STRENGTH CHANGES OF LAYERS OF FACETED SNOW CRYSTALS IN THE COLUMBIA AND ROCKY MOUNTAIN SNOWPACK CLIMATES IN SOUTHWESTERN CANADA

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ABSTRACT: The strength of layers of faceted crystals is important for forecasting snow stability. During the winters of 1993-2000, in the intermountain snowpack climate of the Columbia Mountains and the continental snowpack climate of the Rocky Mountains of southwestern Canada, over 100 strength measurements of 16 layers of faceted crystals were made. Rank correlations are used to relate the strength of layers of faceted crystals with measured snowpack properties and calculated snowpack variables. Additionally, the contrast in snowpack properties between snowpack climates allows comparison between shear strength and snowpack factors. Factors showing the greatest potential for predicting shear strength include load and slab thickness.

KEYWORDS
snow crystals, faceted crystals, snow strength, snow climate, avalanche, avalanche forecasting

1. INTRODUCTION

In southwest Montana 59% of investigated avalanches between 1990 and 1996 (Birkeland et al., 1998) and in Canada 26% of the fatal avalanche accidents between 1972 and 1992 (Jamieson and Johnston, 1992) were a result of failures of layers of faceted crystals. Statistics for Canada show the number of avalanche fatalities is greatest in the continental snowpack climate of the Rocky Mountains and least in the coastal snowpack climate of the Coastal Mountains (Jamieson and Geldsetzer, 1996). To prevent avalanche accidents, avalanche forecasters rely on snowpack data, weather forecasts, and previous avalanche activity. Often weather, snowpack conditions, and time restrict data collection, increasing reliance on snowpack evolution models. However, the shear strength of layers of faceted crystals is often poorly predicted by such models (Fierz, 1998).

Various snowpack variables influence the strength of layers of faceted crystals, but these variables have not been widely studied. In this study, snowpack variables and shear strength of layers of faceted crystals were measured in the continental climate of the Rocky Mountains and the intermountain climate of the Columbia Mountains of southwestern Canada. Relationships between shear strength and snowpack variables are established by using physical arguments and Spearman rank correlations.

2. LITERATURE REVIEW

In a recent study, Stock et al. (1998) observed numerous layers of faceted crystals at Red Mountain Pass, Colorado from December to March. He measured stuffblock scores (Johnson and Birkeland, 1994), and hand hardresses on valley bottoms and north and south-facing slopes. The study found faceted crystals were larger on north-facing slopes and slower to gain stability and strength.

Jamieson and Johnston (1999) used Kendall-Tau correlations and ranked variables associated with the rate of shear strength change for surface hoar layers. They found the predictor variables that most significantly affect shear strength are height of the snowpack, the maximum crystal size, and slab thickness.

3. SNOWPACK CLIMATES

In southwestern Canada there are three snowpack climate zones: coastal, intermountain, and continental (Fitzharris, 1981; Mock, 1995). Each of these climate zones (Figure 1) has different weather and snowpack conditions. The coastal climate of the Coast Mountains produces relatively warm temperatures and heavy snowfall. The Rocky Mountains have a continental climate associated with cold temperatures and shallow snowpacks. The intermountain climate of the Columbia Mountains is due to an overlap between the coastal and continental weather systems. As a result the intermountain climate has less snowfall.

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than the Coast Mountains, but more than the Rocky Mountains (Armstrong and Armstrong 1987). Typical mid-winter snowpack depths at tree line are 2 m to 4 m in the Columbia Mountains and 1 m to 1.5 m in the Rocky Mountains.

In southwestern Canada there has not been a comprehensive study defining different snowpack climates. Average snowpack and weather data collected from two sites in the Rocky Mountains of Canada and three sites from the Columbia Mountains are similar to Armstrong and Armstrong’s (1987) and Mock and Birkeland’s (1999) results for the western United States.

The continental snowpack of the Canadian Rockies is known for its layers of faceted crystals and depth hoar. Typically the temperature gradient averaged over the snowpack is greater than the faceting threshold of 10°C/m (Akitaya, 1974) from the first snowfall until the end of February (Figure 2) (Johnson, In preparation). The result is layers of depth hoar and faceted crystals. By March, facets and depth hoar deep in the snowpack are warm, under a low temperature gradient, and start to round. However, near-surface faceting still occurs due to localized temperature gradients caused by diurnal fluctuations of air temperature and radiation.

In general, the snowpack temperature gradient never reaches the threshold value of 10°C/m for faceting in the Columbia Mountains (Figure 2). Most of the faceting occurs due to near-surface temperature gradients (Birkeland, 1998). After layers of facets are buried, a thick snowpack promotes low temperature gradients that are associated with rounding of grains and strengthening of layers.

Despite clear divisions between intercontinental and continental snowpack climates, variability of snowpack depth within each climate is common (Mock, 1995). Typically the western slopes of the Columbia and Rocky Mountains have thicker snowpacks and are slightly warmer than the eastern slopes. The eastern slopes of the Columbia Mountains have a transitional snowpack climate between the intermountain and continental climates. As a result the snowpack structure includes more layers of faceted crystals on the eastern slopes than on the western slopes.

4. FIELD WORK

During the winters of 1993-2000, in the Columbia Mountains and the Rocky Mountains of southwestern Canada, over 100 strength measurements of 16 layers of faceted crystals were made. The shear strength of layers of faceted crystals was measured with the shear frame. If the faceted layer was deeper than 75 cm and older than two weeks it was only tested once per week, otherwise twice a week. Measurement procedures for air temperature, layer thickness, layer hardness, snowpack depth, crystal type, crystal size, and water content are described in CAA (1995).

4.1 Shear frame test

The shear frame test was used to measure the shear strength of the facet layers. The shear strength of the facet layer was calculated by dividing the recorded minimum force by the area of the frame. The shear strength is...
Table 1. List of predictor factors and response variables.

**PREDICTOR VARIABLES**

<table>
<thead>
<tr>
<th>Load</th>
<th>Weight of the overlying snow per unit horizontal area (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_{\text{slab}}$</td>
<td>Averaged slab density of snow above layer of faceted crystals (kg/m$^3$)</td>
</tr>
<tr>
<td>$H$</td>
<td>Thickness of the slab, the depth of snow over the layer of faceted crystals (cm)</td>
</tr>
<tr>
<td>$R_{\text{slab}}$</td>
<td>Hardness of the faceted layers measured with the hand hardness test (CAA, 1995)</td>
</tr>
<tr>
<td>HS</td>
<td>Depth of snowpack (cm)</td>
</tr>
<tr>
<td>Age</td>
<td>Number of days since the layer of faceted crystals formed</td>
</tr>
<tr>
<td>TG</td>
<td>Temperature gradient measured across layers of faceted crystals. Measurements are taken 5 cm above and 5 cm below the layer ($^\circ$C/m)</td>
</tr>
<tr>
<td>Twl</td>
<td>Temperature of the layer of faceted crystals ($^\circ$C)</td>
</tr>
<tr>
<td>L</td>
<td>Thickness of the layer of faceted crystals (cm)</td>
</tr>
<tr>
<td>TA/HS</td>
<td>Temperature gradient averaged over the snowpack ($^\circ$C/m)</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>Shear strength of layers of faceted crystals measured with the shear frame (kPa)</td>
</tr>
<tr>
<td>$\Sigma_{\text{inter}}$</td>
<td>Shear strength of layers of faceted crystals measured with the shear frame in inter-continental snowpack climates (kPa)</td>
</tr>
<tr>
<td>$\Sigma_{\text{cont}}$</td>
<td>Shear strength of layers of faceted crystals measured with the shear frame in continental snowpack climates (kPa)</td>
</tr>
</tbody>
</table>

then adjusted for the size effects of the shear frame (Sommerfield 1980, Fohn 1987). For a detailed description of the shear frame test see Jamieson and Johnston (In press).

**RESPONSE VARIABLES**

<table>
<thead>
<tr>
<th>$\Sigma$</th>
<th>Shear strength of layers of faceted crystals measured with the shear frame (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma_{\text{inter}}$</td>
<td>Shear strength of layers of faceted crystals measured with the shear frame in inter-continental snowpack climates (kPa)</td>
</tr>
<tr>
<td>$\Sigma_{\text{cont}}$</td>
<td>Shear strength of layers of faceted crystals measured with the shear frame in continental snowpack climates (kPa)</td>
</tr>
</tbody>
</table>

4.3 Snowpack temperatures

The temperature profile of the snowpack was measured with digital thermometers in 10 cm intervals. Temperatures were also measured 5 cm above, below, and in the faceted layers.

5 RESULTS AND DISCUSSION

5.1 Rank correlations

The shear strengths of layers of faceted crystals are a result of the interaction with various snowpack variables. These are termed predictor variables because they might be useful for predicting shear strength (Table 1).

The response variable is the shear strength $\Sigma$. To assess snowpack factors that are associated with changes in shear strength the data were rank correlated in three climatic categories:

1) continental snowpack climate
2) intermountain snowpack climate
3) both snowpack climates.
The response variable $\Sigma_{\text{cont}}$ represents shear strength in continental snowpacks, $\Sigma_{\text{inter}}$ for intermountain snowpacks, and $\Sigma$ for shear strength in both climates.

The distribution of all shear strength measurements shown in Figure 3 failed the Kologorov-Smornov test of normality ($d = 0.258$, $p < 0.01$). Since the response variable is not normally distributed, Spearman rank correlations are used. This correlation technique only requires the data to be at least on an ordinal scale. The Spearman statistic $R$ ranges from $-1$ to $1$, with $1$ and $-1$ being a perfect correlation and $0$ indicating no correlation. The significance level $p$ represents the reliability of a correlation. A $p$-level of 0.05 indicates there is a 5% probability of the analysis revealing a correlation in uncorrelated data (Statistica, 1999).

Serial correlations are a measure of the relationship between past observations and present observations of a variable (Chatfield, 1980, pg 23-32). They are present in the data and cause overestimates of significance levels for correlations between response and predictor variables.

### 5.2 Results of rank correlations

Snowpack properties that correlated with shear strength of faceted snowpack layers are listed in terms of their statistical significance in Table 2 and cross-correlations between the predictors are listed in Table 3. In continental snowpack climates shear strength $\Sigma_{\text{cont}}$ significantly correlated with 6 snowpack variables ($p < 0.05$). In intermountain climates shear strength $\Sigma_{\text{inter}}$ significantly correlated with 9 snowpack properties. When the data were not partitioned into a climatic region, shear strength $\Sigma$ correlated with 10 snowpack properties. The variables that positively correlated with shear strength in all three categories are load, age, thickness of the slab, density of the slab, and hand hardness. In addition to these properties the maximum crystal size correlated with shear strength in the continental $\Sigma_{\text{cont}}$ and intermountain $\Sigma_{\text{inter}}$ climates.

### 5.3 Age

Age positively correlated with shear strength in all three correlation categories (Table 2). However, when strength is plotted over time it reaches maximum values that depend on snowpack climate (Figure 4).
Load hardness roughly measures the resistance to penetration. It is an index of strength.

The positive correlation ($p = 4.8E-11$, Table 2) between hand hardness and shear strength is expected. In this study faceted crystals in continental snowpacks reached maximum hand hardnesses of approximately 1 F+, but rounding facets in intermountain snowpacks sometimes reached $P$. The difference in hand hardnesses for each snowpack climate is primarily due to load ($p = 6.2E-8$, Table 3); load is associated with bond formation and growth.

The temperature gradient weakly but positively correlated ($p = 2.1E-2$, Table 2) with the shear strength $\Sigma_{\text{int}}$ of layers of faceted crystals in the intermountain snowpack of the Columbia Mountains. However, an effect of temperature gradient on shear strength is not expected since most of the temperature gradient data has magnitudes less than $1\degree\text{C/m}$.

Shear strength positively correlated with slab density $\rho_{\text{slab}}$ (Table 2) in all three strength categories. This is not surprising since slab density is a function of slab thickness ($p = 1.6E-12$, Table 3) and load ($p = 1.5E-22$).

Hand hardness roughly measures the resistance to penetration. It is an index of strength. The positive correlation ($p = 4.8E-11$, Table 2) between hand hardness and shear strength $\Sigma$ is expected.

In this study faceted crystals in continental snowpacks reached maximum hand hardnesses of approximately 1 F+, but rounding facets in intermountain snowpacks sometimes reached $P$. The difference in hand hardnesses for each snowpack climate is primarily due to load ($p = 6.2E-8$, Table 3); load is associated with bond formation and growth.

The temperature of the weak layer ($T_w$) positively correlated ($p = 1.3E-7$, Table 2) with shear strength in intermountain snowpacks, but did not for continental snowpacks. In the deep snowpacks of the Columbia Mountains, temperatures gradually increase over the winter, promoting rounding of the faceted crystals and bond growth. The temperature of the weak layer correlated with slab thickness ($p = 1.2E-4$, Table 3) and age ($p = 4.8E-15$) suggesting as layers age they are buriedly deep and well insulated from cold air.

In continental climate of the Rocky Mountains the temperatures of weak layers slowly warm throughout the winter. However, thin overlying slabs reduce insulation from cold air. As a result the temperature of weak layers undergo fluctuations that may reduce correlations.

The temperature gradient weakly but positively correlated ($p = 2.1E-2$, Table 2) with the shear strength $\Sigma_{\text{int}}$ of layers of faceted crystals in the intermountain snowpack of the Columbia Mountains. However, an effect of temperature gradient on shear strength is not expected since most of the temperature gradient data has magnitudes less than $1\degree\text{C/m}$.
Table 3. P-values for cross correlations between snowpack factors. Correlations are considered significant if $p < 5.0 \times 10^{-2}$.

<table>
<thead>
<tr>
<th>Age</th>
<th>HS</th>
<th>Load</th>
<th>H</th>
<th>$R_{wl}$</th>
<th>TG</th>
<th>Twl</th>
<th>Emax</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1E-01</td>
<td>3.1E-14</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8.9E-12</td>
<td>6.1E-20</td>
<td>1.0E-27</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.9E-02</td>
<td>6.2E-08</td>
<td>3.9E-07</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8.2E-04</td>
<td>2.1E-08</td>
<td>5.0E-09</td>
<td>9.0E-03</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4.8E-15</td>
<td>1.2E-04</td>
<td>4.7E-05</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8.0E-14</td>
<td>9.6E-03</td>
<td>4.5E-01</td>
<td>2.1E-04</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9.8E-19</td>
<td>1.5E-22</td>
<td>1.6E-12</td>
<td>3.9E-06</td>
<td>1.8E-03</td>
<td>1.7E-07</td>
<td>1.1E-04</td>
<td>-</td>
</tr>
</tbody>
</table>

The temperature gradient did not correlate with shear strength in continental snowpacks $\Sigma_{\text{cont}}$. Temperature gradients in continental climates fluctuate and may remain greater than $10^\circ\text{C/m}$ for months. As a result, weak layers of well developed faceted crystals form. After temperature gradients dissipate weak faceted layers are slow to gain strength because the crystals are large and they are under little load.

5.10 Maximum Crystal Size ($E_{\text{max}}$)

The maximum crystal size weakly correlated ($p = 3.2 \times 10^{-2}$, Table 2) with strength in both snowpack climates, but field workers regard it as an important property that affects shear strength. The positive correlation indicates that larger crystals have higher strengths. Both field and cold laboratory observations show increases in crystal sizes when faceted crystals are rounding (Johnson In preparation). This suggests growth of rounding faceted crystals is associated with strengthening.

5.11 Faceted crystal type

Faceted crystals are classified as solid faceted particles (4a) or faceted particles with rounding of facets (4c) based on the appearance of rounding (Colbeck et al., 1990). Field workers usually expect increases in strength when faceted crystals show signs of rounding (4c), not further faceting (4a). In each of the layers of faceted crystals from the Columbia Mountains, rounding was observed from mid-December throughout the winter. The layers from continental snowpack areas were not reported as rounding faceted crystals until mid-to-late March.

6.0 CONCLUSIONS

Load and thickness of the slab correlated most significantly with shear strength of layers of faceted crystals in intermountain and continental snowpack climates. These snowpack climates provide contrasts in load and thickness of slabs.

The slab thickness is associated with strengthening of layers of faceted crystals through its association with load and low temperature gradients. Thick slabs insulate weak layers of faceted crystals from cold air temperatures, causing warm weak layer temperatures and low temperature gradients.

Load had a greater correlation with shear strength in the intermountain climate than in the continental climate. The difference in correlations (Figure 4) shows that large loads cause faceted layers to gain strength quickly. Physically, more load pushes faceted crystals closer together resulting in increased density, number of contacts, and bond size.

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References


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