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About the Practical Knowledge to Understand Snow Avalanches – A Chronology

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1. Introduction

At all times settlements and infrastructures in mountainous regions were endangered by avalanches. The following table gives an overview on major avalanche disasters in residential areas.

Year	Venue	Fatalities
1518	Leukerbad/Wallis/Switzerland	60
1598	Graubünden/Switzerland	100
1689	Montafon/Voralberg/Austria	120
1689	Tyrol/Austria	122
1689	Prätigau/Switzerland	57
1718	Leukerbad/Wallis/Switzerland	55
1720	Vorderrhein/Graubünden/Switzerland	100
1888	Tyrol/Austria	53
1916	Front-line between Italy and Austria	some thousand
1951	Graubünden/Switzerland	54
1951	Tyrol/Austria	54
1954	Vorarlberg/Austria	122

Table 1. Selected avalanche disasters in the European Alps (Flaig, 1941; Flaig, 1955; Haid, 2007; Schott, 2005).

However, the development of alpine skiing at the end of the 19th century implicated that an increased number of humans encountered avalanche terrain in the backcountry. Thus many important findings on avalanches were generated by mountaineers and practitioners such as Zdarsky (1916, 1929), Lunn (1926) and Bilgeri (1934); further outstanding contributions were provided by scientists like Welzenbach (1930) and Paulcke (1938). Their findings had huge practical relevance and formed the basis for decision- making in mountaineering and backcountry skiing.

The basic findings from the 1920s and 1930s are still valid; they are certainly still used today and serve as an important tool in avalanche education.

However, the following decades provided a strong increase of knowledge, especially in snow classification and snow stability; the implementation of the stratetic methods at the end of the 1990s intensified the discussion of avalanche education.

This paper describes the most relevant practical findings in the field of snow and avalanches and reviews them in terms of their application for mountaineers and backcountry skiers.

2. Chronology

Although there were some books on avalanches published prior to 1900 (Coaz, 1881 etc.), the chronology of this paper starts with the time when alpine skiing became accepted in Central Europe. The founder of alpine skiing was Mathias Zdarsky who published his 'Lilienfelder Skilauf-Technik' in 1897. Since that time skiing became more and more popular and consequently the information on avalanche danger was an important topic too.

The chronology of this paper therefore starts with Zdarsky's 'Elements of Avalanche Awareness' published in 1916. The chronology is divided into four periods: 1900 to the 1930s, 1940 to the 1960s, 1970 to the 1980s and 1990 up to the present. Table 2 gives an overview including a commentary why just these four periods were prefered.

Period	Findings
1900 – 1930s	basics: influence of topography (slope angle...), meteorology (wind, new snow..) and snowpack on avalanche formation
1940 – 1960s	scientific findings: snow classification, classification of snow hardness
1970 – 1980s	snowpack stability: development of stability tests basic types of ram profiles
1990 up to present	strategic methods

Table 2. Chronology of the developments in the field of snow and avalanches

2.1 The period from 1900 to the 1930s

This is the period when basic findings on snow and avalanches were arrived at. Zdarsky (1916) identified four parameters for avalanche formation: the slope angle, the friction coefficient, the strength of snow and the weight of snow.

According to Zdarsky (1916), avalanches have to be expected when the slope angle is more than 22°. He indicated that the friction coefficient is lowest on unmown meadows. Zdarsky also found that deposited snow is not homogenous and that several layers may exist in an alpine snowpack; he stated that owing to evaporation snow acquires increasing void pockets, and indicated that kind of snow as *dröhnender Schnee* [rumbling snow]. The fourth parameter for avalanche formation is the weight of snow. This is dependent on the kind of snow and the intensity of the snowfall; however, Zdarsky also recognised the wind as another important factor.

In order to get an overview of the internal strength Zdarsky suggested scanning the snow with a pole. He concluded that great avalanche danger exists if the snow can be penetrated easily.

In 1926 Lunn published a book on alpine skiing, including a basic chapter on avalanches. He divided avalanches into four classes (dry powder avalanches, wet new snow avalanches, snow slabs or wind slabs and wet old snow avalanches). With powder avalanches Lunn stated that after a heavy snowfall the danger may last for a day or two, or even more. He also indicated that wind-driven powder may be covered by a fresh snowfall which makes it very difficult to assess the avalanche risk.

A still valid rule from Lunn (cited in Daffern (1992)) is to mistrust all steep slopes after a fresh fall until the pine trees are free from snow.

In 1929 Zdarsky published a more detailed book on avalanches which starts with the very well-known sentence 'Der Wind ist der Baumeister der meisten Lawinen' ('the wind is the architect of most avalanches').

Welzenbach (1930) reported on investigations at the Kaindlgrat (Wiesbachhorn) and the Eigergletscher which he carried out in cooperation with Paulcke; they found a previously not observed kind of snow and called it 'Schwimmschnee' (the term was later designated as depth hoar (Paulcke, 1938)). It was assumed that this kind of snow is able to cause avalanches.

Bilgeri (1934) mentioned the six most important points which have to be considered when travelling through avalanche terrain (angle of the slope, terrain, ground, depth of the snow, consistency of the snow and anchorage of the snow). He indicated that uniform slopes are more dangerous than ridged slopes, and that trees hold the snow better than bare ground. Bilgeri (1934) also recognised the depth of the snow as an other fundamental factor, and noted that the deeper the snow the more dangerous the situation. Furthermore he refers to the consistency of the snow (the more feathery or the wetter the snow, the more dangerous) and the anchorage of the snow (unanchored snow is more dangerous).

Flaig (1935) indicated the steepness of a slope (already mentioned by Zdarsky (1916) and Bilgeri (1934)) as an important influencing value; he gives even 14° as the lowest limit for avalanche release. Flaig (1935) noted that the prevailing conditions are the crucial factor for avalanches and not the terrain; according to Flaig there exist no specific avalanche areas in mountainous regions, only deadly snow and weather situations. Flaig's point of view finds support by several statistical findings; almost every winter the greater part of avalanches are concentrated in a few - short - periods. Fig. 1 shows the distribution of avalanches in Austria in 2009/10. About more than a quarter of all avalanches occurred in just one week (3 to 8 Feb. 2010). In the same period 15 persons were killed by avalanches which is about 50% of all fatalities of an average winter in Austria (Höller and Bilek, 2010).

Flaig (1935) also identified that layering is an important factor, and proposed that skiers should consider the structure of the snowpack when assessing the avalanche risk.

Seligman (1936) specified the most meaningful records which should be available when travelling through avalanche terrain: maps, knowledge of past meteorological conditions, weather forecasts, snow depth, wind direction and snow sections. With reference to snow sections, Seligman (1936) noted that the investigations of snow sections is the best method of ascertaining the facts, more accurate and satisfactory than any consultation of weather records; this finding is more than 70 years old and remains important to the present day.

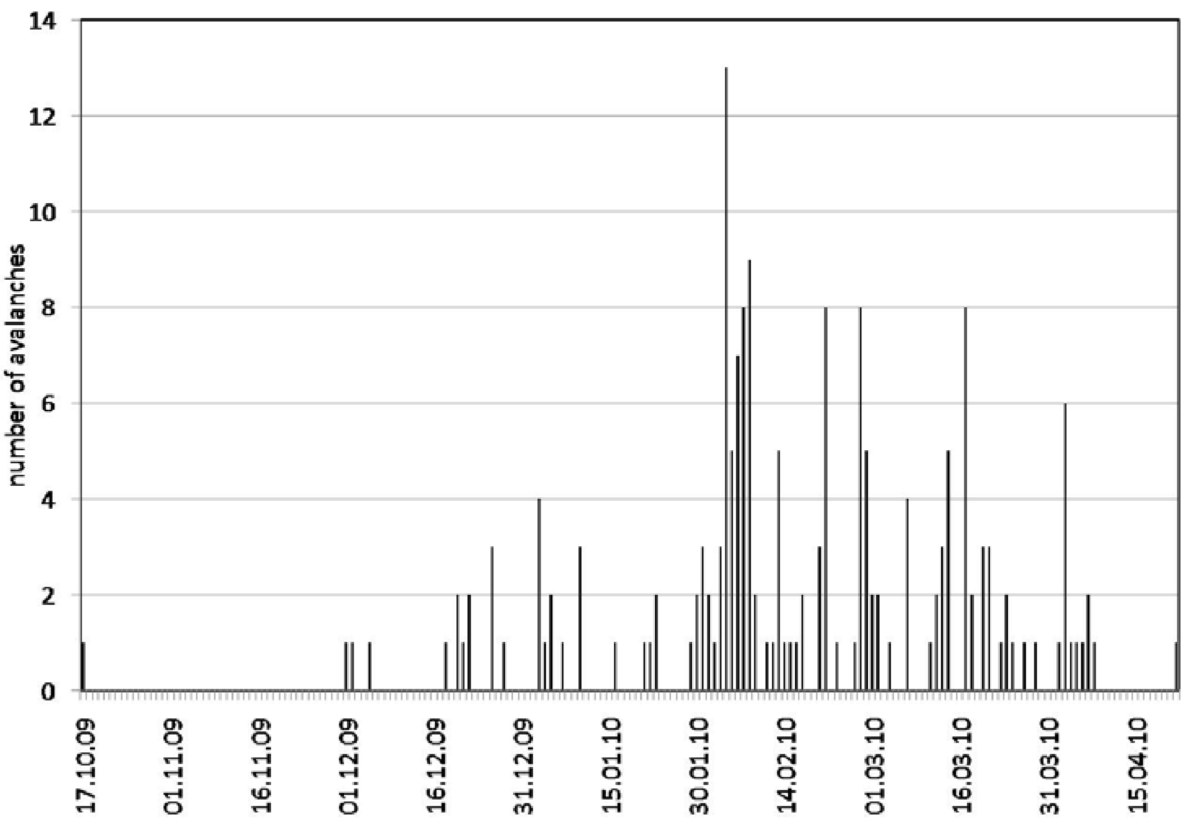

Fig. 1. Distribution of avalanches in Austria in 2009/2010 (Höller and Bilek, 2010).

Paulcke (1938) identified several influencing values that make snow slides more easily: the smoother and steeper the slope, the looser the snow, the wetter the snow, the more massive the depth hoar layers and the higher the loading; on the other hand snow slides less the more it is bonded with the base and the more it is metamorphosed into firn.

Paulcke (1938) pointed out that windward slopes are generally safer than lee sides, and that long periods with cold weather lead to distinctive depth hoar layers. In order to assess avalanche risk backcountry skiers primarily require the following data: total snow depth, the position of crust layers, new snow, depth hoar layers and the depth of these layers (Paulcke, 1938).

Following Seligman's example (1936), Paulcke (1938) also indicated that the basis for the accurate assessment of a prevailing situation is the evaluation of snow profiles (Fig. 2).

Bader et al. (1939) proposed to investigate the relative strength of snow layers by means of a simple test. They introduced the concept of ram resistance, which was measured with the Swiss *Rammsonde*. According to Bader et al. (1939), ram profiles can be used to identify layers in the snowpack and to assess the avalanche danger; snow profiles consisted of investigations of factors like temperature, density, air permeability and layering.

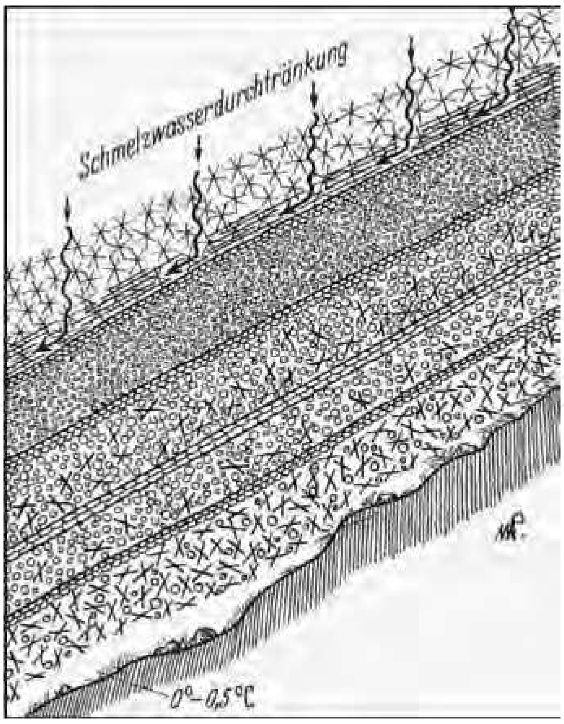

Fig. 2. Snow profile (Paulcke, 1938)

2.2 The period from 1940 to the 1960s

In this period, snow and avalanche science became an important area of research. Backcountry skiers in particular benefited from the snow classification and the classification of snow hardness. The beginning of avalanche warning and the implementation of safety equipment (e.g. avalanche beacon) was another very important subject in that period.

After World War II the first warning services were initiated. In Switzerland the SLF (Swiss Institute for Snow and Avalanche Research) took over the avalanche warning from the Swiss Army. The first avalanche warning center in Austria was established in 1953 in the federal state of Vorarlberg (Längle, 1977).

A simple snow classification was given by Bucher (1948). He divided snow crystals into fragmented particles, small rounded particles and large rounded particles. Bucher (1948) also introduced a degree of safety (the ratio of shear strength and shear stress).

De Quervain (1950) improved the previously used scale of hardness and proposed a simple handtest with five hardness levels.

After 10 years of snow measurements at the Weissfluhjoch (Davos), five different types of profiles were identified (EISLF, 1951): loose; loose base and strengthening in the remaining profile, but some intermediate layers; loose base with strengthening in the remaining profile; strengthening of the profile with the exception of some intermediate layers; strengthened snowpack).

Eugster (1952) introduced the terms destructive metamorphism (the transition to rounded grains) and constructive metamorphism (the transition to depth hoar). Snow profiles were complemented by further parameters: along with temperature, density and layering, profiles should also include grain size and grain shape (in each layer the grain shapes were given in quantiles of tenths) as well as hardness and water content.

In 1954 the first international snow classification was published (Schaefer et al., 1954). Fraser (1968) divided the release factors into two categories: spontaneous release due to gradual influence, and triggering due to a sudden effect. Spontaneous avalanches will be triggered as the result of a decrease in shear strength (increase of temperature, rain) or an increase in shear stress (snowfall, rain). Sudden effects are generated by external effects (skier, climber, deer) or as resulting from the failure of a lateral anchorage.

At the end of the 1960s the first avalanche beacon (SKADI) was applied in America; some years later the PIEPS was developed in Europe (Gayl, 1979; Neubauer, 1979).

In 1969 the 'Field Guide to Snow Crystals' was published by LaChapelle (1969). The book shows dozens of excellent photographs and can also be used by practitioners to identify snow crystals.

Sommerfeld and LaChapelle (1970) proposed a classification of snow metamorphism based on a genetic point of view; they introduced the terms equi-temperature metamorphism (instead of destructive metamorphism) and temperature-gradient metamorphism (instead of constructive metamorphism).

2.3 The period from 1970 to the 1980s

Basically this period was characterised by the development of the stability tests and new safety equipment (e.g. Avalanche airbag...) and the findings by Conway et al. (1984, 1988).

Already in the 1970s Hohenester (1979) reported on a balloon to retain a person on the surface of an avalanche. The device was later improved by Aschauer and is now well-known as avalanche balloon system (ABS).

In 1974 Nils Faarlund und Walter Kellermann (Kellermann, 1990) worked on a simple test to investigate the snowpack; they called it '*Norwegermethode*'. The test determines the force which is necessary to draw off a defined snow trapezoid (front side 0.6m, backside 0.2m) on a weak layer; the result is a measure for the stability of snow. Although the test only uses three levels (weak: 0 - 100 N, medium: 100 – 200 N, stable: > 200 N) to evaluate stability, the '*Norwegermethode*' agreed well with the previously developed *Rutschblock* test. A slightly modified form of the '*Norwegermethode*' is the shovel shear test. An evaluation of the shovel shear test can be found in Schaerer (1988). He noted that the shovel shear test is appropriate for identifying weak layers but requires many tests to get reliable results.

In addition to the shovel shear test the compression test has been applied in Canada since the 1970s (Clarkson, 1993; Jamieson, 1999). The test is done on an isolated snow column of 0.3 x 0.3 m. The shovel blade is placed on top of the column and the applied load is gradually increased: at 'easy' level, a failure occurs before 10 light taps, using fingertips only. 'Moderate' means that a failure occurs before 10 moderate taps with the elbow. A failure due to a higher load (10 firm taps with the whole arm) is classified as 'hard'.

The *Rutschblock* (Fig. 3) which was used in the Swiss Army to demonstrate weak layers in the snowpack was quantified by Föhn (1987). According to Föhn (1987) it is a useful tool for the evaluation of slope stability, but should be used only by experienced persons with an intuitive feel for the slope stability distribution.

The *Rutschblock* is the most sophisticated test, but it needs more time to complete a *Rutschblock*, as seven load levels are used. Levels 1 to 3 indicate that such slopes are unstable for skiers, the levels 4 and 5 indicate that such slopes should be considered as suspicious, the risk of triggering slabs on such slopes can be taken to be low when levels 6 and 7 are found.

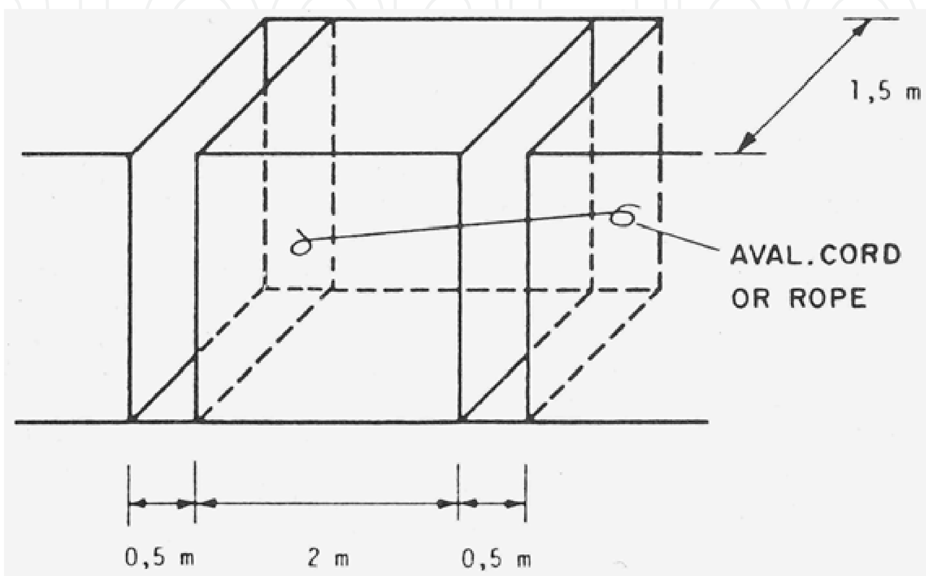

Fig. 3. Rutschblock (Föhn, 1987)

De Quervain and Meister (1987) found six different ram profile types (from very stable - with increasing hardness at the bottom -A in Fig 4 - to very weak - with 'belly-like' shape and very low hardness values at the bottom - F in Fig. 4).

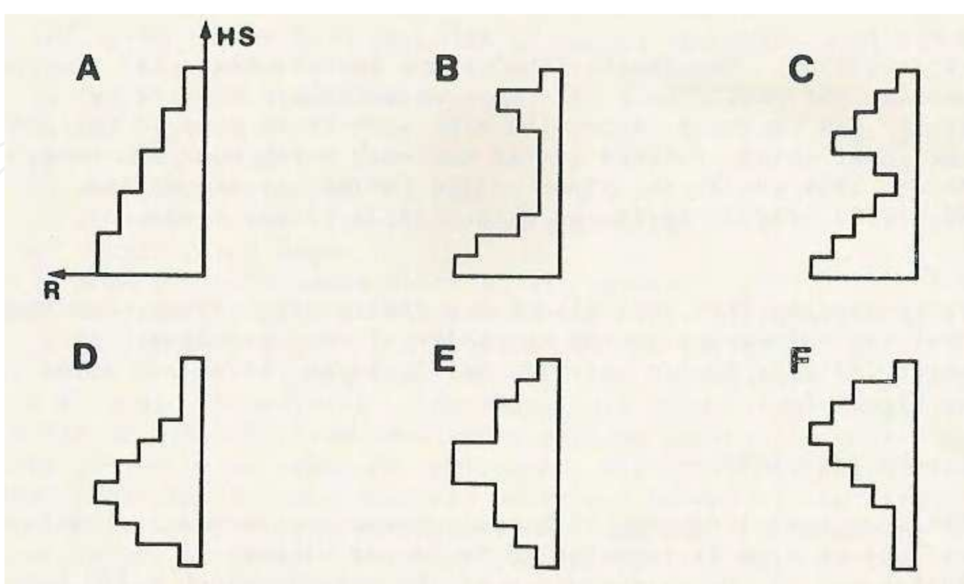

Fig. 4. Basic types of ram profiles (de Quervain and Meister, 1987)

Conway and Abrahamson (1984) measured shear indices on the crown walls of eight avalanched slopes. They found strong variations of stability (between 1 and 3) within short distances. The probability of coming upon an area where an avalanche may be released (shear stability < 1) is about 33%.

Salm (1986) illustrated these findings in a plain figure (Fig. 5), and concluded that on a typical slope areas with a low shear stability alternate with stable areas. Salm (1986) indicated the instability areas (where the shear stability is < 1) as 'Taschen' [hot spots] with a size of less than 3 m.

Föhn (1988) did not detect small 'deficit areas' (S < 1) as defined by Conway and Abrahamson (1984, 1988) on various slopes. However, a few "deficit areas" (S' < 1) and many weak zones (1 ≤ S' ≤ 2) have been found on all slopes. He concluded that either many small 'deficit areas' or a few large 'deficit zones' are needed for avalanche formation.

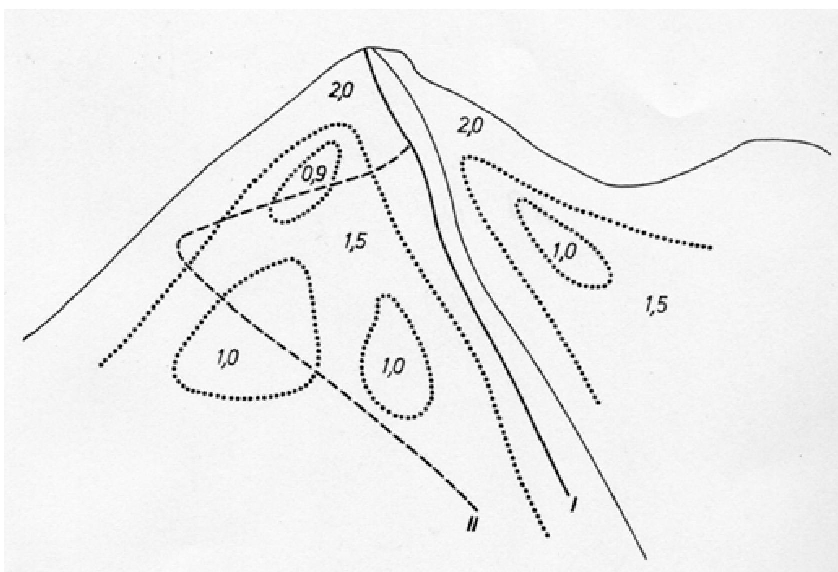

Fig. 5. Possible distribution of stability on a slope (Salm, 1986)

2.4 The period from 1990 up to the present

These two decades were characterised by the improvement of the stability tests and safety equipment (digital transceivers...) as well as by the implementation of a standardised avalanche danger scale and the introduction of strategic methods.

The new snow classification was issued in 1990 (Colbeck et al., 1990).

Föhn (1992) investigated the characteristics of weak snow layers or interfaces and found that - if a weak layer exists - it consists in 80% of all cases either of surface hoar, of faceted particles or of depth hoar; a sliding test (e.g. *Rutschblock*) proves to be the only fast and reasonable method for demonstrating the occurrence of such fragile interfaces.

The new European Danger Scale (Meister, 1994) became effective in the winter season 1993/1994. The scale which is now valid in many alpine countries is characterised by 5 levels (from 1 – low to 5 - very high) and makes it easier to compare the avalanche bulletins of the different countries.

At the end of the 1990s the first digital beacons (Edgerly and Hereford, 1998) were introduced. The advantage over the former transceivers was an optical display where indicators show the direction of a buried person.

Kronholm et al. (2002) studied the spatial variability of snow stability on small slopes. According to Kronholm et al. (2002), slopes with a weak layer with low average stability and low variability are more critical than if either average stability or stability variation is high.

In the 1990s different stability test methods were developed such as the loaded column test (McClung and Schaerer, 1993), the stuffblock test in 1993 (Birkeland and Johnson, 1999) and the quantified loaded column stability test by Landry et al. (2001).

The loaded column is done by loading a snow column (0.3 x 0.3 m) with blocks of snow until failure occurs (McClung and Schaerer, 1993).

The stuffblock test also is carried out on an isolated snow column of 0.3 x 0.3 m. In the first step the stuff sack (a nylon sack packed with snow, weighing 4.5 kg) is gently placed on the shovel blade which is put on the top of the isolated column. A failure of the weak layer at this point indicates a stuffblock drop height of zero. Then the column is loaded dynamically by dropping the stuff sack from 0.10 m, and increasing that height by 0.10 m increments until shear failure in the weak layer occurs (Birkeland and Johnson, 1999).

The extended column test (Simenhois and Birkeland, 2006) and the propagation saw test (Gauthier, 2007 – see Fig. 6) can also be used to evaluate the fracture propagation propensity of slab and weak layer combinations.

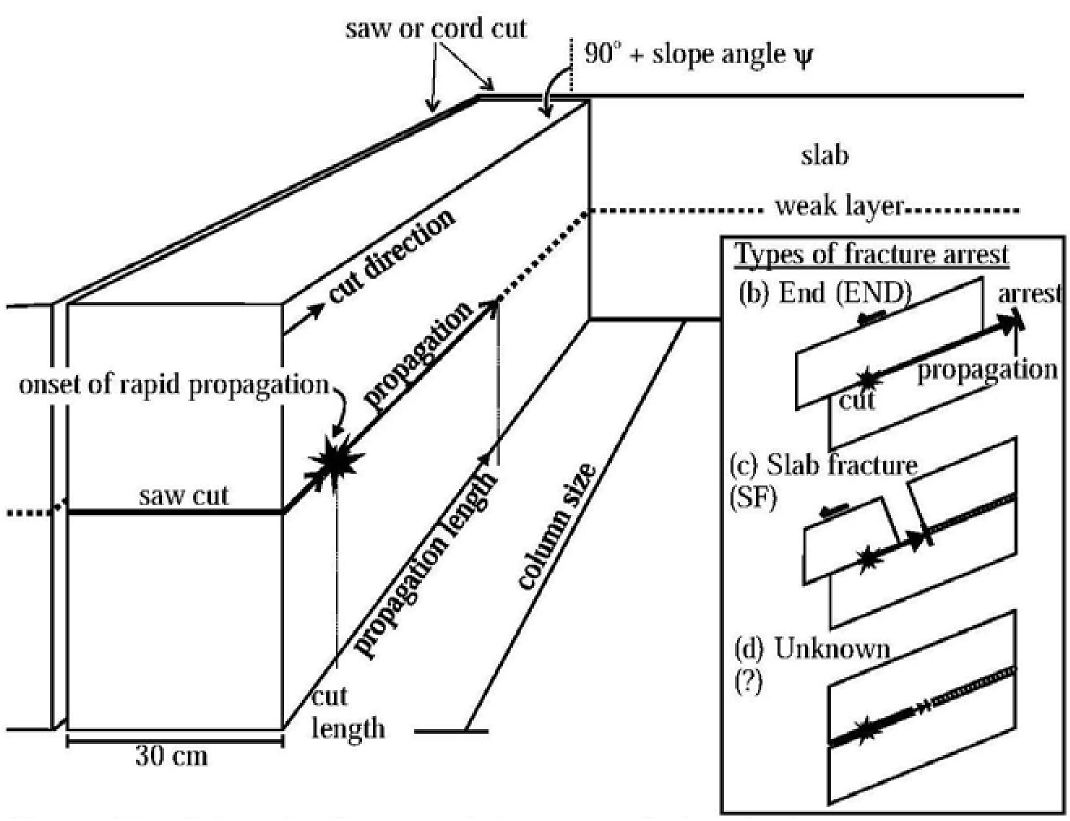

Fig. 6. Propagation saw test (Gauthier, 2007)

The extended column test (ECT) uses a column of 0.9 m cross the slope and 0.3 m upslope. The load (same loading steps as in the compression test) is applied at one end of the column. The following results are possible: (i) a fracture propagates across the full column during isolation, (ii) a fracture propagates across the full column on the same or one additional tap as initiation, (iii) a fracture initiates but does not propagate across the full column, (iv) no fractures are initiated. Propagation is predicted to be likely only when the fracture propagates to the end of the column on the same or one additional tap as initiation (Simenhois and Birkeland, 2007).

The propagation saw test (PST) is accomplished on a column of 0.3 m cross slope and 1.0 m upslope (Fig. 6). After identifying the relevant weak layer the blunt edge of a saw is draged upslope along through this layer at 10-20 cm/s until the fracture jumps ahead of the saw. The point where the fracture began to propagate ahead of the saw is noted. The propagating fracture will either reach the end of column, stop at a slab fracture, or selfarrest within the layer. Propagation is predicted to be likely only when the fracture propagates to the end and less than half the column has been cut (Gauthier et al., 2008).

Schweizer and Wiesinger (2001) and Schweizer and Lütschg (2001) extended the ram profile classification used by de Quervain and Meister (1987), the new classification now consisting of 10 types.

Another method to assess the danger of avalanches is the *Nietentest* (Schweizer, 2006) which is not a stability test but can help mountaineers to get a overview of the structure of the snowpack; the test uses six so-called *Nieten*: large grains (≥ 1 mm), hardness (level 1 - fist), faceted crystals (depth hoar), great difference in grain size between two layers, two levels of difference in hand hardness between two layers, critical layer less than 1 m below snow surface. Five or six discovered *Nieten* indicate that a critical weak layer within the snowpack is very likely; if three or four *Nieten* have been identified a critical weak layer is possible; one or two *Nieten*) suggest that there is no distinct weak layer.

Mair and Nairz (2010) introduced ten avalanche patterns; these patterns are mainly based on meteorological parameters. Mair and Nairz (2010) pointed out the following patterns: the second snowfall, gliding snow, rain, great temperature difference during snowfall, prevailing cold period, new snow and wind, areas with less snow, surface hoar, graupel, spring conditions. These patterns may be a useful tool for those backcountry skiers who are not able to estimate the avalanche danger on the basis of the available meteorological data.

The strategic methods which became popular at the end of the 1990s intensified the discussion of avalanche education.

The accepted risk according to Munter (1997) is the ratio of hazard potential and reduction factor and should be less than one; the hazard potential is defined as 2^L (L is the current hazard level of the avalanche bulletin); the reduction factor is dependent on the slope angle and slope aspect.

Larcher (1999) developed the ‚Stop or Go' method which is similar to Munter's system; however he supplemented the method with the addition of five direct observations (wind deposited snow, new snow, recent avalanches, moist snow, whumpf sounds).

The SnowCard which was developed by Engler and Mersch (2000) is based on the slope angle as well as on the hazard level and shows the risk in different colours (red - high risk, yellow - attention, keep away, green - low risk).

The NivoTest (Bolognesi, 2000) consists of 25 questions (mainly on meteorology and on visible signs (avalanches, visibility, wet snow, weak layers etc.); each question is related to a certain number of scores. If the total number of scores is less than eight the avalanche danger is low, if it is greater than 23 the situation can be described as critical.

The Avaluator (Haegeli et al. 2006) is a rule-based avalanche decision support tool developed in Canada (Fig. 7). The chart on the front of the Avaluator card provides guidance for trip planning by combining the hazard level (vertical axis) with the terrain of the intended backcountry trip (horizontal axis). The back side of the Avaluator card presents a list of seven obvious clues to facilitate slope decisions. 'Normal Caution' is recommended for slopes with two or fewer clues. Backcountry travel is 'Not Recommended' on slopes with five or more clues (Haegeli et al. 2006).

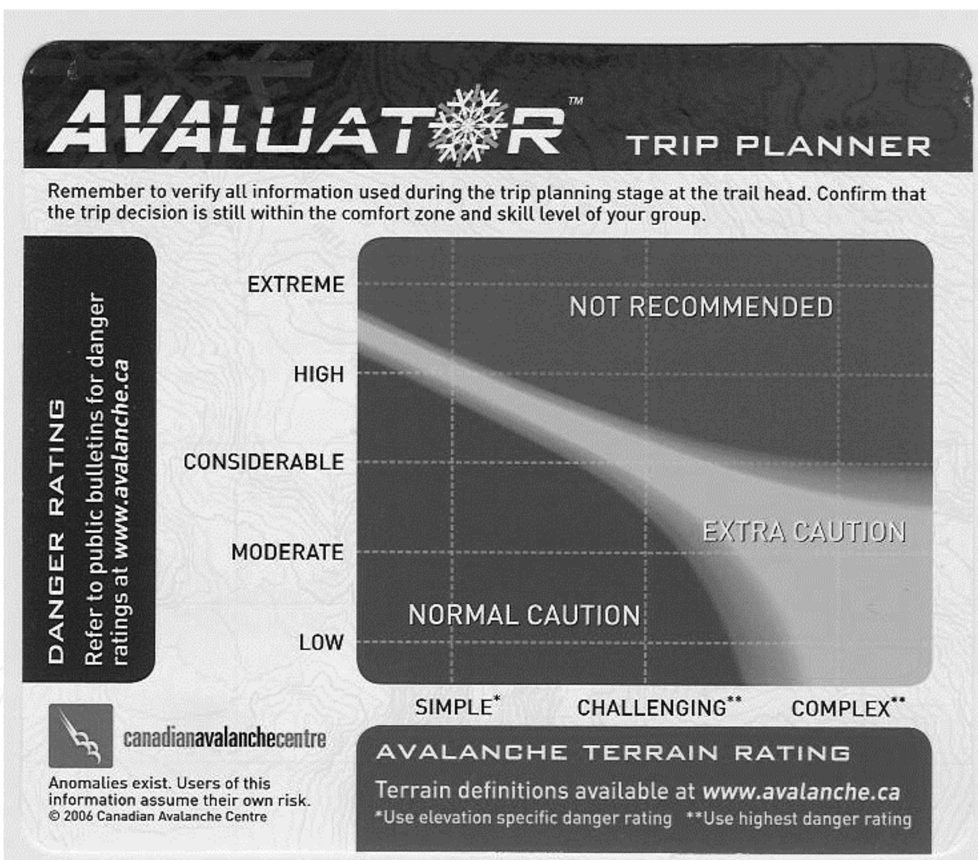

Fig. 7. Avaluator Card. The frontside provides guidance for trip planning by combining hazard level (vertical axis) with the terrain of the intended backcountry trip (horizontal axis). (Haegeli et al. 2006).

3. Discussion and conclusions

The basic principles on snow and avalanches (with regard to the practical application for mountaineers and backcountry skiers) were already set up in the 1920s and 1930s.

Snow classification and the classification of the snow hardness (both developed in the following decades) were also used by many mountaineers and backcountry skiers, and these classifications still play an essential part in evaluating the prevailing avalanche situation (see for example Schweizer 2006 – The '*Nietentest*'). The snow classification standardised snow profile investigations; the hardness classification is an important tool for the assessment of the varying layers in the snowpack. However, hardness measurements with the Swiss *Rammsonde* cannot be applied by backcountry skiers.

The classifications help to get a better overview of the structure of the snowpack and to estimate the current avalanche danger, although snow profiles do not give any information about the bonding of the different layers.

The 1970s and 1980s brought the stability tests which of course had great relevance for practitioners and skiers. However, the validity of these tests is more or less restricted to that location where the test was carried out; backcountry skiers need great experience to interpret the results of these tests.

The investigations from Conway et al. (1980...) indicated that snow stability may be subject to strong variations within short distances. These findings were highly significant; however, in practice it is not possible to identify these areas of instability.

The same is also true for the findings of Föhn (1988) which are of course of great scientific value but cannot be directly applied by mountaineers; skiers cannot locate either a small deficit area or a large deficit zone.

The *Nietentest* is more practicable for mountaineers than other stability tests. Here the diffculty of interpretation of the stability tests does not apply; the user just has to be familiar with the identification of snow crystals, hardness of snow and layering. Strictly speaking the results are valid only for that site where the test was performed; however, as some *Nieten* (e.g. depth hoar layers) normally exist over a greater area it seems to be possible to extrapolate the results from point-measurements.

The avalanche patterns described by Mair and Nairz (2010) may be a helpful tool for backcountry skiers, but cannot compensate for a lack of basic knowledge of snow and avalanche properties. These patterns are based on previous knowledge (in particular the influence of meteorological parameters on avalanche formation), nevertheless they are illustrated in a new style which makes it easier for mountaineers to better interpret the various influencing factors.

The strategic methods which became popular at the end of the 1990s use the fundamental knowledge available. As Höller (2004) mentioned, these methods do not provide any novel results; the only difference is a new design. Nevertheless the scheme can be used as a checklist so that mountaineers cannot forget any important influencing factor. Although the strategic methods will be propagated for less experienced people, these methods cannot be recommended for beginners (Höller, 2004).

The understanding on avalanche formation definitely increased in the last decades; however, with regard to the practical relevance for mountaineers and backcountry skiers the improvements are limited. Backcountry skiers have also to rely on findings which were already available 80 years ago.

Taking into account that the number of backcountry skiers has increased dramatically in the last decades (according to Würtl backcountry skiers in Austria have doubled from the end of the 1990s till today from about 250.000 to 500.000), the number of fatalities almost did not change. As shown in Fig. 8 the total of avalanche fatalities is subject to certain variations, but no significant trend becomes apparent.

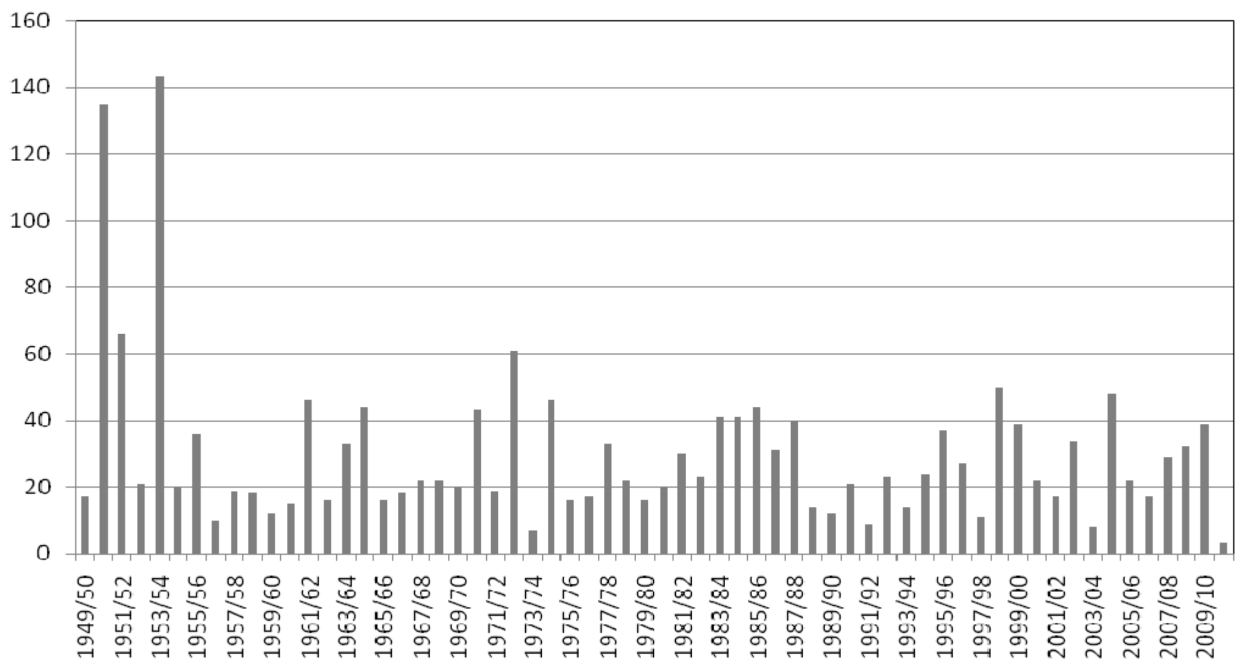

Fig. 8. Avalanche fatalities in Austria (Land Tirol 2000, H. Bilek, personal communication).

The improvement of the safety equipment (avalanche beacons, avalanche balloon,….), the great number of avalanche courses (including many informative brochures, folders and fliers) and the excellent work of the avalanche warning services (including the standardised danger scale) have contributed to the fact that the number of avalanche fatalities were not increasing to the same degree as the number of backcountry skiers.

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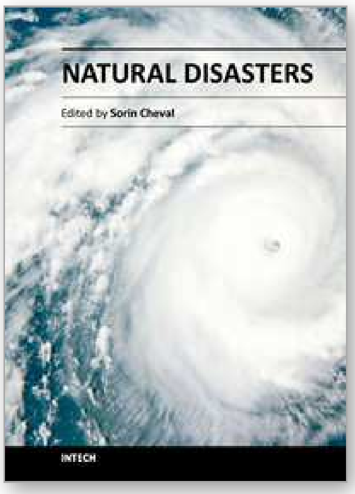

Natural Disasters

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The crossroads between a more and more populated human communities and their changing environment pose different challenges than ever before. Therefore, any attempt to identify and deliver possible solutions is more than welcome. The book Natural Disasters addresses the needs of various users, interested in a better understanding of hazards and their more efficient management. It is a scientific enterprise tackling a variety of natural hazards potentially deriving into disasters, i.e. tropical storms, avalanches, coastal floods. The case studies presented cover different geographical areas, and they comprise mechanisms for being transferred to other spots and circumstances. Hopefully, the book will be beneficial to those who invest their efforts in building communities resilient to natural disasters.

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