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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

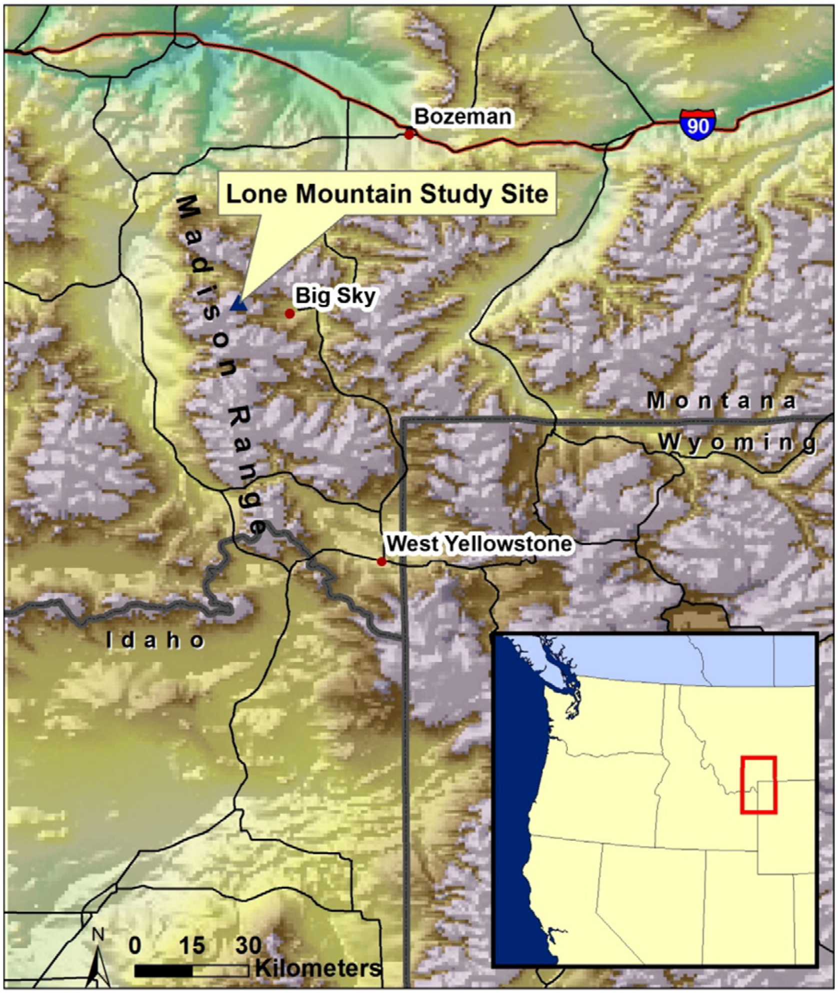

Fig. 1. Lone Mountain study site in the Madison Range, Montana.