MEASUREMENTS AT RECENT DEEP SLAB AVALANCHES

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ABSTRACT: Hard-to-forecast deep slab avalanches can release unpredictably under diverse conditions ranging from storms to clear days to locally induced stress to the snowpack. For the formation of many natural avalanches, a point is reached where the mass loading of overlying snow overpowers the mechanical properties of the weak layer. This can occur from additional loading above the weak layer, such as from precipitation or wind loading. Furthermore, natural failure can occur from solar warming and temperature variations. External stresses applied to the snowpack from skiers, snowmobilers, and other forces can also trigger deep slab avalanches. We collected field measurements of the properties of the failure layers and slab load to determine trends and correlations between such variables. The failure planes were analyzed using the deep tap test, propagation saw test, shear frame tests, and hand hardness and the overlying loads were calculated using density measurements. Spatial variability across the crowns was also assessed by use of multiple profiles and tests. Deep tap tests consistently yielded sudden (Q1) fractures and the cut length in the PST was usually less than 60% of the column length when the fracture propagated to the end. Preliminary results on spatial variability indicate that DT and shear frame results tended to increase with slab depth at some deep slab locations and crown thickness typically varied substantially. Locations with a thin snowpack, such as near rocky cliffs, were likely trigger points for some of the deep slab avalanches.

KEYWORDS: persistent weak layer, cohesive slab, avalanche forecasting, snow stability, snow strength

1. INTRODUCTION

Deep slab avalanches typically release unexpectedly and are capable of generating enormous damage. They are formed when a cohesive slab of snow fractures on all sides and releases above a persistent weak layer (Bradley, 1970; McClung and Schaerer, 2006). They can form naturally, either from increased load or solar warming, or by a localized force such as a skier or snowmobiler. Varying defining characteristics have been applied to deep slab avalanches, including a minimum average crown depth (Savage, 2006; Comey and McCollister, 2008; Tracz and Jamieson, 2010), a minimum age of the persistent weak layer (Tracz and Jamieson, 2010), or stating that they run on the ground (Bradley and Bowles, 1967; Bradley, 1970).

Forecasting deep slab avalanches has been known to be harder than other avalanches (Jamieson et al., 2001). Avalanche forecasting provides the probability of an event occurring, and the probability of deep slab avalanches is typically lower than other avalanches like point releases and storm slabs. The likelihood of them occurring is assessed based on whether other deep slab avalanches have been observed in the forecasted region, analyzing weather forecasts, and from understanding the snowpack of the forecasted region. The latter is done by having an idea of the persistent weak layers present and the stratigraphy of the overlying snow, gained from snow profiles and field observations.

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1.1 Deep slab avalanche formation

Deep slab avalanches are typically found in alpine terrain without great topographic variation, but they can occur on any aspect as well as at and below tree line. Deep slab avalanches tend to occur on inclined terrain in the range of 30-45^{o} and they can pull cohesive slabs from even shallower angles (e.g. Jamieson and Geldsetzer, 1996). Released bed surfaces reload as the winter continues and may re-release later in the season (Voight et al., 1990).

The persistent weak layer plays a vital role in deep slab avalanche formation as it needs a high propagation potential to release a slab and must also have a low enough shear strength to release from increased shear stress from the overlying snowpack (McClung and Schaerer, 2006). The persistent weak layer is often faceted crystals above or below a crust (Tracz and Jamieson, 2010). Other common weak layers include buried surface hoar and depth hoar (Schweizer et al., 2003).

1.2 Previous Research

Studies have been conducted to assess important characteristics of deep slab avalanches and preceding weather (e.g. Bradley, 1970; Fitzharris, 1987; Jamieson et al., 2001; Comey and McCollister, 2008; Tracz and Jamieson, 2010), but limited field observations have been performed in start zones across entire mountain ranges. Many deep slab avalanches are observed in mountainous terrain from afar every year during the winter months, but very few crowns are accessed to perform fracture line profiles and conduct tests to gain insight into the persistent weak layers and overlying slabs.

Bradley and Bowles (1967) and Bradley (1970) performed measurements close to where the snowpack had released at the ground. They analyzed the penetration resistance at the base of the snowpack and the load of the slab and concluded that these two measurements could be used to predict deep slab avalanches. Jamieson et al. (2001) conducted field observations during two winter seasons to assess the importance of weather and snowpack data in relation to natural deep slab avalanches. Statistical analysis showed that previous avalanche activity was the highest ranked predictor of natural avalanches, followed by accumulated snowfall over several days, air temperatures changes over 4-5 days, snowpack properties including a shear frame stability index, and hardness differences between the persistent weak layer and underlying crust.

Snowpack properties are often spatially variable across a start zone which increases the uncertainties involved in forecasting (Jamieson, 2003; Hägeli and McClung, 2004, Schweizer et al., 2008). Previous studies have tried to quantify spatial variability (see Schweizer et al., 2008). Snowpack depth can vary significantly across a slope due to prominent effects such as wind, but the presence of a persistent weak layer is usually uniform at the slope scale (Schweizer et al., 2008). However, weak layer heterogeneity and slab thickness variability are found on any slope, and could be an important factor for deep slab avalanche release with thin spot triggering (Jamieson et al., 2001).

For this research, safely accessible deep slab avalanches were visited to further understand the relationships between the persistent weak layer, the overlying slab, and preceding weather characteristics to try to improve our forecasting abilities. This paper discusses data obtained for the persistent weak layer and slab properties for recently visited deep slab avalanches.

2. DATA AND METHODS

Cohesive slab avalanches that failed on a persistent weak layer that was at least 14 days old, but that did not fail during the cycle of the respective layer, were analyzed in this study across Western Canada (Figure 1). Field observations and measurements were obtained at 9 naturally occurring deep slab avalanches, 20 deep slab avalanches triggered by skiers and snowmobilers, and 12 deep slab avalanches triggered by explosives, helicopters, snowcats, cornice failures, stepdowns, or in sympathy. Most avalanches were accessed within one to three days post-failure to obtain measurements prior to significant changes in the weak layer and slab. General site characteristics including location, aspect, elevation, and slope angle were recorded. Snow profiles were conducted at least 1 m upslope of the crown or to the side of the flank (CAA, 2007) in areas without cracks for an assessment of representative undisturbed snow. The failed persistent weak layer grain type and size were recorded along with the snow grains directly above and below the failure plane.

An assessment of the strength of the weak layer was conducted using the deep tap test (DT) (CAA, 2007) for avalanches studied within the previous three years. Compression tests (CT) were used prior to the inception of the DT. It should be noted that equivalent DT results would be either less than or equal to the CT score, and that fracture character should be identical between CT and DT and are therefore grouped for this

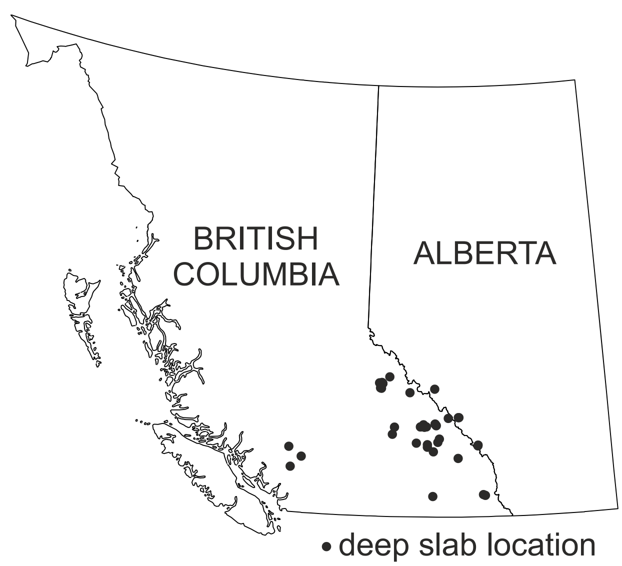

Figure 1: Location map of accessed deep slab avalanches in the provinces of British Columbia and Alberta in Western Canada.

analysis. An exception is a no fracture result for a CT which may have in fact released with a DT, so such results were therefore discarded. The propagation propensity of the weak layer was assessed using the propagation saw test (PST) (Gauthier et al., 2008). Shear frame tests were conducted at some snow profiles to assess the strength of the bonding of the overlying slab to the weak layer. An average of 12 shear frame tests was obtained and results are represented by the Daniels strength, Σ_∞ (kPa) (Jamieson, 1995). Mass loading was evaluated by obtaining bulk density measurements of the snow from surface to directly above the persistent weak layer. Snow hardness measurements were obtained by the hand test procedure described in CAA (2007) and results were converted to the equivalent ram resistance mean value for statistical analysis (Fierz et al., 2009). To estimate slab stiffness, a bridging index was constructed by multiplying the slab layers of certain hand hardness by the hand hardness index, similar to Schweizer and Jamieson (2003). For this index, a number close to one would indicate a relatively weak slab of mainly fist and four finger layers, whereas a layer approaching four would have high cohesion with many pencil-hard layers. Statistical correlations were completed using Spearman's rank correlation coefficient, ρ.

Multiple snow profiles were conducted across some released start zones to assess spatial variability. Extra snow profiles were chosen to reproduce the primary representative snow profile as well as to observe variation of aspect and slope angle. Slab thickness and slope angles were also obtained across the start zone at some deep slab avalanches for an analysis of terrain and snowpack variability, when they could be safely performed.

3. RESULTS AND DISCUSSION

3.1 Terrain

Of the 41 avalanches accessed, 19 were in alpine terrain, 20 at tree line, and 2 below tree line. Deep slab avalanches most often occur in alpine terrain, but accessibility is typically simpler and lower risk at and below tree line. The majority of the avalanches were classified as destructive size 3. Although deep slab avalanches are typically high on the destructive scale due to the thickness of the slab, some are only able to propagate over a small area or not run far in the track. These are represented by observed sizes 1 to 2. The width of the slabs ranged from only a few metres to 700 m and correlates well with destructive size (Figure 2).

Most accessed avalanches had average start zone angles between 30 and 45 degrees (Figure 3). All but one heavy triggered deep slab avalanche occurred on a northerly aspect along with many natural and light triggered deep slab avalanches, where persistent weak layers are more often well preserved. The two natural deep slab avalanches observed on southwest aspects were believed to be triggered by solar warming. Although heavy triggers occurred on average start zone angles up to 45 degrees, the two shallowest

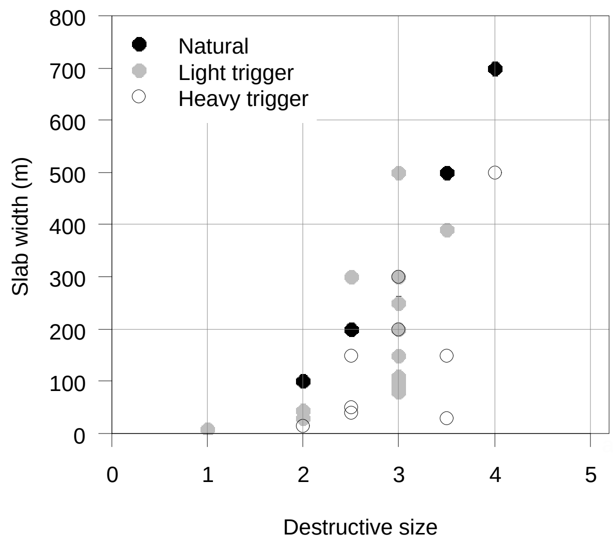

Figure 2: Relationship between deep slab avalanche slab width and destructive size.

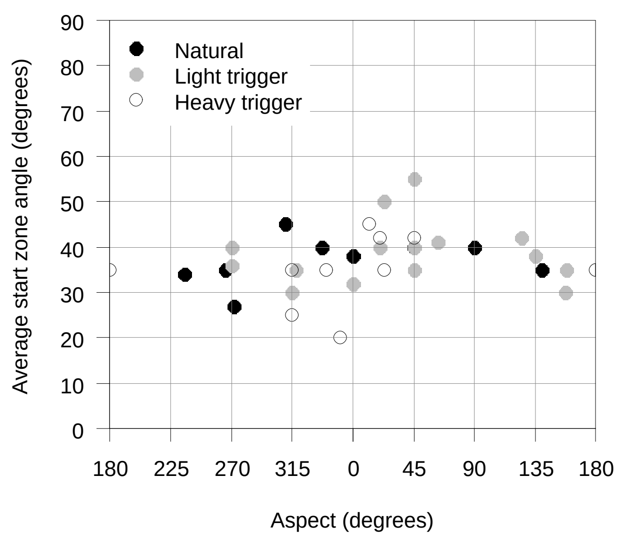

Figure 3: Distribution of average start zone angle with respect to aspect.

average slope angles of 20 and 25 degrees were triggered by a large force, including a cornice failure and a snow cat, respectively.

An effort was made to try to assess whether each deep slab avalanche was triggered from a location with a thin snowpack. Of the 20 avalanches triggered by a skier or snowmobiler, we judged that 7 of them were triggered where the slab was much thinner than the average thickness. Furthermore, we hypothesize that two of the natural avalanches visited within the past winter were triggered in a thin spot. For these two, it is likely that solar warming reduced the slab stiffness by weakening the cohesive strength of the slab in a shallow, rocky region. This caused increased creep and failure of the persistent weak layer from shear strain followed by propagation across the slope and release of the slab. It is unknown whether thin spot triggering occurred at the remainder of the observed deep slab avalanches.

3.2 Weak Layer Types

The majority of the accessed avalanches failed on buried surface hoar with the remainder of the failure layers being facets and depth hoar, both with and without a crust. Surface hoar layers were buried between 14 and 68 days prior to failure, with most of the avalanches occurring between 14 and 40 days of burial. Facets and depth hoar typically failed later than surface hoar, with facets failing between approximately 24 and 147 days from snowfall and depth hoar ranging between 69 and 114 days from snowfall. Although light triggers were observed across a wide range of weak layer ages, skiers and snowmobilers were the cause of the latest avalanche for each weak layer type, likely due to late season excursions. A bridging index between 1 and 3.8 was observed for slabs on buried surface hoar whereas slabs on facets and depth hoar had a bridging index between 2.7 and 3.6. This was likely due to the older slab ages above facets and depth hoar and consequently a more cohesive slab.

Grain sizes varied for each avalanche, but in general surface hoar was between 1 and 15 mm, facets were between 1 and 4 mm, and depth hoar ranged from 2 to 15 mm. Grains above the failed layer were typically 0.5 to 1 mm facets, 0.5 to 1 mm rounded grains, or a melt-freeze crust. Grains below the failed layer ranged from 0.5 to 2 mm facets, 0.5 to 1 mm rounded grains, a melt-freeze crust, ice, or ground.

3.3 Hand Hardness

Hand hardness is a commonly practiced method of qualitatively assessing the strength of a snowpack layer. Hand hardness typically increases with depth, but weak layers can maintain a low rating over time and even decrease as the winter progresses, such as with facets and depth hoar. The hand hardness of the weak layer was typically in the fist to one-finger range whereas the overlying and underlying snow was often pencil to knife. Three avalanches exhibited weak layers with pencil-hard rounding facets or surface hoar.

3.4 Deep Tap and Compression Tests

DTs were performed at 16 of the deep slab avalanches and CTs were conducted at 10 other deep slab avalanches. DT results were typically moderate to hard with three exceptions with no fracture. Fracture character was mostly sudden planar or sudden collapse (Q1), largely depending on the weak layer thickness. The number of taps for DT and CT generally increased as the overlying load increased (Figure 4). This is likely due to the slab ultimately being older as it increased in mass and average density, consequently allowing for increased strength of the weak layer from pressure metamorphism.

3.5 Shear Frame Tests

Shear frame tests were conducted on the weak layer of 18 deep slab avalanches. Most shear frame results were in the Daniels strength range of 1 to 3 kPa with a maximum average of 4 kPa observed. Cohesion of the weak layer to the overlying slab increased as the load of the overlying slab increased (Figure 5), due to the increased gravitational forces applied on the

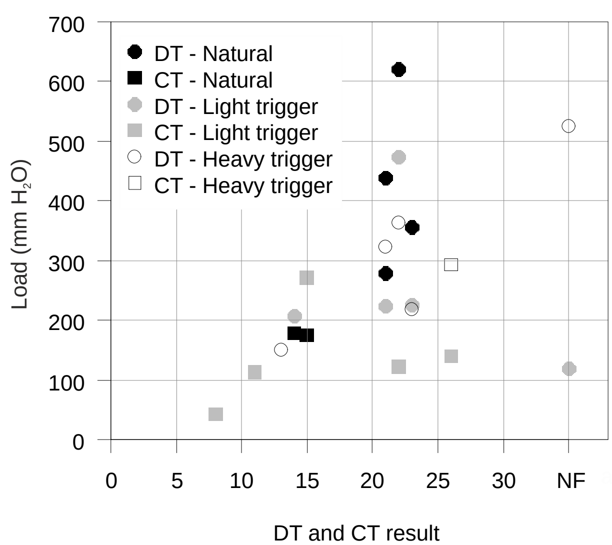

Figure 4: Comparison between deep tap test and compression test results on the persistent weak layer with overlying load.

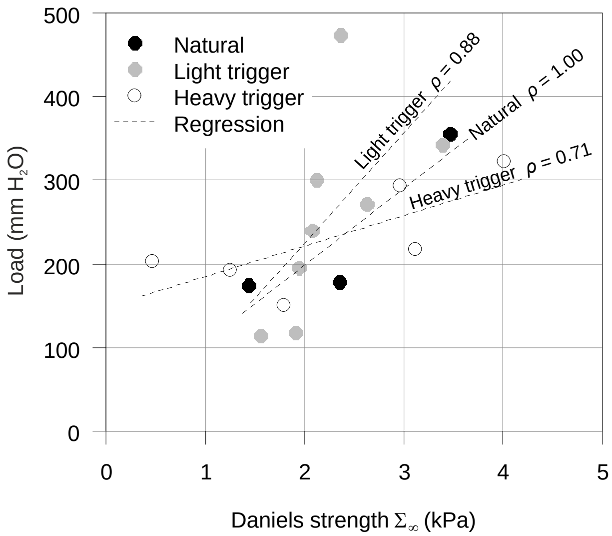

Figure 5: Comparison of load and Daniels strength from shear frame tests on the persistent weak layer.

interface and subsequent pressure metamorphism.

A steeper regression fit was computed for the light triggered deep slab avalanches. It is speculated that this is due to the need for a failure layer that is exceptionally weak to be affected by the stresses of a skier or snowmobiler when the slab is thick. Slab thickness is less important for the much greater forces of heavy triggers as well as the different processes involved with natural avalanches, which are both represented by a shallower regression fit.

3.6 Propagation Saw Test

PSTs were conducted at 21 of the deep slab avalanches. Results for all but 2 of the tests were under 56% of the length of the column. Two results of approximately 90% of the length of the column both occurred at avalanches triggered by explosives. Of the 21 PSTs, 19 propagated to the end of the column, 1 ended at a fracture in the overlying slab, and 1 arrested within the column.

Gauthier et al. (2008) indicate that high propagation propensity was found with 50% or less of the length of the column and low propagation propensity was found with greater than 50% of the length of the column. For this research, the PSTs that produced results between 50 and 56% of the length of the column were generally at depths greater than 1 m, indicating that the columns were larger than those in the study by Gauthier et al. (2008). The results from this study indicate that propagation propensity may be high with cut lengths up to 60% of the length of the column for deep slab avalanches.

PST results were found to be weakly correlated with slab load (Figure 6a) and the bridging index (Figure 6b), suggesting little effect of stiffness on propagation propensity for deep slab avalanches. . However, previous research (e.g. Johnson, 2001; Schweizer et al., 2010) indicates that slab stiffness is an important parameter for fracture propagation in weak layers. It is likely that a dependence of slab stiffness on propagation propensity was not observed due to the limited variability in slab stiffness in our small dataset.

3.7 Spatial Variability

DT results at different locations along a respective crown with varying thickness generally showed a slight increase in score as slab

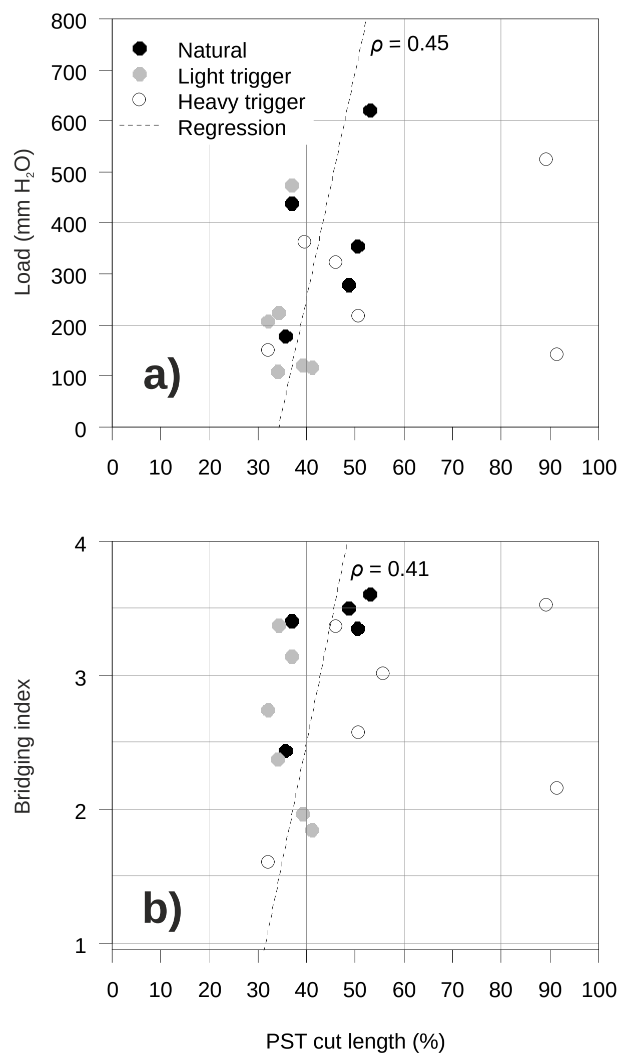

Figure 6: Relationship of a) load and b) bridging index with propagation saw test cut length percent for tests that propagated to the end of the column. Linear regressions and Spearman's rank correlation coefficients ignore the two statistical outliers, as determined by the 95% confidence interval.

thickness increased. Deep tap character was consistent for each representative deep slab event. For five events where spatial variability was assessed with shear frames, Daniels strength was generally stronger with a substantial increase in load (Figure 7). No significant trends were observed with PST results and crown depth, which is consistent with the earlier observation that propagation propensity is only minimally affected by slab thickness for deep slab avalanches.

Minimum and maximum start zone slope angles generally ranged approximately five degrees from the average angle. Avalanche crown thickness varied substantially for some events, with a measured difference of up to 150 cm. No strong trends were found with slab thickness and slope angle, although a detailed crown measurement profile was only conducted at 4 of the 41 avalanches and will be revaluated after further data collection. Aspect variability was also found at some of the deep slab avalanches, varying by up to approximately 90 degrees. Such variability increases the difficulty of forecasting such events and the need for a good understanding of the snowpack in varying regions of start zones.

Bridging was found to vary by up to an index of approximately one across a start zone, often due to increased depth hoar in thin portions of the slab which was typically softer than rounded grains at depth in a thicker snowpack. It is speculated that southerly portions of a start zone may also have a higher bridging index than areas that do not see as much sun due to hard melt freeze layers.

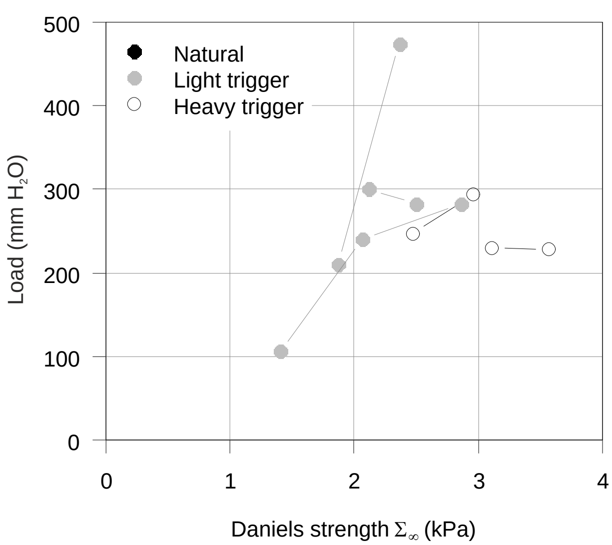

Figure 7: Spatial variability analysis of load and Daniels strength from shear frame tests. Each group of data represents an individual deep slab avalanche event.

4. CONCLUDING REMARKS

Observations taken at 41 recent deep slab avalanches are helping us understand the varying properties of the snowpack associated with these releases. Important parameters analyzed to gain further insight into their release include terrain parameters, strength and propagation potential of the failure layer, properties of the overlying slab including load and bridging strength, and preceding weather leading to the event. The first three are discussed in this paper and provide the following observations:

- Terrain was typically in alpine or at tree line, generally had an average start zone angle between 30 and 45 degrees, and occurred on any aspect but more frequently on northerly slopes.
- Thin spot triggering was important for skiers and snowmobilers and it is speculated that it was also important for natural avalanches that failed from solar warming.
- The persistent weak layer consisted of surface hoar, facets, or depth hoar having failed up to 150 days after the layer was buried by snowfall.
- Weak layer hand hardness was generally fist to one-finger but was found up to pencil-hard.
- Deep tap tests often produced moderate to hard results with sudden planar or sudden collapse (Q1) fracture characters.
- Shear frame tests exhibited Daniels strengths of the weak layer of generally between 1 and 3 kPa but they extended up to 4 kPa as the slab load increased, likely due to stronger bonding from pressure metamorphism.
- Propagation saw tests were typically between 30 and 60% of the column length and propagated to the end of the column, and showed little effect from slab load.
- Spatial variability of crown thickness and slope angle was substantial for some events, indicating the importance of understanding the snowpack across start zones.

Further deep slab avalanches will be accessed over the upcoming winters to increase the number of observations. Preceding weather leading to deep slab avalanche events will also be analyzed in conjunction with field measurements. The analysis will continue with the separation of the different trigger types. As the dataset increases, weak layer types will also be analyzed separately to obtain insight into the similarities and differences of the varying persistent weak layers.

Although snowpack tests jointly show trends within the deep slab avalanches observed, such results can also be found in avalanche start zones that do not release. A decision support tool is therefore the likely result of this research. Such a product will help forecasters make decisions based on typical snowpack results that are currently conducted in mountainous operations along with weather observations from nearby stations.

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