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Review of spatial variability of snowpack properties and its importance for avalanche formation

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Abstract

The seasonal snow cover is spatially variable. Spatial variability of layer properties is due to various external and internal process drivers interacting with terrain and ground cover during and after the deposition process. Many processes that act as process drivers such as radiation and wind cause spatial variations of the snowpack at several scales. The most challenging process is probably wind that might hinder prediction of variability at the slope scale. The complexities and uncertainties involved in snow slope stability evaluation and avalanche prediction are largely due to the variable nature of the snow cover. Many studies have tried to quantify spatial variability. Different methods have been used and the studies covered a variety of scales. Accordingly, some results appear contradictory, suggesting that the degree of spatial variation varies widely. This is not surprising, and is partly due to the methods used and of course, due to varying natural conditions. For example, the variation will strongly depend on the measurement scale — the so-called support — of the method which varies from 10^{-4} m^2 for the SnowMicroPen to 3 m^2 for the rutschblock test. The layering was found to be less variable than, for example, the stability of small column tests. Whereas it is often perceived that the results of the studies were not conclusive, they completely changed our view of spatial variability. The importance of scale issues, in particular for avalanche formation became evident. Geostatistical analysis has been introduced and used to determine the length of spatial autocorrelation and to derive appropriate input data for numerical models. Model results suggest that spatial variation of strength properties has a substantial "knock-down" effect on slope stability and that the effect increases with increasing spatial correlation. The focus on scale has also revealed that spatial variations can promote instability or inhibit it. With the awareness of scale the causes of spatial variability can now be addressed. We will review the present state of knowledge, discuss consequences for avalanche forecasting and snow stability evaluation, and recommend future research directions.

Keywords: Snow cover; Snow stratigraphy; Snow mechanical properties; Snow slope stability evaluation; Avalanche formation; Avalanche forecasting; Spatial variability; Numerical modeling; Scale

1. Introduction

The way spatial variability has been analyzed and treated since the early snow studies differs. Early snow researchers understood that the snow cover varied in

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space, and even suggested that wind was the most significant cause of the variability (Seligman, 1936). The stratigraphy of the snow cover was seen as the result of a sedimentation process causing layers with rather homogeneous as well as layers with rather heterogeneous properties (Paulcke, 1938). However, much research focused on describing the basic properties of the snow cover at a single location and its evolution over time, rather than analyzing spatial variability. This meant that observed variations in snow cover properties such as strength were primarily seen as the result of measurement errors (e.g., Keeler and Weeks, 1968). Only a few spatial investigations were done. For example, Neher (Bader et al., 1939) did a series of ram profiles and temperature measurements in different aspects and elevations, and Bradley (1970) studied the dependence and timing of deep slab instabilities by slope aspect using a specially constructed resistograph to rapidly measure penetration resistance.

When McClung (1979, 1981) presented a model of snow slab avalanche release based on fracture mechanical principles, he indirectly introduced a spatial component. Fracture mechanics assumes that there is no perfect material and describes whether and how a fracture grows from an initial imperfection in the material. In spatial variability terms, applied to avalanche release, the weak layer consisted of areas of lower than average strength (imperfections) and areas of about average or higher than average strength (everywhere else). This was used more as a conceptual model incorporating fracture mechanical principles rather than an actual model of the snow cover. However, Colbeck (1991) already pointed out in his review on the layered character of the snow cover that spatial variation of the weak layer thickness and strength would be critical to determining the likelihood of a failure and whether or not a failure would propagate or arrest.

Conway and Abrahamson (1984) first analyzed field measurements of stability in a spatial context. They measured shear strength along the fracture lines of slab avalanches shortly after triggering, and on slopes that had not failed. Along fracture lines, they found large variations between adjacent measurements, and some of their snow cover samples failed during test preparation. They assigned these measurements to so-called deficit zones where the shear strength of a weak snowpack layer or interface was less than the gravitational stress due to the overlying slab. They concluded that the weak layer or interface below the slab of an avalanche may contain deficit areas and pinning areas. If a deficit area was found by a test, the slope was considered to likely be unstable. Subsequently, Conway and Abrahamson (1988) used spatial statistics to derive the failure probability based on the size of deficit zones.

Conway and Abrahamson's papers triggered two things: (1) an increase in the number of field studies focusing on analyzing the spatial variability of various snowpack properties at the slope scale and concurrently the search for deficit zones, and (2) the representativity or validity (and hence the usefulness — in particular for recreationists) of single point stability tests became questioned (e.g., Munter, 2003). However, the importance of the spatial structure and its scale in the context of avalanche formation got lost in most of the research that followed. During the 1990s field results were rarely analyzed using spatial statistics. One exception is a study by Chernouss (1995) who presented autocorrelation functions for snow depth, snow density and strength from spatial measurements in the Khibini mountains to derive a probabilistic model of avalanche release (Chernouss and Fedorenko, 1998).

Currently, the focus is less on the validity of point observations. Rather, it is recognized that the spatial variability is important for slope stability evaluation and avalanche formation (Schweizer et al., 2003a), and should be investigated and described in detail for that purpose.

Furthermore, spatial variability of the snow cover, including terrain effects, was recognized as a major source of uncertainty in avalanche forecasting (Hägeli and McClung, 2004). They proposed a hierarchical framework that highlights scale issues that are relevant to avalanche forecasting.

Snow cover variability with regard to snow slope stability has been investigated in many studies (see below), and the interpretation of the results varies widely. Sturm and Benson (2004) saw similar differences in the interpretation of snow stratigraphy studies, and attributed this to two contradicting views: regular vs. irregular. In their review on the heterogeneity of snow stratigraphy they proposed that some studies suggest that the snow cover consists of well behaved and laterally homogeneous layers with properties that can be perfectly extrapolated. Other studies describe the layers as being so variable that cross-correlation of layers (finding the same layers) and extrapolation of layer properties is impossible for distances of kilometers or as little as tens of meters. Sturm and Benson (2004) suggested that the truth is probably somewhere in between. This view on snow stratigraphy might also apply for snow stability.

Considering the snow cover as a sediment promotes the understanding of the causes of the spatial variability of the snow cover. These causes (or agents) can be subdivided into external and internal causes acting during and/or after deposition (Sturm and Benson, 2004). External agents causing variability during deposition are precipitation, sublimation and wind, and after deposition mainly radiation, temperature and wind. The most prominent internal driver (after deposition) is snow metamorphism. Most of the variability is the result of the interaction of these drivers with terrain (topography and vegetation/ground cover).

In the following we review studies on spatial variation of strength and stability properties at scales ranging from individual slopes to mountain ranges. The aim is to summarize and discuss previous studies in order to arrive at a description of our current knowledge. Although a number of studies have investigated the spatial variability of snow bulk properties such as snow water equivalent, we only review those that are relevant to snow cover stability. Although, avalanche formation is a process that mainly involves the slope scale, it is essential to consider smaller and larger scales since those influence the multi-scale avalanche formation problem. Therefore, our focus is on the slope scale, but we will also consider smaller scales, and in particular larger scales as well. Before the review, we will introduce some basics on spatial variation and the concept of scale. Based on our review we will highlight key points about spatial variability, its interpretation and consequences on snow slope stability evaluation.

2. Definitions

It is well known that the snow cover is spatially variable. The most obvious spatially variable property is the snow depth. However, for snow stability evaluation purposes, snowpack bulk properties such as snow depth are not as relevant as the properties of individual layers within the snowpack (Colbeck, 1991). In this paper our focus is therefore on layers within the snowpack, and the relationship between layers.

2.1. Layer

A thorough discussion of the definition of a "layer" is outside the scope of the present paper, but it must briefly be mentioned because it is important for studies of spatial variability (see e.g., Pielmeier and Schneebeli, 2003). A layer can be described as "a stratum of snow that is different in at least one respect from the strata above and below" (Colbeck et al., 1990). This description leaves open the definition of both the property of interest and the magnitude of difference necessary. For snow stability evaluation studies, the mechanical properties of the layers are of interest. The exact definition of "different" decides the level of detail and may differ between studies depending on their purpose. A manual snowpack profile made to accompany a snow stability test result may include only a few types of layers; those that are potential weak layers, those that are potential slabs and a limited number of distinct adjacent layers such as melt-freeze crusts, resulting in relatively few layers. On the other hand, a profile made to verify the result of a snow cover model may include a larger number of layers. In addition, the number of layers found by a study is determined by the method used to define each layer. For manually recorded snow profiles the skill of the observer and the time spent on the profile are decisive. More generally, the layer resolution is determined by the sample support, as discussed below.

Spatial variability of snowpack layers is manifested through the presence of individual layers in the slope-perpendicular direction and through appearance and disappearance (pinching) of layers in the slope-parallel (lateral) directions. More succinct spatial variability may be exhibited in individual layers by spatial variation of layer properties such as thickness, density, grain size and strength in both the slope-perpendicular and the lateral directions at a level of detail that is below that used to define layer boundaries for the study, as described above. In the present paper, we focus on studies that have described the lateral variations of mechanical properties of individual layers.

2.2. Scale and scale issues

Blöschl and Sivapalan (1995) reviewed scale issues related to snow hydrology and set up a useful framework for spatial variability studies. They describe the scale characteristics of measurement settings with a scale triplet that includes the spacing (the distance between measurement locations), the extent (the longest distance between two measurement locations, or the area covered by the study) and the support (the area or volume over which each measurement is integrated). In Nature, processes act over a typical scale (or a range of scales) called the process scale. In this framework, spatial variability studies attempt to measure and describe the process scale, but depending on the measurement scale, the scale characteristics of the resulting observations might be different from the true process scale. Similarly, studies with different scale triplets may find different measurement scales. Some recent spatial variability studies have used this framework to describe the sampling methodology of the study (e.g., Kronholm, 2004). Scale and scales

Table 1
Selection of slope scale studies with summary of major results

Study	Property	Results
Sommerfeld and King (1979)	Shear strength	− CV of shear strength was 52–62% for three slopes approximately 24 h after avalanching.
Conway and Abrahamson (1984)	Stability index (derived from shear strength measurements)	− Large changes in stability over 0.5 m, "outliers" not discarded − CV of stability, stable slopes: 65%; unstable slopes: 82% − Critical length of "deficit zone": <1 m
Conway and Abrahamson (1988)	Stability index (derived from shear strength measurements)	− Shear strength measurements from 5 slopes with CV between 31% and 72% (described fully in Conway and Abrahamson, 1984) − Critical length of "deficit zone": >2.9 m − Measurements should be spaced less than 0.5 m apart to capture variability and should span at least 3 m. − The pattern of point stability on a slope is important for slope stability. − Concluded that small deficit zones were not enough to make slopes unstable.
Föhn (1989)	Stability index (derived from shear frame measurements)	− CV, stable slopes: <30% with "outliers" excluded − CV, stable slopes: <38% with "outliers" included
Jamieson and Johnston (1993), Jamieson (1995)	Rutschblock score	− With 97% probability, a rutschblock score on the uniform part of a slope is within ±1 score of the slope median score. − One of nine slopes investigated included a small area of very weak surface hoar, possibly a "deficit zone"; the slope did not fail during measurements.
Birkeland (1990), Birkeland et al. (1995)	Penetration resistance	− CV of average penetration resistance was 28% to 58% on two slopes over two seasons. − Average penetration resistance was positively correlated with snow depth variations caused by wind drifting. − Weaker average penetration resistance was statistically correlated with sites overlying rocks.
Chernouss (1995)	Snow depth, density, strength	− Spatial autocorrelation functions were calculated for four different snow properties.
Jamieson and Johnston (2001)	Shear strength	− CV of 7–12 shear frame measurements within 2 m ranged from 3% to 66% with a mean of 15%. − Larger variation in avalanche release areas than level study plots
Stewart (2002), Stewart and Jamieson (2002), Campbell and Jamieson (2006)	Point stability (drop hammer test)	− Patches of below and above average point stability were found in most of the 39 investigated slopes. − No spatial autocorrelation length was found but many slopes showed a fair degree of spatial continuity. − CV max: 82%, min: 10%, mean: 50% − Twelve of 36 arrays had significant clusters of either high scores, low scores or both, ranging in length from 1 m to 4 m. − Nineteen arrays had significant spatial clusters in slab thickness. In 2 cases clusters of high slab thickness corresponded with clusters of high point stability.
Landry (2002), Landry et al. (2004)	Stability index (derived from shear strength measurements)	− CV of weak layer shear strength between 10% and 50% with a mean of 24% on 11 slopes − Stability variation was in the same range. − Maximum and minimum values on one slope were found in adjacent tests. − 25–39% of pits dug on relatively "uniform" slopes were found to not be statistically representative of that slope. − Layering throughout a mountain range was relatively consistent at the same time shear strength and point stability across a small slope were quite variable.

Table 1 (*continued*)

Study	Property	Results
Kronholm and Schweizer (2003)	Point stability (stuffblock test, rammrutsch test)	– All the sixteen weak layers on eight slopes analyzed were spatially continuous. – The spatial variation of point stability consisted of a strong trend which explained a large part of the variation. – Variation expressed as quartile coefficient of variation was around 40% but dropped to around 20% when the trend was removed. – A stability scheme including information on (a) weak layer continuity, (b) average and (c) variation of point stability was suggested, with continuous weak layers with low average point stability and small variation in point stability being the most critical.
Harper and Bradford (2003)	Stratigraphy	– Investigated the snow layering on a flat glacier using translucent and manual profiles – Thick (5–10 cm) layers were continuous over tens of meters whereas thin features (1–10 mm) within those layers were not. – No quantification of horizontal variability
Birkeland et al. (2004a)	Penetration resistance (SMP)	– No spatial trend in penetration resistance of a buried surface hoar layer on a slope (two sets of measurements from two parts of the slope six days apart) – CV of weak layer thickness varied from 24% to 34%. – CV of the median weak layer penetration resistance varied from 43% to 48%.
Birkeland et al. (2004b)	Penetration resistance	– Analyzed the spatial structure of the penetration resistance for slabs and weak layers on three slopes – Of the eight layers analyzed, three had quantifiable spatial structure and five did not. – The sampling method on a slope can significantly affect the interpretation of the spatial structure.
Kronholm et al. (2004a)	Penetration resistance (SMP)	– Seven layers on a single slope were investigated. – All layers were spatially continuous and had slope scale trends in penetration resistance. – The range of autocorrelation varied from 3.9 m to more than 10 m which was the maximum that could be determined given the extent of the measurement setup (19 m).
Campbell and Jamieson (2007)	Point stability (rutschblock test)	– 84% of RB scores were within ±1 of the median on slopes with variability typical of release zones. – Within some arrays no significant correlations with snowpack and terrain predictors were found. – In others, RB score increased with slab thickness and decreased with slope angle. – In some arrays with weak layers of surface hoar, the point stability decreased with increasing weak layer thickness and increased with increasing weak layer depth.
Logan (2005), Logan et al. (2007)	Shear strength (shear frame), point stability (derived from shear strength)	– 90% of pits were statistically representative of their particular “uniform” slope (using smaller slopes and a different test than Landry, 2002). – Spatial structure of shear strength difficult to quantify, though some autocorrelation observed at distances <1 m – Quartile CV of shear strength ranged from 9% to 13% on the two slopes over 10 sampling days.
Lutz et al. (2007)	Penetration resistance (SMP)	– Looked at different parts of the weak layer using the SMP on two different slopes. – The spatial structure of the penetration resistance of the different parts of the weak layer were difficult to quantify on one slope, but could be quantified on the other slope.

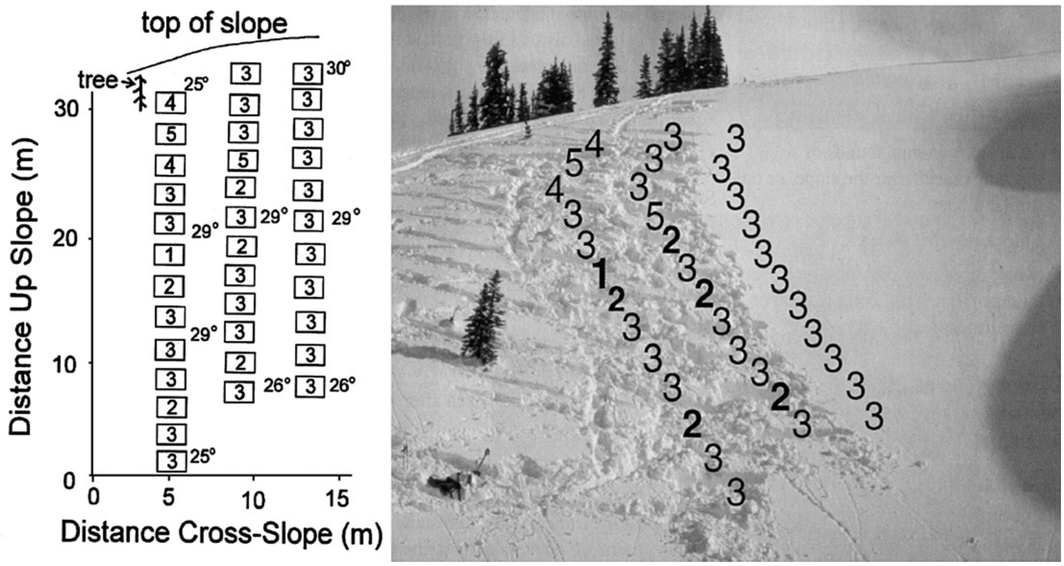

Fig. 1. Spatial measurements of point stability on a small slope (Columbia Mountains, western Canada) using the rutschblock test (N=36). The slope median stability test score was 3 with a quartile coefficient of variation (QCV) of 0 (the interquartile range only included test scores of 3). For comparison, the coefficient of variation which, however, is not an appropriate measure for ordinal stability data was 25%. The slope does not show any spatial structure except some small clusters of lower and higher stability (near the tree at the top of the slope) (from Jamieson, 1995, p.161).

issues in avalanche forecasting were first pointed out by Hägeli and McClung (2001).

3. Slope scale

Table 1 summarizes slope scale variability studies. The properties measured are given as well as the main results. Most studies measured either various indices of point stability, shear strength or penetration resistance and reported, among other findings, the coefficient of variation (CV): a non-spatial measure of variation.

For shear strength measured with a support on the order of 100 cm^2 coefficients of variation were about 15–25% for study plot measurements (Jamieson and Johnston, 2001). Measurements of penetration resistance with a much smaller support (<1 cm^2) showed coefficients of variations in the order of 50% (e.g., Kronholm, 2004). Variations in (point) stability test results were on the order of 30–50% (CV) again depending on the test area (support varying between 0.09 and 3 m^2) (e.g., Stewart, 2002; Campbell, 2004). As there are more sources of variation for point stability

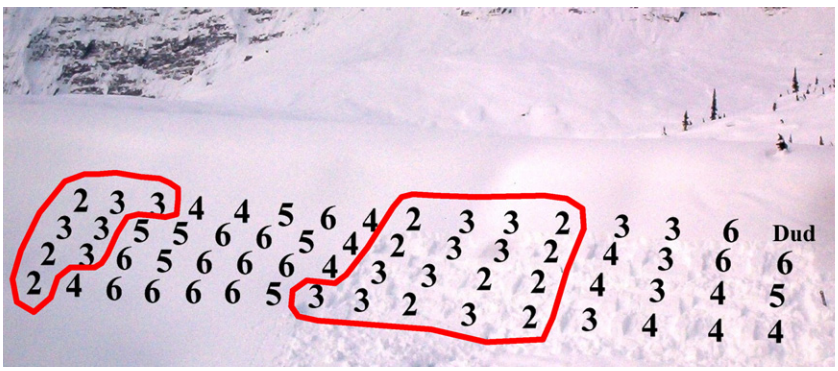

Fig. 2. Spatial array of point stability measurements on a small slope (Mt. Abbott, Columbia Mountains, western Canada) using the rutschblock test (N=63, spacing about 2.5 m, extent about 40 m). The slope median stability test score was 4 with a quartile coefficient of variation (QCV) of 50%. The slope shows distinct patterns of higher and lower stability. A similar pattern, though with some more variations, was found at this same site the following winter. The topography of the bare slope is characterized by cross-slope undulations. Campbell (2004) suggested that the observed stability was probably due to destruction of the surface hoar on higher ground by wind when the surface hoar was on the surface and subsequent preservation of the surface hoar in the more sheltered depressions (from Campbell, 2004, p. 89).

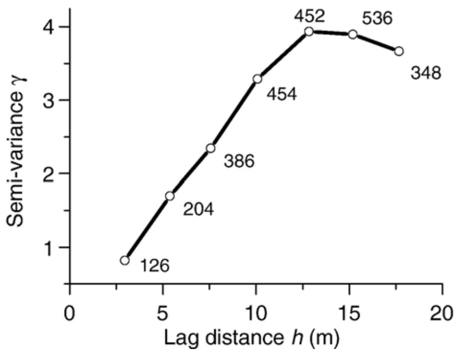

Fig. 3. Semi-variogram for the spatial data from Mt. Abbott shown in Fig. 2. Numbers indicate numbers of point pairs. The geostatistical analysis suggests a range of about 10–15 m (from Campbell, 2004, p. 87).

(at least slab and weak layer properties) the higher variation found in stability tests is not surprising. Of particular interest are the results about the representativity of rutschblock tests (Föhn, 1987), which range from 1 to 7 for low to high stability. On rather sheltered slopes a rutschblock test score was in 97% of the cases found to be within ±1° of the slope median (Jamieson and Johnston, 1993). This proportion decreased to about 70–80% if avalanche start zones were tested, implying such zones were more spatially variable (Föhn, 1989; Campbell and Jamieson, 2007) (Figs. 1–3).

Only recently, explicit geostatistical analyses have been used to analyze field data mainly using the semi-variogram (Cressie, 1993; Kronholm, 2004). These analyses indicate that at the slope scale in some cases the typical weak layer properties were autocorrelated while in other cases they were not. The length of autocorrelation depended on the type of measurement, the type of layer, and on the scale triplet, but often was on the order of several meters. For instance, Kronholm (2004) and Birkeland et al. (2004b) showed that various surface hoar layers can exhibit entirely different spatial structures (using the same measurement and analysis method) despite the fact that surface hoar forms under fairly specific weather conditions. Slab layers were typically more variable in terms of penetration resistance than weak layers reflecting the dynamic conditions of snowfall and wind during deposition of the slab (Fig. 4). 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 (Kronholm, 2004).

Layer properties proved to be more continuous than stability scores and most often layers existed throughout a slope of given aspect and elevation (Kronholm, 2004). Therefore it is assumed that structural instability indices (e.g., McCammon and Schweizer, 2002) are expected to be less subject to spatial variability, though these have yet to be investigated in detail. Also, rutschblock release type proved to be more repeatable than rutschblock scores, especially for low median scores (Campbell and Jamieson, 2007). Similarly, it has been proposed that shear quality (Johnson and Birkeland, 2002) and fracture character (van Herwijnen and Jamieson, 2002) should show less variability than test scores, although this has not been shown yet.

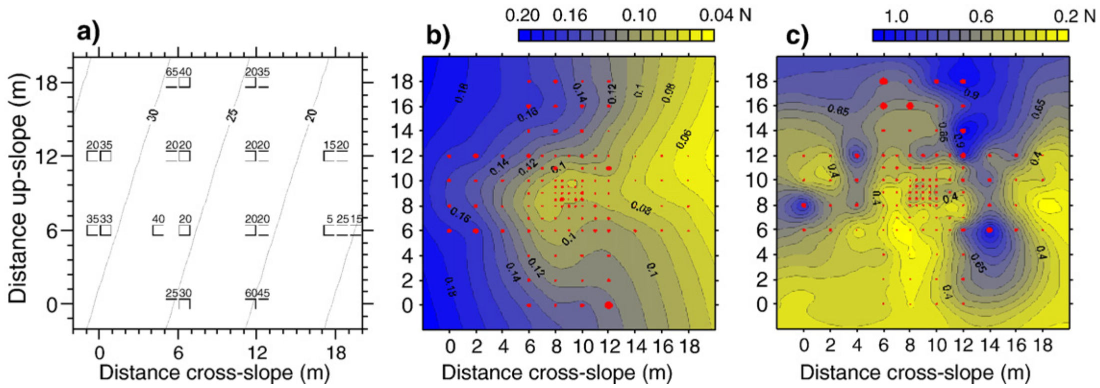

Fig. 4. (a) Results of stability measurements (rammrutsch) on a small slope for a buried layer of surface hoar (17 January 2003). The drop height (in cm) that is a measure of stability, is shown above the test location. A linear slope stability trend was found and indicated by 5 cm contours. The median drop height was 20 cm with a quartile coefficient of variation of 27% before and 22% after trend removal (from Kronholm, 2004). (b) Penetration resistance (SMP) of the same layer of buried surface hoar as shown above in (a). The layer was found at all measurement locations on the slope and showed a strong slope-scale trend in resistance. Red circles indicate measurement locations and are scaled to the measured resistance. A pure-nugget semi-variance was found after trend removal, i.e. no additional spatial structure was found after linear trend removal. (c) Same type of figure as in (b) for a wind-slab of small rounded grains and some facets. The layer showed smaller-scale spatial structure with a range of about 6 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Scale triplet, field and analysis methods used in selected slope scale studies

Study	Property	Support (m^2)	Minimum spacing (m)	Extent (m)	Field method	Analysis method	Autocorrelation length (m)
Conway and Abrahamson (1984)	Stability index	0.09	0.6–0.9	~200	Shear frame with bending moment and variable loading rate	CV	–
Conway and Abrahamson (1988)	Stability index	0.09	0.6–0.9	~200	Shear frame with bending moment and variable loading rate	Geostatistics	n/a
Föhn (1989)	Stability index	0.025	~10	30–300	Shear frame	CV	–
(Jamieson and Johnston, 1993; Jamieson, 1995)	Rutschblock score	3	~2.5	20–30	Rutschblock	Relative variation	–
Birkeland et al. (1995)	Penetration resistance	0.001	1	50	Digital Resistograph	CV	–
Jamieson and Johnston (2001)	Shear strength	0.01, 0.025, 0.05	0.3	6	Shear frame	CV	–
Stewart 2002; Stewart and Jamieson (2002)	Point stability	0.09	0.6	20–50	Drop hammer	Visual clusters, repeatability, geostatistics, CV	–
Landry (2002); Landry et al. (2004)	Shear strength, point stability	0.09	0.5	42	QLCT	CV, *z* scores	–
Kronholm and Schweizer (2003)	Point stability	0.09	1	19	Rammrutsch	QCV, geostatistics	>10
Birkeland et al. (2004a)	Penetration resistance	2×10^{-5}	0.5	30	SnowMicroPen	CV	–
Birkeland et al. (2004b)	Penetration resistance	2×10^{-5}	0.5	30	SnowMicroPen	geostatistics	5–8
Kronholm et al. (2004a)	Penetration resistance	2×10^{-5}	0.5	19	SnowMicroPen	CV, QCV, geostatistics	2 to >10
Campbell and Jamieson (2007); Campbell (2004)	Point stability	3 (0.9)	2.5 (0.6)	10–40	Rutschblock (drop hammer)	CV, QCV, geostatistics, clusters	7–14 (1–5)
Logan (2005); Logan et al. (2007)	Shear strength	0.025	0.5	14–30	Shear frame, stuffblock	*z* scores, geostatistics, QCV	Little autocorrelation found
Lutz et al. (2007)	Penetration resistance	2×10^{-5}	0.5	14–30	SnowMicroPen	geostatistics, CV	n/a

Due to snow internal processes — following from the fact that snow exists close to its melting point — the spatial variability of the snowpack is expected to change over time (Birkeland and Landry, 2002). The rate of change and type of changes which take place are determined by the magnitude and the type of forcing that drives the change. While some ideas about the changes to spatial variability in the snow cover under various forcings have been proposed (e.g. pressure sintering might change the strength/load ratio after loading by snowfall (Jamieson et al., in press-b), conclusive results from field studies have yet to confirm these ideas. It seems plausible that varying slab thickness might affect the initial spatial structure of a weak layer. For instance, weak layer strengthening rate will vary with temperature gradient and load (pressure sintering) depending on slab thickness and density. So far, the best attempt to describe the temporal changes in spatial variability on typical avalanche slopes was made by following the shear strength of several surface hoar layers after burial (Logan, 2005; Logan et al., 2007). However, the results show no typical trends in the type of change and the rate of change of the observed spatial variability. Additional results from these datasets may provide more insight into the temporal evolution of spatial variability.

Within arrays of point stability tests on single slopes within a few hours, Jamieson (1995) and Stewart (2002) found the test scores did not correlate with the order of the tests so spatial variability was not confounded by temporal variability. However, most of these tests focused on slabs overlying persistent weak layers which are known to be slow to change.

Dramatic changes over time have been observed when a slope fractures but does not release. The strength drops significantly but subsequently will increase and heal by sintering relatively quickly (within hours). This implies that sub-critical weak layer fractures assumed as a prerequisite in some snow slab avalanche release models are transient features (Birkeland et al., 2006).

4. Regional and mountain range scale

Table 2 summarizes spatial variability studies at scales larger than the slope scale. These studies mainly focused on weak layer formation at the snow surface ("Today's snow surface is tomorrow's failure layer") (e.g., Feick et al., 2007), on regional stability (i.e. distribution of point stability over terrain) (e.g. Birkeland, 2001) or avalanche danger patterns (Schweizer et al., 2003b) and on avalanche observations (e.g., Stoffel et al., 1998).

Observations of a surface hoar weak layer showed that initially this layer was continuously present across a small mountain range (20 km) (Schweizer and Kronholm, 2007). This may not be the case in other situations and/or for other weak layers. However, Hägeli and McClung (2003) reported that weak layers were consistently found (in certain aspects and elevations) across whole mountain ranges, even over hundreds of kilometers ("process-based terrain correlations" or "patterns"). This, combined with the increase in weak layer strength as a result of increased pressure sintering in response to additional snowfall (Jamieson et al., in press-b), likely explains why stability indices derived from study plot measurements (as well as stability scores from index slopes) were correlated to skier-triggered avalanche activity on persistent weak layers in the surrounding terrain (Zeidler and Jamieson, 2004).

At a smaller scale, patterns in weak layer formation were described depending on the local wind regime (Feick et al., 2007), valley clouds (Colbeck and Jamieson, 2006) and the freezing level during storms (Jamieson, 2006).

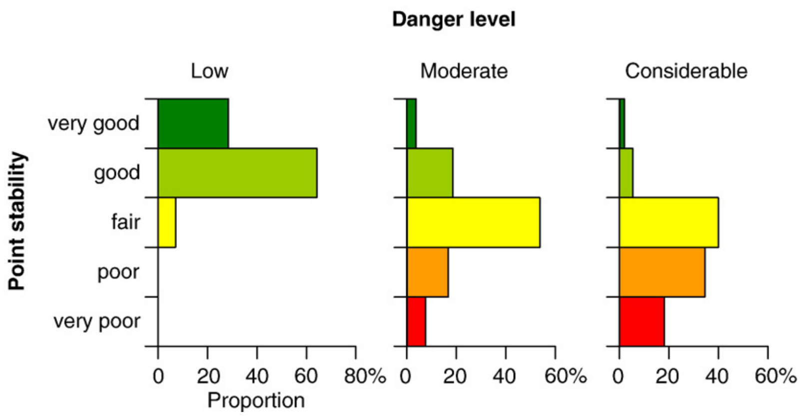

Fig. 5. Characteristic point stability distributions (regional scale) for the three lower danger levels of Low, Moderate and Considerable (from Schweizer et al., 2003b).

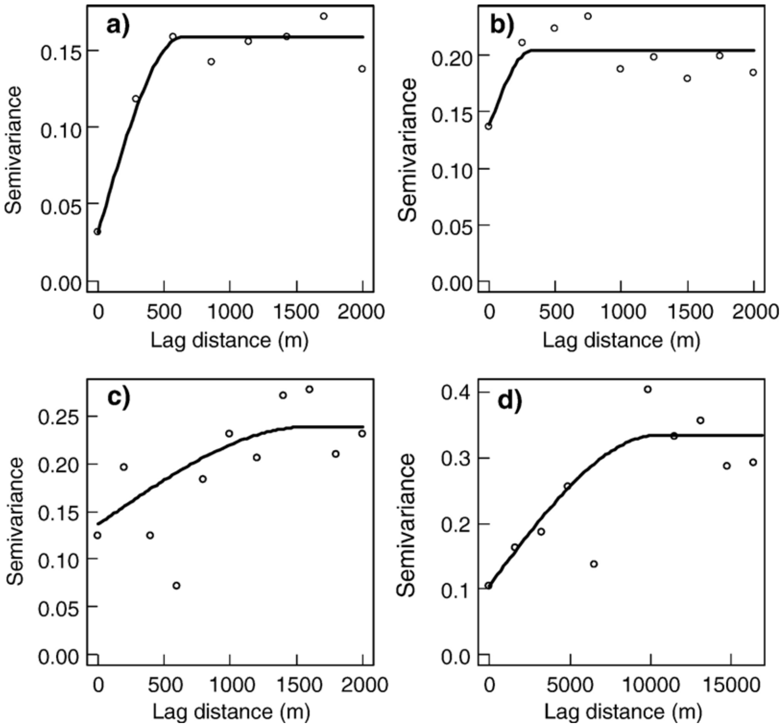

Fig. 6. Multi-scale geostatistical analysis: sample (○) and model (–) indicator semi-variogram for surface hoar presence at increasing scale. a) Using results from 30 SMP profiles and 54 manual profiles within a region. b) Using only results from the 54 manual profiles within the region. c) Using only the 27 manual profiles in another region. d) Using the 30 SMP profiles and all 81 manual profiles from both regions (from Schweizer and Kronholm, 2007).

Patterns of snow stability could be related to terrain, with, for example, more unstable conditions found on higher elevation, northerly-facing slopes. However, on different days different patterns were observed, demonstrating the dynamic nature of the terrain/stability relationship (Birkeland, 2001; Schweizer et al., 2003b). Whereas aspect and elevation were found to affect snow stability and avalanche danger at the regional scale, differences due to snow climate were found at larger scale (e.g., Gruber et al., 2004). Typical stability variations were derived for a given danger rating reflecting the spatial variation of point stability observations on slopes (Schweizer et al., 2003b) (Fig. 5). This indicates the difficulties and hence the limitations of point stability observations when attempting to relate point stability to regional stability. Although, point stability is correlated with regional stability or avalanche danger rating, a reliable prediction from a single point observation is not possible (Jamieson et al., 2006). For example, if predicting the three lower danger levels (1–3) from the point stability data of Schweizer et al. (2003b) (Fig. 5), the overall (non-cross-validated) accuracy was about 58% which is too poor for practical application. This also applies to a lesser degree to study plot observations. However, as these locations are selected by experts to minimize variability the representativity is expected to be higher (and hence the uncertainty lower) than for observations on slopes so that prediction is actually feasible (Zeidler and Jamieson, 2004; Jamieson et al., in press-b).

5. Sub-slope scale

Besides radiation and wind, the terrain roughness (most prominently if trees are present) modifies the snow cover stratigraphy. The large spatial variations in snow layering found in forest stands (Gubler and Rychetnik, 1991; Schweizer et al., 1995) and the fact that avalanches hardly ever release in forests exemplifies that spatial variability affects avalanche formation. Due to different snow temperature conditions, areas over rocks often show a different snowpack (typically weaker than in the surroundings) if the rock size is significant compared to snow cover depth (Arons et al., 1998). Such areas have also been documented as triggering points for avalanches (Logan, 1993) and lower average penetration resistance was found (Birkeland, 1990; Birkeland et al., 1995).

At the scale of the snowpack layer pinching was observed (e.g., Pielmeier, 2003) and dye tracer experiments revealed the large heterogeneity caused by water infiltration (Schneebeli, 1995). Similarly, Takeuchi et al. (1998) reported that a dry snowpack showed more spatial continuity than a snowpack in the melt season. With improved FMCW radar technology (Marshall et al., 2005), the radar signal was related to snow stratigraphy as measured with the SnowMicroPen (Schneebeli and Johnson, 1998) and near-infrared photography (NIR) (Matzl, 2006). All these methods should improve the quantitative description of snow stratigraphy which is needed for spatial variability studies.

6. Multiple scales

Using snow cover extent as an example, Blöschl (1999) pointed out that depending on the measurement scale at which the snow cover data were collected the variograms showed very different correlation length (from about 0.5 mm to 30 km). Although the data were from different dates and locations it can be assumed that the different correlation lengths are related to different physical processes that act at the scale under consideration. A discontinuous semi-variogram exhibiting steps has been proposed for such a multi-scale analysis (Blöschl, 1999).

A multi-scale geostatistical analysis of the presence of a buried surface hoar layer confirmed that the spatial autocorrelation length depended on the scale analyzed (Fig. 6) suggesting that the observed variability was the result of several physical processes with different typical scales (Schweizer and Kronholm, 2007).

Sturm and Benson (2004) investigated variations in snow stratigraphy in the arctic at various scales. Their examples suggested that the heterogeneity increased up to a scale length of about 100 m, after which it remained relatively constant through two orders of magnitude greater scale. However, they did not provide a geostatistical analysis. Recently, Marshall et al. (2006) have shown for similar snow cover data from the arctic that the spatial structure of layers varies with measurement method and scale.

7. Numerical model approaches

Numerical modeling of avalanche release using cellular automata models has been used to investigate the effect of spatial variability on avalanche release (Faillettaz et al., 2004; Fyffe and Zaiser, 2004, 2007; Kronholm and Birkeland, 2005; Zaiser, 2004). While these models are aimed at the slope scale, this is not explicitly the case, and more research is needed to investigate scaling issues associated with such models. Further, these models are simple representations of a complex snow cover and use only a weak layer (with spatially variable properties) and a slab (which may or may not have spatial variation) and require information on the spatial structure of the modeled layers, which can only be given by studies explicitly using coordinates of the sampling locations in the analysis.

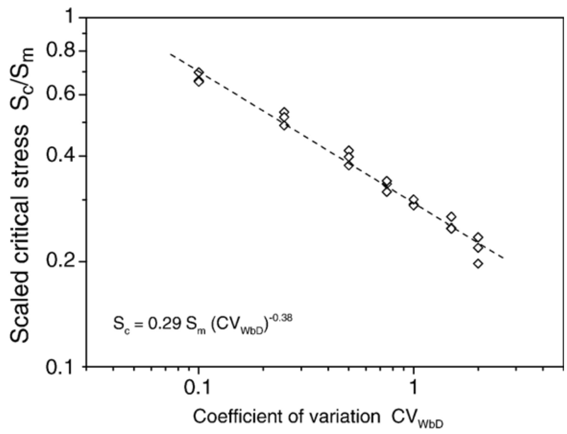

Fig. 7. Simulation results using a lattice automaton model: effect of random variations in weak layer strength on slope failure strength. Variation of weak layer strength is given as the coefficient of variation of the Weibull distribution CV. The critical stress S_c at which the slope fails is scaled to the average weak layer strength S_m. Dotted lines indicate power law fit to simulation results (adapted from Fyffe, 2006).

These models suggest that spatial variations of weak layer strength have a substantial effect on slope stability (e.g., Fyffe and Zaiser, 2004; Kronholm and Birkeland, 2005; Zaiser, 2004). Due to variation in weak layer strength a slope becomes unstable long before the load has reached the average strength (Fig. 7). The simulations by Fyffe (2006) suggest that, for example, assuming a coefficient of variation of weak layer shear strength of 10% (or alternatively 50%), the slope becomes unstable, when the load has reached about 75% (or alternatively about 40%) of the average weak layer strength. This “knock-down” effect on slope stability not only increases with increasing variation, but also with increasing spatial correlation of weak layer strength variation. However, randomness — in presence of a crack — prevents crack propagation (Zaiser et al., 2004). Despite the shortcomings of the models, they are useful tools to circumnavigate the problem that information on slope stability and spatial variations are hardly possible to observe simultaneously in the field.

8. Discussion

8.1. Methods used

The main reason for the diverse and seemingly contradictory estimates of spatial variability seem to be

Table 3
Selection of regional and mountain range scale studies with summary of major results

Study	Property	Results
Bradley (1970)	Hardness	— Studied two slopes — Correlated depth hoar strength to the timing of large avalanches on different aspects
Dexter (1986)	Penetration resistance	— Collected data from 39 points over an area of about 10 km^2 — Penetration resistance increased with elevation on northerly facing slopes and decreased with elevation on southerly facing slopes.
Birkeland (1997, 2001)	Point stability, penetration resistance	— On two days field teams investigated snow stability in a mountain range. — Stability was correlated with terrain using various statistical methods. — On both days elevation and aspect were significant predictors of stability, but the strength of those relationships varied between the two days. — Average point stability (measured with the rutschblock and stuffblock tests) decreased at higher elevations and on more northerly aspects.
Stoffel et al. (1998)	Avalanche observations	— Analyzed and visualized a 14 year long period of avalanche observations in the region around a village. — South-facing release areas produced less avalanches than their proportion of release areas predicted.
Kozak et al. (2003)	Snow slab hardness	— Related spatial variability of snow slab hardness to terrain and meteorological variables. — Hardness increased over time and the rates of hardness increase were related to temperature and incoming shortwave energy on different aspects.
Hägeli and McClung (2003)	Avalanche observations	— Analyzed avalanche observation data from the Columbia Mountains in Canada — Most persistent weak layers with considerable avalanche activity were observed and active across the entire mountain range.
Schweizer et al. (2003b)	Point stability, danger ratings	— On ten days avalanche danger forecasts were verified by numerous point stability observations. — Point stability measurements were coordinated on the slope, regional and mountain range scale. — Regional stability (avalanche danger) depended on aspect and elevation, and snow climate. — Typical stability distributions were derived for the danger levels Low, Moderate and Considerable. — Verification of avalanche forecasts not possible by single point stability observations.
McCollister et al. (2003)	Avalanche observations	— Explored the relationship between specific meteorological conditions and the spatial pattern of avalanche activity. — Avalanche activity related to actual location more closely than simple aspect because of the importance of wind patterns around specific topographic features. — Specific sets of avalanche paths had higher proportions of different types of avalanches.
Feick et al. (2004, 2007)	Weak layer formation	— Related the spatial variations of surface hoar growth and decay in a basin to terrain and meteorology (drainage winds). — Small-scale terrain variables best explained the observed differences.
Zeidler and Jamieson (2004)	Stability index, avalanche observations	— In a sheltered mountain range, study plot stability index correlated with skier-triggered avalanches within kilometers of the study plot.
Heilig (2004)	Penetration resistance, surface properties	— Four slopes of northerly aspect within a drainage were investigated simultaneously to cover the point, the slope and the drainage scale. — Three slopes were fairly sheltered and surface properties were continuous across scales, whereas penetration resistance of the surface layer was found to show more variation. — The fourth slope was wind exposed and its properties were typically different from the ones of the more sheltered slopes.

Table 3 (*continued*)

Study	Property	Results
Schweizer and Kronholm (2005, 2007)	Penetration resistance, point stability, weak layer formation	— Snow stability and weak layer presence was investigated by coordinating field sampling over the slope, regional and mountain range scales: multi-scale study. — Before burial the weak layer (surface hoar) was present everywhere but at the mountain range scale the initial surface hoar size differed due to different growth conditions. — After burial surface hoar presence depended on aspect due to influence by wind immediately before burial and due to faster metamorphic processes on the south-facing slopes after burial. — Initial surface hoar size was related to surface hoar presence after burial such that regions of large initial grains were more likely to have surface hoar for longer periods. — At the slope scale the surface hoar layer was continuous. — Presence of surface hoar strongly influenced stability test results. — Geostatistical analysis revealed different lengths of autocorrelation depending on the extent chosen to calculate the variogram. This indicates that the observed variability was the result of several physical processes with different typical scales.
Jamieson (2006)	Weak layer formation	— Related spatial variations in the presence and vertical location of faceted weak layers to meteorology and terrain
Jamieson et al. (in press-b)	Stability index	— Stability index for natural avalanches varied less than overburden or weak layer strength because weak layer strength increased with overburden.
Colbeck and Jamieson (2006)	Weak layer formation	— Elevation bands of buried surface hoar related to antecedent valley cloud.
Jamieson et al. (in press-a)	Danger ratings	— Agreement of local scale (10 km^2) danger rating with rating from regional bulletins increased as scale of region decreased from 25,000 km^2 to 100 km^2. — Large scale danger ratings are averages over areas with variable avalanche danger.

the large number of methods used to measure and describe the variability and the different characteristics of the study slopes. Below we discuss how differences in 1) slope characteristics, 2) snow cover property, 3) measurement method including support, 4) spacing and extent of the measurement layout, 5) analysis method, and 6) diverging opinions about the interpretation of the analysis results, may lead to the apparent contradictions in the reviewed spatial variability studies.

Clearly slope characteristics are a primary control on the spatial variability observed, and are one reason for the discrepancies in variability between studies. For example, the slopes investigated by Kronholm (2004) are alpine and wind-affected and are different from the wind-protected, more planar slopes utilized by Landry et al. (2004) and Logan et al. (2007). Wind and underlying rocks can greatly affect the amount of spatial variability measured (e.g., Birkeland et al., 1995).

Most importantly, different studies have described the variability of different properties as diverse as point stability and penetration resistance (Tables 1 and 3). Clearly, only results from studies which have investigated the same property are comparable.

A number of methods have been used to measure similar properties. To evaluate variations in point stability at least six different methods have been used: rutschblock tests (Jamieson, 1995; Campbell and Jamieson, 2007); rammrutsch or drop hammer tests (Kronholm, 2004, Stewart, 2002); stuffblock tests (Kronholm et al., 2004b); two types of quantified loaded column tests (Landry et al., 2004). In addition to these methods of measuring point stability using vertical loading, some studies tested the shear strength of the critical weak layer and inferred point stability by relating shear strength to shear stress due to the snow above the weak layer (Conway and Abrahamson, 1984; Logan, 2005). For measurements of other snow cover properties the number of methods is not as diverse as for point stability but still, the variation of most properties have been reported using more than one method (shear strength with shear frames of different areas; penetration resistance with penetrometers of different penetration speed and cone size). These tests differ in a number of ways which may influence the resulting estimates of spatial variability:

A) The methods have different support (Table 2). Since samples (test columns) with larger support are expected to be less variable than samples with smaller support (Blöschl, 1999), results between studies using different sample support cannot be directly compared.

B) The vertical load tests have different ways of loading the sample to failure. The loading methods used differ in many ways, all of which may influence the test results: the mass of the drop weight; the hardness of the drop weight; the stiffness of the load transferring plate; the number of drop increments before a fracture is produced.

C) The weak layer shear strength measurements apply the shear force differently. For example, while the standard shear frame test is conducted by placing the shear frame almost directly above the tested weak layer (Jamieson and Johnston, 1998), Conway and Abrahamson (1984) applied the shear force on top of the full snow column, thus applying more bending moment on the weak layer sample than with the standard test method.

D) The tests used different loading rates, which in the case of a rate sensitive material like snow is problematic (Narita, 1980).

While comparisons between the most similar of these test methods may be possible, they must be treated cautiously. In addition, each measurement method is associated with a specific error, which for most methods is unknown — and seems to depend on the snowpack conditions (e.g. on the slab properties). Observed variations in test results are therefore due to a combination of natural variability of the snow cover and test specific errors. This must be kept in mind when analyzing variability results to avoid associating variability due to test errors with true variability, which in some studies may be smaller than test errors.

When comparing studies which have investigated the same property with the same methods, it is apparent that differences in the scale triplets' spacing and extent (Table 2) may cause different conclusions about the scale of the observed variability (Blöschl and Sivapalan, 1995). For example, the sampling design affects the results by controlling the extent and spacing of the study (Birkeland et al., 2004b; Kronholm and Birkeland, in press) and designs covering multiple scales may show larger variability at certain scales although variability is present at all scales investigated (Schweizer and Kronholm, 2007).

The methods used to describe the variability of the measurement results differ. Some studies describe the variations of a layer property by non-spatial statistics such as the mean and spread of the value (Jamieson, 1995). Other studies analyze the data in a spatial sense either implicitly by comparing results from different locations without respect to the absolute locations (Landry, 2002) or explicitly using methods that include the absolute measurement locations (Kronholm, 2004). One common problem in the analysis of snow cover variability data is the application of statistical methods to datasets that do not satisfy the underlying assumptions of these methods. For example, some properties measured in spatial variability studies are on an ordinal scale (e.g. rutschblock scores) or non-normally distributed (e.g. penetration resistance (Kronholm et al., 2004a,b,c)) and must be treated using appropriate methods. For studies of spatial variability it is preferable to explicitly include measurement locations using for example geostatistical techniques, as already noted by Conway and Abrahamson (1984, 1988). If the coordinates are not included no spatial predictions are possible and hence the data cannot be used for modeling purposes such as CA models, as described above. However, there are several drawbacks using geostatistical methods. Geostatistical methods generally require a large number of measurements to produce reliable results, and such a number of measurements may not be feasible using some current methods (Webster and Oliver, 1992). Further, the analysis of the results depends on the spatial layout of the measurement locations, and changing the layout can sometimes affect the results and the amount of error which might be expected (Kronholm and Birkeland, in press) (Fig. 8). Therefore, while recognizing that the previously used geostatistical methods may not be the best to analyze the present spatial variability datasets, we suggest that in order to advance the analysis of spatial variability data, the location coordinates should explicitly be used in the analyses. Field methods such as digital resistance penetrometers may allow sufficient data to be collected in a day to detect spatial structure not practical with slower field methods such as the rutschblock.

Another problem with the geostatistical analyses is that the results may be harder to interpret than results produced by classical statistics (such as the coefficient of variation) and may seem of little direct value in a practical setting (where, for example, the z scores used by Landry et al. (2004) may seem more useful).

Finally, the interpretation of the outcome of a statistical analysis varies between studies. For example, Stewart (2002, p. 52) showed an array of stability tests with a CV of 49% and described it as an example of "low variability" (due largely to its low mean point stability), whereas Landry et al. (2004) reported "wide variation" in strength (also called "high variability" by Johnson and Birkeland (2002)) across slopes with coefficients of variation in

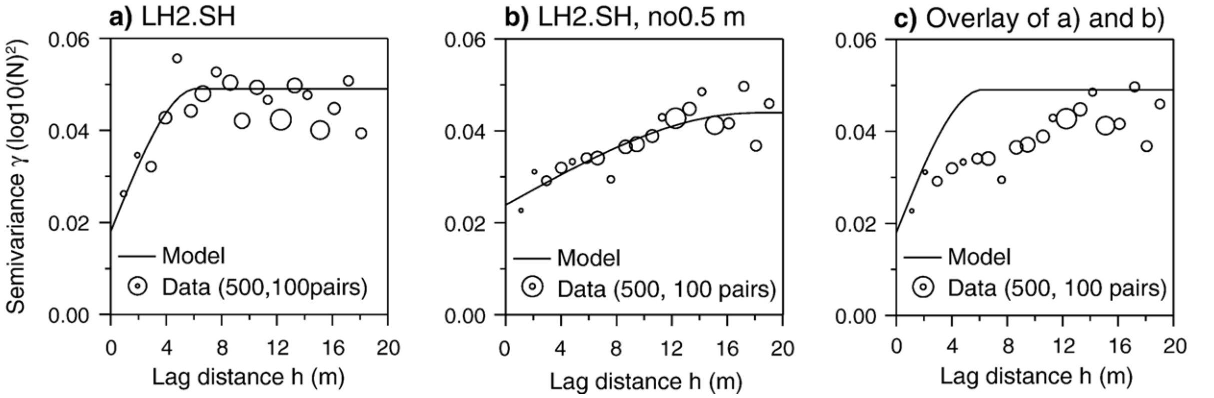

Fig. 8. (a) Spherical semi-variogram model fitted to the penetration resistance (SMP) of a layer of buried surface hoar (LH2.SH) at a planar, wind-protected site. Circles are scaled to the number of point pairs. (b) When the measurements with the smallest spacing (0.5 m) were removed from the data, the semi-variogram changed significantly, demonstrating that the sampling scheme is critically important for interpreting the results of the geostatistical analysis. (c) shows the modeled semi-variogram for all the 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 (from Birkeland et al., 2004b).

weak layer shear strength ranging from 10% to 50% with a mean CV of 24%.

These interpretations may be influenced by the hypothesis being tested. For example, Landry et al. (2004) investigated slopes that appeared relatively uniform to experienced avalanche forecasters, but found that about 30% of the pits on such slopes were not statistically representative of the slope as a whole, and this is why they reported that such CVs represented "wide variation".

For studies using geostatistical analysis methods, a problem has been that the analysis did not indicate spatial structure in more than a few datasets, but mainly random variations (pure nugget semi-variograms). While some studies have concluded that this indicated that the geostatistical method therefore was not useful (Campbell, 2004), other studies have used this result as an important finding (Kronholm, 2004).

8.2. Effect of spatial variability on avalanche formation

Spatial variability affects avalanche formation. Spatial variations of the weak layer and slab properties (strength and stress) were postulated as prerequisites for failure initiation as well as for fracture arrest (Schweizer, 1999). In other words, disorder is considered to be fundamental for the fracture process (Herrmann and Roux, 1990).

Interpreting spatial variability in terms of fracture localization and propagation, Kronholm and Schweizer (2003) suggested that slope stability is controlled by the variation of stability, the length-scale of the variation and the mean stability. A key factor in this view is the relation between the critical length l of the initial failure to the spatial scale of the variability ξ (the length-scale of the variation or the range from the semi-variogram). If, for example, $\xi/l<1$ then it is suggested that the variability has a stabilizing effect (Kronholm et al., 2004c) (Fig. 9). Best estimates from slab avalanche release models (McClung, 1979, 1981; Bader and Salm, 1990) for the critical length l are 0.1–10 m (Schweizer, 1999). Field and laboratory measurements as well as theoretical considerations (Bažant et al., 2003; McClung and Schweizer, 2006; Schweizer and Camponovo, 2001; Schweizer et al., 2004; Sigrist and Schweizer, 2007) suggest that the size is on the order of the slab thickness, i.e. 0.1–1 m. Small scale

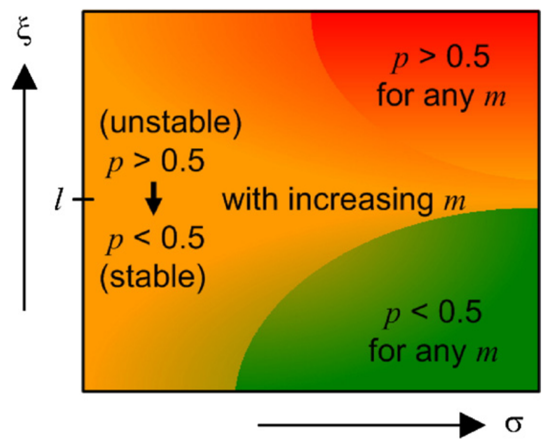

Fig. 9. Stability scheme relating variation in strength σ, the spatial scale of variability ξ, and mean snow stability m to the probability p of snow slab avalanche release. The spatial scale of variability ξ (or the range from the semi-variogram) is crucial in relation to the critical length l of the initial failure — the key parameter in the fracture process. For example, if $\xi/l<1$ then the variability is expected to have a stabilizing effect rather inhibiting slab release.

patterns (less than about 1 m) may therefore help prevent avalanche release.

A single point stability observation inherently includes two sources of uncertainty: spatial variation and measurement errors. Therefore, a single point stability observation is usually not sufficient to assess slope stability, though expert site selection and large support (e.g. rutschblock test) may reduce uncertainty. To further reduce uncertainty and to predict slope stability more reliably additional information is required, for example, from different predictors or repeated observations. In fact, van Herwijnen and Jamieson (2007) showed that fracture character was a better predictor of slope stability than the compression test score. Considering several predictors (related to the fracture process) will result in a more robust estimation (Schweizer et al., 2008-this issue). Conducting more than one test on the same slope can also reduce uncertainty (e.g., Birkeland and Chabot, 2006), though the tests need to be farther apart than the autocorrelation length (which is typically unknown). As the autocorrelation length was found to vary between layers depending on conditions (<0.5 m to >10 m) (Kronholm, 2004; Birkeland et al., 2004b), it is recommended that two tests should be spaced out on the order of at least 10 m in order to get independent test results.

9. Summary and conclusions

Spatial variability of layer properties is due to various external and internal process drivers interacting with topography during and after the deposition process. Though changes after deposition might be less significant than during deposition, they cause temporal variations in spatial variability. The main external process drivers are precipitation, sublimation, wind, radiation and temperature. Internal drivers include metamorphism. Other sources of variability, in particular in shallow snowpacks, may be due to variable properties of the underlying ground.

These process drivers act at different scales and consequently the spatial variation depends on the main process driver at the scale under consideration. Scale and scale issues are therefore crucial for studying and understanding spatial variability, in particular since the scale of variation also crucially affects dry-snow slab avalanche release.

After the landmark papers of Conway and Abrahamson (1984, 1988) spatial variability became synonymous with any unexpected human-triggered avalanche and a subject of much heated debate, also on the value of snowpack observations for recreationists. Many field studies have shown that a wide range of spatial variation in layer properties and stability exists. Widely varying conditions (in terms of the non-spatial measure of the coefficient of variation) have in particular been observed in avalanche start zones above tree line where wind might cause the random spatial variation. However, as these studies have differed in scale triplet, measured property, measurement and analysis method a direct comparison is not possible in most cases — explaining the apparently contradicting interpretation of results. Also, the coefficient of variation is of limited usefulness, in particular as it has been often applied to ordinal data that have a small range, and as it strongly depends on the mean.

Besides spatial heterogeneity most studies have demonstrated that layers, and in particular critical weak layers, are often spatially continuous at the slope scale. However this continuity was occasionally broken by obvious external disturbances at the perimeter of the slope such as snow falling from trees. An experienced observer would have avoided these disturbed locations for point stability observations. As layer properties, as well as rutschblock release type (and possibly other indicators of fracture propagation potential such as shear quality and fracture character) are more continuous than stability scores, also structural instability indices (lemons, yellow flags etc.) (McCammon and Schweizer, 2002; Jamieson and Schweizer, 2005) are expected to be less subject to spatial variability.

Analytical methods explicitly using the coordinates are the methods of choice to develop models that take into account spatial variations of layer properties. These geostatistical analyses have shown that different layers have different spatial structure which needs to be considered for modeling the effect of spatial variability on avalanche formation. The sampling design as well as the scale of measurements affect the results of the autocorrelation analysis. This is of particular relevance for multi-scale studies.

The scale of spatial variation is crucial for avalanche formation. If the autocorrelation length is less than the critical length for self-propagating fractures an initial failure might not propagate. Small scale patterns (less than about 1 m, or on the order of several 10 cm) may therefore help prevent avalanche release. Numerical models suggest that spatial variation of strength properties has a substantial “knock-down” effect on slope stability and that the effect increases with increasing length of spatial correlation.

The observed spatial variation can often be described with a deterministic and a stochastic component. However, the amount of variation in each component and the process drivers that contribute to variation in each component is determined by the scale of the study.

Spatial variability measurements are useful as input data for models to study the triggering of instabilities in geosystems. Distributed snowpack modeling ultimately shall not only provide information on the regional stability but as well on its variation. However, a prerequisite is that it will be possible to link the observed spatial structure of, for example, a weak layer to the causes, i.e. the meteorological conditions during weak layer formation and the time until burial.

For stability evaluation, spatial variability is a burden and it may be impractical to measure some important aspects of spatial structure with existing methods, but experienced avalanche professionals are obviously able to compensate the uncertainty to a large degree by filtering and relying on redundant information (LaChapelle, 1980). They have developed skills for dealing with scale issues in the forecasting process, for example, to transfer relevant information across scales (Hägeli and McClung, 2004). It is crucial to seek patterns and relate them to the avalanche formation processes. Examples for specific patterns in weak layer formation are surface hoar growth due to valley clouds, and faceting near crusts in the elevation band of the freezing level during the last storm. Research to understand and analyze terrain-correlated patterns of weak layer formation is important.

Despite spatial variability, point observations can reveal useful results. For example, stability indices derived from study plot measurements were related to avalanche activity in the surrounding terrain indicating that predicting regional stability in a general sense from point stability is possible to a certain degree despite local variations in point stability. Similarly, stability tests are useful (as one important piece of information in combination with other observations), and their interpretation has been improved to counterbalance their drawbacks. Frequently, in particular when seeking instability (targeted sampling) (McClung, 2002) a single rutschblock score can expected to be within ± 1 score of the slope median score. However, as always snow slope stability evaluation should never rely on a single snowpack observation and best results are achieved by combining predictors (Schweizer et al., 2008-this issue).

Even with improved understanding of the causes and patterns of spatial variations of the snowpack, spatial variability remains one of the principal sources of uncertainty in stability evaluation and avalanche forecasting (Hägeli and McClung, 2004; Jamieson, 2003). A risk-based approach to decision making seems best suited to cope with this uncertainty (McClung, 2002), complemented with skilled use of terrain during backcountry travel and by paying attention to human factors — which are another important source of uncertainty. Greater than usual uncertainty, e.g. in case of a surface hoar layer deep in the snowpack, requires a greater than usual margin of safety during backcountry travel.

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