CASE STUDY OF A DEEP SLAB INSTABILITY AND ASSOCIATED DRY AVALANCHES

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ABSTRACT

This study considers the predictive merit of weather and snowpack data for avalanches that released throughout the winter on a layer of faceted crystals that formed on a rain crust in November 1996 in the North Columbia Mountains of western Canada. The facet-crust combinations formed as a result of a cold air mass cooling a layer of dry snow on top of a rain-wetted layer. The highly ranked variables associated with natural avalanches include previous avalanche activity, accumulated snowfall over several days, changes in air temperature over four to five days, snowpack properties, including a shear frame stability index, and the difference in hardness between the facet layer and the crust. Increases in air temperature over four to five days correlate with increased avalanche activity, however current theories for warming do not explain decreased stability especially where the slab is thick. We argue that the fractures that release deep slab avalanches may be initiated where the slab is locally thin.

Keywords: Avalanche forecasting, avalanche formation, faceted crystals, snow cover stability, snow cover structure, snow stratigraphy

1. INTRODUCTION

Avalanche forecasters report that the stability of deep slabs is difficult to forecast. Consequently, large explosive charges are sometimes used to test the stability of deep slabs (Wilson, 1978).

In mid-November 1996 a weak layer of faceted crystals, subsequently referred to as November facets, formed on a much harder crust. This facet-crust combination was widespread, releasing fatal avalanches in the Coast Range, the Columbia Mountains and in the Rocky Mountains of western Canada. In the North Columbia mountains, dry slab avalanches, many over 150 cm thick, were reported on this layer until mid March 1997 and many wet slab avalanches, not considered in this study, occurred in May and June 1997.

Manual snowpack and conventional meteorological measurements are used to determine the dominant weather and snowpack factors associated with the formation of the facet-crust combination and the occurrence of the deep slab avalanches that occurred naturally on this facet-crust combination.

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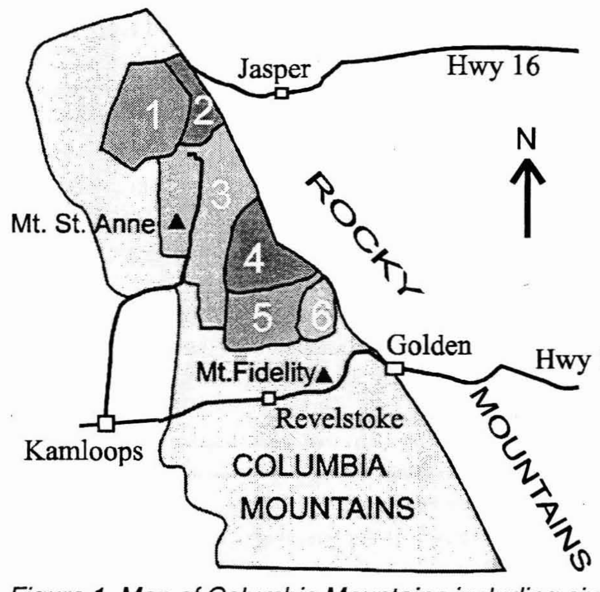

Figure 1. Map of Columbia Mountains including six forecast areas as well as locations of weather stations and study plots at Mt. St. Anne and Mt. Fidelity. The North Columbia Mountains are north of Highway 1.

2. LITERATURE REVIEW

Atwater (1954) identified eight weather and two snowpack factors associated with avalanching. Focusing for large avalanches near Alta, Utah, Perla (1970) found precipitation and wind direction to be the most important factors. McClung and

Table 1. Definitions of weather and snowpack variables

Meteorological measurements		
HS	m	Height of snow on ground, measured vertically
HN	cm	Height of new snow that fell in 24 hours
T_{MIN}	°C	Minimum air temperature in 24 hours
T_{MAX}	°C	Maximum air temperature in 24 hours
Calculated meteorological variables		
HST	cm	Sum of HN since last day with HN < 0.3 cm
$\Sigma_M HN$	cm	Sum of HN over the last M days including the current day
$\Delta_M T_{MIN}$	°C	Change in T_{MAX} over last M days
$\Delta_M T_{MAX}$	°C	Change in T_{MIN} over last M days
Snowpack measurements		
H_{SLAB}	cm	Slab thickness, measured vertically
σ_V	kPa	Load: weight per unit horizontal area of slab overlying weak layer
F		Grain type of weak layer (Colbeck et al., 1990)
E	mm	Largest dimension of particles (Colbeck et al., 1990), often a range
T_{WL}	°C	Temperature of weak layer
TG	°C/m	Temperature gradient of weak layer
h_{WL}		Hardness index of weak layer of facets using hand hardness scale
h_{SUB}		Hardness index of crust (substratum) below weak layer
Calculated snowpack variables		
Δh_{SUB}		Hardness index of crust minus h_{WL}
S_{N38}		Stability index for natural avalanches (Jamieson, 1995)

Tweedy (1993) report that various measures of precipitation, wind direction and wind speed correlated best with avalanche activity along the highway through Kootenay Pass, British Columbia. Avalanche books for recreationists (e.g. Fredston and Fesler, 1994) consistently emphasize the importance of precipitation, wind, air temperature and snowpack stratigraphy for forecasting avalanche hazard.

Slab avalanches require a slab consisting of one or more layers of cohesive snow overlying a weak layer or interface. Although weak layers of faceted crystals can form under crusts (e.g. Seligman, 1936, p. 70) the weak layer in this study consists of faceted crystals overlying a crust. When cold dry snow falls on a wet snow surface, latent heat from the wet layer creates a temperature gradient favourable to faceting of the overlying dry snow (Armstrong, 1985; Fukuzawa and Akitaya, 1993; Birkeland, 1998; Colbeck and Jamieson, 2000). Once buried by subsequent snowfalls, the faceted layer may remain weak while overlying layers gain strength and stiffness due to equilibrium metamorphism which is usually dominant in the deep snowpack of the Columbia Mountains.

3. METHODS

Weather measurements were averaged from automatic weather stations at Mt. Fidelity (1905 m) and Mt. St. Anne (1900 m) and checked with manual observations. Mt. Fidelity and Mt. St. Anne (Figure 1) are at tree-line and close to the starting elevations of many of the avalanches considered in this study. For this study, daily values were obtained by combining the morning reading with the previous afternoon reading to obtain values for the 24-hour period similar to the reporting period for avalanches. In this study storm snow HST is the accumulated the daily snowfall values from meteorological instruments since the last day with less than 0.3 cm of snowfall.

Manual snow profiles (CAA, 1995) observed periodically during the winter include measurements of slab thickness H_{SLAB}, temperature of the weak layer T_{WL}, temperature gradient across the weak layer TG from temperature measurements 5 cm above and 5 cm below the facet-crust interface, grain form F, and grain size E of the weak layer (Colbeck et al., 1990). The hand hardness index (Geldsetzer and Jamieson, 2000) for the weak layer (h_{WL}) and the crust below the weak layer (h_{SUB}) were also observed. The load (weight per unit horizontal area) over the weak layer is calculated from density and thickness of the overlying layers. Alternatively, the load was determined by dividing the average weight of core samples from the surface to the weak layer by the cross-sectional areas of the cylindrical sampling tube. The shear strength of the weak layer was measured with the

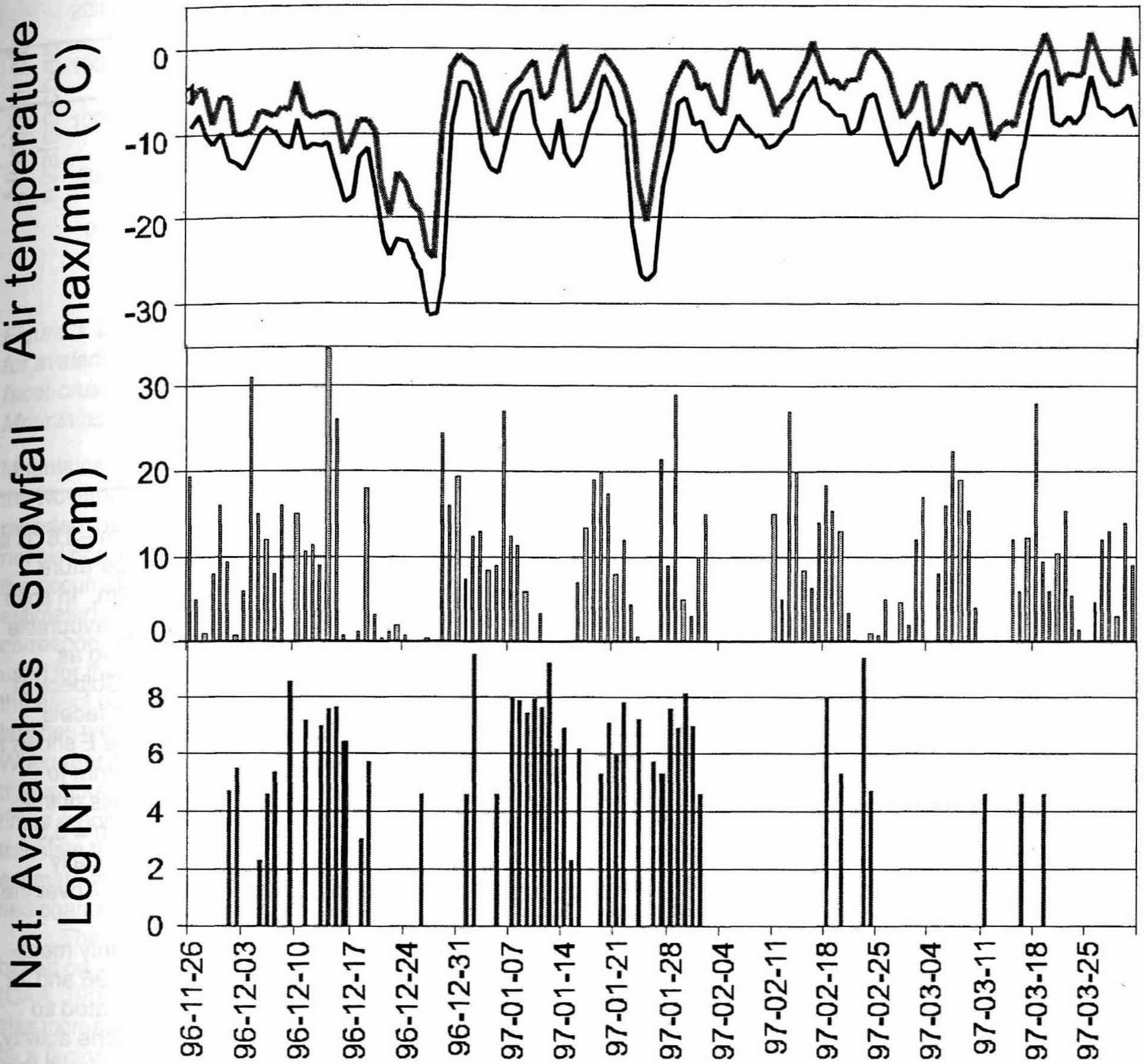

Figure 2. Weather and natural avalanche activity for facet-crust combination during winter 1996-97.

shear frame test as described by Jamieson and Johnston (in press). The strength is the ratio of maximum force to the area of the frame, which is then adjusted for size effects (Sommerfeld, 1980; Föhn, 1987) but not for normal load since Jamieson and Johnston (1998) did not find the normal load effect on weak layers of facets to be significant.

4. OBSERVATIONS

4.1 Formation

From 9 to 13 November 1996, 28 mm of rain and 16 cm of snow fell at Mt. Fidelity, and maximum temperatures were above freezing, forming a wet snow layer on the surface. From 14 to 17 November, 15 cm of dry snow fell with temperatures below freezing. From 18 to 23 November, 8 cm of snow fall and the maximum temperature ranged from –9.5°C to –17.0°C (average –13°C). Assuming the snow surface temperature was approximately equal to the air temperature and allowing settlement of 40% in the lower, warmer, dry layer over 4 to 9 days, the average temperature gradient in the dry snow would have exceeded 10°C/m (necessary for faceted crystals to form) while the wet layer released latent heat.

No snow fell on 24 and 25 November at Mt. Fidelity, but an average of 20 cm fell on 26 November at Mt. Fidelity and Mt. St. Anne (T_{MAX} –6.5°C) (Table 1), providing sufficient overburden for slab avalanches.

Table 2. Snowpack properties for slab, weak layer of facets and crust at Mt. St. Anne

Date	HS (cm)	H_{SLAB} (cm)	Load (kPa)	F	E (mm)	T_{WL} (°C)	TG (°C/m)	h_{WL}	Δh_{SUB}	S_{N38}
96-12-11	170	87	1.58	4c	1.5	-3.6	-8	2	3	1.2
96-12-14	172	89	1.58	4	1.5	-3.3	-7	2	3	1.5
96-12-20	178	109	2.10	4	1.5	-3.0	-6	2.7	2	1.1
97-01-10	230	161	4.27	4	2	-3.2	-4	3	2	0.9
97-01-18	225	163	4.47	4	1.5-2	-2.6	-4	3	2	0.7
97-01-27	252	180	5.47	4	2	-3.0	-3	3.7	1	0.7
97-02-04	265	205	6.31	4	2	-2.4	-3	3	2	0.8
97-02-11	257	192	6.36	4	2	-3.7	-3	2.7	1	0.5
97-02-19	283	217	6.83	4	1.5-2	-2.3	-3	3.7	1.3	1.1
97-02-25	272	210	6.66	4	2.5-3	-2.0	-2	3.3	1.7	1.1
97-03-04	312	243	8.32	4	1.5-2	-2.3	-4	3.7	1.3	0.9
97-03-13	318	258	7.43	4	2-2.5	-2.2	-5	3.3	1.7	1.3
97-03-21	302	261	8.93	4	1.5-2	-2.0	-1	3.3	1.7	1.2

A snow profile observed beside the Mt. Fidelity weather station on 1 December 1996 shows a 6-cm thick layer of facets (faceted crystals) overlying a frozen crust. The lower 2 cm of the faceted snow had a hardness of 4F ($h = 2$) and the crust had a hardness of P ($h = 4$).

By 11 December 1996 at Mt. St. Anne, the top of the crust was 87 cm below the surface. A 6-cm layer of facets ($h = 2$) was observed over the knife-hard crust ($h = 5$). On other profiles in the Columbia Mountains north of Mt. Fidelity, the crust was reported as knife-hard, probably because of more rain from 11 to 13 November 1996 than at Mt. Fidelity.

4.2 Weather

To give representative values for the North Columbia Mountains, T_{MIN}, T_{MAX}, and HN from Mt. St. Anne and Mt. Fidelity are averaged in Figure 2 for the period from 26 November 1996 to 31 March 1997. The North Columbia Mountains were influenced by arctic air from 21 to 28 December 1996 and 24 to 26 January 1997. During these periods there was little snowfall. Storms with consecutive days with HN > 10 cm occurred frequently throughout the winter but neither the snowfall amounts nor temperatures were unusual.

4.3 Snowpack

Manual snowpack measurements were made at the Mt. St. Anne Study plot on thirteen days over the 100-day period from 11 December 1996 to 21 March 1997 (Table 2). Except for the pronounced facet-crust combination, snowpack properties during the winter were not unusual. The height of snow on the ground reached over 300 cm by early March at Mt. St. Anne and Mt. Fidelity. The load increased from 1.58 kPa to almost 9 kPa. The temperature of the facets increased from −3.6 °C to −2.0°C while the magnitude of the temperature gradient decreased from 8°C/m to 1°C/m. In spite of these conditions which are generally favourable to rounding, the grain type F was reported as rounded facets (Class 4c according to Colbeck at al., 1990) on 11 December 1996 and as facets (Class 4) every day after that. Grain size E shows a slight increase over the winter from 1.5 mm to approximately 1.5 to 2 mm. The hardness of the weak layer increased from $h = 2$ (4F) to $h = 3.3$ (1F+). The difference in hardness was initially pronounced ($\Delta h = 3$) but decreased to 1.7 over the 100-day period.

Since snowpack variables were only measured 13 times between 11 December 1996 and 12 March 1997, daily values must be calculated so they can be correlated with daily avalanche activity. Daily values of load σ_V and S_{N38} are calculated from field measurements taken approximately once per week and daily values of snowfall as described in Jamieson (1995). The calculation S_{N38} assumes that the shear strength of the weak layer increases linearly between measurement days.

The other variables, which are expected to change monotonically and more slowly as the winter progresses, are calculated from a power law (Johnson and Jamieson, in preparation)

$$V/V_1 = (t/t_1)^A \quad (1)$$

where V is the variable, t is time, V_1 is the fitted value of the variable at $t_1 = 1$ day and A is an empirical constant.

4.4 Avalanche activity

We used natural avalanches from six helicopter skiing operations in the North Columbia

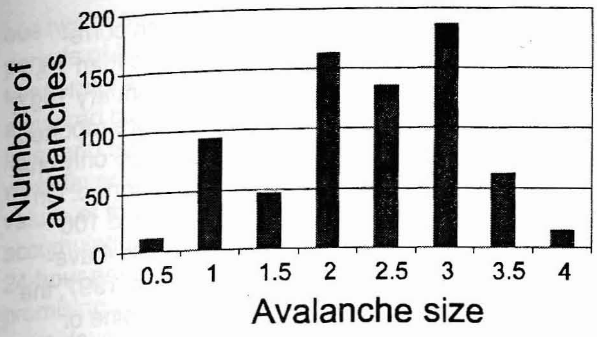

Figure 3. Distribution of dry slab avalanches by size for avalanches reported to have slid on November facet-crust combination in the North Columbia Mountains.

Mountains (Figure 1) in which the avalanche slid on the November crust, in the opinion of the guide who reported the avalanche. Since heliskiing guides do not ski or observe each valley in the area each day, the occurrence date of some avalanches was estimated. The avalanche "day" used by guides corresponds approximately to the 24-hour period used for the weather data in this study. To minimize the effect of inaccurate dating of natural avalanches we focus on days with many avalanches. When reporting more than two similar avalanches throughout the large forecast areas, guides sometimes report "few" or "numerous" avalanches, we translate these into 3 and 10, respectively, to estimate the number of avalanches with the specified characteristics.

The size classification of an avalanche is based on an estimate of its destructive potential (CAA, 1995) and ranges from 1 to 5. As avalanche size increases by one, the typical mass increases by a factor of 10. In our data, class 1 (small) natural avalanches are not consistently reported. However, we define a daily index of natural avalanche activity that weights larger avalanches

$$N10 = \Sigma N_i 10^{i-1} \qquad (2)$$

where N_i is the number of avalanches of size i reported, for avalanches of size 1 to 5. Half-sizes, e.g. 2.5, are rounded up to the nearest integer. The distribution of avalanches by size is shown in Figure 3 and the number of size 3 and 4 avalanches indicates the importance and destructive potential of these avalanches released by this facet-crust combination. Using the typical mass associated with the various size classes (McClung and Schaerer, 1993, p. 253), over 700 dry slab avalanches were reported on the November facets by 31 March 1997 with a total estimated mass of over 500 000 tonnes.

5. RESULTS

5.1 Rank correlations

To assess the predictive merit of previous avalanche activity, we define $\Sigma_M N10$ as the sum of N10 over the previous M days. The measures of previous avalanche activity are correlated with N10 in Table 3. Due to the autocorrelations of these variables, the significance levels are not as good as estimated. The four correlations with the best significance levels are for the three previous days, indicating the persistence of avalanche activity on a particular layer over time.

Table 3. Rank correlations of previous natural avalanche activity with natural avalanche activity N10

Variable	Min.	Max.	Correlation *R*	*p*
Σ_1N10	0	13300	0.40	4.E-06
Σ_2N10	0	13400	0.47	4.E-08
Σ_3N10	0	15370	0.47	3.E-08
Σ_4N10	0	17100	0.42	9.E-07
Σ_5N10	0	19710	0.42	7.E-07

Avalanche activity N10 is correlated with daily values of snowpack variables S_{N38}, σ_V, Δh_{SUB} and T_{WL} in Table 4. All correlations are significant ($p < 0.01$). Physical interpretations of the correlations with T_{WL} and Δh_{SUB} are possible: Increasing T_{WL} favors bonding and strength gain for the facets. Also, the decrease in avalanche activity as Δh_{SUB} decreases may be due to a decreasing stress concentration where the stiffness changes at the facet-crust interface. However, T_{WL} and σ_V may have little predictive merit for future deep slab instabilities. S_{N38} is more interesting; rather than increasing or decreasing monotonically, it varies through the winter and is negatively correlated with avalanche activity. Because this strength-load ratio has a physical interpretation, it may have predictive merit for other deep instabilities.

In Table 5, avalanche activity N10 is correlated with meteorological variables HST, T_{MIN}, T_{MAX} and changes in maximum and minimum air temperature over 1 to 5 days, $\Delta_M T_{MIN}$ or $\Delta_M T_{MAX}$, as well

Table 4. Rank correlations of daily values of snowpack variables with natural avalanche activity N10

Variable	Min.	Max.	Correlation *R*	*p*
S_{N38}	0.5	1.26	-0.19	3.E-02
σ_V (kPa)	0.81	9.55	-0.30	6.E-04
Δh_{SUB}	1.3	3.9	0.30	7.E-04
T_{WL} (°C)	-4.6	-2.2	-0.30	7.E-04

Table 5. Spearman rank correlations of daily meteorological variables with natural avalanche activity N10 over 126 days

Variable	Min.	Max.	Correlation R	p
Σ_1HN (cm)	0	35	0.01	9.E-01
Σ_3HN (cm)	0	70	0.18	4.E-02
Σ_7HN (cm)	0	110	0.30	6.E-04
Σ_{11}HN (cm)	27	163	0.40	4.E-06
Σ_{13}HN (cm)	28	195	0.41	2.E-06
Σ_{15}HN (cm)	49	205	0.42	1.E-06
Σ_{17}HN (cm)	64	229	0.33	1.E-04
HST (cm)	0	168	0.14	1.E-01
T_{MAX} (°C)	-25	2	0.05	6.E-01
Δ_1T_{MAX} (°C)	-8	16	0.03	7.E-01
Δ_2T_{MAX} (°C)	-12	22	0.11	2.E-01
Δ_3T_{MAX} (°C)	-16	24	0.17	6.E-02
Δ_4T_{MAX} (°C)	-18	23	0.22	1.E-02
Δ_5T_{MAX} (°C)	-19	23	0.18	4.E-02
T_{MIN} (°C)	-31	-2	0.10	3.E-01
Δ_1T_{MIN} (°C)	-12	18	-0.03	7.E-01
Δ_2T_{MIN} (°C)	-17	23	0.06	5.E-01
Δ_3T_{MIN} (°C)	-19	27	0.12	2.E-01
Δ_4T_{MIN} (°C)	-22	27	0.17	5.E-02
Δ_5T_{MIN} (°C)	-24	27	0.14	1.E-01

as accumulated snow fall over periods up to 17 days. For the accumulated snowfall Σ_MHN, the most significant correlation is obtained over 15 days. This correlation is influenced by the 12-day period with little snowfall from 17 to 28 December and the three following days with substantial snowfall before N10 increased. It is likely that the correlations over such long periods are statistical rather than physical relationships and lack predictive merit for other deep instabilities. Nevertheless, the positive correlations for period of 3 days and longer are better than for HST indicating that a single day without snowfall may not effectively interrupt the response of a deep weak layer to increased load.

T_{MIN} and T_{MAX} are not significantly correlated with avalanche activity. The most significant correlations for temperature change are over four and five days for T_{MAX} and T_{MIN}, respectively, suggesting that multi-day temperature changes may affect the stability of deep slabs. These correlations are positive, associating increased avalanche activity with warming.

5.2 Deep slab avalanches with little recent snowfall

During the winter, forecasters reported many large spontaneous avalanches with little or no recent snowfall. There were 32 days for which Σ_1HN < 5 cm and Σ_3HN < 10 cm, which corresponds to increases in slab load of less than 1% per day after σ_V reached 4 kPa on 4 January 1997. On 24 of these days no avalanches were reported to have occurred. On 26 December 1996 only one class 3 avalanche (N10 = 100) was reported. On the remaining seven days, N10 exceeded 100 indicating multiple avalanches or a class 4 avalanche. On 14 January and 24 February 1997, the wind speed was above critical level for nine or more hours so the avalanches on these days may have been caused by wind blown snow increasing the load in avalanche start zones. The other six days exemplify the challenge faced by avalanche forecasters during the winter. With little or no recent snowfall or wind loading, large avalanche occurred spontaneously.

Such avalanches are often attributed to changes in air temperature or snow surface temperature. However, the temperature changes would not have been conducted down to the faceted layer anywhere with average snowpack properties since the average thickness of the avalanches in this study exceed 120 cm (perpendicular to a 38° slope) by 10 January 1997. McClung and Schaerer (1993, p. 82) explain that warming can release thin slabs by reducing the stiffness of a significant fraction of slab depth. We hypothesize that the temperature effect must be coupled with a start zone where the slab thickness is highly variable. One of the forecasters, B. Howatt (personal communication, 1997), confronted with this difficult series of avalanches, reported that by mid-winter only start zones with a relatively thin snowpack or rocky outcrops were producing the deep avalanches, a statement which supports our hypothesis. Also, the layer of faceted crystals or depth hoar may be more developed and weaker near rock outcrops (Logan, 1993), favouring avalanche initiation.

Three large deep slab avalanches occurred on 26 January 1997 after five days of marked cooling. Seligman (1936, p. 324) hypothesized that cooling of the surface could cause sufficient contraction and related stresses to trigger avalanches; however, no theory has yet been developed to support this hypothesis. Further, any theory must take into account the stress dissipation of snow.

6. SUMMARY

During the winter of 1996-97, deep slab avalanches starting on the November facets were associated with avalanche activity over the previous two or three days, accumulated snowfall over periods of three or more days, increasing air temperature over four to five days, the presence of a marked hardness difference between the facet layer and the underlying crust, strength tests of the weak layer that result in planar fractures, and low values of the shear frame stability index S_{N38}. The accumulations of snowfall that was reset to zero by 24-hour periods without precipitation was not as promising as accumulated snowfall over three or more days.

Given a widespread meteorological condition that forms a layer of facets on a crust, snowpack characteristics observed in a study plot can be useful predictors of avalanche activity over time within the area of the formative weather. While we did not consider roving snowpack observations at sites that vary from day to day, such observations at carefully chosen sites may be able to identify key snowpack characteristics and their variation over terrain.

Warming over four to five days may reduce the stability of deep slabs, especially where the snowpack is locally thin or has rocky outcrops. Experienced forecasters report occasional unexpected avalanches during periods of cooling with little or no precipitation. Research into the effect of rapid cooling on the stability of deep slabs may prove valuable.

The stability of start zones where snowpack properties are highly variable may be less stable, unstable for longer periods and more difficult to predict. Because of this spatial variability, remote meteorological and snowpack measurements, by themselves, will not be adequate for forecasting avalanches in specific start zones.

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