OBSERVATION AND MODELING OF A BURIED MELT-FREEZE CRUST

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ABSTRACT: Melt-freeze crusts often occur as a result of wet snow, rain or strong insolation. Past observations have revealed the formation of weak layers at their boundaries, even when the depth-averaged temperature gradient favours rounding. Research has, however, predominantly targeted temperature regimes dominated by kinetic growth. During the winter of 2007-2008 University of Calgary researchers undertook systematic observations of the early December melt-freeze crust that was present throughout much of Western Canada. The data gathered included ongoing measurement of the temperature gradient across the crust, snow load and shear strength. These observations were used along with meteorological measurements to drive the Swiss SNOWPACK model, a physically based single column model which simulates the evolution over time of a number of microstructural and mechanical properties of the snowpack. We present here the observations from the first year, initial efforts to identify parameters with the greatest influence on mechanical properties and results from model simulations.

KEYWORDS: avalanche forecasting, snow stratigraphy, snowpack modeling

1 INTRODUCTION

Melt-freeze crusts form throughout the winter in Western Canada as the result of rain, wet snow or solar insolation followed by freezing. These layers are often several centimetres thick and, depending on the snowpack, may persist for much of the season. A similar phenomenon is the temperature crust, which forms in warm conditions under cloudy skies. A review of mechanisms of formation is given by Jamieson (2006). Stiff crust layers may concentrate shear stress (Jamieson, 1999) or indeed may bridge a weak layer below. Substantial historical observations (e.g. Atwater, 1954) document the ability of buried crusts to act as a bed surface for large avalanches throughout the season. Perhaps more importantly, in areas of high snowfall their increasing depth makes long term observation and prediction difficult.

A number of lab and field-based studies have been undertaken to observe the effect of crusts on the surrounding snowpack. Colbeck (1991) published one of the first comprehensive reviews of the effects of a layered snowpack, including the breakdown of crusts under high temperature gradients. In addition, he attempted to explain from a theoretical standpoint facet growth below impermeable crusts. Colbeck and Jamieson (2001) gave a theoretical framework for the growth of facets above a wet layer.

A number of authors (e.g., Brown et al., 2001; Miller et al., 2003) have more recently attempted to model snow metamorphism under generalized thermal conditions. Implementation for the purpose of operational modeling has so far been limited to techniques that treat kinetic (or temperature gradient-driven) metamorphism separately from equilibrium (low temperature gradient) metamorphism. Several lab studies (Adams and Miller, 2002; Adams et al., 2001) have employed a scanning electron microscope to observe changes in bond and crystal growth under a variety of conditions. Jamieson and van Herwijnen (2002), Jamieson and Langevin (2004) and Jamieson and Fierz (2004) have conducted observational and lab-based experiments targeting facet growth at the interface of dry snow overlying wet snow. Greene (2007) conducted a detailed lab-based analysis of the effects of impermeable crust layers at high temperature gradients. Among his recommendations was that metamorphism at layer boundaries and dominated by sintering be more adequately addressed. Long-term observations of snow metamorphism near crusts and under low temperature gradients, typical of a deep snowpack, are lacking.

The goals of this study are twofold: Systematic observations of a number of melt-freeze crusts will be recorded throughout the winter, including tests of stability, shear strength, presence of ice lenses or laminations and spatial continuity of these features. These observations will

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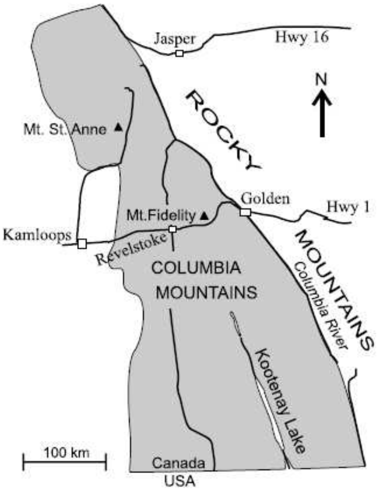

Figure 1: *Map of the study area.*

be used to identify parameters important to the evolution of buried crusts. This will facilitate the second goal, which is modeling of such crusts including features such as laminations and disaggregation (localized in-situ fracturing of bonds, sometimes but not always associated with faceting). Throughout the winter of 2007-2008 University of Calgary researchers at Blue River and Rogers Pass, British Columbia undertook such observations and began modeling a layer that formed on 5 December 2007. In this paper we report on results thus far as well as plans for the coming winter seasons.

2 CRUST FORMATION

On 4 December 2007 a mass of warm moist air from over the Pacific Ocean (often referred to as a "Pineapple Express") crossed into British Columbia. In central portions of the province the frontal passage was marked by a low level inversion while southern portions of the province experienced an elevated freezing level. Precipitation amounts and types varied; however most regions experienced either rain, freezing rain or wet snow. By late on the 5^{th} a ridge began building off the coast of BC. This brought cold temperatures and clear skies to most of the province and allowed the crust to form, often with a thickness of 10 cm or more. In the Columbia Mountains this crust remained an identifiable feature until at least the beginning of April 2008.

Although the date of formation varied throughout the study area, this layer is referred to in this paper as the 5 December crust. Temperature and hourly liquid precipitation from Mt Fidelity in Glacier National Park are shown in Figure 2. A period of warm air and moderate precipitation occurred throughout the latter part of 4 December, followed by cooler temperatures and more precipitation throughout the 5^{th}. Wind speeds in this sheltered plot were generally light throughout the period of formation, averaging 0.5 m/s from the SE during the 4^{th} and veering to the SW then W with increasing windspeed as the cold air moved in. It is important to note that these winds were likely not representative of conditions at all locations discussed in this paper. A high degree of variability was often observed between several Parks Canada weather stations located throughout Glacier National Park.

3 METHODS

The 5 December crust was tracked at a number of locations within the two broad study areas shown in Figure 1. From 2 January until 29 March the crust was studied by means of shear strength tests, stability tests, buried thermistors and photographs.

At Mt Fidelity, two pairs of thermistors, each spanning 10 cm, were inserted on 14 January above and below the crust to monitor the bulk temperature gradient across the layer. The location chosen was at an elevation of 1865 m, with slope of 35°and ENE aspect. Initially the crust at this location was at a depth of 140 cm and had an ice lens at the lower boundary. This site was re-visited approximately once every seven days until the end of February. During each site visit the pit was dug back by a minimum of 1 m and a set of manual observations was recorded including temperature, crystal type and extent, density and hand hardness. An overburden sample was taken using a coring tube with inside cross-sectional area of 28.3 cm^3. This was used to calculate an approximate load at the top of the crust. The presence or absence of an ice lens as well as degree and spatial extent of faceting above, within or below the crust was noted. Photographs of thin sections of crust were attempted though in many cases were not possible due to heavy disaggregation within the layer. In this paper, disaggregation refers to the localized weakening and breaking of bonds within the crust before extraction of samples. It was often, but not always, observed in the presence of faceted crystals.

A minimum of 12 valid shear tests were conducted on each visit using a 250 cm^2 shear frame. Snow was removed parallel to the upper boundary of the crust until just enough remained to place the frame, allowing for a 5 mm space above the crust itself. A 30N pull gauge was used to pull the sample to failure in a smooth motion lasting less than 1 s and the maximum force was recorded along with fracture character. Any failures judged to have been non-planar were rejected. A correction was applied based on the size of the shear frame, after Sommerfeld (1980).

A number of stability tests including the deep tap test, rutschblock test and compression test were performed as outlined in the Canadian Avalanche Association's Observational Guidelines and Reporting Standards (CAA, 2007). A number of extended column tests (ECT,

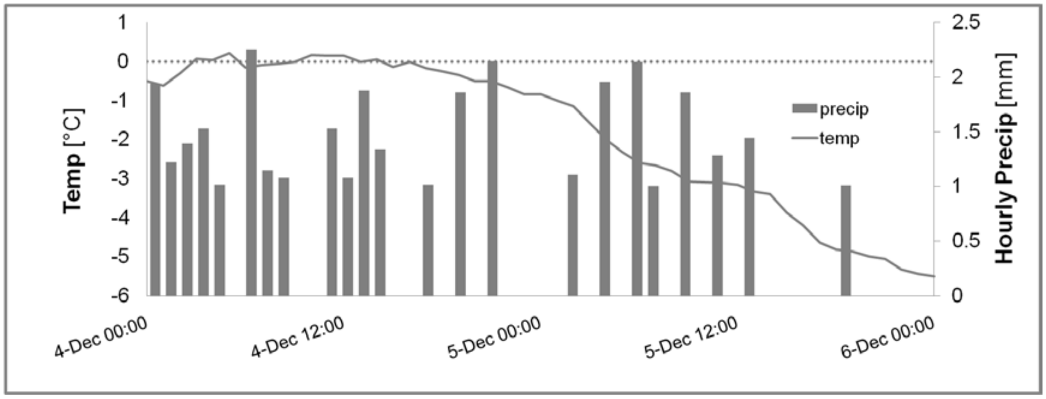

Figure 2: *Temperature and liquid precipitation during 5 December 2007 crust formation.*

Simenhois and Birkeland, 2007) and propagation saw tests (PST, Gauthier and Jamieson, 2008) were also performed. The PST provided the most complete record of all snowpack tests as it is easy to perform on deep layers. Snowpack tests and profiles were also performed at a number of field sites throughout Glacier National Park and near Blue River, BC in the Columbia Mountains.

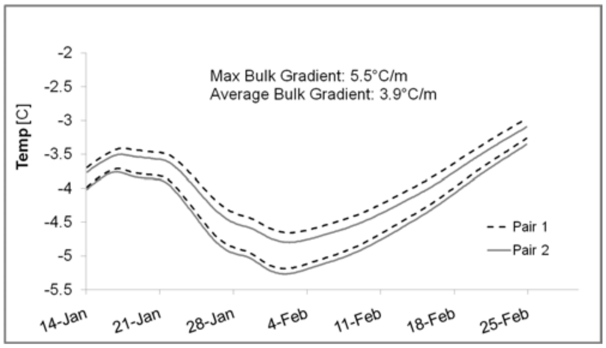

Figure 3: *Time series of temperature above and below 5 December crust.*

4 RESULTS

Owing to small sample sizes and autocorrelation among certain data sets, many of the results reported below are qualitative rather than quantitative. A time series of temperatures above and below the crust, used as a proxy for water vapor gradient, is shown in Figure 3. The average and maximum bulk temperature gradients are well below that required for kinetic growth. A simplified calculation assuming saturated conditions over ice shows that the maximum vapor gradient would be 1.8 hPa/m, which is also below the threshold for kinetic metamophism. Because the crust thickness varied somewhat the thermistor temperatures do not always correspond exactly to the top and bottom of the layer. Based on manual observations at the same site the error in the bulk temperature gradient is likely negligible.

Jamieson (2006) notes that crust thickness and structure may be a function of elevation, slope and aspect. A correlation of 0.53 ($n=13$, $p \leqslant 0.05$) between aspect and thickness was found in the subset of slopes >29°. Data in this subset came from 5 different locations whose snowpack characteristics (specifically snow depth) varied widely; this should act to mitigate the effects of autocorrelation. Analysis of the subset of data from the elevation range 1800m – 1900m (not shown) revealed a relationship between aspect and crust thickness, with greater thicknesses on East and Southeast aspects. In south-facing slopes at elevations between 1600 m – 2200 m the crust increased with elevation. No strong relationships between crust thickness and slope angle were found in any of the data subsets. The possible skewing of results by the high proportion of measurements at Mt. Fidelity (15 of 30) was addressed by testing all other records separately; No significant change was recorded in strength of the relationships.

A total of 5 days of shear frame data were analyzed, comprising 59 valid tests. The distribution of shear strength (σ) is shown in Figure 5. Three of the five days have little spread in results while the remaining two show a relatively large degree of variability. It should be noted that all pulls on 14 February were of marginal quality; typically the majority of pulls on other days yielded clean (planar) shears. Shear strength variance is plotted against load and crust age (number of days since freezing) in Figure 4.

Load ($\rho g h$ [Pa]) was found by dividing the average sample weight by the cross-sectional area of the core tube. Average shear strength from each day is plotted against snow load and crust age in Figure 6. Both relationships are moderately strong and positive but statistical significance cannot be judged because all data come from one location and are autocorrelated. The strong relationship between shear strength and load was reported previously by many authors (e.g. Jamieson et al., 2001). The bulk

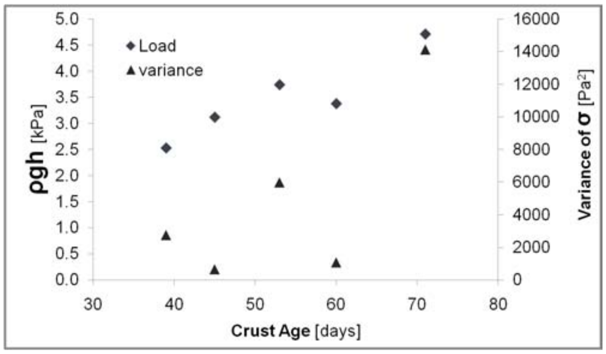

Figure 4: *Time series of load and variance of shear strength.*

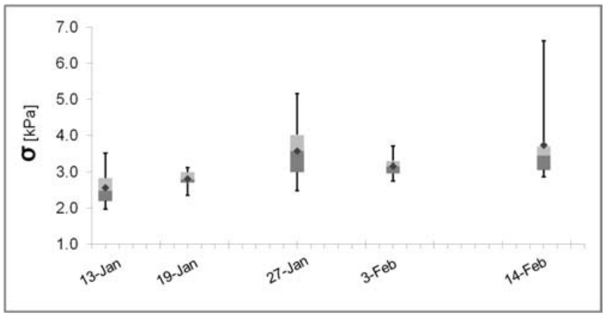

Figure 5: *Box whisker plot of all valid shear pulls.*

temperature gradient (not shown) had a moderately positive relationship with average shear strength while crust temperature did not. The possibility of a relationship between lagged temperature gradients and shear strength was also examined using thermistor data; the strongest relationships all occurred at a lag of 0 days. The average strengthening rate $\Delta\sigma/\Delta t$ is plotted against average loading rate $\Delta\rho g h/\Delta t$ and rate of change of the bulk temperature gradient in Figure 7.

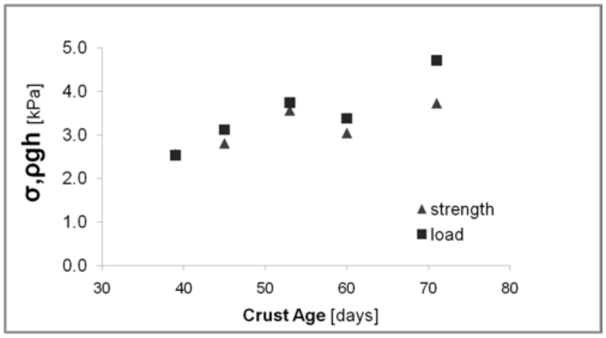

Figure 6: *Time series of average shear strength and load from Fidelity Study Slope.*

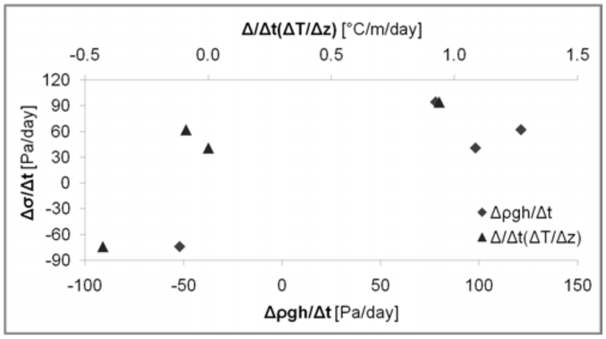

Figure 7: *Average strengthening rate plotted against average loading rate and change in bulk temperature gradient.*

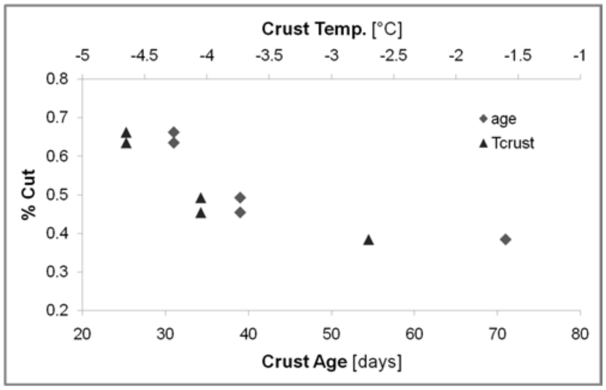

Figure 8: *Mt. Fidelity study slope PST: % cut plotted against crust age and temperature.*

A total of 57 propagation saw tests were performed on the crust, 48 of which resulted in a propagation to the end of the isolated column; 8 had propagations that arrested before reaching the end of the column and one, on 27 February, propagated a short distance before the slab fractured vertically. Results were not categorized by location of the saw cut (top, middle or bottom of crust) since generally the cut was made wherever the snow appeared weakest. All results were examined as a whole as well as by sub-region and specific slope. The PST test dictates that the length of the isolated column is either 1 m or the depth of the weak layer in question; because of this the percent of column cut was used to evaluate all results, and only those tests that produced a failure to end were included. The Blue River PSTs had a correlation of 0.74 (n=26, $p \leqslant 0.01$) between % cut and load. A series of 5 tests from the Fidelity Study Slope had moderate to strong relationships between % cut and load, temperature gradient, crust age and weak layer temperature. The latter two are plotted in Figure 8. As with shear strength results, these relationships cannot be assessed for statistical significance due to autocorrelation.

Compression tests (CT) and extended column tests (ECT) were discontinued as the crust became deeply buried. Of 24 compression tests performed at Rogers Pass over a period of 28 days, 8 resulted in failures. No definitive relationships were found when examining

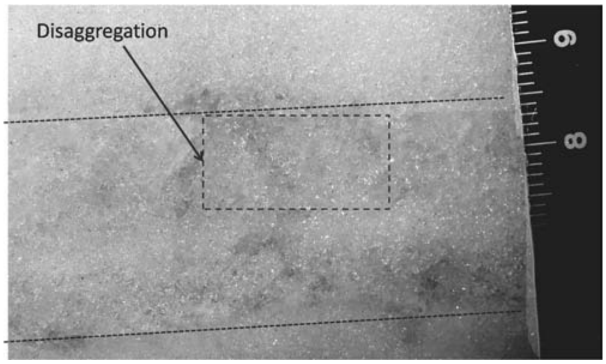

Figure 9: *Crust disaggregation on 31 January 2008.*

the entire dataset; however several relationships emerged when examining subsets. Failures East of the pass, comprising 6 tests from 3 locations, had a moderately strong positive relationship between crust age and taps to failure. A subset of 8 tests from 5 different locations had a Spearman rank coefficient of 0.73 ($p \leqslant 0.05$) between crust age and location of failure as it progressed from the top to the interior of the crust, with one failure on the bottom midway through the winter. Insufficient data exist for a similar analysis on PST results; however, there were a number of occasions when propagations jumped either into or out of the crust. Results from the extended column test and deep tap test produced no useful relationships, for the most part due to a paucity of failures.

Qualitative visual observations may be useful in explaining trends observed in data. In addition to shear and stability tests, written notes were kept, tracking crust properties including disaggregation, interior faceting, presence of ice lens and spatial continuity of features. Figure 9 shows an area of disaggregation on 31 January. Relatively discontinuous pockets of faceting and disaggregation were observed as early as mid-January. The crust at Kicking Horse, where the snowpack was only 1 – 2 m deep, quickly decomposed and became difficult to discern. Some of these observations are tabulated in Table 1. Sufficient areas of weakness developed to allow propagating failures within the crust in compression tests and PSTs. Figure 10 shows an ice lens within a 10 cm thick crust. Lenses were observed at a number of locations and were not usually spatially continuous beyond several metres.

5 DISCUSSION

The temperature gradient over 10 cm was below that required for faceting in all of our observations and the assumption in these analyses is that all observed changes occurred under similar gradients. Theory does, however, suggest that high temperature gradients are possible over very small distances at the boundary of an impermeable, or semi-impermeable layer. The observational methods used in this study did not allow for the resolution of such gradients. The caveat of small sample size also applies to all results discussed here.

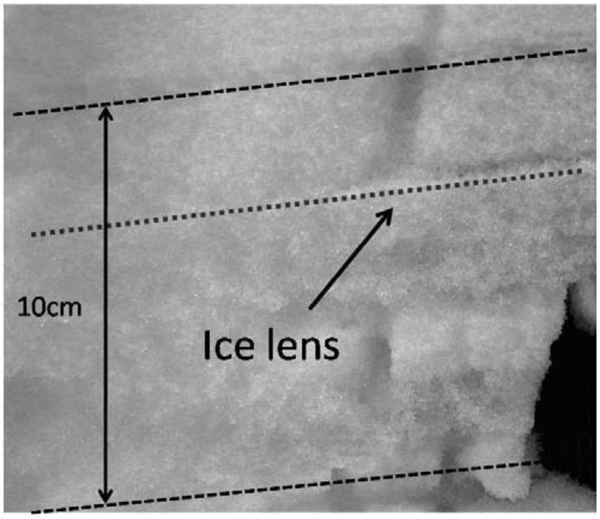

Figure 10: *Ice lens visible within 5 December crust.*

The lack of a strong relationship between crust thickness and aspect makes sense given the light winds recorded at Mt. Fidelity: No aspect would have been preferentially exposed to more intense precipitation. The very weak relationship with slope is somewhat surprising; if freezing rain was responsible for the crust, steeper slopes should have thinner layers; however, this was not observed. A number of other factors may mitigate the effect of slope including permeability of the existing snow layer, type and spatial variability of precipitation. South aspects, taken as group, had a moderate relationship between elevation and crust thickness, possibly indicative of heavier precipitation at higher elevations or of an upper inversion. Thickness and crust age were compared for the fixed study site on the Fidelity study slopes. The weak correlation at that location hints that spatial variability may be more important than temporal variability for this particular layer.

Shear strength and its variance in this study are related to load and crust age. The upward trend of variability in time may be due to the discontinuous pockets of disaggregation and faceting that were observed. These in turn may have been caused by percolation channels within the crust. The relationship of shear strength with the manual temperature gradient is moderately strong; this may suggest importance of large gradients over smaller distances, or simply that it is a less important parameter for prediction of shear strength. Likewise the lack of a relationship with time-lagged bulk temperature gradient may be attributable to either the physical scale of measurement or to the fact that significant evolution in strength occurs over periods of less than 24 hours. The importance

Table 1: *Summary of structural observations on 5 December crust.*

Location	Date	Observations
Fidelity Study Slope	13 Jan	Ice layer at bottom of CR
Fidelity Study Slope	27 Jan	Variable hardness P to K
Fidelity Study Slope	14 Feb	FC sz. 1.5 within: variable hardness 1F
Fidelity Poetry Slope	28 Jan	Ice lens at bottom of CR
Fidelity Poetry Slope	12 Feb	No ice lens, FC 1-1.5 at top of CR
Fidelity Poetry Slope	29 March	Decomposing CR & FC sz. 1-1.5
Kicking Horse Mountain Resort	11 Jan	Decomposing
Kicking Horse Mountain Resort	15 Feb	Possible remnants of CR

of load to shear strength is reflected in the relationships of load with average shear strength and average loading rate with average strengthening rate.

An attempt to find patterns in the different snowfall regimes on the East and West side of Rogers Pass did not yield any stronger results; however, the consideration of the subset of tests from the Fidelity Study Slope revealed strong relationships with several parameters including crust age and load. The existence of these relationships may be due to the fact that tests were performed close together on one small slope, negating some effects of spatial variability. Higher load, older crust and warmer layer temperature all relate positively to increased propagation potential (propagation to the end of the column with a lower % cut) while an increasing temperature gradient is related, though not as strongly, to decreased potential. The weaker relationships with temperature and gradient indicate that load and slab thickness are more important to propagation potential; in the absence of other influences one would expect a cooler, stiffer slab to act as a stress concentrator, increasing propagation potential. It is important to note that the range of temperature gradients and crust temperature were small; 3°C/m to 5°C/m and -2.7°C to -4.7°C respectively.

Similar to PST results, CT tests did not show any notable trends when taken as a group; however the examination of subsets led to potentially useful conclusions. Most promising is the correlation between age and location of failure, which shifted from the top of the crust to the interior of the crust as it aged. This result fits well with qualitative observations of increasing disaggregation and faceting within the crust as it aged. Unfortunately, these tests extend over only one month, with the first occurring almost a month after crust formation. Nevertheless the relationship is worth re-examining as datasets become more extensive.

The observations tabulated in Table 1 fit well with snowpack tests as they indicate an increasing complexity and weakening of crust structure. The shallower snowpack at Kicking Horse allowed the crust to facet much more quickly than at Rogers Pass. By late February it had become difficult to discern from surrounding layers. Ice lenses were observed at many locations throughout Rogers Pass; in some cases up to 3 were present throughout the crust layer. Areas of faceting and disaggregation were not generally continuous and existed on the scale of 10–20 cm throughout the winter. Jamieson (2006) proposes a process whereby a laminated crust may develop over time under relatively low temperature gradients due to preferential deposition of water vapour in smaller-grained snow. Obvious laminations were not observed in this study, but the presence of an ice lens at many locations suggests the possibility that such a process may have been responsible for locally high temperature gradients as percolating water froze, leading to some of the faceting that was observed within the crust.

Overall these results, though limited, show good agreement between qualitative and quantitative observations. Load and crust age are most consistently related to strength at the top of the crust, stability and propagation propensity while other factors such as rate of loading, temperature gradient and crust temperature only appear to be related to specific crust parameters. The crust at all locations trended toward stronger bonding at its top and bottom interfaces while simultaneously experiencing disaggregation and faceting in its interior.

6 THE SNOWPACK MODEL

The SNOWPACK model (Bartelt and Lehning, 2002; Lehning et al., 2002a,b) is a single-column physically-based model that models evolution of microstructural and mechanical properties for a given snowpack. Snow is treated as a 3-component heterogeneous mix of ice, water and air. Sintering, faceting, settling and heat transfer are all modeled. Numerous options exist for inputs; for this application longwave and shortwave radiometers, air temperature and wind speed were used to drive model processes. Snow depth may be constrained with an additional sensor; however, this was not available at Fidelity so snow water equivalent was used instead. Initialization was done using data from a manual profile. SNOWPACK has been used by numerous groups around the world (e.g. Greene, 2007; Hirashima et al., 2008; Lundy et al., 2001) with reasonable success and is presently used in as part of the Swiss avalanche hazard forecasting effort.

SNOWPACK uses manual profiles to perform a statistical evaluation of model results (Lehning et al., 2001) and also includes a stability index calculation (Schweizer et al., 2006). However, this was not used for the present study.

7 RESULTS

The SNOWPACK model was initialized from a Parks Canada profile dug 11 November 2007 adjacent to the Mt. Fidelity meteorological instruments. Unfortunately, surface meteorological measurements were not adequate for the model to reproduce the formation of the 5 December crust. There are a number of possible reasons for this, the most likely being that precipitation was warmed due to an upper level inversion. This represents a weakness in the model configuration; however the reality is that adequate information to overcome this hurdle is not available at most locations. A second run was initialized from a profile dug 2 December and stopped on 4 December. The resultant model profile was then slightly modified to include wet snow and rain on the upper layers. SNOWPACK was restarted and the new crust layer was allowed to freeze; the new run was allowed to proceed until 27 March 2008. A number of artificially-imposed crusts were tested. No one attempt reproduced all of the characteristics observed by Glacier National Park crews on 15 December.

Based on the analysis from Section 4 a number of output parameters can be examined for accurate reproduction of observations. A total of three Parks Canada profiles were available at the Mt Fidelity location: 15 December, 13 January and 7 March. Although more profiles would be desirable these dates are useful as they represent the short-term metamorphism of the crust, behaviour during subsequent loading and structure after 3 months of ageing. The statistical comparison module allows comparison of the entire modeled snowpack with observations; results for some important parameters are shown in Table 2.

The score of 'n/a' for temperature comparison on 15 December indicates that values were too poorly reproduced to assign a score. This is not surprising since the crust was artificially imposed. Temperature is well-modeled for January but the score becomes relatively poor by March. This was shortly after a period of strong warming. Density is generally well-modeled. The grain type score, which is determined from a matrix of all possible grain types, (Lehning et al., 2001) slowly improves as the influence of the artificially-imposed crust diminishes in the overall snowpack. The ratio of model snow height/observed snow height is near unity indicating that the algorithm for estimating new snow density from measured snow water equivalent functions well. This, coupled with the good modeling of layer density, indicates that the settling routine is also effective.

Simple ratios of modeled/observed properties are given in Table 3. Model performance when considering just the crust is relatively poor. Specifically, density is closest to observed values on 15 December, the same time when this layer is presumably responsible for the poorest overall score (Table 2). SNOWPACK modeled an increase from 380 kgm^{-3} on 15 December to 470 kgm^{-3} on 13 January. The observed densities on these two days were 320 kgm^{-3} and 295 kgm^{-3}. The model temperature gradient is higher than observed on the same day and remains slightly higher than measured values throughout. The increasing ratio of grain sizes was mainly due to disaggregation and faceting leading to smaller observed, but not modeled, grain size. The load is quite consistently well-modeled. This is encouraging given the strong correlation with shear strength identified in Section 4. From these limited results it appears that SNOWPACK does a good job in modeling many aspects of snowpack structure; however in this case it was not able to reproduce observations of the crust. The 5 December crust had a complex, spatially discontinuous structure; some of the factors leading to its formation were likely due to 2-dimensional processes that cannot be implemented in a 1-dimensional model. The artificial imposition of the crust almost certainly led to some errors that propagated through the model results.

8 FUTURE WORK

The results from the first winter of work have suggested a number of improvements and new observations that may be useful for the future. A number of potentially important physical parameters have been identified from observations taken during winter 2007-08. First, these must be supplemented by more data as at present sample sizes are very small. Although fixed sites were already selected for thermistors and shear frames, this should be expanded to include snowpack stability and propagation tests. A large gap in data exists between the formation of the 5 December crust and the first detailed observations. The time during and immediately after formation is especially important to observe since the crust is likely exposed to higher temperature gradients.

The poor modeling of crust evolution may be attributed to a number of factors, but given SNOWPACK's good performance when considering the snowpack as a whole, there is likely a structural problem with model treatment of the thick melt-freeze crust. Long term systematic observations of evolution at low temperature gradients are currently lacking and a set of experiments under controlled conditions in a cold lab would help to remedy this. SNOWPACK is a physically-based model and it is important that any changes have solid grounding in theory and are not simply empirical formulations.

Finally, photography is very useful for a record of characteristics that are not necessarily captured by quantita-

Table 2: *Model scores for reproduction of observed snow profile.*

Date / Parameter	Temperature	Density	Grain Type	HS
15 Dec	n/a	0.84	0.63	0.91
13 Jan	0.96	0.89	0.68	0.96
7 Mar	0.69	0.95	0.76	1.01

Table 3: *Model reproduction of important parameters (ratio SNOWPACK/observed) for the 5 December crust at Mt. Fidelity.*

Date / Parameter	Temperature	$\Delta T/\Delta z$	density	grain size	ρgh	lyr thick
15 Dec	1.51	5.69	1.18	1.00	0.88	0.77
13 Jan	1.66	1.27	1.59	1.52	0.99	1.36
7 Mar	2.00	2.47	1.52	2.05	1.21	1.31

tive testing. The photographic record of the 5 December crust is severely lacking. More effort must be expended in coming seasons to ensure a continuous series of useful crust photographs.

9 SUMMARY

This paper has summarized observations of the 5 December crust performed by University of Calgary researchers in the Columbia Mountains during the winter of 2007-08. Notable observations include increased variability in crust properties and interior faceting as the crust aged. The temperature gradient averaged over 10 cm remained low, indicating conditions favorable to rounding rather than faceting. Although theoretical explanations exist for such behaviour they have never been tested under controlled circumstances. Analysis presented here has identified a number of physical parameters that are potentially important to this observed evolution in structure, stability and shear strength. A number of suggestions are made for improvements in methods as well as the inclusion of cold lab experiments. As the quantity of observations grows and more definitive conclusions may be drawn, the data may be used to modify crust behaviour within the SNOWPACK model.

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