FRACTURE CHARACTER IN COMPRESSION TESTS

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ABSTRACT: Stability tests are widely used to identify and qualify potential failure layers for slab avalanches. As an addition to stability test scores, some avalanche safety programs have recorded the character of fractures for many years. Researchers at the University of Calgary have been systematically classifying fractures in compression and rutschblock tests since the winter of 1996-97. The classification system was refined in December 2002 and presently comprises five categories: Progressive Compression (PC), Resistant Planar (RP), Sudden Planar (SP), Sudden Collapse (SC) and non-planar Break (B). Some 4621 fractures were classified in over 2200 compression tests performed at study slopes in the Columbia Mountains of British Columbia, Canada. Of these, more than 1000 compression tests were performed on recently skier-tested slopes. Specific snowpack characteristics, including hardness difference and difference in crystal size across the failure layer, associated with the different fracture characters were identified. Data from skier-tested slopes show that fracture characterization can improve the interpretation of compression test results. Sudden fractures (Sudden Collapse and Sudden Planar) are more often the failure layer of slab avalanches than other fractures. Furthermore, limited observations suggest that the evolution of fracture character for weak layers can provide information on the potential for skier-triggered dry slab avalanches to occur.

KEYWORDS: stability test, avalanche forecasting, fracture initiation, fracture propagation, stability evaluation.

1. INTRODUCTION

The compression test is a stability test widely used by avalanche workers and researchers to identify potential weak layers and estimate the stability of the overlying slab. The test is relatively easy to perform and it has been shown that the compression test score correlates with the frequency of skier-triggered slab avalanches (Jamieson, 1999; van Herwijnen and Jamieson, 2003).

For decades, avalanche professionals have recognized that the compression test score is not the only result relevant to avalanche forecasting. Additional information about the character of the fracture can provide valuable information. For instance, since 1981, the Canadian Avalanche Association's Guidelines for Weather, Snowpack and Avalanche Observations have assigned special attention to collapsing fractures in shovel tests (NRCC, 1981).

Systems for classifying fractures have been proposed since the late 1990's. In 1999, Birkeland and Johnson proposed a three level shear quality description: Q1 is a clean fast shear or a collapse, Q2 is an average shear and Q3 an irregular shear. Johnson and Birkeland (2002) summarized six years of shear quality data from stuffblock, compression and rutschblock tests. Comparing the data with nearby signs of instability in the region they reported improved interpretation of stability test results, particularly for tests with high scores. In Switzerland, a rating system for the fracture type (clean, partly clean, rough) in stability tests is in use (Schweizer and Wiesinger, 2001). Schweizer and Jamieson (2003) report that there is a significant difference in fracture character in rutschblock tests between human triggered slopes and slopes not triggered.

Using a system proposed by Jamieson (1999) and refined by van Herwijnen and Jamieson (2003), this study analyzes over 4500 fractures observed in compression tests performed in the Columbia Mountains of western Canada. The objectives are to determine specific snowpack characteristics associated with the different fracture characters and determine whether the proposed system can improve the interpretation of compression

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test results for avalanche forecasting.

2. METHODS

In 1997 researchers from the University of Calgary started systematically classifying fractures in compression tests (Figure 1) performed in the Columbia mountains of British Columbia, Canada, using a four level description of fracture character (Jamieson, 1999; van Herwijnen and Jamieson, 2002). After analyzing data from five winters of using this system, it was refined in December 2002 (van Herwijnen and Jamieson, 2003). Presently a five level description of fracture character is used by field workers of the University of Calgary, as well as by several avalanche safety operations in Canada (Table 1) .

The definitions of PC, SC and B have not changed since introduced in 1997. This enabled us to use some of the older data in the analysis.

Figure 1: The compression test is a stability test. The column of snow is loaded by repeatedly tapping on the shovel. The first ten taps are with the fingertips, moving the hand from the wrist, followed by ten taps moving the forearm from the elbow and finally ten taps moving the whole arm from the shoulder.

In all, 4621 fractures in compression tests were classified as PC (38%), RP (9%), SP (15%), SC (30%) and B (8%).

At each test site we usually performed three compression tests and observed a snow profile, giving us information about crystal type (*F*), crystal size (*E*), layer thickness (*Th*), density (ρ), depth (*D*) and hand hardness of snowpack layers (CAA, 2002). This enabled us to relate snowpack properties to fracture character in compression tests. Each layer that failed in a compression test is referred to as "weak layer" (*WL*). Special attention was given to weak layer properties as well as the properties of the layer above (*A*) and the layer below (*B*) the weak layer.

Also important are differences in snowpack properties between the weak layer and the adjacent layers (Schweizer and Jamieson, 2003), namely the relative crystal size and the difference in hand hardness. The hand hardness measurements were therefore converted to a hand hardness index *h* ranging from 1 (F-) to 15 (K+). We hypothesize that the properties of the layer above the weak layer affect both fracture initiation and fracture propagation, whereas the properties of the layer below the weak layer mainly affect fracture initiation. Therefore, we considered both the layer above and the layer below the weak layer separately.

Since 1997, over 1000 compression tests, resulting in 2512 fractures, were performed on 441 slopes where dry slabs were skier-tested. However, only 980 of these fractures were classified using the new classification system (Table 1). Including whumpfs (i.e. fracture propagation on low angle terrain without slab avalanche release; Johnson, 2001) and remotely triggered avalanches, 160 of these slabs were triggered. Until December 2002, non-planar fractures (B) were only systematically recorded if these were associated with the failure plane of a slab avalanche. This introduces a strong bias towards skier-triggered slab avalanches for these fractures. Therefore, all non-planar breaks recorded before December 2002 were not included in the stability analysis.

Fractures in compression tests that were on the failure plane of an adjacent triggered slab avalanche are referred to as "unstable" (190 classified fractures). All other fractures in compression tests performed on skier-tested slopes are labelled “stable" (790 classified fractures). This enabled us to objectively compare stable and unstable data, without targeting specific weak layers. To evaluate stable and unstable data, we used the non-parametric Mann-Whitney U-test (Walpole and others, 2002, p. 605). This test is useful when dealing with ordinal data (e.g. hand hardness) without having to make restrictive assumptions about data distributions (e.g. normality).

3. RESULTS

An overview of various snowpack properties by fracture character, for the weak layer as well as the adjacent layers, is given in Table 2.

Table 1: Descriptive classification of fracture character in stability tests

Fracture character	Code	Fracture characteristics
Progressive Compression	PC	Fracture usually crosses column with one loading step, followed by gradual compression of the layer with subsequent loading steps
Resistant Planar	RP	Planar or mostly planar fracture that requires more than one loading step to cross column and/or block does not slide easily* on weak layer.
Sudden Planar	SP	Planar fracture suddenly crosses column with one loading step and the block slides easily* on weak layer.
Sudden Collapse	SC	Fracture suddenly crosses column with one loading step and causes noticeable slope normal displacement.
Non-planar Break	B	Irregular fracture surface.

* Block slides off column on steep slopes. On low angle slopes, hold sides of block and note resistance to sliding by gently pulling.

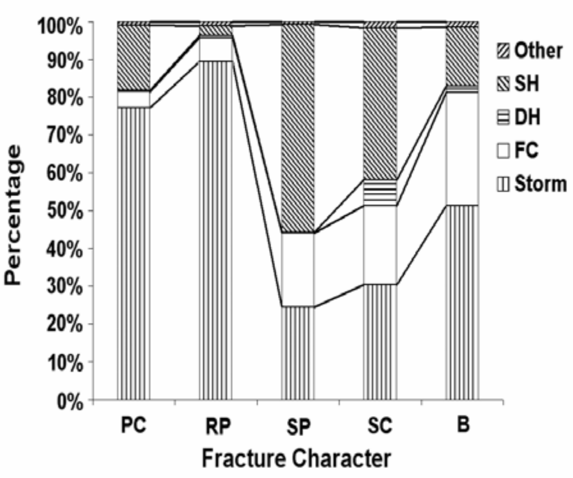

Figure 2: Percentage of weak layer grain type by fracture character in compression tests. Weak layers consisting of either Precipitation Particles (PP), Decomposed Fragments (DF) or Rounded Grains (RG) were grouped in one category labelled *Storm*. Surface Hoar (SH), Faceted Crystals (FC) and Depth Hoar (DH) are each in separate groups. Wet Grains (WG), Crusts (Cr) and Ice (I)) were grouped in a category named *Other*.

3.1 Weak layer properties

Figure 2 shows the percentage of weak layer grain types by fracture character. The percentage of weak layers consisting of storm snow (PP, DF and RG) was greatest for PC (77%) and RP (89%) fractures. On the other hand, most sudden fractures (SP and SC), fractured in weak layers consisting of persistent snow crystals (FC, DH and SH). Finally, there were approximately as many storm snow weak layers (51%) as persistent weak layers (47%) associated with non-planar breaks.

Persistent snow crystals, especially surface hoar and depth hoar crystals, are generally larger than grains in non persistent weak layers. Therefore, the median weak layer crystal size, as well as the 90% range, were larger for SP and SC fractures than for PC, RP and B fractures (Table 2).

The median depth for PC and RP fractures (15 and 27 cm, respectively) was lower than that for SP, SC and B fractures (52, 40 and 49 cm, respectively). Moreover, the 90% range indicates that the vast majority of weak layers associated with PC and RP fractures were shallow (Table 2). Since there is a strong correlation between the hand hardness of a

Table 2: Descriptive statistics for snow-pack properties of the weak layer (WL) and the adjacent layers (La and Lb): Number of observations (N), Median (Med), and 90% range* ($R_{90\%}$).

	PC			RP			SP			SC			B		
Variable	N	Med	$R_{90\%}$	N	Med	$R_{90\%}$	N	Med	$R_{90\%}$	N	Med	$R_{90\%}$	N	Med	$R_{90\%}$
D_{WL} (cm)	1748	15	5-40	397	27	7-61	707	52	18-121	1387	40	3-135	382	49	16-122
E_{WL} (mm)	659	1.5	0.6-0.6	257	1.0	0.5-2.5	515	4.5	0.5-14.0	857	2.5	0.8-17.0	185	1.3	0.5-7.0
h_{WL}	715	F	F– to 1F	255	4F-	F– to 1F	513	4F	F to 1F	888	4F	F– to 1F+	187	4F+	F to P-
ρ_{WL} (kg m^{-3})	419	97	54-192	193	118	75-208	107	170	102-248	396	185	59-291	92	176	90-280
Th_{WL} (cm)	724	8.0	0.2-23.0	257	11.0	0.5-36.5	517	1.3	0.3-27.0	900	5.0	0.5-22.0	193	8.0	0.2-41.0
CT score	1748	7	1-20	397	12	1-26	101	18	3-28	1387	13	1-26	382	21	6-29
E_A (mm)	400	1.5	0.8-3.0	165	1.3	0.5-2.5	444	0.8	0.4-2.0	653	1.0	0.4-2.7	154	1.0	0.5-2.5
h_A	524	F	F– to P	206	4F-	F– to K-	503	P	F to P+	840	P	F to K-	181	P	F to P+
ρ_A (kg m^{-3})	284	99	54-226	120	116	50-244	358	200	110-302	575	185	66-314	128	170	78-295
Th_A (cm)	528	6.0	1.0-16.5	209	6.0	1.0-21.0	503	10.0	1.5-33.0	848	6.0	1.0-21.0	182	11.0	1.0-27.0
E_B (mm)	621	1.0	0.5-2.0	217	1.0	0.4-5.5	363	0.8	0.4-1.5	641	1.0	0.5-2.0	141	1.0	0.4-2.5
h_B	716	4F	F– to P	256	4F+	F to P+	501	1F+	4F to K-	740	1F	F to P+	184	1F+	4F to K
ρ_B (kg m^{-3})	464	131	61-242	157	143	75-272	308	230	160-320	503	219	87-319	127	227	117-344
Th_B (cm)	720	10.9	1.5-25.0	256	9.0	0.3-33.0	503	10.0	1.0-26.8	748	10.0	1.5-26.0	184	13.0	2.0-35.0
E_{WL}/E_A	399	1.0	0.5-5.3	165	0.8	0.3-2.5	442	6.0	0.6-25.0	649	3.8	0.5-40.0	152	1.2	0.3-12.0
E_{WL}/E_B	616	1.3	0.6-6.0	217	1.3	0.2-3.1	355	6.0	0.7-25.0	630	4.3	0.7-20.0	136	1.3	0.7-9.2
$h_A – h_{WL}$	515	0	-3 to 6	204	-1	-3 to 6	502	2	-3 to 7	833	3	-2 to 7	175	1	-3 to 6
$h_B - h_{WL}$	708	2	-1 to 6	254	2	-1 to 7	494	3	0 to 9	718	3	-1 to 7	177	3	-1 to 7

* The 90% range is defined as the middle 90% of the data. Five percent of the data are below, and five percent of the data are above $R_{90\%}$.

snowpack layer and its depth (N = 8340, Spearman R = 0.74, $p < 10^{-6}$), it is not surprising that the median weak layer hand hardness for PC and RP fractures (F and 4F-, respectively) was lower than for SP, SC and B fractures (4F, 4F and 4F+, respectively). Similarly, density correlates with depth (N = 8469, Pearson R = 0.71, $p < 10^{-6}$), which explains why the median weak layer density for PC and RP fractures (97 and 118 kg m^{-3}, respectively) was also lower than for SP, SC and B fractures (170, 185 and 176 kg m^{-3}, respectively).

The median weak layer thickness was lowest for SP fractures (1.3 cm), followed by SC fractures (5 cm). Resistant planar fractures, on the other hand, had the largest median weak layer thickness (11 cm).

Finally, the compression test score correlates with weak layer depth as well (N = 10313, Spearman: R = 0.73, $p < 10^{-6}$). This is consistent with the median number of taps being lowest for PC fractures and highest for B fractures. However, even though SC fractures were associated with deeper weak layers (Median = 40 cm, $R_{90\%}$ = 3-135 cm), the median number of taps was rather low (13 taps), comparable to RP fractures (12 taps).

3.2 Properties of the adjacent layers

The majority of the layers adjacent to weak layers that failed in compression tests, consisted of storm snow (PP, DF and RG), regardless of fracture character. Crusts comprised a smaller percentage of the layers adjacent to PC fractures (9.8% above and 4.3% below) than for other types of fractures. Faceted crystals were also commonly observed in layers adjacent to weak layers associated with SP, SC, and B fractures. Consequently, the median crystal size for the adjacent layers was relatively small and comparable for all fracture types (Table 2).

The hand hardness by fracture character for the layers adjacent to the weak layer is shown in Figure 3. Generally, the layer above the weak layer was softer (i.e. lower hand hardness) than the layer below the weak layer (Table 2). The median hand hardness for the layers adjacent to the weak layer increased from PC to RP to SP, SC and B. A similar trend was also present for the density of the adjacent layers (Table 2).

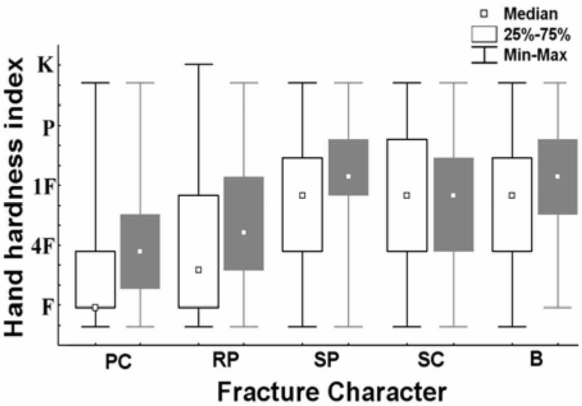

Figure 3: Hand hardness index by fracture character for the layer above (black and white) and layer below (grey) the weak layer.

3.3 Properties of the weak layer relative to the adjacent layers

The median ratio of crystal size between the weak layer and the adjacent layers was smaller for PC, RP and B fractures than for SP and SC fractures (Table 2). Likewise, the median difference in hand hardness between the weak layer and the adjacent layers was smaller for PC and RP fractures than for SP, SC as well as B fractures.

3.4 Stability and fracture character

The frequency of skier-triggering by compression test score, as well as by fracture character, is shown in Figure 4. The frequency of skier-triggering increased from 33% for compression test scores ranging from zero to six taps to 42% for compression test scores ranging from seven to twelve taps. Thereafter, the frequency of skier-triggering decreased to 17% for compression test scores ranging from 25 to 30 taps (Figure 4(a)). Clearly, fractures with a high compression test score are less likely to be the failure plane of a slab avalanche (N = 2276, U-test $p = 6 \cdot 10^{-4}$).

There is also a significant difference between the fracture character of stable and unstable fractures. As can be seen in Figure 4 (b), sudden fractures (SP and SC) were more often the failure plane of a slab avalanche than PC, RP or B fractures.

Figure 5 shows the frequency of skier-triggering by fracture character grouped by compression test scores in the easy, moderate and hard range. The majority of the weak layers

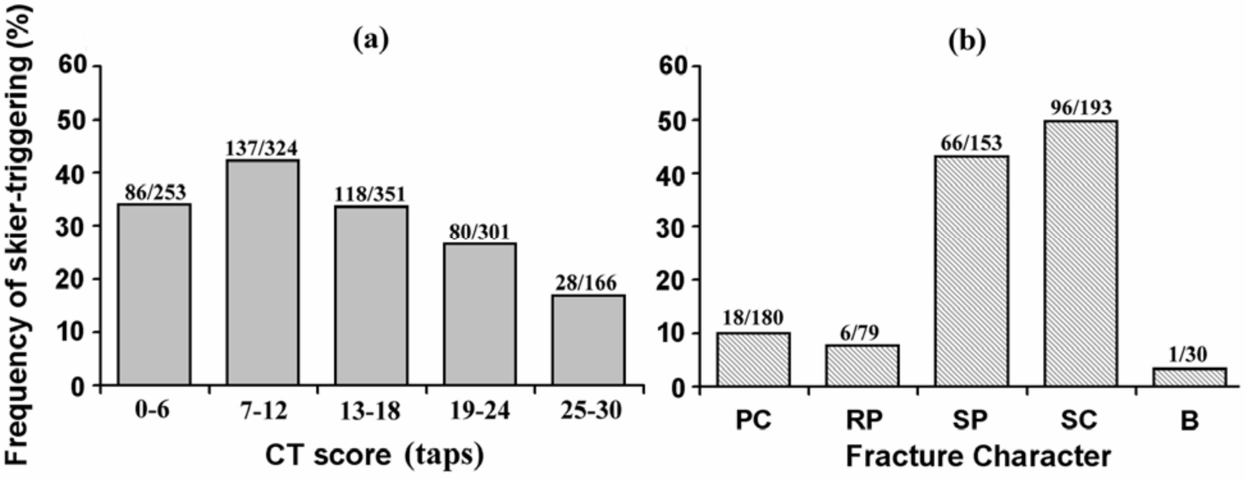

Figure 4: Frequency of skier-triggering by (a): compression test score and (b): fracture character. The compression test score is grouped in five categories: 0-6 taps, 7-12 taps, 13-18 taps, 19-24 and 25-30 taps.

that were the failure plane of slab avalanches produced sudden fractures in compression tests, regardless of the compression test score. However, the frequency of skier-triggering for SP and SC fractures did decrease from 56% and 48% respectively in the easy range, to 27% and 19% respectively in the hard range. On the other hand, PC, RP and B fractures were rarely the failure plane of slab avalanches. Moreover, none of the compression test results in the hard range that produced PC, RP or B fractures were the failure layer for slab avalanches.

4. DISCUSSION

The comparison of stable and unstable compression test results revealed that fracture character has high predictive merit. Johnson and Birkeland (2002) stated that reducing the uncertainty associated with 'conditionally stable' stability tests (i.e. compression test scores in the hard range) is crucial to improve the interpretation of stability test results for avalanche forecasting. Clearly, incorporating fracture character into compression test interpretations can reduce some of these uncertainties since sudden fractures (SP and SC) are more often the failure plane of slab avalanches (Figure 5).

To understand why these types of fractures are more susceptible to skier-triggering, the snowpack properties are discussed in relation to fracture initiation and fracture propagation, both of which are required for slab avalanche release (Schweizer and others, 2003). Most PC and RP fractures were in the easy or moderate range and were associated with shallow, soft weak layers consisting of PP, DF or RG crystals. These conditions are favourable for fracture initiation. Nevertheless, the frequency of skier-triggering was low for these types of fracture. This is because the hand hardness difference was generally small (Table 2), indicating that there is little stress concentration in the weak layer. Therefore, stress in the weak layer can dissipate in the adjacent layers, hindering fracture initiation. Moreover, the layer above the weak layer was usually soft (less stiff) and therefore less conducive to fracture propagation in the weak layer (Schweizer and others, 2003).

PC and RP fractures are however different from one another. PC fractures are characterized by the gradual compression of the weak layer over several loading steps (Table 1). Physically, the fracture involves gradual rearrangement of the weak layer crystals due to the external loading (van Herwijnen and Jamieson, submitted). However, about 17% of the weak layers exhibiting PC fractures consisted of SH crystals, which are generally thin weak layers (< 1 cm) consisting of one layer of crystals (Jamieson and Schweizer, 2000). The gradual compression of such thin weak layers would not be noticeable, which indicates that soft layers above and below the weak layer can be involved in the fracturing process as well. On

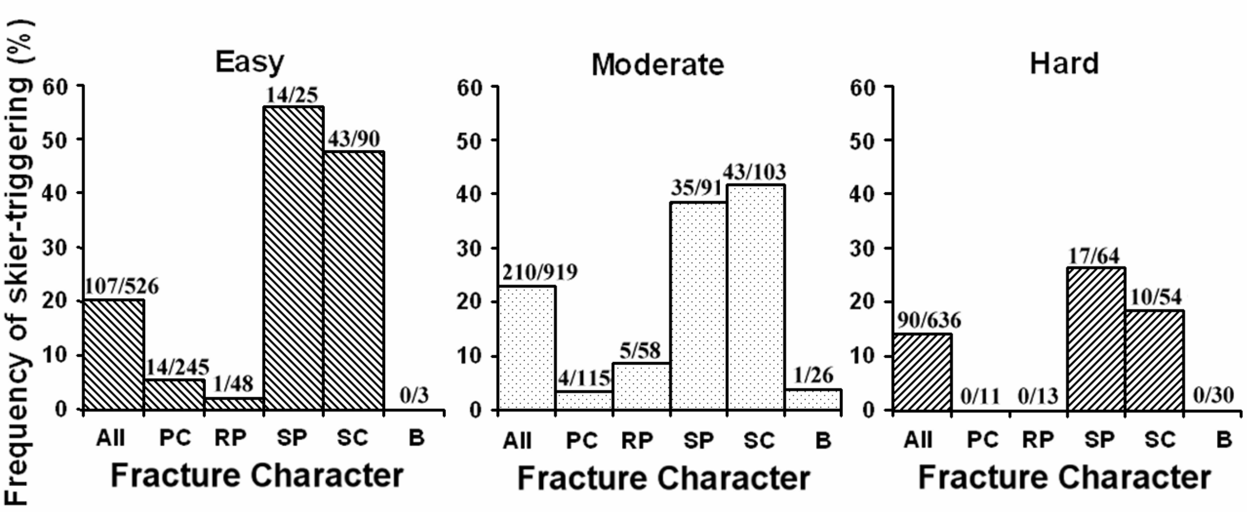

Figure 5: Frequency of skier-triggering by fracture character for compression test results in the easy (1-10 taps), moderate (11-20 taps) and hard (21-30 taps) range. The first column (All) for each range shows the frequency of skier triggering for all fractures, including unclassified fractures and fractures that were classified using the old classification system.

the pther hand, RP fractures are thin, planar fractures at the interface between the weak layer and one of the adjacent layers. These fractures are caused by the rearrangement of the crystals at the interface (van Herwijnen and Jamieson, submitted) and require one or more loading steps to cross the column. In most cases the block of snow does not slide easily on the weak layer, indicating that not all the bonds between the weak layer and the adjacent layer are fractured or that there are minor irregularities (non-planarities) in the fracture surface. Moreover, the weak layer depth as well as the hardness of the weak layer and the adjacent layers were significantly larger for RP fractures than for PC fractures (Table 2).

Most sudden fractures (SP and SC) were associated with harder and deeper weak layers than PC and RP fractures. These are less favourable snowpack conditions for fracture initiation partly because the stress below the skier reduces with depth, and partly because harder, deeper weak layers are stronger. However, the median depth for these fractures was still well within the range for skier-triggering (e.g. Schweizer and Jamieson, 2001) and persistent weak layers, commonly associated with sudden fractures, are more often the failure layer of skier-triggered slab avalanches (Schweizer and Jamieson, 2001). Additionally, the larger hand-hardness difference indicates stress concentration in the weak layer and the larger relative crystal size indicates less bonding (Colbeck, 2001), facilitating fracture initiation. Finally, the layer above the weak layer was harder and therefore stiffer, which promotes fracture propagation (Schweizer and others, 2003).

There are also some important differences between SP fractures and SC fractures. Persistent weak layers causing SC fractures were significantly thicker than weak layers causing SP fractures ($N = 392$, U-test $p < 10^{-6}$). Moreover, the number of taps was significantly lower for SC fractures than for SP fractures ($N = 2080$, U-test $p < 10^{-6}$). Finally, more SC fractures (76%) than SP fractures (45%) were on the failure plane for whumpfs. Whumpfs are generally regarded as good indicators of high instability (e.g. McClung and Schearer, 1993, p.135) implying snowpack conditions are favourable for fracture propagation. This suggests that the amount of collapse during fracture contributes to fracture propagation, which is consistent with a recent theory for fracture propagation on low-angle terrain (Johnson, 2001).

Most snowpack properties for non-planar breaks are similar to those for SP fractures (Table 2). However, the hardness difference between the layer above and the weak layer was less for B than for SP fractures. Moreover, the ratio of crystal size between the weak layer and the adjacent layers was smaller for B fractures than for SP fractures. The fact that B fractures were rarely the

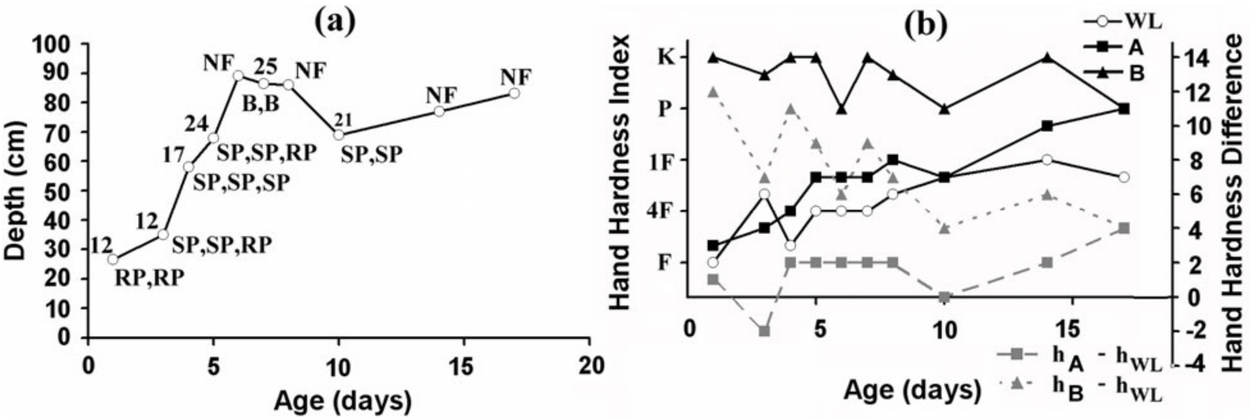

Figure 6: Evolution of snowpack parameters by age for a weak layer consisting of faceted crystals buried on 040312. (a): Depth of the weak layer as well as the average compression test score (above, NF=no fracture) and recorded fracture character (below). (b): Hand hardness index of the weak layer and the adjacent layers (black) as well as the difference in hand hardness index between the adjacent layers and the weak layer (grey).

failure plane of slab avalanches indicates that a large hardness difference and relative crystal size favour slab avalanche release.

None of the released slab avalanches associated with PC and RP fractures were remotely triggered avalanches and only one PC fracture was associated with a whumpf. Moreover, nearly all fractures on the failure layer of slab avalanches larger than size 1.5 were sudden fractures (SP 58% and SC 38%). Finally, only one B fracture was associated with a whumpf. This indicates that the snowpack properties for PC, RP and B fractures are typically not favourable for widespread fracture propagation.

4.1 Evolution of fracture character for weak snowpack layers

The median depth of weak layers by fracture character (Table 2), as well as the median hardness, density and compression test score, suggests that the fracture character of some weak layers may evolve as they age and are buried more deeply.

In general, the hardness of snowpack layers increases with depth. However, weak layers typically gain strength and hardness slower than the surrounding layers. For shallow depths, the hardness difference between the weak layer and the soft adjacent layers is usually very low (PC and RP fractures). As weak layers get buried deeper in the snowpack, the hand hardness difference between the weak layers and their adjacent layers increases (SP and SC fractures). Over time, the hardness of weak layers slowly increases, decreasing the hand hardness difference (B fractures). Persistent weak layers gain strength much slower than storm snow weak layers, suggesting that the transition in fracture character would be much faster for storm snow weak layers than for persistent weak layer.

We have observed that soon after burial (e.g. the first day), many persistent weak layers do not produce compression test results. However, when the slab over the weak layer thickens and becomes more cohesive, persistent weak layers generally produce SP fractures, or SC fractures if the weak layer is relatively thick. Finally, once a weak layer is buried deep enough in the snowpack, it stops producing stability test results because insufficient stress from dynamic surface loading reaches the weak layer.

Our observations on the evolution of fracture character for storm snow weak layers are very limited. Nevertheless, we observed that initially most storm snow layers produce PC fractures. As the snow becomes more cohesive, many storm snow interfaces evolve to RP fractures, followed by breaks and no results, within days. However, during the initial stages of the evolution, some slabs can become cohesive faster (and comprised of smaller particles) than the weak layer (e.g. weak layer of large PP), increasing the hand hardness difference and difference in crystal size. These weak layers would evolve into SP or SC fractures, indicating that at this stage skier-triggered slab avalanches are more likely.

An example of the evolution of fracture character, for a thin weak layer (approximately 1 cm) that consisted of faceted crystals on top of a crust, is shown in Figure 6. This weak layer was formed after a cold storm deposited dry snow on top of a moist snow layer, which subsequently froze. The hand hardness difference between the weak layer and the layer above did not change much over time; however, h_B - h_{WL} decreased from 12 to 4 (Figure 6 (b)). As the weak layer got buried deeper in the snowpack, the fracture character evolved from mostly RP to mostly SP and then to B and NF (Figure 6 (a)). However, the weak layer did produce two SP fractures after 10 days. This was probably because more energy was transmitted to the weak layer in compression tests after the slab had densified with no additional precipitation.

5. SUMMARY AND CONCLUSIONS

With the proposed classification system we have identified the five most common types of fractures in compression tests. The data show that fracture character is a valuable addition to the compression test score since most failure layers of slab avalanches produce sudden fractures (SP and SC) in compression tests.

The analysis of compression test results in combination with snow profile data has revealed that the typical snowpack characteristics for SP and SC fractures favour slab avalanche release. Moreover, there is an indication that the additional slope normal displacement in SC fractures favours fracture propagation. On the other hand, typical snowpack properties for PC, RP and B fractures do not favour fracture propagation.

Tracking the evolution of potential weak layers through fracture character can prove to be useful. During the initial stages of the slab becoming cohesive, fracture character can provide information on the potential for avalanches to occur.

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