FACETING ABOVE CRUSTS AND ASSOCIATED SLAB AVALANCHING IN THE COLUMBIA MOUNTAINS

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ABSTRACT: Numerous slab avalanches including unexpected human triggered avalanches are reported on crusts. For 70 dry slab avalanches that slid on a crust in the Columbia Mountains of western Canada, detailed profiles showed faceted crystals (60%) or surface hoar (33%) on the crust. Many of the facet layers were thin (<5-10 mm thick) and difficult to observe in manual snow profiles without snowpack tests. Two field studies with closely spaced thermistors showed faceting at the base of the overlying dry snow within a day. One time series of shear frame tests of facets-on-crust showed an initial strength loss during faceting followed by a slow strength increase. Observations of the spatial distribution of near crust faceting are summarized.

KEYWORDS: avalanche forecasting, snowpack stratigraphy, crusts, melt-freeze layers, faceted crystals

1. INTRODUCTION

Wet layers on the snow surface that freeze into crusts form the bed surface for many slab avalanches (e.g. Seligman, 1936, p. 308-310, 387; Atwater, 1954; Fig. 1), including many difficult-to-forecast avalanches. An understanding of the cause of the poor bond between the crust and the overlying snow is helpful for anticipating the presence and distribution of the poorly bonded crusts over terrain, and hence to avalanche forecasting. This paper focuses on weakly bonded crusts due to faceting and associated avalanches in the Columbia Mountains based on field observations on or near Mt. Fidelity and Mt. St. Anne (Fig. 2).

Fig. 1. Crown of a natural dry slab avalanche that slid on faceted crystals within a layered crust.

In this paper, wet or moist surface layers that freeze are referred to as crusts, although these may be classified as frozen wet grains (WGcl or WGmf), rain crusts (CRrc), sun crusts (CRsc) or melt-freeze crusts (CRmfc) according to Colbeck et al. (1990). The snow surface can become wet

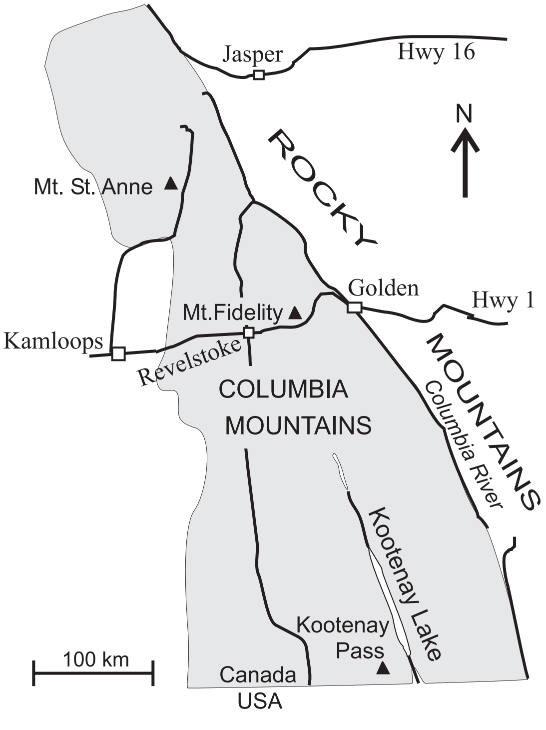

Fig. 2. Map of Columbia Mountains in western Canada showing study sites at Mt Fidelity in Glacier National Park and at Mt. St.

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due to rain, wet snowfall or a net energy balance that is positive (into the snow) long enough to wet snow at or near the snow surface. The crusts due to rain and sun observed in the Columbia Mountains are rarely thin and transparent as required for the international definition of rain crusts and sun crusts (Colbeck et al., 1990). We record these non-transparent layers as melt-freeze crusts (CRmfc) but retain the labels *rain crust* and *sun crust* in field notes to identify the cause whenever weather data or field observations support the distinction.

2. FORMATION OF POOR BOND TO CRUSTS

For avalanches that slid on crusts in the Columbia Mountains, profiles summarized in Section 3 of this paper show that the weak layers usually consist of faceted crystals (facets) or surface hoar. These layers are known to be slow to bond, typically comprise relatively large grains and can remain weak in the snowpack for a week to several months. Although surface hoar layers on crusts are important to avalanche forecasting in the Columbia Mountains (Hägeli and McClung, 2003), this paper focuses on facets above crusts.

Faceted crystals (facets) and depth hoar result from kinetic growth of crystals due to a temperature gradient drawing water vapour though the pore spaces in snow. The scale of the temperature gradient is relevant. We define $\mathrm{d}T/\mathrm{d}Z$ as the temperature gradient (perpendicular to the slope) on the grain or millimetre scale, and ΔT_{10} as the average temperature gradient over 10 cm. Avalanche workers commonly measure ΔT_{10} (vertically) during manual snow profiles. The threshold magnitude of the temperature gradient for faceting ($\mathrm{TG_F}$) is approximately 10°C/m but depends on temperature, snow density and grain/pore size (Miller et al., 2003). Formation of recognizable facets in the snowpack is expected where $|\mathrm{d}T/\mathrm{d}Z| > \mathrm{TG_F}$ is sustained for sufficient time. While a few hours is sufficient in low density snow for gradients around 100°C/m and higher (Fukuzawa and Akitaya, 1993; Birkeland et al., 1998), several days or longer are usually required for gradients close to 10°C/m. Once faceting has started, the characteristic small bonds and slow densification will limit conductivity (Adams and Brown, 1983), potentially increase the temperature gradient (Colbeck and Jamieson, 2001), and thereby contribute to further faceting.

Using the age of 109 layers that consistently fractured in compression tests (CAA, 2002, p. 32-34) as an index of persistence, Figure 3 shows that layers comprised of larger facets and depth hoar were more persistent (slow to stabilize). The median persistence in compression tests increased to 78 days for facets larger than 2.3 mm. Our limited data for facet layers with average grain size less than or equal to 0.7 mm suggests such layers usually do not remain weak for long in the Columbia Mountains. Layers consisting of large grains are expected to bond slower and hence gain strength slower than layers of smaller grains (Colbeck, 1998). Also, the bonds between larger grains will typically be farther apart. For grain sizes between 0.7 and 1.7 mm, Figure 3 shows little difference in the persistence of "sharp" facets (FCfa, FCsf) compared to facets that exhibit signs of rounding (FCmx).

2.1 Faceting of dry snow near crusts

Before focusing on facets found at the upper boundary of buried crusts, we note there have been theoretical approaches (Adams and Brown, 1989; Colbeck, 1991) to explain potential faceting above and below crusts even when the magnitude of the *depth-averaged* temperature gradient is too low for faceting ($|\Delta T_{10}| < \mathrm{TG_F}$). For more on faceting within and below crusts, see Adams and Brown (1983), Colbeck (1991) and Jamieson

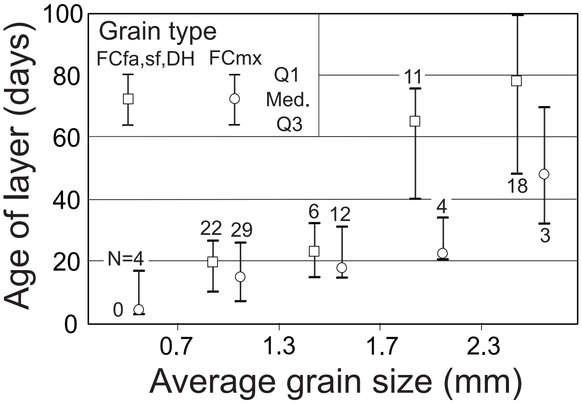

Fig. 3. Box and whisker graph showing the age of facet layers (since burial) when they fractured consistently in compression tests. For each range of particle size, e.g. > 0.7 mm and ≤ 1.3 mm, the whisker shows the first and third quartiles of age (Q1 and Q3). Squares and circles indicate the median ages of faceted crystals including depth hoar (FCfa, FCsf, DH) and rounded facets (FCmx), respectively. The number above or below the whisker indicates the number of layers that fractured consistently in a set of compression tests at a specific site and date.

(2004).

2.2 Dry-on-Wet (DW) faceting

When dry snow falls on wet snow, the dry snow at the interface can form facets (DW faceting) within a day when the temperature of the new snow surface is below freezing (Fukuzawa and Akitaya, 1993; Jamieson and van Herwijnen, 2002; Section 4). These observations are supported by analytical solutions and simulations (Colbeck and Jamieson, 2001; Jamieson and Fierz, in press).

2.3 Distribution of DW faceting in the Columbia Mountains

DW faceting will only occur where dry snow falls on a wet snow with sufficient latent heat to sustain $|dT/dZ| > TG_F$ at the interface. As a consequence, DW faceting on a rain crust is sometimes confined to an elevation band that is less than the difference in freezing levels of precipitation between two storms (Fig. 4). DW faceting will occur where dry snow from the second storm overlies wet snow with sufficient latent heat (band below Elevation 1b). From the freezing level of the first storm (Elevation 1a in Fig. 4) down to Elevation 1b, dry snow buries a moist layer but there is insufficient latent heat in the moist snow to sustain the temperature gradient for long enough for faceting at the interface. We became convinced that the elevation band for DW faceting is often narrow in the Columbia Mountains based on our attempts to place an array of thermistors in rain-wetted snow before dry snow fell. The following day we often discovered the array was a little too high or too low. (Section 4 summarizes two successful attempts.)

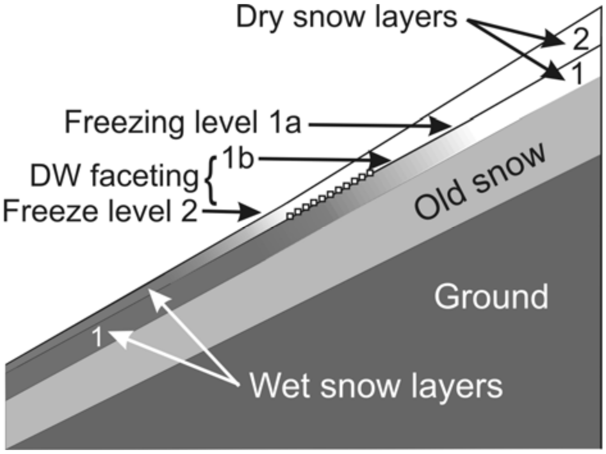

Fig. 4. Diagram showing that favourable condi-tions for dry-on-wet (DW) faceting occurs within a elevation band that is less than the difference in freezing levels in two consecutive

In the case of the facets-on-crust that formed in November 1996 in the North Columbia Mountains (Jamieson et al., 2001), the facets were more advanced at elevations near treeline than at higher elevations where the crust was thinner and less latent heat was available to drive DW faceting. At lower elevations, moist snow or rain fell on the already wet surface, inhibiting DW faceting.

In the late winter and spring in the Columbia Mountains, it is common for solar radiation and warm air to melt the snow surface on steep sunny slopes. Storms, including convective cells, may locally deposit dry snow, including on some slopes with sufficient latent heat in the wet surface, resulting in areas of DW faceting and hence areas where the resulting crust is poorly bonded. While the wet layers may be thin, data presented in the next two sections indicate such layers sometimes have sufficient latent heat to create thin layers of facets at the base of overlying dry snow.

3. OBSERVATIONS OF FACETS-ON-CRUST COMBINATIONS IN THE COLUMBIAS

For natural avalanches in the Columbia Mountains, Hägeli and McClung (2003) report 17% released in facets-on-crust combinations and 7% occurred on “pure” crusts without a weak crystal type reported on the crust. They proposed that unreported facets and surface hoar layers overlie many pure crusts, which is consistent with our detailed profiles.

3.1 Detailed profiles at slab avalanches in the Columbia Mountains

From 1990 to 2004 in the Columbia Mountains, University of Calgary avalanche researchers and collaborators have observed 335 detailed profiles near dry slab avalanches and “whumpfs”— where each whumpf is a fracture in a weak layer under a snow slab that did not release an avalanche (Johnson et al., 2001). Of these avalanches and whumpfs, 70 had crusts as the bed surface, implying the failure occurred in the overlying weak layer, and likely at the interface of the crust and weak layer where shear stress was concentrated. The primary grain types for the weak layers were: 39 layers of faceted crystals (FC), 23 of surface hoar (SH), 1 of depth hoar (DH), 3 of rounded grains (RG), 3 of decomposing and fragmented particles (DF), and 1 of precipitation particles (PP). All three of the weak layers of rounded grains had facets as their secondary (less evident) grain form. Grouping these three layers with the other layers of facets, we see that 94% of the weak layers included facets, depth hoar or surface hoar, the three grain types of weak layers known for their persistence in the snowpack (Jamieson and Johnston, 1992). This leaves four non-persistent weak layers: 1 of PP and 3 of DF particles. From the weather records, the age of the PP and three DF layers were 2, 2, 3, 6 days on the day of the avalanche. Hence, in the Columbia Mountains when a dry slab avalanches releases on a crust that has been buried for more than 3 days, facets or surface hoar are usually the release layer.

Of the 39 facet-on-crust avalanches, the percentage of the facet layers less than 10 and 20 mm thick was 39% and 58%, respectively, indicating the importance of *thin* facet layers for slab avalanche release on crusts in the Columbia Mountains.

Since our dataset of facet-on-crust avalanches was too small to show that the thickness of the facet layers varied during the winter, we examined the distribution of thickness of weak layers of facets on crusts that fractured in compression tests. Since December 1996, our field research staff have observed 2943 fractures of weak layers of facets on crusts in compression tests. Almost all these tests were in groups of three adjacent tests and rarely was there more than one facet-on-crust combination per test. Consequently, these fractures are from almost 1000 sets of compression tests, with each set being at a different location and/or day. For weak layers in the thickness ranges of 0-5, 6-10, 11-20, 21-50 and > 50 mm, the percentages are 14%, 11%, 11%, 15% and 49%, respectively. Breaking this distribution down by month between November and April in Figure 5, we see the percentage of facet layers (on crusts) more than 5 mm thick does not change systematically over the winter; however, the percentage of such layers less than or equal to 5 mm increases steadily over the months from November to April. We attribute this to the increase in periods of surface melting as the winter progresses.

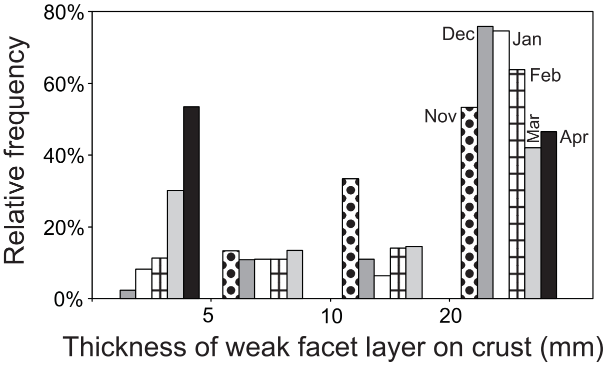

Fig. 5. Thickness of facet layers on crusts from 2943 fractures in almost 1000 sets of compression tests over the winter months in the Columbia Mountains, 1996-2004.

4. FIELD EXPERIMENTS OF FACETING OF DRY SNOW ON WET LAYERS

In the winter of 2002-03 on Mt. Fidelity and again in 2003-04 on Mt. St. Anne, we monitored one case of DW faceting and the evolution of the resulting facets on crusts. For each of these cases, the measurement sites were near automated weather stations at approximately 1900 m that provide hourly measures of temperature and precipitation. The temperature gradient across the dry layer was measured with thermistors (Fig. 6) calibrated to ±0.1°C and recorded hourly with a datalogger. Manual snow profiles were observed several times within a week. By pulling on a 250 cm^2 shear frame placed a few millimetres above the wet layer or crust (Fig. 7), the shear strength was measured (e.g. Perla and Beck, 1983) and adjusted for size effects (Sommerfleld, 1980).

Fig. 6. Photograph showing three vertically oriented pairs of thermistors that were placed in wet snow before dry snow fell. Only the top thermistor of each pair is visible above the dry snow. The thermistors are connected to a datalogger in the white box that reads each temperature every two minutes and records the average temperature of each thermistor every hour.

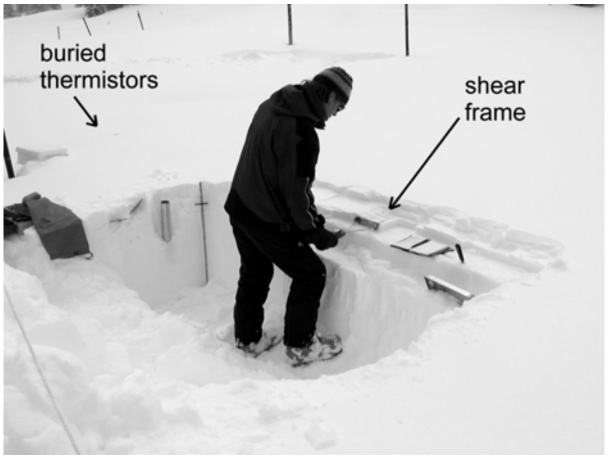

Fig. 7. Photograph of operator performing a shear frame test on a layer of facets on a crust. The bottom of frame is placed a few millimetres above the facet-crust interface and pulled to fracture within a second. The layer being tested was buried 2004-01-14 at Mt. St. Anne.

4.1 Wet layer buried 2003-03-14 at Mt. Fidelity

On 2003-03-14, dry snow fell on a wet layer at 1890 m elevation on Mt. Fidelity. At 1300 h with light snow falling at –2.5°C, we observed 3.5 cm of dry new snow (PP) on a 1.8 cm thick wet layer (Fig. 8). A pair of thermistors was placed across the dry layer. Overnight the air temperature approximately 2 cm above the snow surface cooled to –4°C and the magnitude of the temperature gradient across the dry layer reached 59°C/m at 2100 h. Data from an upward-facing long wave radiometer approximately 200 m from the study site indicate the sky remained overcast overnight except from 0300 to 0500 h. The upper boundary of the wet layer froze at 0200 h on 2003-03-15. At 0900 h, the crystals just above the crust and 2 cm above the crust were FC 1, and DF 1 FC 0.5-1, respectively, indicating the faceting was more advanced just above the crust. On 17 March 2003, the crystals just above the crust were observed to be FC 0.5-1 indicating that no further faceting was apparent. In subsequent observations on 17, 18 and 22 March 2003, the crystals just above the crust showed evidence of rounding (Fig. 9).

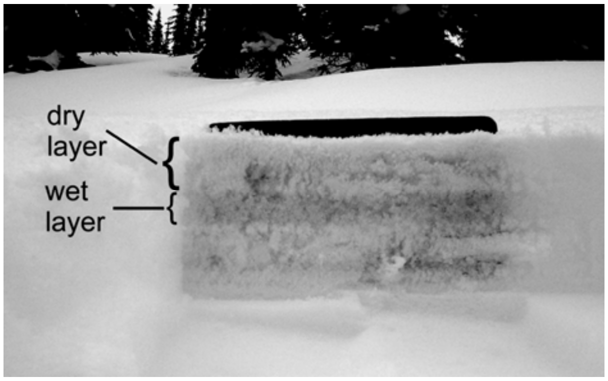

Fig. 8. Photograph of a vertical section of the upper snowpack showing the wet layer and overlying dry snow on 14 March 2003 on Mt. Fidelity.

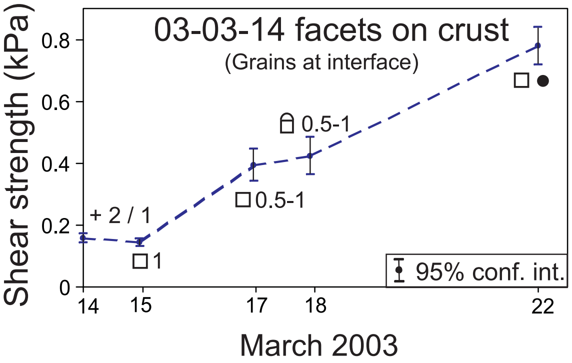

Fig. 9. Change in shear strength and type of grains at the upper boundary of the wet layer then crust buried on 2003-03-14 on Mt. Fidelity in the Columbia Mountains.

For the grains at the interface, the mean of 12 shear strength tests on each of the observation dates is plotted in Figure 9. The strength change from 14 to 15 March was statistically insignificant. The expected strength gain given the warm snow temperature favourable to densification and bonding (0°C then cooling to –4°C after the wet layer froze) did not occur probably because the strong temperature gradient caused faceting of the crystals just above the wet layer. As with many other cases of small faceted crystals (e.g. 0.5 mm) we have observed, this layer gained strength quickly. At Glacier National Park and at nearby backcountry ski operations, no slab avalanches were reported on this weak layer. On 19 February 2003 at a site 50 m lower and about 250 m south of the 1890 m study slope, a snow profile showed 1 mm rounded facets (FCmx) on a 1.2 cm thick crust, indicating that the facets-on-crust existed outside the study slope, at least within a narrow elevation band.

4.2 Wet layer buried 2004-01-15 at Mt. St. Anne

During the night of 2004-01-14, light rain was reported at lower elevations in the mountains near Mt. St. Anne. At 1200 h on 2004-01-15 (Fig. 10) at 1600 m elevation on Mt. St. Anne, 4 cm of dry new snow (PP) had accumulated over about 5 hours on a 6-cm-thick layer of rain wetted (moist) snow classified as Wet grains (WGcl). The air temperature was 1°C, snow was falling at 2 cm per hour and the sky was obscured by fog. Four thermistors were positioned similarly to the placements in shown Figure 7. Initially, the upper thermistor was about 3.5 cm above the snow surface. The shear strength of the dry snow just above the moist snow was 0.36 kPa (Fig. 11). The moist layer had a hand hardness of 4-Fingers (4F). According to readings from an ultrasonic snow depth sensor at 1900 m on the same mountain, the upper thermistor was buried by 1600 h.

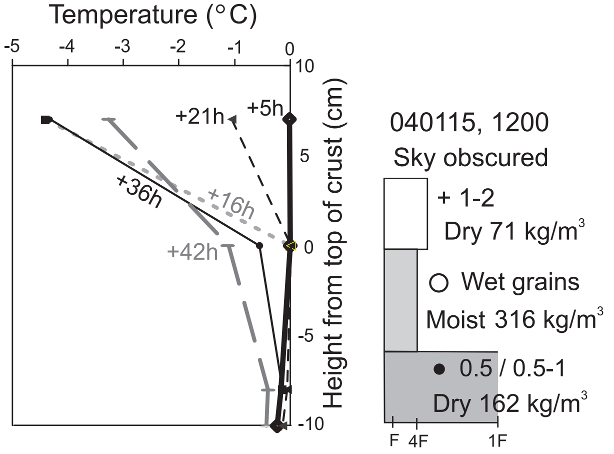

Fig. 10. Graph of five different temperature profiles taken from the hourly profiles of the dry-on-wet layer combination buried 2004-01-15 at 1600 m on Mt. St. Anne.

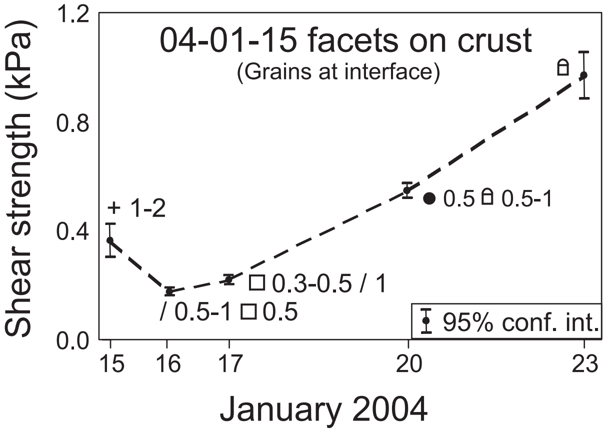

Fig. 11. Change in shear strength and type of grains at the upper boundary of the wet layer (later crust) buried on 2004-01-15 on Mt. St. Anne in the Columbia Mountains.

At midnight, 16 h after the wet layer was buried by dry snow, the magnitude of the temperature gradient between the top two thermistors spanning most of the dry layer was 63°C/m. Three hours later, the magnitude of the temperature gradient in the dry layer reached a maximum of 91°C/m. The top of the initially moist layer froze between 21 h (Fig. 10) and 26 h after burial by dry snow.

The next day at 1000 h (about 27 h after the start of dry snowfall on the rain-wetted layer), the air temperature was –2°C, snowfall had stopped and the sky remained obscured by fog. The upper 3.5 cm of the initially moist layer had frozen and was a Pencil-hard (P) crust. The grains at the interface were classified as decomposed and fragmented particles (DF) and faceted crystals (FC). Shear frame tests revealed a 50% drop in shear strength (Fig. 11), which we attribute partly due to the formation of facets at the interface and partly to a shear stress concentration resulting from freezing wet layer and consequent stiffening of the crust.

At the site of thermistors, profiles and shear frame tests (elevation 1600 m) on 2004-01-17 at 1100 h, 7 cm of dry snow lay on the initially moist layer that had now frozen into a knife-hard (K) crust. The dominant grain type in the 2-mm-thick layer on top of the crust was facets (FCfa), overlain by decomposed and fragmented particles. Shear frame tests showed a slight increase in the mean shear strength. Observations and tests on this layer on 20 and 23 January showed rounding of the grains at the interface and substantial increases in strength (Fig. 11).

On 2004-01-16, the crust was found in a profile on Mt. St. Anne at 1900 m but it was only 1.6 cm thick—much thinner than at 1600 m. No facets were found on the crust, probably because there was insufficient latent heat in the initially moist layer to sustain the temperature gradient in the overlying dry snow. These observations at 1600 and 1900 m apparently bound the minimum conditions for forming a weak layer of facets.

On 2004-01-21, profiles 10 km to the south-southwest at 1745 m and 1905 m revealed the crust, 2 cm and 0.2 cm thick, respectively, but no facets were found on the crust at these elevations. We attribute the thinner crust and the absence of facets to less rain on the night of 2004-01-14 at these elevations and hence less latent heat to sustain the temperature gradient in the overlying dry snow. Two kilometres to the west and 100 m lower, the rain crust and the overlying facets were more developed. Between 2004-02-06 and 2004-02-12 (23 to 29 days after the wet layer was buried), we observed a total of five profiles, 37 rutschblock and 12 compression tests. The facet layer produced fractures in all these tests. The median rutschblock score was 4 and the average compression score was moderate (19 taps). As further evidence of the instability at this elevation, while traveling on skis, we triggered two whumpfs where the faceted layer fractured but the slab only moved about 1 cm downslope. Compared to the site of the thermistors and shear strength measurements located 100 m higher on the mountain, the profiles revealed a thicker layer (1-1.5 cm) of larger facets (1-2 mm) on a thicker rain crust (> 10 cm) that was, by this date, 52 to 72 cm below the snow surface. Clearly, the facets on the rain crust were more developed and less stable for longer at a slightly lower elevation where more rain created a thicker wet layer with more latent heat to sustain the temperature gradient in the overlying snow for longer.

5. SPATIAL VARIABILITY OF A POORLY BONDED SUN CRUST

Cam Campbell and Antonia Zeidler observed an array of 23 closely spaced rutschblocks tests on the east and northeast sides of a knoll (Fig. 12) on Mt. Fidelity in Glacier National Park on 2004-03-18 (Campbell and Jamieson, this volume). Ignoring the bottom row of tests where slab thickness varied substantially, the rutschblocks scores on the sunnier (more easterly) aspect of the knoll are significantly lower than on the shadier (more north-easterly) aspect. The facets were more developed and the crust harder on the sunnier aspect of the knoll where the rutschblocks scores where generally lower. Such localized variations in the bond to a sun crust can be difficult to anticipate but understanding the cause (e.g. dry snow on a surface melted by solar radiation) can help.

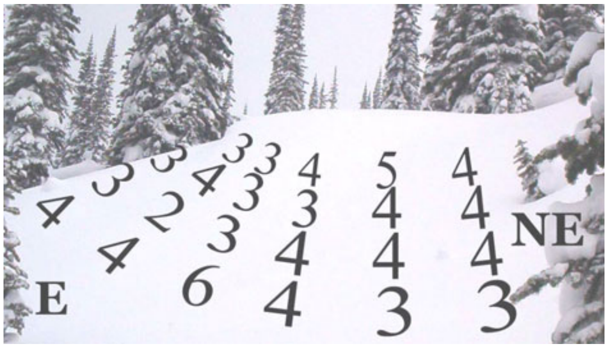

Fig. 12. Array of closely spaced rutschblock tests on Mt Fidelity on 2004-03-18. The weak layer consisted of facets on a sun crust. The scores were mostly lower on the sunnier (left) side of the roll where the crust and facets were better developed than on the shadier (right) side. The slab thickness was more variable in the bottom row where the only score of 6 occurred.

6. DISCUSSION

Is DW faceting a common cause of poorly bonded crusts in the Columbia Mountains? As noted above, $|\Delta T_{10}|$ in the Columbia Mountains is *usually* not sufficient over long enough periods to form thick layers of facets, although important exceptions occurred in the winter of 2000-01 (Hägeli and McClung, 2003). Certainly, diurnal near-surface faceting can and does sometime extend through surface layers to facet the snow on crusts; however, the increase in thin layers of facets on crusts in late winter (Fig. 5) suggests a process which concentrates dT/dZ in the dry snow just above the wet layer or crust rather than at the snow surface. There are several factors and observations indicating that DW faceting does form an important portion of the weak faceted layers on crusts:

- Warm fronts capable of producing rain or melting of the snow surface below a specific elevation are sometimes followed by cold fronts capable of precipitating dry snow in the same elevation range.
- Some thin layers of facets on crusts are found in a narrow elevation band, which is more likely for DW faceting (Fig. 4) than for facets that form on an already frozen crust (DC faceting).
- In the spring, several hours of sunshine can warm and melt the snow surface followed by convective snow showers. The wet layers are usually thin (limited latent heat) and the facet layers on spring crusts are often thin (Fig. 5).
- Although many cases of dry-on-wet faceting in the Columbia Mountains have been reported (Section 4, 5; Jamieson et al., 2001; Hägeli and McClung, 2003), our literature review revealed no cases of faceting above a *frozen* crust (DC faceting) when $|\Delta T_{10}| < TG_F$. This does not disprove the theories of Adams and Brown (1989a) and Colbeck (1991);

however, the lack of observations suggests DC faceting may be uncommon when $|\Delta T_{10}| < TG_F$. Perhaps the lack of observations is related to insufficient temperature gradient measurements over time. Nevertheless, faceting of dry snow on a crust should be easier to observe than dry-on-wet faceting, which is highly variable over terrain.

- Facets on a sun crust are sometimes better developed on the sunny aspects where the crust is thicker (Section 5), and hence where the original wet layer would have supplied more latent heat for DW faceting. Bruce McMahon and Chris Stethem (pers. comm., 2003, 2004) report that a weaker bond to sun crusts on sunny aspects compared to shadier aspects is not uncommon.

7. CONCLUSIONS

In our Columbia Mountain observations, facets, depth hoar or surface hoar are found at the interface of most crusts that release dry slab avalanches more than three days after the snow or surface hoar layer on the crust is buried.

The magnitude of the temperature gradient at a dry-over-wet interface can exceed 50°C/m for hours while heat is drawn upwards towards the cooler surface of the snow. Facets can form within a day at the interface where dry snow overlies wet snow and the snow surface temperature is below 0°C.

Facets can continue to grow after the wet layer freezes; the relatively small area of bonds between facets and the tendency of facet layers to resist densification can contribute to additional faceting.

Snowpack tests such as rutschblock or compression tests are helpful for locating thin layers of facets or surface hoar on crusts.

If the staff of a forecasting program suspect that a crust may be poorly bonded due to DW faceting, then where the crust is relatively thick—as determined by manual probing—the bond of the overlying snow to the crust may be poor. At these sites further snowpack tests and perhaps profiles may be helpful.

Theory and our Columbia Mountain observations indicate the that persistence of weak layers of facets increases with grain size. Many layers of facets, including rounded facets (FCmx) from 0.8 to 1.7 mm in size fracture consistently in compression tests two to four weeks after burial. In our compression tests, 1-1.5 mm facets (FCmx) were about as persistent as “sharp” facets (FCfa) of similar size. Along with other observations, crystal size of persistent weak layers is helpful for avalanche forecasting.

Facets that form at the base of dry snow overlying wet layers form an important portion of the facet-on-crust combinations in the Columbia Mountains. These include poorly bonded rain crusts in early and late winter and poorly bonded sun crusts in March and April. Thin facet layers (≤ 5 mm thick) are more common in March and April when sun crusts are more common.

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