Patterns of snow stability throughout the Bridger Range.

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ABSTRACT: Though avalanche workers and scientists recognize that distinct patterns of snow stability exist in mountainous terrain, no field-based research has been conducted to rigorously analyze those patterns at a scale of interest to backcountry avalanche forecasters. This research investigates snow stability throughout a small mountain range. Using helicopter access, sampling teams collected data from over 70 sites on each of two sampling days. Variables generated were analyzed using a variety of statistical techniques. Results demonstrate that links exist between terrain and stability, and that those relationships change over time. The data structure is complex, providing insights into the myriad difficulties faced by avalanche forecasters.

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1. INTRODUCTION

Avalanche scientists and practitioners recognize that avalanches occur in distinct patterns in the mountains. On a given day, certain slopes might be unstable, while other nearby slopes might provide safe skiing or snowmobiling conditions. Reasons for these differences are numerous, and relate to slope characteristics such as elevation, aspect, slope angle, wind exposure, and vegetation, all of which affect the snow conditions. When analyzing stability patterns, backcountry avalanche forecasters rely on experience and the general rule-of-thumb that "similar avalanche conditions are found at similar aspects and elevations", and this spatial information is passed on to the public in through avalanche advisories. In spite of these known patterns, no previous field research has attempted to quantify snow stability patterns at a scale larger than a single slope or a couple of slopes. The purpose of this research is to expand that scale to several hundred square kilometers by examining patterns of stability as a function of terrain, snowpack and snow strength variables throughout the Bridger Range in southwest Montana. The following paper presents this information briefly and informally for the practitioner. For a more quantitative and rigorous examination of the subject the reader is referred to either Birkeland (1997) or Birkeland (under review).

Though most field-based research on snowpack patterns has focused on individual slopes (i.e., Conway and Abrahamson, 1984; Föhn, 1988; Jamieson and Johnston, 1992; Birkeland and others, 1995), there have been a couple larger scale studies. In the 1960s Charles Bradley (C. Bradley, Unpublished Manuscript, 1968) used his resistograph to investigate depth hoar layers on a couple slopes over an area of about 1 km^2. In an investigation of a larger area of the Colorado Front Range, Dexter (1986) quantified snowpack and snow strength variables over an area of 10 km^2, but did not measure snow stability. There are no field-based studies known to this author that have attempted to analyze snow stability patterns over areas of hundreds of square kilometers, a scale of interest to regional avalanche forecasters. In an attempt to address this scale, this research examines the following question: how does snow stability vary in relation to terrain, snowpack and snow strength over the course of a snow season?

2. STUDY AREA

The area chosen for study is the Bridger Range, located five kilometers northeast of Bozeman, Montana (Figure 1). The range was chosen for its relatively simple topography (a single ridge of mountains with 1400 m of relief), small size (approximately 40 km long by 10 km wide), abundant snowfall (Bridger Bowl Ski Area receives about 6.44 m of annual snowfall), and extensive avalanche terrain (there are an estimated 1000 avalanche paths within the range).

3. METHODS

A helicopter shuttled six two-person sampling teams around the Bridgers to collect data on two sampling days, February 6th and April 2nd, 1997. Winter-like weather through the spring insured a winter-like snowpack on the latter sampling day. Each day over 70 snowpits were dug in avalanche terrain with slope angles from 28 to 44 degrees (Figure 1). At each sampling location, teams collected terrain, snowpack, snow strength, and snow stability data (Table 1), with an emphasis on fast, consistent, and reliable measurements. For snow stability, we conducted rutschblock (Föhn, 1987) and stuffblock (Johnson and Birkeland, 1994; Birkeland and others, 1996) tests. I also included failure depths as a variable (since such depths represent the slab depths of potential avalanches) and computed failure indices based on slab depths and stuffblock drop heights. I used a variety of statistical techniques (correlation analyses, multiple regression analyses, canonical correlation analyses, and others) for data analysis. Refer to either Birkeland (1997) or Birkeland (under review) for a complete description of these methods, including explanations of the failure indices and statistical techniques.

4. RESULTS AND DISCUSSION

Terrain can be statistically linked with snow stability, and these relationships change over time. On February 6th the data demonstrate only subtle linkages between terrain and stability, though there is some evidence that stability decreases at higher elevations and on more northerly aspects. On the other hand, data from April 2nd show strong linkages between terrain and stability. On this particular day there are many significant correlations between variables, and I generated valid regression models predicting four snow stability variables using only terrain variables. Similar to the first sampling day, the most important terrain variables for predicting stability are elevation and aspect, with the most unstable conditions found on upper elevation, northerly facing slopes.

The reason the strength of the relationship between terrain and stability varies is the weather leading up to each sampling day. The 1996-97 winter in Montana began with 10 weeks of mostly stormy weather. From mid-November until February the total snow depth at Bridger Bowl Ski Area climbed steadily from 0.75 m to 2.75 m (Birkeland, 1997). Periods between storms were windy and primarily overcast, and it was impossible to do any sampling because the project helicopter could not access the numerous ridgetop landing zones in the bad weather. Due to the weather, few significant weak layers existed in the snowpack, and differences between north and south aspects were minimal since the sun rarely shone. The relatively uniform weather conditions led to similarly uniform stability conditions, with relatively subtle changes in stability at different elevations and on different aspects. More heterogeneous weather conditions prevailed prior to sampling on April 2nd, with sunny weather interspersed with storms and more defined weak layers (Birkeland, 1997). These weather conditions created increasingly discernable patterns in the snowpack, and this is reflected in the strength of the relationship between terrain and stability. On both days more unstable conditions existed on upper elevation, northerly facing slopes, which is not an unfamiliar scenario for avalanche forecasters. High elevation, north facing slopes are colder, so weaknesses in the snowpack strengthen more slowly, and these upper elevations receive more snow and wind, resulting in more loading and windloading on the weak layer. However, this research merely provides two quick slices of a dynamic system. Avalanche forecasters understand that, while more unstable conditions are often observed in on upper elevation, north facing slopes, this is only the roughest of guidelines for during what might be considered "typical" conditions. We often face atypical conditions, however. For example, Schweizer and others (1996) documented a layer of surface hoar that formed only within a specific elevational range, thereby creating dangerous instabilities at mid-elevations and more stable snowpacks at higher elevations. Numerous other examples exist of extraordinary weather conditions leading to widely differing patterns of instability. Further, as demonstrated in this research, the strength of the relationships can also vary. The complexity of the system demonstrates the difficulty in modeling such systems and emphasizes the importance of the holistic approach taken by conventional avalanche forecasters.

TABLE 1: Variable codes and descriptions for terrain, snowpack, snow strength, and snow stability variables.

Variable Code

Description

Terrain

loc e Universal transverse mercator (UTM) meters east (m) *loc n* UTM meters north (m) *elev* Elevation above mean sea level (m) *dis rdg* Distance from the main ridge (m) *RI* Radiation index based on aspect (degrees away from true north) *ang* Slope angle (degrees) Snowpack *dpth* Total snow depth (m) *t30* Snow temperature 0.30 m below the snow surface (degrees C) *tgrad* Average temperature gradient (|(*t30*/(dpth-0.30m))|) (degrees C/m) Snow strength *ram drp* Initial drop of the ram penetrometer (m) *ram avg* Average ram hardness of the top 1.50 m (N/m) Snow stability *df wk sb* Depth of failure to the weakest stuffblock failure (m) *df wk rb* Depth of failure to the weakest rutschblock failure (m) *sb wk* Stuffblock drop height (m) of the weakest stuffblock failure *rb wk* Weakest rutschblock (rutschblock number) *sb wk rb* Stuffblock drop height (m) of the stuffblock failure associated with the weakest rutschblock *FI wk sb* Failure index (FI) of the weakest stuffblock failure ((sb wk)/(df sb wk)) *FI sb wk rb* FI of the stuffblock associated with the weakest rutschblock ((sb wk rb)/(df wk rb) *TFI* Total Failure Index based on the total number of stuffblock failures (N), stuffblock drop heights (sb), and depths to failure (df) $[((sb_1/df_1) + (sb_2/df_2) + ... + (sb_N/df_N))/N][1/N]$

One purpose of this study was to identify the most useful data for predicting stability. The first level of analysis attempted to predict stability patterns using terrain. Subsequently, snowpack variables, and then snow strength variables (Table 1) were added to the regression models to see if they improved stability predictions. On the first sampling day, when the relationships between stability and the other variables were weak, the addition of snowpack and snow strength variables improved the prediction of stability, but only marginally. However, on April 2nd the addition of these other variables improved the prediction of the various stability variables. Out of a possible total of eight valid models, I generated four models using only terrain. Adding snowpack variables allowed the generation of six models, and using terrain, snowpack and snow strength allowed the generation of valid regression models for all eight stability variables. Additionally, the predictive capabilities of the models improved. What does this say about the variables used for avalanche prediction? This tends to back up the conclusions of LaChapelle (1980), who discussed conventional avalanche forecasting as an iterative process which benefits from large amounts of diverse data. Additional data help improve forecasts and decrease uncertainty. Further, since none of the multiple regression models generated in this study explain more than 50% of the variance of any stability variable, numerous other variables besides those addressed in this research are obviously important for predicting snow stability.

A final interesting note is that each regression model generated for the April 2nd data used different inputs to predict stability. The differences between the models further emphasizes the underlying data complexity, and some of the difficulties that avalanche scientists face when trying to understand and predict avalanches. This situation is not dissimilar to a comparison of conventional avalanche forecasters. When LaChapelle (1980) asked several forecasters with similar forecasting success rates to rate the importance of data variables they used for avalanche forecasting, they chose different variables and weighed them differently. He concluded, "there is more than one way to forecast an avalanche" using conventional means (LaChapelle, 1980, p.78). This research suggests that, quantitatively, there may be more than one way to predict snow stability.

5. CONCLUSIONS

This research is the first field study investigating snow stability patterns at the scale of a small mountain range. Results show that terrain can be linked to snow stability, with more unstable conditions found on upper elevation, northerly facing slopes, and that the strength of this relationship changes over time. Adding snowpack and snow strength variables to terrain increased the predictability of snow stability, and emphasized the complexity of the data used for predicting patterns of snow stability.

Though this research takes a valuable first step in exploring the nature of snow stability patterns, much research remains to better explain these patterns. Adding variables might improve the models generated by this study, and this presents avenues for future research. One factor inadequately addressed in this investigation is the effect of the wind on various snowpack, snow strength, and snow stability variables. A meso-scale wind model combined with a blowing snow model might produce a useful variable approximating wind deposition and scouring in various areas. Another factor adding to the uncertainty of the models is small scale variations in snowpack and snow stability due to micro-scale variables such as wind effects, substrate or vegetation. Clearly defining sample locations that provide "average" stability measures of a slope is difficult, and research to define those places would be helpful. In spite of the difficulties, the present research makes progress in quantifying patterns of snow stability, and forms an encouraging baseline for future research about variations in snow stability at the regional scale.

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FIGURE 1: The Bridger Range is located approximately 5 km northeast of Bozeman, Montana, U.S.A. This hillshades map, generated with U.S. Geological Survey 30 m digital elevation models, shows the sampling locations (represented by the white dots) for this study. A helicopters shuttled teams to the ridgetop for sampling location access.

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