TRACKING MELT-FREEZE CRUST EVOLUTION

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Melt-freeze crusts are one of the most critical layers for slab avalanche formation. These layers usually undergo complex metamorphism and associated snow cover stability may increase or decrease over time. Typical field observations are of a subjective nature and hence tracking changes to these layers can be inconsistent amongst multiple observers. In order to improve the way melt-freeze crusts are observed we present three tracking systems used over the 2011-12 winter season: a set of quantitative measurements, a simple new crust index (CI), and the use of a thermal imager. During the winter season 2011-12, six melt-freeze crusts were tracked over time with these methods in the Columbia Mountains, British Columbia, Canada. The physical properties of a melt-freeze crust can be best described using a set of quantitative measurements - shear frame, push gauge and density – but these may be operationally impractical. The crust index consists of two parts: the first part describes the bonding at the upper and lower interface of a melt-freeze crust; the second part describes the internal lamination or bonding within the crust. In addition, a thermal camera was used to measure small scale temperature gradients. This allowed us to monitor changes in the temperature gradient over time above and below melt-freeze crusts.

Keywords: melt-freeze crust, snowpack evolution, persistent weak layer, Columbia Mountains, thermal imaging, crust index

1. INTRODUCTION

Melt-freeze crusts can be a critical layer for slab avalanche formation. In the Columbia Mountains of British Columbia, Canada, 32% of natural avalanches are in some way associated with melt-freeze crusts (Haegeli and McClung, 2003). These crusts form by rain, solar radiation, or warm air causing the surface of the snow cover to melt and then subsequently refreeze. This process causes the density and hardness of the layer to increase, and porosity to decrease. Two important properties of melt-freeze crusts can lead to avalanche formation. The first is near-crust faceting which is caused when dense, less permeable crust layers cause localized changes to the temperature and vapour gradients within the snowpack (Jamieson, 2006). The second is that applied stresses in the snowpack are concentrated at these hard, dense layers which can lead to avalanche release (Schweizer and Jamieson, 2001; 2003). However, a well bonded crust can have the opposite effect, bridging applied stresses that would otherwise reach deeper layers within the snowpack (Habermann et al., 2008).

While the nature of melt-freeze crusts and their role in avalanche formation have long been recognized (Horton, 1915; Seligman, 1936; Atwater, 1954), there is a lack of information on how the properties of these crusts change over time. Smith and Jamieson (2010) used a near infrared camera to track the evolution of specific surface area of crusts over weeks in a deep snowpack.

Traditional observations and methods used to measure the properties of a snow cover are an effective way to describe the snow cover at a point in time or to track general trends. Unfortunately they lack the detail required to effectively track changes to thin layers such as melt-freeze crusts. We used several methods, including two new ones, to measure crust properties. The shear strength of snow has long been measured using the shear frame test (Jamieson, 1995). The resistance or hardness of snow can be measured using the thin-blade hardness test (Borstad and McClung, 2011). Detailed temperature profiles can be captured using a thermal camera (Shea et al., 2012). This paper summarizes the application of these methods to the tracking of melt-freeze crust evolution.

2. METHODS

Regular study areas were established on Mt. Fidelity located in Glacier National Park, British Columbia, Canada, and on Mt. St. Anne near Blue River, British Columbia, Canada (Figure 1). Both of

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the study areas have been used in previous studies and are considered representative of the Columbia Mountains snow climate (Jamieson et al., 2001; Haegeli and McClung, 2003).

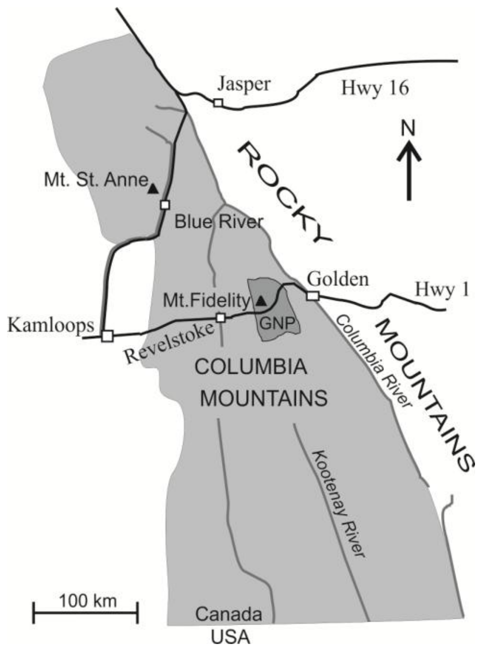

Fig. 1: Map of the Columbia Mountains, British Columbia, Canada. The primary study areas for this project were Mt. St. Anne, located near Blue River, British Columbia, and Mt. Fidelity, located in Glacier National Park (GNP), British Columbia.

2.1 Site Selection

Selection of good evolution sites within the study areas requires meeting several criteria to minimize spatial variability of the snow cover at a slope scale. The first important site property is a planar slope to ensure consistent melt-freeze crust formation. A planar slope minimizes the variability associated with changes in slope angle and slope aspect. Another important site property is exposure to sun and wind. Constant exposure to sun is important to sun crust formation and we aim to minimize variations in sun exposure by selecting sites with limited tree shading. Exposure to non-uniform wind sources causes variations in the surface energy balance and causes variability in snow loading which changes the properties of the snow cover. Non-uniform wind also causes variability in the formation of rain crusts. To reduce the effect of non-uniform wind we selected sites with limited tree shielding on the windward side of the site. We also avoided areas with non-uniform wind loading such as areas in lee of ridges. These methods require some observation prior to selection, especially during windy periods. The last important criterion is available space. For our weekly field measurements, at least 100 m² of representative snow cover was required to ensure an adequate number of profiles could be dug throughout the season. The profiles occupy roughly 1.5 m x 2 m area with at least 1 m spacing between profiles.

2.2 Field Observations

The data collected during each observation includes field weather data, basic snow properties around the crust, density measurements of the crust, thin-blade hardness, shear frame tests, thermal photos, and compression tests. In addition to these established methods, a new set of observations called the crust index (CI) were recorded during each site visit. Our field weather, snow layering observations, and compression test methods followed the Canadian Avalanche Association observation standards (CAA, 2007).

Density was measured by isolating a block of crust using a small saw, measuring the length of the three sides, and weighing the sample. During the 2010-2011 winter a single density measurement was taken. This was increased to three samples for the 2011-2012 winter to reduce uncertainty.

The thin-blade resistance test was developed to be applied slope parallel to snow cover layers (Borstad and McClung, 2011). The primary variability of hardness within a crust is normal to the slope and the layers are often thin, making the thin-blade resistance test difficult and more subjective in the slope parallel direction. The test was modified to be done normal to the crust layer. The snow above the crust was removed and 14 tests were performed for each site visit. A 10 cm paint scrapper attached to a force gauge measures the maximum force for each test. Testing slope normal effectively measures the resistance of the hardest part of the layer. During each test the resistance of the layer below the crust was tested to ensure it was less than the crust so as to not bias the results. Once the layer below had a similar resistance to the crust, the test was no longer performed.

The shear frame test methods follow those established by Sommerfeld (1984) with the use of a 250 cm² shear frame and 12 tests being performed for each observation. This test is only applicable to the upper interface of the melt-freeze crusts.

The use of the thermal camera follows the methods established by Shea and Jamieson (2011) and Shea et al. (2012). A FLIR B300 thermal camera was used with a resolution of 320 x 240 pixels. The basic method was to excavate a planar pit wall and take the photos within one minute of exposing the pit wall. Creating a planar wall can be difficult, especially with a brittle crust. Initially the crust was used as the spatial reference, but later other methods were attempted. This includes using a ruler in the edge of the photo, inserting a crystal screen into the wall normal to the crust, and making two marks with a warm tool or finger and recording the spacing. The latter works best as the markings on the ruler can be difficult to see and the thermal boundaries of the crystal screen can become blurred. All spatial marking methods involve some uncertainty and we attempt to account for this uncertainty in the analysis. Temperature gradients within the snow are subject to diurnal effects and we aim to reduce this effect by taking all the photos at the same time of day, typically between 10am and 12pm.

2.3 Crust Index

The crust index is an ordinal classification meant to enhance repeatability amongst observers for common observations of melt-freeze crusts. There are two primary scales used with the crust index. The first scale describes the bonding at the upper and lower interfaces and the second describes the internal lamination of the melt-freeze crust. Each scale has five definitions which are shown in Table 1. The index also includes six attributes which are used to ensure the consistency of the observations and reduce variability during analysis. These attributes describe the horizontal and vertical variability, planar or non-planar upper and lower interfaces, existence of an ice lens, and existence of near-crust faceting. The crust index is based on common observations recorded as notes throughout the 2010-2011 field season.

2.4 Thermal Imaging Analysis

The thermal camera produces a raster image of temperature data with each pixel having a single value. When taking thermal photos with the FLIR B300 approximately 40 cm from the pit wall, the pixels represent roughly 0.25 mm² (0.5 mm x 0.5 mm). There is inherently uncertainty associated with taking thermal photos at this scale. This includes ability of the operator to create a smooth pit wall, orientation of grains along the pit wall, orientation of the camera relative to the pit wall, heat exposure from the operator, exposure time after excavating the pit wall, and the ability to interpret the spatial reference in each photo. In order to reduce some of this uncertainty, five transects were taken from each image. These transects – a single line of pixels - were selected perpendicular to the crust as shown in the example in Figure 2a. These lines were placed on the photo where the temperature gradient appeared the least disturbed and generally where the gradient appeared strongest. The data extracted from these lines produce a temperature profile like the one shown in Figure 2b. From this temperature profile three variables were calculated including the average upper temperature gradient (UG), the average lower temperature gradient (LG), and temperature difference (TD) between the crust and the average of the snow above and below. The

Table 1: Crust Index definitions. The interface bonding describes the bonding between a melt-freeze crust and the layers above and below. The internal lamination describes the bonding between grains within a melt-freeze crust.

Interface Bonding		**Internal Lamination**	
1	Little to no bonding between layers, clean separation with minimal shearing force	**1**	Little to no bonding. Very difficult or not possible to handle without breaking / crumbling.
2	Poorly bonded, separates easily, fractures with light pressure, light brushing may be required to isolate crust layer	**2**	Bonds between individual ice grains are discernible, but not strong or extensive. Difficult but possible to isolate block. Sample crumbles easily.
3	Moderate bonding, requires hard brushing or very light scraping to isolate crust layer	**3**	Bonding between individual ice grains is moderate. Bonds are discernible and hold the sample together with light handling. Sample crumbles slightly with light handling.
4	Well bonded, requires light to moderate scraping to isolate crust layer	**4**	Well bonded. Sample has strong bonding between individual ice grains. Sample maintains shape with handling and cutting. Sample has a tendency to break rather than crumble when handled roughly.
5	Very well bonded, difficult to separate layers, requires hard scraping or saw to isolate crust layer	**5**	Sample is almost completely bonded. Bonds and grains are difficult to discern as the sample is nearly uniform. Pure ice would be 5+ as it would be entirely bonded. Sample does not crumble, but rather breaks if loaded to failure.

extraction of the data from the temperature profiles involves some subjectivity. For the upper and lower gradients, we determined the deflection point where the influence of the crust ceased. The gradient was then calculated from this point to the maximum or minimum temperature of the crust, depending if the crust is warmer or colder than the surrounding snow. The temperature difference was determined by drawing a line through the upper and lower deflection points and measuring horizontally from this line to the maximum or minimum temperature of the crust.

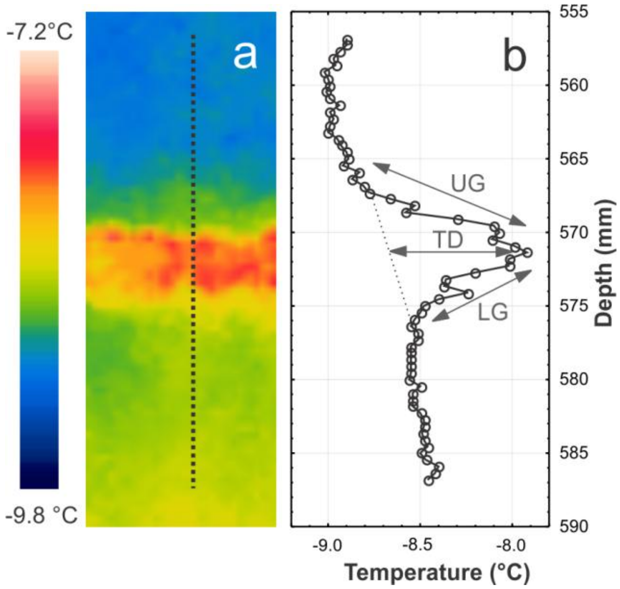

Fig. 2: A thermal image from 11 January 2012 of the 3 January 2012 freezing rain crust (a). The pixels along the transect line produce the temperature profile (b). The average upper temperature gradient (UG) and average lower temperature gradient (LG) were calculated from the upper and lower deflection points and the maximum temperature. The temperature difference (TD) was measured from the maximum temperature and the line connecting the upper and lower deflection points.

3. DATA

During the 2011-12 winter a total of six melt-freeze crusts were tracked at the two study areas. This includes four sun crusts, one freezing rain crust, and one rain crust. Table 2 shows the crusts observed during the 2011-12 season including the number of unique observations for each crust. Density evolution data was also collected for two sun crusts and one rain crust during the 2010-11 winter. Thermal images were taken for two crusts. The 3 January 2012 freezing rain crust includes seven thermal observations and the 9 February 2012 sun crust includes eight observations.

4. RESULTS

For the seven melt-freeze crusts with density evolution data, five showed an increase in density over time while dry. Once the presence of free-water was noted in or above the crust, the density increased substantially and the density measurements were excluded from the time series. All four of the shear frame time series show an increasing trend with time and three of these crusts show an increase in upper bonding index (CBu) while one remains constant. Only one of these crusts underwent near-crust faceting, but this faceting occurred at the bottom of the crust where the shear frame test was impractical. Of the six crusts with thin-blade resistance data, four crusts showed increasing trends. One of the crusts that showed a decreasing trend was a rain crust below treeline and the other was a sun crust at treeline that showed a higher than average variability between measurements. At our deep snowpack study plots, crusts typically increased resistance over time, which is expected to increase bridging. Of the six crusts, two showed increasing trends in crust lamination index, three showed decreasing trends, and one remained constant.

The 3 January freezing rain crust initially showed strong temperature gradients compared to the 9 February sun crust where only weak temperature

Table 2: Data collected during the 2011-12 winter season. For density, shear frame test, thin-blade resistance, and crust index, the value in the table indicates the number of days on which the property was observed.

Crust ID	Study Location	Crust Type	Elevation Band	Duration (Days)	Density	Shear Frame Test	Thin-Blade Resistance Test	Crust Index
3 Jan	Mt. Fidelity	Freezing Rain	Treeline	76	-	8	10	12
9 Feb	Mt. Fidelity	Sun	Treeline	56	10	9	6	10
28 Feb	Mt. Fidelity	Sun	Treeline	36	6	4	3	6
26 Mar	Mt. Fidelity	Sun	Treeline	9	4	-	3	4
12 Feb	Mt. St. Anne	Sun	Treeline	45	6	5	6	6
5 Mar	Mt. St. Anne	Rain	Below Treeline	15	3	-	3	3

gradients were initially apparent. The data from the 3 January freezing rain crust are shown in Figure 3. Initially the average upper temperature gradient was greater than the average lower temperature gradient. Over time the trend in the strength of these gradients gradually reverses, with the lower gradient becoming greater than the upper gradient.

4.1 3 January 2012 Freezing Rain Crust

Between the afternoon of 2 January 2012 and the morning of 3 January 2012, a thin freezing rain crust formed at treeline on Mt. Fidelity in Glacier National Park. This crust thickness varied between 3 and 4 millimeters at the south, north, and flat study sites. This crust was tracked at the flat site until 19 March 2012, for a total period of 76 days. Figure 4 shows the data recorded for the 3 January 2012 freezing rain crust at the flat study site on Mt. Fidelity and shows increasing shear strength and resistance over time. This is the only crust in the dataset that underwent near crust faceting. This commenced between 16 January 2012 and 19 January 2012 when air temperatures reached a low of -26° C. The faceting occurred at the lower interface of the crust. This faceting caused a decrease in the lower bonding index

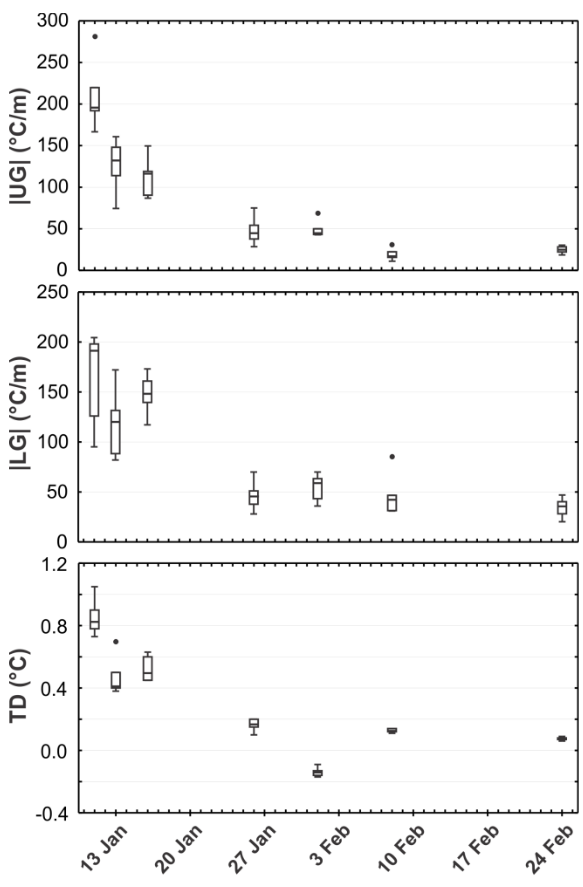

Fig 3: Thermal evolution of the 3 January 2012 freezing rain crust at the flat study site on Mt. Fidelity in Glacier National Park. The average upper temperature gradient (UG), average lower temperature gradient (LG), and temperature difference (TD) were each sampled 5 times in order to account for the uncertainty in the photographs.

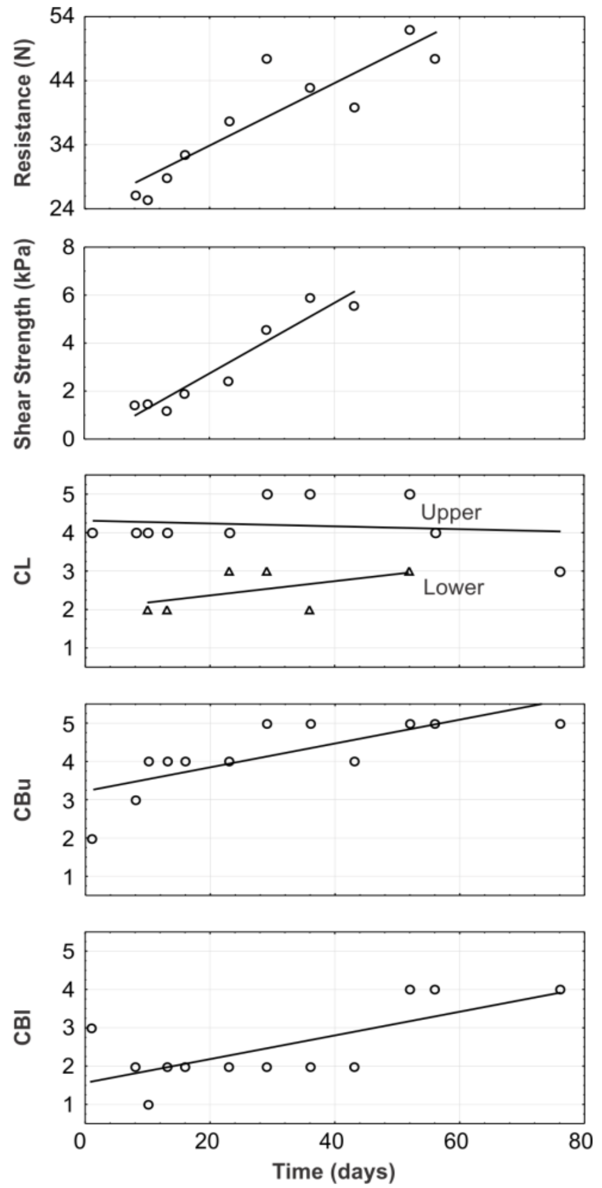

Fig. 4: Time series data for the 3 January 2012 freezing rain crust at the flat study site on Mt. Fidelity in Glacier National Park. In sequence, the plots are the thin-blade resistance test, the shear frame test, crust internal lamination index (CL), crust bonding index upper (CBu), and crust bonding index lower (CBl). The crust internal lamination index (CL) has two parts, upper and lower, following the crust faceting that occurred in mid-January. Each of the upper and lower parts represents 2 mm of the 4 mm thick crust. By the end of February the two parts had merged.

(CBl) and changed the internal lamination properties of the crust. Initially the lamination was uniform throughout but the faceting caused a decrease in bonding in the lower 2 mm of the 4 mm thick crust. Once the crust was segregated, two values were recorded for the crust lamination index (CL) until the layers merged around 28 February 2012. Observations after 26 January 2012 showed a progressive rounding of this lower facet layer likely due to warmer air temperatures. The average lower temperature gradients in Figure 3 show a substantial decrease on 26 January 2012 compared to the preceding observations.

4.2 9 February 2012 Sun Crust

The 9 February 2012 interface was best known for the surface hoar that caused large avalanches until the end of winter. The approximately seven days of clear weather that formed the surface hoar also formed a sun crust on south aspects. At the south study site on Mt. Fidelity this sun crust was typically 20 mm thick with surface hoar up to 9 mm overlying it. While this crust did not evolve substantially or undergo faceting, it became a bed surface for avalanches releasing in the surface hoar. Figure 5 shows the data collected for the 9 February sun crust. This shows increasing shear strength while the upper bonding index (CBu) remains constant. The density and resistance of the crust increase with time while the crust lamination index (CL) decreases.

5. DISCUSSION

The importance of site selection to an evolution project is critical. Numerous data were discarded at the early stages of this project due, in hindsight, to spatial variability. Finding an appropriate site below treeline can be quite difficult, especially if trees cannot be removed. While the principles of site selection are described for research applications, they apply directly to operational setting. Reducing snow pack variability increases confidence in observations of weak layer evolution.

While increasing trends in the upper bonding index of the crust were typically correlated to increases in the shear strength of the layer, the one inconsistency is the 9 February crust/surface hoar combination. The surface hoar layer gained shear strength over time, likely bonding at the upper and lower interfaces. Based on propagation saw tests (PST), the propagation potential of the 9 February SH layer changed little over time (Horton, 2012). Assuming similarity between the study site and

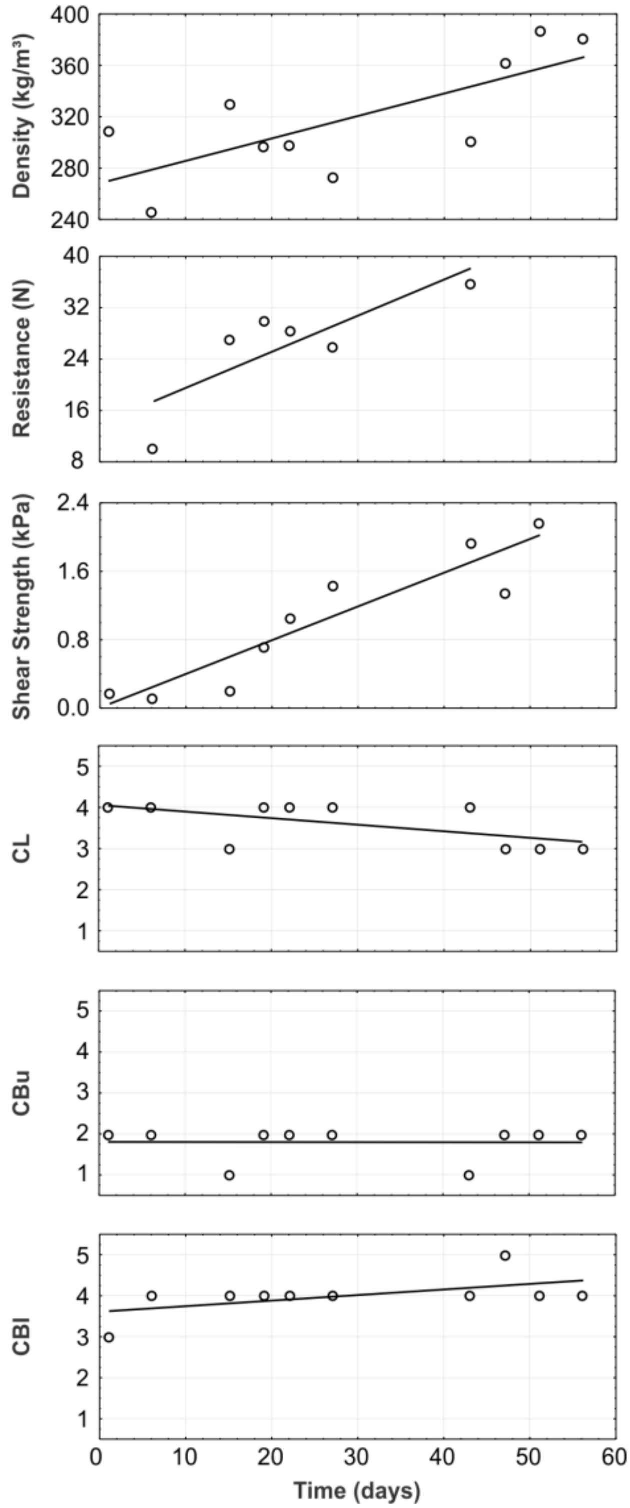

Fig. 5: Time series data for the 9 February 2012 sun crust at the south study site on Mt. Fidelity in Glacier National Park. In sequence, the plots are density, thin-blade resistance test, shear frame test, crust internal lamination index (CL), crust bonding index upper (CBu), and crust bonding index lower (CBl).

nearby start zones, the SH layer produced large avalanches until the end of the winter. In this context, maintaining the crust upper bonding index at two until the end of the observations was accurate and the crust index may prove to be a better tool than the shear strength for describing evolution of avalanche likelihood.

The relationship between resistance and the crust lamination index remains unclear. The lamination index was intended to describe the internal bonding of a crust which may be related to resistance. However, as density and resistance are related (Geldsetzer and Jamieson, 2001), it is possible that as grain size within a crust increases the bonding may decrease. This could cause an increase in resistance and a decrease in the perceived bonding between grains. This may be related to the process known as crust disaggregation, a term used to describe weakening of a crust without the obvious presence of faceting (Smith et al., 2008).

There are several factors that likely affect the temperature gradient around a melt-freeze crust including the following: crust depth, time of day, density difference of crust and surrounding snow, permeability of crust, snow surface temperature, and rate of change of snow surface temperature. The thermal evolution data from the 3 January freezing rain crust initially shows a strong temperature gradient above and below the crust. This contrasts to the 9 February sun crust which initially has no perceptible temperature gradients. This is likely related to the permeability of the crusts. The 3 January crust appeared to be of low permeability, whereas the 9 February crust appeared more permeable. The low permeability could affect the temperature gradient due to the latent heat flux caused by net water vapour being deposited at the lower interface and/or departing the upper interface (Colbeck, 1991).

6. CONCLUSIONS

Three primary methods for tracking melt-freeze crust evolution were established. These methods were applied to six melt-freeze crusts during the 2011-12 winter in the Columbia Mountains of British Columbia, Canada. Measurements showed that for a typical crust at treeline, dry density will increase over time, shear strength at the upper interface will increase, and resistance will increase over time. The crust index showed similar results and is promising when measurements are impractical. Thermal evolution data captured about once a week with a FLIR B300 shows that crusts with an initially strong temperature gradient had a decreasing temperature gradient over time.

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