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Characteristics of human-triggered avalanches

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Abstract

In order to find characteristics of human-triggered dry snow slab avalanches, 10 years of avalanche occurrence data from the Swiss Alps have been analysed. Avalanche release and snowpack patterns were studied. Avalanches triggered by recreationists contribute to about 90% of the avalanche fatalities in Switzerland. Nearly exclusively dry snow slab avalanches were triggered. The slab detached of a human-triggered slab avalanche is (median values given) 50 m wide, and 80 m long; the overall avalanche (path) length is 150 m. The fracture depth is 45 cm, and the inclination in the starting zone is 38°. The slab failure is at the boundary between storm snow and old snow in only 38% of the cases. The other failures are due to weak layers or interfaces within the old snowpack. A weak layer was found in 50% of the cases. In all other cases, the failure was between two adjacent layers, a so-called interface failure. The thin (1 cm) weak layer is usually soft, found between one or two harder layers (above and below) and consists primarily of large crystals (≥ 2 mm) with plane faces: surface hoar, faceted crystals and depth hoar. The analysis of the 90 profiles available did support most of the mainly unstructured knowledge used in stability evaluation based on snow profiles and supports the simple model of skier triggering. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Snow; Avalanche; Avalanche accidents; Avalanche release; Snow stability; Avalanche forecasting; Skier triggering

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1. Introduction

Assessing the danger of human-triggered avalanches is the key factor of modern avalanche forecasting in most countries of Europe and North America. Except during heavy snow storms that occur only a few days per winter, avalanche forecasting is primarily done for the recreationist. The recreational skier, snowboarder or climber has to consider triggering by himself as well in his stability evaluation in the field. Accordingly also avalanche education is focused on human triggering. We use *human-triggered* to refer to avalanches intentionally or accidentally initiated by a skier, a snowboarder, a climber or any other recreationist, e.g. on snowshoes.

In Switzerland, the Swiss Federal Institute for Snow and Avalanche Research (SLF) collects the reports on avalanche accidents and involvements since the 1940s. The reports are compiled and published in the annual report on the snow and avalanche conditions in the Swiss Alps, the so-called "SLF-Winterbericht".

In order to better understand the mechanics of human-triggered avalanches, a 10-year period (1987–1988 to 1996–1997) of avalanche report data has been entered in a database and analysed. We focused on avalanche release and snow cover characteristics rather than burial and rescue statistics

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(Tschirky et al., 2001). Field measurements of dry snow slab avalanche features provide important information for safe travel in avalanche terrain, i.e. for avalanche education and on how slab avalanches fail (McClung and Schaerer, 1993).

Perla (1977) has given the first comprehensive description of dry snow slab avalanche characteristics based on field measurements at fracture lines. His database contained a variety of dry snow slab avalanches, naturally released and some artificially triggered. Meister (1987) studied 50 years of fatal accidents in the Swiss Alps, and Jamieson and Geldsetzer (1996) compiled the Canadian avalanche accidents from 1984 to 1996 and analysed trends and patterns. Logan and Atkins (1996) analysed the avalanche accidents in the United States. Some of the key features are also described in McClung and Schaerer (1993). Snowpack properties of slab avalanches have been studied by Stethem and Perla (1980), Ferguson (1984) and Jamieson and Johnston (1992).

Our study is the first one that exclusively is focused on human-triggered avalanches. The analysis is based on a large number of cases: 636 avalanche records, including 90 cases investigated in detail for which a snow profile is available.

2. Data

The database contains the data on human-triggered avalanches that can be found in the annual reports on the snow and avalanche conditions of the years 1987–1988 to 1996–1997 (SLF, 1989-99). Naturally released avalanches are not considered. Included were reports from the sections describing the avalanche accidents (called: “accidents“) and the snow and avalanche conditions in the region of Davos (called: “Davos”).

The source “accidents” contains the reported avalanche incidents (i.e. at least one person has been caught) from the whole area of the Swiss Alps. The number of cases reported varies and did increase in the more recent years likely due to slightly more consistent reporting. This indicates that the data set is neither complete nor homogeneous. The reports are very different concerning size and quality. For some fatal avalanches very detailed information, including photographs and one or two complete snow profiles, can be found. For the other ones, only very basic information, even often without data on inclination and fracture depth, is given. A few cases were not considered as the data were too incomplete.

The second source (“Davos”) contains avalanches from the surroundings of Davos reported primarily by the ski patrol of the various ski stations around Davos, by professional guides working in Davos and by SLF-members. This data set includes many cases of avalanches with no severe consequences (no fatalities and injuries). Sometimes, cases are reported when not even a person was caught, or when an avalanche was intentionally triggered, so-called skier-controlled avalanches. The data are basic, but usually complete. Most cases represent avalanches that were triggered by skiers and snowboarders during out-of-bounds (off-piste) skiing. The data set was explored for the first time. For some analyses only the avalanches from the region of Davos were considered. This Davos data set includes all cases from the source “Davos” and in addition all cases from the region of Davos from the source “accidents”. Accordingly, it should be one of the most complete and homogeneous avalanche data sets of human triggered avalanches. It contains 310 cases.

The data found in the annual reports (“SLF-Winterbericht”) were completed by going through all the original files of the SLF archives (avalanche accidents and expertise reports of investigated cases). Additionally, some data (primarily fracture line profiles) from specific studies on avalanche release were used. The database contains in total 636 cases.

Analysing avalanche data always includes the problem of incompleteness, since many more human-triggered avalanches occur than are reported (selection bias). Accordingly, the question is whether the sample is representative for the population. Our data set is no exception. From the about 640 records more than 300 are from the region of Davos suggesting that the number of unknown cases for the rest of the Alps must be large.

The inhomogeneous geographical distribution of the data is no problem for some of the parameters studied as, e.g. the slope angle or the altitude, but, e.g. the aspect is biased by the primarily northwest to southeast direction of the valleys in the region of Davos.

The majority of records from the Davos region describe avalanches triggered during out-of-bounds skiing. The data set of the Davos region includes quite a few small avalanches that were skier controlled. On the other hand, the data set from the Davos region is probably rather complete and should give some interesting results. In general, to check the effect of inhomogeneities different data subsets (samples) were analysed. If differences showed up during the data exploration between the samples this is reported in the following. Otherwise, the result based on the complete data set of the 636 cases is given.

3. Methods

The database is structured into the sections: general information (date, location, etc.), avalanche (size, etc.), release (single skier, group, etc.), snow cover, weather, damages and data source. The “Filemaker Pro” database software was used for data entering and queries. An example of a data record can be found in Schweizer and Lütschg (1999). To generally analyse the data, the Filemaker Pro records were exported into an Excel worksheet. For statistical analysis the statistical software SYSTAT was used.

Since many parameters are not normally distributed the median is usually given instead of the mean. To compare different samples, the non-parametric Kruskal–Wallis test (H-test) was applied, and to denote whether samples are different or not the level of significance (p-value) is given. Values of $p < 0.05$ indicate that the two samples are statistically significantly different. To compare profiles layer by layer (paired data), the Wilcoxon ranked sign test was used. Not ordinal data as the grain type was compared by cross-tabulating the data and calculating the Pearson chi-squared statistic.

Except as noted, snow cover properties are classified according to Colbeck et al. (1990). Hand hardness for individual layers are indexed from 1 to 6 for fist (F), 4 fingers (4F), 1 finger (1F), pencil (P), knife blade (K) and Ice (I), respectively. Intermediate values are allowed, e.g. 1–2.

To enter the data some interpretation was necessary. Below some details are given.

The *fracture height* is given either as average, or a range describing minimum and maximum value.

The *shape of the starting zone* was taken from the map or from photographs if available. Several characteristics may apply.

For the *inclination* the slope angle in the steepest section of the starting zone was taken, but this value had to be representative for a considerable part of the starting zone, in particular in the case that the starting zone was very large. The slope angle was taken from the map (scale 1:25,000), if there was no value given in the files. In the source “Davos”, the inclination is given in classes: $< 30°$, 31°–35°, 36°–40°, $> 40°$. However, if possible in all cases, based on the given location the inclination was checked on the map by using a specific ruler and a hand lens. In many cases, the slope angle given in the report files was underestimated compared to the value that could be retrieved from the map. In all these cases, the value from the map was used which still represents an average value and likely underestimates the real small-scale terrain steepness.

The *aspect* is usually given according to the eight principal directions (N, NE, E, etc.), but for many cases it is given based on a division in 16 directions (N, NNE, NE, ENE, etc.). Accordingly, there is some systematic bias and the aspect should only be analysed based on the eight principal directions.

We have been particularly interested in the actual release location (trigger point) that obviously can even be outside of the starting zone (remote triggering). However, the information on the *trigger point* and *triggering* in general are usually incomplete. Often it is not known how many people, and during which kind of activity, had been involved. If it is known that the fall of a skier has most likely triggered the avalanche, that information is entered as comment. Similarly, if the triggering skier was the second, or third who skied the slope. Groups guided by ski instructors were entered as professionally guided groups, giving the information “ski instructor” as comment.

Snow profiles were available in about 14% of all cases. In the rare cases were there was more than one profile, the one that was assumed to be the most characteristic for the trigger point was chosen. The profiles had to be generalised for data entry. The weak layer, and the layers above and below are recorded in detail. If there is no weak layer but the failure occurred at an interface, just the layers above

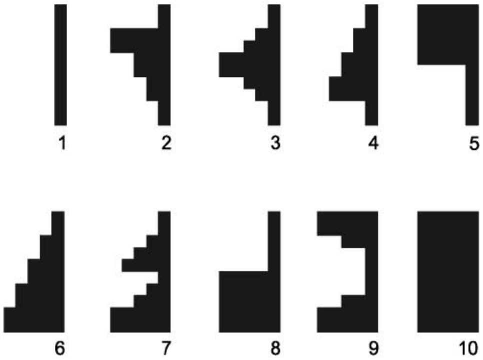

Fig. 1. Ten basic types of hardness profiles for classification.

and below are given. The slab and the underlying (remaining) snowpack (called substratum) are each characterised by just one value for type and size of grains, the hardness and liquid water content. In addition, the hardness profile was characterised according to the types given in Stoffel et al. (1998), based on the original work by deQuervain and Meister (1987). Two more types (now 5, 10) have been added, so there were 10 types used now (Fig. 1). Types 1–5 all have a weak base, whereas types 6–10 are well consolidated at the bottom. Opposed to the above mentioned two previous studies, the slab and the underlying snowpack were each characterised independently. So to both, the slab and the substratum, one of the 10 hardness profiles was assigned.

Generally, we expect a *weak layer* to be rather thin. In this study, any weak layer where the failure location (upper or lower boundary) is not clear or unknown will be classified as weak layer (failure) regardless of its thickness. Weak layers where the failure location (interface) is reported will still be classified as weak layer if they are less than 5–6 cm thick. The failure location will be recorded separately, and the failure classified as interface failure. Accordingly, failures at the boundary of thick weak layers will be classified as interface failures, and no weak layer is recorded. However, since the layers above and below of a weak interface are recorded, it is always possible to evaluate the weaker of the two adjacent layers as the weak layer (e.g. for grain type/size characteristics). Crusts are never weak layers, but often are one of the two adjacent layers at interface failures.

4. Results

Before the results on human-triggered avalanches are shown it is quickly reviewed where and how the fatal accidents happened. Although our database exclusively includes the human-triggered avalanches, we will for that purpose shortly consider all fatalities (Table 1). For the 10-year period considered, the vast

Table 1
Avalanche fatalities of the years 1987–1988 to 1996–1997 in regard to activity and triggering. Total number of fatalities for the 10-year period is 229

Year	Total	Free terrain					Transportation				Buildings
		Total	Skier triggered	Other human triggering	Natural release	Other triggers or unknown	Total	Human-triggered	Natural release	Other triggers or unknown	Total
87–88	24	21	19	2	0	0	2	0	1	1	1
88–89	16	14	10	4	0	0	2	0	1	1	0
89–90	28	28	18	3	7	0	0	0	0	0	0
90–91	38	37	22	5	9	1	1	0	1	0	0
91–92	13	7	7	0	0	0	6	1	5	0	0
92–93	28	28	19	5	4	0	0	0	0	0	0
93–94	21	18	17	1	0	0	3	1	2	0	0
94–95	20	20	12	8	0	0	0	0	0	0	0
95–96	17	17	12	5	0	0	0	0	0	0	0
96–97	24	23	18	5	0	0	1	0	1	0	0
Total	229	213	154	38	20	1	15	2	11	2	1

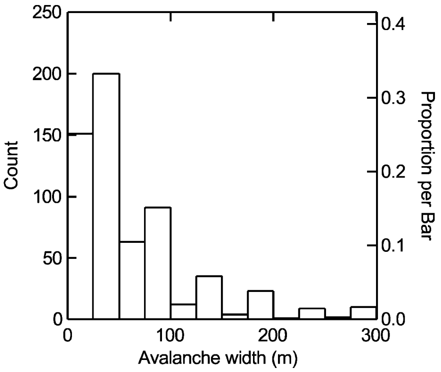

Fig. 2. Avalanche width. All cases considered, $N = 611$. Mean: 74 m, median: 50 m. Nine cases with width >300 m are not shown.

majority of avalanche accidents (93%) happened in the free terrain, i.e. during recreational activities. Ninety percent of the recreationists in the free terrain were killed by an avalanche that was triggered by themselves or by one of their party members. The differences from year to year are substantial (Table 1), but the general picture holds. In general there is a slight (not significant) decreasing trend in avalanche fatalities for the 1990s (Tschirky et al., 2001). The portion of fatalities in the free terrain (primarily recreational accidents) increased from 71% in the 1970s, to 82% in the 1980s, and finally to 87% in the 1990s. The increase started after World War II, and ever since the 1960s the avalanche victims caught in the free terrain represent the greater part.

4.1. *Avalanche characteristics*

4.1.1. *Avalanche type*

The database nearly exclusively (99%) contains slab avalanches. Only six cases are known that are due to a loose snow avalanche. Three of them were wet ones that caused the fall of the involved skiers/climbers leading to four fatalities. There is only one case in the database reporting a wet slab avalanche reflecting the fact that wet slabs can hardly be triggered by skiers. However, if only natural release is considered, contributing to about 14% of the fatalities for the 10-year period (Table 1), wet slab avalanches contribute to 45% of the fatalities, wet loose snow avalanches another 7%. Accordingly, 52% of the fatalities caused by naturally released avalanches are due to wet snow avalanches.

4.1.2. *Avalanche size*

The median width of human-triggered slab avalanches is 50 m (considering all cases) (Fig. 2). However, differences exist depending on the selection of the subset analysed from the database. Considering the cases from the Davos region, including many skier-triggered avalanches while out-of-bounds skiing reveals a lower value of 40 m. Considering only the avalanches that were triggered during out-of-bounds skiing the median width is 40 m. Whereas the median width of avalanches triggered during ski touring is larger: 70 m. The larger the width the smaller seems to be the chance of survival since if only accidents are analysed that led to fatalities, the median width is 80 m.

Whereas the width is rather consistently reported, the length is less conclusive. Usually, the overall length is given, not the length of the slab detached (from the fracture line to the stauchwall). Considering all cases the median overall length is 150 m, i.e. the typical avalanche is just about three times as long as wide (Fig. 3). This relation approximately holds for any subset (factors vary between 2.75 and 3.9) with a tendency to longer avalanches if fatalities were caused. The median overall length for the fatal avalanches is 310 m. The median length of the starting zone is 80 m considering all cases, and 100 m for the fatal avalanches. Considering different

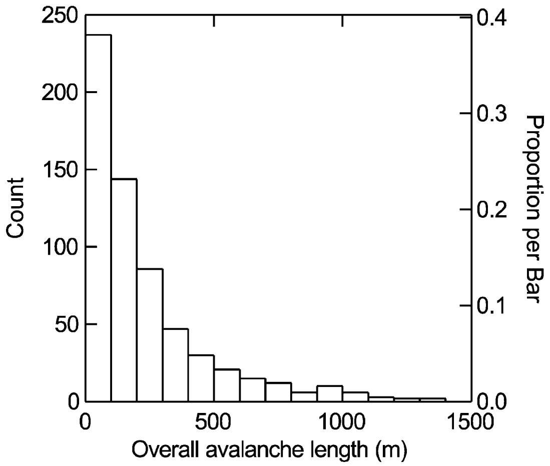

Fig. 3. Length of avalanche (overall). All cases considered, $N = 619$. Mean: 256 m, median: 150 m. Two cases with length >1500 m are not shown.

samples always reveals a length between 80 and 100 m. The proportion of width to length for the slab released is typically around 1.5. However, it has to be noted that the length of the slab detached is only known in 9.5% of all cases, compared to 97% for the overall length of the avalanche.

The fracture depth is probably one of the most interesting parameters in view of the mechanics of avalanche release (Fig. 4). The mean fracture depth reported is usually measured at the fracture line (not necessarily being representative for the trigger point). The median of the mean fracture depth is 45 cm. This value increases to 50 cm if only the fatal avalanches are considered, and decreases to 40 cm if the sample with only the cases from the Davos region (including many small avalanches) is analysed. The mean fracture depth is reported for 522 cases representing 82%. In 98% of the cases reported, the mean fracture depth is $\leq$ 100 cm clearly showing that a skier is not a very effective trigger for deep weak layers. In 38 cases (representing only 6% of all cases), the fracture depth at the estimated trigger point was given revealing a median value of 40 cm, and a maximum value of 90 cm.

4.2. Terrain

4.2.1. Slope angle

The slope angle in the starting zone (Fig. 5) is known in 97% of all cases. Considering all cases the median value is 38°. In 40% of the cases, the slope angle is 40° or more. It has been suggested that out-of-bounds skiers prefer steeper terrain than backcountry skiers. There is statistically no significant difference (H-test, $p = 0.42$) in slope angle between avalanches triggered while out-of-bounds skiing vs. ski touring: median value 39° (out-of-bounds skiing) vs. 38° for avalanches triggered during ski touring. Again only for some cases (102) the inclination at the trigger point is known. There, the median slope angle is 35°. These lower values are primarily due to the fact that in about 15% of these cases, the avalanche was triggered from terrain that was less than 30° steep. In addition, avalanches are obviously not triggered in general at the steepest part of the slope, since in the 102 cases the median slope angle of the starting zone is 39°. The median difference between the slope angle at the trigger point and at the steepest part of the slope is about 3°, only considering the cases for which the avalanche was triggered from terrain steeper than 30°.

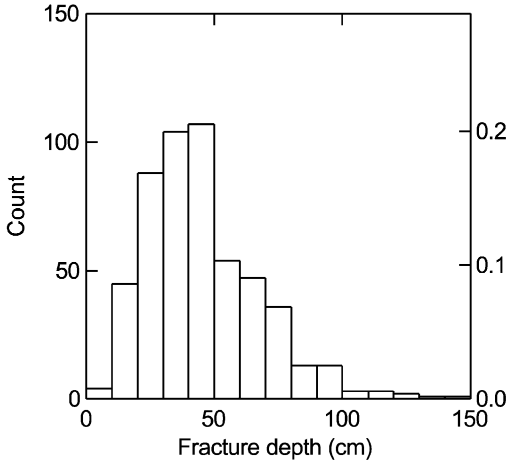

Fig. 4. Mean fracture depth of slab. All cases considered ($N=$ 522). Mean: 49 cm, median: 45 cm. Two cases with depth >150 cm not shown.

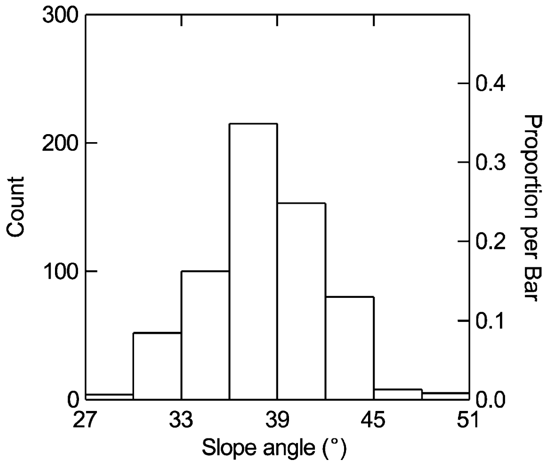

Fig. 5. Slope angle. All cases considered ($N = 617$). Mean: 38.7°, median: 38°.

Fig. 5 shows that most avalanches are triggered on slopes of about 38°. However, this does not mean that these slopes are the most critical ones. The frequency of skiing and the frequency of slope angle are generally unknown. The latter one was determined for the region of Davos using a GIS for the analysis of the digital terrain model. Fig. 6 shows that the frequency of slope angle decreases between

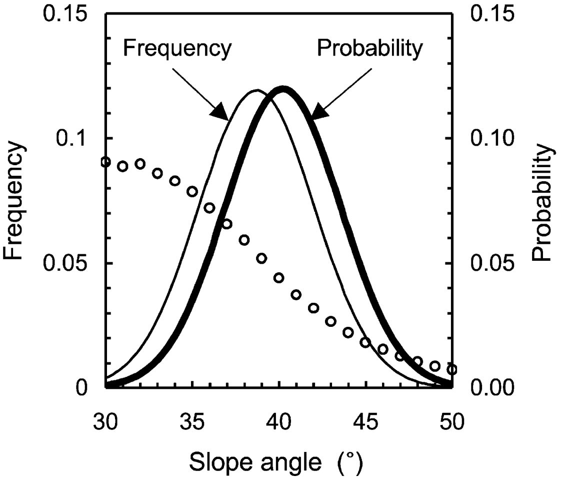

Fig. 6. Slope angle in the Davos region. The bell-shaped curve denoted “Frequency” is a Gaussian fit to the slope angle avalanche data (mean 38.7°). The dots indicate the actual frequency of slope angle in the Davos region. The bold curve denoted “Probability” shows the frequency of avalanche slope angle in respect to the actual frequency of slope angle in the Davos region (mean: 40.2°).

30° and 50°. Accordingly, the frequency curve is shifted to higher values of slope angle by about 1.5°. This means, e.g. that the frequency of triggering increases from 35° to 40° not by a factor of about 2, but by a factor of 3. However, this is still not yet the probability of triggering since the frequency of skiing is unlikely the same for all slope angles. Assuming a decreasing frequency of skiing with slope angle might compensate the above effect.

4.2.2. Aspect

The aspect is known for nearly all cases (99.7%). Considering all cases the most frequent aspect was found to be northeast (26%) (Fig. 7, left). However, as opposed to most other parameters the aspect seems to be biased by the large number of cases from the Davos region where most valleys run typically northwest to southeast (Fig. 8) so that the typical shady slope is northeast. Accordingly, omitting the cases of the Davos region decreases the dominance of the northeasterly direction. But still, northeast is the most frequent aspect (23%), followed by north (19%) and northwest (17%) (Fig. 7, right). About 60% of the avalanches are triggered in the shady slopes. On the northeasterly slopes, the unfavourable factors shady slope and lee slope cumulate. The southern aspects (SE, S and SW) contribute 18%. The rest is triggered in the eastern (15%) and western (8%) aspect.

Considering only the avalanches that caused fatalities, the northern aspect is the most frequent one (23%), followed by northeast (18%) and northwest (17%). This result is not quite clear and suggests that the survival chance in an avalanche triggered on a northerly slope is smaller (58%) than in one triggered on a northeasterly slope (73%). In fact, the difference is just about significant ($p = 0.049$). The result could, e.g. mean that avalanches triggered on northerly slopes are larger than on northeasterly ones, implying higher probability of death. Although avalanche width and fracture depth are in fact slightly larger for avalanches triggered on slopes in the

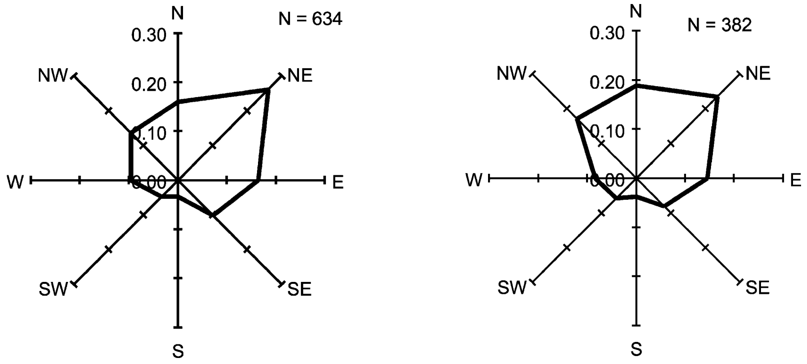

Fig. 7. Aspect of human-triggered avalanches. Portions shown. Left graph shows all cases, right graph without the cases from the Davos region.

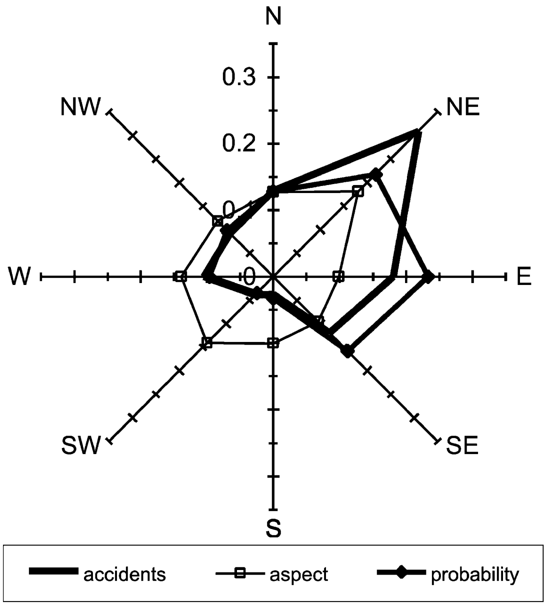

Fig. 8. Frequency of aspects in the Davos region. The frequency of accidents is shown (dashed line) together with the actual frequency of aspects in the Davos region. The thick solid line, denoted as "probability", shows the frequency of accidents relative to the frequency of aspects.

northern aspect than for ones triggered in the northeastern aspect, the difference is statistically highly not significant.

As in the case of the slope angle, the frequency of aspects in the region of Davos was evaluated based on a digital terrain model using a GIS. Only aspects in starting zones between 30° and 50° were considered. All densely forested slopes were excluded from the analysis. Due to the regional topography NE and SW are the most frequently found aspects. This changes the relative frequency of triggering. On the eastern and northeastern aspects relatively the most avalanches are triggered: 23% and 22%, respectively. Surprisingly, slightly more avalanches are triggered on the southeastern (16%) than on the northern slopes (13%). Again, of course, the frequency of skiing is unknown, so that real probabilities of triggering cannot be derived.

4.2.3. *Elevation*

The median altitude of the starting zone is about 2410 m a.s.l. Independent of the choice of the sample, the altitude is always about 2400 to 2500 m a.s.l. Splitting the database according to the type of skiing activity (ski touring, out-of-bounds skiing) reflects the fact that the touring terrain reaches higher elevations than the near-ski area terrain, the median elevations found are 2520 and 2410 m a.s.l., respectively.

4.2.4. *Terrain features*

For 470 out of 636 cases some terrain features are given. Most avalanches are triggered on spots close to the ridge top (52%), and/or in bowls, gullies and on open slopes (Table 2).

4.3. *Triggering*

The vast majority (80%) of all human-triggered avalanches are triggered by skiers, 11.5% by snowboarders and 6.8% by climbers. The rest is mixed or other type of human triggering. The portion of triggering by snowboarders is clearly increasing. It increased from about 5% on the average for the first 5 years to 15% on the average for the second 5-year period. In the last two years (1995–1996, 1996–

Table 2
Frequency of terrain features and combinations thereof. Total number of cases considered: 420. Multiple selection was possible

Terrain feature	Counts	Frequent combinations		Counts
Close to the ridge top	245	Close to the ridge top	Bowl	81
Bowl	147	Close to the ridge top	Gully	53
Open slope	139	Close to the ridge top	Open slope	51
Gully	121	Close to the ridge top	Below rock wall	20
Below a rock wall	40	Gully	Forest, open forest	16
Forest, open forest	38	Bowl	Below rock wall	11
Glacier	17	Open slope	Below rock wall	11
Ridge	10	Close to the ridge top	Glacier	10

1997), the portion increased to about 20%. This trend did continue in the years 1997–1987 and 1998–1999.

The majority of human-triggered avalanches in the present database (i.e. considering all cases) are triggered while out-of-bounds skiing (58%). The rest was primarily triggered while ski touring (41%) and less than 1% was triggered within controlled ski areas. The large portion of avalanches triggered while out-of-bounds skiing is due to the many reported cases from the Davos region. Omitting the cases from the Davos region just reveals the reverse proportions: 58% ski touring vs. 41% out-of-bounds skiing. However, we suspect that the unreported cases are in general more frequent for out-of-bounds skiing. Accordingly, and considering the likely higher frequency of out-of-bounds skiing, it might well be that out-of-bounds skiing contributes the majority of cases to human-triggered avalanches in the Swiss Alps.

Considering only the avalanches that caused fatalities 66% are triggered during ski touring and 34% during out-of-bounds skiing. However, the fatalities occurring during out-of-bounds skiing represent only 27% of the total number of fatalities. This follows from the fact that less skiers are caught per avalanche during out-of-bounds skiing than during ski touring.

Sixty percent of the human-triggered avalanches are triggered by a single person who is either a party member (56%) or travelling individually (44%). Single triggering is more common in out-of-bounds skiing (73%), and occurs obviously nearly exclusively (99%) during the descent, i.e. during skiing. Single triggering during out-of-bounds skiing is about evenly distributed between individually travelling persons (49.7%) and groups (50.3%). During ski touring, triggering by a whole group (two or more persons) is more common (54%) than single triggering (46%). Group triggering is evenly distributed between ascent (49.6%) and descent (50.4%). Single triggering while ski touring is more common during the descent (65%) than during climbing up (35%). Overall, during ski touring 44% of the avalanches are triggered during climbing up, 56% while skiing. In total, 81% of the human-triggered avalanches in the database are triggered during the descent. Table 3 summarizes the most common combinations.

Triggering from outside the starting zone is not uncommon, but occurs in about 10% of the cases. Slabs were triggered from remote points in 22 cases, distances reported vary between 2 and 300 m. In 32 cases, the slab was triggered from outside the starting zone, but the trigger point was hit by the avalanche, i.e. in particular triggering from below.

Going through the reports, we tried to find particularly interesting or unusual facts about the triggering. This was the case for 172 avalanches and these data were entered in an additional comment line. In 112 cases, the additional information given concerns the person involved (ski patrol, ski instructor, etc.), the place of triggering or other features. Often, the comment says that the type of triggering is unclear. The comments for 60 cases concerning the type of triggering could finally be analysed. A substantial number of avalanches (22) were triggered not by the first member of the party who entered the slope, but by the second or third, etc. Typically, only five out of the 22 cases occurred during climbing up. The other 17 avalanches were triggered during skiing when obviously more variation in stability can be

Table 3
Triggering characteristics: compilation of the most common combinations considering type of triggering, activity and grouping. Total number of cases with according data is 421

Triggering	Touring/Out of bounds skiing	Ascent/Descent	Individual/group	Counts
Single	Out of bounds	Descent	Group	73
Single	Out of bounds	Descent	Individual	72
Group	Out of bounds	Descent	Group	62
Group	Ski touring	Ascent	Group	58
Group	Ski touring	Descent	Group	57
Single	Ski touring	Descent	Group	42

expected. In five out of theses 22 cases, it was reported that the triggering person did fall, i.e. clearly induced an additional sudden load on the snow cover. In general, a fall as cause for triggering was reported in 11 more cases. In five other (additional) cases, the slope was skied or crossed by the same party or other skiers a certain short time before the release. So in a few cases (22 in total, omitting the five cases for which a fall was reported), not yet analysed in view of the snow cover conditions in more detail, the triggering must be considered as rather unusual. On the other hand—considering all cases—the vast majority (hence more than 95%) was triggered either by the first person entering the slope or by several persons (group triggering). If only single triggering by skiing (descending) groups is considered, the portion of triggering by the first person entering the slope is some more than 90%, i.e. that about 5–10% are triggered by the second or third, etc., skier entering the slope. This portion increases to about 10–15% if only cases during ski touring are considered, since most of the unusual triggering cases reported happened during ski touring.

Grouping up at the same spot (e.g. at the bottom of a slope) contributed to seven releases. Keeping distances between group members could not avoid triggering in 14 cases.

4.4. *Involvements*

Once the avalanche was triggered, most recreationists were fortunately not even caught or could escape (Table 4). The sample with only the human-triggered avalanches from the region of Davos shows that in 38% of the cases a person was caught by the avalanche. From the ones caught, about a quarter got completely buried and 42% of the completely buried victims died. Considering all cases shows that the portion of completely buried persons that were found dead is higher (58%). However, due to the small number of cases in the Davos sample the difference is statistically not significant ($p = 0.07$). Tschirky et al. (2001) estimate the survival rate for completely buried victims to be about 50%. The difference between the two samples is likely due to the negative selection bias. The Davos sample is much more complete, including many cases that had no severe consequences that are missing from the other regions of the Swiss Alps.

Table 4
Number of avalanches triggered, of persons caught and consequences for the cases of the Davos region and for considering all cases. Percentage gives rate of death for completely buried victims

Sample	Avalanches	Caught	Completely buried	Found dead (% of completely buried)
Davos	311	119	31	13 (42%)
All cases	634	807	330	194 (58%)

Our data clearly show that the number of people caught in an avalanche during out-of-bounds skiing is smaller compared to ski touring, and that the survival rate (number of surviving recreationists vs. completely buried ones) is larger while out-of-bounds skiing than ski touring. During out-of-bounds skiing, often one skier only enters the slope from above, and the avalanches are rather small (both factors favour survival), but triggering is relatively frequent.

Independent of the sample chosen, it becomes clear that if an avalanche is triggered on a ski touring trip the number of people caught is smaller during skiing than during climbing up. Comparing ascent and descent, from the persons caught about the same portion is completely buried and of the completely buried about the same portion dies. So the survival rate is independent of the activity (climbing up or skiing) in the case of ski touring.

On the other hand, again independent of the sample chosen, if only avalanches are considered triggered by descending skiers, either during out-of-bounds skiing or ski touring, less people are caught in case of out-of-bounds skiing than in case of ski touring. From the persons caught, about the same portion becomes completely buried. There seems to be a slight trend towards less completely buried people during ski touring. But finally from the completely buried ones, clearly more of the ones caught during ski touring die than from the ones caught during out-of-bounds skiing, i.e. the survival rate is clearly higher for the out-of-bounds skiers than for the backcountry skiers (see above). This might be due to, e.g. faster rescue or smaller burial depth in case of out-of-bounds skiing compared to ski touring. In fact, it was found that the avalanches triggered are smaller during out-of-bounds skiing than during ski touring, clearly favouring survival.

It has been suggested that snowboarders are less frequently buried if they are caught than skiers. This hypothesis was checked with the data set from Davos. Only the avalanches triggered while out-of-bounds skiing/snowboarding (descent) were considered. Snowboarders triggered 48 avalanches, 18 snowboarders were caught, of them only two were completely buried and one was killed. Whereas skiers triggered 196 avalanches, 56 skiers were caught, of them 18 were completely buried, six of the completely buried died. These data suggest in fact that snowboarders are less frequently completely buried than skiers. However, due to the small data set the difference is statistically not significant ($p = 0.08$).

Multiple burials are neither rare nor frequent. From the 635 cases recorded, in only 389 cases somebody was caught, thereof, in 178 cases (46%) more than one person was caught. If only the avalanches are considered that caused one or more completely buried victims the proportion of multiple burials is 28%. If the analysis is restricted to the avalanches triggered during ski touring the proportion of multiple burials increases to 33%, whereas during out-of-bounds skiing the proportion of multiple burials is 19%.

4.5. Snow cover characteristics

For 90 cases (14%), there is detailed snow cover information available, i.e. a snow profile of varying completeness.

The slab failure is at the boundary between storm snow and old snow in only 38% of the cases. Storm snow means the new snow from the recent snowfall (storm), usually less than 5 days old. The other failures are due to weak layers or interfaces within the old snowpack. There is no failure plane reported within the storm snow layer. The portion of new snow instability is higher during out-of-bounds skiing (44%), compared to 28% during ski touring. However, the difference is not statistically significant. Groups guided by professionals triggered avalanches with failure planes primarily (83%) in the old snowpack. These findings suggest that avalanche education is rather successful in recognizing new snow instabilities but not so much in detecting old snow instabilities such as persistent weak layers.

A weak layer was found only in 50% of the profiles. In all other cases, the failure was between two adjacent layers, a so-called interface failure. In nine cases, the failure in the weak layer could be associated with the upper or lower layer boundary of the weak layer. Accordingly, overall, in 60% of the cases the failure occurred at a layer boundary. Interface failures are more frequently (71%) found in the case of new snow instability. However, the difference is not significant ($p = 0.11$).

A rutschblock test was done in only 55 cases (Fig. 9). The median rutschblock score is 3, the average is 3.6. Four cases exist with scores 6 or 7. The high scores can be explained either by a substantial time delay (e.g. one profile/RB test was done 4 days after the release) or by the location (e.g. profile at fracture line, far from trigger point).

In the following, we will try to find some characteristics of the slab layer, the substratum and the weak layer or interface, and the layering in general.

Ideally, the analysis should be complemented with another 90 profiles of slopes that were skied but not triggered to derive real criteria for profile interpretation.

4.5.1. Slab properties

Although the weak layer and the slab cannot be separated when dealing with the avalanche release

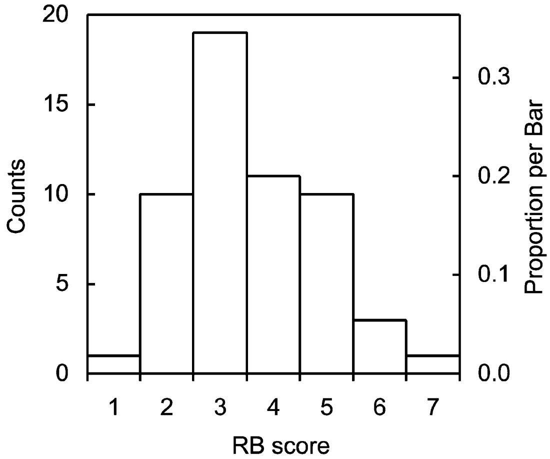

Fig. 9. Rutschblock score of RB tests adjacent to or at fracture lines of human-triggered slab avalanches ($N = 55$).

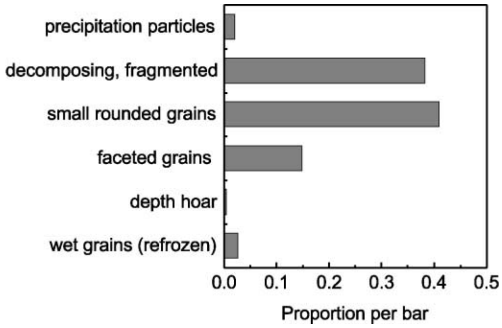

Fig. 10. Grain type of slab ($N = 90$).

problem, the slab properties are of crucial importance for the stress transformation to the weak layer. The typical slab (79%) consists of either decomposing and fragmented precipitation particles or small-rounded grains, or a mixture of the two (Fig. 10). The median grain size is 0.75 mm. The slab is usually rather soft (median: 2). In 76% of the cases, the hand hardness index is ≤ 2. The median slab temperature is -4.5 °C and the median density is 206 kg m^{-3}. The median value of slab thickness found in the profiles is 52 cm, in accordance with the values of fracture depth given above. The hardness profile of the slab is most frequently characterized as either type 1 (37%) or type 6 (42%) (Fig. 1). The above values reflect typical snow cover conditions in general showing that the slab properties alone are not conclusive for profile evaluation. Only in three cases (3.4%), a crust at the top of the slab was found, supporting the experimental and theoretical results on the effect of crusts at the snow surface on skier triggering.

4.5.2. Substratum

The substratum is the part of the snow cover that remains after slab release. It consists of all layers below the weak layer or below the failure interface. Again, as in the case of the slab, it is tried to summarize the different layers and describe the substratum as just one layer. The typical grain type in the substratum are faceted grains and depth hoar (77%), the median grain size is 2 mm. The hardness varies strongly. There are many soft (hand hardness index ≤ 2) substrata (51%), but hard ones (hand hardness index ≥ 3) are frequent (36%) as well. The median temperature of the substratum is -2.5 °C and the density is about 300 kg m^{-3}. All types of hardness profiles are present. Most frequently, but still in only 25% of the cases, the hardness profile of the substratum was characterized as type 1. Types 4, 5 and 6 are quite frequent as well. Together these four types cover 64% of all cases.

The variety of hardness profiles in the substratum suggests that it is hardly possible to classify profiles only based on the generalised hardness profile. The combination of the hardness profiles of the slab and the substratum shows that in 55% of the cases the failure was at the transition from hard to soft or vice-versa from soft to hard. In the large rest of the cases, there was no distinct discontinuity in the generalised hardness profile at the failure level: 39% of the failures occurred within a soft portion of the simplified hardness profile and the remaining 6% in a hard section. This result is partly due to the fact that the characterisation into the 10 different types did not take into account the hardness of the single layers, but the general feature of the profile, thereby neglecting the hardness of thin layers. However, the layer hardness of the weak layer and the two adjacent layers is recorded and subsequently the analysis will focus on the discontinuities in hardness at the weak layer boundaries, or in the case of an interface failure between the two adjacent layers. Theoretically, 100 different hardness profile combinations exist, but only 34 did occur. The five most frequent combinations, but still covering only 36% of all 89 cases, are given in Fig. 11.

4.5.3. Weak layer or interface

In the 90 profiles analysed, a weak layer was found in 45 cases (50%). The database for the weak

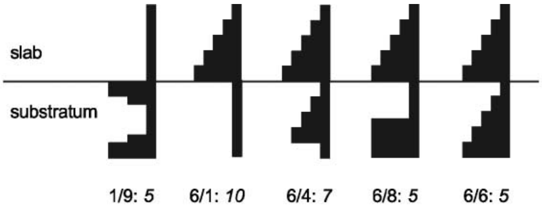

Fig. 11. Most frequent combinations of hardness profiles each for slab and substratum. Numbers give type of profile (Fig. 1) and frequency (in italic). Total number of profiles represented: 32, total number of profiles analysed: 89.

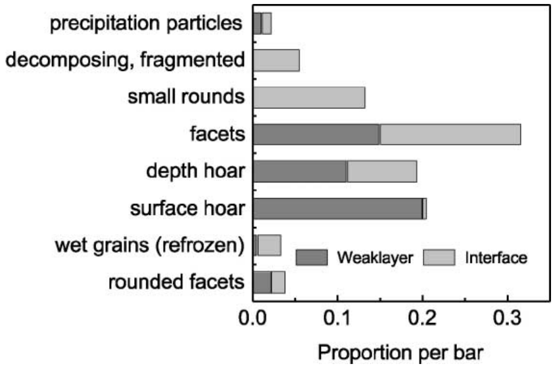

Fig. 12. Grain type of weak layer ($N = 45$) and in weaker/softer layer of the two layers adjacent to an interface failure ($N = 45$).

layer is accordingly relatively small. More than 90% of all weak layers found consisted of large crystals with plane faces: surface hoar, faceted grains and depth hoar, i.e. of persistent grain types (Jamieson, 1995) (Fig. 12). The median grain size is 2 mm. In 56% of the cases, the weak layer thickness is equal to or less than 1 cm, median hand hardness index is 1 and median temperature is −4 °C (Fig. 13).

The layer above the weak layer typically (57%) consists of fragmented precipitation particles and rounded particles of median size 0.75 mm. The grains in the layer above the weak layer are statistically significantly smaller than in the weak layer ($p < 0.001$) (Fig. 15). The median hardness of the layer above the weak layer is 2–3. (Fig. 15). Accordingly, the layer above the weak layer is statistically significantly harder than the weak layer ($p < 0.001$), and additionally also significantly harder than the slab ($p < 0.001$).

The layer below the weak layer consists of a variety of grain types, but faceted grains and depth hoar are most frequently found (71%). Quite common are rounded grains, depth hoar and crusts (refrozen wet grains)/ice layers. The median grain size is 1.5 mm, still statistically significantly ($p = 0.001$) smaller than in the weak layer (Fig. 14). The hardness is variable (median: 2), but the layer below the weak layer is statistically significantly harder ($p < 0.001$) than the weak layer (Fig. 15). In about 40% of the cases, the hand hardness index of the layer below is larger than 2.

The above analysis suggests that it should be not too difficult to detect weak layers—provided, of course, that a detailed snow profile is available, since it seems that based on hardness, grain type and size the weak layer should show up clearly. However, the existence is only an indication of instability, but not conclusive. Furthermore, the weak layer strength, the skier stability (that also depends on the slab characteristics) and finally the propensity for fracture propagation are relevant for stability evaluation.

If there is no weak layer the detection of a potential instability is more difficult. The layer above

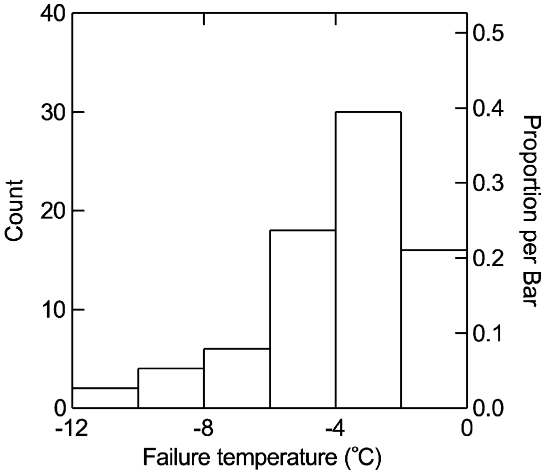

Fig. 13. Temperature in weak layer or at failure interface ($N = 77$).

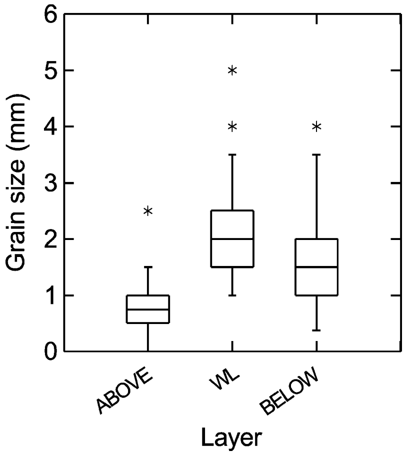

Fig. 14. Grain size in layer above, weak layer and layer below ($N = 45$).

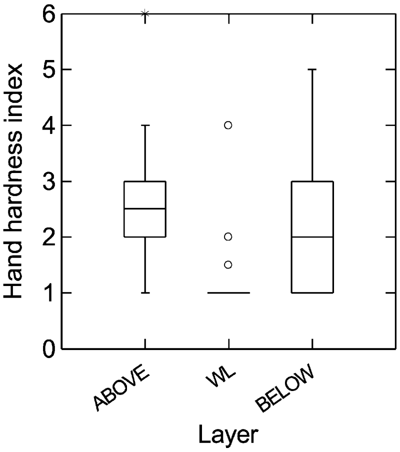

Fig. 15. Hardness of layer above, weak layer and layer below ($N = 45$).

typically (60%) consists of rounded grains and fragmented precipitation particles of median size 0.5 mm. Crusts/ice lenses are occasionally found as well. The median hand hardness index is 2. In the layer below the failure interface faceted grains, depth hoar and crusts/ice layers dominate (81%). The median grain size is 1.75 mm, statistically significantly larger than in the layer above the failure interface ($p < 0.001$) (Fig. 16). In the weaker/softer of the two adjacent layers persistent grain types dominate (54%), followed by grains from storm (recently deposited) snow layers (36%) (Fig. 12). The layer below is harder (median: 3) than the layer above the failure interface. Yet there is no statistically significant difference between the hardness of the layers above and below the failure interface ($p = 0.34$). However, there is usually a hardness difference, but sometimes the upper layer is harder than the lower one, and vice versa. Accordingly, as mentioned, there is on average no difference in hardness. But analyzing the hardness difference pair by pair shows that the median absolute difference in hardness is 1 1/2 degrees of the hardness index scale. In 53% of the cases, the hardness difference is 1 1/2 or more levels of the hardness index scale. The hardness difference is statistically significant ($p < 0.001$) (Fig. 17). Whereas there is usually a prominent hardness difference, in 9% of the cases there is only a difference of one-half level of hardness, and in 7% of the cases there is no hardness difference at all.

Failures on or below crusts are frequently found (60%) in the case of interface failures. These types of failure occurred six times below a crust and 21 times on a crust. In four of the six cases where the failure was below a crust, the layer below the crust consisted of faceted grains or depth hoar. On the other hand, when the failure was on the crust, in 38% the crust itself included faceted grains or depth hoar, and in 16 of the 21 cases in the layer above fragmented precipitation particles and small rounded grains were found. Facets above the crust were recorded in six cases (29%).

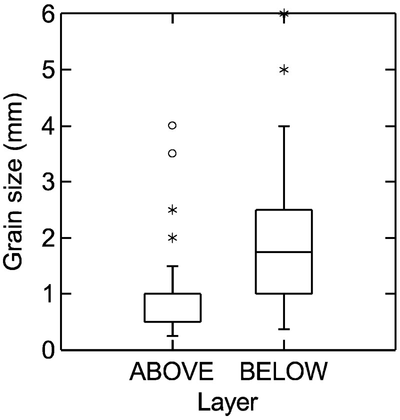

Fig. 16. Grain size in layer above and layer below of failure interface ($N = 45$).

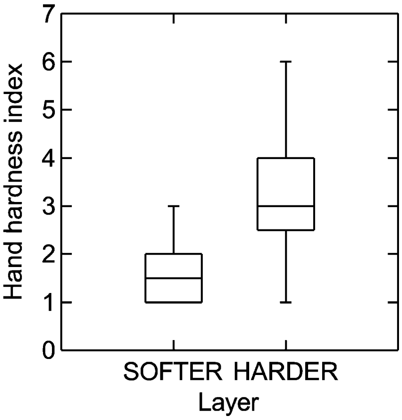

Fig. 17. Hardness in layers adjacent to failure interface. Hardness difference is shown by pair-wise sorting the data ($N = 45$).

5. Conclusions

In order to find characteristics and to better understand the mechanics of human triggered avalanches, 10 years of avalanche occurrence data from the Swiss Alps were analyzed (636 cases). We focused on avalanche release and snowpack patterns. Between 1987–1988 and 1996–1997, the average number of avalanche fatalities in the Swiss Alps was 23 per year. More than 90% of the victims were skiers, snowboarders, climbers, etc.—people killed during recreational activities in the free (not controlled) terrain. The vast majority (90%) of these recreationists were killed by an avalanche that was triggered by themselves or by another member of their group.

The recreationist nearly exclusively triggered dry snow slab avalanches of medium size. The slab detached of a human-triggered slab avalanche is about 50 m wide and 80 m long. The overall length is about 150 m. The fracture depth is about 45 cm. The inclination in the starting zone is about 38°. The main parameters are summarized in Table 5.

The vast majority of avalanches was triggered by the first person entering the slope or by several persons (group triggering). Test skiing seems to be a reliable stability test in at least about 90% of the cases. The fact that many avalanches are triggered by whole groups while ski touring, usually with serious consequences, suggests that the avalanche risk might be substantially reduced by more consequently skiing one by one on critical slopes, improved route selection and keeping (probably rather large) distances while climbing up.

Table 5
Characteristics of human-triggered avalanches. Between the first and third quartiles 50% of the cases are found. In the case of the aspect the mode is given

Parameter	*N*	First quartile	Median	Third quartile
Width (m)	611	29	50	100
Length of slab (m)	61	50	80	150
Path length (m)	619	80	150	300
Fracture depth (cm)	522	30	45	60
Slope angle (°)	617	36	38	40
Elevation (m a.s.l.)	629	2190	2410	2610
Aspect	634	–	NE	–

The analysis of the 90 profiles available did support most of the mainly unstructured knowledge used in stability evaluation based on snow profiles (Schweizer et al., 1992). However, the results of the present study should be compared with profiles from slopes that were skied but did not fail to make sure that the characteristics found are really relevant for stability evaluation. A weak layer was found in 50% of the cases. In all other cases and in a few more cases where a weak layer was present, the failure was between two adjacent layers (layer boundary), a so-called interface failure (60%).

Nearly all the slabs found were relatively soft at the surface suggesting good deformation transfer to the weak layer. This finding was expected based on the theoretical and experimental work by Schweizer (1993) and Schweizer et al. (1995). Detection of weak layers seems to be feasible based primarily on layer thickness, grain type, grain size and hardness difference. Weak layers consist of large crystals (2 mm) of persistent grain types (90%). If there is no weak layer the detection of the instability is more difficult. However, there is in most cases a significant difference in hardness and grain size. Crusts are commonly found above or even more frequently below the failure interface.

The above results support the findings of similar studies by Föhn (1993), Jamieson and Johnston (1992), Jamieson and Geldsetzer (1996) and Föhn et al. (1998), in particular regarding the weak layer properties. However, the present study did investigate the snow cover characteristics in more detail, in particular the slab–weak layer interaction in view of triggering. The data analysis has shown that the typical slab is relatively shallow supporting the simple model of skier loading. If the typical slab is about 45 cm thick, rather soft at the top and relatively hard above the weak layer, then this configuration is exactly the one that is suggested as the most critical one for skier triggering in view of the present knowledge about skier triggering (Schweizer, 1999; Schweizer and Camponovo, 2001). The slab must be soft to enable the skier to efficiently impart deformations to the weak layer. The slab has to be relatively shallow, since the skier's impact strongly decreases with increasing depth. A distinct difference in hardness favours stress concentrations at the interface to the weak layer. Finally, the frequently found interface failure makes the detection of potential instabilities more difficult, but is well in accordance with the hypothesis by Jamieson and Schweizer (2000) who propose that most failures, even in the presence of a weak layer, are likely interface failures, i.e. occur at the lower, or upper boundary of the weak layer—at the discontinuity.

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