A CLOSER LOOK AT SLOPE ANGLES OF ACCIDENTALLY TRIGGERED PERSISTENT AND DEEP PERSISTENT SLAB AVALANCHES

Roger Atkins[1]*, John Sykes[2], Nicholas Rigby[2], and Pascal Haegeli[2, 3]

[1] *Unaffiliated, Johnsons Landing, BC, Canada*
[2] *Simon Fraser University Avalanche Research Program, Burnaby BC, Canada*
[3] *WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland*

ABSTRACT: Persistent slab avalanches remain a challenge for backcountry avalanche risk management. Of the 222 fatal avalanche accidents in Canada with known weak layer grain type information since the winter of 2000, 56% involved FC and 29% SH layers. The median weak layer ages of these avalanches were 33 days for FC and 14 days for SH layers. Building on existing research on typical slope angles of avalanche release, our analysis of several long-term datasets provides a new perspective into the evolution of persistent slab avalanche problems and where accidental avalanches are triggered. The identified patterns offer practical insight into the characteristics of hazardous terrain in the evolution of persistent slab avalanche problems. A better understanding of incident patterns related to persistent slab avalanche problems can help practitioners better understand how to avoid these challenges. The nature of very low angle avalanches and lingering deep persistent avalanches on moderate terrain as statistical outliers coupled with the possibility to have long years of experience without encountering them causes them to be disregarded in education and snow safety programs alike. In spite of their infrequent occurrence, these avalanches are responsible for some very high profile accidents that disproportionately impact the guiding profession and the guides involved. This study shows that lingering deep persistent avalanches tend to persist on large moderate angled slopes; they do not occur only in steep terrain. These avalanches will always pose a dilemma for risk management, but recognizing the conditions when they are more likely to occur and that they can occur on lower than expected slope angles allows us to make decisions on the basis of their possibility, not their probability.

KEYWORDS: Avalanche risk management, Perception gap, Lingering instability, Low angle avalanches

1. INTRODUCTION

The objective of this study is to investigate the characteristics of two recurring themes in backcountry avalanche risk management: accidentally triggered very low angle avalanches and lingering deep persistent slab avalanches. Avalanches of this type are often disregarded as statistical outliers, but they can be involved in a disproportionate number of accidents and incidents (Black Swan Events). These avalanches are investigated from a risk-based perspective, which requires the assessment of the natural hazard as well as the risk incurred in consideration of human activity.

Steepness of terrain is often considered the most important characteristic of terrain for evaluating potential release areas, but a single value of incline cannot fully capture the relationship between steepness and avalanche release in complex start zones. Even for mostly planar slopes, the accuracy of slope angle measurements, much less estimates, is questionable (McCammon, 2023). The actual frequency with which any piece of terrain produces avalanches is the combination of the underlying terrain features including steepness, site specific aspects of how the snowpack tends to form, and the relationship to connected terrain.

* Corresponding author address:
Roger Atkins
Kaslo, BC, V0G 1M0;
tel: +1 250 353 3292
email: rogeratkins@earthlink.net

2. DATA DISCUSSION

Data used in this study is sourced from a combination of available data sets from western Canada. These data include avalanche observations from operational data collected in the Canadian Avalanche Association's InfoEx system, operational data collected in Canadian Mountain Holidays (CMH)'s SnowBase system, and data from Avalanche Canada's database of fatal avalanche investigations. Collectively, these data sources yield a database of 4400 accidentally triggered avalanche observations of size D1.5 or greater from 1996 through 2025. The analyses presented in this paper are based on subsets of these data that meet criteria specific to each analysis.

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In addition to analyzing these data, Roger Atkins was integrally involved in the design of the data structures and systems that sourced these data and he contributed observations to these databases for decades during his professional guiding career. His understanding of the methods and processes involved in the data collection process provides important insight into the strengths and weaknesses of the datasets. For Roger, these datasets are more than avalanche observation records, they are experiences.

The avalanche records examined in this study include both estimated and measured values of avalanche release area incline. While estimated slope angles raise uncertainty about the precision, accuracy and consistency of these observations, considerable variability has also been identified for measured values (McCammon, 2023).

The majority of the reported slope angles are estimates made by guides and other avalanche professionals. These are skilled observers with a great sensitivity to variations in slope angle and a strong sense of the terrain and frequency where avalanches occur. Values tend to be clustered in 2 to 3 degree increments. This reflects a reasonable resolution that can be expected by estimation or by measurement, but this resolution does not imply accuracy.

In addition to the inherent variability of measured and estimated slope angles, avalanche release areas are not planar features; they can be very complex pieces of terrain involving many different slope angles. Vontobel et al., (2013), for example, found a difference between the average and the maximum slope angle of avalanche release areas on the order of five degrees. While we do not know how the observers assessed the terrain for their estimates, Roger's experience suggests that the estimates tend to be based on relatively steeper portions of the release area but overlook small steep features.

Guides are hyper-alert to steepness in their terrain choices. They may use inclinometers when first learning, when making snowpack observations, or for special investigations, but generally not for making terrain choices. This is the norm for experienced guides that Roger has worked with. Attention to slope angles makes guides sensitive to variations of slope angles to a resolution of about three degrees, but that sensitivity is calibrated against experience with the terrain where they actually observe avalanches, not against inclinometer measurements.

Theory meets practice when terrain steepness is translated into numeric values to report avalanche observations. In the process of analyzing data for this study, we have found a remarkable consistency between slope angle frequency distributions found in our data and slope angle distributions found in the literature and referenced in education. This may not represent numerical accuracy in our estimates; it is possible that the reported observations are essentially reverse engineered to fit the distributions that we have all learned in theory. This could mean that our datasets are less of a database of slope angles, but rather a database where 'slope angles' are used as a proxy for the observers' assessments of the frequency that avalanches occur on terrain of similar steepness.

Variability and inaccuracy in the data mean that it has limited or no value for predictive modelling, but that is not our objective. This study seeks to analyze the data for relative patterns and trends that identify when and where avalanches occur on terrain that is less steep than expected. The large size and span of the data sets is conducive for this purpose.

3. HAZARD CHARACTERISTICS

This section presents patterns in the data relevant to both very low angle avalanches and lingering deep persistent avalanches.

3.1. Incline versus trigger type

On average, skier-accidental (Sa) and skier-remote (Sr) triggered avalanches report lower slope angles compared with all trigger types (Table 1). A likely explanation is that accidentally triggered avalanches reflect a sampling bias because skiers preferentially select lower angle terrain during elevated avalanche hazard. Table 1 provides an expected average incline of 36.3 degrees for accidentally triggered avalanches in this dataset.

Table 1: Average incline versus trigger type.

Trigger	***n***	***Mean incline***
Sa and Sr triggers	3436	36.3
All triggers	5263	38.1

3.2. Incline versus weak layer grain form

Surface hoar (SH) is notorious for producing avalanches on lower-than-expected slope angles. Within our data, the mean incline of accidentally triggered surface hoar avalanches (Figure 1) shows a 1.8-degree difference (34.5 versus 36.3) relative to accidentally triggered avalanches on other weak layer grain forms (Table 1). This ob-

servation is consistent with the results of McCammon (2009), who compared avalanche start zone inclines for different weak layer grain types. A closer look at the incline distribution indicates that 14 percent of these avalanches were reported to have release area inclines less than 30 degrees.

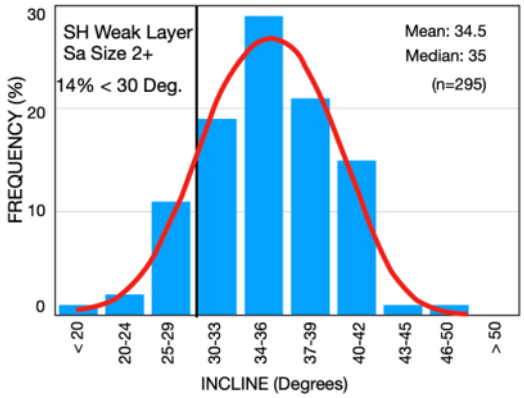


Figure 1: Incline distribution of skier-accidental (Sa) triggered avalanches on surface hoar layers.

3.3. *Very low angle avalanches*

'Very low angle' avalanches in the data sets are identified as Size D2 or larger avalanches with reported slope angles less than 30 degrees. It is notable that 14 percent of the accidentally triggered avalanches on surface hoar weak layers meet this criterion, compared to an expected value of 3 percent for other grain types.

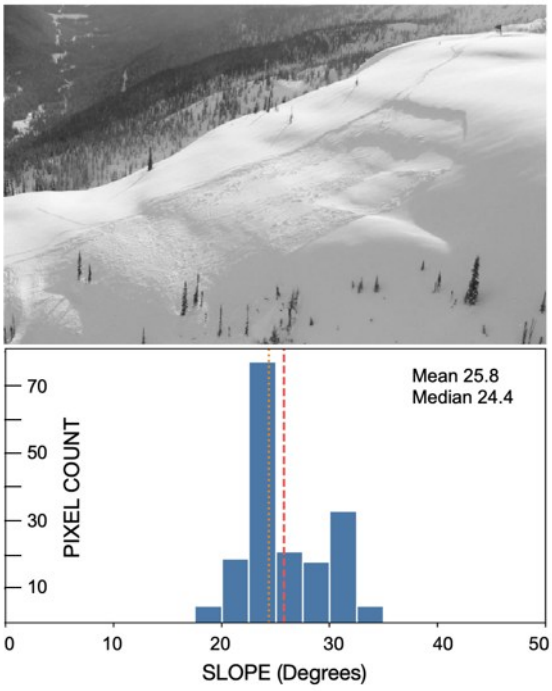


Figure 2: Skier triggered very low angle avalanche on the run "Red Baron" in conjunction with the distribution of slope angles across the release area.

Using a 5-meter resolution digital elevation model (DEM) derived from stereoscopic satellite imagery, we performed a detailed analysis of the incline distribution over manually entered release areas of several known avalanches. Our analysis of an unusually low angle avalanche on "Red Baron" (Figure 2) shows a median incline of 24.4 degrees with inclines less than 30 degrees over 80% of the release area.

Under close scrutiny, very low angle release areas tend to include some areas of steeper incline. These steeper areas can encompass such a small portion of the overall area that they are overlooked completely or just considered surface roughness. The Red Baron avalanche has two steeper bands that are evident in the photograph; one is the trigger point at the crown, and the other one is the shaded area slightly below. The maximum elevation change of each of these bands is only about 3 meters, barely enough to make one ski turn. Inherent inaccuracies of both measured and estimated inclines have been discussed, but even a 5-meter DEM also contains artifacts. Significant edge effects occur when the DEM resolution is relatively large compared to the scale of the modelled polygon and very small features are subject to smoothing.

In the Columbia Mountains of western Canada, 2010 was a standout year for very low angle avalanches due to multiple very well-established surface hoar instabilities (Figure 3). Avalanches were accidentally triggered almost every day, and they came back to haunt guides in their dreams. One co-worker of Roger said "It's not the nightmares that worry me, it's the daymares!". 2010 was the most relentless season in Roger's recollection for this type of avalanche activity, but other years have also had periods of similar instabilities.

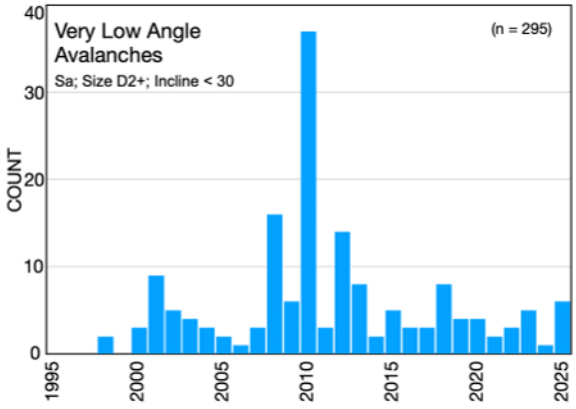


Figure 3: Number of skier-accidental triggered very low angle avalanches per season.

The winter season 2010 was chosen for comparison to other years because of the exceptionally

large number of very low angle avalanches (Incline < 30). The seasons 2008 and 2012 also show elevated numbers of low angle avalanches, but we have not seen such seasons since then. Hence, it is possible to have decades of experience without encountering conditions favorable for very low angle avalanches.

Surface hoar weak layers account for 75% of the very low angle avalanches in our dataset, 15% are facets and 10% other types. Due to pervasive surface hoar instabilities throughout the season, incline distributions for 2010 compared to other years exhibit a similar offset as found for surface hoar related avalanches when compared to other weak layers (Figure 4). The percentage of very low angle avalanches during other years is just 4% (typical of expected avalanche incline distributions), compared to 16% for 2010. This difference is illustrated in Figure 4 by the shaded areas under the incline distribution curves comparing 2010 with all other seasons.

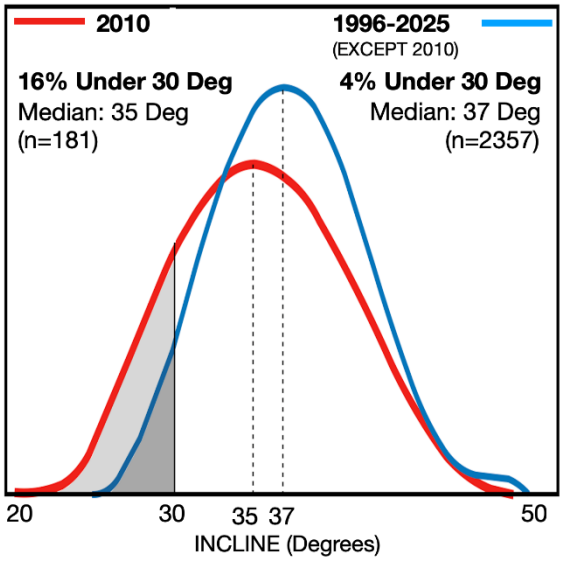


Figure 4: Incline distribution of accidentally triggered avalanches (SaSr) during the 2010 season versus all other seasons.

3.4. Lingering deep persistent avalanches

'Lingering avalanches on moderately angled terrain' are identified within our dataset as avalanches of size D3 or larger with slope angles less than or equal to 35 degrees occurring 50 days or more after weak layer burial. Any instability producing avalanches 50 days after weak layer burial has to be considered a persistent instability. The intent behind differentiating 'Deep Persistent' from 'Persistent' slab avalanches is not so much about the depth of the weak layer in the snowpack as it is to differentiate risk treatment implications, including the potential for avalanches to occur long after the weak layer was buried (Haegeli, Atkins, & Klassen, 2010). 'Long Persistent' might have been a better choice of terminology than 'Deep Persistent'.

In this paper, any dry slab avalanche of size D3 or larger occurring 50 days or more after burial is considered a lingering deep persistent avalanche. Slope angles between 30 and 35 degrees are considered 'moderate' steepness; These inclines are well within the recognized range for avalanche release area inclines, but less than median values and usually not perceived as 'steep' terrain.

Figure 5 shows how avalanche size increases with time after weak layer burial while frequency of occurrence decreases at the same time. The inflection point at 50 days is chosen as a threshold to identify "lingering" avalanches in the datasets. Lingering avalanches with weak layer ages more than 50 days have an average size of D2.4.

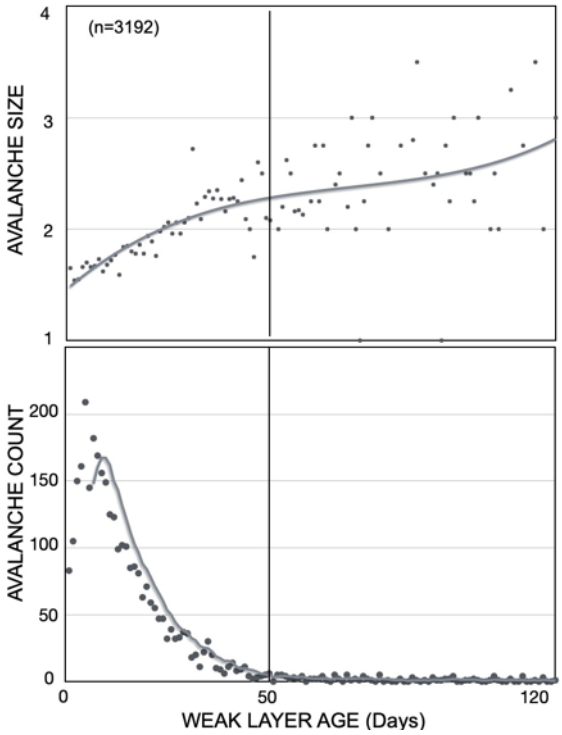


Figure 5: Avalanche size and frequency as a function of time.

Eighty-three percent of the avalanches with known weak layer grain form and weak layer age equal or greater than 50 days are associated with facet (FC) or depth hoar (DH) weak layers. Only one of these avalanches was reported on surface hoar at 52 days weak layer age.

Incline trends of skier accidental avalanches size D2 and larger from the weak layer burial date are shown for different weak layer grain forms in Figure 6. The life span of instabilities associated with

different weak layers is also evident in this diagram. Whereas weak layers with facets (FC) exhibit accidentally triggered avalanche activity up to 135 days after weak layer burial, the activity ceases on surface hoar (SH) and precipitation particles/decomposing fragments (PP/DF) after approximately 35 and 20 days respectively.

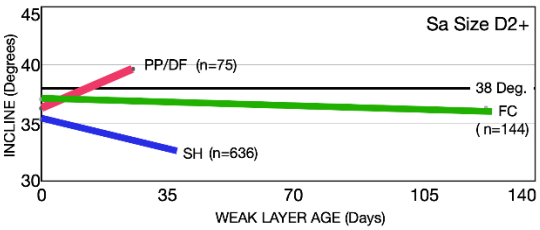


Figure 6: Release area incline trends of skier accidental (Sa) avalanches by weak layer grain form.

Limited data is available for storm slabs and wind slabs failing on precipitation particle (PP) and decomposing and fragmented (DF) weak layers because the failure grain form is usually not reported. The available data shows a maximum life span of about 20 days for PP/DF instabilities, during which time the inclines of skier accidental avalanches tend to increase. This agrees with experience with the caveat that most storm instabilities stabilize much more quickly. Longer lasting storm instabilities are often seen in association with 'semi-persistent' weak layers, typically stellar dendrites under favorable conditions for preservation.

Surface hoar avalanches account for most persistent slab avalanche observations. Skier-accidental triggered surface hoar avalanche inclines show a noticeable negative trend over a maximum life span of approximately 35 days, although they sometimes last a little longer.

Facet and depth hoar avalanches have a potential life span of up to 4 months or more but only occur sporadically after 50 days. The data suggests a slight decreasing incline trend, but the incline distribution remains essentially unchanged over their entire life span. More importantly, however, none of our analyses indicated a statistically significantly increasing trend in slope incline for these types of avalanches over time.

4. RISK CHARACTERISTICS

In a backcountry travel context, risk occurs at the intersection of hazard with exposure and vulnerability resulting from the travelers' actions. This paper focuses on accidentally triggered persistent slab avalanches with special attention to avalanches occurring on inclines that may be perceived as too low to be 'avalanche terrain' at the time.

The incline dataset analyzed in this study is a database of perceived slope angles. As a result, patterns presented here are patterns of risk and not necessarily patterns of hazard as our records represent the interaction of hazard and travelers.

4.1. Very low angle avalanches

Very low angle avalanches are typically considered 'Low Probability, Low Consequence' events. Avalanche education tends to dismiss terrain under 30 degrees as essentially non-avalanche terrain. This is true in most places and most of the time, but not always. Very low angle avalanches require a specific combination of terrain and snowpack, and it is possible to have decades of professional experience without encountering any 'very low angle' avalanches. Education and experience can combine to create a strong belief that they do not exist. Experienced guides have said "if I hadn't seen it with my own eyes, I never would have believed it".

At times, very low angle avalanches are much more frequent than expected. The observed frequency of accidentally triggered very low angle avalanches was 16% in 2010 compared to 4% for all other years. The shaded areas under the curve in Figure 4 represent a 'perception gap' between the expected frequency and the actual frequency of these avalanches in 2010.

By themselves, these avalanches tend to be dismissed as having limited destructive potential, but Table 2 identifies 127 reports of accidentally triggered avalanches reported as size D2 or greater with inclines less than 30 degrees. Twenty-four percent of these avalanches were size D2.5 or greater; these avalanches also accounted for one fatal accident.

Table 2: Size distribution of very low angle avalanches.

Size	***n***	***Percent***
D2.0	96	76
D2.5	25	20
D3.0	4	3
D3.5	1	1

Risk associated with these avalanches is exacerbated because they occur when conditions are also favorable for remotely triggering terrain overhead and/or pulling skiers off of the lower angle terrain into large avalanches in adjacent steep terrain.

Roger's personal experience also highlights that very low angle avalanches are a serious red flag for other surprising avalanche behaviour. Conditions favorable for very low angle avalanches are also favorable for avalanches in moderate (30-35 degree) terrain and for avalanches initiated in steeper terrain to propagate and release larger areas of apparently unconnected very low angle terrain.

4.2. Lingering deep persistent avalanches

Patterns in our data highlight that lingering deep persistent avalanches on moderately inclined slopes are 'Low Probability, High Consequence' events. Figure 7 shows that most fatal avalanche accidents occur on weak layers with age less than 50 days, but lingering persistent weak layers can continue to cause accidents for an entire season. Avalanche size and weak layer grain form are the most distinguishing features of fatal avalanches with weak layers aged 50 days or more. Facets and depth hoar are almost exclusively responsible for these lingering avalanche accidents, while fatal avalanches with weak layer ages less than 50 days primarily involve a mix of surface hoar and facets along with a smaller percentage of non-persistent weak layers. As shown in Figure 6, slope incline distributions of accidents involving facetted weak layers do not appear to show any significant trend with weak layer age.

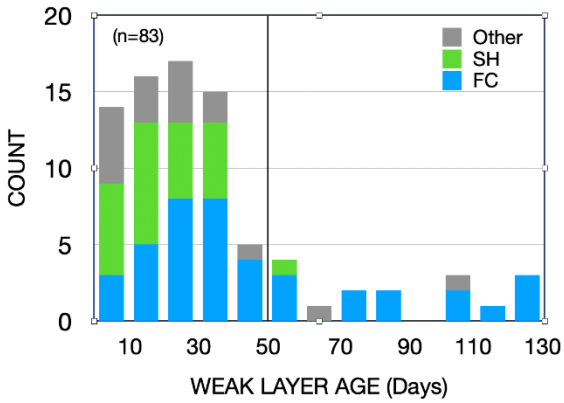


Figure 7: Number of fatal avalanche occurrences as a function of weak layer age in 10-day increments broken down by weak layer grain form.

5. RISK TREATMENT

Risk treatment refers to mitigating danger through actions that reduce the severity of the hazard (e.g., avalanche control), limit our exposure (e.g., terrain choices and travel practices), and/or decrease our vulnerability (e.g., slope size and safety equipment).

Very low angle avalanches and lingering deep persistent avalanches pose dilemmas for avalanche risk treatment. The primary backcountry risk treatment strategy is to use terrain selection and travel practices to limit exposure and vulnerability. Perception of potential release area size and steepness under current conditions each play important roles for this.

5.1. Perception Gaps

Danger occurs in the gap between perception of risk and reality. The 'low consequence' perception of very low angle avalanches can create a perception gap between the perceived and the actual risk. It is possible to underestimate the risk posed by very low angle avalanches, especially if the implications for the surrounding terrain are not taken into consideration.

The shaded areas under the curve in Figure 4 reveal a potential 'perception gap' between the perceived likelihood and the actual likelihood of avalanches on low angle slopes at times of significant surface hoar instability.

Familiarity with storm instabilities creates the belief that avalanches typically become smaller and less frequent on lower angle terrain as conditions stabilize. However, Figure 6 shows the opposite incline trend for skier-accidental triggered avalanches, which also become larger over time. Perhaps this incline trend is the product of the interaction of skiers' decisions and the hazard. A similar trend may not be true for natural and other artificial triggers, but it implies a perception gap between the perceived and actual incline trend.

A similar perception gap exists regarding lingering deep persistent avalanches on moderate angle terrain. Our data does not show a significant change in incline over time for lingering deep persistent avalanches. Please note that what the data shows is less important than what it does not show. The data does not show an increasing trend in the incline frequency distribution for lingering deep persistent avalanches. A perception gap is created by the misperception that the potential for these avalanches becomes limited to steeper terrain in their later stages. These instabilities are prone to linger on very large, moderate angled slopes that tend to preserve the weak layers as well as on steeper slopes where the potentially unstable snowpack structure has remained intact.

In addition to the misperceptions about the potential for release on lower-than-expected terrain discussed in this paper, many other factors contribute to uncertainty surrounding persistent instabilities. Persistent weak layers initially form with greater spatial variability than storm snow weak layers, spatial variability increases over time while size, and therefore consequence, increases as well. Eventually frequency decreases, but instabilities linger that may become active in

response to subtle environmental changes or be triggered remotely or unexpectedly and produce deep avalanches with very extensive propagations through seemingly unconnected terrain. All of these uncertainties require different risk treatment strategies than storm snow.

The risks associated with very low angle avalanches are much less than the risks associated with lingering persistent avalanches, but not negligible. The common threads between the risks of these two avalanche scenarios are that there is a gap between the slope angles of concern and the perception of the slope angles of concern. Both scenarios are associated with low probability in conjunction with high residual uncertainty including uncertainty as to the specific timing and location where these avalanches might be triggered. However, there is very low uncertainty as to whether conditions are favorable versus negligible for these avalanches to occur.

6. CONCLUSIONS

The main motivation for this research is that the nature of these avalanche scenarios as statistical outliers coupled with the challenges they pose for risk treatment causes them to be disregarded in both education and snow safety programs. In spite of their infrequent occurrence, Roger had one close call when a very low angle avalanche came within a few metres of pulling his entire group off of a very broad low angle ridge into an adjacent size 3 avalanche. Roger has also experienced close calls with lingering deep persistent avalanches on moderate terrain; these are the classic ‘low probability, high consequence’ scenarios that pose a dilemma for risk treatment and are responsible for very high profile avalanche accidents that disproportionately impact the guiding profession and the guides involved.

The main result of this study is that, although these avalanche scenarios are challenging to forecast, it is easy recognize the terrain and snowpack conditions that make them possible. It is important to realize that lingering deep persistent avalanches tend to persist on large moderate angled slopes; they do not occur only on steep terrain.

The main take home messages are that there are easily recognized conditions when these avalanches are more likely to occur, they can occur on lower than expected slope angles, and the first step to manage their risk at these times is to make decisions on the basis of their possibility, not their probability.

ACKNOWLEDGEMENTS

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