SPATIAL VARIABILITY OF RUTSCHBLOCK RESULTS IN AVALANCHE START ZONES

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ABSTRACT: During the winters of 2003 and 2004, 29 spatial arrays consisting of a total of 705 rutschblock tests were performed in avalanche start zones in the Columbia Mountains of British Columbia. Correlation analysis and multivariate least-squares linear regression were used to identify predictor variables as causes of variability. Snowpack variables that affected stability include slope angle and slab thickness. Stability, with respect to skier-triggering, tended to increase with slab thickness and decrease with increasing slope angle. Variability was found to increase with slope median rutschblock score. Fracture characteristics were found to be less variable than stability.

Keywords: rutschblock test, fracture character, variability, start zones, avalanche forecasting, snow stability.

1. INTRODUCTION

The existence of large variations in point stability and shear strength over short distances has been confirmed by many field studies (e.g. Keeler and Weeks, 1968; Conway and Abrahamson, 1984, 1988; Föhn, 1989; Jamieson, 1995; Jamieson and Johnston, 1992, 1993, 2001; Stewart, 2002; Landry, 2002; Landry and others, 2004; Kronholm, 2004). Relatively few field studies have looked at the spatial variability of fracture properties such as fracture character (Landry, 2002; Kronholm, 2004). Johnson and Birkeland (2002) proposed that shear quality (fracture character) is related to fracture propagation and should be less variable within slopes than point stability. Landry (2002) and Kronholm (2004) often found slopes with homogeneous shear quality, supporting this hypothesis.

Figure 1 is a conceptual flow diagram outlining the stages of slab avalanche formation where variability can be introduced. The sources of variability in stability can be described in terms of the sources of variability in shear strength of the weak layer and the sources of variability in the stress transmitted by or through the slab to the weak layer. The variability in measured properties of snow, including stability, is due to a combination of various processes that act on the snowpack with various correlation lengths (ξ). Causal processes are influenced by factors such as buried rocks (assumed $\xi \sim 1$ m), wind drifting (assumed $\xi \sim 2$ to 10 m), slope angle (assumed $\xi \sim 2$ to > 50 m) and surface hoar formation (assumed $\xi \sim 1$ to > 50 m). However, relating the spatial variability of stability within avalanche start zones to causal processes can be difficult with current methods (Kronholm, 2004).

For this study, rutschblock tests are used to define point stability in terms of skier-triggering. Furthermore, it is the spatial variability of point stability across an avalanche start zone, rather than overall slope stability that is examined.

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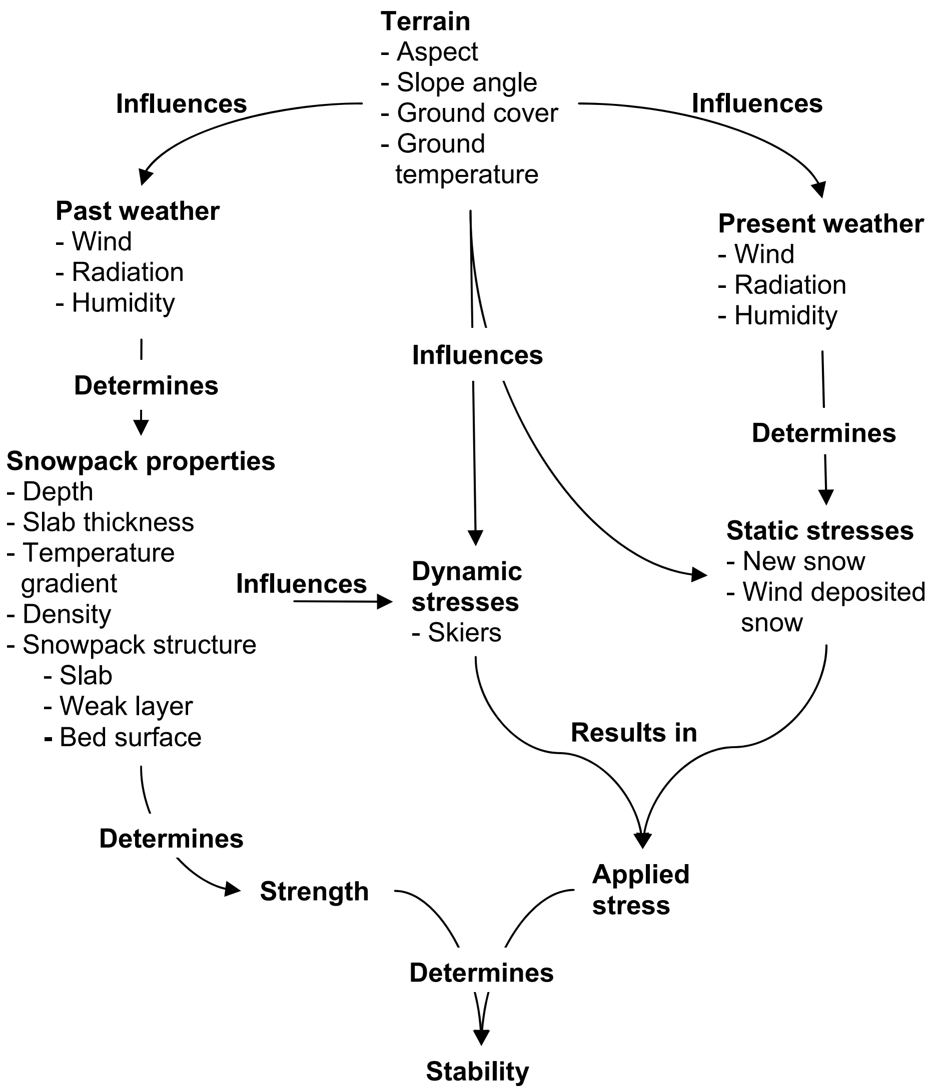

Figure 1 – Conceptual diagram showing how several terrain and meteorological variables interact to determine stability with respect to skier triggering (after Birkeland, 1997, p. 4). Terrain and weather parameters that can act as sources of variability of stability within a slope, and their influences, are shown.

2. METHODS

Field research for this study was carried out in the Columbia Mountain Range of British Columbia. Following Stewart (2002) and Jamieson (1995), array sites were chosen for a wide range of slope angle, aspect, and/or slab thickness. Sites had to be undisturbed by skiers, previous avalanches, over-snow vehicles, etc. In order to minimize the effect of temporal variability on test results all arrays were performed as quickly as possible, most within a few hours. Furthermore, any source of temporal variability (e.g. marked warming, heavy snowfall or increased solar radiation) during the course of an array was noted and if deemed necessary, the array was abandoned.

The rutschblock tests were arranged in a regular grid pattern separated by 0.5 m in the cross-slope direction and 1 m (measured slope parallel) in the up-slope direction. Rutschblock tests were performed according to the Canadian

Avalanche Association's Observation Guidelines and Recording Standards (CAA, 2002). For each test, fracture character (van Herwijnen and Jamieson, this volume) and release type observations were recorded. Fracture character was described as either sudden planar (SP), sudden collapse (SC), resistant planar (RP), progressive compression (PC) or non-planar break (B). The release type was recorded as the whole block (W), most of the block (M) or only an edge of the block (E), as per Schweizer and Wiesinger (2001).

In addition to a manual snow profile performed for each array site, various snowpack and terrain variables, which are potential sources of variability for that particular array, were measured for each test. These variables were: total snowpack depth (HS); weak layer depth also known as slab thickness (H); weak layer thickness (Thick); slope angle (Ψ); aspect (Asp); and weak layer crystal size (E). Spearman rank order correlation coefficients (R_S) and multivariate least-squares linear regression were then used to asses the effects on point stability. Correlation and regression coefficients were considered significant if $p < 0.05$ and marginally significant if $0.05 \leq p \leq 0.20$.

3. RESULTS AND DISCUSSION

During the winters of 2003 and 2004, a total of 705 rutschblock tests were performed in 29 separate spatial arrays. Eighteen of these arrays had buried surface hoar layers as the failure layer, with the remaining failing on either faceted crystals (six arrays), precipitation particles (two arrays) or on multiple weak layers (three arrays).

The median rutschblock (RB) score for the individual arrays ranged from 2 to 7 with a median of 4 (Figure 2). The non-parametric version of the coefficient of variation, namely the quartile coefficient of variation (QCV), for the individual arrays ranged from 0% to 33% with a median of 14%. The non-parametric version of the standard deviation, namely the semi-interquartile range (SIQR), ranged from 0 to 1.5 with a median of 0.5. The most variability was found for the array performed on 2004-03-06/07, where RB scores ranged from 2 to 7. Several arrays showed very little variability, including the largest (performed on 2004-02-27). The number of tests in each array ranged from 8 to 65 with a median of 20 tests and all but three arrays were performed in a single day.

As can be seen in Figure 2, there is a tendency for variability (QCV) to increase as slope median RB score increases (R_S = 0.39, p = 0.04, N = 27 for 2 ≤ median RB ≤ 6), which is consistent with Keeler and Weeks' (1968) results for weak layer strength, and Conway and Abrahamson's (1984) and Stewart's (2002) results for point stability. The increased variability with median RB score could be intrinsic to the snowpack or due to the possibility of increased operator variability associated with higher rutschblock loading steps. Regardless, it seems that a single rutschblock test can better indicate the overall slope stability when the median RB score is low.

The threshold RB score (Figure 2) for skiers initiating fractures in the weak layer was assumed to be 3. Sufficient fracture propagation for slab release was not assumed (Campbell, 2004). When the portion of the slope equal to or below this assumed threshold for point instability (RB score ≤ 3) is considered, slopes with higher median stability can have the same portion that is susceptible to skier-initiated fractures as slopes with lower median rutschblock score. Such is the case for the array performed on 2003-02-27/28 (median RB = 4) when compared to the array performed 2002-12-17 (median RB = 3.5) with the same portion (25% of the area of the slope) susceptible to skier-initiated fractures (below the threshold).

Figure 3 shows that 84% of randomly sampled rutschblock tests in avalanche start zones are within ±1 RB score of the slope median. For uniform slopes in the Columbia Mountains, Jamieson and Johnston (1993) found that 97% of tests are within ± 1 RB score of the slope median. This agrees with Stewart's (2002) conclusion that the stability of start zones is substantially more variable than the stability of uniform slopes.

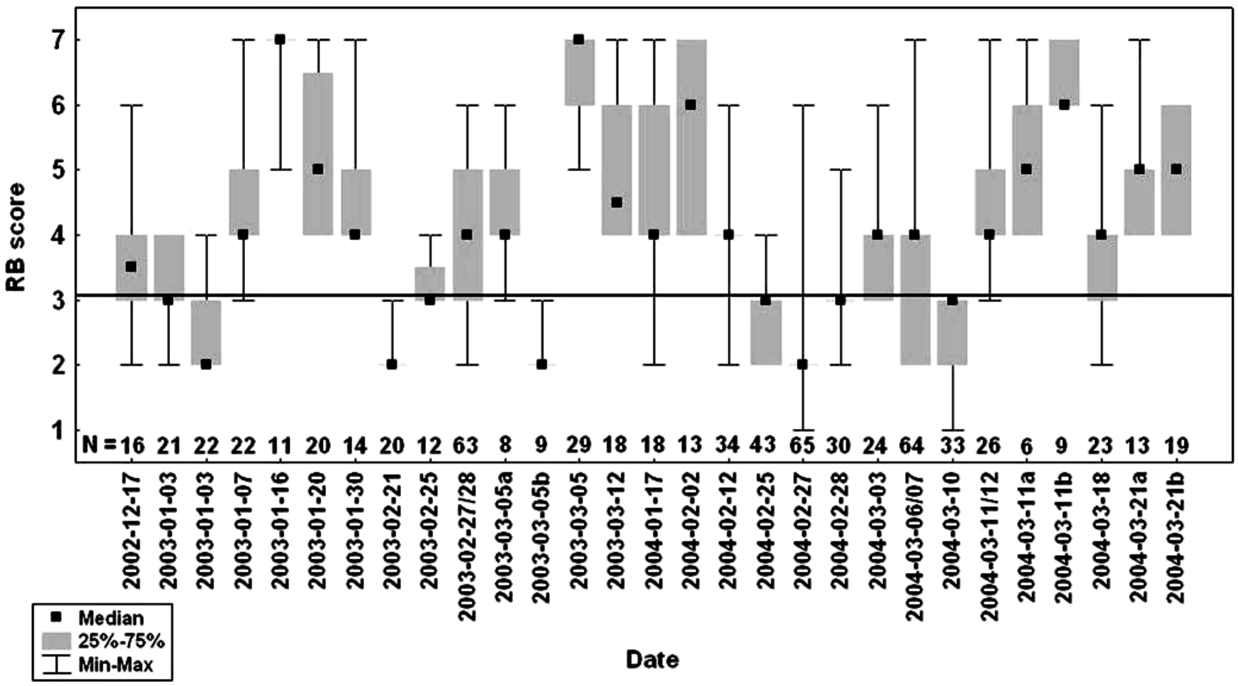

Figure 2 – Box and whisker plots of rutschblock arrays showing the median, interquartile range (the middle 50% of the data), minimum and maximum RB score for each array. The assumed threshold rutschblock score of point instability (RB score ≤ 3) and number of tests in each array (N) are also shown.

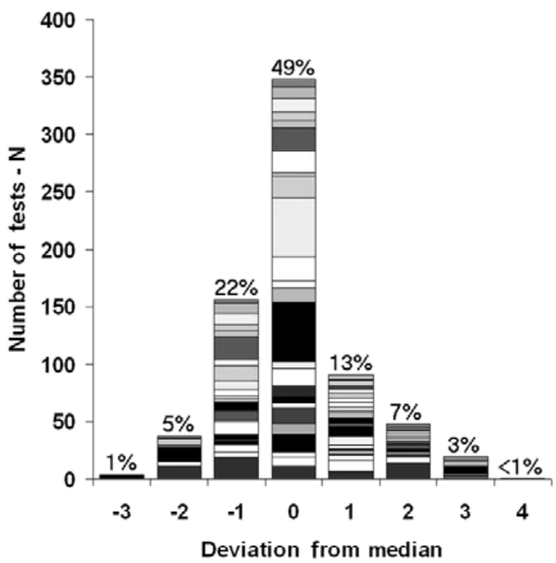

Figure 3 – Histogram showing the combined distribution of the deviations from the median for the 29 rutschblock arrays summarized in Figure 1. Each bar in the columns represents one array (N = 705).

3.1 CORRELATION ANALYSIS

Four of the 28 (14%) arrays in which H was measured for each test have significant ($p < 0.05$) positive correlations between RB score and H, and no arrays have significant negative correlations (Table 1). This suggests that some areas with thinner slabs are less stable. When the significant and marginally significant ($0.05 \leq p \leq 0.20$) correlations are considered, seven of the nine (78%) correlation coefficients with H are positive. Nevertheless, only 7 of 28 arrays showed significant positive correlations with slab thickness. However, when the data from all 28 arrays were normalized with the median and SIQR and then combined (Campbell, 2004), a significant positive correlation between RB score and H was found ($R_S = 0.13$, $p = 0.003$, $N = 534$).

Slope angle also emerged as a potential source of variability, with a general trend for steeper parts of the slope to have lower scores. When significant and marginally significant correlations were considered, seven of the ten (70%) correlation coefficients with slope angle were negative, but only two were significant ($p < 0.05$). The array performed on 2003-02-21 had 14 tests that failed during the isolation process or with only one ski partially weighting the block. When these tests are assigned a RB score of 1.5, instead of 2, another significant negative correlation emerges with slope angle. Nevertheless, only 7 of 29 arrays showed significant negative correlations with slope angle.

Table 1 – Number of arrays with significant ($p < 0.05$) and marginally significant ($0.05 \le p \le 0.20$) positive and negative Spearman rank order correlations between RB score and snowpack and terrain variables. The total number of correlations (N_a) can differ from the total number of arrays (29) because certain snowpack and terrain variables were not measured for all arrays.

	Snowpack variables				**Terrain variables**			
	H (cm)		**HS (cm)**		**Ψ (°)**		**Asp (°)**	
	+	**-**	**+**	**-**	**+**	**-**	**+**	**-**
***p* < 0.05**	4	0	2	2	1	2	0	0
0.05 ≤ *p* ≤ 0.20	3	2	2	2	2	5	2	1
N_a	28		28		29		8	

The proportion of arrays with significant correlations between RB score and H increases to 3 of 20 (15%), when only the large arrays ($N > 15$) are considered. The proportion of arrays with significant correlations between RB score and slope angle also increases when only large ($N > 15$) arrays are considered (15% versus 10%, when the array performed on 2003-02-21 is included as significant). This suggests that larger arrays would have detected additional effects.

Four arrays had significant correlations between RB score and HS; however, two were positive and two were negative. The general lack of association between stability and HS is not surprising considering variations in HS generally only affect the faceting process, while most of these arrays had buried surface hoar weak layers. No arrays showed significant correlations between RB score and aspect, but the aspect of every test was only measured for eight arrays. Furthermore, aspect was identified as a source of variability in two of the arrays discussed later.

When all of the 29 arrays were considered, the median RB score as well as the SIQR had significant positive correlations with the weak layer hardness measured in the manual snow profiles. This suggests that slopes with harder weak layers tend to have a higher median point stability and were more variable. Both the SIQR and the QCV had significant positive correlations with the weak layer depth measured in the snow profiles. This suggests that the point stability of slopes with deeper weak layers tended to be more variable.

3.2 EXAMPLE ARRAYS

3.2.1 ABBOTT HEADWALL 2003-02-27/28 AND 2004-03-06/07

Figure 4 and Figure 6 show two rutschblock test arrays that demonstrate the effects of microscale weather phenomena and microscale terrain features on spatial variability. These arrays were performed on the same slope with similar snowpack conditions, each over two days during different winters. This slope is characterized by cross-slope undulations (~ 1 m) in terrain height. Cross-loading often occurs on this slope with the predominant wind direction being from the left hand side to the right hand side of the photographs.

For the array performed on 2003-02-27/28 (Figure 4), a depression in the snow surface can be seen just right of the centre of the array. This corresponded with an area of lower RB scores where the surface hoar layer was distinct and easy to find, and the crystals appeared well preserved. The group of high scores near the left side of the array was on higher ground where a distinct layer was hard to find. There were no signs of prior avalanching, or other disturbances such as skiers, snow falling from trees, cornice debris, etc., so the weak layer discontinuity may be due to wind when the surface hoar was on the surface (B. McMahon, pers. comm., 2004; Feick and others, 2004).

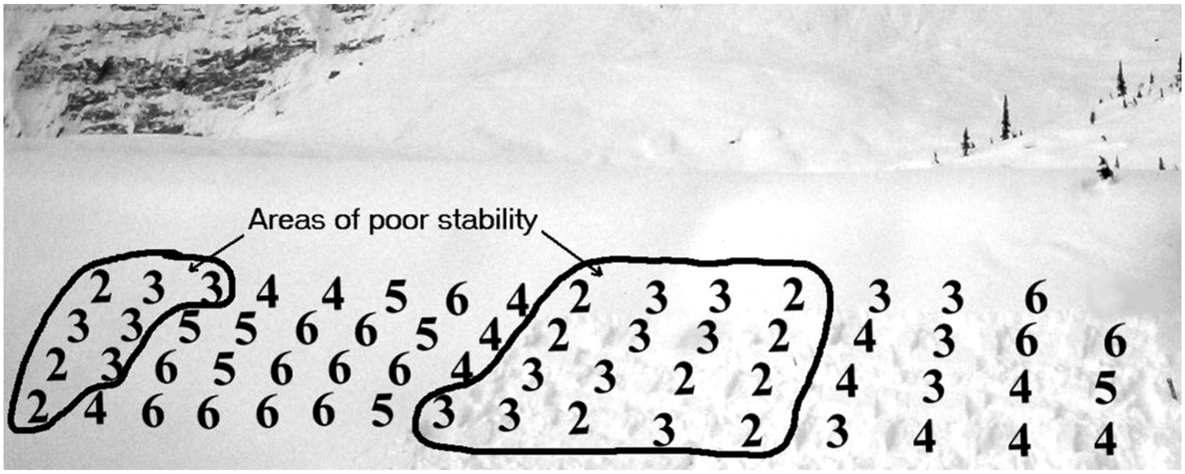

Figure 4 – Rutschblock test array performed on the headwall above the Abbott weather plot on 2003-02-27/28. All the tests failed on the 030215 surface hoar layer at an average depth of 52 cm. Areas of low rutschblock scores are circled. The average slope angle was 33°.

When the cross-slope variability is considered, the spatial structure of stability for this array appears to be sinusoidal (Figure 5) with a wavelength of about 27 m. The average up-slope RB score was regressed on a sine function of cross slope position yielding:

RB score = 1.8 sin (0.21 X + 5.5) + 4.0 (1)

where *RB score* is the up-slope average and *X* is the cross-slope distance in metres. This stability pattern is consistent with the cross-slope undulations in terrain height seen in Figure 4. Based on this result, it is conceivable that the spatial scale of variability for this particular slope is about 14 m, or half the wavelength of the sinusoidal stability pattern. Even though this array had a median RB score of 4, over 30% of the slope was below the assumed threshold for skier-triggering (RB score ≤ 3) as can be seen in Figure5.

A similar stability pattern was observed on the same slope for the array performed on 2004-03-06/07 (Figure 6), although it exhibited greater variability than the 2003-02-27/28 array. Once again, the RB scores corresponded very well with the properties of the surface hoar layer (RB score vs. Thick: $R_S = -0.46$, $p < 10^{-3}$, $N = 62$; RB score vs. E: $R_S = -0.55$, $p < 10^{-3}$, $N = 63$). However the areas of low and high scores were not nearly as consistent as for the array on 2003-02-27/28. One possible explanation is that there was a different wind pattern. This was indicated by the presence of a small cornice at the top of the slope that was not there the year before. The presence of the cornice indicates that the slope was leeward and subject to turbulent wind eddies while the surface hoar was on the surface, which can cause discontinuity in the weak layer. The results from these two arrays suggest that slope-scale stability patterns can be repeatable given similar weather and snowpack conditions.

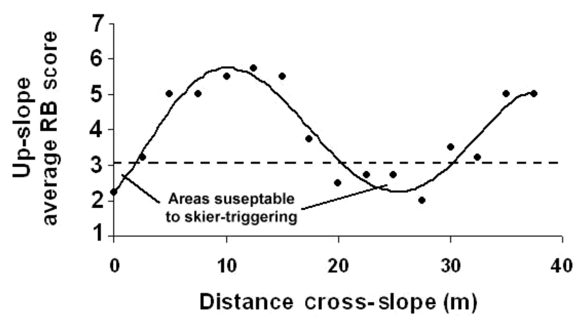

Figure 5 - Scatterplot of average RB score versus cross slope distance (m) for the array performed on the headwall above the Abbott weather plot on 2003-02-27/28. The distribution is fitted with a sine curve based on Equation 1. The assumed threshold RB score for skier-triggering (RB score ≤ 3) is also shown (dashed line).

*Figure 6 – Rutschblock test array performed on the headwall above the Abbott weather plot on 2004-03-06/07. Most (57) tests failed on the 040224 surface hoar layer, at an average depth of 82 cm, while the remainder (marked with *) failed on the 040214 surface hoar layer which was about 10 cm deeper. The tests marked 2- failed during isolation with the saw or during partial weighting with one ski. The average slope angle was 36°.*

3.2.2 MONASHEE VIEW 2004-02-07

The array shown in Figure 7 was performed on Mt. St. Anne in the Cariboo Mountains at treeline on a buried surface hoar layer. When performing the array, it became apparent that size of the surface hoar crystals affected the rutschblock result, such that larger surface hoar crystals generally gave lower RB scores (RB score vs. E: R_S = -0.27, p = 0.04, N = 65). When a RB score of 1.5 is assigned to every test that failed with only one ski partially weighting the block (2- in Figure 7), significant point stability correlations emerge with slope angle (R_S = 0.27, p = 0.03, N = 65) and aspect (R_S = 0.28, p = 0.02, N = 65). The positive correlation coefficients suggest that stability decreases for less steep areas of the slope with a more northerly aspect. Lower angled terrain features have a better view of the open sky, which can result in increased radiant cooling of the snow surface, and northerly aspects receive less direct sunlight. Therefore, the stability patterns found for this array can be explained by better conditions for surface hoar growth in areas with lower point stability.

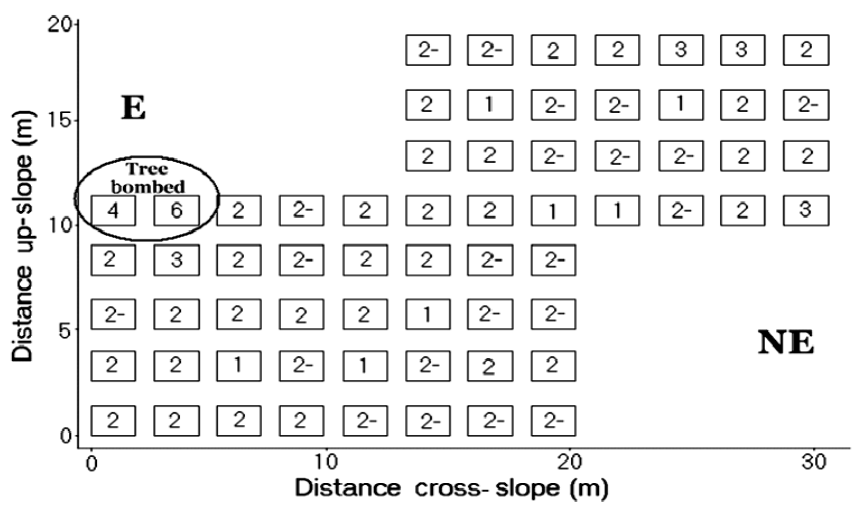

Figure 7 – Rutschblock test array performed at Monashee View on 2004-02-07. All the tests failed on the 040214 surface hoar layer with an average depth of 39 cm. Average slope angle was 34°. For two tests on the left side of the array, the continuity of the weak layer was interrupted by hard chunks of snow that had fallen off of a tree, known as "tree bombs".

Multivariate linear regression was used to assess the combined affect of slope angle and aspect on stability (Figure 8) based on the following equation:

$$RB\ score = 0.054\Psi + 0.025Asp - 1.30 \qquad (2)$$

where Ψ is the slope angle in degrees and *Asp* is the aspect in degrees from north. The aspect term in Equation 2 is significant (p = 0.001, N = 65), and the slope angle term is marginally significant (p = 0.061, N = 65). The assumption of normality of the residual values was rejected (Lilliefors p < 0.01), suggesting that least-squares linear regression is not suited to this dataset. Nonetheless, given the linear trend in Equation 2, a 10˚ decrease in slope angle combined with a 20˚ northerly change in aspect would result in a decrease in point stability of one RB score.

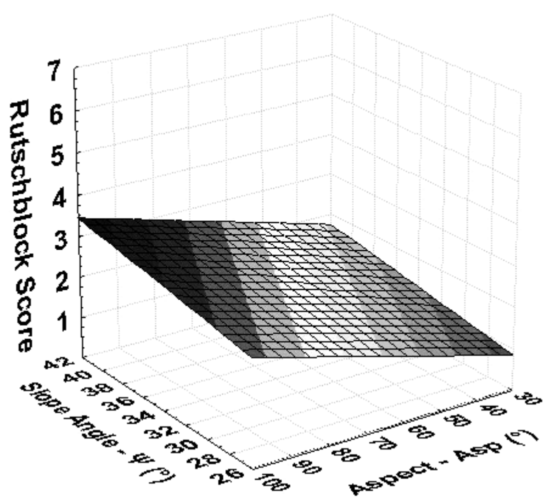

Figure 8 – Linear trend surface for the array at Monashee View on 2004-02-07 based on Equation 2. The surface is shaded based on RB score.

3.2.3 SOUTH RUN 2004-03-18

The array in Figure 9 shows how changing conditions for the growth of facets on a crust can affect stability. The array was performed on the side of a knoll where the aspect changes from easterly, on the left side of the slope, to northeasterly on the right side. The bed surface for the fractures was a buried crust which was formed from a melt-freeze process caused by direct solar radiation. When the bottom row of tests, which was influenced by varying slab thickness, is ignored, a significant correlation between RB score and aspect (R_S = -0.70, p = 0.002, N = 17) emerges. The crust on the easterly aspect was harder and thicker, and had bigger and sharper facets on it, which resulted in lower stability (RB score vs. E: R_S = -0.42, p = 0.04, N = 23) than on the more northerly (shadier) aspect.

Figure 9 – Rutschblock test array performed on the upper slopes of South Run on Fidelity Mtn. All the tests failed on a thin layer of faceted crystals on top of a melt-freeze crust. Average slab thickness was 73 cm and average slope angle was 30°.

3.3 FRACTURE CHARACTER AND RELEASE TYPE

Ninety-five percent of the 644 fracture character observations made for rutschblock tests were SP, 3% were RP, 1% were SC, 1% were B and < 0.5% were PC. These data are influenced by weak layer crystal type (van Herwijnen and Jamieson, this volume) in that the high proportion of SP fractures is probably due to the large number of arrays performed on buried surface hoar weak layers.

Twenty-two (76%) of the 29 rutschblock arrays have consistent SP fracture character. Another array is over 95% SP fractures. This is consistent with Landry's (2002) and Kronholm's (2004) findings. No relationship between fracture character and RB score was found.

Of the 626 release type (RT) observations made for rutschblock tests, 76% were W, 22% were M and 2% were E. Only 8 of the 27 (30%) arrays where RT was observed have consistent RT (all W).

The proportion of either W or M release type observations (which ever is greatest) within an array was analyzed with respect to array median RB score. As shown in Figure 10, the homogeneity of RT depends on overall slope stability, that is, less stable slopes are more likely to have homogeneous RT. However, this relationship is affected by the truncated distribution of RB scores. Furthermore, as RB score increases, the proportion of the less frequent release types (M and E) increase.

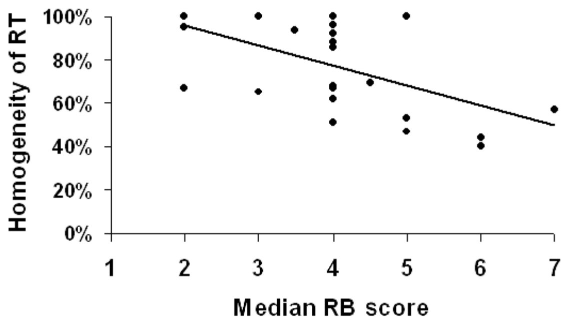

Figure 10 – Proportion of either W or M release type observations (which ever is greatest) as a function of slope median RB score (R_S = -0.53, p = 0.01, N = 27). Each point represents one rutschblock test array.

4. CONCLUSIONS

Based on the data and ideas presented in this paper, the following conclusions can be made:

- The interaction between terrain (e.g. ground cover and concave features) and meteorological phenomena (e.g. wind and radiation) can cause variability in point stability as measured with the rutschblock test.
- Varying slab thickness is a common cause of spatial variability in point stability within avalanche start zones, with areas of relatively thin slabs tending to have lower RB score.
- Varying slope angle can cause spatial variability in point stability within avalanche start zones, with areas having relatively steep slope angles tending to have lower point stability (RB score).
- Varying aspect can sometimes cause spatial variability in point stability within avalanche start zones. In one array with a weak layer of surface hoar, the rutschblock scores were lower where the crystals were larger and the aspect more northerly. For another array with a weak layer of facets on a sun crust, the rutschblock scores were lower on the less northerly aspect.
- Spatial variability of stability within avalanche start zones can be caused by a combination of factors that can be difficult to separate with current methods and the number of tests per array sizes used in this study.
- Locations with stability patterns that are influenced by ground cover or terrain features can show repeatability on a year-to-year basis.

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6. ACKNOWLEDGEMENTS

For their careful studies, we thank Antonia Zeidler, Alec van Herwijnen, Ryan Gallagher, Paul Langevin and Ken Matheson. The Avalanche Control Section of Glacier National Park including Dave Skjönsberg, Bruce McMahon, John Kelly and Jeff Goodrich as well as Mike Wiegele, Derek Frechette and the guides of Mike Wiegele Helicopter Skiing provided a stimulating environment for field research. Thanks to Laura Bakermans, Dave Gauthier and James Floyer for proofreading this article.

For financial support we are grateful to the BC Helicopter and Snowcat Skiing Operators Association (BCHSSOA), the Natural Sciences and Engineering Research Council of Canada, Mike Wiegele Helicopter Skiing, Canada West Ski Areas Association (CWSAA) and the Canadian Avalanche Association. The supporting member of the BCHSSOA include Baldface Mountain Lodge, Bella Coola Heli Sports, Black Tusk Helicopter Inc., Canadian Mountain Holidays, Cariboo Snowcat Skiing and Tours, Cat Powder Skiing, Chatter Creek Mountain Lodges, Coast Range Helskiing, Crescent Spur Heli-skiing, Great Canadian Heli-skiing, Great Northern Snow Cat Skiing, Highland Powder Skiing, Island Lake Resort Group, Klondike Heliskiing, Last Frontier Heliskiing, Mica Heli Guides, Monashee Powder Adventures, Northern Escape Heli-skiing, Peace Reach Adventures, Powder Mountain Snowcats, Purcell Helicopter Skiing, R.K. Heli-Skiing, Retallack Alpine Adventures, Robson Helimagic, Selkirk Tangiers Heli-Skiing, Selkirk Wilderness Skiing, Snowwater Heli-skiing, TLH Heliskiing, Valhalla Powdercats, Whistler Heli-Skiing and White Grizzly Adventures. The supporting members of Canada West Ski Areas Association include Apex Mountain Resort, Banff Mount Norquay, Big White Ski Resort, Hemlock Ski Resort, Intrawest Corporation, Kicking Horse Mountain Resort, Mt. Washington Alpine Resort, Silver Star Mountain Resorts, Ski Marmot Basin, Sun Peaks Resort, Sunshine Village, Whistler Blackcomb, Whitewater Ski Resort, and Resorts of the Canadian Rockies including Skiing Louise, Nakiska, Kimberley Alpine Resort, Fortress Mountain and Fernie Alpine Resort.