A COMPARISON OF THE SPATIAL STRUCTURE OF THE PENETRATION RESISTANCE OF SNOW LAYERS IN TWO DIFFERENT SNOW CLIMATES

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Abstract. This paper compares the spatial structure of the compressive strength of slab and weak layers from two different snow climates. Our data come from arrays of SnowMicroPen (SMP) measurements in southwestern Montana, USA, and near Davos in eastern Switzerland. In both cases, buried surface hoar comprised the critical snowpack weakness. We analyzed the SMP data by manually delineating the surface hoar layers and a number of layers within the slabs above the weak layers. Using the log-10 transformed mean of the penetration resistance for our layers of interest, we investigated the spatial structure of the data by looking for linear slope-scale trends and assessing the residuals of any trends with semivariograms. Our results demonstrate that the layers investigated had variable spatial structures, both in terms of their linear trends and their semivariograms. This suggests that each snowpack layer has a unique spatial structure possibly arising from its depositional pattern and the subsequent changes to the layer when buried. We also demonstrate that the specific layout used for the measurements strongly influences the observed spatial variability. The complicated spatial structures of individual layers, and how they interact, likely contributes to the sometimes confounding overall patterns of spatial variability of stability observed on snow slopes.

Keywords: avalanches, avalanche forecasting, spatial variability, snow layers, stratigraphy

1. INTRODUCTION

Since snow avalanches release from zones of localized weakness, understanding the spatial variations of snowpack properties on a particular slope is important for determining slope stability and for mitigating avalanche danger using explosives. Several field studies have verified snow stability and structure or hardness variations in potential avalanche starting zones with areas of 10^2 to 10^4 m^2 (e.g., Bradley, 1970; Conway and Abrahamson, 1984; 1988; Föhn, 1988; Birkeland and others, 1995; Jamieson, 1995; Kronholm and Schweizer, 2003; Landry and others, 2004; Kronholm and others, *in press*). The purpose of this paper is to compare the spatial structure of a few slab layers and typical weak layers in two different snow climates.

Avalanche workers have long recognized that data from specific snowpits sometimes do not represent the stability conditions on those slopes. Further, even when efforts to trigger some slopes with explosives have failed, another explosive in a different location can cause the entire slope to release. These observations can be explained by the spatial variability of the snowpack and the fracture mechanics controlling snow slab release. Conway and Abrahamson (1984; 1988) first quantified stability variations by making measurements using modified shear frame tests adjacent to recently avalanched slopes. Föhn (1988) conducted similar work using a different shear frame test and found somewhat less variability. Subsequent studies have employed rutschblock tests (Jamieson, 1995), drop hammer, stuffblock, or quantified loaded column tests (Stewart, 2002; Kronholm and others, 2001; Campbell and Jamieson, 2003; Kronholm and Schweizer, 2003; Landry and others, *in press*), and various penetrometers (Birkeland and others, 1995; Kronholm and others, *in press*) to assess variations in stability, penetration resistance, and structure of individual slopes. Comparisons between studies have been hindered by the use of different methods, approaches, and interpretations employed by each investigation. Additionally, each study has only provided a snapshot in time of

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a dynamic system at one site. This paper will compare two studies conducted in different snow climates using similar methods, and look at results from the same layer sampled at two different times.

With the exception of only a few studies (i.e., Conway and Abrahamson, 1988; Kronholm and Schweizer, 2003; Kronholm and others, *in press*), the investigations mentioned above have not rigorously studied the spatial structure of the data using spatial statistics. Such an analysis is important since it gives an indication of the distances over which snow characteristics might reliably be extrapolated. Kronholm's work has given an initial indication of the spatial structure of some layers in Switzerland; our paper will use similar techniques to compare those layers to the spatial structure of a weak layer and several slab layers in Montana, U.S.A.

2. METHODS AND FIELD AREAS

2.1 Measurements

We used the SnowMicroPen (SMP) to measure the penetration resistance of the snowpack (Johnson and Schneebeli, 1999). The SMP is a motor-driven, constant speed micropenetrometer which generates high resolution data, sampling approximately 250 measurements of hardness (penetration resistance) per mm. The conical sensor tip has a diameter of 5 mm and a length of 5 mm. Previous work with the SMP demonstrates it is capable of discriminating between different crystal types and different layers (Johnson and Schneebeli, 1999; Schneebeli and others, 1999; Schneebeli, 1999; Pielmeier and others, 2001; Pielmeier and Schneebeli, 2003; Birkeland and others, *in press*). To analyze specific layers we first delineated the most distinct layers utilizing the SMP data, supplemented with manual profiles collected on each day. Thus far, no adequate algorithms exist for automatically delineating layers, so we did this manually, as has been done previously (Birkeland and others, *in press*; Kronholm, 2004). Our technique was relatively straightforward for most profiles, and a previous analysis demonstrated that this technique is reasonably robust for analyzing the signal through a weak layer (Birkeland and others, *in press*).

2.2 Spatial Analysis

Once we delineated specific layers, our data analysis involved four primary steps. First, we transformed the penetration resistance data. The resistance data for our layers typically involved thousands of points for each profile, and these data are highly skewed. In order to improve comparisons between profiles, we log-10 transformed the data. Previous analyses have shown this transformation to be most effective in attempting to normalize the data (Pielmeier, 2003; Kronholm, 2004). In this paper our analysis focuses on the mean value of the log-10 transformed penetration resistance for each layer of interest.

The second step of our analysis was to remove outliers. As with many other statistical analyses, even a few outliers can change the data analysis. We examined the data with quartile-quartile plots and histograms to identify and remove outliers. Between one and six data points were removed from our datasets during this step (Table 1).

The final two steps of our analysis involved removing any linear slope-scale trend from the data and then constructing semivariograms. The spatial structure of penetration resistance $Z(\mathbf{s})$, where $\mathbf{s}$ indicates the spatial location, was identified by decomposing the data into a slope-scale trend $t(\mathbf{s})$ and its residuals $\varepsilon(\mathbf{s})$ (Webster and Oliver, 2000) such that

$$Z(s) = t(s) + \varepsilon(s)$$

The slope-scale trend was defined as a linear trend on the local cross-slope coordinates x and upslope coordinates y such that

$$t(s) = \alpha x + \beta y + c_t \ ,$$

where c_t is a constant. The trend was calculated using linear least squares regression. The linear trend surface likely oversimplifies the observed variability, but it allows us to filter out some slope-scale linear trends on our slopes before further analysis. If the linear trend was significant ($p < 0.05$) and explained at least 10% of the variance of the penetration resistance ($r^2 > 0.10$) then the

Table 1: Linear trend for the log10-transformed mean of the penetration resistance within each layer.

Layer	N	Outliers removed	α x	β y	c_t	r^2	p-value	Trend removed?
Montana								
LH1.slab	84	2	-0.0001	0.0035	-1.3301	0.16	< 0.01	Yes
LH1.SH	84	6	-0.0001	-0.0019	-1.5557	0.01	0.81	No
LH2.crust	125	3	-0.0047	-0.0120	-1.0970	0.38	< 0.01	Yes
LH2.lay3	126	5	-0.0017	-0.0132	-1.4966	0.46	< 0.01	Yes
LH2.lay4	126	3	-0.0001	-0.0084	-1.2326	0.37	< 0.01	Yes
LH2.SH	125	2	-0.0017	0.0088	-1.4565	0.08	< 0.01	No
Switzerland								
GR.windslab	112	4	-0.0029	0.0236	-0.3290	0.12	< 0.01	Yes
GR23.SH	113	1	-0.0215	0.0029	-0.8500	0.18	< 0.01	Yes

trend was removed and the residuals were analyzed as a random stationary field. For layers where this was not the case, we analyzed the original data as a random stationary field (i.e. $t(\mathbf{s})$ = 0. The stationary residuals $\varepsilon(\mathbf{s})$ were analyzed using the sample semivariogram $\gamma(\mathbf{h})$, where ($\mathbf{h}$) is a lag distance (e.g. Cressie, 1993):

$$\gamma(\mathrm{h}) = \frac{1}{2N(h)} \sum \left(z(s) - z(s+h) \right)^2,$$

where N($\mathbf{h}$) is the number of pairs in each bin. The sample semivariograms were modeled using either a spherical model with a nugget, a linear model with a nugget, or a pure-nugget model (Cressie, 1993).

2.3 Field Areas

For our Montana site, we utilized a slope in the Lionhead area, located about 15 km west of West Yellowstone, Montana, U.S.A. (approximately 44˚ 45' N; 111˚ 15' W). The slope is northeast facing, generally planar, and protected from ridgetop winds, and the areas sampled have slope angles ranging from 25 to 28 degrees. A layer of 15 to 20 mm surface hoar formed on the slope from December 21st to 26th, 2001. This layer was buried on December 27th, and we sampled areas on the slope on January 9th and 15th, 2002, when the surface hoar was buried under about 30 cm of snow and total snow depths were around 110 cm to 120 cm. The January 9th data comprise our Lionhead 1 dataset (LH1), and the January 15th data make up our Lionhead 2 dataset (LH2). Between the 9th and the 15th little new snow fell and the measured shear stress on the weak layer – calculated from the slope angle, slab density, and slab thickness – increased from 148 to 170 Nm^{-2} (Birkeland and others, *in press*).

The Swiss site was located approximately 4 km west of Davos in the eastern Swiss Alps (approximately 46˚ 47' N; 9˚ 46' E). The slope faces northeast and the slope angle ranged from 43 degrees in the upper part to 30 degrees in the lower part. The site is above treeline and more exposed to wind than our Montana site. The snow cover depth was around 180 cm, which was normal for the area. A layer of surface hoar formed in early December 2002 and was buried around December 12th. The slope was sampled on February 19th, 2003 when the surface hoar layer was buried under about 70 cm of snow. This dataset is denoted GR23.

2.4 Sampling Schemes

The spatial sampling layout of the grid utilized for the sites varied, though each was sufficient to analyze the spatial structure of the data. For the Montana data, we sampled two areas located within 50 m of each other. We took our SMP

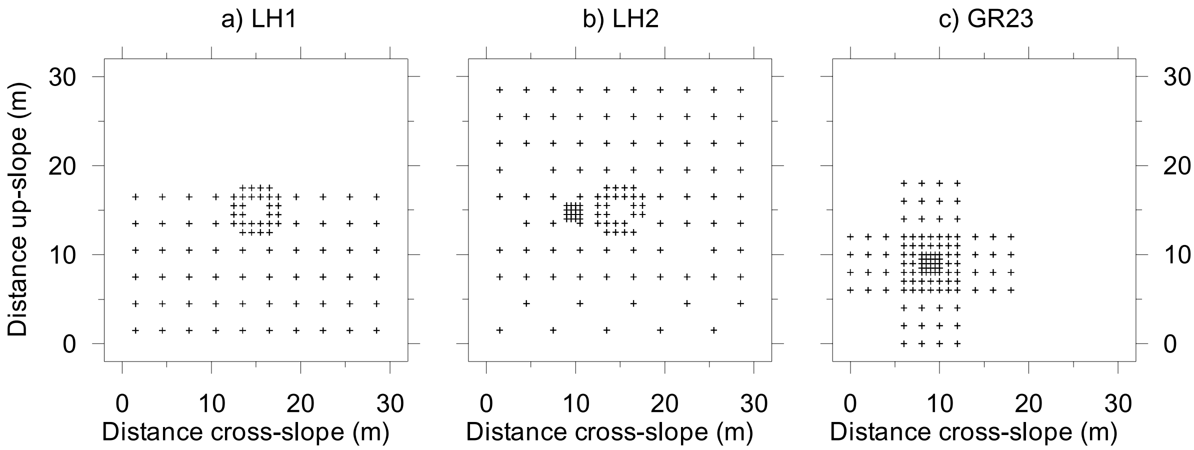

Figure 1: a) Montana grid – LH1, b) Montana grid – LH2, c) Swiss cross

measurements in a nested grid with 3 m spacing throughout the area, and a finer grid with 1 m spacing around a central pit where we conducted stability measurements; adjacent to that area we sampled a small grid with 0.5 m spacing. A total of 86 SMP profiles were collected for the Lionhead 1 dataset (Figure 1a) and 129 for the Lionhead 2 dataset (Figure 1b); equipment difficulties on the first day prevented the collection of additional data, so no 0.5 m grid was sampled on that day and the planned total sampling area of 900 m^2 (30 m by 30 m) was only achieved on the second day. In our analyses we removed the 0.5 m grid from the Lionhead 2 data (around the coordinates (10,15), Figure 1b) to better compare those data with Lionhead 1 and to also see the effect of removing those data on our results.

The Swiss dataset (GR23) utilized a sampling scheme optimized for the analysis of the semivariogram. This involved nested sampling in a cross with 2 m spacing between the SMP measurements in the outer part of the grid; in the center of the grid the SMP measurements were spaced 1 m and 0.5 m apart (Figure 1c). The sampling layout on the Swiss site was more focused on the small-scale variability than the Montana datasets, i.e. the extent of the layout was smaller (18 m in the cross-slope and the up-slope direction) and a higher number of points were placed at small (0.5 m) spacings.

4. RESULTS

Investigating the SMP profiles from our sites resulted in the delineation of several distinct layers. The buried surface hoar layer was our primary layer of interest at each site, so we delineated it first. Additionally, we delineated a few of the slab layers to look at their spatial structure. For the Lionhead 1 data we looked at the slab as one layer (Figure 2a). At Lionhead 2 we divided the slab into several layers and looked at each one independently (Figure 2b). Finally, for the Swiss data we delineated several layers. However, for simplification in this paper we focus only on one particular wind slab layer within the whole slab overlying the surface hoar (Figure 2c).

Once delineated, the analysis first focused on whether linear trends in penetration resistance of specific layers existed across the study sites. Our results varied widely between the layers we tested. Some layers had significant trends that explained over 40% of the variance of log-10 transformed penetration resistance for those particular layers while others either had no significant trend or the trend explained only a small portion of the variance (Table 1). All of our slab layers displayed significant linear trends at the scale of our study plots. Interestingly, the slab layer for Lionhead 1 showed a linear trend that explained only about 16% of the variance for that layer. When Lionhead 2 was sampled six days later in an area adjacent to Lionhead 1, all three slab layers identified had highly significant linear trends explaining more than 35% of the variance of those particular layers. In contrast to the slab

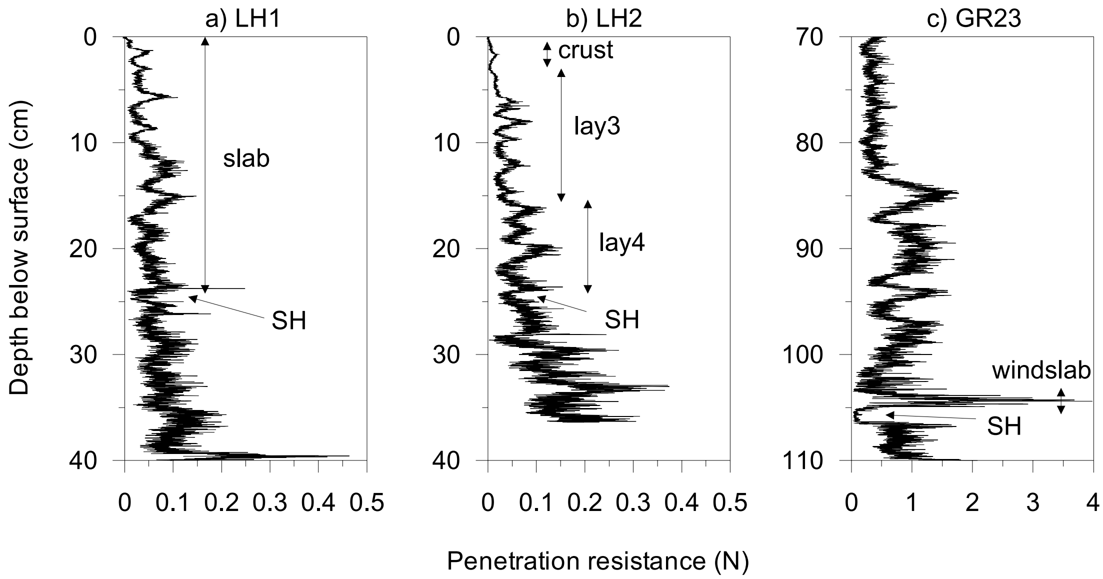

Figure 2: A “representative” SMP profile with the layers investigated for this research for a) LH1, b) LH2 and c) GR23. Note the different scales for the three profiles.

layers, no linear trend existed for the buried surface hoar layer at either Lionhead site. However, a linear trend did exist in the penetration resistance of the surface hoar layer tested in Switzerland.

With the linear trends removed from the layers indicated in Table 1, we investigated the spatial structure of the transformed penetration resistance for each of our layers using semivariograms. The best fitting semivariogram model varied depending on the particular layer, with the best fit for some layers being a pure nugget model, while for other layers spherical or linear models proved better (Table 2). For the Lionhead 1 data in Montana,

Table 2: Calculated semi-variogram using the classical estimator modeled with either pure-nugget, linear or spherical semi-variogram model.

	Best variogram	Slope	Range	Partial sill	Nugget
Montana					
LH1.slab	Pure nugget	-	-	-	0.00217
LH1.SH	Pure nugget	-	-	-	0.01989
LH2.crust	Spherical	-	7.9	0.00251	0.00973
LH2.lay3	Pure nugget	-	-	-	0.00957
LH2.lay4	Pure nugget	-	-	-	0.00566
LH2.SH	Spherical	-	6.2	0.03103	0.01801
Switzerland					
GR.windslab	Spherical	-	4.7	0.02707	0.03154
GR23.SH	Linear	0.0006948	-	-	0.02726

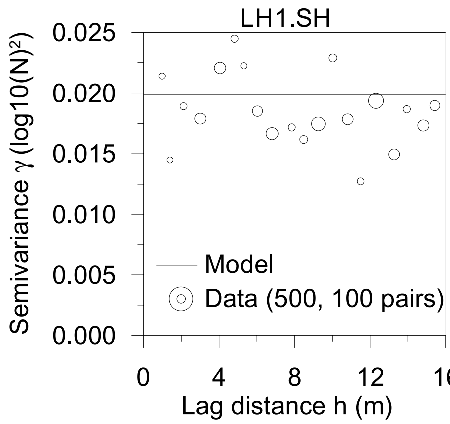

Figure 3: A pure nugget variogram model best fit the penetration resistance for the surface hoar layer at Lionhead 1 (LH1.SH).

the penetration resistance for both the slab and the surface hoar layer did not demonstrate spatial structure (other than the linear trend); the pure nugget semivariogram for the surface hoar layer is shown as an example (Figure 3). However, at the Lionhead 2 site, located just 50 m from Lionhead 1 and sampled six days later, spatial structure around the linear trend existed for at least one of the layers comprising the slab as well as for the surface hoar layer itself (Figures 4a and 4b). Yet, only the semivariogram for the Lionhead 2 surface hoar layer had a small nugget to partial sill ratio (0.58), thus explaining a reasonable part of the spatial structure. Similar to the Lionhead 1 site, at the Swiss site a part of the slab had spatial structure in the trend residuals (Figure 5a). In the buried surface hoar layer the spatial structure was mainly in the form of a trend while the additional spatial structure was modeled with a linear

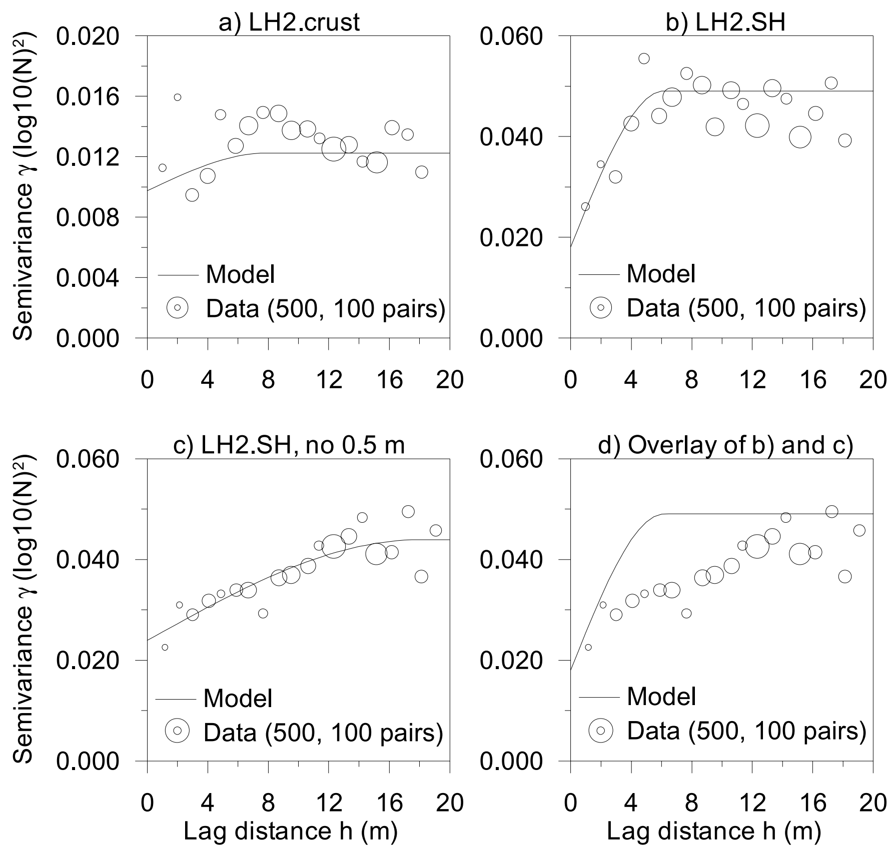

Figure 4: We fit a spherical model to the penetration resistance of the a) crust layer (LH2.crust) and the b) surface hoar layer (LH2.SH) at Lionhead 2. When the 0.5 m grid is removed from the Lionhead 2 data, the semivariogram changes significantly (c). d) shows the modeled semivariogram for all the Lionhead 2 data, with the data points for the data with the 0.5 m grid removed to emphasize the difference when the fine grid is removed.

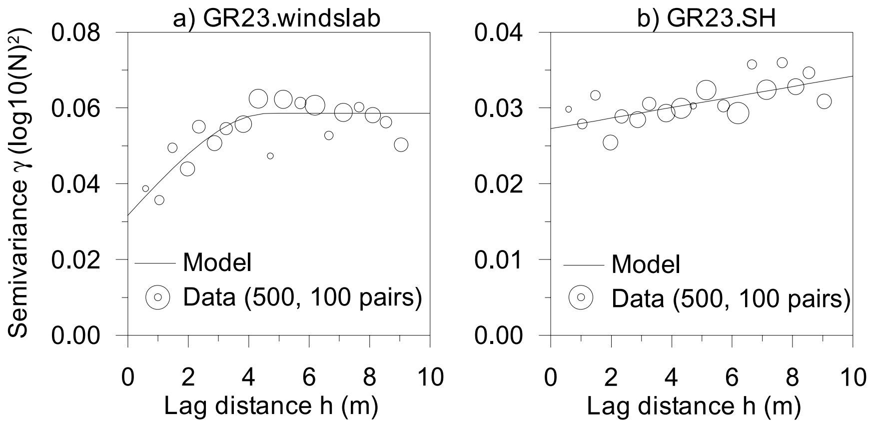

Figure 5: At the Swiss site a) a spherical model provided the best fit for the slab (GR.windslab), and b) the buried surface hoar layer (GR.SH) was best fitted with a linear model plus a nugget.

semivariogram. However, the small slope angle of the model (Figure 5b), indicates that little of the spatial structure is explained by the model.

5. DISCUSSION

Because surface hoar existed at all three sites, our discussion focuses on the spatial structure of the transformed penetration resistance of the surface hoar layers. This research shows that various surface hoar layers can exhibit entirely different spatial structures despite the fact that surface hoar forms under fairly specific climatic conditions. These conditions include clear, cold, and mostly calm weather (Tremper, 2001), which we expect to deposit a fairly uniform layer with little spatial structure. We hypothesize that the cause of the observed differences in the spatial structure between the layers is due to either spatial differences in microclimate between our sites or temporal differences due to the amount of time the layers have been buried, or both. In addition, some of the differences between sites could be due to our different sampling schemes.

Each of our sites differed, and variations between sites could explain the differences in spatial structure observed. The Lionhead 1 site is the most sheltered from wind of the three sites, which might have resulted in a uniform layer of surface hoar with essentially no spatial structure as a trend (Table 1) or as residual structure (Table 2, Figure 3). The Lionhead 2 site is slightly more exposed to wind than the Lionhead 1 site but still more sheltered than the Swiss site. Though we believe it is unlikely, wind may have affected the surface hoar layer on the Lionhead 2 slope and resulted in the observed spatial structure. At the Swiss site the spatial structure was mainly in the form of a linear trend. The shape of this slope, which was slightly concave, may have played a factor in a changing surface hoar layer across this slope through minor but important changes in wind influence and incoming radiation which resulted in the observed trends.

On the other hand, the spatial structure of specific layers might undergo temporal changes. Metamorphic processes and creep within the snowpack might change the spatial structure of layers depending on how long they have been buried and on how strong the forcing has been. The burial times of the three surface hoar layers varied, with the Lionhead 1 layer buried about 11 days, the Lionhead 2 layer 17 days, and the layer at our Swiss site buried around 60 days. The data from our Montana sites are interesting since the two sites are located within 50 m of each other. Although the Lionhead 1 site is slightly more sheltered, both sites are well sheltered from the wind and we would expect to find similar conditions on these two slopes. If conditions were similar on both slopes the first sampling day, the development of spatial structure between the two days might imply that internal snowpack forcings play a role in the evolution of spatial structure on some slopes. However, more studies on the temporal evolution of the spatial structure of individual layers must be made to answer this question; some of this work is currently ongoing in Montana.

Another reason for the observed differences in the spatial structure of the trend residuals in the surface hoar layers could also be due to the different spatial layouts (Figure 1). In particular the lack of measurements at spacings of 0.5 m at the Lionhead 1 site might influence our interpretation of the spatial structure of this layer. To test this hypothesis, we reanalyzed the Lionhead 2 data without the closely spaced penetration measurements. With this reanalysis both the trend ($\log10(R) = –0.0049x + 0.0082y – 1.366$, $r^2=0.109$, $p<0.01$) and the semivariogram (Figure 5c) change. Apparently, the central fine grid has so many points that variations (or similarities) within that grid strongly affect multiple point pairs and thereby significantly affect the final modeled semivariogram The semivariogram modeled for the Lionhead 2 data clearly does not fit the data when the fine grid is removed (Figure 5d). This result implies that a rigorous comparison of data for different sites is only possible if the sampling schemes for the sites are identical, and that the comparisons we discuss above must be treated only in a general sense and not as a direct comparison.

Given the different and complicated spatial structures exhibited by surface hoar layers, which are formed under similar climatic conditions, the variety of spatial structures exhibited by our slab layers is not surprising. Slabs typically form under dynamic conditions of snowfall and wind and something as simple as a changing wind direction might be responsible for the existence of spatial structure in a specific layer (Kronholm, 2004). Many layers typically comprise a slab; when those layers are binned into a single ‘slab’ the spatial structure will be less than if individual layers are analyzed separately. Further, once the layers are formed and are on the ground, internal snowpack forcings such as metamorphism and creep might continue to change the observed structure through time. The layered structure of the snowpack is critically important for assessing snowpack stability and avalanche conditions. Since the snowpack is made up of multiple layers, each with a unique spatial structure, and each potentially affecting the snow stability, it is not surprising that rigorous field observations of stability are sometimes confounded by a great deal of spatial variability (e.g., Conway and Abrahamson, 1984; Föhn, 1988; Jamieson, 1995; Landry and others, *in press*).

5. CONCLUSIONS

Though our results are not conclusive, they suggest that many factors, especially spatial and temporal changes, may affect the spatial structure of penetration resistance of a snowpack layers. Further, the sampling method for a slope can significantly affect the interpretation of the spatial structure for a particular slope. What emerges from this work is a complicated picture of the spatial variability of penetration resistance at the slope scale. For the future, we may not view the snowpack as a group of layers with similar spatial structures, but we may have to accept that each layer is unique, as pointed out by Kronholm (2004). This has several implications. First, rigorously predicting the exact pattern of penetration resistance for individual slopes may be difficult or impossible. Since patterns of penetration resistance may correlate with snow stability, this suggests that avalanche assessment will continue to rely on expert knowledge of slopes supplemented with a variety of additional data. Second, people working toward modeling snow characteristics on slopes will have to take into account the wide fluctuations in measurements and their sometimes seemingly random spatial distribution in their models. In terms of field work, we need more measurements to definitively assess the magnitude of the variability, and additional tests that focus on the sensitivity of our spatial analyses.

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7. REFERENCES

Birkeland, K.W., K.J. Hansen, and R.L. Brown. 1995. The spatial variability of snow resistance on potential avalanche slopes. *J. Glaciology* **41**(137), 183-190.

Birkeland, K., K. Kronholm, M. Schneebeli, and C. Pielmeier. *In press*. Changes in the shear strength and micro-penetration hardness of a buried surface hoar layer. In press for Annals of Glaciology **38**.

Campbell, C. and B. Jamieson. 2003. Spatial variability of stability and fractures in avalanche start zones: Results from the winter of 2002-03. Avalanche News **66**, 23-25.

Conway, H. and J. Abrahamson. 1984. Snow stability index. *J. Glaciology*, **30**(106), 321-327.

Conway, H. and J. Abrahamson. 1988. Snow-slope stability – A probabilistic approach. *J. Glaciology,* **34**(117), 170-177.

Cressie, N.A.C. 1993. Statistics for spatial data. Revised edition. Wiley series in probability and mathematical statistics. John Wiley & Sons, New York, 900 pp.

Föhn, P.M.B. 1988. Snow cover stability tests and the areal variability of snow strength. *Proceedings of the 1988 International Snow Science Workshop*, Whistler, Canada, 262-273.

Jamieson, J.B. 1995. Avalanche prediction for persistent snow slabs. (Ph.D. thesis, University of Calgary.)

Johnson, J., and M. Schneebeli. 1999. Characterizing the microstructural and micromechanical properties of snow. *Cold Reg. Sci. Tech.* **30**(1-3), 91-100.

Kronholm, K. 2004. Spatial variability of mechanical snow cover properties with regard to avalanche formation (Ph.D. thesis, Department of Geography, University of Zurich).

Kronholm, K. and J. Schweizer. 2003. Snow stability variation on small slopes. *Cold Reg. Sci. Tech.* **37**(3), 453-465.

Kronholm, K., M. Schneebeli, and J. Schweizer. *In press*. Spatial variability in penetration resistance in snow layers on a small slope. In press for *Ann. Glac*. **38**.

Kronholm, K., J. Schweizer, M. Schneebeli and C. Pielmeier. 2001. Spatial variability of snowpack stability on small slopes studied with the Stuffblock test. To be published in the proceedings of the *II International Conference "Avalanches and Related Subjects"* Kirovsk, Murmansk, Russia, September 3 - 7, 2001.

Landry, C., K. Birkeland, K. Hansen, J. Borkowski, R. Brown, and R. Aspinall. *In press*. Variations in snow strength and stability on uniform slopes. In press for *Cold Reg. Sci. Tech.*

Pielmeier, C. 2004. Textural and mechanical variability of mountain snowpacks. (Ph.D. thesis, Department of Geography, University of Bern).

Pielmeier, C. and M. Schneebeli. 2003. Stratigraphy and changes in hardness of snow measured by hand, ramsonde and snow micropenetrometer: a comparison with planar sections *Cold Reg. Sci. Tech*. **37**(3), 393-405.

Pielmeier, C., M. Schneebeli, and T. Stucki. 2001. Snow texture: a comparison of empirical versus simulated texture index for alpine snow. *Ann. Glaciol.* **32**, 7-13.

Schneebeli, M. 1999. High resolution penetrometry in the high-porosity material snow. In *Proceedings of the International Workshop on Penetrometry in the Solar System.* Vienna, Verlag der Österreichischen Akademie der Wissenschaften Wien, 61-72.

Schneebeli, M., C. Pielmeier, and J. Johnson. 1999. Measuring snow microstructure and hardness using a high resolution penetrometer. *Cold Reg. Sci. Tech.* **30**(1-3), 101-114.

Stewart, K. 2002. Spatial variability of stability within avalanche start zones. (M.Sc. thesis, University of Calgary).

Webster, R. and M. Oliver. 2001. Geostatistics for environmental scientists. Wiley, Chichester, 271 pp.