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Relating complex terrain to potential avalanche trigger locations

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ABSTRACT

More winter recreationists are venturing into "extreme" terrain each year, and avalanche fatalities in that terrain are increasing. The slope-scale spatial variability of snow stability and how it relates to this complex terrain is critically important but poorly understood. In this study, we use terrain parameters to model potential trigger locations (PTLs) of slab avalanches, which are defined based on a minimum slab thickness overlying a persistent weak layer or the presence of a weak layer on the snow surface which could be subsequently buried. In a sample of seventeen couloirs from Lone Mountain, Montana, field teams tracked and mapped persistent weak layers and slabs with probe and pit sampling. We used terrain parameters derived from a one-meter digital elevation model to explore the relationships between PTLs and terrain, and our results show strong statistical relationships exist. However, results varied widely from couloir to couloir, suggesting that the relationships between terrain and PTLs in each couloir are unique and highly complex. For these steep alpine couloirs, parameters relating to wind deposition, wind scouring, and sluffing are most strongly associated with PTLs. The influences of these and other terrain parameters vary, depending on broader-scale terrain characteristics, prior weather patterns, and seasonal trends. With an understanding of the broader scale influences and physical processes involved, we can use terrain to optimize stability test locations, explosive placements, or route selection. The unique nature of each couloir means that simple rules relating terrain to PTLs will not apply, although couloirs in the same cirque generally share similarities. This study will help to improve practical decision-making as well as future modeling efforts.

1. Introduction

Avalanches pose a serious threat to human life and infrastructure in mountainous areas worldwide. In the United States, avalanches kill more people on average annually than earthquakes, landslides, or other mass movement phenomena (Voight et al., 1990). During the 2011–12 season, 34 people were killed in avalanches in the United States (avalanche.org, 2012). One of the best ways to mitigate avalanche deaths is an increased understanding of avalanches and the snowpack.

The release of a slab avalanche requires the failure of a weak layer or weak interface underneath a cohesive snow slab (Schweizer et al., 2003). Understanding the structure and spatial pattern of weak layers and slabs as they interact with the terrain is crucially important for improving avalanche prediction and mitigation. Depth hoar, near surface facets, and surface hoar are the primary weak-layer types that persist for long periods of time. These weak layers are difficult to detect after burial and account for the failure layer in most avalanche fatalities (Schweizer and Jamieson, 2001). Many laboratory, field, and theoretical studies have demonstrated the properties of these persistent weak layers and the environmental conditions related to their growth and preservation (e.g., Akitaya, 1974; Birkeland, 1998; Lang et al., 1984).

The spatial distribution of weak layers and overlying slabs vary and are often difficult to predict. Numerous studies in the past half century have characterized the spatial variability of snow properties such as penetration resistance, shear strength, and stability test scores. Results vary tremendously due to differences in scale triplets (support size, spacing, and extent of measurements (Blöschl, 1999)), field methods, analysis methods, and natural variability (Schweizer et al., 2008). Terrain is commonly cited as a potential source of variability (e.g., Campbell and Jamieson, 2007; Föhn, 1988; Harper and Bradford, 2003; Jamieson, 1995), and it is likely our best tool for predicting slope-scale variability.

Point assessments of snow stability are a common technique for slope forecasting. With a documented 10% to 15% "false-stable" ratio (Birkeland and Chabot, 2006), and no clear optimal spacing for snow pits (Birkeland et al., 2010), targeting locations with the presence of weak layers is critical for identifying slope instabilities. Several studies have tracked weak layers or snow strength across slopes (e.g., Bellaire and Schweizer, 2011; Kronholm and Schweizer, 2003; Kronholm et al., 2004), but these did not utilize terrain to predict the variability in the snowpack. Numerous studies have successfully modeled snow depth or snow water equivalent using terrain (e.g., Elder et al., 1998;

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Erickson et al., 2005; Winstral et al., 2002; Wirz et al., 2011), but studies predicting weak layer presence using terrain at the slope-scale are limited to only a few cases, all on slopes below treeline (Birkeland et al., 1995; Lutz and Birkeland, 2011; Shea and Jamieson, 2010). Furthermore, due to the challenging nature of working in steep avalanche terrain, and the complexity of the problem in such alpine areas, previous studies exploring spatial variability typically characterize the snowpack on relatively uniform or simple slopes that are typically less than 35°. Few snow scientists have attempted to characterize or predict the snowpack in the highly variable and complex terrain that many skiers, snowboarders, climbers, and snowmobilers now venture into on a regular basis. The present study is unique in that it looks at spatial patterns of snowpack characteristics in complex alpine terrain by sampling patterns of weak layers and slabs in steep, snow-filled gullies, chutes, or couloirs bounded on either side by rock (hereafter referred to as couloirs).

2. Methods

2.1. Study area

This study reports on data collected from seventeen couloirs on Lone Mountain in the Madison Range of Southwest Montana, near Big Sky (Fig. 1). Lone Mountain typically has a snowpack that is characteristic of a continental climate due to its relatively colder and drier winters (Mock and Birkeland, 2000). Few other peaks in the region approach the elevation of Lone Peak, so it receives exceptionally strong winds.

The couloirs sampled on Lone Mountain are from five different headwalls and cirques above treeline. These couloirs were chosen based on logistical accessibility, the existence of snowpacks relatively undisturbed by skiers or explosives, and their wide range of aspects and snowpacks. Guy (2011) provides thorough descriptions and images of each couloir sampled.

Field teams conducted sampling during the winters of 2009–10 and 2010–11. We sampled couloirs in the same cirque within several days or weeks of each other to minimize temporal variability in the snowpack structure. Weather patterns for the two winters varied considerably. The winter of 2009–10 was an El Niño winter, with drier than usual conditions, while the winter of 2010–11 was a La Niña winter, with unprecedented snowfall amounts in Montana's Madison Range. Despite these varying years, depth hoar at the base of the snowpack was still widespread on Lone Mountain both winters, and avalanches occurred near the ground throughout the season in both winters in the Madison Range.

2.2. Field data

To sample each couloir, field teams used an avalanche probe to track changing slab thicknesses and identifiable weak layers, as well as total snow depth. In all of the couloirs, we tracked depth hoar or faceted snow near the base of the snowpack, which was present in about half of our sampling points and located in portions of all seventeen couloirs. In general, these layers were easily identified from probing as soft or hollow layers. For a number of couloirs, we were also able to track a weak layer that had recently formed near or at

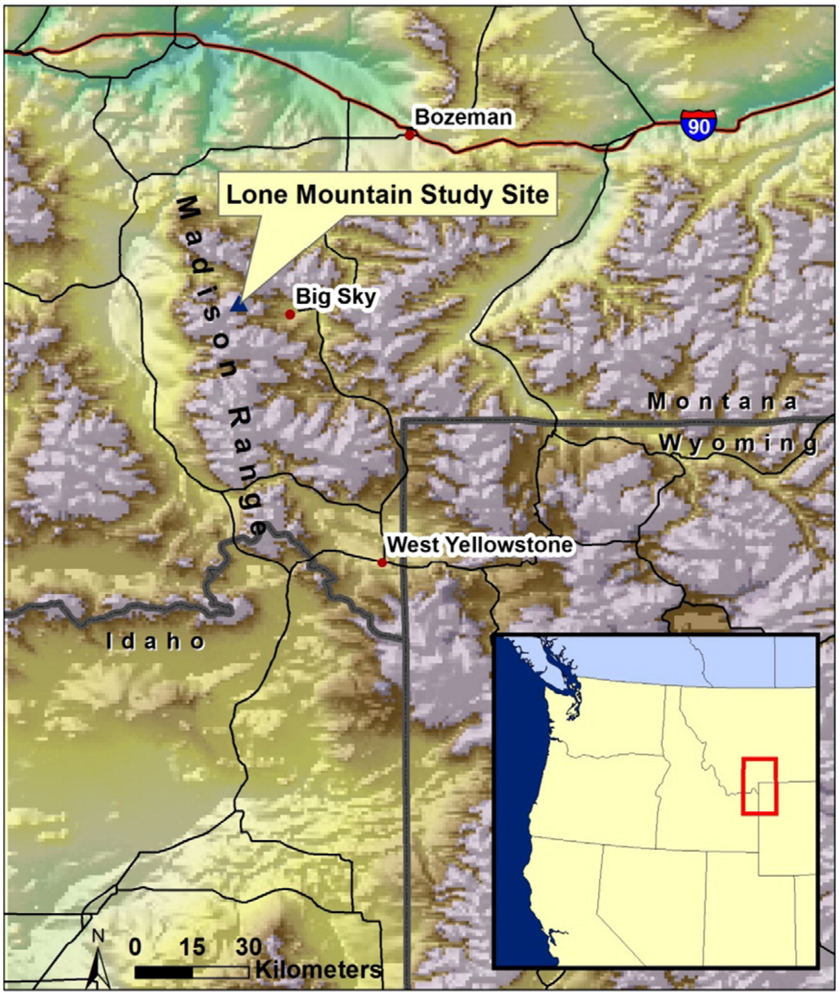

Fig. 1. Lone Mountain study site in the Madison Range, Montana.

the surface of the snow (surface hoar or near-surface facets) identified visually or with hand pits. Frequent snow profiles and hand or shovel pits for cross-verification improved our certainty, and the senior author conducted all of the probing except in two couloirs to maintain consistency. Due to potential safety concerns, we only conducted our research during periods of good stability with the goal of identifying locations with poor snowpack structure. Although operator error exists with these techniques, the benefits of probing are quick data collection (which allowed a larger sample size) and the ability to conduct research in steep terrain without burdensome equipment.

We collected 56 to 120 observations per couloir in a semi-systematic, stratified sampling scheme through repeated transects across the width of each couloir. Snow observations were made with approximately equal spacing of several meters, and the design was stratified in that we made an effort to collect samples without bias from the top, bottom, sides, and middle of the path.

2.3. Spatial analysis

We utilized a Trimble GeoXH 2008 handheld Global Positioning System (GPS) to map sampling locations and couloir boundaries, and we spatially overlaid these observations on a one-meter Digital Elevation Model (DEM) derived from Light Detection And Ranging (LiDAR) data. Using post-processing differential corrections for the GPS data, the average estimated horizontal accuracy for the sample points in each couloir is 52 cm.

We utilized a one-meter DEM to derive twelve terrain parameters potentially capable of modeling the observed snowpack structure (Table 1). Effectiveness in previous snow research (e.g., Birkeland, 2001; Erickson et al., 2005; Winstral et al., 2002; Wirz et al., 2011) and expert opinion dictated the use of these parameters and how they were derived in a Geographic Information System (GIS) – further explanation is given in Guy (2011). These parameters were derived and spatially overlaid with snow observations using ArcMap 9.3.

Table 1
Terrain parameters derived from a one-meter DEM and used for analysis.

Parameter name	Description	Example value(s)
rel.elev	Relative elevation within the couloir (%) from an elevation grid (in meters)	0.892 (near the top); 0.128 (near the bottom)
slope	Slope angle (degrees)	49.2°
EW.aspect	East–west component of aspect (Sine of aspect)	−0.299 (from 342.6°)
NS.aspect	North–south component of aspect (Cosine of aspect)	0.954 (from 342.6°)
prof	Profile curvature at 10 m resolution	−0.8(convex); 1.6 (concave)
plan	Plan curvature at one-meter resolution	−8.5(concave); 2.3(convex)
rel.solar	Relative solar radiation within the couloir (%), calculated from cumulative direct and diffuse insolation (in WH/m^2)	0.441
wind	Wind exposure index; the difference between the cell of interest and the mean elevations in a 10 m radius 120° wedge into the seasonally averaged prevailing winds	0.42(exposed); −1.36 (sheltered)
rel.view	Relative viewshed within the couloir (%), based on visibility from the major windward ridgeline	0.70 (more visible); 0.2 (less visible)
expo	Exposure index; the difference between the cell of interest and the mean elevations within a 4 m donut-shaped search surrounding the cell.	0.32 (exposed); −0.46 (sheltered)
edge	Distance from the couloir's edge (meters)	8.1 m
wind.edge	Distance from the windward edge of the couloir (meters)	19.7 m

2.4. Statistical analysis

The objective of our analysis is to create a terrain-based model that predicts "weak zones," or locations where one would be more likely to trigger an avalanche, find instability in a snow pit, or have success with explosive control work. To do this, we designed a binary response: the presence or absence of a Potential Trigger Location (PTL). The criteria for a PTL were defined on a case-by-case basis for each couloir based on the field observations and discussions with avalanche professionals.

For all of the couloirs sampled, depth hoar is one of the layers of concern because it was present in numerous locations throughout the couloir. In these cases, the criteria for a PTL were defined as any location with the presence of depth hoar and an overlying slope normal slab thickness greater than 15 cm. We required a minimum slab thickness because we frequently observed pockets of very shallow, faceted snow. However, with no slab in these locations, triggering an avalanche would not be possible. The minimum slab criterion filtered out these non-threatening locations from being identified as PTLs.

We chose the minimum slab depth with careful consideration. After discussions with several local avalanche experts and ski patrollers on Lone Mountain, we concluded that 15 cm was the most appropriate minimum slab depth for defining a PTL. Schweizer and Lütschg (2001) found the lower quartile of fracture depths from a sample of 522 skier triggered avalanches was 30 cm (measured slope vertical). From a sample of 93 fatal avalanches in Canada, Jamieson and Johnston (1992) reported the lower quartile of slab thicknesses was 54 cm, and from 181 avalanche accidents from the Canadian Interior Ranges, the lower quartile was 30 cm (measured slope vertical). When corrected to slope normal thicknesses on a 45° slope, these are 38 cm and 21 cm slab thicknesses, respectively. Patrollers at Moonlight Basin are concerned with fractures propagating to full depth from around 15 cm or deeper (Carpenter, pers. comm., 2011). In addition, a number of techniques in our analysis deal with the uncertainty of defining the minimum slab depth.

We also considered imposing a maximum slab depth on the definition of a PTL. Incorporating a maximum slab depth would require detailed slab properties, such as a hardness profile, from each observation. This would have been unreasonable to collect in the field given the large number of observations we planned to collect to exhaustively cover each couloir. A maximum slab depth becomes complicated when defining what type of trigger: skier, explosive, cornice fall, etc., and would also likely change depending on temperatures. Thus, for simplicity, our definition of depth hoar PTLs is any location with the structural ingredients – a slab and a weak layer, with the *potential* for instability given the right load.

In several couloirs, we frequently observed weak faceted layers between crusts. These were typically shallowly buried without a significant slab, but reactive in our stability tests. In this case, we defined PTLs as any location with the layer of facets found between two crusts. In a few select couloirs, we observed near surface diurnal faceting or surface hoar formation at or near the surface of the snowpack. Because these layers had not been buried, we defined a PTL based simply on the weak layer presence. In these last three cases, for those locations to become true PTLs, a slab of new or windblown snow would need to be added to the slope.

For a robust analysis, we employed a number of statistical techniques to explore and model the relationships between the twelve terrain parameters (Table 1) and PTLs using R Statistical Software (R Development Core Team, 2009). First, we compared the distribution of all the terrain parameters associated with the presence of PTLs against the distribution of all terrain parameters associated with the absence of PTLs using the KS-test (Massey, 1951). Significantly different distributions indicate that the terrain parameter in question is associated with the response of PTLs. Since the KS-test isolates the effects of each parameter, we also modeled the combined effects of multiple terrain parameters for a more complete understanding. Thus, we used two different model structures to further explore the data.

We used classification tree modeling to capture hierarchal and non-linear relationships (Breiman et al., 1993). Using the Gini index, the data is recursively partitioned into an overfit tree but then pruned to an optimal size using a cross-validation process (Breiman et al., 1993). We also implemented a more robust boot-strapping based technique called Random Forest (Breiman, 2001). This technique averages 500 classification trees by repeatedly re-growing trees while withholding a random subset of variables and data. This technique also allows for quantification of parameter importance by calculating the mean decrease in accuracy (MDA) of the model when each parameter is iteratively withheld from modeling. The accuracy of the Random Forest model is determined using the "out-of-bag" sample, that is, the data withheld during each fitting, to calculate the success rate (Breiman, 2001). We also compare the True Skill Statistic (TSS), which is a measure of the model's ability to correctly discriminate between PTLs and non-PTLs (Allouche et al., 2006).

As described previously, our carful minimum slab thickness criterion is still subject to uncertainty. We investigated the robustness of parameter importance findings with a Monte Carlo approach. We iteratively redefined the minimum slab thickness for PTLs, in 1 cm increments from 1 cm to 60 cm and refit the Random Forest model for each unique slab thickness. At each iteration we recorded the MDA for each parameter as it changed across the range of minimum slab thicknesses. We then calculated the averaged MDA over all slab thicknesses, which shows how important the parameter is over the entire range of varying minimum slab thicknesses.

Lastly, we modeled PTLs using logistic regression, which is essentially a multiple linear regression on the probability of a PTL, but based on a binomial distribution (Hosmer and Lemeshow, 2000). A genetic algorithm, glmulti, is used to reduce the full model with all of the main effects as well as the following quadratic terms which are hypothesized to have quadratic effects: $rel.elev^2$, $slope^2$, $prof^2$, $wind^2$, $edge^2$, and $wind.edge^2$. Glmulti populates a ranked list of "best" models by performing a semi-exhaustive search of all possible models and selecting models that minimize the corrected Akaike's Information Criterion (AICc) (Calcagno and de Mazancourt, 2010). In the cases where overdispersion was suspect, we modeled the logistic regression using a quasibinomial distribution and reduced the full model using the quasi-AICc (QAICc). All of the models that fall within 2 values of the minimum AICc or QAICc value are averaged as a final multi-model (Burnham and Anderson, 2002). Model performance is assessed by using a 2×2 confusion matrix comparing predicted outputs with observations, where a cutoff value of $c = 0.5$ is used to transform predicted probabilities to binary data. This allows success rates and a TSS to be calculated, as with the classification trees. Parameter importance is also quantified by calculating the relative support of each parameter. The relative support is the sum of relative evidence weights for each of the top models that the parameter appears in. In other words, it measures how frequently each term appears in the best models, weighted by how well each model fits.

As with the Random Forest modeling, we explored the uncertainty in the minimum slab criterion for a PTL for the logistic regression modeling. We refit the final multi-model and calculated relative support (i.e., parameter importance) for varying minimum slab thicknesses. Because of the extensive computation time needed to reduce and fit a final model, we refit at only two other slab thicknesses. For couloirs where deeper slabs were found, we redefined the minimum slab criterion at 30 cm and 45 cm, and for shallower snowpacks, we refit the logistic multi-models for slabs at 5 cm and 25 cm. We then averaged the relative support over these range of slab thicknesses as a way to quantify the importance of each parameter for varying slab thicknesses. We performed the statistical analysis described above on all data within a single couloir for each of the weak layer types in each of the seventeen couloirs. We repeated the analysis for all observations within groups sharing similar geographic qualities or the same weak layer type. Thus, our analysis includes two PTL types (depth hoar or near surface layers) and three scales (the individual couloir scale, the cirque or headwall scale, and the mountain scale (Fig. 2)). A more in-depth discussion of the statistical analysis is provided in Guy (2011).

With the goal of assessing which terrain parameters are most influential in describing the location of PTLs, we use a number of measures to assess the importance of each of the twelve terrain parameters for these different statistical techniques. Any parameter with significant KS-test results at the 0.05 confidence level is considered important because the results suggest that the parameter is independently capable of discriminating the locations of PTLs. The first node in the pruned classification tree has the most partitioning power. Thus, the parameter in the first node has the greatest ability of predicting PTLs and is highly important. In the Random Forest modeling, the parameter with the greatest mean decrease in accuracy (MDA) is highly important because the modeling success rates would decrease the most in the absence of that parameter in comparison to the absence of other parameters. Lastly, in the logistic regression modeling, the parameters with the highest relative support are important because they appear in the top logistic models most frequently.

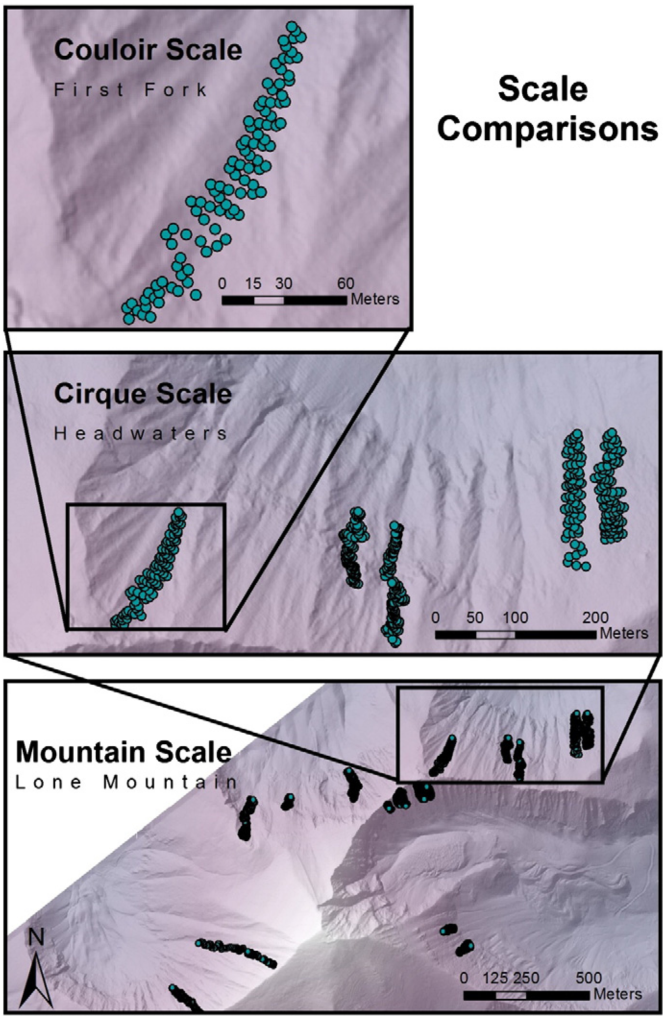

Fig. 2. An illustration of the three different geographic scales used for modeling PTLs: couloir (or slope) scale, cirque (or headwall) scale, and mountain scale.

Table 2
Comparison of modeling performance at three scales and for two different weak layer types.

PTL weak layer	Scale	Sample size	Random Forest model		Logistic regression model	
			Success rate (%)	TSS	Success rate (%)	TSS
Depth hoar	Couloir	17	64	0.19	75	0.40
Depth hoar	Cirque	5	63	0.17	61	0.23
Depth hoar	Mountain	1	62	0.18	52	0.10
Near surface layers	Couloir	9	80	0.31	88	0.65
Near surface layers	Cirque	2	78	0.38	62	0.22

3. Results and discussion

3.1. Modeling success rates

Of the seventeen couloirs sampled from five cirques on Lone Mountain, we tracked depth hoar potential trigger locations (PTLs) in all seventeen, near surface facet PTLs in eight, and surface hoar PTLs in one of the couloirs. The two more robust multi-model techniques, Random Forest and logistic regression modeling, show relatively high model performance for slope-scale modeling (Table 2). The logistic regression modeling does best for modeling of individual couloirs, with a 75% success rates for depth hoar PTLs and an 88% success rate for near surface weak layer PTLs (Table 2). At the cirque scale, success rates drop for both model structures, with a substantial decrease for the logistic regression models, down to 61% for depth hoar PTLs and 62% for near surface PTLs. When fitting all of the depth hoar PTLs for the entire Lone Mountain in one model, success rates decrease even further for both model structures, bottoming out at 52% for the logistic regression models (Table 2). Although the decreasing success rates from the individual couloir scale to the cirque scale to the mountain scale are not as pronounced for the Random Forest modeling, the pattern is the same.

The successful modeling results, particularly for individual couloirs, confirm that the terrain in each couloir is strongly related to the snowpack that develops within it for both near surface weak layers and deeper weak layers. Given the highly complex and variable nature of these couloirs and their snowpack, finding statistically valid relationships is encouraging. The decreasing model performance from the couloir scale to mountain scale has strong implications: PTLs are related to terrain, but these relationships, in general, are unique to each couloir or in some cases each cirque. Extrapolating relationships beyond a single couloir yields decreasing modeling success. In many cases, slope-scale terrain parameters can still be used to describe the presence of PTLs across cirques or headwalls, but these relationships are not as strong: predictive ability suffers as a consequence. While many physical processes and their related slope-scale parameters may be operating across an entire cirque, other processes occur independently on each individual slope. With success rates of 52% and 62% for the mountain-scale model, it is clear that a simple “rule of thumb” to relate PTLs to terrain is inadequate. All of the unique interactions between terrain and PTLs at the slope scale and cirque scale are averaged out through geographic and temporal variability, minimizing consistent relationships at the mountain-scale.

Modeled success rates of the near-surface facets are noticeably better than those for depth hoar (Table 2). This suggests that these near-surface processes may be easier to predict based on terrain. This makes sense because the layers we tracked were recently formed. Therefore, the new layers have been exposed for less time to dynamic meteorological and metamorphic processes that may interact with terrain to create less predictable spatial patterns.

Table 3
A summary of important parameters (variable names defined in Table 1) from four statistical methods for the individual couloir analysis of depth hoar PTLs.

Important parameters for depth hoar PTLs				
Couloir ID#	Classification tree first node	Random Forest largest MDA	Logistic model parameters with highest relative support	Significant ($p<0.05$) KS test results
1	*rel.elev*	*rel.elev*	*prof, expo, rel.elev, rel.solar, wind*	*rel.elev*
2	*rel.elev*	*rel.elev*	*rel.elev, wind*	*rel.elev, edge, wind, EW.aspect, NS.aspect, solar, wind.edge*
5a	*rel.elev*	*rel.elev*	*rel.elev*	*rel.elev, slope, wind, expo, EW.aspect, NS.aspect, prof, plan, solar, wind.edge*
6a	*wind*	*wind*	*wind*	*wind, expo, plan*
7a	*edge*	*slope*	*expo, rel.view*	*rel.elev, slope, edge, solar*
8a	*rel.elev*	*rel.elev*	*prof, expo, rel.elev, plan, wind.edge*	*rel.elev*
9a	*edge*	*rel.elev*	*prof, slope*	*edge*
12	*wind*	*wind*	*edge, slope, rel.elev, rel.solar, wind*	*wind*
13	*plan*	*wind*	*expo*	*plan*
14	*edge*	*edge*	*prof*	*rel.elev, edge*
15a	*edge*	*edge*	*edge, wind.edge*	*edge*
16	*rel.elev*	*rel.elev*	*rel.elev*	
17a	*NS.aspect*	*rel.elev*	*edge, rel.elev, wind.edge, wind*	
18	*wind.edge*	*rel.solar*	*edge*	*rel.elev, solar*
19a	*plan*	*plan*	*prof, expo, rel.elev*	*expo, plan*
20	*EW.aspect*	*expo*	*expo*	*EW.aspect, NS.aspect*
21a	*rel.elev*	*rel.elev*	*edge, rel.elev*	*rel.elev, edge, prof*

Table 4
A summary of important parameters (variable names defined in Table 1) from four statistical methods for the individual couloir analysis of near surface facet and surface hoar PTLs.

Important parameters for near surface PTLs				
Couloir ID#	Classification tree first node	Random Forest largest MDA	Logistic model parameters with highest relative support	Significant ($p<0.05$) KS test results
Near surface facet PTLs				
5b	*edge*	*edge*	*edge, prof, rel.elev, plan*	*edge, expo, plan*
6b	*wind*	*wind*	*edge, expo, wind*	*Wind*
7b	*edge*	*edge*	*expo, rel.view, wind*	*rel.elev, edge, wind, expo, slope, solar*
8b	*expo*	*expo*	*prof, expo, rel.elev*	*rel.elev, expo*
9b	*rel.elev*	*rel.elev*	*edge, rel.view, slope, wind.edge*	*rel.elev*
17b	*EW.aspect*	*EW.aspect*	*wind*	*EW.aspect*
19b	*wind.edge*	*EW.aspect*	*edge, slope, rel.elev, wind.edge*	*EW.aspect, wind.edge*
21b	*prof*	*prof*	*prof, rel.view*	*rel.elev, slope, prof*
Surface hoar PTLs				
15c	*prof*	*prof*	*edge, rel.view, rel.elev, wind.edge*	*Rel.elev, edge, wind, slope, EW.aspect, prof, wind.edge*

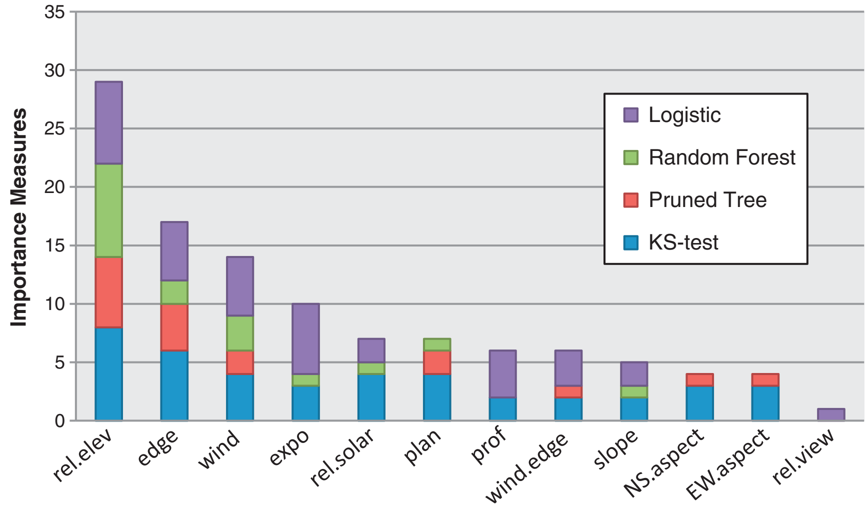

Fig. 3. Cumulative measures of importance for each parameter for individual couloir analysis of depth hoar PTLs (variable names are defined in Table 1). Importance measures are tallied from the data in Table 3 based on whether a parameter: a) is significant in the KS test; b) is in the first node of the pruned classification tree; c) has the greatest MDA in the Random Forest modeling; and d) has the highest relative support from the logistic regression modeling.

3.2. Parameter importance

A number of terrain parameters show a consistently stronger relationship with PTLs across all statistical measures. Relative elevation within the couloir (*rel.elev*) and distance from the edge of the couloir (*edge*) are most frequently statistically significant or of highest importance in the various model structures and statistical tests for individual couloir models of both depth hoar PTLs and near surface weak layer PTLs (Tables 3 and 4; Figs. 3 and 4). The prevailing wind exposure index (*wind*), terrain exposure index (*expo*), and profile curvature (*prof*) are also of relatively high importance for both weak layer types when compared to other parameters, particularly for near surface layers. These results imply that differences in the locations of PTLs are most frequently associated with different elevations along the couloir, different distances from the edge of the couloir, different levels of wind or terrain exposure, and different slope curvatures downslope (e.g., Fig. 5). All five of these parameters are related to the effects of wind loading, wind scouring, and wind protection. Relative elevation and profile curvature are also related to snow sluffing. The strong importance of wind-related parameters in alpine terrain are in accordance with previous snow depth modeling studies that cite wind as most influential, such as Erickson et al. (2005) and Wirz et al. (2011). Parameters relating to other physical processes such as solar effects are also related to PTLs in some cases, but they are not as frequently important for the couloirs used in this complex alpine environment sampled mid-winter.

The Monte Carlo techniques used to assess the uncertainty in the minimum slab criterion for defining depth hoar PTLs further validate our results. These techniques show that the most important parameters identified by both Random Forest modeling and logistic regression modeling remain largely consistent for variations in minimum slab thickness. For the Random Forest modeling we iteratively refit the model and recalculated the MDA for each parameter for minimum slab thicknesses varying from 1 cm to 60 cm; the most important parameter for each couloir remains the same when compared with the 15 cm fixed slab thickness for 82% of the couloirs (Fig. 6). Results were similar with the logistic regression modeling, where our Monte Carlo approach demonstrated that the most important parameters for

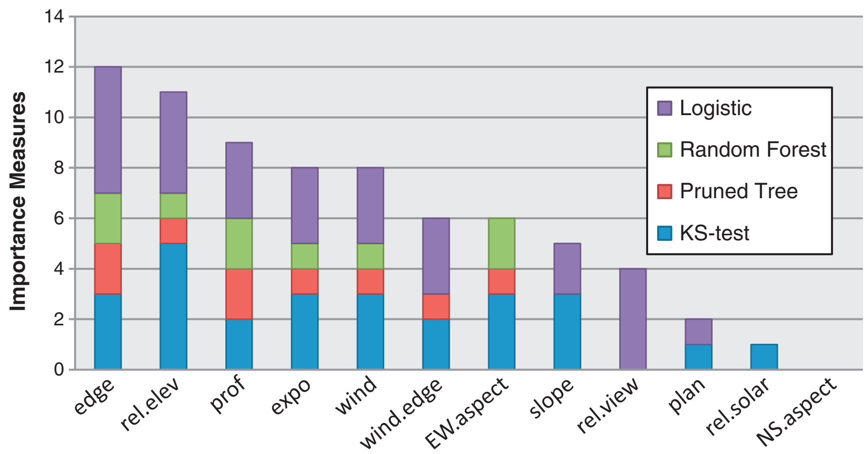

Fig. 4. Cumulative measures of importance for each parameter for individual couloir analysis of near surface PTLs (variable names are defined in Table 1). Importance measures are tallied from the data in Table 4 based on whether a parameter: a) is significant in the KS test; b) is in the first node of the pruned classification tree; c) has the greatest MDA in the Random Forest modeling; and d) has the highest relative support from the logistic regression modeling.

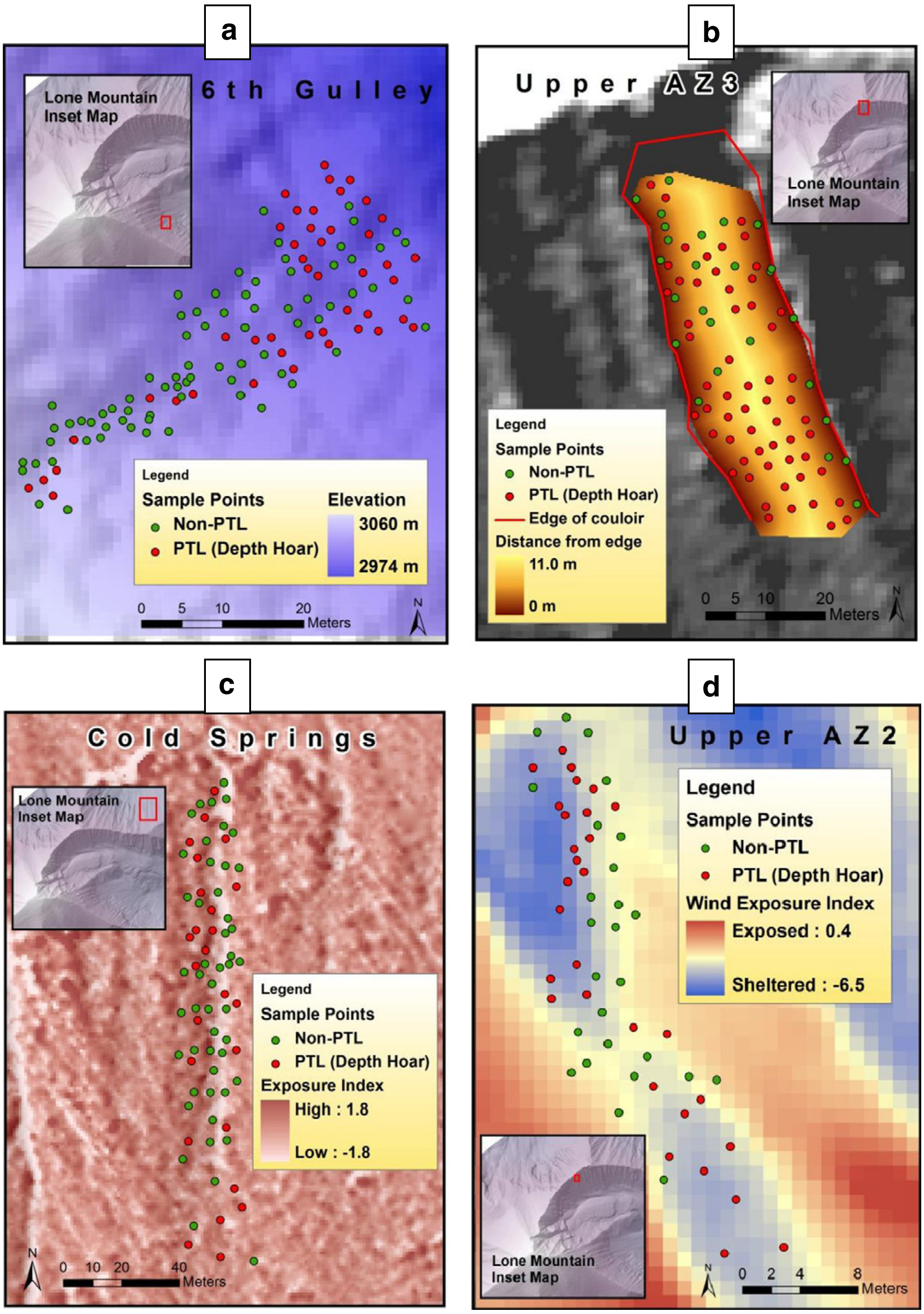

Fig. 5. Examples of four parameters that are most commonly associated with presence/absence of PTLs for individual couloirs. (a) Relative elevation (where higher elevation values have a higher relative elevation within the couloir); (b) distance from the edge of the couloir; (c) exposure index (where higher positive values indicate the terrain is higher and more exposed relative to its surroundings); (d) wind exposure index (where higher positive values indicate a greater amount of wind exposure and scouring with prevailing winds).

the varying slab thicknesses match the most important parameters for the 15 cm fixed slab thickness in 86% of the cases (Fig. 7). These results further validate our inferences that wind-related and sluffing-related parameters are most critical for PTLs, despite our uncertainties in defining the minimum slab thickness (Guy, 2011).

Terrain parameters are related to PTLs through their association with physical processes that form or preserve weak layers. One of the key physical processes in this study relating terrain to depth hoar formation is a strong temperature gradient driven by a shallow snowpack. For near-surface layers, faceting is enhanced in high porosity snow (McClung and Schaerer, 2006); thus, facet formation is more likely in low density, high porosity snow that has not been heavily affected by winds. After formation, near-surface layers are also easily destroyed and swept away in alpine terrain by winds or sluffing, but the layers are preserved if they are protected prior to burial. These and other physical processes are incorporated into modeling of PTLs with the use of the most important terrain parameters.

Relative elevation (*rel.elev*) is identified as an important parameter in over half of the couloirs, and its importance is supported by all of the models and statistical tests (Tables 3 and 4; Figs. 3 and 4).

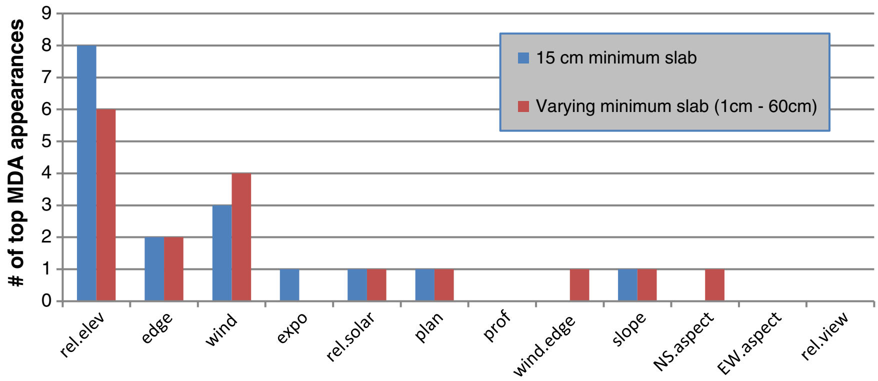

Fig. 6. Comparison of the most important parameters for depth hoar PTLs identified by the Random Forest modeling for a fixed minimum slab criterion of 15 cm versus a minimum slab criterion that varied between 1 cm and 60 cm. Regardless of the slab depth used to define a depth hoar PTL, the most important parameters (i.e., those with the highest number of top Mean Decrease in Accuracy (MDA) appearances in the modeling) are reasonably consistent. The MDA for the varying minimum slab thickness is the averaged MDA from 60 Monte Carlo iterations between 1 cm and 60 cm in defining the minimum slab thickness for PTLs.

This means that the distribution of PTLs commonly varies by elevation within the couloir. These results have important implications. A person digging a snow pit at the bottom of a couloir during an approach should suspect different conditions higher in the couloir. Likewise, the same concept applies when assessing snow stability from just the top. This complicates our assessments since typically the only places to approach this terrain are from the top or the bottom. Relative elevation is an important parameter in this study because the snowpack frequently varied due to varying wind and snow loading patterns at different elevations along each couloir and sluff accumulations near the bottom (e.g., Fig. 5a). In some cases, cold air pooling at the bottom of cirques may have affected snow metamorphism. Elevation has been cited in previous studies as an important parameter in describing variability of avalanches or snowpack (e.g., Birkeland, 2001; Dexter, 1986; Gleason, 1996; McClung and Schaerer, 2006), but at a much coarser scale. Profile curvature (*prof*) often has similar associations as relative elevation. However, profile curvature may have stronger associations with specific physical processes such as sluffing, wind scouring, or snowpack tension and compression; thus, it is a more important parameter in some cases.

Distance from the edge (*edge*) is also strongly associated with the presence of weak layers and the thickness of slabs above them (Tables 3 and 4; Figs. 3 and 4). Again, this implies that a snow pit dug near the side of a couloir is unlikely to be representative of the snowpack in the middle, and vice versa. In relatively deeper snowpacks, the edges of couloirs are more likely to have depth hoar development because of the shallow snowpacks overlying rock and talus, whereas depth hoar formation is inhibited at greater distances from the edge due to deeper snow depths. This is consistent with the findings of Arons et al. (1998) and Birkeland et al. (1995) who noted depth hoar growth and weaker snow near rock outcrops or shallowly buried rocks. The interplay of slab depth and faceting near the sides of couloirs combine to form a general "sweet spot" for depth hoar PTLs around one meter from the edge of many couloirs (e.g., Fig. 8). Proximity to the edge also can enhance warming on more sunlit aspects or affect the amount of wind scouring. This can have the effect of strengthening snow near edges to prevent depth hoar (e.g., Fig. 5b) or protecting or destroying near surface layers. Distance from the windward edge (*wind.edge*) has similar associations as distance from edge, but it is more appropriate where the physical processes favor one side or the other in wind-affected terrain.

The degree of wind sheltering (*wind*) is highly important in the many of the models for both depth hoar and near surface PTLs (Tables 3 and 4; Figs. 3 and 4). Its association with PTLs varies, depending on whether it is describing the process of building a slab over depth hoar that is sizeable enough to be a threat (e.g., Fig. 5d), loading of deep and stable snowpacks without depth hoar formation, or protection of weak layers from wind scouring and erosion (e.g., Fig. 9). The importance of the wind-sheltering index is consistent with the work of Gleason (1996), who found a "wind factor" was one of four most influential terrain parameters associated with natural avalanches on Lone Mountain.

Terrain exposure (*expo*) also relates to influences from wind and is also highly important in many of the models (Tables 3 and 4; Figs. 3 and 4). As with the wind sheltering index, how exposure relates to PTLs depends on numerous other variables, from protection from

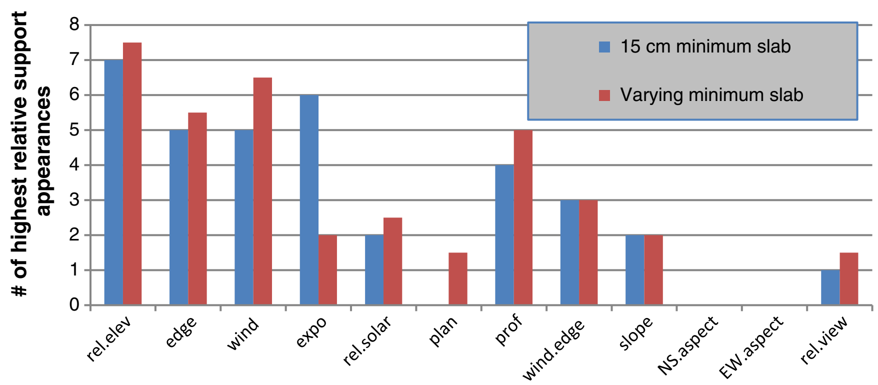

Fig. 7. Comparison of the most important parameters for depth hoar PTLs identified by the multi-model logistic regression modeling for a fixed minimum slab criterion of 15 cm versus varying minimum slab criterion. The most important parameters (i.e., those with the highest frequency of top relative support) are fairly consistent, despite changes in the slab depth used to define the PTL.

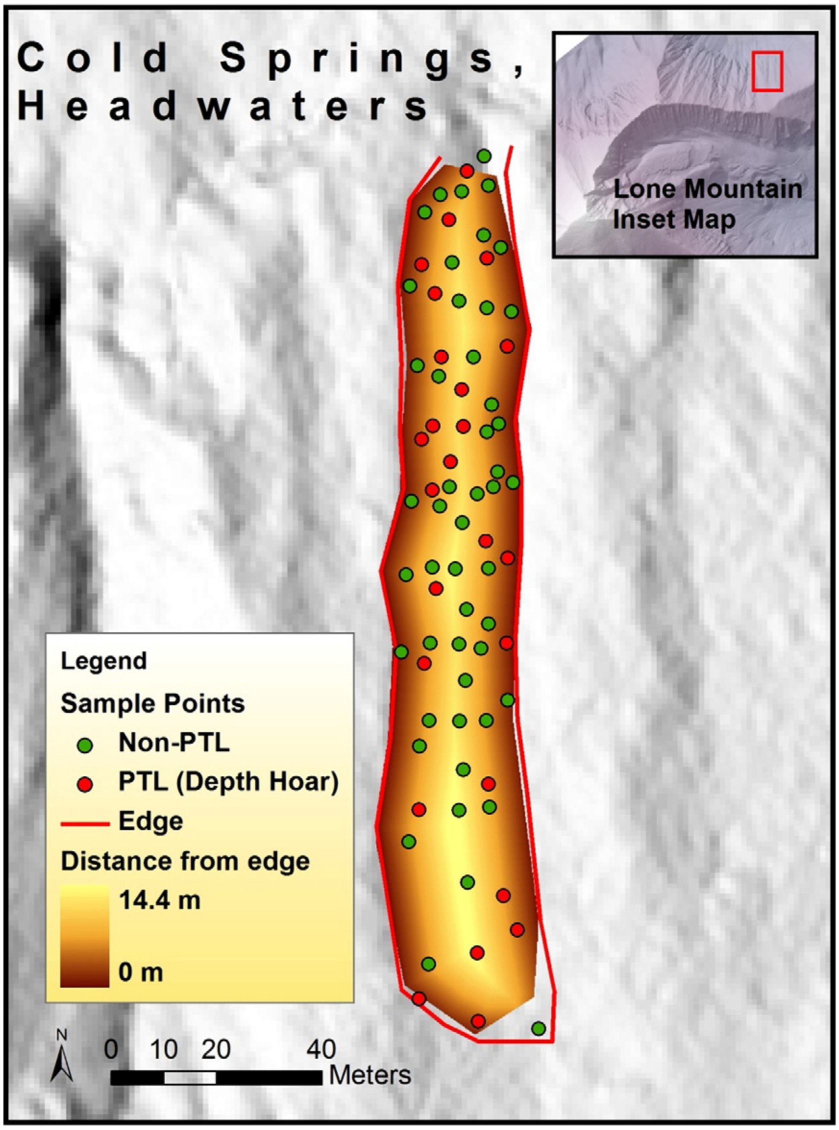

Fig. 8. Map of Cold Springs, which exemplifies the "sweet spot" relationship between depth hoar PTLs and distance from edge. More PTLs are clustered between 0.5 m and the first several meters from the edge of the couloir.

wind erosion to loading of deeper snowpacks (e.g., Fig. 5c). Exposure differs from the wind index in that it indicates how sheltered or exposed a cell is independent of the prevailing wind direction, so it may be more important in environments with highly variable wind directions. Exposure is also associated with warming and strengthening of snow on southerly aspects because more exposed locations are closer to low albedo rocks that readily absorb solar radiation.

Other terrain parameters used in the modeling process, such as slope angle, solar radiation, and aspect, were important in some models but not as frequently important in all of the models. Their lesser importance may be attributed to correlations with parameters that capture the physical processes more accurately or because they describe physical processes that are not dominant in this alpine environment. However, their usage in some of the models suggests that these parameters should not be ignored and may be controlling the location of PTLs in some cases.

In summary, fine scale parameters that relate to the physical processes of wind scouring, wind protection, and wind-loading, as well as sluffing, are most important for predicting PTLs for couloirs in the complex alpine terrain used in this study. These processes are most frequently modeled by relative elevation within a couloir, distance from the edge of the couloir, a wind exposure index, a terrain exposure index, and profile curvature of the slope. The strong importance of wind-related parameters in alpine terrain is consistent with previous snow depth modeling studies that cite wind as most influential, such as Erickson et al. (2005) and Wirz et al. (2011).

3.3. Broader scale influences

The reason that the influence of slope-scale terrain parameters are so variable from couloir to couloir is because they depend on processes occurring at a broader scale, a point that has been pointed out in previous studies (e.g., Schweizer and Kronholm, 2007; Schweizer et al., 2008), but is further emphasized in this research.

Seasonal and recent weather patterns affect how terrain parameters relate to PTLs. Near-surface weak layers are especially sensitive to short-term wind or solar patterns. This is illustrated by the surface hoar layer that was observed in Jack Creek couloir (Fig. 10), where a change from the prevailing wind patterns over a period of less than one day changed how wind sheltering parameters interacted with

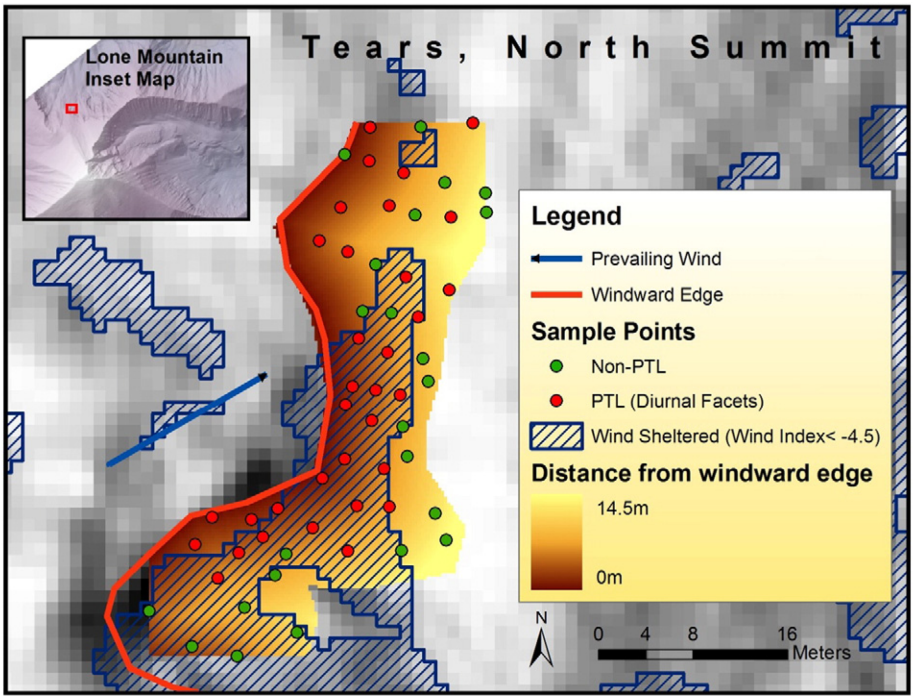

Fig. 9. Map of Tears Couloir showing how the presence of near-surface diurnal facets are strongly associated with protection from the wind. This can be explained with the wind exposure parameter (where large negative values indicate a high degree of wind sheltering) or distance from the windward edge (where the windward edge of the couloir typically provides more wind sheltering).

this fragile surface layer. Surface hoar was destroyed in what is normally wind protected terrain, whereas it was preserved in wind exposed terrain (Fig. 10). The changing influences of terrain as a result of weather patterns or seasonality agree with the results of Birkeland (2001), who found that the relationship between terrain parameters and regional scale stability observations was highly variable over the course of a season depending on the weather patterns leading up to the sampling day.

Regional, mountain, and cirque scale processes clearly affect how slope-scale terrain parameters interact with the snowpack. For example, in Lone Lake Cirque (Fig. 11), there is a strong association between low elevations and an absence of PTLs, particularly in the more windward couloir. This is due in part to the sheltering effects of the west wall of the cirque against the prevailing winds, where the more wind protected lower elevations developed a deeper and stronger snowpack without depth hoar (Fig. 11).

3.4. Unexplained variability

While the success rates of models for individual couloirs are encouraging, the models do not account for all of the observed variability. Clearly, these terrain parameters are unable to account for all of the complex processes involved in PTL spatial variability. The use of numerous terrain parameters in the various individual couloir models emphasizes the importance of collectively incorporating all available terrain parameters into the decision-making process, rather than relying on a single parameter. Equipped with knowledge of how the broad scale and meteorological processes are interacting with the slope-scale terrain parameters, one can significantly improve their chances of finding a PTL with slope-scale terrain parameters, which allows for educated decision making. For example, in the case of Jack Creek couloir (Fig. 10), the anomalous wind patterns following the surface hoar forming event could be used to understand how the wind protection parameter interacted with the surface hoar layer and therefore enable an educated prediction of where buried surface hoar would be found.

Some of the unexplained variability in the modeling can be attributed to error inherent in the study design. The accuracy of GPS locations and resolution induced error from LiDAR data are two potential sources of error. However, sub-meter GPS accuracy and one-meter DEMs are at the cutting edge of technology for research at this scale, and measures were taken to verify that GPS recordings aligned with the DEMs. Uncertainty in weak layer identification during field measurements was minimized with cross-verification using hand or shovel pits and by collecting large sample sizes. Our estimated error for measuring slab thickness and total snow depth in the field is less than 3 cm; the results of our Monte Carlo analysis on varying slab thicknesses show that this amount of error has minimal effects on our results.

Another source of uncertainty is the definition of PTLs, especially for depth hoar layers which also included a minimum slab depth. Experts do not agree on the minimum slab thickness required for initiation and propagation of a slab avalanche, mainly because it is dependent on the strength and hardness of the slab, as well as the properties of the weak layer below it. The minimum slab criterion of 15 cm is a conservative estimate based on previous research and discussions with avalanche professionals. We address this uncertainty in the statistical analysis by allowing the minimum slab criteria to vary for both model types, and results show that most of the important parameters are robust against changes in the minimum slab criteria (Figs. 6 and 7). Guy (2011) provides more details on this uncertainty analysis.

One other assumption in this research is that the presence of a weak layer qualifies it as a “Potential Trigger Location.” The probe measurements or snow surface observations in this study do not quantify snow stability measurements. However, our data are simple qualitative measures of change in snow hardness (for deep layers) or grain type (for surface layers), and both of these are closely associated with avalanche events (McCammon and Schweizer, 2002). The presence of a weak layer does not necessarily indicate instability, but we specifically use the terminology “Potential Trigger Location” because a snowpack with persistent weak layers has a structure that could potentially become unstable given the right load, and weak layers are

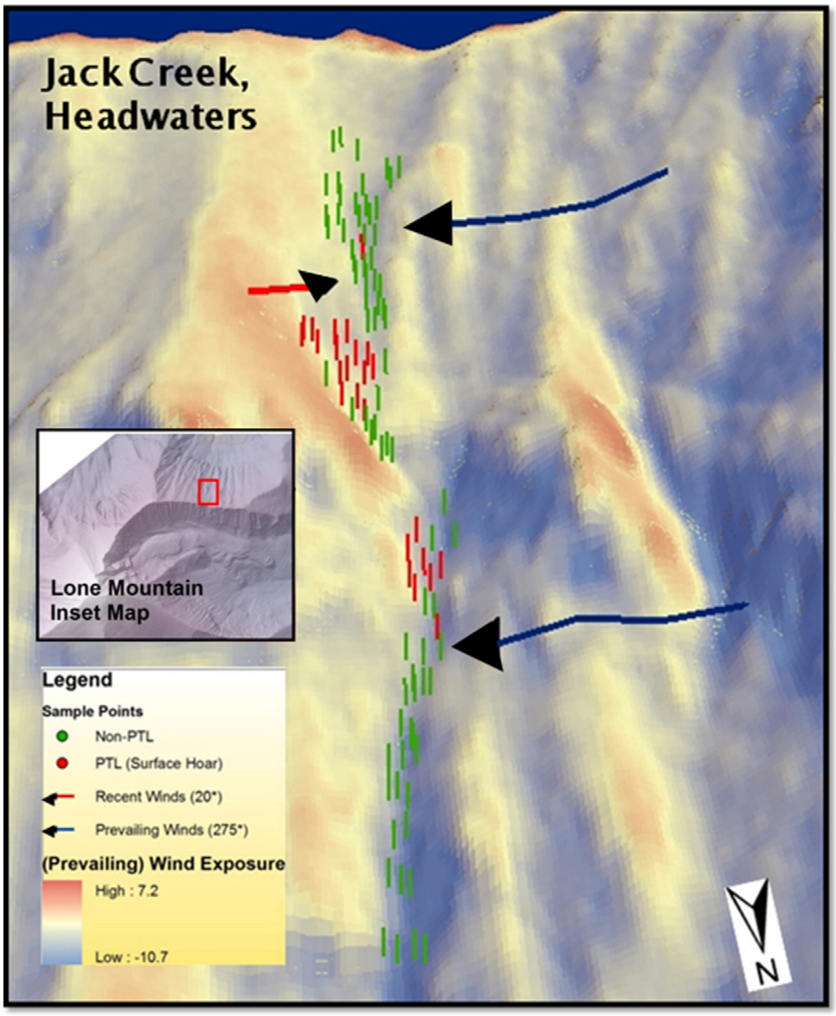

Fig. 10. Three-dimensional map of surface hoar PTLs on Jack Creek Couloir, showing how a shift in wind patterns after the surface hoar formation could have unexpected effects on parameters relating to wind protection. Areas that are normally exposed to prevailing winds (with higher wind exposure index values in red), offer more wind sheltering with a shift in wind direction to the northeast rather than the prevailing westerly winds.

more commonly associated with instability (Schweizer and Wiesinger, 2001).

Lastly, to accommodate for uncertainty in model structures and parameters used and to optimize the validity of the statistical results, we incorporated different model structures and tests, multi-model averaging, and boot-strapping techniques.

Because this is a non-random observational study, inferences made to other couloirs outside of the sample or different time periods cannot be statistically supported. However, our results make sense physically, and they form a basis for improving our understanding of other couloirs and other winters. Of course, these results must be extrapolated with care, especially if they are to be applied to other snow climates or different terrain types. Despite the uncertainties involved, this is the first field study to show that snow weaknesses and slabs can be related to terrain parameters in steep couloirs, and it provides an encouraging baseline for improving decision making in this type of terrain.

4. Conclusions

From a group of 17 couloirs on Lone Mountain in Montana, we examined the importance of terrain parameters as they relate to potential trigger locations (PTLs) of slab avalanches with exploratory analysis and robust classification tree and logistic modeling techniques.

The successful but widely varying results from the individual couloir models demonstrate how complex and variable the influence of terrain parameters are on the presence of weak layers, slabs, and PTLs. The clear message from our results for individual couloirs is that we can do a reasonable job of explaining observed patterns given our terrain parameters. The equally clear message from our relatively poor modeling results when we group all of the couloirs into one mountain-scale model is that terrain interacts with the snowpack differently in each couloir, making extrapolating results from one couloir to other couloirs challenging and potentially misleading. This does not imply that terrain patterns cannot be used to predict PTLs, but that specific thresholds and relationships from one slope may not fit well for other slopes. Rather, a more general understanding of how each slope-scale terrain parameter interacts with the snowpack under varying climatic and broader scale terrain inputs enables educated decision making. Results support that more general interactions between terrain and PTLs enable predictive capability for couloirs in the same headwall or cirque, but with less success than for individual slopes.

For these data, which were collected in steep alpine terrain, parameters relating to the physical processes of wind deposition, wind scouring, and sluffing appear to be the most influential. Distance from the edge of a couloir, relative elevation in the couloir, the degree of wind sheltering, the degree of exposure of the terrain, and profile curvature are the most important parameters associated with PTLs by a number of modeling standards. Other parameters are likely to

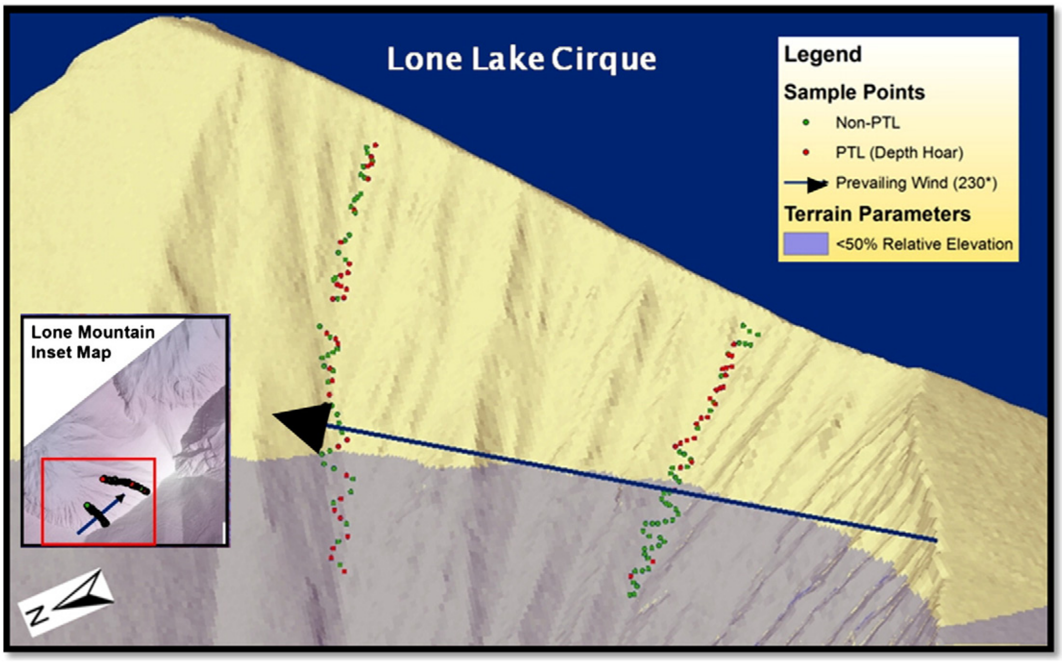

Fig. 11. Distribution of depth hoar potential trigger locations (PTLs) in Lone Lake Cirque, illustrating how the influence of slope-scale parameters, such as relative elevation, depend on the broader-scale influences, such as the wind sheltering effects of the cirque's west wall. This three-dimensional map shows how the cirque's topography influenced the location of PTLs, with the lower halves of the couloirs (below 50% relative elevation) developing fewer PTLs. These locations were stronger due to a deeper snowpack that grew from enhanced wind deposition in the protection of the windward wall, especially for the more windward couloir on the right.

be equally or more important for different topography or different snow climates, such as slope angle and solar radiation. The specific influences from these slope-scale parameters vary depending on the characteristics of the cirque or region, prior weather patterns, and seasonal trends. However, the results of this study show that the presence or absence of PTLs can be strongly associated with these parameters, with average model success rates ranging from 80% to 88% for near surface layers and 64% to 75% for depth hoar layers. The practical implications of these findings are that the distribution of PTLs in a couloir is likely to vary depending on the influence of the above parameters, so careful consideration needs to be given when assessing the stability from a single point observation or before extrapolating the results from one couloir to the next.

Because of the high spatial variability of PTLs in complex terrain, the best strategy to successfully manage or evaluate a steep couloir requires:

(1) A complete understanding of how the broader scale terrain and meteorological conditions interact with the slope (e.g., prevailing wind and snow patterns, wind anomalies, suspect weak layers, general snowpack conditions and history).
(2) Expert intuition incorporating an understanding of how these and other important slope-scale terrain parameters interact with the snowpack for careful route selection or pit or explosive placement with continued reassessment as conditions change.
(3) A holistic approach, incorporating all possible information including current meteorological conditions, recent avalanche activity, and other signs of instability.

The success of this study in finding meaningful relationships between terrain and potential trigger locations in such highly variable and complex terrain is encouraging for future modeling. This work improves our understanding of the physical processes involved with the snowpack development and avalanche formation. Numerous possibilities exist for future work. A larger and more diverse sample size, as well as repeated sampling over several seasons, would further increase our understanding. Higher resolution probing methods, such as the snow micropenetrometer (Schneebeli and Johnson, 1998), more quantifiable tests relating directly to instability, such as the ECT (Simenhois and Birkeland, 2009), or more exhaustive coverage of weak layers, such as with FMCW radar (Marshall and Koh, 2008) could increase the certainty in results. Modeling for predictive purposes could incorporate hierarchal and linear relationships at different scales from slope to mountain range while accounting for changing meteorological conditions. Furthermore, comparing modeled potential trigger locations with field observations of trigger locations identified during explosive control work would provide useful insight into the problem. This research provides solid progress toward understanding the complex processes occurring in steep avalanche terrain, improving our understanding of the relationship between terrain and optimal locations for snowpits or explosive placements. This, in turn, has the potential to improve safety in complex avalanche terrain for both recreationists and avalanche professionals.

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