SLOPE SCALE SPATIAL VARIABILITY ACROSS TIME AND SPACE: COMPARISON OF RESULTS FROM TWO DIFFERENT SNOW CLIMATES

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ABSTRACT: Understanding the spatial variability of the snowpack is a crucial step to improve accuracy in field data collection and avalanche forecasting. While there has already been a large volume of literature assessing the spatial variability of the snowpack, inconsistent sampling designs make comparing results difficult. This work uses an overlapping 10 by 10 m grid to collect Extended Column (ECT), Compression (CT) and Stuffblock (SB) test data at the slope scale across a range of environmental settings and climatic regimes in Montana and New Zealand. The overlapping grid methodology standardizes data collection between our sites, as well as allowing for repeat data collection on the same slope, thereby providing a new method for attempting to assess changes in spatial variability over time. Preliminary results suggest that the spatial variability of fracture propagation and fracture initiation may increase over time, and that the spatial variability of the fracture propagation propensity may be related to the processes causing the instability. As we collect more data, these results will provide further insight into the problem of snow pit location and representivity, both in terms of space and time.

KEYWORDS: Spatial variability, Temporal variability, Fracture initiation, Fracture propagation.

1. INTRODUCTION

Seasonal snow varies in space (spatially) and time (temporally). Both of these aspects of variability have been examined for a wide range of snowpack properties (e.g. Birkeland et al. (1995), resistance; Blöschl (1999) and Derksen et al. (2000), snow water equivalence; Dyer and Mote (2006), snow depth). The spatial and temporal variability of both fracture initiation and fracture propagation are important since both are required for avalanche activity. Most previous spatial variability work has focused on fracture initiation such as shear tests, compression tests or rutschblock tests (e.g., Conway and Abrahamson, 1984; 1988; Föhn, 1989; Jamieson, 1995; Kronholm, 2004). With the recent development of fracture propagation tests (Gauthier and Jamieson, 2006; Simenhois and Birkeland, 2006) we can now also explore the spatial and temporal variability of this property.

While a large volume of literature assessing the spatial variability of the snowpack stability and in particular fracture initiation exists (see Schweizer et al., 2008 for a review), there remain some key deficiencies in this work. The main deficiency is the inconsistency in the sampling design and the resultant lack of comparability in results from previous studies. The layout of a sampling scheme and the area tested has often been termed the "scale triplet" (Blöschl and Sivapalan, 1995). This refers to the "Spacing" between the samples, the area or "Support" of each sample or test, and the "Extent" of the sampling. Recent work by Skøien and Blöschl (2006) suggests that even in the absence of instrument error, the biases caused by sampling design (as defined by the scale triplet) can be up to two orders of magnitude; Kronholm and Birkeland (2007) quantified the differences between sampling schemes in several studies focused on variations in snow resistance. This varying scale triplet in previous work prohibits accurate assessments and comparability of the spatial variability of different slopes. This also means that results from one study cannot easily be compared to those from another. Any changes in the spatial variability (often in terms of the correlation length scale) and thereby inferred process have therefore not been assessed in a standard manner across a range of climatological and or environmental settings.

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Therefore, our focus in this paper is to apply consistent methods to slopes in differing snow climates in both the USA and New Zealand. Our preliminary results on the spatial and temporal variability of fracture propagation and fracture initiation at the slope scale provides insights into comparing these two different climatological environments.

2. STUDY AREAS

The research was undertaken in Montana (USA) and Canterbury (New Zealand). These two locations have snowpacks that differ greatly from one another. At the time of preparing this paper, results were available for two sites in Montana and one site in Canterbury (Figure 1).

The two Montana sites are both situated in southwestern part of the state near the resort town of Big Sky. They are both situated within the intermountain avalanche climate zone which typically has a snowpack that exhibits a variety of avalanche and snowpack conditions, including persistent weak layers (Mock and Birkeland, 2000). The one site in Canterbury is situated in the Craigieburn Range, a maritime avalanche climate zone which typically has a snowpack that experiences large snowfalls and fluctuating temperatures above and below freezing (Hendrikx et al., 2005). This produces a variety of avalanche and snowpack conditions, including storm snow instabilities, melt freeze layers, and occasional persistent weak layers. We targeted persistent weak layers or near surface weaknesses for this research.

We collected snowpack data on two days at each of the three field sites. Field site selection focused on differences in exposure to the wind, with the Beehive site in Montana representing typical sheltered conditions (where most of the previous spatial variability work has been undertaken), while the Cedar site in Montana represented wind swept conditions. Data from Canterbury was collected at the Broken River site, a relatively sheltered, but alpine location similar to the Cedar site. The data from the two sites in Montana have been more thoroughly described and analysed in Hendrikx et al., (submitted).

3. METHODS

3.1 Field Methods

We collected data using a standardized approach at the slope scale. At all sites two days of observations were made. On the first day we collected data using a large gridded layout of between 3x4 (12 pits) and 5x7 (35 pits) with 10m spacing (i.e. 600 – 2400 m^2). At each point on the grid we did compression (CT) or stuff block (SB) tests (Birkeland and Johnson, 1999), and the extended column test (ECT) (Simenhois and Birkeland, 2006; 2007). For every stability test we also recorded the test score, shear quality (Johnson, and Birkeland, 2002), fracture type (van Herwijnen and Jamieson, 2002), snow depth, depth to failure, aspect and slope. At Beehive we used the SB test and completed 35 pits, while at Cedar and Broken River we used the CT and completed 16 and 12 pits respectively due to logistical constraints.

On the second day at each field site the rectangular or square grid was off-set by 5m up and across the slope, so that tests were performed in the middle of the approximately 80m^2 of undisturbed snow (Figure 2). This methodology permitted us to attempt to assess temporal changes the spatial variability of the SB, CT and ECT results on the same slope. Although our method allows the sampling of undisturbed snow on both days, the slope is clearly disturbed to some extent by the first day's sampling.

The time between the two sampling days varied between the sites depending on the nature of the instability. At the Beehive site the snowpack contained a persistent weak layer of faceted grains so we waited for nine days between sampling. At the Cedar and Broken River sites the snowpack did not contain persistent weaknesses. Instead, the layers of interest consisted of a variety of wind deposited layers sitting on relatively lower density snow. As such, we waited only four days between samples at both of these sites. We collected manual snow profiles each sampling day at the lower left corner of the grid (when observed from down slope) (Figure3).

3.2 Data Analysis

We analyzed all of the sites in the same way. At each site, we have two observation days, and each day has been treated as a separate data set, with changes between the days regarded as temporal changes to the same slope. Our analysis concentrates on the spatial variability of the propagation or non-propagation of the ECT test and the changes in the mean and standard deviation in the stability score from the CT and SB tests.

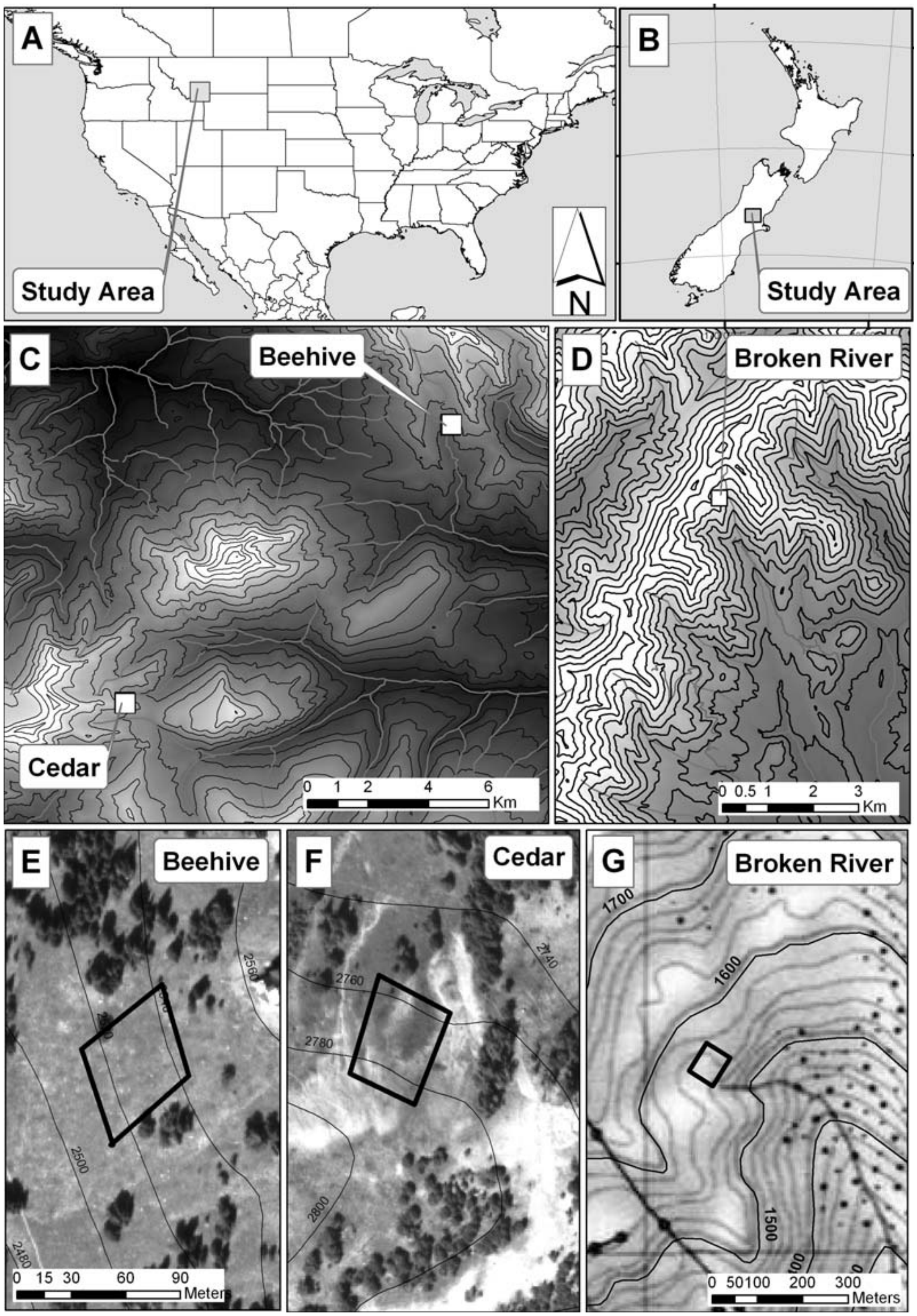

Figure 1: (A) Map of North America, showing the United States and the field area in southwestern Montana. (B) Map of New Zealand, showing the field area in Canterbury. (C) 1:150,000 scale DEM with 100m contour intervals showing the locations of the two field sites; Beehive and Cedar (Montana). (D) 1:100,000 scale DEM with 100m contour intervals showing the locations of the Broken River field site (New Zealand). Inset maps of Cedar (E) Beehive (F) and Broken River (G) with the approximate location of the data collection (polygon), 20m contour intervals are also shown and data is presented on an aerial photograph of the area (E and F) or topographic map sheet (G) showing vegetation and general slope surroundings.

Figure 2: Photo from day two at Broken River, showing the day two CT results (in grey) and the remnants of the day one CT results (in black) in between and below the day two grid, illustrating the 10m spacing in the grid, and the 5m offset layout (up slope and to the left) for the second day. The * represents a CT result on a different layer. (Photo: Irene Henninger, Broken River / Yellowstone Club Patroller).

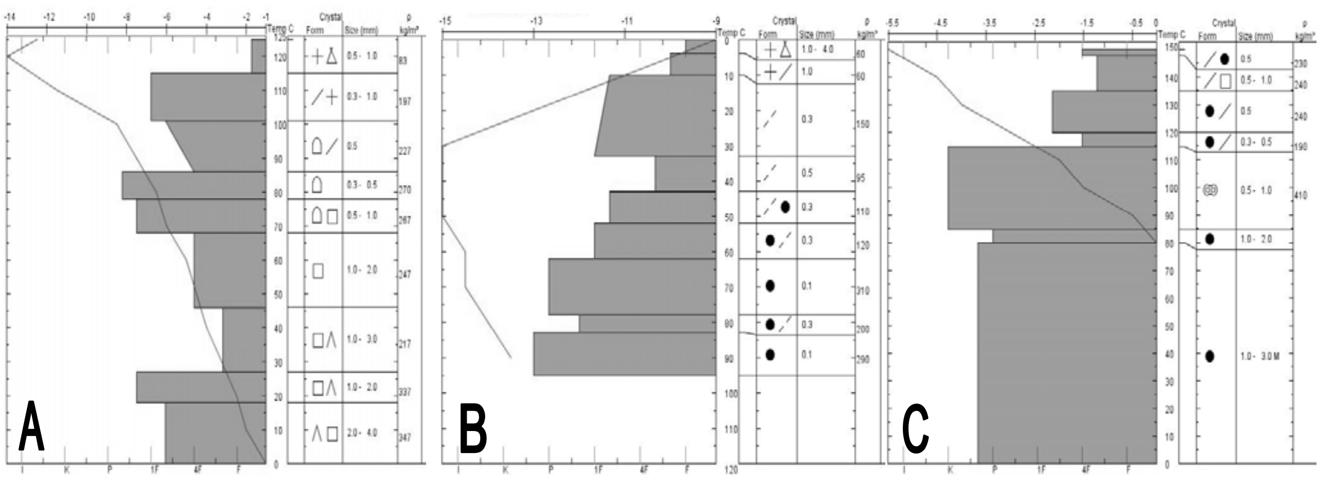

Figure 3: Snow profiles at (A) Beehive showing the relatively shallow snowpack with persistent weaknesses, and the location of the fracture at the bottom of the layer of faceted grains (at 46cm). (B) Cedar showing the deeper snowpack with multiple wind deposited layers and the location of the fracture at the bottom of the layer of relatively lower density snow (43cm down from the surface). (C) Broken River showing the refrozen snow layer, a layer of relatively lower density snow and the higher density storm snow on top. The location of the fracture was consistently at the interface of the lower density snow and the denser storm snow (at 120cm).

For the ECT we plotted the results (propagation or non-propagation) on the grid and assessed changes in the spatial pattern. We used two methods to address this issue: Moran's I (Moran, 1948; Fischer et al., 1996) and a Modified Ripley's K (Ripley, 1981; Cressie, 1993) using a Monte Carlo simulation. More details on the ECT analysis methodology can be found in Hendrikx et al. (submitted).

4. RESULTS

4.1 Results from Montana, USA

Aspects of the fracture propagation (ECT) data from the two sites in Montana have been more thoroughly described in Hendrikx et al., (submitted). However, the following section provides a short overview and highlights the most pertinent issues for this paper.

The ECT data at both Montana sites showed considerable spatial variability in terms of propagation (ECTP) and non propagation (ECTN). Interestingly, on the first day at both sites we observed a random distribution of fracture propagation potential results (as defined by the Moran's and Ripley's K analysis), while on the second sampling day for both sites we observed evidence of increased spatial clustering at the scale of our observations. The mean fracture initiation value for ECTP results, as defined by either the drop height in cm (Beehive) or the number of taps (Cedar) showed an increasing trend between day 1 and day 2 at both sites, but was only significantly different at Cedar (P value = 0.0058, N = 6 & 8, Note the very small sample size). The standard deviation for ECTP at Beehive remained unchanged at 17cm, but at Cedar increased from 2.9 to 5.9 taps.

When we consider the fracture initiation (SB or CT) data at both sites we also observe temporal changes in the results from day 1 to day 2. The mean drop height for the SB data at Beehive went from 25cm (day 1) to 28cm (day 2) and the standard deviation in drop height increased from 10cm (day 1) to 16cm (day 2). At Cedar the mean number of taps increased from 8.9 (day 1) to 13 (day 2), while the standard deviation remained about the same (from 7.2 to 7.0). Table 1 provides a summary of the ECT, SB and CT results for both days at Beehive and Cedar. None of these observed temporal changes in the fracture initiation results differed sufficiently to be statistically significant.

4.2 Results from Canterbury, New Zealand

The ECT data on both days at the Broken River site showed consistent, non-spatially variable results with all but one test resulting in an ECTN result. As only one of the 24 tests resulted in an ECTP, we did not undertake a more thorough temporal variability analysis of the ECT results using Moran's or the Ripley's K analysis.

When we consider the fracture initiation (CT) data at this site we observe statistically significant temporal changes in the mean results from day 1 to day 2. The mean number of taps increased from 13.8 (day 1) to 19 (day 2) (P value = 0.0006, N = 12, Note the small sample size), while the standard deviation in taps also increased from 2.5 (day 1) to 3.7 (day 2). Table 1 provides a summary of the ECT and CT results for both days at Broken River.

5. DISCUSSION

In contrast to previous fracture propagation test research (Simenhois and Birkeland, 2006; 2007), our data from Montana (as presented in Hendrikx et al. (submitted)) demonstrates considerable spatial variability in fracture propagation potential. However, the data from Broken River is much more similar to the findings of previous work, showing consistent results. Where a spatial pattern in propagation was discernable (Beehive and Cedar), we observed evidence of increased spatial clustering over time at the scale of our observations (Hendrikx et al., submitted).

It is unclear why the spatial variability of ECT results differs so much between sites. However, these differences may be related to the processes responsible for the instability. In the case of Broken River, rain saturated the snowpack the week before sampling, followed by freezing temperatures. Subsequently a short period of light, low density snowfall occurred followed by higher density storm snow. The CT reliably fractured at the interface of this lower density snow and the overlying higher density storm snow. We hypothesize that the low spatial variability in the ECT results at the Broken River site are the result of the homogenizing influence of the rain and subsequent refreezing. Essentially this process provided a “clean slate” and the only variability remaining was then in the new low density snow and subsequent changes with additional storm snow.

Table 1: Summary of test results for the Extended Column Tests (ECT), Stuffblock (SB) tests and Compression Tests (CT) for the two days at each of the three sites. Beehive and Cedar are situated in Montana, USA, while Broken River is in Canterbury, New Zealand.

Site	SB / or CT Count	Mean SB drop height (cm) / or CT (Taps)	Std Dev SB drop height (cm) / or CT (Taps)	ECTP Count	Mean ECTP drop height (cm) / or Taps	Std Dev ECTP drop height (cm) / or Taps
Beehive Day 1	34 of 35	25 cm	10 cm	23 of 35	42 cm	17 cm
Beehive Day 2	34 of 35	28 cm	16 cm	20 of 35	50 cm	17 cm
Cedar Day 1	16 of 16	8.9 Taps	7.2 Taps	8 of 16	5 Taps	2.9 Taps
Cedar Day 2	16 of 16	13 Taps	7.0 Taps	6 of 16	14 Taps	6.9 Taps
Broken River 1	12 of 12	13.8 Taps	2.5 Taps	1 of 12	22 Taps	N/A
Broken River 2	12 of 12	19 Taps	3.7 Taps	0 of 12	N/A	N/A

Conversely, Montana's more complex snowpack had not undergone any significant homogenizing influence (such as rain). As such the spatial variability observed in the ECT data was much greater, possibly due to other parameters which vary more across aspect and slope (e.g. ground cover, radiation and wind).

As expected, there is an increasing trend in the test scores for the ECT, CT or SB from day 1 to day 2 (Table 1). In addition, in most cases there is also an increase in the standard deviation of the drop height or number of taps from day 1 to day 2 (Table 1). The increasing trend in standard deviation suggests that the spatial variability of fracture initiation increases over time unless there is a homogenising influence to remove this instability (e.g. rain and refreezing). Our limited data support the hypotheses put forth by Birkeland and Landry (2002) about changes in spatial variability through time and are consistent with the increasing variability in shear test results for a specific persistent weak layer observed by Logan et al. (2007).

The results presented here and by Hendrikx et al., (submitted) build on those presented by Logan et al. (2007) and are among the first to statistically demonstrate temporal changes in snowpack spatial variability at the slope scale. However, our conclusions should be viewed with appropriate scientific scepticism since they are based on a small data set. In order to definitively address the question of temporal changes in spatial patterns, much more work is needed on many slopes with varying weak layers and snowpack conditions. We plan on collecting additional data to try to confirm our findings, and to present some of those data at ISSW in September.

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