backcountry Access, the B.C. Ministry of Transportation and Infrastructure Avalanche and Weather Programs, the Canadian Avalanche Foundation, and Tecterra for their financial support towards ASARC. Finally, we thank Canadian Mountain Holidays (CMH) Heli-Skiing, in particular CMH Galena, for their logistical assistance and weather data.

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