SNOWPACK FACTORS ASSOCIATED WITH STRENGTH CHANGES
OF BURIED SURFACE HOAR LAYERS

Bruce Jamieson* and Colin Johnston
Dept. of Civil Engineering, University of Calgary, Calgary, Alberta T2N 1N4 Canada

ABSTRACT: Every winter in North America, failures in layers of buried surface hoar (frost) release many slab avalanches, some of which kill recreationists. Some surface hoar layers stabilize within a week of burial and others require a month or more. Little is known about whether snowpack factors such as crystal size, snowpack depth, slab thickness, load, temperature and temperature gradient are associated with strength changes of these layers.

We tested buried surface hoar layers once or twice per week at study sites in the Columbia Mountains from 1994 to 1998, and measured over 300 changes in shear strength.

We assess the factors associated with the rate of strength change using rank correlations. The factors are ranked to identify which are most relevant for forecasting changes in strength. Useful predictors include the total snowpack depth, the maximum grain size, the strength at the start of the interval, the depth and temperature of the surface hoar layer, the air temperature and the load on the SH layer. The correlations between these predictors and the measured rate of strength change are discussed in terms of physical processes.

We illustrate the predictive potential of combined factors by comparing measured values of the rate of strength change with fitted values from a regression tree.

KEYWORDS: snow strength, avalanches, avalanche forecasting, snow metamorphism, snow physical properties, snow temperature

1. INTRODUCTION

In the Columbia Mountains of Western Canada, surface hoar (SH) crystals (Figure1) comprise the failure layers (Figure2) of fatal slab avalanches more often than any other grain type (Jamieson and Johnston, 1992). Yet little is know about the factors such as load, temperature and temperature gradient that may influence the rate at which the strength (and stability) of SH layers change over time.

There have been numerous studies of changes in the shape and size of snow crystals/grains over time (metamorphism). However, strength depends on bonding which is not directly related to grain shape and grain size. We focus on strength change and consider grain size as a possible predictor of the rate of strength change.

* Bruce Jamieson, Dept. of Civil Engineering, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4 Canada
Phone 1-403-220-7479. Fax 1-403-282-7026.
E-mail jbjamies@ucalgary.ca

Figure 1 Surface hoar crystals on a tree and on the snow surface. Once buried by subsequent snowfall, buried surface hoar layers often form persistent weak layers and potential failure layers for slab avalanches.
The objectives of this paper are to:

- identify some merits and difficulties of measurements associated with strength changes, and
- determine which factors are associated with the rate of strength change of buried SH layers. We regard this as a first step towards developing a model for predicting strength changes based on measurements that are easier to make than repeatedly measuring the shear strength of the layers with the shear frame.

2. LITERATURE REVIEW

In a cold lab, de Quervain (1958) studied the effect of various temperature gradients and loads on the shear strength and hardness of snow that was initially "fresh". Also in a cold lab, Akitaya (1974, 1975) studied the interacting effect of temperature gradient and density on change in hardness. Fierz (1998) made a detailed field study of a layer of faceted crystals and depth hoar that had formed just under a crust, focussing on the temperature, density and texture of the layer. However, none of these studies assessed surface hoar.

Lang and others (1985) monitored a SH layer in the field from formation through metamorphic and strength changes after burial. Strength increased from 25 to 390 Pa over about 44 days. They focussed on the micro-meteorological conditions that contributed to surface hoar formation and did not discuss the factors that contributed to the measured strength increase. Jamieson and Johnston (1995), Jamieson (1995) and Schweizer and others (1998) measured strength changes of buried SH layers. However, they focussed on the stability trends and associated avalanche activity. These authors did not assess the factors which may have influenced the measured strength changes.

3. FIELD METHODS

We conducted field studies in the Columbia Mountains of western Canada between December 1994 and March 1998. Of the nine study plots, five range in slope angle from 10° to 36° and four are level or almost level (Table 1). The total depth of the snowpack, HS, ranged from 36 cm to 490 cm. Table 1 also gives the aspect, elevation and number of strength changes measured at each site.

To measure strength changes in areas of relatively thin snowpack, two "air boxes" were constructed during the summer (Figure 3). These plywood

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Figure 2. Fractured and unfractured portions of buried surface hoar layer. The fracture produced a "whumpf" sound.

Table 1 Attributes of Study Sites

<table>
<thead>
<tr>
<th>Study Site</th>
<th>Aspect</th>
<th>Elevation (m)</th>
<th>Slope (°)</th>
<th>HS (cm)</th>
<th>No. of strength changes</th>
<th>No. of strength changes with continuous temperature measurements</th>
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<td>Mt. St. Anne</td>
<td>E</td>
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<td>127-255</td>
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<td>19</td>
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End view of air box with accumulation of undisturbed snow. Early in the winter, snow that accumulates on top of the box is shovelled off until the adjacent snowpack is slightly above the height of the box. Subsequent snow layers are allowed to accumulate naturally for the rest of the winter. During early and mid-winter, stronger temperature gradients are expected in the shallow snowpack on the air box compared to the nearby full depth snowpack.

Boxes were 14.5 m long, 2.5 m wide. One was 1 m high and placed in an area where the snowpack typically reaches 1.5 m. The other was 2 m high and placed in an area where the snowpack typically reaches 3 m. During early winter the snow was shovelled off the top of each box until the snowpack reached the height of the box. Subsequently, the snow was allowed to accumulate on top of the box. Once SH layers were buried in the snowpack on top of the box, they were tested in the same manner as in the adjacent full-depth snowpack, except that the distance between pits was reduced to 0.5 m (1.0 m standard) and the pits were carefully back-filled after the measurements were completed.

The air temperature, $T_a$, and depth of the SH layer, $H$, are measured as described in snow observation manuals (e.g. CAA, 1995).

3.1 Shear frame test
Andre Roch of Switzerland was instrumental in the development of the shear frame test (de Quervain, 1951; Roch, 1966). The avalanche forecasting program at Rogers Pass has used the shear frame test since 1962 (Schleiss and Schleiss, 1970). The test is also used by the avalanche safety programs at the Kootenay Pass Highway and some ski operations.

Before the shear frame test is performed, the weak SH layer is identified with a profile of snow layers, a tilt board test, a shovel test, or a rutschblock test (CAA, 1995). Overlying snow is removed, leaving approximately 40-45 mm of undisturbed snow above the weak layer (Figure 4). The shear frame is then gently inserted into the undisturbed snow so that the bottom of the frame is approximately 2-5 mm above the weak layer (Perla and Beck, 1983). For a detailed discussion of the shear frame test and frame placement, see Jamieson (1995). Shear strength is determined by dividing the maximum load on the force gauge by the area of the frame, usually 250 cm$^2$ in the present study. Coefficients of variation of shear frame measurements average 14% (Jamieson, 1995). Average shear strengths of weak layers were based on sets of 12 shear frame tests to reduce the standard error of shear strength. The shear strengths reported in this paper are adjusted for size effects (Sommerfeld, 1980; Föhn, 1987) and denoted $\Sigma$.

3.2 Grain size
The SH crystals are manually separated from the snowpack and observed under low magnification (e.g. 8x) on a crystal screen with 1-mm, 2-mm, 3-mm and 10-mm grids. The minimum size, $E_{\text{min}}$, and maximum size, $E_{\text{max}}$, of the characteristic crystals are observed and recorded.

3.3 Load
The load over a SH layer is measured in two ways. Most often, we sample the snow layers over the SH layer by pushing a tube vertically down
through the layers. The load is calculated as 

\[ \text{Load} = mg/A \]

where \( m \) is the mass of the sample, \( g \) is the acceleration due to gravity and \( A \) is the cross-sectional area of the tube (28 cm\(^2\) in our study). We also calculate the load from the density measurements and thickness of the layers overlying the SH layer

\[ \text{Load} = g \left( \rho_1 h_1 + \rho_2 h_2 + \ldots \right) / A \]  

where \( \rho \) and \( h \) are the density and thickness of the \( j \)th layer. When load over a particular SH layer is measured both ways, the values are averaged.

### 3.4 Thickness of layer

The thickness of a buried SH layer, \( L \), is measured by placing a scale graduated in millimetres against a vertical wall of the snow pit. This measurement was made for 175 changes in the last two winters. \( L \) and related predictors are used for the rank correlations but not for the multi-variate regression since this would have limited the data to 175 of the 337 changes.

### 3.5 Manual temperature measurements

On each test day, the temperatures are measured 5 cm above and below the SH layers with handheld digital thermisters with 20 cm-long probes. The temperature of the SH layer, \( T_{wl} \), is taken to be the average of the temperatures 5 cm above and below the SH layer. The temperature gradient, \( TG \), is calculated from the two temperatures. The average temperature of the SH layer over the 1-8 day interval, \( T_{wl_{avg}} \), is calculated from the average of \( T_{wl} \) at the start and end of the interval. The average temperature gradient across the SH layer over the 1-8 day interval, \( TG_{avg} \), is calculated by averaging \( TG \) values at the start and end of the interval. \( T_{wl_{avg}} \) and \( TG_{avg} \) are available for all 337 changes analyzed in this paper.

### 3.6 Continuous temperature measurements

We used thermisters connected to a datalogger to measure snowpack temperatures continuously. The thermisters were individually calibrated in slush to achieve an accuracy of approximately ±0.1°C. However, there are larger errors associated with the placement of the thermisters. We excavate a square pit in undisturbed snow near where the shear frame tests are made. Into the vertical wall aligned down the slope, we make 25 cm-deep horizontal holes into the undisturbed snow, 5 cm above and below the SH layer, with a rod the same diameter (8 mm) as the thermisters in their protective sheaths. We insert the thermisters into these holes (Figure 5) and backfill the pit, being careful not to disturb the thermister cables. Typically 7-14 days later we carefully dig out the thermisters, noting the distance they are above and below the SH layer. About half the time we find the thermisters are 7-9 cm apart, implying that the thermisters were initially 10 cm apart and the snow between the thermisters compressed by 1-3 cm. However, we have occasionally excavated thermisters and found them to be more than 10 cm apart or less than 4 cm apart, indicating that the thermisters were placed inaccurately. We minimize this source of error by placing two pairs of thermisters across most SH layers, and using the results from the best-placed pair for calculating the temperature of the SH layer and temperature gradient across the layer.

The thermisters readings are recorded hourly by a datalogger. The average temperature of the SH layer based on thermister measurements over the 1-8 day interval is denoted by \( T_{th} \). The average temperature gradient calculated from the hourly thermister measurements over the 1-8 day interval is denoted by \( TG_{th} \). Not all SH layers we tested with shear frames were monitored with thermisters. Consequently, \( T_{th} \) and \( TG_{th} \) are available for 98 of the 337 changes analyzed in this paper. \( T_{th} \) and \( TG_{th} \) are used for the rank correlations but not for the multi-variate regression since this would have limited the data to 98 of the 337 changes.

### 3.7 Comparison of continuous and manual temperature measurements

To compare manually measured temperatures with continuously measured temperatures, we plotted the difference, \( T_{wl_{avg}} - T_{th} \), in Figure 6a. The difference decreases with depth. Below 30 cm, the two measurements differ by less than 1°C in most cases. We attribute the improved agree-
ment with depth to decreased diurnal temperature fluctuations with depth that make \( T_{th} \) less sensitive to inaccurate placement of the thermisters.

The difference between manually and continuously measured temperature gradients, \( TG_{avg} - TG_{th} \) is plotted in Figure 6b. The greatest differences occur near the surface. Below 30 cm, most values differ by less than 5°C/m. Based on this comparison, we expect manual and continuous measurements to give similar results below 30 cm.

4. PREDICTOR VARIABLES

A predictor variable is a measurement that might be useful for predicting the rate of strength change and is easier to measure than shear strength. These are listed in Table 2. Some predictors are measurements such as snowpack depth or air temperature. Others are calculated values such as strength or load. We also used some elaborated variables such as \( TG/Twl \), \( TG_{th}/Tth \), \( Ta/HS \) and \( Emax-Emin \) to assess their merit as possible predictors of the rate of strength change. We use subscripts to distinguish between the measurement at the start of a 1-8 day interval, e.g. \( H_0 \), and at the end of the interval, e.g. \( H_1 \). From these two values we calculate \( H_{avg} \) which is the average of the values at the start and end of the interval, and \( \Delta H/\Delta t \) which is the average rate of change during the interval, \( \Delta t \).

We consider the shear strength at the start of the interval, \( \Sigma_0 \), as a possible predictor for the rate of change during the interval.

5. RESPONSE VARIABLES

In the following analyses we seek associations between the predictors and the response variable, \( \Delta \Sigma/\Delta t \), which is the average rate of change of shear strength during the 1-8 day interval. To assess whether the correlations were better for

<table>
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deeper or shallow layers, we also calculated \( \Delta \Sigma/\Delta t_{<30} \) and \( \Delta \Sigma/\Delta t_{\geq30} \), which are, respectively, the rate of strength change for SH layers less than 30 cm below the surface, and for layers at least 30 cm below the surface at the start of the 1-8 day interval. To assess whether the correlations were better for shorter or longer intervals, we calculated \( \Delta \Sigma/\Delta t_{1-4} \) and \( \Delta \Sigma/\Delta t_{5-8} \) for 1-4 and 5-8 day intervals, respectively.

These response variables and the number of data for each are summarized in Table 3.

Measures of correlation and regression fit such as \( R^2 \) can be over-estimated if the data are serially correlated. However, this concern is reduced since the 337 data are from 61 different series.

The 337 values of \( \Delta \Sigma/\Delta t \) are partitioned into 100 Pa intervals and plotted along with the expected normal curve in Figure 7. The fit to the normal curve appears poor. The hypothesis of normality is rejected by the Kolmogorov-Smirnov test (\( d=0.125, p < 0.01 \)) and the Chi-squared test (\( \chi^2 = 79, \text{df} = 6, p < 10^{-7} \)). For the Chi-squared test, intervals with less than 5 data were combined. The non-normality of the response variable, \( \Delta \Sigma/\Delta t \), precludes the use of statistical techniques such as Pearson correlations.

### 6. RANK CORRELATIONS

Rank correlations between the predictor variables and the five response variables are listed in Table 4. We used Kendall tau rank correlations since \( \Delta \Sigma/\Delta t \) is not normally distributed as shown in Figure 7.

#### 6.1 Effect of the depth of the surface hoar layer on correlations

We assess whether the correlations are better for deeper or shallow layers by considering the correlations of \( \Delta \Sigma/\Delta t_{<30} \) and \( \Delta \Sigma/\Delta t_{\geq30} \) with the predictors in Table 4. There are 19 significant correlations (\( p < 0.05 \)) between \( \Delta \Sigma/\Delta t_{<30} \) and the predictors (\( N \leq 285 \)) whereas there are only 10 significant correlations between \( \Delta \Sigma/\Delta t_{\geq30} \) and the predictors (\( N \leq 52 \)). Also, only 4 of the predictors correlate significantly with both \( \Delta \Sigma/\Delta t_{<30} \) and \( \Delta \Sigma/\Delta t_{\geq30} \). Since \( \Delta H/S/\Delta t, \Delta H/I/\Delta t, \Delta \text{Load}/\Delta t \) correlate significantly with \( \Delta \Sigma/\Delta t_{<30} \) but not with \( \Delta \Sigma/\Delta t_{\geq30} \), it suggests that shallow layers are more sensitive to changes in load and depth than deeper layers. Nevertheless, we expect more significant correlations for the deeper layers because there are more data and because of the more accurate temperature measurements for deeper SH layers as shown in Figure 6a and 6b.

All the predictors that correlate significantly with \( \Delta \Sigma/\Delta t_{<30} \) also correlate significantly, and with the same sign, with \( \Delta \Sigma/\Delta t_{\geq30} \) (\( N = 337 \), all depths). Consequently, in subsequent analyses we do not partition the data according to the depth of the surface hoar layer.

#### 6.2 Effect of interval length on correlations

We usually tested SH layers buried less than 75 cm below the surface every 3-4 days, although there are a few changes for 1-2 day intervals. We measured 162 changes over 1-4 intervals (response variable \( \Delta \Sigma/\Delta t_{<4} \)). We measured 175 changes over 5-8 day intervals and denote the response variable for these generally deeper SH layers as \( \Delta \Sigma/\Delta t_{5-8} \). Combining these data sets gives 337 changes over 1-8 days for layers of various depths (response variable \( \Delta \Sigma/\Delta t \)).
Rank correlations (Kendall tau) between the response variables \( \Delta \Sigma/\Delta t \), \( \Delta \Sigma/\Delta t_{1-4} \), \( \Delta \Sigma/\Delta t_{5-8} \) and \( \Delta \Sigma/\Delta t \) and the predictors are shown in Table 4. \( \Delta \Sigma/\Delta t_{1-4} \) is significantly correlated with 17 predictors \((p < 0.05)\) and \( \Delta \Sigma/\Delta t \) is significantly correlated with 22 predictors. The only improved correlation for the 1-4 day strength changes of shallower layers compared to the 1-8 day strength changes for layers of various depths is \( \Delta Twl/\Delta t \) which is only significant at the 5% level.

\( \Delta \Sigma/\Delta t_{5-8} \) is significantly correlated with 20 predictors \((p < 0.05)\) compared to \( \Delta \Sigma/\Delta t \) which correlates significantly with 22 predictors. Only \( TGth/Tth \) is better correlated with the strength changes of deeper layers over 5-8 day intervals than for layers of various depths over 1-8 day intervals.
Since the larger data sets for strength changes of layers of various depths over 1-8 day intervals are better correlated with the predictors than changes for shallower layers over 1-4 day intervals and for deeper layers over 5-8 day intervals, the combined data set is used in subsequent analyses.

7. RANKING PREDICTOR VARIABLES
The top 10 predictors in order of decreasing significance level of their rank correlations are: \( HS_{avg}, E_{max} \), \( H_{avg}, TG_{avg}/Twl_{avg}, Twl_{avg}, Emin_{avg}, \) \( Load_{avg}, E_{max} - Emin_{avg}, L_0, Ta_{avg} \). These are discussed subsequently in terms of their correlations with other predictors and the underlying physical processes.

8. REGRESSION TREE
To assess the combined predictive potential of the variables associated with the rate of strength change we use a regression tree (Breiman and others, 1984). This technique detects associations between a response variable with interval properties and predictors. Tree regressions do not require normalizing transformations of the predictors, and allow for non-monotonic and complex relationships between the predictors and the response variable (Davis and Elder, 1995). Regression trees recursively split the data into two groups based on critical values of the predictors. These critical values are chosen to minimize the node deviance, which is the measure of fit (Breiman and others, 1984). A deviance of zero indicates a perfect fit. Potentially, the data could be partitioned until there is only one datum in each node. However, while the initial splits reflect structure in the data (which is important), splitting into very small subgroups results in fitting a tree to individual data (which is not relevant to most problems). For the analysis of \( \Delta S/\Delta t \) and its predictors, we allowed trees to continue to grow if there were at least 10 data at a node and stopped the growth if there were less than 5 data at a node.

For the regression tree we use \( Twl_{avg} \) and \( TG_{avg} \) \((N = 337)\) in preference to \( Th \) and \( TGth \) \((N = 94)\) because there are 3.5 times more data and because the rank correlations (Table 4) are more significant. Except for \( S_0 \) and \( Age_0 \), we excluded the initial values \( Ta_0, HS_0, H_0, Load_0, Twl_0, TG_0, Emin_0, \) and \( E_{max_0} \) and used their respective average values which in most cases correlate as well or better with \( \Delta S/\Delta t \) (Table 4) than the initial values. We also excluded the predictors involving the thickness of the weak layer, \( L_0, L_{avg} \) and \( \Delta L/\Delta t \) because the thickness was only measured for 175 of the 337 changes (last two winters).

Using the recursive binary partitioning algorithm for regression trees, we regressed \( \Delta S/\Delta t \) on \( Ta_{avg} \), \( \Delta Ta/\Delta t, HS_{avg}, H_{avg}, Hi/\Delta t, Load_{avg}, \) \( \Delta Load/\Delta t, Twl_{avg}, \Delta Twl/\Delta t, TG_{avg}, \Delta TG/\Delta t, \) \( TG_{avg}/Twl_{avg}, L_{avg}, \Delta L/\Delta t, Emin_{avg}, E_{max_{avg}}, \) \( E_{max_{avg}}, Emin_{avg}, E_{max_{avg}}, Emin_{avg}, Ta_{avg}/HS_{avg}, \) \( Age_0 \), and \( \Sigma_0 \). The upper part of the tree is shown in Figure 8.

Figure 8: Upper portion of regression tree showing splits involving important predictors. For each split, the left branch is for the observations for which the “less than” condition is true.
The preferred way to assess the predictive merit of a model is to use some data to develop the model and other data to compare predicted values with measured values. However, we are reluctant to split our data because regression trees require large data sets. Consequently, we plot the fitted values against the measured values of $\Delta \Sigma/\Delta t$ in Figure 9. This gives an optimistic indication of the predictive potential of the predictors. The majority of the fitted data are within ± 100 Pa/d of the measured values, showing that the predictors have the potential to distinguish between rapid and slow strength gains of buried SH layers.

9. DISCUSSION

In this section we discuss the highest ranked predictors in terms of their correlations with other predictors and the underlying physical processes that are probably affecting the rate of strength change of buried SH layers. Relevant correlations between predictors are noted in the following discussion but the complete matrix is not given.

9.1 Snowpack depth HS

Deeper snowpack correlates positively with $\Delta \Sigma/\Delta t$ ($p = 2 \times 10^{-11}$). This is not surprising since HS is negatively correlated with $|T_G|$ ($p < 10^{-6}$) [associated with bonding] and positively correlated with Load ($p < 10^{-6}$) and strength at the start of an interval ($p < 10^{-4}$).

9.2 Maximum crystal size $E_{\text{max}}$

$\Delta \Sigma/\Delta t$ is negatively correlated with $E_{\text{max}}$ ($p = 10^{-6}$), indicating that larger grains are slower to gain strength. This is consistent with reports of field workers, and supports the idea that bigger umbrellas (Davis and others, 1997) are associated with bigger pore spaces and fewer bonds per unit area. Larger crystals are also negatively correlated with snowpack depth ($p = 10^{-2}$), load ($p = 10^{-4}$), slab thickness ($p = 10^{-5}$), and initial strength ($p < 10^{-6}$), which are likely associated with lower elevation study sites. $E_{\text{min}}$ has similar correlations as $E_{\text{max}}$ but generally slightly lower significance levels.

9.3 Slab depth $H$

Deeper slabs are positively correlated with $\Delta \Sigma/\Delta t$ ($p < 10^{-4}$). This is expected since deeper slabs are associated with greater load ($p < 10^{-6}$) which causes pressure on the bonds, lower magnitude of temperature gradient ($p < 10^{-5}$) generally associated with increased bonding, and greater insulation between the SH layer and the colder air.

9.4 Load

The rate of strength change, $\Delta \Sigma/\Delta t$, is positively correlated with Load ($p = 10^{-4}$) since strength increases faster when greater loads are applied. Increased loads probably push surface hoar crystals into adjacent layers, thereby contributing to bonding and strength.

9.5 Range of crystal size $E_{\text{max}}-E_{\text{min}}$

The rate of strength change, $\Delta \Sigma/\Delta t$, is negatively correlated with the range of crystal size, $E_{\text{max}}-E_{\text{min}}$ ($p = 10^{-4}$). A large range of crystal size is only likely for large $E_{\text{max}}$. Consequently, large values of $E_{\text{max}}-E_{\text{min}}$ are associated with slow strength gain because large grains are slow to gain strength.

9.6 Temperature of SH layer $T_{\text{th}}$

Surprisingly, the temperature of the SH layer is negatively correlated with the rate of strength change ($p = 3 \times 10^{-6}$). However, the temperature of the SH layer is negatively correlated with snow depth ($p < 10^{-6}$), so the negative correlation of $\Delta \Sigma/\Delta t$ with temperature is probably a result of slower strength gains in shallower snowpack areas. The correlation with temperature of the SH layer measured with thermisters, $T_{\text{th}}$, is positive as expected (but less significant).

9.7 Strength at the start of an interval $\Sigma_0$

The rate of strength change, $\Delta \Sigma/\Delta t$, is positively correlated with the strength of the layer at the start of the interval ($p = 10^{-4}$), suggesting that stronger
layers are faster to gain strength. This is surprising since strength is roughly proportional to density squared (e.g. Perla and others, 1982) and densification slows over time (e.g. Armstrong, 1980). The positive correlation between $\Delta \Sigma / \Delta t$ and strength is probably due to the fact that initial strength is positively correlated with $HS (p < 10^{-6})$, Load ($p < 10^{-6}$), slab thickness ($p < 10^{-4}$) and $Twl (p = 10^{-6})$. Strong layers are usually found under heavy loads in areas of deep snowpack and they tend to continue to gain strength during the changes we observed.

9.8 Air temperature $Ta$
The rate of strength change, $\Delta \Sigma / \Delta t$, is negatively correlated with the air temperature, $Ta$, during the interval. This suggests that strength increases faster at colder temperatures. However, $Ta$ is negatively correlated with $HS (p = 10^{-4})$, Load ($p < 10^{-6}$) and slab thickness ($p = 10^{-4}$) suggesting that the fastest strength increases took place at higher elevations where the temperature was generally colder, the snowpack deeper, the slabs thicker and the loads greater.

9.9 $TG/Twl$
Except for some shallow SH layers and some measurements in late March, most values of $TG$ are negative (cooler toward the surface). Since $Twl$ is never positive in any field study of dry snow and negative in our data set, $TG/Twl$ is usually positive. $TG/Twl$ is negatively correlated with $TG (p < 10^{-6})$ but not with $Twl (p = 0.17)$. Consequently, $TG/Twl$ decreases as the magnitude of $TG$ decreases (and the value of $TG$ increases).

The rate of strength change, $\Delta \Sigma / \Delta t$, is negatively correlated with $TG/Twl (p = 10^{-6})$ presumably because higher values of $TG/Twl$ are associated with shallow snowpack ($p < 10^{-4}$) and thinner slabs ($p = 10^{-4}$) and decreased magnitudes of $TG (p < 10^{-4})$.

9.10 Temperature gradient across the surface hoar layer $TG$
The rate of strength change, $\Delta \Sigma / \Delta t$, is weakly but positively correlated with the temperature gradient, $TG (p = 0.04)$, suggesting that the fastest strength gains occurred for the higher values of $TG$ and lower magnitudes of $TG$. This is consistent with increased bonding when the magnitude of the temperature gradient decreases.

9.11 Thickness of the surface hoar layer $L$
The rate of strength change, $\Delta \Sigma / \Delta t$, did not correlate with the thickness of the SH layer ($p = 0.8$). We interpret this as a result of the competing effect of grain size ($Emax$ is positively correlated with $L$, $p < 10^{-8}$, and negatively correlated with $\Delta \Sigma / \Delta t$, $p = 10^{-3}$) and initial strength ($\Sigma_0$ is negatively correlated with $L$, $p = 10^{-4}$ and positively correlated with $\Delta \Sigma / \Delta t$, $p = 10^{-6}$). 

9.12 Average temperature gradient of the snowpack $Ta/HS$
The rate of strength change, $\Delta \Sigma / \Delta t$, did not correlate with $Ta/HS (p = 0.7)$. This suggests that the strong correlation between $\Delta \Sigma / \Delta t$ and HS may be more related to greater $Load$ where $HS$ is greater than to the average temperature gradient of the snowpack as estimated by $Ta/HS$.

10. SUMMARY
The air temperature, $Ta$, and the temperature of the SH layer, $Twl$, gave correlations with $\Delta \Sigma / \Delta t$ with unexpected signs. However, these are explained in terms of strong correlations between these temperature variables and the predictors $Load$, $H$ and $HS$.

The three variables that correlate most significantly ($p < 10^{-4}$) with $\Delta \Sigma / \Delta t$ are $HS$, $Emax$ and $H$. The effect of each of these variables on the rate of strength change can be interpreted physically. In summary, $\Delta \Sigma / \Delta t$ increases with $HS$ and $H$ and decreases with $Emax$. We believe:

- The thickness of the slab, $H$, contributes to increased strength of the underlying SH layer through its association with load and because thicker slabs contribute to warmer SH layers with lower $|TG|$ across the SH layer by insulating the layer from the usually colder air.
- The snowpack thickness, $HS$, contributes to increased strength through its correlations with $Load$ (pressure on the bonds) and $H$. Also, areas of deeper snowpack generally have lower $|TG|$, thereby contributing to bonding.
- SH layers consisting of larger crystals are generally slow to gain strength probably because they reduce the number of grains that fall between the SH crystals and bond (Davis and others, 1997).

The strong correlations of $HS$, $Emax$ and $H$ with the rate of strength change suggest that micro-
structure and bond-stress may be important to understanding and modelling strength changes of buried SH layers.

As expected, $\Delta\Sigma/\Delta t$ is positively correlated with $TG$ (and negatively correlated with $|TG|$) since bond growth is associated with lower $|TG|$ and rounding. However, $TG$ is a weaker predictor than $HS$, $E_{max}$, $H$ and $Load$. $\Delta\Sigma/\Delta t$ correlates better with $TG/Twl$ than with $TG$.

In future studies we plan to:
• improve the accuracy of continuously measured temperature and temperature gradient at the weak layers,
• increase the number of observations with continuously measured temperature and temperature gradient, and
• average the magnitude of the temperature gradient to improve correlations for shallow layers where temperature gradients often vary from positive to negative within 24 hours.

ACKNOWLEDGEMENTS
We thank Jürg Schweizer, Robert Davis and Sam Colbeck for stimulating discussions on surface hoar and bonding. We are grateful to Adrian Wilson, Mark Shubin, Steve Lovenuik, Rodden McGowan, Greg McAuley, Nick Irving, Jill Hughes, Sue Gould, Brian Gould, Torsten Geldsetzer, Joe Filippone, Christian Camponovo, James Blench, Ken Black and Leanne Allison for their careful field work, and to Julie Lockhart for proofreading this paper. We appreciate the logistical support and productive environment for field studies provided by Mike Wiegele Helicopter Skiing and Canadian Mountain Holidays. This study is part of a Collaborative Research and Development Project supported by the BC Helicopter and Snowcat Skiing Operators Association, the Natural Sciences and Engineering Research Council of Canada, Canada West Ski Areas Association, Mountain Equipment Co-op, the Canadian Avalanche Association, the Snow Avalanche Programs of the BC Ministry of Transportation and Highways, and Parks Canada.

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