Between a slab and a hard layer:

Part 1 – Formation of poorly bonded crusts in the Columbia Mountains

Bruce Jamieson
Dept. of Civil Engineering, Dept. of Geology and Geophysics
University of Calgary, Calgary, Alberta

1. Introduction

For decades, avalanche observers (e.g. Seligman, 1936, p. 308-310, 387; Atwater, 1954) have noted that wet layers on the snow surface that freeze into crusts subsequently form the bed surface for many slab avalanches (e.g. Fig 1), including some difficult-to-forecast avalanches. This article – the first of three on poorly bonded crusts – focuses on the formation of poorly bonded crusts and their distribution over terrain. The next article assesses profiles of slab avalanches that slid on poorly bonded crusts and the effect of grain size on the persistence of facets on crusts. The final article summarizes two field experiments in which facets formed within a day on buried wet layers, and tracks the evolution of these layers.

Fig. 1. Photo of observer at crown of a natural dry slab avalanche that slid on a layer of faceted crystals within a layered melt-freeze crust.

In this series, wet or moist surface layers that freeze are referred to as crusts although they may be classified as frozen wet grains (WGcl or WGmf), rain crusts (CRrc), sun crusts (CRsc) or melt-freeze crusts (CRmfc) according to Colbeck and others (1990) or CAA (2002). The snow surface can become wet due to rain, wet snowfall or a net energy balance that is positive (into the snow) long enough to melt or 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 and others, 1990). The Applied Snow and Avalanche Research Group at the University of Calgary 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. I'll do the same in this series.

2. Formation of wet layers and crusts in the Columbia Mountains

In this section, the formation of wet layers is discussed by considering rain, sensible heat and solar radiation separately. While one source often dominates wetting of the snow surface, secondary sources can be substantial and add complexity to the formation and distribution of wet layers at and near the snow surface.

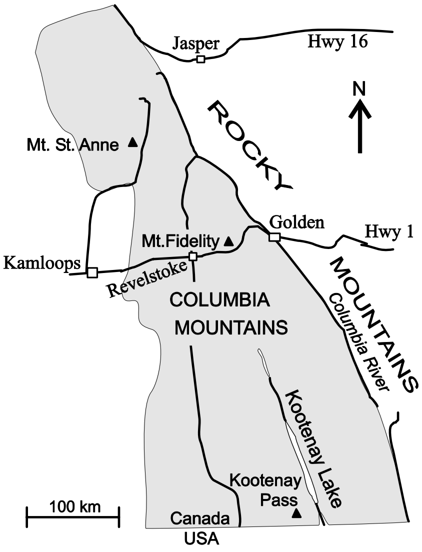

Fig. 2. Map of Columbia Mountains in western Canada showing study sites at Mt Fidelity in Glacier National Park at Mt. St. Anne near Blue River, BC.

2.1 Rain and resulting rain crusts

At treeline on Mt. Fidelity in the Columbia Mountains (Fig. 2), Figure 3 shows that rain can occur in all winter months. From 1966 to 1986, the average amount was usually less than 3-5 mm per month in November through March, with about 12 mm in April and 50-60 mm in October and May. However, in several Novembers since 1995, rain has caused prominent rain crusts (Jamieson and others, 2001a; Hägeli and McClung, 2003).

In November, Figure 3 shows that wetting of the snow surface in the Columbia Mountains is typically due to rain because:

- On average, there is more rain per month than in December through March.
- The air temperature is usually below 0°C so sensible heat is often insufficient for surface melting.
- The average range of air temperature is less than in other winter months.
- The effect of solar radiation on the snow surface is reduced due to the low number of hours of bright sunshine, which is a consequence of the earth's tilt and amount of cloud.

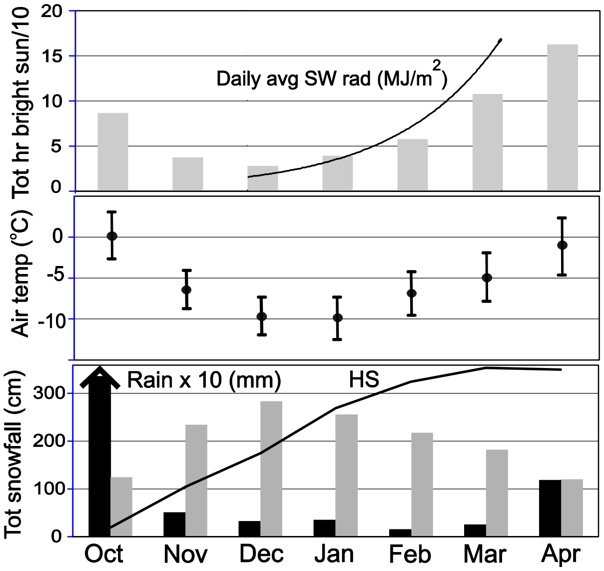

Fig. 3. Snow climate graphs for Columbia Mountains. Total snow height (HS), snowfall (gray columns) and rain (black columns) are from Schleiss (1989) for the winters of 1966-86 at 1905 m on Mt. Fidelity in Glacier National Park. Short-wave radiation is a smoothed average of daily totals from the winters of 2001-02 to 2003-04 at Mt. Fidelity. Monthly hours of bright sunshine are averaged from Revelstoke and Blue River, BC from the winters of 1970-1990 (Environment Canada).

Compared to December through March in the Columbia Mountains, rain becomes more abundant (Fig. 3) and hence rain crusts become more common and are often thicker in April.

Elevation is a major terrain factor that affects the distribution of a rain crust. However, since liquid water often penetrates less on steep slopes than on gentle and flat slopes (Wankiewicz, 1979), slope angle is another factor that affects the distribution of a rain crust (i.e. crusts may be shallower on steeper slopes). Also during rain storms, the windward slopes may receive more rain per unit area than leeward slopes, resulting in wetter or thicker wet layers on windward slopes than on leeward slopes.

2.2 Melting of the snow surface by warm air and resulting "temperature" crusts

During October, the daily maximum air temperature is often above freezing and warm air (sensible heat) is likely to melt the snow surface. However, in the Columbia Mountains, the October snowpack is often thin and in places there is no snow. The ground roughness (uneven ground, rocks, vegetation) frequently extends through or close to the resulting crusts so that they are less likely to provide smooth, continuous bed surfaces over sufficiently large areas for slab avalanches. During November to February, the air temperature is typically below freezing and too cool to melt the snow surface. In March and April, the number of days with maximum air temperatures above freezing increases and surface melting by sensible heat transfer becomes more common. Once refrozen, these layers are often referred to as "temperature crusts".

Usually the air is warmer at lower elevations, and hence each resulting temperature crusts will be observed below a certain elevation. Increased wind speed can increase the exchange of sensible heat between the air and snow surface (Brun and others, 1989; Fierz and others, 2003) and potentially cause more surface melting on slopes that are locally windward. If there is little wind, slope angle will have limited effect on the melting of the snow surface by sensible heat and therefore on the resulting crusts.

2.3 Melting by solar radiation and resulting sun crusts

Approximately 85-95% of solar radiation (approximate wavelength 0.3-3 μm) reflects off the surface of fresh snow (Male and Gray, 1980). Nevertheless, the portion of solar radiation that is absorbed (5-15%) can dominate outgoing long wave radiation and be sufficient for surface melting (e.g. Ozeki and others, 1995).

In the Columbia Mountains, the increase in hours of bright sunshine and solar radiation combined with the warm air temperature makes melting of the snow surface on sunny slopes (without rain) likely in March and April (Fig. 3). In late winter and spring, absorbed solar radiation, especially on slopes tilted into the sun, can be sufficient to melt the snow surface. Consequently sun crusts are often spatially variable, conspicuous on steep slopes facing southeast to southwest, thinning where the slope angle is less or the aspect is less southerly, and often absent on north-facing slopes, especially steep north-facing slopes. (More aspects are affected by solar radiation in late winter and spring.) These effects of aspect and inclination on sun crust formation exist over scales ranging from less than a metre to kilometres.

2.4 Spatial variability of crusts in the Columbia Mountains

By identifying the causes of the surface wetting, the distribution of the crust over the terrain as summarized in previous sections and in Table 1 can be better anticipated. If the cause of the initial wet layer is not considered, then the location of buried crusts, including poorly bonded crusts, can be difficult to anticipate as shown in the last row of Table 1.

Table 1. Terrain effects and timing for wet layers in the Columbia Mountains

	Major terrain effects			When likely in the period from November to April
Cause	Aspect	Elevation	Incline	
Rain	(windward)	Yes	Yes	Nov., March, April
Warm air		Yes		March, April
Sun	Yes		Yes	March, April
All causes	Yes	Yes	Yes	Less frequent in Dec., Jan.

3. Formation of poor bond to crusts

The next article in this series uses detailed fracture line profiles from the Columbia Mountains. These profiles show that most weak layers that are more than three days old and release dry slab avalanches on crusts, consist of facets or surface hoar. So, in these articles, a poorly bonded crust is defined as a refrozen layer directly overlain by a persistent weak layer, that is, one consisting of surface hoar, facets or depth hoar (Jamieson and Johnston, 1992). These grain types 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.

Faceted crystals (facets) and depth hoar result from kinetic growth of crystals due to a temperature gradient – predominantly perpendicular to the slope – drawing water vapour though the pores. The scale of the temperature gradient is relevant. In this series of articles, dT/dZ is defined as the temperature gradient (perpendicular to the slope) on the grain or millimetre scale, and TG_{10} is defined as the average temperature gradient over 10 cm. TG_{10} is usually measured vertically during manual snow profiles. The critical temperature gradient for faceting, TG_F, is around 1°C per 10 cm but depends on temperature, snow density and grain/pore size (e.g. Akitaya, 1974; McClung and Schaerer, 1993, p. 49-52). It is typically between 10 and 20°C/m (Miller and others, 2003). Faceting is faster for warmer (subfreezing) temperature, lower density and larger pores. Formation of recognizable facets in the snowpack is expected where $|dT/dZ| > TG_F$ 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 and others, 1998;

Jamieson and van Herwijnen, 2002), 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, 1991), and thereby promote further faceting.

3.1 Faceting of dry snow near crusts

Colbeck's (1991) idea for the temperature profile in dry snow near crusts is illustrated in Figure 4. The temperature gradient is greater above and below the crust (or other less permeable layer) than away from the crust. This implies that the hard-to-measure temperature gradient next to the crust can be sufficient for faceting ($|dT/dZ| > TG_F$) even though the depth-averaged temperature gradient, as is usually measured in the field, may be less than the commonly used threshold for faceting ($|TG_{10}| < TG_F$).

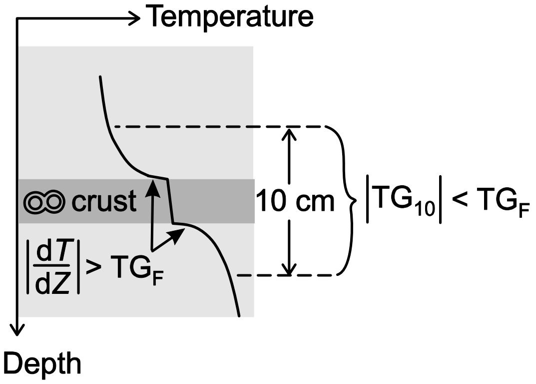

Fig. 4. Graph showing increased temperature gradient just above and below a melt-freeze crust (after Colbeck, 1991). In this hypothetical example the temperature gradient next to the crust is strong enough for faceting although the temperature gradient averaged over 10 cm (as usually measured in profiles) is below the usual threshold.

In his 1982 ISSW presentation, Mark Moore reported faceting and increased temperature gradients at the upper boundary of some crusts which were only a few degrees below freezing. There have been theoretical approaches (Adams and Brown, 1989; Colbeck, 1991) to explain the field observations of faceting above and below crusts even when the magnitude of the temperature gradient over 10 cm is too weak for faceting ($|TG_{10}| < TG_F$).

Condensation of the upward flowing water vapour at the lower surface of less permeable layers (e.g. Seligman, 1936, p. 70) can contribute to faceting below crusts (e.g. Fierz, 1998; Greene and Johnson, 2003). The formation of laminations of facets within a crust (Fig. 5) may be the result of below-crust faceting combined with above-crust faceting acting on the slight differences in density and permeability within a visually uniform crust (C. Stethem, pers. comm., 1999). Based on observations in the coast range of western Canada, John Hetherington (pers. comm., 2004) reports that *continuous* areas of facets within *rain* crusts are often less than 1 m in length, presumably between percolation channels. Occasionally dry slab avalanches are reported on layers of facets within crusts (e.g. Fig. 1), suggesting that areas of continuous faceting are sometimes large enough for fracture propagation. Although faceting below crusts and within crust is fascinating, this paper focuses on the poor bond at the upper boundary of a crust, which is more often the failure layer or interface for slab avalanches involving crusts.

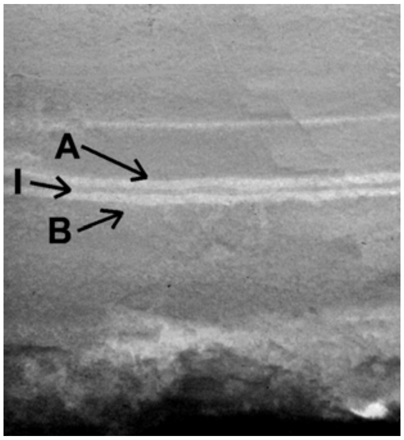

Fig. 5. Translucent profile of snowpack layers including a laminated crust. The poor bond can occur at the upper boundary of a crust (A), which is the focus of this article, in softer snow laminated within a crust (I), or below a crust (B).

3.2 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). Recent analytical solutions and physically based simulations (Colbeck and Jamieson, 2001; Jamieson and Fierz, in press) support these observations.

DW faceting will only occur where dry snow falls on wet snow with sufficient latent heat to sustain a strong enough temperature gradient ($|dT/dZ| > TG_F$) 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. 6). From the freezing level of the first storm (Level 1a in Fig. 6) down to some elevation 1b, dry snow buries a moist layer but there is insufficient latent heat in the moist snow to sustain the temperature gradient for sufficient time for faceting to substantially affect the shape of the grains or the bonding at the dry-wet interface. Faceting will occur where dry snow overlies wet snow with sufficient latent heat, that is, from Level 1b down to the freezing level of precipitation during the second storm.

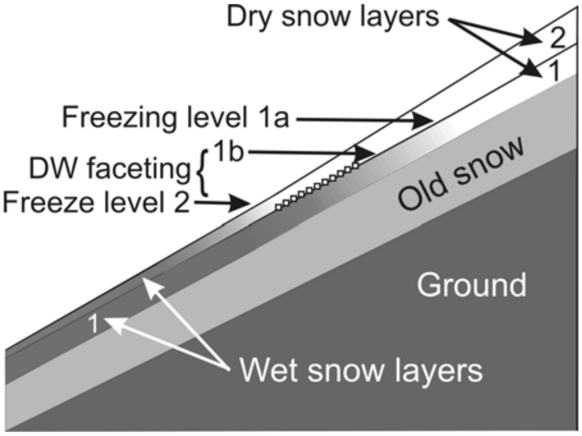

Fig. 6. Diagram showing that favourable conditions for dry-on-wet (DW) faceting occurring within an elevation band that is less than the difference in freezing levels in two consecutive storms.

For example, in the case of the facets-on-crust that formed in November 1996 in the North Columbia Mountains (Jamieson and others, 2001a, b), the facets were more advanced at elevations near treeline. At higher elevations 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. Also, during attempts by U of C avalanche research staff to place thermistor arrays in rain-wetted snow before dry snow fell (Part 3 of this series), the thermistor strings were often placed at the wrong elevation, convincing us that the elevation band for DW faceting is often narrow in the Columbia Mountains.

In the late winter and spring in southern Canada, it is common for strong 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 crust is poorly bonded. These areas can be on the scale of an avalanche start zone and of sufficient area for slab avalanche release. While the wet surface layers may be thin, field experiments summarized in the third article show they sometimes have sufficient latent heat to create thin layers of facets in overlying dry snow.

4. Spatial variability of a poorly bonded sun crust

On 18 March 2004, Cam Campbell and Antonia Zeidler made an array of 23 closely spaced rutschblocks tests (Fig. 7) on the east and northeast sides of a knoll on Mt. Fidelity in Glacier National Park (Campbell, 2004; Campbell and Jamieson, 2004). 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 northeasterly) aspect. The facets and the crust were more developed and the crust harder on the sunnier aspect of the knoll where the rutschblocks scores were generally lower. Such localized variations in the bond to a sun crust can be difficult to

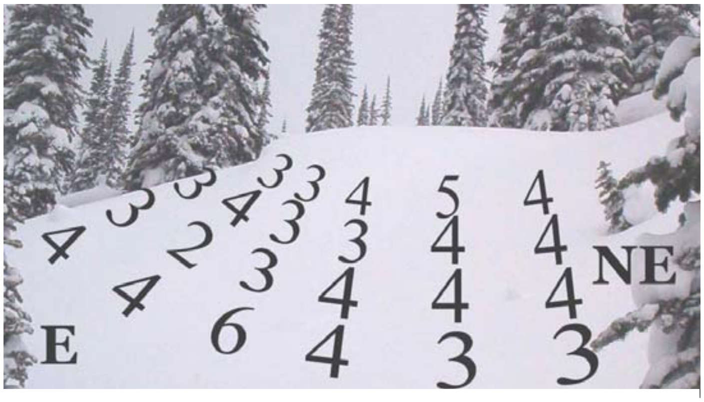

Fig. 7. Array of closely spaced rutschblock tests on Mt Fidelity on 2004-03-18. The weak layer consisted of facets on a sun crust. The scores were mostly lower on the sunnier (left) side of the roll where the crust and facets were better developed than on the shadier (right) side.

anticipate but understanding the cause (e.g. dry snow on a surface melted by solar radiation) can help.

In many cases, sun crusts become thinner and then disappear as the terrain wraps around towards shadier aspects. Consequently, facets formed by DW faceting before the sun crust froze will also diminish as the aspect becomes shadier.

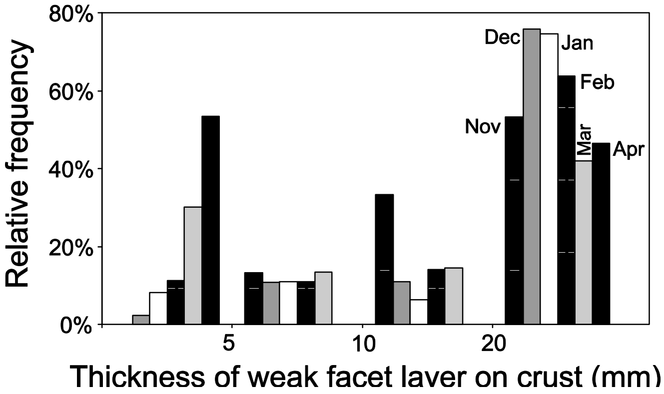

Fig. 8. Thickness of facet layers on crusts from 2943 fractures in almost 1000 sets of compression tests over the winter months in the Columbia Mountains, 1996-2004. The portion of thin facet layers (not more than 5 mm thick) increases from November to April.

5. Discussion

As noted previously, $|TG_{10}|$ in the Columbia Mountains is *usually* not sufficient over long enough periods to form thick layers of well developed facets, although Hägeli and McClung (2003) note an important exception that occurred in the winter of 2000-01. 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. 8) suggests a process which concentrates the temperature gradient 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 dry-on-wet faceting (Fig. 6) than for facets that form on an already frozen crust.
- In the spring, direct solar radiation that melts the snow surface is sometimes followed by local convective snow showers. The wet layers are usually thin (limited latent heat) and the facet layers on spring crusts are often thin (Fig. 8).
- Cam Campbell (2004) gives an example of facets on a crust that are better developed on the sunny aspects (Fig. 7) where the crust was thicker, 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 less sunny aspects is not uncommon.
- Although the recent studies (Jamieson and others, 2001a, b; Hägeli and McClung, 2003; Jamieson and Langevin, 2004) have identified cases of dry-on-wet faceting in the Columbia Mountains, while reviewing the literature I found no cases of faceting of new snow, DF particles or rounded grains above a *frozen* crust when $|TG_{10}| < TG_F$. This does not disprove the theories of Adams and Brown (1989a) and Colbeck (1991); however, the lack of observations suggests the process may be uncommon when $|TG_{10}| < TG_F$. The lack of observations is intriguing since faceting of dry snow on a crust should be easier to observe than dry-on-wet faceting, which is variable over terrain and rarely lasts longer than a day.

6. Conclusions

- Facets that form at the base of dry snow overlying wet layers form an important portion of the poorly bonded crusts 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) on crusts are more common in March and April when sun crusts are more common.

- The cause of a crust is an important clue as to where it may be poorly bonded: Rain crusts may be poorly bonded within a narrow elevation band where dry snow fell on a wet layer with sufficient liquid water content (latent heat) to cause faceting. When dry snow falls on a snow surface melted by warm air, the resulting crust may be poorly bonded below a specific elevation. After melting by direct solar radiation, the snow surface can by buried by dry snow, sometimes from a convective cell, resulting in faceting of the dry snow and hence a poor bond. In this situation the bonding may be weaker on the sunnier slopes than nearby shadier slopes. In this situation, snowpack tests on more southerly slopes are more likely to reveal the poor bond to the crust.
- Because many surface hoar and many facet layers on crusts are thin, snowpack tests such as rutschblock, shovel or compression tests are helpful for locating the weak layers or interfaces. Understanding the cause of the crust can improve site selection for snowpack tests.

Acknowledgements

This topic attracted thoughtful comments and observations from Sam Colbeck, Charles Fierz, John Hetherington, Ed LaChapelle, Bruce McMahon, Mark Moore, Ron Perla and Chris Stethem. Thanks also to Alec van Herwijnen and Paul Langevin for proofreading a draft of this article.

The Avalanche Control Section of Glacier National Park including Dave Skjönsberg, Bruce McMahon, John Kelly and Jeff Goodrich as well as Mike Wiegele, Derek Frechette and the guides of Mike Wiegele Helicopter Skiing provided a stimulating environment for field research.

For financial support I am grateful to the BC Helicopter and Snowcat Skiing Operators Association (BCHSSOA), the Natural Sciences and Engineering Research Council of Canada, Mike Wiegele Helicopter Skiing, Canada West Ski Areas Association (CWSAA) and the Canadian Avalanche Association. The supporting member of the BCHSSOA include Baldface Mountain Lodge, Bella Coola Heli Sports, Black Tusk Helicopter Inc., Canadian Mountain Holidays, Cariboo Snowcat Skiing and Tours, Cat Powder Skiing, Chatter Creek Mountain Lodges, Coast Range Helskiing, Crescent Spur Heli-skiing, Great Canadian Heli-skiing, Great Northern Snow Cat Skiing, Highland Powder Skiing, Island Lake Resort Group, Klondike Heliskiing, Last Frontier Heliskiing, Mica Heli Guides, Monashee Powder Adventures, Northern Escape Heli-skiing, Peace Reach Adventures, Powder Mountain Snowcats, Purcell Helicopter Skiing, R.K. Heli-Skiing, Retallack Alpine Adventures, Robson Helimagic, Selkirk Tangiers Heli-Skiing, Selkirk Wilderness Skiing, Snowwater Heli-skiing, TLH Heliskiing, Valhalla Powdercats, Whistler Heli-Skiing and White Grizzly Adventures. The supporting members of Canada West Ski Areas Association include Apex Mountain Resort, Banff Mount Norquay, Big White Ski Resort, Hemlock Ski Resort, Intrawest Corporation, Kicking Horse Mountain Resort, Mt. Washington Alpine Resort, Silver Star Mountain Resorts, Ski Marmot Basin, Sun Peaks Resort, Sunshine Village, Whistler Blackcomb, Whitewater Ski Resort, and Resorts of the Canadian Rockies including Skiing Louise, Nakiska, Kimberley Alpine Resort, Fortress Mountain and Fernie Alpine Resort.

References

Adams, E.E., Brown, R.L., 1983. Metamorphism of dry snow as a result of temperature gradient and vapour density differences. *Ann. Glaciol.,* 4, 3-9.

Adams, E.E., Brown, R.L., 1989. A constitutive theory for snow as a continuous multiphase mixture. *Int. J. Multiphase Flow*, 15(4), 553-572.

Akitaya, E., 1974. Studies on depth hoar. *Contrib. Inst. Low Temp. Sci., Ser. A*, **26**, 1-67.

Atwater, M., 1954. Snow avalanches. *Scientific American*, 190(1), 26-31.

Birkeland, K.W., Johnson, R.F., Schmidt, D.S., 1998. Near-surface faceted crystals formed by dirurnal recrystalization: a case study of weak layer formation in the mountain snowpack and its contribution to snow avalanches. *Arct. Alp. Res.,* 30(2), 200-204.

Brun, E., Martin, E., Simon, V., Gendre, C., Coleou, C., 1989. An energy and mass model of snow cover suitable for operational avalanche forecasting. *J. Glaciol.* 35(121), 333-342.

CAA, 2002. *Observation Guidelines and Recording Standards for Weather, Snowpack and Avalanches*. Canadian Avalanche Association. Revelstoke, BC, Canada.

Campbell, C.P., 2004. *Spatial variability of slab stability and fracture properties in avalanche start zones*. MSc thesis, Dept. of Civil Engineering, University of Calgary, Calgary, Canada, 245 pp.

Campbell, C.P., Jamieson, J.B., 2004. Spatial variability of rutschblock results in avalanche start zones. Submitted to the International Snow Science Workshop.

Colbeck, S.C., 1991. The layered character of snow covers. *Reviews of Geophysics* 29(1), 88-96.

Colbeck, S.C., Jamieson, J.B., 2001. The formation of faceted layers above crusts. *Cold Reg. Sci. Technol.*, **33**(2-3), 247-252.

Colbeck, S.C., Akitaya, E.,Armstrong, R., Gubler, H., Lafeuille, J., Lied, K., McClung, D., Morris, E., 1990. *The international classification for seasonal snow on the ground.* International Association of Scientific Hydrology. International Commission for Snow and Ice.

Fierz, C., 1998. Field observations and weak layer modelling of weak-layer evolution. *Ann. Glaciol.,* 26, 7-13.

Fierz, C., Riber, P., Adams, E.E., Curran, A.R., Föhn, P.M.B., Lehning, M., Plüss, M., 2003. Evaluation of snow-surface energy balance models in alpine terrain. *Journal of Hydrology*, 282, 76-84.

Fukuzawa, T., Akitaya., E., 1993. Depth-hoar crystal growth in the surface layer under high temperature gradient. *Ann. Glaciol.*, 18, 39-45.

Greene, E., Johnson, G., 2003. Characterization of a deep instability. *In* Stevens, J.R., *ed. International Snow Science Workshop 2002, 29 September—4 October 2002, Penticton, British Columbia, Proceedings.* Victoria, B.C., B.C. Ministry of Transportation, Snow Avalanche Programs, 491-498.

Hägeli, P., McClung, D.M., 2003. Avalanche characteristics of a transitional snow climate – Columbia Mountains, British Columbia, Canada. *Cold Reg. Sci. Technol.* 37(3), 255-276.

Jamieson, J.B., Fierz, C., in press. Heat flow from wet to dry snowpack layers and associated faceting. *Ann. Glaciol.,* 38.

Jamieson, B., Geldsetzer, T., Stethem, C., 2001a. Forecasting for deep slab avalanches. *Cold Reg. Sci. Technol.,* 33(2-3), 275-290.

Jamieson, B., Geldsetzer, T. and Stethem, C., 2001b. Case study of a deep slab instability and associated dry slab avalanches. Proceedings of the International Snow Science Workshop in Big Sky Montana, October 2000. American Avalanche Association, PO Box 1032, Bozeman, Montana, 59771, USA, 101-108. Reprinted in Avalanche News 60, 29-36.

Jamieson, J.B., Johnston, C.D., 1992. Snowpack characteristics associated with avalanche accidents. *Can. Geotech. J.*, 29, 862-866.

Jamieson, B., van Herwijnen, A., 2002. Preliminary results from controlled experiments on the growth of faceted crystals above a wet snow layer. *In* Stevens, J.R., *ed. International Snow Science Workshop 2002, 29 September—4 October 2002, Penticton, British Columbia, Proceedings.* Victoria, B.C., B.C. Ministry of Transportation, Snow Avalanche Programs, 337-342.

Jamieson, B., Langevin, P. 2004. Faceting above crusts and associated slab avalanching in the Columbia Mountains. In press for the Proceedings of the 2004 International Snow Science Workshop in Jackson Hole, Wyoming, USA. American Avalanche Association.

Male, D.H., Gray, D.M., 1980. Snowcover ablation and runoff. In: D.H. Male and D.M. Gray (eds.), *Handbook of Snow*. Pergamon Press, Toronto, Canada.

McClung, D.M., Schaerer, P.A., 1993. *The Avalanche Handbook.* The Mountaineers, Seattle, Washington, U.S.A.

Miller, D.A., Adams, E.E., Brown, R.L., 2003. A microstructural approach to predict dry snow metamorphism in generalized thermal conditions. *Cold Reg. Sci. Technol.* 37(3), 213-226.

Ozeki, T., Akitaya, E., Suzuki, K., 1995. Observations of sun crust formation. Proceedings International Snow Science Workshop, Snowbird, Utah, U.S.A., 30 October-3 November 1994, 2-13.

Moore, M., 1982. Temperature gradient weakening near crusts in a maritime snowpack. Presented at the 1982 International Snow Science Workshop in Bozeman, Montana.Seligman, G., 1936. *Snow Structure and Ski Fields*. International Glaciological Society, Cambridge, 555 pp.

Schleiss, V.G., 1989. *Rogers Pass Avalanche Atlas, Glacier National Park, British Columbia, Canada.* Parks Canada, Revelstoke, BC.

Wankeiwicz, A., 1979. Movement of liquid water in snow. In: S.C. Colbeck and M. Ray (eds.), Proceedings of a Meeting on Modeling of Snow Cover Runoff, Hanover, New Hampshire, 26-28 Sept. 1978). Cold Regions Research and Engineering Research Laboratory, Hanover, NH, USA, 222-252.