The influence of water on snow:

micro-structural measurements and wet snow stability assessment

Masterarbeit

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Abstract

In the Swiss Alps, wet snow avalanches can be a danger to mountain communities and infrastructure, but also to winter recreation. Often passive measures, like the temporal closure of areas at risk, is the only option available. To minimize closure times, the wet snow avalanche hazard needs to be forecast correctly, in time and space. However, wet snow avalanche forecasting is difficult. While meteorological information is most easily available, alone it is insufficient to predict the timing of avalanche release (Trautmann, 2008). The snowpack is one of the keys to wet snow avalanche forecasting (Fierz and Föhn, 1994). Unfortunately, snowpack observations in wet snow are time-consuming, have a limited temporal relevance and are difficult to interpret. Many aspects, such as water infiltration in snow and the influence of liquid water on wet snow stability, are poorly understood.

It is therefore the goal of this Master thesis to contribute to the general understanding of the influence of water on wet snow stability, but also on assessing wet snow stability in the field. For this, the focus is threefold:
(i) evaluate methods to quantitatively and qualitatively observe liquid water in the snowpack,
(ii) monitor the change in snow micro-structure following wetting and
(iii) systematically evaluate methods normally applied to assess dry snow stability (like manual snow profiles and stability tests) in wet snow conditions.

The approach taken included field observations, but also artificial wetting experiments in natural snowpacks. Prior to the field work, a survey was conducted among international avalanche experts to establish a theoretical base. Additionally, the snow profile data-base of the Swiss Avalanche Institute was searched for wet snow avalanche fracture line profiles.

(i) Estimating the liquid water content of snow is difficult. Quantitative measures are more reliable. The comparison between two tools to measure the liquid water content in snow, the Snow Fork and the Denoth wetness meter, showed a good correlation between recorded values. However, the measured volumetric water content using the Snow Fork is generally 1.4 times higher than with the Denoth meter. Still, the Snow Fork was found to be advantageous over the Denoth meter, as the water content can be efficiently measured at depth without the need to dig holes.
(ii) The micro-structural penetration resistance, measured with the Snow Micro Pen (Schneebeli and Johnson, 1998), decreases significantly with the first introduction of liquid water into

facet and depth hoar layers. This reduction, by approximately 50%, occurs already at relatively low water contents (about 2…3 vol.%). In layers consisting of non-persistent grains (such as small round grains or precipitation particles), no reduction in hardness could be observed at low water content. For a data-set consisting of dry and wet layers, penetration strength was positively correlated to snow density in non-persistent snow. The discrimination of different snow grain shapes using solely the Snow Micro Pen's force signal was not satisfactory. Relatively similar grain shapes, such as coarse-grained, soft layers consisting of wet grains or of persistent grains, could not be distinguished.
(iii) Observations from stability tests, in particular the Rutschblock test, support the observations made using the Snow Micro Pen: failure planes consisting of moist, non-persistent grains tend to fail harder than failures occurring in moist or wet persistent grain layers or wet grains. Fracture propagation, as observed in Rutschblock or Extended Column Tests (ECT) is also grain form dependent in wet snow: whole block failures (Rutschblock) and full propagation (ECT) occur more frequently if the failure planes consist of moist, persistent grains. These findings correlate to a set of unstable wet snow profiles observed at avalanche fracture lines or in slopes where signs of instability (as cracking or settlement noises) were observed. In the Swiss Alps, these unstable, wet snowpacks are typically relatively soft (hand hardness 1-2), fully moist (estimated water content 2-3) and considerable wet snow metamorphism has occurred. However, moist, very soft layers consisting of persistent grain forms, such as facets or depth hoar, are still present. These facet or depth hoar layers are often the failure plane for wet snow avalanches. The layers above the failure plane are generally slightly wetter and harder than the full profile. The Rutschblock test was found to be the best predictor of current wet snow instability, while snowpack variables like the moisture content and hardness of the snowpack are better indicators of snow stability for forecasting.

This is the first study quantitatively investigating a relatively large set of manual snow profiles including shear and stability tests in wet snow conditions. Though caution in the data interpretation is necessary, the results may be used to aid in the assessment of wet snow stability in the field. Further, the results obtained from the micro-structural penetration resistance experiments and the stability tests indicate that snow stratigraphy and grain structure play a role at least as important as the actual moisture content in the formation of wet snow avalanches.

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Abbreviations

Latin symbols

Greek symbols

α	level of statistical significance
ρ	snow density [kg m^{-3}]
σ	standard deviation
θ	liquid water content in equations
Δ	difference between values

Other abbreviations

Aval	avalanche fracture line profile
cap.barr	capillary barrier index
CT	Compression Test
d	distance between measurements [cm]
DF	decomposing precipitation particles
DH	depth hoar
Dn	Denoth wetness measuring tool
ECT	Extended Column Test
ECTfrac	Extended Column Test fracture propagation potential
ECTsc	Extended Column Test score
Edg	edge only (RB release type)
f	micro-structural hardness measured using the SMP [N]
f.rel	relative micro-structural hardness measured using the SMP
FC	facets
FCxr	facets undergoing rounding
fp	full propagation (ECT fracture propagation potential)
GF	grain form
HH	hand hardness

LWC	measured liquid water content [vol.%], corrected for calibration error of -0.8 vol.%
LWC_{uncor}	measured liquid water content [vol.%], uncorrected for calibration error
LWC_{Dn}	liquid water content [vol.%], measured with Denoth tool
LWC_{SnF}	liquid water content [vol.%], uncorrected, measured with Snow Fork
MF	melt-freeze form
mWC	estimated (manual) water content [index]
n	number of cases or measurements
n_{Dn}	number of Denoth measurements
n_{SnF}	number of Snow Fork measurements
np	no propagation (ECT fracture propagation potential)
NF	no failure (stability tests RB or ECT)
NP	non-persistent grain
Q1, Q3	first and third quartile
p	p-value for statistical significance
pBr	partial break (RB release type)
PCA	principal component analysis
pp	partial propagation (ECT fracture propagation potential)
PG	persistent grains
(PG)	persistent grains as secondary grain form
r / r^2	Pearson product momentum correlation coefficient
R	statistical software
RB	Rutschblock test
RBfrac	Rutschblock test fracture quality
RBrel	Rutschblock test release type
RBsc	Rutschblock test score
RG	round grains
r_s	Spearman's rho correlation coefficient
sd	standard deviation of micro-structural hardness measured with the SMP [N]
SLF	WSL-Institute for Snow and Avalanche Research SLF, Davos
SIQR	standard interquartile range
size	grain size [mm]
SMP	Snow Micro Penetrometer
SnF	Snow Fork - tool to measure liquid water content in snow
ST	Shovel Shear test
struct.index	structural threshold sum [index]
wBl	whole block failure (RB release type)
WG	wet grain

Chapter 1

Overview

In this chapter, the reader will be familiarized with some of the problems avalanche forecasters are confronted with when assessing wet snow stability. Following this, the aim and research objectives are introduced, the contents and lay-out structure of this Master thesis is briefly presented.

1.1 Examples, problem statement

The forecasting of wet snow avalanche hazard is difficult. To illustrate these challenges, two examples from the last spring are given.

Forecasting wet snow stability at a slope-scale: an example from the Upper Engadine, March/April 2009[1].
The ski area of St. Moritz is situated in the Upper Engadin, in the South-Eastern Swiss Alps. In the ski area, several ski runs may be threatened by avalanches. The ski run which traverses the avalanche run-out zones of the steep slope of Piz Saluver is of particular concern in spring.
The winter 2008/2009 was a well-above average snow season in the Engadine region. A period of mild and sunny weather began on 30 March 2009. Wet snow avalanches had to be expected following day-time warming. This led the avalanche safety personnel to close the Saluver ski run every day around 11 a.m. In the following six days only small avalanches released. These were limited to surface layers.
On 5 April 2009, after almost a week of warm, sunny weather a large wet slab avalanche released late in the afternoon. The avalanche was more than 100 m wide and failed at a depth of up to two meters below the snow surface (Fig. 1.1, left). The ski run was covered by dense debris, several meters thick in places. The magnitude of this avalanche was not expected. The meteorological parameters (like air temperature, snow surface temperature

[1]based on information provided by Locher, 2009, head of ski-patrol and snow safety officer, Bergbahnen Engadin

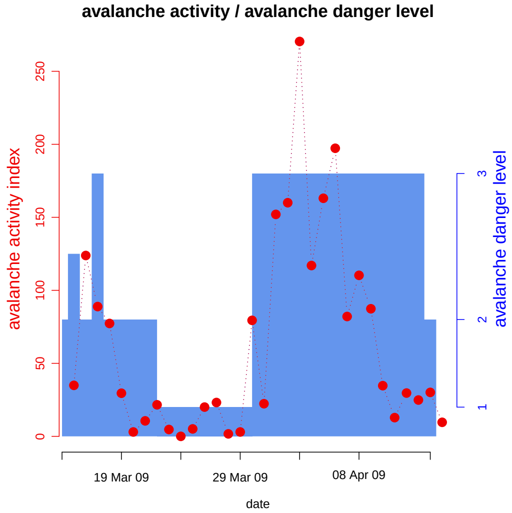

Figure 1.1: Left: Debris of wet slab avalanche, Piz Saluver, Upper Engadine, 5 April 2009. The 150 m wide avalanche released late in the afternoon, failed 30 - 200 cm deep in the snowpack and deposited up to 3 m dense, wet snow on the ski run. Photo: Locher, 2009. Right: wet snow avalanche activity in the Swiss Alps during March and April 2009 (red line, expressed as avalanche activity index, based on data received from Dürr, 2009). The peak was observed on 3 April. The forecasted wet snow avalanche hazard is shown as the shaded blue area, where 1 is Low, 2 is Moderate and 3 is Considerable avalanche hazard.

and solar radiation) measured at the nearby automatic weather station were not different on this day than on previous days.

Forecasting wet snow stability at a regional scale: the avalanche bulletin in spring 2009

In winter, the SLF[2] issues a daily avalanche forecast for the Swiss Alps. During the two-week period mentioned in the example above (March/April 2009), a *Considerable* wet snow avalanche hazard was forecast indicating the potential of medium, even large avalanches to release naturally (Etter et al., 2009). During this time, many wet avalanches were observed in the Alps. However, wet snow avalanche activity[3] was much higher during the first week of this period than during the second week (Fig. 1.1, right).

The peak of wet snow avalanche activity (3 April) was not forecast in particular, a situation, which has been addressed in previous years (Wiesinger, 2004). Stucki (2006), head of the SLF avalanche warning team, says that the peak of wet snow avalanche activity is indeed sometimes missed and only included in a general description of an avalanche cycle.

These examples high-light some of the challenges when dealing with wet snow stability assessment and avalanche forecasting:

- Meteorological parameters alone are often insufficient to accurately forecast the onset

[2]WSL-Institute for Snow and Avalanche Research SLF Davos

[3]avalanche activity is expressed using the avalanche activity index AAI, which is an index sum incorporating the number of avalanches, weighted by their mass (Schweizer et al., 1998)

of wet snow avalanching.

- The temporal closure of exposed areas is frequently the only safety measure available.
- The role of snowpack information used to assess wet snow stability is limited as neither the advancement of the wetting front, nor the influence of penetrating melt-water on snow stability, are understood sufficiently.

1.2 Aim and research objectives

It is the aim of this Masters project to contribute towards a better understanding of wet snow stability by investigating the methodology applied when assessing wet snow stability and defining snowpack criteria typical for unstable wet snowpacks. Further, micro-structural properties of wet snow and the liquid water content in snow are quantitatively measured.

Research objectives:

1. Evaluate methods to estimate and measure liquid water in the snowpack, with a special regard on wet snow stability assessment.
2. Investigate the role of liquid water on the micro-structure of snow.
3. Assess methods to observe current wet snow stability with an emphasis on snowpack properties and the applicability of shear and stability tests.
4. Determine typical parameters of unstable wet snow slopes.

1.3 Content

As outlined in the box above, this Master thesis deals with several, rather independent topics. Often different methods were applied. Therefore, it is advantageous to present them as individual research projects. The content of the chapters of this report is:

- Chapter 2 introduces the **theoretical concepts** covering the topics:
  - wet snow (water flow and mechanical properties),
  - wet snow avalanches and
  - snow stability assessment.
- Chapter 3 introduces the reader to general **methods** applicable to all or several of the chapters.

- Chapter 4 discusses the estimation and measurement of the **liquid water content** in snow.
- Chapter 5 investigates the **micro-structural evolution of wet snow** and tests a snow characterization algorithm based on the penetration force signal of the Snow Micro Penetrometer (Schneebeli and Johnson, 1998).
- The **wet snow stability assessment** is the focus of several chapters:
  - Chapter 6 presents results of a **survey** of experienced avalanche forecasters concerning their experience assessing and forecasting wet snow stability.
  - Chapter 7 investigates a **snow-profile data-base**, focusing on avalanche fracture line profiles and the Rutschblock test in wet snow.
  - Chapter 8 evaluates the applicability and usefulness of **shear and stability tests** in the field, focusing on diurnal changes of wet snow stability.
- The final chapter 9, attempts to put the results from the individual chapters into context and relates them to existing knowledge. Finally, practical implications are discussed and topics for further research suggested.
- The appendices provide supplementary information.

1.4 Structure

It the intention that the reader can read the chapters 4. . .8 individually. Therefore, each of these chapters is structured like a separate research paper with:

- Summary
- Research hypothesis
- Introduction highlighting the most important aspects and indicating where to find additional information in other chapters
- Methods
- Data
- Results
- Discussion
- Conclusion and further research
- Acknowledgements

1.5 Acknowledgements

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Thank you!

Chapter 2

Introduction

This chapter introduces the basic concepts of wet snow physics (based in parts on soil physics), highlights the most important processes and reviews the current knowledge concerning wet snow (Section 2.1). It is followed by an introduction to wet snow avalanches (Section 2.2) and wet snow stability assessment and avalanche forecasting (Section 2.3).

2.1 Wet snow

Snow, in general, and wet snow in particular, is a complex three-phase-system consisting of ice, air and water just below or at its melting point (Colbeck, 1997; Denoth, 2003). The volume ratio between ice, air and water determines many of the physical and mechanical properties of snow (Jordan et al., 2008).
The **wetness or liquid water content (LWC)** in snow can be expressed relative to the total volume or the total mass (equations based on Hillel, 2004).

- **Mass wetness** $w = M_w/M$,
  where M_w is the mass of the water and M the total mass of the sample.

- **Volume wetness** $\theta = V_w/(V_a + V_w + V_i)$,
  where V_w is the volumetric part of the water, V_a the volumetric part of the air and V_i the volumetric part of ice. At saturation the volume wetness equals porosity.

In this report, LWC always refers to the volumetric water content. Often, as in manual snow profiles, LWC is qualitatively estimated as being dry, moist, wet, very wet or slush (Colbeck et al., 1990). The amount of water present has a large influence on many processes. Therefore, it is often referred to as being in the pendular or funicular regime of saturation (Colbeck, 1973):

- **Pendular regime**. At low water saturations (LWC<8%), air is present in continuous paths throughout the pore space while water exists only in isolated pockets (Fierz and Föhn, 1994). Water is held by capillary forces in grain clusters (Colbeck, 1997) or in ring-shaped bodies surrounding snow grains (Denoth, 2003). Freely draining snow is in the pendular regime (Colbeck, 1997).

- **Funicular regime**. At high water saturations, only pockets of air exist and liquid water is continuous (Fierz and Föhn, 1994). The volumetric part of the air may still be larger than the volumetric part of the water. Snow at high water saturation is only found above impeding layer boundaries (Colbeck, 1997).

Porosity is a measure of the relative pore space (Hillel, 2004). The **density** of snow is inversely related to porosity (McGurk and Kattelmann, 1986).
Snow **texture** is independent of porosity. It describes shape and size of the ice particles and the pore space (Jordan et al., 2008). Snow texture evolves with time (metamorphism) and is highly variable. Mechanical properties of snow depend on snow texture (Arons and Colbeck, 1995).
Once liquid water is present, physical snow properties, like grain size, grain shape and bonding between grains, alter rapidly (Colbeck, 1997).

2.1.1 Wet Snow metamorphism

Wet snow metamorphism starts as soon as small quantities of water are present (Jordan et al., 2008), which leads to "major reconfigurations of both grains and bonds" (Colbeck, 1997, p. 9, Fig. 2.1). The mean grain size increases rapidly when liquid water enters snow at 0°C (Marsh, 1991). Grain growth rates depend on LWC (Brun, 1989). Growth rate decreases with time (Marsh, 1991).
To explain wet snow metamorphism, mass exchanges between the three water phases must be considered (Jordan et al., 2008). The melting point temperature of snow is not precisely at a temperature of 0°C. It varies depending on ice grain curvature and grain size. Convex surfaces and larger grains have a lower melting temperature (McClung and Schaerer, 2006; Jordan et al., 2008). These small temperature differences cause melting of the smallest grains and most convex surfaces. This leads to grain coarsening and rounding (McClung and Schaerer, 2006). Despite this minimal difference, very small grains may double their size within an hour, if they are completely immersed in water (Raymond and Tusima, 1979). Physical processes guiding wet snow metamorphism differ depending on moisture content. In snow at high LWC, metamorphism is rapid, while in snow with low LWC, metamorphism is much slower (Colbeck, 1997; McClung and Schaerer, 2006).

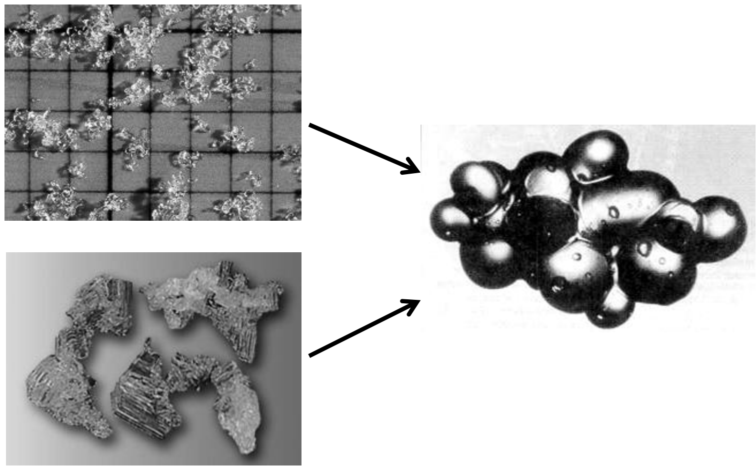

Figure 2.1: Wet snow metamorphism commences with the introduction of liquid water into snow. During wet snow metamorphism, initial grain forms (left) undergo rounding and small grains grow to wet grains (right). Exemplary for initial grain forms are small round grains (upper left) and facet - depth hoar (lower left). Photos: SLF (2008); avalanche.org (2009); Colbeck (1995)

2.1.2 Mechanical properties of wet snow

Knowledge concerning mechanical properties of wet snow is still scarce (Schneebeli, 2004). When dry, frozen snow becomes wet it looses strength or as Conway et al. (1988, p. 8) wrote: "...if bonds or crystals break faster than they form, then snow strength will decrease."
Snow at very low liquid water contents (**pendular regime**) is often reasonably cohesive, strong ice-to-ice bonds exist between grains (Colbeck, 1997).
Following Colbeck (1982) and Kattelmann (1985), the transition from the pendular to the funicular regime is expected to have a severe consequence on snow strength.
In the **funicular regime** a film of water continuously surrounds snow grains and fills many pore spaces reducing strength further (Trautmann et al., 2006). Colbeck (1997) reasons that slush has the lowest strength due to the continuous liquid film between grains and hence the lack of inter-granular bonding.
In dry snow, **shear strength** depends largely on snow density and grain form (Jamieson and Johnston, 2001). In wet snow, poor correlations between density and strength were observed (Perla et al., 1982). Of primary importance is the amount of liquid water present in the snow. Brun and Rey (1987) and Bhutiyani (1994) observed no significant strength decrease at LWC<6 vol.%, but once the LWC was higher (Bhutiyani, 1994). (Fierz and Föhn, 1994) point out that none of these early field studies have been able to show without doubt the significant decrease of shear strength at the pendular - funicular transition (LWC≈8 vol.%). More recently, Yamanoi and Endo (2002) showed that shear strength decreases as an exponential function of LWC. Trautmann et al. (2006) monitored the weakening part of a melt-freeze crust in the field. Shear strength decreased by as much as 50% in less than 20 minutes. Further, they conclude that shear strength and micro-structural snow hardness measured using a snow micro penetrometer (SMP, Schneebeli and Johnson, 1998) are linearly

correlated.
Snow hardness has been used as an indicator of wet snow stability (Armstrong, 1976). It is known to decrease substantially with increasing LWC (Wakahama, 1975; Izumi and Akitaya, 1985; Izumi, 1989). Izumi (1989) indicates that, with an increase in moisture, the total bond area between grains decreases proportionally to the logarithm of snow hardness. First results presented by Techel et al. (2008b) support these observations. Micro-structural hardness of facet and depth hoar layers decreased significantly at very low water content (LWC$\leq$3 vol.%).
Rapid **compaction** and **densification** has been observed when new, low density snow becomes wet (Marshall et al., 1999), but also when depth hoar moistens (Jordan et al., 2008). During compaction, snow rheological properties change (e.g. grain bonds, melting, Jordan et al., 2008). Viscous **deformation** depends on snow density, micro-structure, temperature and liquid water content (Jordan et al., 2008). **Creep** movement continuously occurs in a snowpack due to constant metamorphism, grain re-arrangement and down-slope settlement (Conway, 1998; McClung and Schaerer, 2006). The creep rate in snow increases with snow temperature approaching 0°C (McClung and Schaerer, 2006). Following the onset of rain-on-snow, creep rates at the snow surface have been noted to be three times faster than at 55 cm snow depth (Conway, 1998).

2.1.3 Water flow

Despite the fact that tracking water flow in snow using dye tracers "is nearly as old as snow science itself" (Schneebeli, 1995, p. 89), it remains one of the least understood aspects of snow hydrology (Marsh, 1991; Williams et al., 1999).
Water flow in granular materials like soils and snow is similar (Jordan et al., 2008). Relations between capillary effects, conductivity and wetness are complex (Fig. 2.2). However, in comparison to other granular materials, textural discontinuities, freeze-thaw effects and snow metamorphism further complicate water flow processes (Jordan et al., 2008). Spatial variability adds to the complications when trying to describe unsaturated water flow patterns (Hillel, 2004).
Water flow in a porous medium like snow depends on the porosity and permeability properties of the snow layer (McGurk and Kattelmann, 1986). **Permeability** describes the geometry of a porous medium (Hillel, 2004). It depends on grain size (Shimizu, 1970, quoted by McGurk and Kattelmann, 1986), but also density and snow texture (Wankiewicz, 1979). The geometry defines the way a fluid can percolate (Wankiewicz, 1979). Coarse grained snow (like depth hoar) is more permeable than fine grained old dry snow (Wankiewicz, 1979). A phenomenon, which is also observed in soils (Hillel, 2004).
Hydraulic **conductivity** depends on the wetness of a medium. The wetter a draining porous medium, the higher the conductivity (Hillel, 2004). This also applies to snow with the additional feedback-cycle of increased wetness leading to faster snow metamorphism, which again changes permeability (Fig. 2.2). If wet grain metamorphism is more advanced, higher water flow rates are possible (Marsh, 1991).
In a partially saturated medium like snow, flow regimes dominated by gravity forces are matrix flow and preferential flow (Marsh, 1991, Fig. 2.3).

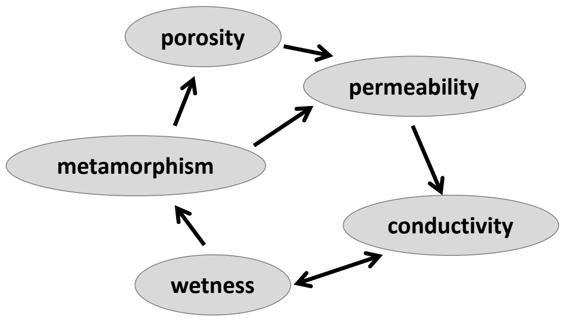

Figure 2.2: Feedback mechanism in wet snow.

- **Matrix flow** or background wetting is the area above which all snow is wet.

- **Preferential flow**, or finger flow, is the most common component of water movement in snow (Schneebeli, 1995). Often flow fingers form at layer interfaces, regardless of snow properties above or below (Marsh, 1991). Small variations in seemingly homogenous snow lead to small differences in hydraulic conductivity which may also trigger finger flow (Marsh, 1991). In these vertical flow channels, water penetrates the snowpack much deeper much faster resulting in isothermal conditions at lower depth than during homogeneous wetting (Schneebeli, 1995; Conway, 2004). Water infiltration into snow is fast compared to other porous media and may range between 0.01 to 0.1 m/s (Schneebeli, 2004). Flow channels may cover only parts of the snowpack (e.g. McGurk and Kattelmann, 1986: 15 - 25 % of the surface area) with surrounding areas remaining dry. Slope inclination may reduce the area covered by vertical flow channels (Kattelmann, 1985). Flow paths are persistent due to the positive feedback between grain growth and hydraulic conductivity (Colbeck, 1979). Flow paths of subsequent melt-freeze cycles, however, often change (Schneebeli, 1995).

The gravity component is the most significant part of water flow in snow (Wankiewicz, 1979). Vertical flow dominates until the water flux reaches a stratigraphic horizon (Fig. 2.3).

- **Lateral flow along a capillary barrier**. Lateral diversion of water flow may occur at a capillary barrier or above an ice lens (Wankiewicz, 1979; Colbeck, 1979). A capillary barrier impeding water flux forms when water pressure differences between layer interfaces exist (Wankiewicz, 1979). This is often the case when a fine-grained layer overlies a layer with coarser grains (Jordan, 1994; Waldner et al., 2004). High-over-low capillary suction leads to interruption of vertical water movement and a horizontal flow along this barrier until a pressure-equilibrium is established. After break-through, the flow form is most often in the form of finger flow (Wankiewicz, 1979; Waldner et al., 2004). Coarse over fine barriers, on the other hand, have no or little impedance on water flow (Jordan, 1994; Waldner et al., 2004).

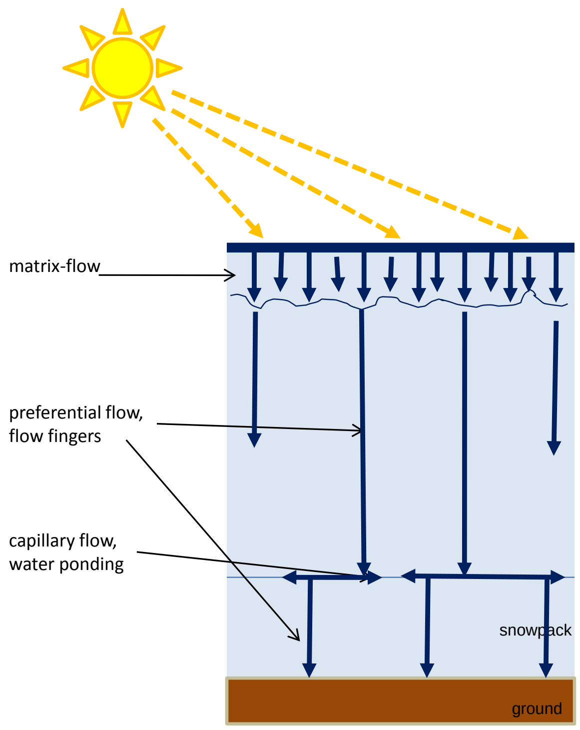

Figure 2.3: Flow patterns in a layered snowpack: matrix flow, preferential flow and capillary flow.

The modeling of the spatial and temporal evolution of water flow is still not possible (Schneebeli, 1995). Knowledge about snow stratigraphy and stability prior to melting or rain remains one of the keys to understand the water movement in a layered snowpack and its effect on slope stability (Fierz and Föhn, 1994).

2.2 Wet snow avalanches

Most practitioners make a distinction between loose and slab avalanches, and between dry and wet snow avalanches.
Snow of low cohesion may fail as **loose avalanches**. This may be the case when the slope angle exceeds a critical angle (the angle of repose, McClung and Schaerer 2006). They are also called point-releases as the initial loss of cohesion is confined to a very small area. On the descend they form triangular patterns and, especially in the case of wet avalanches, may scour lower snowpack layers. The basic cause of **wet loose avalanches** is the increase in water content, which reduces the strength of the snow. The grain form also plays a role (McClung and Schaerer, 2006). Wet loose avalanches are probably more frequent than wet slab avalanches (Reardon and Lundy, 2004).
Increased stress, like new snow or a person's weight, is often the trigger for dry slab avalanches.

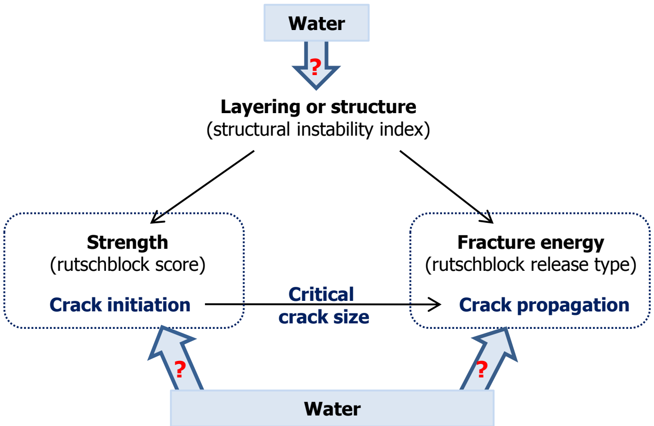

Figure 2.4: Schematic of dry avalanche release mechanism and Rutschblock test, based on Schweizer et al. (2008), expanded by author. Crack initiation depends on strength, while crack propagation is driven by fracture energy. Layering or snowpack structure (investigated with the structural instability index, Tab. 3.5) influences both strength and fracture energy. Both can be observed in the field using the Rutschblock stability test. Water influences strength, fracture energy and snowpack layering, though many aspects are still poorly understood.

In wet slab avalanche release, it is rather the decrease in strength due to increased water content than additional loads (Tremper, 2001). However, there is no clear line between wet and dry avalanches. Mixed forms exist. A **mixed avalanche** (dry and wet) is often one where the surface is wet but the failure plane dry, or where the avalanche releases as a dry avalanche but entrains wet snow on the descend.[1]
Slab avalanches fail as a slab of snow. Dry slab avalanche release proceeds in three stages (Schweizer et al., 2008, p. 112, Fig. 2.4):

1. "initiation of a local failure (crack)

2. widespread fast propagation of that fracture beneath the slab

3. detachment of the slab from its margins"

A local failure may be initiated when the additional stress (for example due to a person's weight) overcomes the strength of the weak layer or interface (Schweizer et al., 2008). For a slab avalanche to occur, the initial crack must reach a critical size. Further crack propagation will detach the slab. Presently, the failure mechanism at the micro-structural scale is unclear. At the slope-scale, the slab slides down due to a loss of shear strength (Schweizer et al., 2008). To assess dry snow slope stability in the field, snow profile analysis (observations on snow structure) combined with stability tests (like the Rutschblock-test) provide information on snowpack structure, fracture initiation and propagation. Typical structural properties

[1] how wet avalanches are defined varies between different observational guidelines (Weir and Schreiber, 2000; SLF, 2008) and is discussed in more detail in Chapter 6.4.

of skier-triggered slopes have been identified (e.g. Jamieson and Schweizer, 1995, Schweizer et al., 2008, see also Chapter 3, Tab. 3.5).
The introduction of water causes significant changes in the snowpack. In new snow, small amounts of water increase its tendency to stick (Tremper, 2001). Often, it is believed that the strength of snow decreases significantly once the water content exceeds approximately 8 vol.% (Kattelmann, 1985). More recently, Techel et al. (2008b) presented data indicating a rapid decrease in micro-structural hardness with very small amounts of water in weak facet layers (LWC<3vol.%).
Special conditions are required for wet slab avalanches to form. A rain- or melt-water flux is necessary, the failure layer (generally a persistent weak layer) needs to be influenced by water while the over-lying slab must still retain some of its slab-like properties (Reardon, 2008; Peitzsch, 2008). If the water flux is large enough to percolate vertically through the snowpack, water may accumulate temporarily above stratigraphic boundaries (capillary barriers) and almost simultaneously reduce friction at these interfaces over relatively large areas (Conway and Raymond, 1993; Peitzsch, 2008; Baggi and Schweizer, 2009).
Processes involved and trigger mechanism for **wet slab avalanches** are somewhat less known. Conway and Raymond (1993) and Conway (1998) discussed slope stability evolution during rain-on-snow events in a maritime climate. The following summary is largely based on Conway and Raymond (1993), but has been complemented with information from transitional snow climates (Montana: Reardon, 2008, Swiss Alps: Baggi and Schweizer, 2009):

1. **Immediate avalanching with onset of rain or melt - mixed avalanches**
   - **Gravitational loading** due to rain (or snow). While this may occasionally trigger instabilities, in general, initial additional loads are too small to be relevant.
   - **Inertial loading**. Small loose avalanches from steep slopes, rock faces or trees could trigger deeper instabilities.
   - **Redistribution of longitudinal stress**. If the strength of a snow slab was critical for maintaining stability, losses of tensile strength could be relevant.
   - **Surface perturbations by water weakening grain bonds**. Surface perturbations at onset of rain or melt may increase surficial creep rates, which might put additional strain on a shear plane deeper in the snow pack (Fig. 2.5A).
2. **Delayed avalanching - wet avalanches**
   - **Gravitational loading**. Continued heavy rain causes additional stress but may also weaken potential slide planes.
   - **Loss of strength due** to water infiltration. Water spreading slope-parallel above capillary barriers or in persistent weak layers. Water flowing through flow fingers could affect large areas almost simultaneously (Fig. 2.5B).
   - **Inertial loading**. Wet loose avalanches with considerable weight could trigger deeper instabilities.
   - **Melting of grain bonds** leads to a reduction of friction between grains.

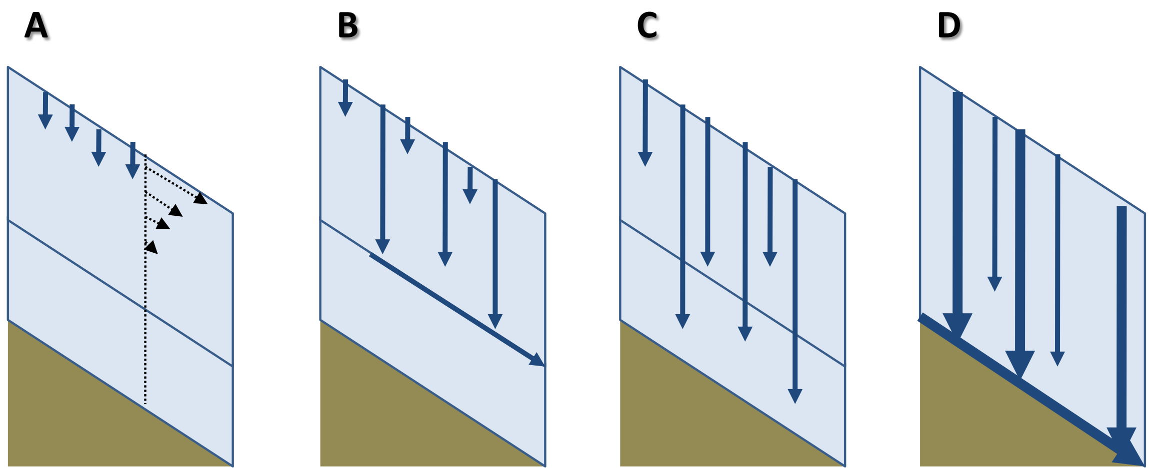

Figure 2.5: Wet snow stability evolution. A. Water penetrates surface layers. This causes a decrease in the strength of the slab, redistribution of longitudinal stresses and increased snow creep. If the snow stability is critical, avalanching may occur (failure plane in dry snow, mixed avalanches). B. Preferential flow reaches impeding layers or layer boundaries. Slope parallel flow reduces friction between grains. Failure may occur (wet avalanches). C. Gradual weakening of weak snowpack base due to water infiltration (wet avalanches). D. Return to stability if flow channels are well developed and the snowpack has fully metamorphosed to wet grains. Graphs based on Conway and Raymond (1993); Carran et al. (2002); Tremper (2001); McClung and Schaerer (2006).

- **Metamorphic processes**. Rapid grain shape alterations due to percolating water result in increased vertical and down-slope strain contributing to instability.
- **Gradual weakening of snowpack base** (Fig. 2.5C).

3. **Return to stability**

- Avalanching may stabilize a snowpack.
- In fully established drainage channels water is routed to the base of the snowpack thus not further weakening interfaces or adding weight. Water flow at the base may occasionally release full-depth avalanches (Fig. 2.5D)."

2.3 Wet snow stability assessment and wet snow avalanche forecasting

Predicting size and timing of avalanches is critical in many ways: avalanches may threaten populated areas or infrastructure, the winter tourism industry depends on avalanche-safe ski runs, many back-country skiers venture into untouched slopes. While some forecasting operations have the possibility to actively control some slopes by using explosives (thus testing and/or removing parts of the snowpack), passive measures like ski run or road closures are

more frequently applied. These closures result in a loss of economic income, which of course needs to be minimized. Therefore the release of natural avalanches needs to be accurately predicted.
An avalanche forecaster has to assess all factors influencing snow stability to forecast size and timing of avalanches. These factors are (McClung and Schaerer, 2006):

- **Class I - avalanches, stability information**
  information concerning the load (stress) on weak layers (strength)
  - natural avalanches
  - loading tests (by explosives, skiing or *stability tests*)
  - fracture propagation and cracking of the snowpack
- **Class II - snowpack information**
  - snowpack structure
  - weak layers
  - ... (many more, Section 2.3.2)
- **Class III - meteorological information**
  - rain
  - solar radiation
  - ... (many more, Section 2.3.3)

2.3.1 Avalanches and snow stability information

Class I information is considered direct stability information. Clear indications of unstable conditions are natural avalanches, remote-triggering of avalanches by persons, explosives or machinery, collapsing of the snowpack, crack-formation and whoompf-sounds. Standard snow stability tests are particularly valuable to assess snow stability when other direct stability information is not available (which is often the case at a *Moderate* or *Low* avalanche hazard).

Stability tests

A stability test is a snowpack test where an isolated column of snow is loaded by a weight. A large number of stability tests exists. Some of the most popular include the

- **Rutschblock Test** (RB[2], Föhn, 1987), which is loaded by a skier's weight, (Fig. 2.6 right). The Rutschblock test, described by Schweizer (2002) as a "mini-slab avalanche", has the distinct advantage of testing a relatively large area.

[2] more information on RB and ECT are found in Chapter 3, p. 23

Figure 2.6: Compression test (left) and Rutschblock test (right). Photos: Pearce, 2006, Techel, 2008.

- **Compression Test** (CT, Jamieson, 1999), very popular in North America, is loaded by tapping on the back of a shovel-blade placed on top of the snow column (Fig. 2.6 left).
- **Extended Column Test** (ECT, Simenhois and Birkeland, 2006) is a relatively new test similar to the CT. However, it also provides information on fracture propagation.

For each test, a loading score is recorded. Additionally, most observers record:

- **release type (RB)** - unstable if the whole block fails (Schweizer et al., 2006)
- **fracture propagation (ECT)**- unstable if the fracture occurs through the whole column within two loading steps (Simenhois and Birkeland, 2006)
- quality of the failure plane
  - **fracture quality (RB)** (Schweizer et al., 2006)
  - **fracture character (CT)** - unstable if failure occurs sudden, may be either collapse-type failure or planar (van Herwijnen and Jamieson, 2003)
  - **shear quality**

In dry snow situations, the Rutschblock and the Extended Column Test are useful tools to assess slope stability (Winkler and Schweizer, 2009). In particular, RB release type and ECT fracture propagation have a high potential to detect unstable slopes (Schweizer et al., 2006; Simenhois and Birkeland, 2006; Birkeland and Simenhois, 2008). Generally, test scores are spatially more variable, as they depend on the depth of the failure plane. Thus, it is not surprising that forecasters rank Rutschblock release type as most important criteria when assessing snow profiles (Schweizer, 2002).

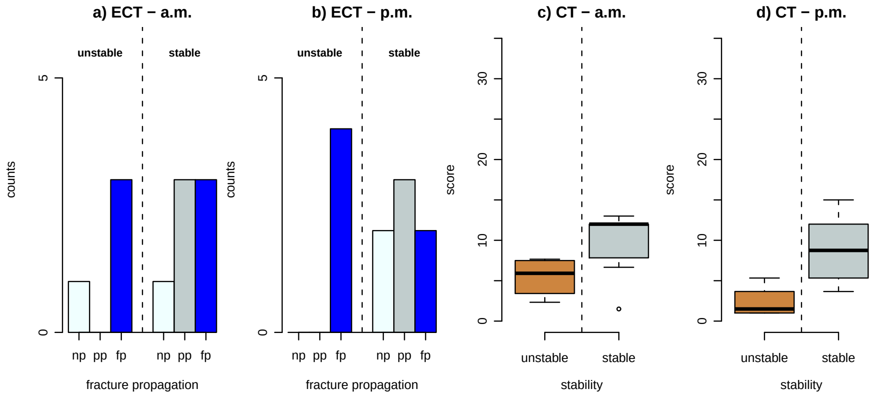

Figure 2.7: Diurnal evolution of Extended Column Test (ECT) fracture propagation (a, b) and Compression Test (CT) scores (c, d) contrasting unstable (n=4) and stable (n=7) slopes and days. Histograms and box-plots showing the first set of tests in the morning and the last set of tests in the afternoon, data kindly provided by A. Brown (Brown, 2009), plots Frank Techel. Afternoon CT scores are significantly lower in unstable than stable slopes, while fracture potential in all unstable slopes was high in the afternoon. ECT fracture propagation (generally two tests): fp - both tests fractured across whole column, pp - only one of several tests propagated fully, np - none of the tests propagated fully. CT scores: mean of several tests.

In **wet snow**, stability tests are often considered as difficult to interpret or unreliable (Birkeland and Johnson, 1999; Schweizer, 2002; Reardon and Lundy, 2004). Very few studies exist, which specifically investigate the applicability of these tests in wet snow. One of the few exceptions has been Brown (2008). He compared CT, ECT, propagation saw test (Gauthier et al., 2008) and shovel shear test ST (Greene et al., 2004) during spring melt of a continental snowpack with basal depth hoar. His data indicates that the diurnal weakening of the snowpack may be observed (Fig. 2.7). CT scores decrease from moderate to low or very low on days when snow stability was considered critical. ECT fracture propagation is for all unstable slopes and days high (Brown, 2009). Afternoon CT scores significantly differ between stable and unstable slopes and days[3].

Shear test

Shear tests provide information on the shear strength of potential weak layers. Principal objectives are the location of potential failure planes and weak layers (McClung and Schaerer, 2006).

The shovel shear test (ST) provides qualitative information on weak layer strength (McClung and Schaerer, 2006). However, it has its limitations: it does not work well in softer snow and the force applied can be hard to judge (Schaerer, 1988).

In the maritime climates of the western USA and southern New Zealand, the ST is operationally used (e.g. Andrews, 2004; Techel, 2006a). Both authors give examples for the corre-

[3]statistical tests and plots Frank Techel, based on data provided by Adam Brown. Mann Whitney test, $p \leq 0.05$

lation between ST scores (including shear quality ratings) and avalanche activity. Andrews (2004) relates the energy stored in the slab to the moment of release of deep instabilities. Techel (2006a), based on a small data-set, proposed that *Very Easy* ST scores relate to avalanche activity during times of intense precipitation.
In wet snow, neither Brown (2008), during spring warming in Colorado, nor Techel (2006b), during a sequence of rain-on-snow events in Southwestern New Zealand, could detect a significant change in ST scores following wetting of a persistent weak facet layer. Brown's data suggests further, that ST scores are not a significant discriminator between stable and unstable slopes.

2.3.2 Snowpack information

Snowpack properties (Class II) play a major role in stability assessment but they require additional interpretation (Tremper, 2001). Baggi and Schweizer (2009) suggested that snowpack parameters may play an equally important role for the release of wet slab avalanches as they do for dry snow avalanches. In particular, the time since 0°C-isothermal snowpack temperatures have been reached and layer interfaces where water may temporarily accumulate (capillary barriers), seem most important. The magnitude of change has also been observed to influence wet snow stability (Hartmann and Borgeson, 2008), in particular, if: snow temperatures are rapidly approaching 0°C, liquid water content is rising and a change in snowpack structure is occurring.
Wide-spread **wet slab avalanching** has been linked to the existence of persistent weaknesses in the snowpack (Andrews, 2004; Reardon and Lundy, 2004; Techel, 2006b). Immediate failure at onset of rain is associated with already critical snow stability (Conway and Benedict, 1994; Conway and Wilbour, 1999) or the presence of new snow (Heywood, 1988).
A strength decrease due to the presence of high liquid water content in surface layers is playing a role in **wet loose avalanches** (Trautmann et al., 2006; McClung and Schaerer, 2006). The snowpack remains relatively stable and no avalanches are observed if flow-paths are well developed and water outflow responds almost immediately following onset of rain or melt (Carran et al., 2002; Conway, 2004).

2.3.3 Meteorological information

Class III information is important for avalanche forecasting. Sufficient energy input is a prerequisite for the formation of wet snow. However, meteorological factors alone are not a discriminator between avalanche and non-avalanche days (Armstrong, 1976; Reardon and Lundy, 2004; Trautmann, 2008). Typically, intense solar radiation and high air temperatures are observed on avalanche days. Rain causes immediate avalanching if snowpack stability is close to critical (Conway and Raymond, 1993; Conway, 2004). Similar meteorological conditions may one day trigger avalanches while some other day nothing happens. The snowpack remains the key to the forecasting of wet snow avalanches (Fierz and Föhn, 1994; Baggi and Schweizer, 2009).

Chapter 3

Methods

This chapter introduces the standard methods used in several or all of the following chapters. Methods, which are specific to one chapter only, are discussed in that respective chapter.

3.1 Field methods

Field methods followed Swiss or international observational guidelines (SLF, 2008; Colbeck et al., 1990; Greene et al., 2004).

3.1.1 Site selection

Most of the field observations were carried out in avalanche terrain. Thus, most important criteria when selecting sites was personal avalanche safety.
Ideally, suitable locations for snowpack investigations have had little previous disturbance by skiers or avalanches, are in potential avalanche terrain (slopes steeper than 30°) and have less than average snowpack depth.

3.1.2 Snowpack observations

Snowpack observations followed Swiss observational guidelines (SLF, 2008). In manual snow profiles, snow depth, layer stratigraphy including hand hardness, moisture content, grain shape and grain size are observed (Tab. 3.1). Additionally, location, slope angle, elevation, aspect, date and time are recorded. Further information containing avalanche occurrences, avalanche hazard or observed signs of instability were noted. Snow profile observations were graphically presented using the snow profile software *SLF snowprofiler* (SLF, 2007).
The focus of this project was the investigation of wet snow stability. Therefore, quantitative

Table 3.1: Field observations: observed snowpack parameters and shear and stability tests.

Parameter	Signature		Values	Definition
Snow profile				SLF (2008)
hand hardness	HH	F, 4F, 1F, P, K, I	1 - 6	
water content	mWC	dry, moist, wet, very wet, slush, ice	1 - 5, 8	
grain form	GF			
grain size	size	in mm		
Rutschblock	RB			SLF (2008)
score	RBsc	1 - 7	1 - 7	
release type	RBrel	wBl, pBr, Edg (Tab. 3.6)		
fracture type	RBfrac	smooth, rough, irregular		
Extended column test	ECT			Simenhois and Birkeland (2006)
score	ECTsc		0 - 30 , no failure=35	
fracture propagation potential	ECTproj	fp, pp, np (Tab. 3.6)		
Shovel shear test	ST			Greene et al. (2004)
score	ST	Collapse, Very Easy, Easy, Moderate, Hard, No Failure	0 - 5	
Measurement tools				
micro-structural hardness	SMP			Snow Micro Penetrometer (Schneebeli and Johnson, 1998)
liquid water content	LWC	in vol.%		Snow Fork (Sihvola and Tiuri, 1986)

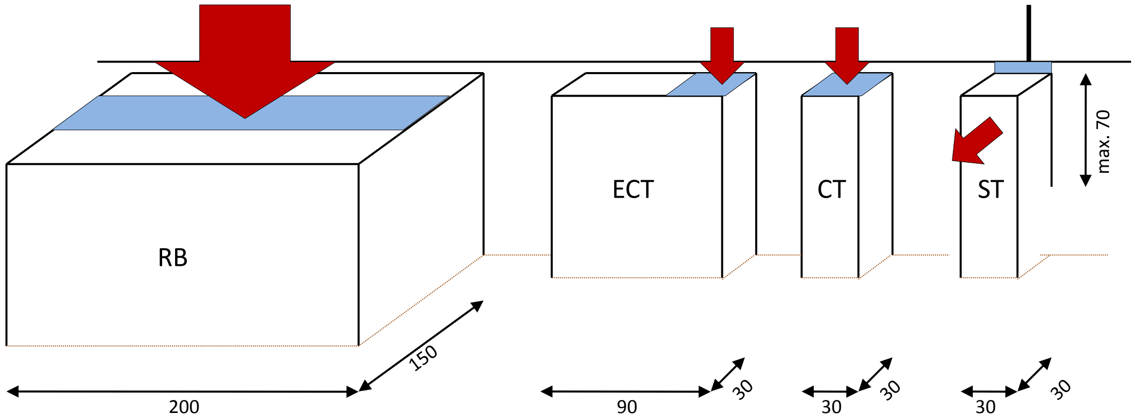

Figure 3.1: Schematic overview of Rutschblock RB, Extended Column Test ECT, Compression Test CT and Shovel Shear Test ST. Dimensions (in cm) are given below. The blue shaded area is the approximate size part of the column / block which is loaded by a person (on skis, RB) or the snow shovel. RB, ECT and CT are loaded from above. The ST is pushed from behind.

liquid water content (LWC) measurements complemented almost all snow profiles. The Snow Fork (Sihvola and Tiuri, 1986; Toikka, 2009) was used for these measurements. The Snow Fork is suitable to measure LWC between 0 and 10 vol.%. A more detailed description on LWC measurements is given in Chapter 4.
Micro-structural penetration measurements using the Snow Micro Penetrometer (Schneebeli and Johnson, 1998) are discussed in Chapter 5.
The sampling design specific to certain observations is shown in each of the chapters.

3.1.3 Shear and stability tests

Several different shear and stability tests were used in the field. These were the Rutschblock test (RB, Föhn, 1987), the Extended Column Test (ECT, Simenhois and Birkeland, 2006) and the Shovel Shear Test (ST, Greene et al., 2004). Test dimensions, recorded observations and loading steps according to observational guidelines are shown in Fig. 3.1 and Tab. 3.2.
During the field campaign (Chapter 8), the tested depth of the tests was often limited to 100 to 120 cm. The reason for this was the time limit to observe snow stability in several locations in the morning and afternoon. Also, most of the skier-triggered avalanches in dry snow release within the upper meter of the snowpack (Schweizer et al., 2008).

Table 3.2: Specifications of shear and stability test.

Test		Dimensions width x length [in cm]	Loading by	Recorded observations
Rutschblock (SLF, 2008)	RB	200 x 150	person's weight (on ski)	score release type fracture quality
Compression Test (Greene et al., 2004)	CT	30 x 30	tapping on back of shovel blade	score fracture character
Extended Column Test (Simenhois and Birkeland, 2006)	ECT	90 x 30	tapping on back of shovel blade	score fracture propagation
Shovel Shear test (Greene et al., 2004)	ST	30 x 30	push with shovel	score

3.2 Methods for data analysis

3.2.1 Snowpack parameters and test results

Index values, including half-scores of hand hardness (HH) and estimated water content (mWC) observed in manual snow profiles were used (Tab. 3.1).
In manual snow profiles **grain shape** is classified according to Colbeck et al. (1990). The Swiss observational guidelines use a simplified scheme with ten main grain shape classes (Tab. 3.3, SLF, 2008). For the purpose of data-analysis, the number of grain shape groups is further reduced and follows in part (Jamieson and Johnston, 1995b). They stated that it often suffices to classify grain shape as either persistent or non-persistent grains. As most of the results show (for instance in Chapter 5), layers consisting of grain shapes belonging to one group can often be described using the same regression function (as is the case for the relationship density - penetration resistance). The three grain shape groups used in this report are:

- wet grains and melt-forms (WG/MF)
- persistent grains (PG)
- non-persistent grains (NP, see also Tab. 3.3)

The effect of snowpack layering on water flow is investigated using the **capillary barrier index** (cap.barr, Baggi and Schweizer 2009, Tab. 3.4).
Structural weaknesses in the snowpack are assessed applying the structural instability index developed for dry snow (struct.index, Schweizer et al. 2008, Tab. 3.5).
Persistent weak layers (pWL) are defined as hand hardness index ≤1.5 and with persistent grains as primary or secondary grain form.
Liquid water content (LWC) was corrected by -0.8 vol%. The median of three measurements is used for LWC (see Chapter 4 for details).

Table 3.3: Grain form classification SLF (2008). Grain shape is grouped into non-persistent, persistent (Jamieson and Johnston, 1995b), wet and melt-freeze forms

Grain form		**Group**	
precipitation particles	PP	non-persistent	NP
decomposing fragments	DF		
rounded grains	RG		
faceted grains	FC	persistent	PG
depth hoar	DH		
surface hoar	SH		
faceted grains undergoing rounding	FCxr		
wet grains	WG	wet grains	WG
melt-freeze forms	MF		MF
ice lenses	IFil		
Graupel	PPgp		

Shear and stability test scores were treated like ordinal values according to their score. If no failure occurred, the score 35 was used for the ECT. Release type (RB) and fracture propagation (ECT) were given weights based on the approximate test area which failed while testing (Tab. 3.6).

Table 3.4: Capillary barrier index (table taken from pre-print Baggi and Schweizer, 2009, p. 15)

Potential effectiveness	**Criteria**	**Weight for index**
I: Low	Grain size difference [0.5 mm; 1 mm], smallest grains ≤0.5 mm Grain size difference [1 mm; 1.5 mm], smallest grains >0.5 mm	0.01
II: Intermediate	Grain size difference [1 mm; 1.5 mm], smallest grains ≤0.5 mm Grain size difference [1.5 mm; 2 mm], smallest grains >0.5 mm	0.1
III: High	Grain size difference >1.5 mm, smallest grains ≤0.5 mm Grain size difference >2 mm, smallest grains >0.5 mm	1

Table 3.5: Structural variables to calculate the stratigraphical threshold sum for dry snow (Schweizer et al., 2008). Critical ranges are shown.

Structural variable	**Critical threshold**
difference in grain size [mm]	≥ 0.75
failure layer grain size [mm]	≥ 1.25
difference in hand hardness	≥ 1.7
failure layer hand hardness	≤ 1.3
failure layer depth [m]	0.18...0.94
failure layer grain type	persistent grain

3.2.2 Statistical methods

Analyzed data was of nominal, ordinal and continuous form. Therefore, statistical analysis needed to be appropriate to data structure, sample size and sample distribution. Data-distribution was graphically inspected using histograms and box-plots, and in some cases

Table 3.6: Treatment of ordinal variables release type (RBrel) and fracture propagation (ECTprop) for data-analysis. Index approximates the portion of the block which failed. Index values are used for rank-order correlation analysis.

Test	**Type of failure**		**Index**
RBrel	whole block	wBl	1
	partial break	pBr	0.5
	edge only	Edg	0.33
	no failure	NF	0
ECTprop	twice fp	fp	1
(two tests)	once fp	pp	0.66
	no fp	np	0.33
	no failure	NF	0

Q-Q-plots and the Shapiro-Wilks normality-test.
Standard central tendency parameters were calculated. Often, especially when data-sets were small, the more robust median and interquartile range (the middle 50% of the data) was given preference over the mean. In this report, box-plots are often presented to high-light the data-distribution. In the case of continuous, large data-sets the mean, standard deviation and coefficient of variation are used (Chapter 5, Crawley, 2007).
Categorical data, in particular count data, was analyzed in contingency tables. Appropriate statistical tests are χ^2-tests or the Fisher test (see below, Boslaugh and Watters, 2008). Bar-plots are used to present count-data.
Classical parametric and non-parametric tests were used for hypothesis testing. Parametric tests may be used in the case data distribution is normal, no outliers exist and sample size is large (n>30). In most cases, however, non-parametric tests were given preference as these assumptions were not met. Non-parametric tests provide more conservative estimates of significance (higher p-values). Thus, if a non-parametric test is significant, a parametric test will also be significant (Crawley, 2007). Applied tests include:

- parametric-test (Crawley, 2007)
  - Students t-test may be used to compare the means of populations if errors are normal. Paired samples were tested using the Paired t-test or One Sample t-test, for two unpaired samples the Welch Two Sample t-test was used.
- non-parametric-tests
  - The Sign-test is suitable to investigate if a sample population is significantly different than a median. It tests if values are larger or smaller than the selected median. They are especially suitable for detecting trends in paired variables (for instance if diurnal changes are significantly different from 0, Ross, 2006).
  - The Wilcoxon rank sum test or the paired Mann Whitney U-test are suitable to compare two populations. The Kruskall-Wallis H-test is suitable to test more than two populations for similarities. These tests compare the ranks of the data rather than the absolute values (Crawley, 2007).

- χ^2 based hypothesis testing is suitable to investigate contingency tables (ordinal and cardinal data). These tests require expected and observed frequencies to be larger than 5. χ^2-tests using a Yates continuity correction might be applied for small sample sizes. However, there is debate about the validity of these tests. Generally, exact tests should be given preference (Crawley, 2007).
- Fisher's Exact test for count data is suitable if sample sizes are very small. The Fisher's test may be applied to test the likelihood that a certain distribution is as extreme, or more extreme, as observed (Crawley, 2007).

Correlation between variables was tested using the Pearson product momentum correlation coefficient r and Spearman's rho r_s. The latter is suitable for ordinal data, while the first may be applied if data is continuous. Both, r and r_s provide information on the strength and direction of an association (Boslaugh and Watters, 2008).
Bivariate linear models included linear regression of the form $y = ax + b$ and exponential regression models $y = a * e^{bx}$. Model quality was tested using the coefficient of determination r^2, which describes how much of the variation in a data-set can be explained by the linear regression model (Boslaugh and Watters, 2008). To compare two models, the model with the higher r^2 was selected.
Multivariate statistics included Principal Component Analysis (PCA) and Linear Discriminant Analysis, both were used in Chapter 5. The thought behind PCA is to find a small number of linear combinations (by creating new variables) explaining a large part of the variance (Crawley, 2007). Data was inspected using two- and three-dimensional scatter-plots. Linear Discriminant Analysis (LDA) can be used to cluster data if the identity of each individual is known (Crawley, 2007). LDA was used to predict the grain shape characterized in Chapter 5.
The application of regression tree models was suitable for Chapter 8 with many explanatory variables for stable and unstable slopes. The goal behind tree models is to filter the most significant variables explaining best the two groups. Tree models may also be applied for categorical data (Crawley, 2007). If the number of observations is unbalanced and small, as was the case in the data tested in Chapter 8, a random selection of observations was used for the construction of the regression tree. For robustness, this procedure was repeated 100 times. The interpretation is based on the frequency a variable was used to split the data-set into stable or unstable slopes.
All statistical analysis was carried out using the algorithms as defined in the statistics software *R*.

3.2.3 Software

Utilized software included *EXCEL*, R (R Development Core Team, 2008) for statistical analysis and plots. Specialized software (*IDL*) was needed for the large SMP files (Chapter 5). For the questionnaire with many comments (Chapter 6), the software *ATLAS.ti* was used.

Chapter 4

Liquid water in natural snowpacks - observations and measurements

The estimation and measurement of liquid water in snow plays a major role throughout the following chapters of this report.
In this chapter, a detailed introduction on applied measuring methods is given and results on spatial and temporal variability of measured liquid water content are presented. Water flow in snow will be discussed based on qualitative observations.

Research hypothesis:

1. The Denoth wetness meter and the Snow Fork are comparable tools for the measurement of liquid water content in snow.
2. The manual estimation of liquid water content is not a reliable method to record snow wetness in the field.
3. The measured liquid water content is influenced by the opening of a snow-pit and also by the sampling design.
4. Spatial distribution of water must be considered when interpreting estimated or measured liquid water content profiles.
5. Water flow pattern varies between snow layers consisting of different grain types and sizes.

4.1 Introduction

The introduction of liquid water into snow (by melt or rain) leads to "major reconfigurations of both grains and bonds" (Colbeck, 1997, p. 9). The distribution, flow pattern and amount of liquid water in snow influence many phenomena such as wet snow metamorphism (Colbeck, 1997), which is a faster process when the water content is higher, or wet snow stability, which generally decreases with increasing water content (i.e. Kattelmann, 1985; Conway and Raymond, 1993).

Water flow in snow is heterogenous (Conway and Benedict, 1994). Gravitational flow components dominate. However, capillary phenomena also play a role.
Once melting at the snow surface starts, water can penetrate the snowpack rapidly, in particular if water is routed through vertical flow fingers (Schneebeli, 2004). If less permeable layers or capillary barriers are present, water may flow slope-parallel along these layer interfaces (Conway and Raymond, 1993; Peitzsch, 2008). This may cause an almost simultaneous reduction in friction over relatively large areas, and may consequently cause slope instability (Conway and Raymond, 1993; McClung and Schaerer, 2006).
Schneebeli (2004) pointed out that snow stratigraphy must be interpreted in respect to possible capillary barriers. Following the conceptual model by Peitzsch (2008), wet slab avalanching may occur if flow fingers form and if capillary barriers exist.
A more detailed introduction on wet snow and water flow in snow can be found in the introductory chapter (Chapter 2.1).

In the field, the **manual estimation of the liquid water content** is an integral part of manual snow profile observations (Colbeck et al., 1990; SLF, 2008, Tab. 4.1).
Measuring liquid water in snow is difficult (Colbeck, 1973). Applied methods are mostly destructive. One appropriate method is based on the determination of the dielectric permittivity at micro-wave frequencies (Frolov and Macheret, 1999). The dieletric permittivity differs between air ($\epsilon_i^{'} \approx$1), ice ($\epsilon_i^{'} \approx$3) and water ($\epsilon_i^{'} \approx$86, Frolov and Macheret, 1999). The permittivity of ice depends on frequency, temperature and anisotropy (Frolov and Macheret, 1999). For dry snow at the melting point, the measured dielectric permittivity $\epsilon_d^{'}$ is (Frolov and Macheret, 1999):

$$\epsilon_d^{'} = (1 + 0.857\rho_d)^2, \tag{4.1}$$

where ρ_d is dry snow density.
Empirical equations are used to calculate the liquid water content. These differ between different measurement tools and data-sets (Frolov and Macheret, 1999). For the combined Finnish (Tiuri et al., 1984) and Austrian (Achammer and Denoth, 1994) data-sets, Frolov and Macheret (1999) derived an equation approximating the two data-sets (r^2=0.82).

$$\Delta\epsilon_s^{'} = 16.7\theta + 42.5\theta^2, \tag{4.2}$$

where $\Delta\epsilon_s^{'}$ expresses the change in dielectric permittivity from dry to wet snow and where θ is the liquid water content in vol.%. The wetness measurement devices developed by the

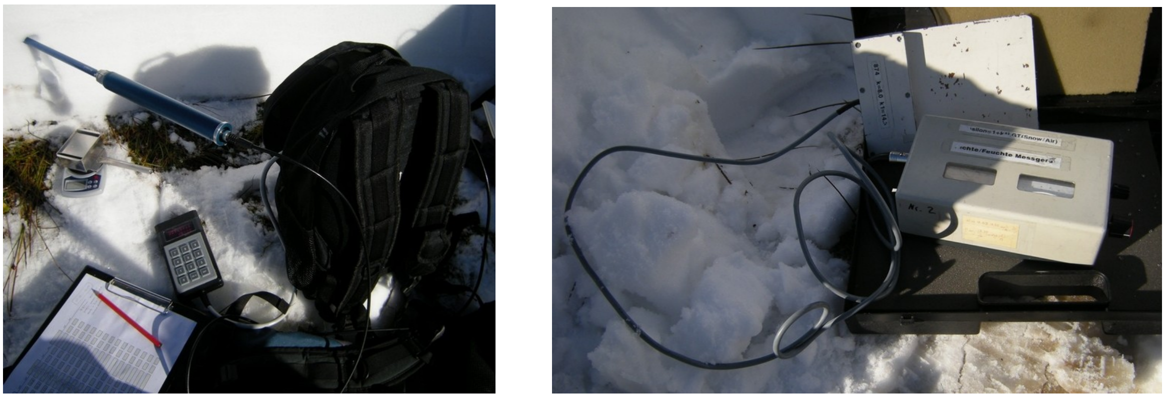

Figure 4.1: Snow Fork measuring device (left) and Denoth wetness meter (right). The Snow Fork consists of a battery box (hidden in the back-pack), the keyboard-display unit and the almost 1 m long steel fork. The Denoth tool has a plate-like sensor-unit and a control unit for manual tuning. Photos: Techel, 2009.

Table 4.1: Qualitative estimation of liquid water content (mWC), a detailed description is given in observational guidelines (Colbeck et al., 1990; Greene et al., 2004; SLF, 2008)

Moisture Content	Signature	Approximate water content [vol. %]	Regime
Dry	1	0	
Moist	2	<3	Irreducible
Wet	3	>3...8	Pendular
Very Wet	4	8...14	Funicular
Slush	5	>14	

Finnish and Austrian research groups were used in this study: the Snow Fork (SnF, Sihvola and Tiuri, 1986) and the Denoth wetness meter (Dn, Denoth, 1994, Fig. 4.1).

4.2 Methods

4.2.1 Field methods

Estimation and measurement of the liquid water content in snow

The qualitative estimation of liquid water content (mWC) was part of the standard observation procedure in all manual snow-profiles (SLF, 2008; Colbeck et al., 1990, Tab. 4.1). **Liquid water content** was measured using the Snow Fork (SnF, Sihvola and Tiuri, 1986). On occasion, the Denoth wetness meter (Dn, Denoth, 1994) was used for a comparison between the two tools.

Finnish **Snow Fork** (SnF) (Fig. 4.1, left):
"The sensor is a steel fork used as a microwave resonator. The Snow Fork measures the electrical parameters: resonant frequency f, attenuation and 3-dB bandwidth B. The measured results are used to calculate accurately the complex dielectric constant of snow." (Toikka, 2009, p. 1). Advantageous is the reduced compression around the fork's sensor. No density sampling is needed. Disadvantages are the relatively large size and the weight of battery box and sensor (5 kg). Data is shown on a display and stored in an internal memory. Data can be transmitted to a computer (Toikka, 2009).
The calculation of liquid water content (LWC) and density of snow is based on semi-empirical equations. The Snow Fork uses the following equation to calculate the LWC (Toikka, 2008):

$$LWC_{uncor} = -0.06 + \left(0.0036 + \frac{118667.(B - 0.04(-400 + f))}{f^3}\right)^{0.5}, \tag{4.3}$$

where f is the resonant frequency and B the bandwidth. These displayed results are uncorrected for any offset-errors. They will always be referred to as LWC$_{uncor}$

Denoth wetness device (Dn) (Fig. 4.1, right):
The Dn device consists of a control unit for manual tuning and a sensor unit. The sensor unit, which is placed horizontally in the snow or on the snow surface, has a width of 12.5 cm and a length of 19 cm. The operating frequency is 20 MHz. The unit is battery powered (Denoth, 1994). The LCD display shows a value related to the capacity of the dielectric sensor. Values for air (A) and snow (S) need to be obtained and the snow density must be measured (ρ in kg m^{-3}). With these, the dielectric constant of snow can be calculated and the liquid water content measured with the Denoth meter (LWC$_{Dn}$) derived (Schneebeli, 2007):

$$LWC_{Dn} = 4.69\left(k \log\frac{S}{A} - 2\rho\right), \tag{4.4}$$

where k is a sensor-specific calibration constant.

Sampling design for liquid water content measurements in natural snowpacks

Liquid water content was measured in one of the following three ways:

- *horizontal* - These preceded all slope profiles. Three measurements beside each other were taken. The distance between measurements was 20 cm (across the slope) with measurement intervals of 5 cm (into the snowpack, Fig. 4.2A). When, additional to standard snow profile observations, micro-structural penetration resistance measurements were carried out (discussed in Chapter 5), a second set of three measurements was taken out on the other side of the snow-pit (Fig. 4.2A).

- *profile* - These accompanied all slope profiles. Measurements were undertaken beside manual snow profile and always on a side wall of the snow-pit. Measurements were

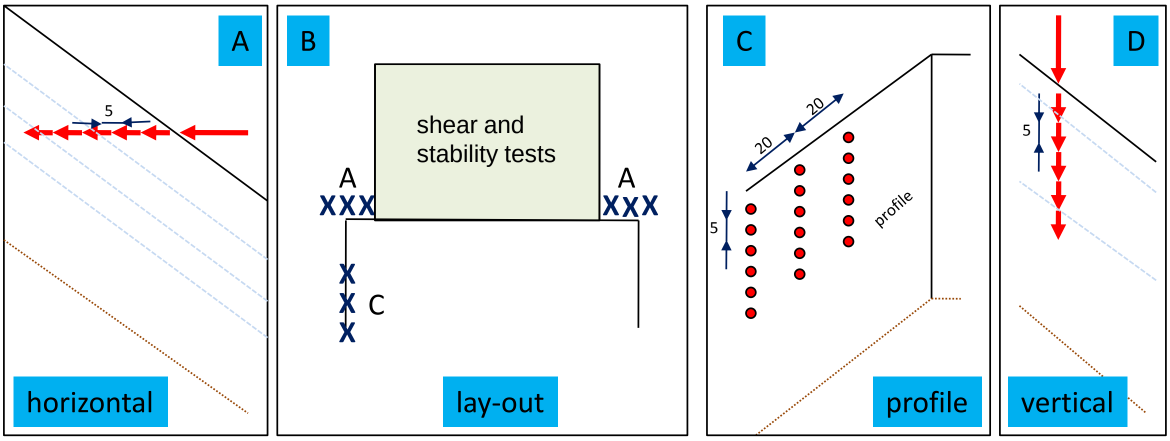

Figure 4.2: Liquid water content measurements: sampling design for horizontal, vertical and profile measurements. A) horizontal measurements in 5 cm steps to a depth of 75 cm. B) lay-out of LWC measurements accompanying all slope profiles and stability tests. Distance between neighboring LWC profiles is 20 cm. C) observations adjacent to manual snow profile, vertical distance 5 cm, slope-parallel distance 20 cm. D) vertical measurements for spatial variability observations, measurement steps 5 cm.

slope- and layer-parallel, and generally less than 50 cm away from *horizontal* measurements. Vertical measurement intervals were 5 cm and the distance between the three measurement rows d=20 cm (Fig. 4.2B, Fig. 4.2C)

- *vertical* - This measurement lay-out was carried out to observe spatial variability of water content distribution (Fig. 4.2D).

Sampling design for the comparison of Denoth wetness meter and Snow Fork device

Denoth (Dn) and Snow Fork (SnF) devices were compared by measuring two or three Denoth and four to six Snow Fork measurements. The measurements were always undertaken on a side-wall of a snow-pit and parallel to the layer stratigraphy. The horizontal sampling sequence was:
SnF - SnF - Dn - SnF - SnF - Dn - SnF - SnF
Horizontal and vertical distance between measurements was 5 cm. Snow densities were sampled immediately above and below the Denoth placement (Fig. 4.3).

Artificial wetting experiments

Artificial wetting experiments were carried out to investigate the changes in micro-structural penetration resistance of selected layers during first wetting (topic of Chapter 5). Here, the

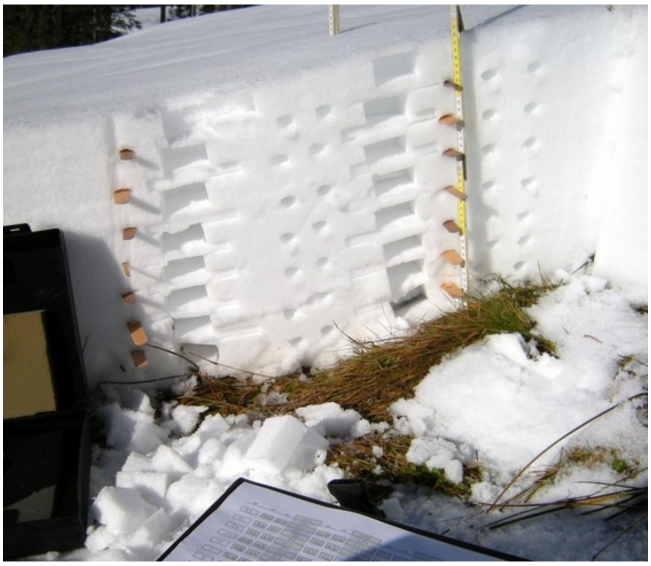

Figure 4.3: Comparison between Snow Fork and Denoth tools: sampling design. Snow Fork and Denoth tool were compared by observing at least four Snow Fork and two Denoth measurements within the same layer. Two density samples were taken immediately above and below (square holes) the Denoth meter placement (thin slots between density holes). The Snow Fork measurements are the small round holes. Photo: Techel, 2008.

procedure will be briefly described, as observed water infiltration patterns will be qualitatively discussed. The procedure followed the experimental set-up and lay-out as shown in my BSc thesis (Techel, 2007):

1. slope selection, manual snow profile, layer selection
2. exposure of selected layers, ∼1 m wide, 3 m up-slope
3. measurements (penetration resistance, slope-parallel liquid water content and density measurements)
4. leaving layers exposed to the sun to warm (until approximately isothermal)
5. artificial wetting cycles (Fig. 4.4, left)
6. layer-parallel cuts of snow surface to photograph infiltration patterns (Fig. 4.4, right)

Before water could be sprayed onto the snow surface, exposed layers were left to warm until approximately isothermal (snow temperature close to 0°C). This was considered necessary as experiments in 2007 showed that spraying water on a sub-zero snow-pack prohibits infiltration (re-freeezing occurs). While layers warmed, about ten liters of ice-water (temperature 0°C) was mixed with 2.5 g tracer (Brilliant Blue). The snow surface was sprayed with approximately one liter water at a time, followed by measurements. The procedure was repeated

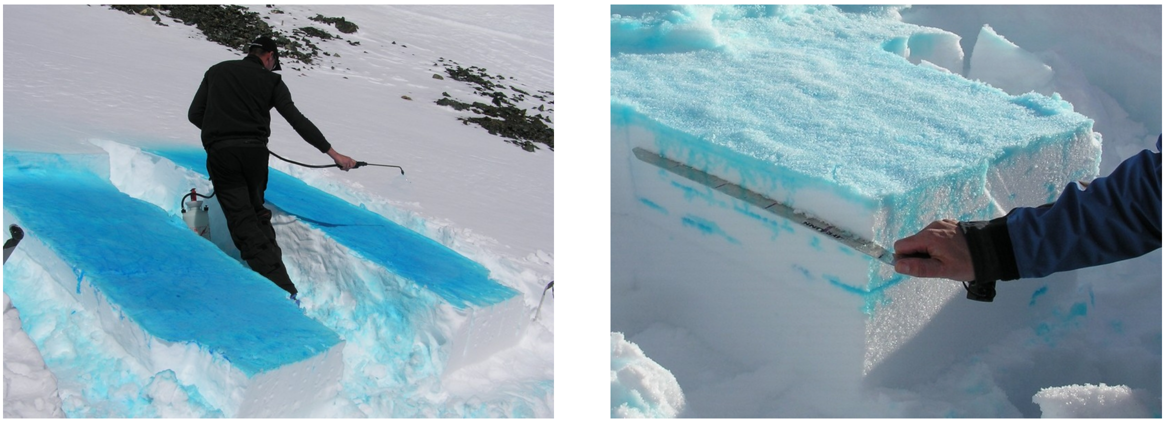

Figure 4.4: Artificial wetting experiments. Left: Exposed layers were sprayed with an ice-water-tracer mixture. Right: Slope-parallel cuts followed experimentation to observe infiltration pattern. Photos: Pielmeier, 2009.

approximately every 20…30min. The duration of the experiments varied between 3 and 5 hours. The total infiltration rates were between 2 and 6 l m^{-2} (see Tab. B.1, App. B).
The infiltration pattern was qualitatively documented by photographing slope-parallel and vertical cross-sections.

4.2.2 Data

A large number of LWC measurements were conducted using the Snow Fork in naturally wet snow. More than 7000 measurements were taken accompanying slope profiles (horizontal measuring mode n=3690, profile measuring mode n=3449, Tab. 4.2). These were recorded in more than 2500 different measurement depths or layers.
In artificial wetting experiments, approximately 1000 measurements were taken. These were sampled in nine different layers, within the upper 15 to 20 cm of the wetted layer.
To investigate spatial variability, the LWC was measured in five different layers over a distance of 300 cm (total number of measurements 150). Vertical wetness cross-sections of the snowpack were done over 5 m wide areas and to a depth of 80 cm. However, most data was lost due to false handling of the Snow Fork. This left only one cross-section for analysis.
The comparison of Snow Fork and Denoth is based on measurements in 150 layers, where several recordings were taken.

4.2.3 Data analysis

The **liquid water content** is directly calculated by the Snow Fork and stored in a memory. In all cases, several LWC measurements were taken for each measurement depth. The median of each set of observations is taken to reduce the influence of extreme values. If not other stated, it is always this median LWC or snow density which is referred to.

Table 4.2: Data overview. Number of days when liquid water content was measured accompanying slope profiles using the Snow Fork (SnF), during artificial wetting or for the comparison between SnF and Denoth (Dn).

	days (locations)	**different depths**	**single measurements**
natural wet snowpack	24 (60)	ca. 2500	ca. 8000
artificial wetting	5 (9)	ca. 300	>1000
Dn - SnF comparison	6 (8)	ca. 150	284 - 487

Snow densities were collected when working with the Denoth tool and during artificial wetting experiments. For each density two to six samples were taken and the mean calculated.
Grain shape was grouped according to the simplified classification introduced in Chapter 3.2.1 (Tab. 3.3). The three main groups are: non-persistent (NP), persistent (PG) and melt-freeze / wet grain (MF/WG) snow. This simplified approach seems suitable, as it reduces the splitting of the data-set into many groups and keeps the main grain shapes apart (persistent and non-persistent grains have different mechanical properties, Jamieson and Johnston, 1995b).

Wetness classification

So far, the wetness of the snowpack is not considered in profile classification schemes (Schweizer and Wiesinger, 2001). Here, a wetness classification is introduced using either manual water content estimates (mWC) or measured water content (LWC). Four profile wetness groups (*dry*, *dry-moist*, *moist*, *wet*) are defined (Fig. 4.3).
Manual snow profiles are classified based on the estimated water content (mWC), excluding surface layers (top 15 cm). Surface water content was not considered for this classification, as it changes significantly during the day. For the purpose of this classification the mWC-value for ice (code 8), was set to 1 (which equals dry snow).
For the classification based on liquid water content measured using the Snow Fork (LWC_{SnF}), the LWC-profiles were simplified to minimize the influence of extremes (like isolated vertical or layer-parallel flow channels). Each profile was split into sub-layers of equal thickness (25 cm), but excluding the uppermost 15 cm. For each sub-layer, the median, corrected LWC_{SnF} was calculated.
The LWC- and mWC-classification was compared for all profiles observed in the morning (n=44), where LWC was measured. Temporal changes from morning to afternoon, were compared based on the LWC-classification, as only few afternoon manual profiles were observed.

4.2.4 Statistical methods

Linear regression models were derived for continuous variables and the Pearson coefficient of determination r^2 calculated. For categorical variables, the Spearman correlation r_s was used.

Table 4.3: Definition of wetness categories based on estimated and on measured liquid water content in their order of testing the database.

wetness	mWC-classification	LWC-classification
4-wet	all layers at least wet	all sub-layers at least wet (LWC_{SnF} >3 vol.%)
3-moist	all layers at least moist	all sub-layers at least moist (LWC_{SnF} >0 vol.%)
2-dry-moist	at least one layer not dry	at least one sub-layer not dry (LWC_{SnF} >0 vol.%)
1-dry	all layers are dry	all sub-layers with LWC_{SnF} =0 vol.%

Non-parametric tests were applied if sample sizes were small (Wilcoxon rank-sum test, Mann Whitney U-test, Kruskal-Wallis test). The one-sample sign-test was used to test if changes were significantly different from a median. For large sample sizes, parametric test procedures were utilized (one- and two-sample t-tests).

Remark

To avoid confusion between the many different liquid water content measurements using different tools and before and after data treatment, the following abbreviations are used throughout the following sections:

LWC	liquid water content
LWC_{Dn}	liquid water content [vol.%], measured with Denoth tool
LWC_{SnF}	liquid water content [vol.%], uncorrected, measured with Snow Fork
LWC_{uncor}	measured liquid water content [vol.%], uncorrected for calibration error
mWC	manually estimated water content

4.3 Results

4.3.1 Liquid water content measurements using the Snow Fork

Almost 9000 single Snow Fork measurements were recorded, in a variety of measurement arrays and snow wetness situations including many dry snow layers. Recorded values ranged from 0 to 23.6 vol%. The range, where the SnF measurements are considered reliable, lies between 0 and 10 vol.% (Toikka, 2008). In this data-set, 3.5% of the recorded values were higher than 10 vol.%. These high values were observed more frequently when measuring across layers in an undisturbed snowpack (before digging the snow-pit, horizontal measurement mode, Fig. 4.2A) than in measurements taken at the sidewall of a snow profile (*profile* measurement mode, Fig. 4.2C). In *horizontal* measurements, the frequency of these high values is strongly correlated to the median LWC_{uncor} of three adjacent measurements. Also, these high values occur more frequently in layers relatively close to the snow surface. None of these correlations could be noted for layer-parallel measurements at the side-wall of a snow-pit.
Liquid water content measurements before digging the snow-pit (*horizontal*) and following manual snow profile observations (*profile*) are compared for 86 locations. For median LWC_{uncor} less than 1.3 vol% (dry or barely moist snow), there is no significant difference

between either mode of measuring the water content (Sign-test). In moist and wet snow, however, *horizontal* measurements are significantly wetter than the measurements at the side-wall following snow profile observations. The median difference is 0.43 vol.% ($p=0.03$). In a variety of snow wetness situations ranging from dry to wet snow, the Snow Fork measures approximately 1.4 times the liquid water content as calculated using the Denoth meter ($r^2=0.81$, $p\leq0.001$, Fig. 4.5a).

$$LWC_{uncor} \approx 1.4 * LWC_{Dn} + 0.6 \tag{4.5}$$

where LWC_{uncor} is the uncorrected water content measured with the Snow Fork and LWC_{Dn} the respective value for Denoth meter measurements.
Snow Fork measurements in **dry snow** showed a mean of 0.8 vol.% (standard deviation $\sigma=0.2$ vol.%). The **Denoth** tool, which was sometimes used for comparison, had a mean of 0.1 vol.% ($\sigma=0.17$ vol.%) in dry snow. These two tools were directly compared in 83 layers. Each comparison consisted of several measurements ($n_{Dn}=281$, $n_{SnF}=487$). Measured water content in **dry snow** is generally 0.65 vol.% higher using the Snow Fork than with the Denoth meter (Fig. 4.5b). In dry snow, both tools measure higher LWC with increasing snow density. The slope of the regression line is highly significant for the SnF ($r^2=0.28$, $p\leq0.001$). The regression line for the Dn tool explains a much smaller number of the observed values ($r^2=0.11$, $p<0.05$).

4.3.2 Qualitative water content observations and measurements using the Snow Fork

Manually estimated water content (mWC) and liquid water content measured with the Snow Fork (LWC_{SnF}) are strongly correlated ($r_s=0.73$, $p\leq10^{-16}$). Correctly estimated water content decreases with increasing LWC_{SnF} (Fig. 4.5c). Very few layers were estimated as being very wet. In almost all of these cases, mWC was overestimated. Wet layers (LWC>3vol.%) are more frequently observed in wet grain or melt-freeze layers (>20%) and rarely in layers consisting of persistent or non-persistent grains (<4% of cases, n=356). Non-persistent layers estimated as being wet were almost always overestimated while persistent *wet* layers were normally correctly estimated (see Fig. A.2a-c in App.A).
Hardness of snow is influenced by the liquid water content. This can be observed in both the estimated and measured water content data. The correlation is strongest in layers classified as melt-freeze or wet grains (r_s=-0.76 for mWC, r_s=-0.43 for LWC_{SnF}, $p\leq10^{-15}$). Not surprisingly, the transition from dry (frozen) to wet infers a significant hardness decrease. There is no clear trend for persistent grains. However, all persistent grain layers estimated as being wet (n=6), or measured as being wet (LWC_{SnF} >3 vol.%, n=9), have a hand hardness of 1. This is significantly softer than the dry hand hardness ($p\leq0.01$, Kruskal-Wallis test). A weak, positive correlation exists between LWC_{SnF} and hand hardness in non-persistent layers ($r_s=0.31$, $p\leq0.01$).

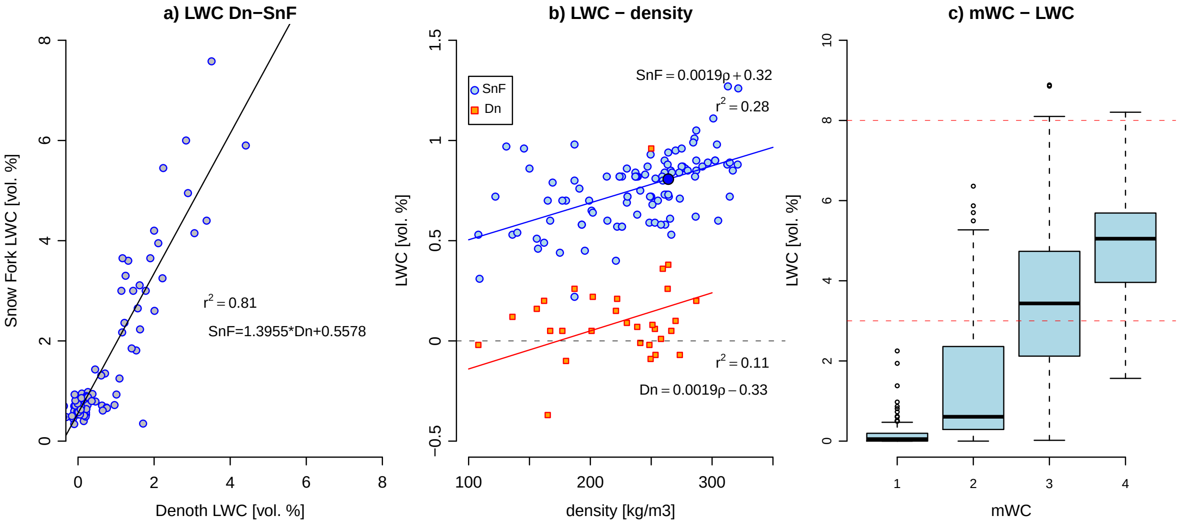

Figure 4.5: Scatter-plots showing uncorrected liquid water content measurements (LWC) comparing the Denoth (Dn) and the Snow Fork (SnF) tools. a) Denoth and Snow Fork in dry and wet snow (n=83). b) shows measured, uncorrected LWC in dry snow as a function of snow density for Snow Fork (blue circles) and Denoth meter (orange squares). In both plots (a, b) the best-fit linear regression line, the Pearson correlation coefficient r^2 and the linear regression equation are shown. c) Comparison of estimated liquid water content (mWC) and measured, corrected LWC. mWC wetness classes are: 1-dry, 2-moist, 3-wet, 4-very wet (Tab. 4.1). The dotted red lines mark the limits of the moist range (0. . . 3 vol.%) and the wet range (0. . . 3 vol.%) as defined per the international guidelines (Colbeck et al., 1990). Grain form specific observations can be found in App. A, Fig. A.2.

4.3.3 Wetness classification

Wetness of a snow profile was classified using the manually estimated water content (mWC) and the measured and corrected liquid water content using the Snow Fork (LWC_{SnF}).
While the definition of the wetness categories in the mWC- and LWC-classification schemes (*dry*, *dry-moist*, *moist* and *wet*) is very similar, it is not identical. Still, in 45% of the cases profiles were in the same wetness class. The largest difference occurs in the classes *dry* and *dry-moist*. *Dry* LWC-profiles are less often observed than *dry* mWC-profiles, while the opposite is true for the *dry-moist* class. Very few profiles were classified as wet (mWC=1, LWC=2). Typical wetness profiles are shown in Fig. A.1 (in App. A).

4.3.4 Variability in water content distribution and water flow patterns

The variability in measured liquid water content (LWC_{uncor}) was investigated by comparing three measurements at the same depth with a horizontal distance of 20 cm. The variability, the range between the highest and the lowest of the three measurements, increases with increasing wetness of the snowpack. Over short distances (40 cm), the variability increased from dry snow (median LWC_{uncor} <0.8 vol%, σ±0.2 vol.%) to wet snow (median LWC_{uncor} >3.8 vol%, σ±1.08 vol.%, Tab. 4.4, Fig. 4.6).

Table 4.4: Small-scale variability in uncorrected liquid water content (LWC_{uncor}) measurements. Shown are the median values of three LWC measurements, and the standard deviation of the half-range (σ) between highest and lowest water content recording. The increase in variability from one group to the next is highly significant ($p \leq 0.001$, t-test).

LWC_{uncor}	σ	**n**
<0.8 vol.%	0.20	207
0.8 vol.%...1.3 vol.%	0.38	355
1.3 vol.%...3.8 vol.%	0.77	188
>3.8 vol.%	1.08	133

Over wider areas (horizontal distance of 300 cm, measurement spacing 10 cm), the variability was investigated in five selected layers. In these layers, the variability (σ of 30 measurements) is not generally higher than in the 40 cm distance measurements (Fig. 4.6).
The cross-section over a 5 m wide area showed high variability in vertical and horizontal water content distribution (Fig. 4.7). Layer-parallel flow (at depth 45...55 cm) and preferential flow patterns (at distance=300 cm) can be recognized. Prominent is also the predominantly dry snowpack below 50 cm depth.
The advancement of the wetting front could be noted in water content measurements, and, more visually, from the water-tracer mixture applied during the artificial wetting experiments. Following wetting, the LWC measured just below the surface increased immediately in all layers. In persistent grains, the wetting front advanced relatively homogenously with further wetting. In the non-persistent layers, the advance of the wetting front was much slower and more variable (Fig. 4.8a).
Observed water flow patterns in artificial wetting experiments were:

- frequently of preferential type in layers consisting of non-persistent grains (new snow, small rounded grains). Slope-parallel water flow was noted in most experiments (Fig. 4.9).
- more matrix-like in layers consisting of persistent grain-forms. However, if layer boundaries were present, slope-parallel flow diversion was also noted (Fig. 4.10).

4.3.5 Temporal changes in snow wetness: morning to afternoon

Diurnal changes occurred predominantly within the upper 15 cm of the snowpack (Fig. 4.8b). Seen over the whole data-set, these changes are significant only in the uppermost 10 cm ($p < 0.05$, Mann-Whitney test). This is supported by the fact that 70% of the profiles remained in the same LWC wetness class from morning to afternoon. Only one profile increased by more than one class (from dry to moist), while seven decreased and two increased by one class.

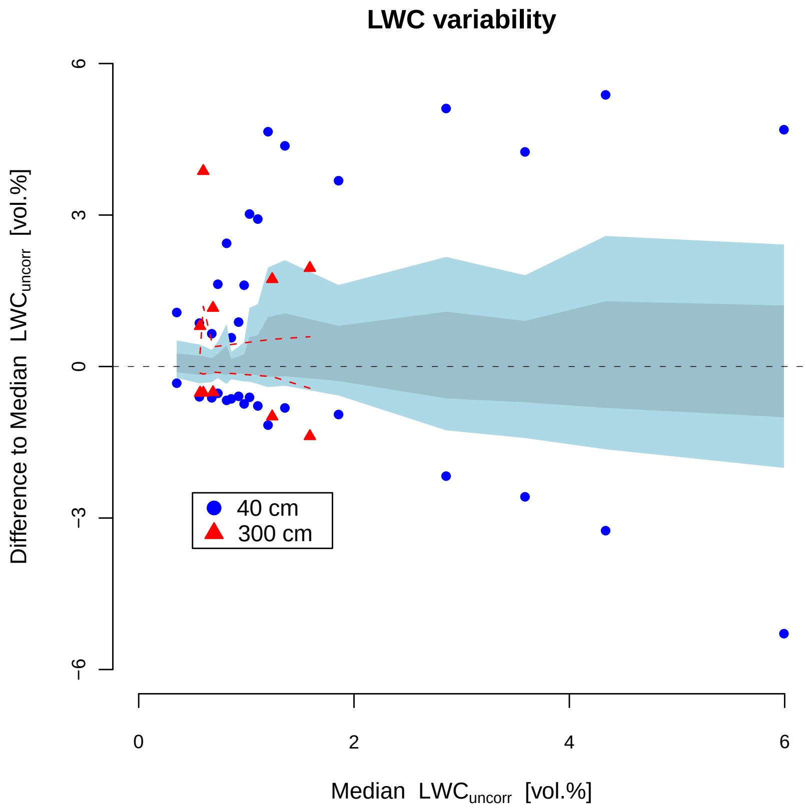

Figure 4.6: Variability of three adjacent, uncorrected liquid water content measurements (LWC_{uncor}) within 40 cm horizontal sections (n>900). Shown is the difference from the median measured LWC for each set of three measurements. The differences are shown as ± one standard deviation (dark shaded area) and ± two standard deviations (light shaded area). The blue dots mark the maximum and minimum observed values. Extremes and standard deviation were calculated for sets of 50 measurements. The red lines show ± one standard deviation from median LWC_{uncor} and the red triangles the maxima and minima for data-sets observed over a distance of 300 cm with a measurement spacing of 10 cm (5 layers).

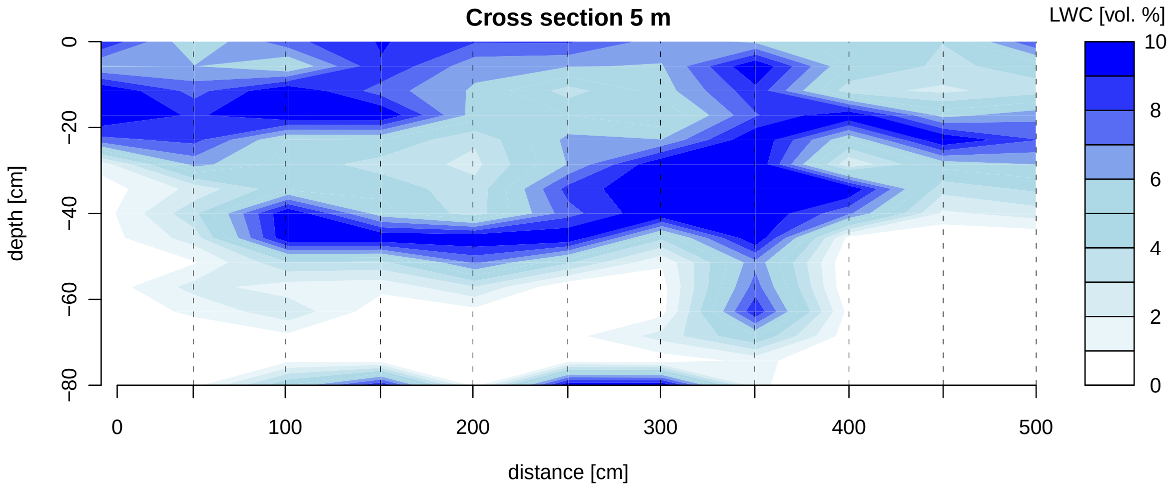

Figure 4.7: Spatial variability of liquid water content (LWC). This 5 m wide cross-section with measurements carried out with distance of 50 cm (dotted lines), vertical distance between measurements is 5 cm. LWC between measurements is interpolated. The cross-section was observed on 04 April 2009, Weissfluhjoch, S, 2662 m, 30°. In the same slope, about 10 m away, the snowpack collapsed while walking into the slope (see Fig. 8.1, Chapter 8 for details).

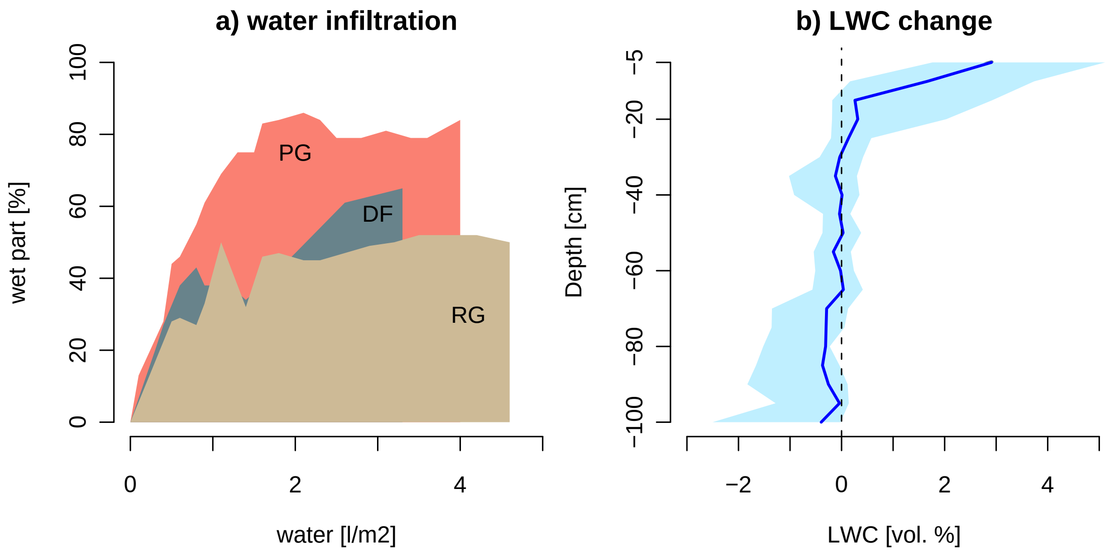

Figure 4.8: a) Percentage of wetted snow layer following artificial water spraying (water, in l m^{-2}), curve is averaged over 6 measurements. Different polygons are drawn for each main grain form (PG-persistent grains, DF-decomposing precipitation particles and small round grains, RG-round grains). A measurement was considered not dry when the uncorrected LWC (LWC_{uncor}) was larger than 1.3 vol.%. Three experiments for each grain type. b) Difference between afternoon and morning liquid water content (LWC), measured in 33 locations. Positive values indicate an increase in LWC.

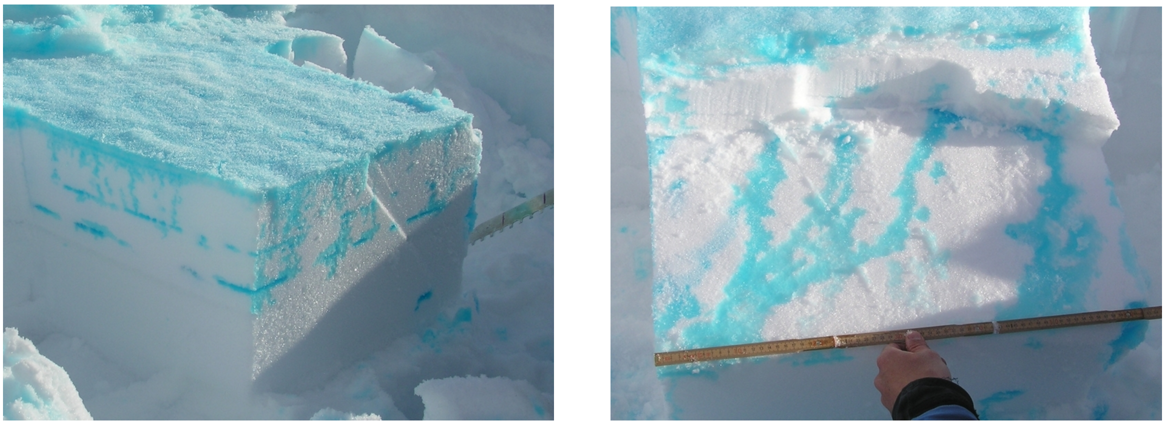

Figure 4.9: Water flow during artificial wetting experiments - non-persistent snow. Prominent slope-parallel water flow channels were noted in this profile (at the depth of the second stratigraphic horizon, visible in the left figure). The surface layers consisted of non-persistent grains (new snow, decomposing snow and small rounded grains, study-plot SLF, 1640 m, N, 8°, 13 March 2009). Photos: Pielmeier, Techel

Figure 4.10: Water flow during artificial wetting experiments - persistent snow. The density of preferential flow channels was often high in layers consisting of coarse-grained persistent crystals. Surface layers showed matrix flow. Figure shows flow channel distribution at depths of 5, 15 and 25 cm below the surface (left to right, Weissfluh, Institutsgipfel, 2600 m, N, 38°, 10 April 2009). Photos: Pielmeier

4.4 Discussion

4.4.1 Liquid water content: measurement and estimation

Two tools were compared to quantitatively measure the liquid water content in snow: the **Snow Fork** and the **Denoth wetness meter**. The Snow Fork was found to have several advantages over the Denoth meter: the water content can be read on the display in the field. Measured values can also be stored in a memory. This allows very efficient measuring. The Denoth meter requires the observer to take density samples before the water content can be claculated. Also, data can not be stored in the device. Another feature, which proved extremely useful with the Snow Fork, was the long probe allowing measurements of up to one meter depth, without disturbing the snowpack previously by digging a snow pit. Both tool's sensors might be affected by solar radiation if the sensor is placed close to the snow surface (Lundberg et al., 2008). One set-back with the Snow Fork is the relatively large size and heavy weight of the battery box (5 kg).
Snow Fork measurements were efficient and obtained data seemed very reliable. In dry snow, the median recorded water content is 0.8 vol.%. This is believed to be a calibration error. In dry snow, measured water content increases with snow density. Temperature, which may also influence dielectric measurements (Frolov and Macheret, 1999), was not consistently recorded and therefore not considered. The recorded, uncorrected water content measured with the Snow Fork (LWC_{SnF}) is approximately 1.4 times higher than using the Denoth wetness tool. These results are very similar to Williams et al. (1996), who reported a factor of 1.5 between Denoth and Snow Fork for water content measurements observed close to the snow surface. In wet snow, however, it is not clear, if the Snow Fork or the Denoth instrument record a better representation of the true water content. Following the Snow Fork's instruction manual (Toikka, 2008), recordings higher than 10 vol.% must be considered suspect and not reliable. These high recordings were more frequently observed when measurements were across layer boundaries before opening a snow-pit. In freely draining snow, the liquid water content is generally less than 8 vol.%, while above less permeable layers, the water content may be higher (Colbeck, 1997). Thus, it can only be speculated if water ponding at layer interfaces leads to these high recordings, or if the tool did not measure accurately.
The correlation between **estimated water content** (mWC) and water content measured with the Snow Fork (LWC_{SnF}) is strong. In hand profiles, comparatively higher water contents are generally correctly estimated. However, it is of note that layers estimated as being *wet* were generally only in the measured *moist* range. These observations are very similar to an existing study by Martinec (1991). He showed that dry and moist layers are normally well described. However, water content is often overestimated if the LWC is higher than approximately 2 vol.%. A trend which increases with increasing wetness (data interpretation based on Tab. 1, Fierz and Föhn, 1994). Our observations strongly confirm these observations. Fierz and Föhn (1994) correctly pointed out that the estimated wetness must not be interpreted rigorously according to international guidelines (Colbeck et al., 1990). Our data indicates further that is is more difficult to estimate the water content in melt-freeze - wet-grain layers than in persistent or non-persistent layers. It is not clear, why this is the

case. Possibly, relatively hard (seemingly frozen) melt-freeze-layers can contain comparably large quantities of water, or water has started flowing through the layer. Observers may unconscientiously consider hand hardness, grain shape and size when estimating water content. Estimated water content was often observed to be very questionable when investigating a data-base of snow profiles (Chapter 7). It may be the most difficult parameter to estimate when recording manual snow profiles.
Comparing the influence of water on hardness based on the hand hardness test (HH) and estimated water content has many limitations. Firstly, both parameters are relatively subjective estimates of snow hardness or water content. And secondly, snow layers have developed differently over the course of a winter and may therefore not necessarily be compared with each other. Still, keeping these circumstances in mind, the weakening influence of liquid water on snow hardness can be seen. This is most prominent in the case of *wet* layers consisting of persistent grain forms which were all very soft (HH=1, LWC_{SnF} <5 vol.%). The trend of lower snow hardness being observed with increasing wetness is significant for melt-freeze and persistent grain layers. Non-persistent layers, on the other hand, showed very little influence of hand hardness at low water content. This may indeed be typical for this grain shape, as small non-persistent grains tend to cluster tightly at low water contents (Colbeck, 1997).

4.4.2 Spatial and temporal variability

Aspects, which must be considered when describing liquid water in snow, are its spatial distribution and temporal evolution.
Within the same layer, over horizontal distances of less than 40 cm, the variability increases with increasing liquid water content. Relatively robust measurements may be achieved by repeating several measurements. However, the selected distance of 40 cm may not be a representative distance, as was noted in larger scale measurement arrays. Within the same layer, variability of measured water content was sometimes relatively minor (as in Fig. 4.6), or in other situations enormous fluctuations were noted (Fig. 4.7). Explanations for this could be the snow stratigraphy and the duration of wetting: with first wetting, isolated flow fingers may locally produce very high water contents, while other regions remain completely dry. This high heterogeneity has been documented in several previous studies: water flow in snow may follow a "step-and-fill" pattern (Conway and Benedict, 1994, p. 649) or flow fingers may advance rapidly (Marsh, 1991; Conway and Benedict, 1994). After prolonged wetting the snowpack homogenizes and water may be more evenly distributed.
Therefore, important information when describing liquid water in a snowpack would not only be the water content itself, but also its spatial distribution. As indicated, the latter would require several measurements and a geostatistical approach. For such measurement arrays, the Snow Fork would be an ideal tool.
The water flow experiments (see Fig. 4.9 and Fig. 4.10) indicate different flow patterns in non-persistent (preferential flow) and persistent grains (matrix-like preferential flow, close spacing between channels). However, the representability of these experiments is questionable as layers were exposed prior to wetting.
In the course of a day, it was mostly the snow surface (uppermost 10…15 cm) which changed

wetness from morning to afternoon. At depth, both increasing and decreasing water contents were recorded. It is unclear, in-how-far water content profiles were measured in regions of drier or wetter snow (in comparison to surrounding snow). Melt-water, which forms at the surface, is believed to be more uniformly distributed close to the surface, though considerable variability may exist(Williams et al., 1996). For avalanche forecasting purposes, it might be a first suitable approach to monitor the snow surface wetness. Possible options may include remote micro-wave sensing technologies (Lundberg et al., 2008). In a second step, it would be useful to measure and model the water distribution in the snowpack. With water infiltration being highly variable and depending on layer stratigraphy and layer characteristics, the two- or three-dimensional modeling of water distribution in snow is very complex. However, Hirashima et al. (2009) successfully integrated an one-dimensional water-flow model in the snow cover model SNOWPACK (Bartelt and Lehning, 2002) and were able to simulate water ponding above capillary barriers. Snow Fork measurements could again be used to verify simulated water flow in the field.

4.4.3 Wetness classification

A simple wetness classification of snow profiles was proposed. The snowpack wetness was classified as being either *dry*, *dry-moist*, *moist* or *wet* (Tab. 4.3, p. 36).
Both, the classification based on measured (LWC-classification) and estimated water content, showed a similar number of moist or wet profiles. Very few of these profiles changed wetness class from morning to afternoon (LWC-classification only). Explanations for this could be twofold: firstly, the (too) robust classification method which is little influenced by isolated extreme wetness values. Secondly, and this is confirmed by the diurnal changes in wetness (Fig. 4.8b), overall water content generally changed hardly in the course of one day (with the exception of surface layers).
This very simple classification shall provide very basic information relevant to current or future water infiltration. A profile classified as *dry* would indicate that wetting has not really influenced the snowpack. In such cases, capillary barriers may play a more important role for future water infiltration than in an already wet snowpack. In a fully *moist* or *wet* snowpack, on the other hand, drainage channels may be well established and water may be routed to the bottom of the snowpack rather efficiently (Kattelmann, 1985). Such snowpacks are often associated with relatively stable conditions (Carran et al., 2002). While such a wetness classification may be a valuable tool to communicate snowpack wetness between forecasters, it certainly has many short-comings and must be tested in the field. A first application to wet snow stability will be attempted in Chapter 8. Short-comings include, most of all, the spatial component of water distribution. Like many other snow pack observations, such wetness profiles only represent a point observation. To include spatial information in a future wetness description, several observations must be carried out. The proposed classification also does not account for a variety of snow wetness situations such as dry above wet (new snow above wet snow layers) or if the upper layers are wet and the bottom layers are dry.

4.5 Conclusion and further research

In this chapter, observations and measurements on liquid water content and liquid water distribution in snow were presented.
The Snow Fork proved to be a very suitable tool to measure the water content in the field. Care is needed when inserting the pronged fork into very dense or hard snow (melt-freeze-crust), as this might damage the fork leading to false measurements. The Denoth wetness meter and the Snow Fork are suitable, comparable tools for the measurement of liquid water content in snow (hypothesis 1, p. 29). The following results must be remembered, in particular in regard to the interpretation of the results in the following chapters:

- The mean recorded liquid water content in dry snow using the Snow Fork was 0.8 vol.%. For the purpose of this study, all liquid water content values presented in the subsequent chapters are corrected by this value.
- The variability of the measured liquid water content increases with increasing water content. In general, recorded values vary by less than ± 0.4 vol.% in dry snow and approximately 1.1 vol.% in wet snow. In part, the variability in dry snow can be explained by differences in snow density, which influences the recorded wetness value.
- The liquid water content measured with the Snow Fork (LWC_{SnF}) is generally higher than the water content recorded with the Denoth (LWC_{Dn}) tool: $LWC_{SnF} \approx 1.4 * LWC_{Dn} + 0.6$

Experienced observers can reasonably well estimate liquid water content in the field (hypothesis 2). However, estimated snow wetness must not be interpreted strictly according to the international guidelines but should be understood as an indication only. Wetness estimations by less experienced observers should be interpreted with considerable caution.
It does indeed matter, how water content is measured (hypothesis 3). Higher water content values were recorded, when the measurements were carried out before a snow-pit was excavated than on the side-wall of a snow-profile. For practical purposes, I recommend to always observe wet snow profiles on a side-wall rather than a front wall. This may reduce the amount of water flowing into the pit-wall giving a false impression of snow wetness.
The spatial variability must be considered when interpreting point observations (hypothesis 4). This may be particularly valid in the case of a partially wet snowpack (as shown in Fig. 4.7). Due to the spatially and temporally variable nature of liquid water in snow, a tool like the Snow Fork could be extremely helpful in the field. One of the biggest advantage using the Snow Fork might be its capability to quickly measure the water content at depth without the need to dig holes. Unfortunately, this type of measurement was rarely carried out. However, this method seems very promising when spatial distribution of liquid water in the snowpack is of interest.
Different flow patterns have been noted during the artificial wetting experiments (hypothesis 5) with matrix-like flow patterns dominant in coarse-grained persistent layers and preferential flow frequently observed in layers consisting of non-persistent, fine-grained layers.

Future research should focus on

- developing a quick and reliable method to measure liquid water in the field:
  - for the snowpack: a tool similar to the Snow Fork, but of smaller size and weight
  - for the snow surface wetness: remote sensing technologies should be explored
- methods to train less-experienced observers how to estimate the liquid water content and possibly re-evaluating the German wetness classification (which, if translated, means: dry, *barely moist*, moist, . . . instead of dry, moist, wet, . . . as in (Colbeck et al., 1990))
- evaluating and further developing the proposed wetness classification for manual snow profiles
- spatial arrays of liquid water content, maybe in combination with micro-structural penetration resistance measurements using the Snow Micro Penetrometer (see Chapter 5).

Chapter 5

Micro-structural measurements in wet snow - field experiments using the Snow Micro Pen

Digital, high-resolution penetrometers, like the Snow Micro Pen (SMP, Schneebeli and Johnson, 1998), have been developed and been used over the last decade to measure the penetration resistance and structure of snow at the micro-scale.
In this chapter, experiments using the SMP in artificially wetted snow will be presented and discussed. This part of the project is the continuation of the measurements conducted during my BSc thesis (Techel, 2007; Techel et al., 2008b). However, SMP measurements have been expanded to naturally wet snow-packs.

Research hypothesis:

1. The rapid decrease of micro-structural penetration resistance at low liquid water content in layers consisting of persistent grains, as presented by Techel et al. (2008a), can be confirmed.
2. The influence of liquid water on micro-structural penetration resistance depends also on grain shape and size.
3. Changes in micro-structural snow texture following first wetting can be observed within the time-span of several hours.
4. The snow characterization, as introduced by Satyawali et al. (2009), can be applied to wet snow.

5.1 Introduction

Snow structure plays an important role in the formation of avalanches (Reardon, 2008; Schweizer et al., 2008). Traditionally, snow stratigraphy is observed and recorded by researchers and avalanche professionals in manual snow profiles. Profiles using the hand hardness index capture about 80% of the layers (Pielmeier and Schneebeli, 2003). Beside a certain subjectivity assessing the hardness, the hand test is also limited by the area of the measuring device (i.e. fist, pencil, knife)(Pielmeier and Schneebeli, 2003).

Snow Micro Penetrometer

A high-resolution snow micro penetrometer, the Snow Micro Pen (SMP), has been developed to investigate micro-structural properties of snow (Schneebeli and Johnson, 1998). It records penetration force with very high resolution (4μm) at a constant speed of 20 mm s^{-1}.
The sensor tip is cone-shaped, has a diameter of 5 mm and is highly force sensitive (resolution 0.005 N, Schneebeli et al. (1999)). Most of the penetration resistance acts on the uppermost millimeter of the tip. This allows a vertical resolution of 1 mm (Pielmeier and Schneebeli, 2003).
The Snow Micro Pen detects even very thin stratigraphic features, which are often missed in hand-hardness profiles (Pielmeier and Schneebeli, 2003). Hand-hardness and penetration force are correlated (Pielmeier and Schneebeli, 2003). Beside the mean penetration resistance, micro-textural and micro-mechanical information may be derived from the SMP force signal.
A micro-mechanical model was first developed by Johnson and Schneebeli (1999) and has been expanded since (i.e. Marshall and Johnson (2009)). Micro-structural observations using the SMP have been used to investigate snow structure, weak layers and weak layer interfaces, but also spatial and temporal aspects.
Snow texture and density are key elements defining mechanical properties of snow (Schneebeli et al., 1999). Based on the penetration-force signal, a texture index (TI) has been derived (Schneebeli et al., 1999). Pielmeier and Schneebeli (2000) define the TI as the fraction of the mean grain size [mm] to the snow density [kg m^{-3}]. The TI is correlated to the coefficient of variation (CV[1]) and can be empirically expressed as $TI = 1.45 + 5.72CV$ (r=0.89, p<0.001) (Schneebeli et al., 1999). Based on just three SMP force signal properties (mean, standard deviation and coefficient of variation), Satyawali et al. (2009) could characterize different grain shapes. They developed a rule-based algorithm to extract grain type information from SMP penetration force signals. While there is considerable overlap between grain forms, the algorithm correctly detects more than 70% of grain shapes (Fig. 5.1a). Satyawali et al. (2009) did not present any results on wet grain forms.
Stability information has been derived by many researchers and focused on the description and detection of failure layers (as observed in Rutschblock or Compression tests (for instance van Herwijnen et al., 2009; Pielmeier and Marshall, 2009). One of the most important criteria

[1] ratio of standard deviation to mean

differentiating between stable and unstable failure planes is the weak layer strength (Pielmeier and Schweizer, 2007; Pielmeier and Marshall, 2009). More recently, a semi-automatic failure layer detection in SMP profiles has been introduced (Bellaire et al., 2009).
Spatial variability is a prominent feature of mountain snow-packs. Variability exists at all scales: from a grain bond (10^{-4}m) to entire mountain-ranges (10^5m) (Schweizer and Kronholm, 2004). Micro-structural penetration resistance can be highly variable (Schweizer and Kronholm, 2004). Thus, weak layer properties can be classified with greater accuracy if several, adjacent SMP profiles are analyzed (Pielmeier and Marshall, 2009).
In laboratory experiments, Schneebeli et al. (1999) monitored the **temporal evolution** of the penetration resistance of snow undergoing temperature-gradient metamorphism (Fig. 5.1b). With grain shape changing from precipitation particles to facets and depth hoar, there was also a change in CV and penetration resistance.
In **wet snow**, two studies have used the SMP. Trautmann et al. (2006) measured the changes in shear strength and penetration resistance of the snow surface during spring day-time warming. They observed a significant decrease in shear strength of melt-freeze snow and correlated the SMP force signal to measured shear strength. In my BSc thesis (Techel, 2007), I investigated the effect of first wetting on dry snow. Already at low water content (less than 3 vol.%), penetration resistance decreased significantly. The decrease was most pronounced in layers containing persistent grain forms (Fig. 5.1c). Previously, Izumi and Akitaya (1985) noted the exponential decrease of snow hardness with increasing water content.

5.2 Methods

SMP measurements were conducted in the field during artificial wetting experiments of selected layers (data-set 1). On some days, they also accompanied the observations carried out during the wet snow stability campaign (data-set 2, stability observations are discussed in chapter 8). These data-sets will always be referred to as data-set 1 or data-set 2.
For both studies, the SMP was used to record micro-structural penetration resistance and the Snow Fork (see Chapter 4 for details) to measure the liquid water content of snow.

5.2.1 Field methods

For all wet snow experiments and observations, sunny and relatively warm days (air temperature above 0°C) were necessary.

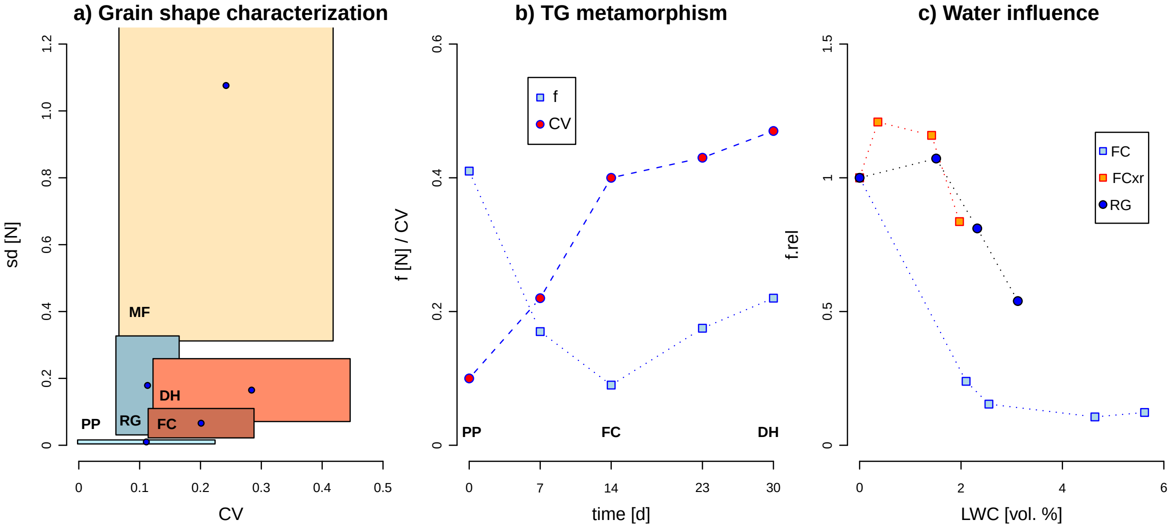

Figure 5.1: Examples for the application of SMP measurements: a) Grain form characterization based on standard deviation (sd) and coefficient of variation (CV) for different grain shapes (Satyawali et al., 2009, PP - precipitation particles, RG - round grains, FC - facets, DH - depth hoar, MF - melt-freeze crusts). The dot indicates the mean for each group, the surrounding squares give the ranges of ± one standard deviation. b) Evolution of penetration resistance (f, blue squares) and CV (red circles) of new snow (PP) under temperature gradient (TG) metamorphism. Grain form changed to FC (after 14 days) and large DH (30 days, Schneebeli et al., 1999). c) Evolution of relative penetration resistance (f.rel, relative to initial dry snow resistance) during artificial wetting for three layers (Techel, 2007), where facets undergoing rounding is FCxr.

Data-set 1: Artificial wetting experiments

During my BSc thesis (Techel, 2007; Techel et al., 2008b), we conducted first experiments investigating the changes in penetration resistance during first wetting. Experiences gained during these measurements in March 2007 provided the basis for the subsequent measurements carried out in the spring of 2008 and 2009. The procedure followed the experimental design as shown in Techel (2007):

1. slope selection, snow profile, layer selection
2. exposure of selected layers, ~1 m wide, 3 m up-slope
3. first set of measurements (Fig. 5.2)
    (a) five SMP measurements (distance d=10cm), slope-vertical
    (b) Snow Fork (SnF) measurements (liquid water content), four beside each other (d=10 cm), three or four below each other (d=5cm), slope-parallel
    (c) snow density sampling, four beside each other (d=10 cm), three or four below each other (d=5cm), beside Snow Fork measurements, slope-parallel

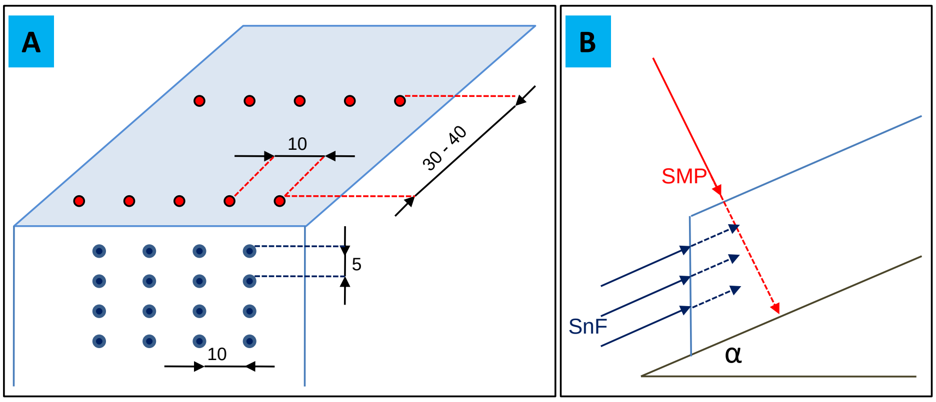

Figure 5.2: Layout of field experiments. A) shows frontal overview with SMP measurements (red circles) and Snow Fork (blue circles). Densities were sampled between Snow Fork measurements. B) side-ways view showing slope-vertical SMP and slope-parallel Snow Fork measurements. Distances are given in cm.

4. leaving layers exposed to the sun to warm (until approximately isothermal)
5. artificial wetting cycles (Fig. 5.3, left)
6. repetition of measurements (a, b, c) approximately 30…40 cm up-slope from last measurements, followed by next wetting cycle

Primary criteria for selecting suitable slopes were an undisturbed snowpack, relatively homogenous snow layering and a short and safe access. The short access was necessary as equipment was relatively large and heavy. Additionally, at least 10 l water were necessary to wet two layers.
Necessary equipment included:

- standard field equipment (section 3.1)
- SMP, frame for the SMP (Fig. 5.3, right), Snow Fork, 100 cm^3 density cutter, scale
- manual spray bottle (5 l), large bucket to mix snow, water and tracer
- Brilliant Blue tracer

Once a manual snow-profile was recorded, suitable layers were selected. These layers had to be relatively homogenous and sufficiently thick (>15 cm). All snow above these layers was carefully removed and the surface cut smoothly (using a cord or a snow saw). This was followed by the first set of measurements. Before water was sprayed onto the snow surface, exposed layers were left to warm until approximately isothermal (snow temperature close to 0°C). This was considered necessary as experiments in 2007 showed that spraying water on a sub-zero snow-pack prohibits infiltration (re-freeezing occurs). While layers warmed, 10 l ice-water (temperature 0°C) was mixed with 2.5 g tracer (Brilliant Blue). The snow

Figure 5.3: Left) artificial wetting of exposed layers using an ice-water-tracer mixture (Brilliant Blue food coloring). Right) SMP measurements. The SMP was mounted to a frame allowing easy positioning for measurements. Photos: Pielmeier, 2009, 2007

surface was sprayed with approximately 1 l water, followed by SMP measurements (a). The down-slope side of the layer was cut back to about 10 cm below the SMP penetration holes, before Snow Fork measurements were taken and densities sampled . In general, two different layers were prepared side-by-side.
A detailed overview on infiltration rates and duration of experiments is given in App.B, Tab. B.1

Data-set 2: Naturally wet snow

These observations complemented some of the wet snow stability field days (Chapter 8).
At first, liquid water content (LWC) was measured in 5 cm steps. LWC measurements were repeated three times (distance d=20 cm) on either side of the snow-pit (d=4 m across slope, Fig. 5.4). Beside each LWC measurement (d=10 cm), a slope-vertical SMP profile was recorded. Afterwards, a snow-pit was dug, snow layer stratigraphy recorded (chapter 3.1) and shear and stability tests carried out (Chapter 8).

5.2.2 Data

Micro-structural measurements were undertaken in artificial wetting experiments (data-set 1) and in naturally wet snow-packs (data-set 2). Detailed overviews of both data-sets are given in App. B, Tab. B.1 and Tab. B.2.

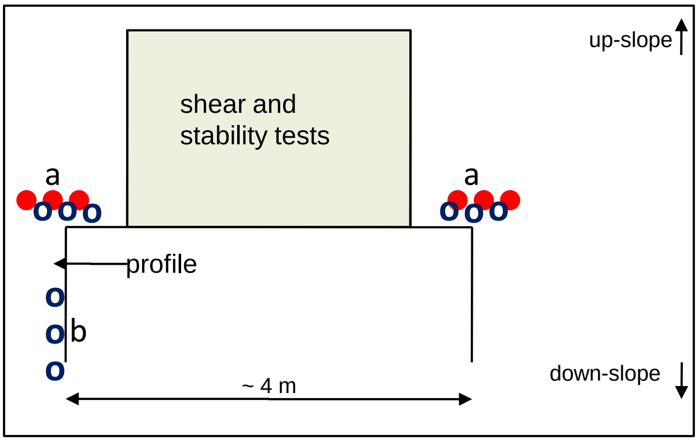

Figure 5.4: Layout of field measurements to measure micro-structural penetration resistance accompanying snow stability assessment. SMP measurements (red circles) were conducted beside liquid water content measurements (empty circles) and stability tests. First SMP and water content measurements were carried out (a), followed by opening the snow-pit, recordings a manual snow-profile and measuring liquid water content (b). Shear and stability tests were conducted last.

Data-set 1: Artificial wetting experiments

Field experiments were carried out on five days in spring 2008 and 2009.
In total, nine layers were artificially wetted and micro-structural penetration resistance, density and liquid water content measured. Different layers were selected to sample a range of different snow types. Eight of the nine layers were initially dry. One layer (layer H) consisted of small round grains, but was already slightly moist (liquid water content LWC<0.5 vol.%). It was the aim to select relatively homogeneous layers. However, as can be seen in Fig. 5.5, considerable variability can be observed within a given layer, both layer-vertical (same SMP profile) as well as between neighboring SMP-profiles. Artificial wetting was repeated three to eight times, depending on available time and weather.
In total 1051 single LWC-measurements, 261 SMP-profiles and 630 snow densities were sampled. SMP data quality was considered and will be discussed separately in the following section.

Data-set 2: naturally wet snow-pack

Micro-structural hardness measurements in naturally wet snow-packs were planned for five days in the canton Grison. However, on one day the SMP malfunctioned and no observations could be carried out (1 April). On 18 March, it remained too cold; no afternoon measurements were undertaken. Finally, on 11 April major SMP data quality problems were noted in the field and SMP measurements abandoned, while data-quality of measurements on 17 March was poor and had to be excluded from analysis. Thus, the data-set was greatly reduced with just two locations comprising 26 SMP-profiles being available for comparison of morning and afternoon penetration resistance in regard to LWC.

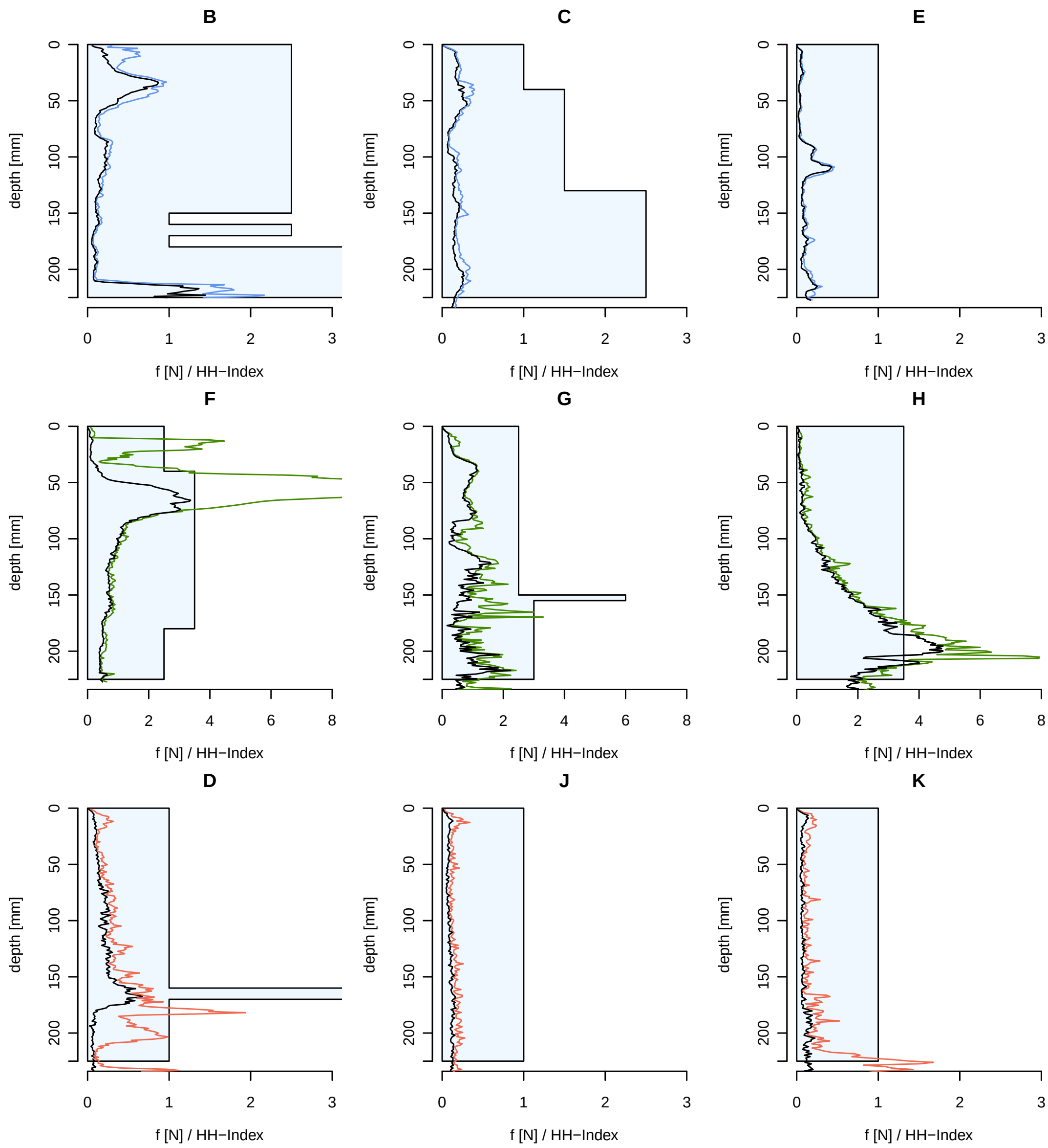

Figure 5.5: Overview of hand hardness [HH] and penetration resistance [f] over all artificially wetted layers. Upper row-layers B, C, E are non-persistent grains consisting of small round grains, precipitation particles and decomposing precipitation particles; F, G, H are non-persistent grains (small round grains) and bottom row layers D, J, K are persistent grain forms (facets, facets undergoing rounding, depth hoar). For details on layers refer to Tab. B.1. Depth is given as mm below surface of exposed layer. Shown is hand hardness profile (light blue shaded background), overlain by the median (black line) and maximum (different colors) of initial dry micro-structural resistance f (median / max of 3…5 SMP measurements, averaged over 1 mm windows).

All SMP profiles observed in the vicinity of the manual snow profile were used to compare snow layer grain type with the penetration force signal. In total, 20 SMP profiles beside manual profiles in seven locations were investigated. Data quality was often poor, as discussed in the following section.

5.2.3 Data quality

Variable SMP data quality was observed. Thus it was necessary to visually inspect all SMP files. Data quality was then assessed following the recommendations of Lutz et al. (2009) and Pielmeier and Marshall (2009), who quality-rate all SMP signals as either having

- no signal error
- artificial trend or offset (Fig. 5.6a)
- dampened or disturbed SMP force micro-variance (Fig. 5.6b)
- both, artificial trend or offset and dampened or disturbed SMP force micro-variance (Fig. 5.6b, c) .

Despite cooling the SMP prior to measurements, the most frequent error was artificial trend (observed in about 90% of signals). This might be typical for operating the SMP in relatively warm conditions (Pielmeier, 2009). The remaining force signals in data-set 1 showed either disturbed or dampened signals. Pielmeier and Marshall (2009) suggest that despite these signal errors, the mean penetration force signal may still be used for analysis if trend or offset is correctable. However, they recommend refraining from using dampened or disturbed signals for calculation of micro-structural estimates. In our case, the artificial trend (drift) was generally observed to be approximately linear. An example of non-linear drift is shown in Fig. 5.6a. Artificial trends were almost always negative and ranged generally between -10^{-5} and -10^{-6} N mm^{-1}. However, in some cases, signals had negative trends larger than 10^{-4} N mm^{-1}.
In data-set 2, of 79 SMP profiles the majority showed drift, anomalous signal peaks or negative force values in snow (71%). Only 23 did not show significant signal errors (29%). Seven SMP profiles were excluded from analysis (17 March 2009).

5.2.4 Data analysis and statistical methods

The following **data preparation procedure** was maintained for both data-sets. Utilized software included PeneWin (SLF, 1999 - 2002), IDL[2] and the statistical software R (R Development Core Team, 2008).

[2]utilized routines were written by K. Kronholm, C. Pielmeier, M. Schneebeli

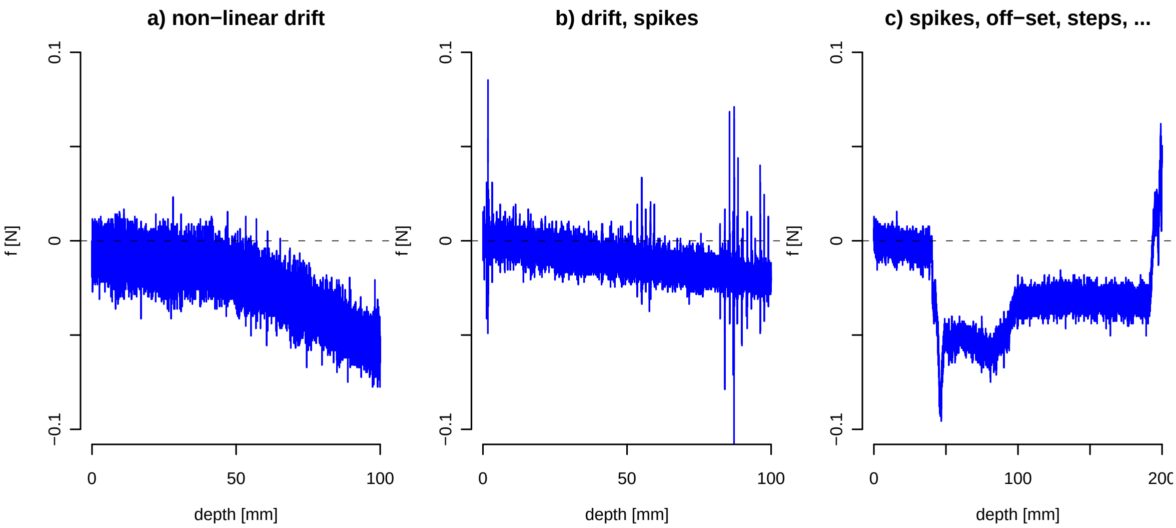

Figure 5.6: Examples of typical signal errors as observed in SMP data. Data quality is best assessed checking the signal in air, when penetration force f should fluctuate around zero. a) shows non-linear drift, b) shows linear drift and anomalous spikes in data (linear drift was the most frequent measurement error observed in almost all SMP profiles) and c) shows signal with many signal errors.

1. graphical quality check of SMP signal (PeneWin)
2. export of penetration resistance as .tab-files (PeneWin)
3. manual definition of snow surface using IDL-routines
   - pnt2var.pro,
   - lay2var.pro,
   - fsc_color.pro,
   - define_layer.pro
4. removal of linear trend in penetration resistance data (R),

   $$y_c = y - \Delta y = y - (az + b), \tag{5.1}$$

   where y_c is the corrected penetration resistance, y the original signal, Δy the linear trend and z the measurement depth. a and b are constants derived based on the drift in air (Fig. 5.7)
5. export of corrected penetration resistance and depth to .txt-file
6. graphical inspection of corrected data
7. mean f, standard deviation sd and the coefficient of variation CV are calculated for 1 mm non-overlapping windows of the SMP signal, where the CV is defined as

   $$CV = \frac{sd}{f}. \tag{5.2}$$

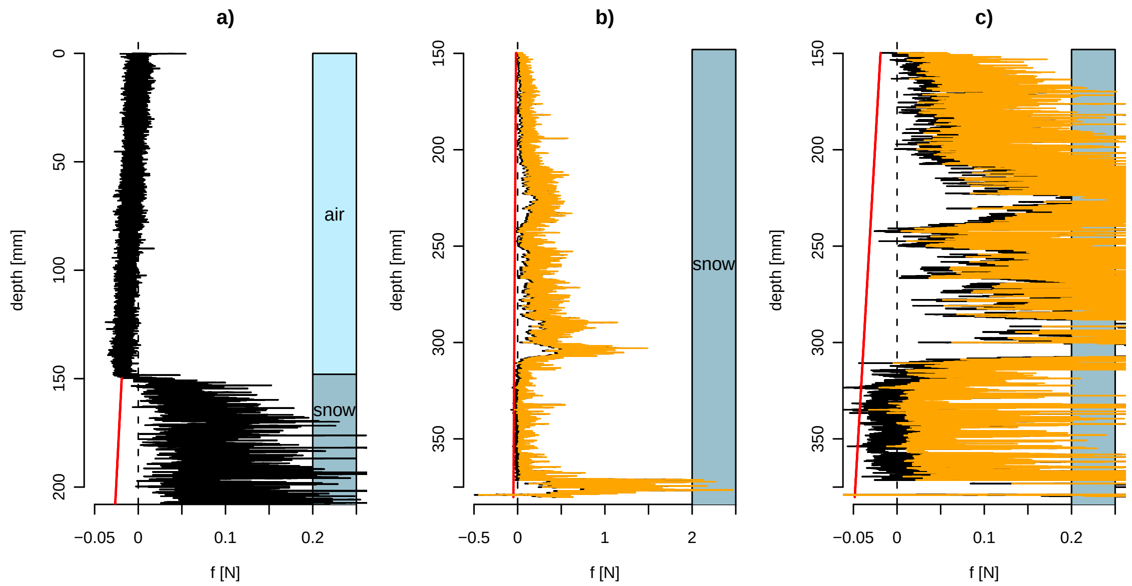

Figure 5.7: De-trending of SMP micro-structural hardness measurements. a) shows initial data (black curve) for measurements in air and in snow for the upper 220 mm. The red line indicates the linear fit to the drift in air. b) Original data shown for measurements within the snow, including the fitted line from the drift in air (red line). The corrected SMP signal (orange line) overlying the original data is the original value plus the difference between linear drift and zero-line. c) Zoomed into plot b). It can be seen that after data correction most of the values are above zero, while original data was negative. The slope of the trend line (red) in this extreme example is -1.3*10^{-4}N/mm (13 Apr 2008, Julierpass, SMP-file 13).

8. adjustment of SMP profile to layer stratigraphy based on slope angle

Qualitative inspection of the de-trended data showed that removing the linear trend was appropriate and sufficient to eliminate most of the negative force measurements. Only these corrected penetration force signals were used for further analysis.
The derivation of the three parameters f, sd and CV follows the statistical approach as introduced by Satyawali et al. (2009). Satyawali et al. (2009) used these three measures to characterize snow texture in an Alpine snowpack based on the SMP signal. This relatively simple approach was chosen over a more complex micro-mechanical model(Johnson and Schneebeli, 1999). Applying the micro-mechanical model would have been beyond the scope of this Master thesis. However, it is planned for a future analysis. A list of investigated variables is shown in Tab. 5.1.

In **data-set 1**, the artificial wetting data, the selected layers were split into four sub-layers of equal thickness (50 mm) and one layer comprising the full 150 or 200 mm. These sub-layers were centered so that the liquid water content measurement was in the middle of the layer. Depending on initial layer thickness, three or four sub-layers were analyzed. The upper-most 25 mm were excluded from analysis, as it is believed that these were most disturbed by

Table 5.1: Investigated variables for data-set 1 and data-set 2. Sub-layers are defined in Tab. 5.2 for data-set 1. Sub-layers for data-set 2 were split according to the snow-profile stratigraphy.

Variable			**1 mm sections**	**Sub-layers**
Penetration	mean	f	x	
resistance [N]	std. deviation	sd	x	
	coeff. of variation	CV	x	
	median	f	x	x
	relative f	$f.rel$		x
LWC [vol. %]	median	LWC		x
Density [kg m^{-3}]	median	ρ		x
Time [h]				x

Table 5.2: Sub-layer definition for data-set 1.

Layer ID	**Layer Depth [mm]**	**SnF Depth [mm]**
W	25. . . 75	50
X	75. . . 125	100
Y	125. . . 175	150
Z	175. . . 225	200
V	25. . . 175	
	25. . . 225	

water-spraying. Also, in several experiments the surface started to refreeze. Sub-layers are defined in Tab. 5.2.
The relative penetration resistance (f.rel) was calculated to compare changes in penetration resistance between layers.

$$f.rel = \frac{f_0}{f_x}, \tag{5.3}$$

where initial penetration resistance in dry snow conditions is f_0 and penetration resistance at time x is f_x.

In **data-set 2**, the measurements in naturally wet snow-packs, corrected SMP profiles were graphically aligned with the layer stratigraphy as observed in the hand hardness profile (software: SPPpen, R). Despite SMP profiles being recorded in close proximity (at a distance of 10. . .40 cm) from the manual snow profile, considerable differences between them existed. Some layers were missed in the hand hardness profiles, which were recorded in the high-resolution SMP profile. Ice-bodies, which are frequently observed in wet snow, would hardly be noticed or not recorded in manual snow profiles, but may show as very hard layers in the SMP signal. Additional complications arise due to small-scale spatial variability or due to the SMP not being perfectly perpendicular to the slope when measuring. The latter requires additional corrections beside taking into account the slope angle. This problems made layer alignment difficult and a somewhat subjective process.
Profiles and layers which could be aligned reasonably well were kept for further analysis. These profiles, all observed on 7 and 11 April, are dominated by either wet grains or persistent

grain forms. Thus, only layers consisting of wet grains or persistent grains, or transitions between those, were analyzed. I consider this a useful approach as the introduction of liquid water into weak, persistent layers is expected to play a role in the release of wet slab avalanches (Reardon, 2008). Therefore, it would be of interest to know if the SMP signal allows to differentiate between these grain types. Layer boundaries were defined by the manual snow profile. The upper and lower 10 mm of each layer were excluded from analysis to eliminate errors due to poor alignment with the manual snow stratigraphy. Layer statistics were then extracted using semi-automatic routines (software R) averaging the the mean penetration resistance f, the standard deviation sd and the coefficient of variation CV for each layer (Tab. 5.1). To expand the variety of grain shapes, the initial and final SMP profiles of data-set 1 (artificial wetting experiments) were added for analysis. For this, averaged values of f, sd and CV for individual 50 mm sub-sections of the SMP-profile were calculated. This data-set provided the basis for the grain shape characterization discussed in section 5.3.2.
The number of locations where morning and afternoon SMP profiles were available was very limited (two locations) and aligning stratigraphic layers with the SMP signal difficult. Thus, the influence of changing LWC and penetration resistance was restricted to surface layers. For this, the SMP signal was split into equal windows of 40 mm (which is equivalent to measurement intervals using the Snow Fork). Again, mean f, sd and CV were calculated for each sub-layer.

Liquid water content measurements measured with the Snow Fork seemed appropriate to circumstances. Values larger than 10 vol.% were sometimes observed. This was mostly the case when strong preferential flow was noted, or close to the snow surface. Following recommendations of the Snow Fork's manual (Toikka, 2008), values larger 10 vol.% may be unreliable. However, these values were not included but taken as 10 vol.%. To further decrease the influence of extreme measurements, the median of several (normally more than 3) measurements was taken. Presented liquid water content values are referred to as LWC. These are always measured with the Snow Fork and measurement values have been corrected (for details please refer to Chapter 4, p. 47).
Layers were analyzed individually. The grouping of the data into fewer grain-from specific sub-groups facilitated the analysis for layers with similar properties (Tab. 5.3). As the results show, it often suffices when **grain form** is grouped into persistent (PG), non-persistent grains (NP) and melt-freeze - wet grains (MF/WG) according to the simplified grain shape classification introduced in Chapter 3. (Jamieson and Johnston, 1995a, Tab. 3.3).

Statistical methods included linear regression models for the relationship between f and density. Both, linear models of the form $y = ax + b$ and exponential models $y = a * e^{bx}$ were derived. These models were compared based on the resulting coefficient of determination r^2 and the significance level p. Non-parametric LOWESS-filters were used to high-light changes in f with water content. Correlation between variables was investigated using the Pearson product momentum correlation coefficient r and the Spearman rank-sum correlation coefficient r_s. The latter was given preference if data was non-normally distributed or if variables were of non-continuous nature. Sample populations were compared using Wilcoxon rank-sum tests, like the Mann-Whitney U test. The Kruskal-Wallis H test was applied when more than

Table 5.3: Simplified grain form classification applied to nine artificially wetted layers (Jamieson and Johnston, 1995a, see also Tab. 3.3, Chapter 3). The two main groups are persistent grains (PG, n=3) and non-persistent grains (NP, n=6). As considerable differences were noted, particular in initial snow density, the non-persistent grain forms were further separated into those consisting of round grains only (RG, n=3) and those containing also decomposing precipitation particles (DF/RG, n=3). Shown are the observed grain shapes and the ranges for grain size, the initial snow density ρ_{init} and the initial penetration resistance f_{init}

Grain form group	**Observed grain forms**	**Grain size** [mm]	ρ_{init} [kg m^{-3}]	$\mathbf{f}_{init}$ [N]
PG	DH, FC, FCxr	1...6	244...278	0.10...0.21
NP	PP, DF, RG	0.25...1	113...340	0.10...1.53
DF/RG	PP, DF, RG	0.25...1	113...191	0.10...0.25
RG	RG	0.25	289...340	0.81...1.53

Table 5.4: Changes in liquid water content LWC, snow density ρ, mean penetration force f, standard deviation sd and the coefficient of variation CV, calculated for 1 mm windows and averaged over the full layer. Significant changes between initial conditions and after the final wetting cycle are indicated by arrows: $\nearrow$ indicates significant increase, $\searrow$ significantly decreasing values. The small number represents the number of times this was observed in each grain form group. Detailed results are shown in Tab. B.3, App.B

Grain shape	ΔLWC	$\Delta\rho$	Δf	Δsd	ΔCV
DF/RG	$\nearrow^1$	$\nearrow^1$	$\nearrow^1$	$\nearrow^1$	$\searrow^1$
RG	$\nearrow^2$	$\nearrow^1$	$\nearrow^1$		$\searrow^2$
PG	$\nearrow^3$	$\nearrow^1$	$\searrow^3$	$\searrow^3$	$\searrow^2$

two populations needed to be compared. The selected level of significance is $\alpha \leq 0.05$.
Principal component analysis and linear discriminant analysis (Crawley, 2007) were applied for testing the grain shape characterization scheme.
Data was graphically inspected using box-plots, histograms, scatter-plots and three-dimensional cloud plots. However, only box-plots and scatter-plots are shown. Additional details on statistical procedures can be found in chapter 3.2.2.

5.3 Results

In this section, the focus lies on the evolution of micro-structural penetration resistance in association with liquid water content and snow densities for the artificial wetting data as well as changes in surficial penetration strength of natural snow-packs (Section 5.3.1). The following section 5.3.2 investigates the statistical grain shape characterization by Satyawali et al. (2009) for a data-set combining dry and wet snow conditions.
Large tables and additional plots are appended in App. B.

5.3.1 Changes in penetration resistance, density and liquid water content

Nine different layers were artificially wetted. Infiltration rates were in the range between 2 and 6 l m^{-2} (Tab. B.1, Appendix B).
Following wetting, six of the nine layers were significantly wetter than in the beginning. The final **liquid water content** (LWC) in layers consisting of persistent grains (PG, LWC 3.1. . .3.3 vol.%) was higher than in rounded grains (RG, LWC 0. . .2.9 vol.%) or those consisting initially of both decomposing precipitation particles (DF) and RG (LWC 0. . .0.6 vol.%). Qualitative observations confirmed this. Matrix flow was dominant in PG layers, while water flow patterns in DF/RG layers were often of preferential and layer-parallel type.
Changes in snow **densities** (ρ) were variable. ρ increased significantly in three experiments (by 10. . .30%). A schematic overview of significant changes in LWC and ρ is given in Tab. 5.4). A full table has been appended (App. B, Tab. B.3). The measurement uncertainty for the snow density is approximately ±6% (based on approximately 1700 density samples).
The correlation between snow **densitiy** ρ and **median penetration resistance** f for 50 mm thick sub-layers is moderate to poor for the full data-set (r^2=0.27, linear regression function (^{L}), Tab. 5.5). If only wet snow data is included (LWC>0.5 vol.%), the correlation increases marginally (r^2=0.34, ^{L}), while for dry data it decreases. Significant improvements can be achieved by splitting the data-set according to the simplified grain shape groups into the groups persistent grains (PG, n=100) and non-persistent grains (NP, n=149). For NP there is a strong association between ρ and f, which is best, if both dry and wet data are included in the same regression curve (r^2=0.71, Fig. 5.8a):

$$f = 0.0364e^{0.0111\rho} \tag{5.4}$$

Regression coefficients for persistent grain data are poor, with best fits achieved if different exponential curves are fit for dry and wet data.
Penetration resistance is affected differently by the amount of **liquid water** in snow layers consisting of different grain shapes. Both PG and WG layers show a moderate to strong negative trend (Fig. 5.8b, c; Tab. 5.6). Graphically, no clear trend can be noted for the DF/RG or RG grain shapes (Fig. 5.8b, c). However, the Spearman rank order coefficient indicates a significant positive association (Tab. 5.6).
Considering **relative penetration resistance** (f.rel, relative to initial dry snow penetration resistance f), shows that f.rel decreases already at low **water content** (LWC<3 vol.%) in PG layers (Fig. 5.9a), while no clear, or an increasing trend can be observed for either the DF/RG or RG groups (Fig. 5.9b, c). For these two groups it should be noted that very few measurements with LWC>3 vol.% were recorded. If melting of frozen wet grains (MF) occurs during day-time warming, than penetration resistance decreases by about one magnitude (Fig. 5.9d, blue diamonds). Changes in already wet WG show variable results (Fig. 5.9d, green triangles). Again, larger increases in water content generally reduces penetration resistance.
The positive correlation between **water content** and **density** can only be observed for non-persistent grains, but not for persistent grains (Tab. 5.6).

Table 5.5: Regression coefficients r^2 for relationship density ρ - penetration force f (Fig. 5.8a), ^{L} indicates linear function provided best fits, otherwise exponential function. The respective correlation coefficients are shown in bold.

Grain shape	all	dry	wet	best fit function
all	0.27^L	0.24	0.34^L	
NP	**0.71**	0.61	0.67	$f = 0.0364e^{0.0111\rho}$
PG	0.14^L	**0.29**	0.14	$f = 0.00415e^{0.0131\rho}$

Table 5.6: Spearman correlation coefficient r_s between variables (var1,var2) LWC, f and density for persistent grains (PG) and non-persistent grains (NP) and melt-freeze-wet grains (WG).

Var1	Var2	all	PG	NP	WG
LWC	f	-	-0.39	0.40	-0.64
LWC	density	0.37	-	0.46	NA
f	density	0.50	0.38	0.83	NA

5.3.2 Grain shape characterization

The three parameters, mean (f), standard deviation (sd) and coefficient of variation (CV), calculated for non-overlapping 1 mm windows of the SMP profile, are investigated for the artificial wetted layers, and for layers observed in natural snow profiles.
Following artificial wetting (data-set 1), liquid water content increased substantially in persistent grain layers (PG) and in layers containing small round grains (RG), while low-density layers (decomposing precipitation particles and small round grains, DF/RG) showed only surface wetting and isolated preferential flow channels with the majority of the layer remaining dry. The introduction of water, brought no clear trend in measured snow densities. In three layers, significant changes occurred (densities increased by 10…30%). The remaining layers showed increasing trends (RG) within the range of density measurement uncertainty ($\pm$6%).
Over the course of the artificial wetting experiments, f, sd and CV decreased significantly in the investigated 50 mm sub-layers consisting of persistent grains (Wilcoxon rank-sum test, $p \leq 0.001$, Tab. 5.4, see also Tab. B.3, Appendix B). In non-persistent layers, changes were variable. Low-density layers consisting of decomposing precipitation particles and small round grains (DF/RG) showed significant changes in penetration resistance and standard deviation, while sub-layers containing small round grains (RG) showed mostly changes in CV.
Particularly interesting are the opposing trends in f and sd in persistent grains and non-persistent grains (NP, containing groups RG and DF/RG), while CV decreases in eight of nine layers. The final value of CV is similar for the non-persistent layers.
Following the grain characterization scheme based on f, sd and CV, introduced by Satyawali et al. (2009) and applying principal component analysis (PCA) to the recorded SMP measurements in data-set 1 (initial, dry and final measurements) shows that grain shape classes can be well distinguished if separate principal component analysis is calculated for dry or non-dry data (final measurements, Fig. 5.10a, b). Using two factors, approximately 97% of the variance can be explained. For all calculated two-factor PCA, factor 1 contains almost exclusively strong loading of mean penetration strength, while factor 2 contains information

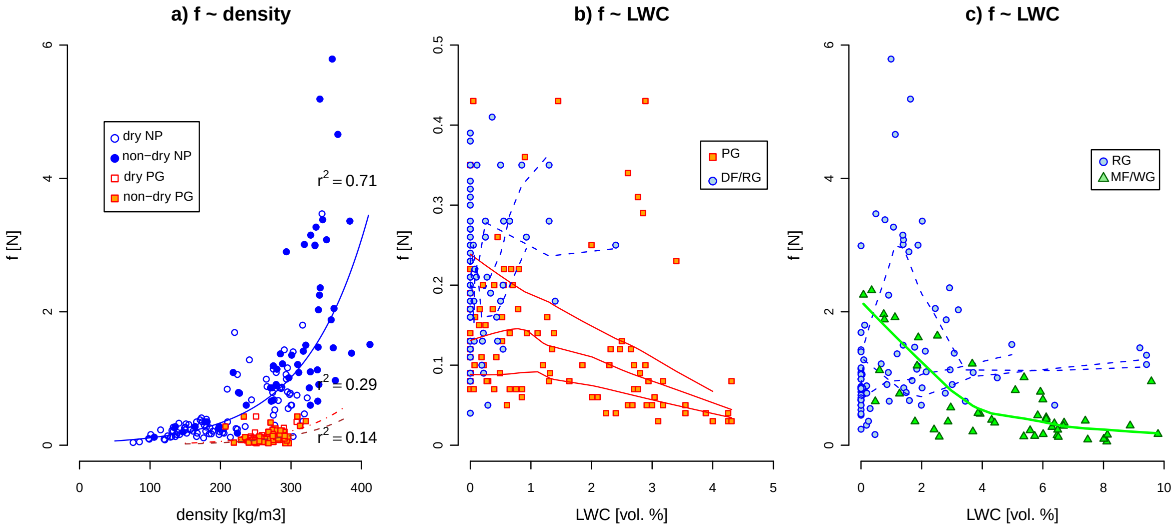

Figure 5.8: Relationship between micro-structural penetration resistance, snow density and liquid water content for different grain shapes. a) Micro-structural penetration resistance f [in N] and snow densities [kg/m^3] for non-persistent grains (RG, DF/RG, blue circles) and persistent grains (PG, orange squares). Filled symbols indicate wet data (LWC<0.5 vol.%). Best fitting regression curves are shown for NP (all data, blue curve) and for PG (wet and dry data separately, red and brown curve). b) and c) show scatter-plots for LWC - f relationship for NP-data (DF/RG, RG) and PG-data (all data-set 1). Additionally, wet grain forms (WG, green triangles) are shown (two locations, morning and afternoon observations, data-set 2). Non-parametric LOWESS-curves are shown for each of the nine artificial wetting experiments to high-light the trend LWC has on penetration resistance, indicating stronger negative correlations for PG and WG data.

on CV, and to a much lesser part, on sd. If all these dry and wet 50 mm sub-layers are included in the same PCA, considerable overlap can be noted (Fig. 5.10c). However, data is clearly clustered with three major clusters recognizable: one containing mostly PG data, while a cluster extends from the DF/RG group to the RG cluster.

From a snow stability perspective, it is of interest to be able to detect changes in snow structure, especially when the transition occurs from persistent grains to well-developed wet grains (wet slab avalanche activity has been linked to wet persistent weaknesses, Reardon and Lundy, 2004; Reardon, 2008). To investigate this, 25 suitable layers observed in naturally wet snow-packs were selected (data-set 2). The three PG layers (initial and final measurements) from data-set 1 were added to increase the number of observations to 31 layers with 88 SMP profiles. For the layers from data-set 1, final observations were assumed to represent transitional grain shapes with persistent grains as main form and wet grains as secondary form PG(WG). All seven PG layers were dry, all other layers wet.

Differences between grain shape groups are significant for all three parameters ($p \leq 0.01$, Kruskal-Wallis-test) with penetration resistance f and standard deviation sd being lowest in wet layers where persistent grains are dominant PG(WG) ($p \leq 0.01$, Mann-Whitney test, Fig. 5.11a, b). The coefficient of variation is significantly higher for PG than for the PG(WG) and WG groups ($p \leq 0.05$, Fig. 5.11c). However, there is considerable overlap between groups,

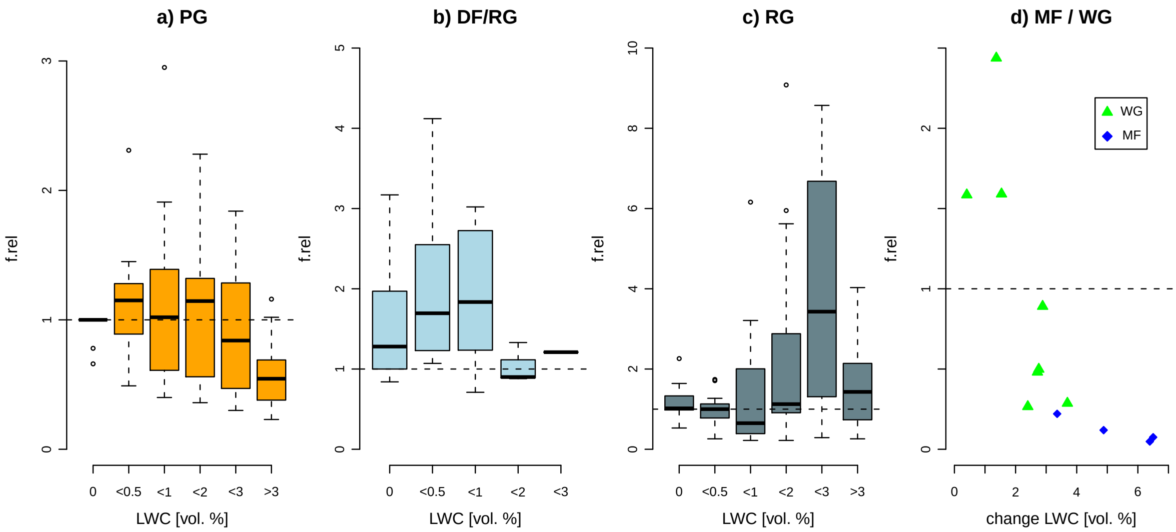

Figure 5.9: Relative micro-structural penetration resistance ($f.rel$, relative to initial values at beginning of measurement campaign) versus liquid water content LWC [vol. %] in a) for persistent grain forms (PG), b) non-persistent grain forms (DF/RG) and c) non-persistent grains (RG). d) $f.rel$ to diurnal changes of LWC for transition of frozen wet grains (MF) to wet grains (WG, blue diamonds) and WG which were wet in the morning. Initial values were dry only for the MF group (data-set 2).

but also scatter within groups. This is particularly evident in the WG group. All three variables are moderately correlated with each other.

For these dry and wet layers, a moderate positive correlation exists between hand hardness and penetration resistance f (r_s=0.43, p<0.001).

Combing both data-sets (artificial wetting experiments (50 mm sub-layers), naturally wet snow-packs, n=366) and calculating again a PCA (Fig. 5.12a) leads to similar results as could be noted in Fig. 5.10. Again, similar clusters for dry and wet persistent grains and for non-persistent grains (DF/RG, RG) can be noted. Wet grains, on the other hand, show no real cluster center. In fact, they are sometimes close to the non-persistent group, though more often in the PG cluster.

Calculating linear combinations including the variables f, sd, CV for the 366 layers and then using these combinations to predict the grain shape for the same data-set, shows that soft, low-density layers consisting of precipitation particles and small round grains and persistent grain layers are often correctly classified (Fig. 5.12b). For these grain shapes, the shape itself is often correctly predicted (about two third of cases), while the moisture content can not be detected (dry or not-dry). The group containing small round grains (RG), has a much higher error rate: only in 50% of the cases, the grain shape is correctly predicted. However, the falsely classified grains all belong to the DF/RG group (which also contains RG). The only grain shape classification yielding absolutely no useful results, was the wet grain group (WG). Only one case was correctly predicted. Most often WG were classified as PG or DF/RG.

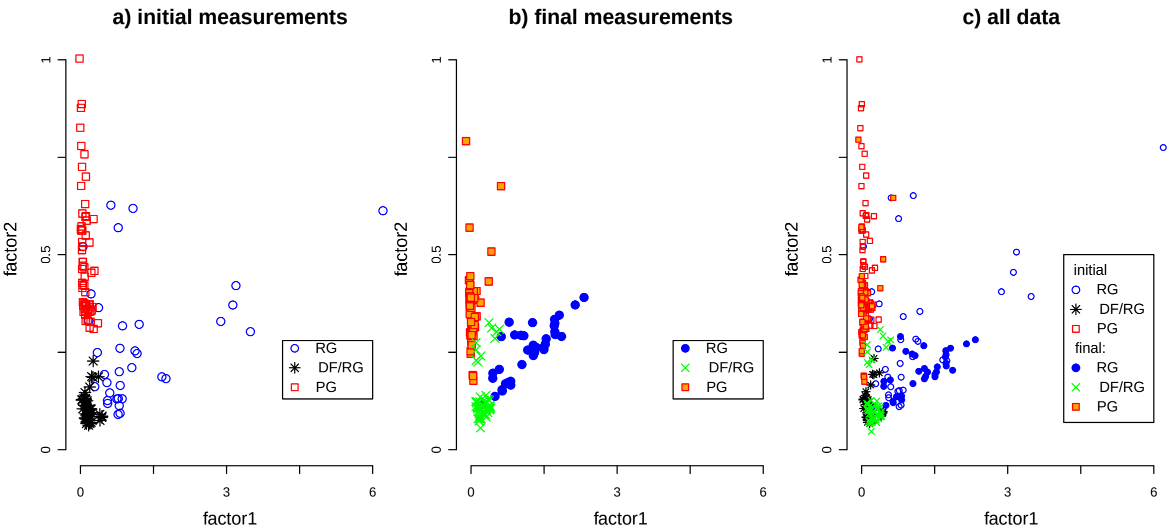

Figure 5.10: Principal component two-factor analysis (PCA) for artificially wetted layers, before (a) and after (b) wetting and including the full data-set (c). a) all layers were dry, b) layers consisting of persistent grains (PG) and round grains (RG) were wet with liquid water content larger than 2 vol.%, while layers initially consisting of decomposing precipitation particles and small round grains (DF/RG) remained predominantly dry, but showed densification. For each shown data-set, the respective data was used for developing the PCA. In all examples, mean penetration strength had strongest loadings in factor 1 and the coefficient of variation in factor 2. For a layer-specific version of plot c, please refer to Fig. B.1, App. B.

5.4 Discussion

5.4.1 Penetration resistance

Primary objective of this project was the investigation of the role of liquid water (LWC) and snow density (ρ) on micro-structural penetration resistance (f) in snow. This was tested in nine artificial wetting experiments.

During artificial wetting experiments, layer **settlement** and **densification** was noted, though not consistently investigated. In many cases the snow surface settled by two or three cm, in some cases up to 5 cm. Assuming that this settlement occurred within the upper 20 cm (the selected layer), this would imply a density increase of more than 10%. However, density measurements did not consistently confirm this. Four of the non-persistent layers, and one of the persistent layers, increased in density by more than 20%. The other layers showed only minor increases or density decreased slightly. The largest increase in density (>30%) was noted in a low density layer of precipitation particles and rounded grains. Similar observations have been reported by Marshall et al. (1999). They reported a rapid increase in density with first wetting of initially dry new snow layers. High density old snow showed little increase in density following wetting.

For the mixed (dry and wet) data-set, **penetration resistance** and **density** are moderately correlated. Exponential relationships provided best fits to the data. This is consistent with

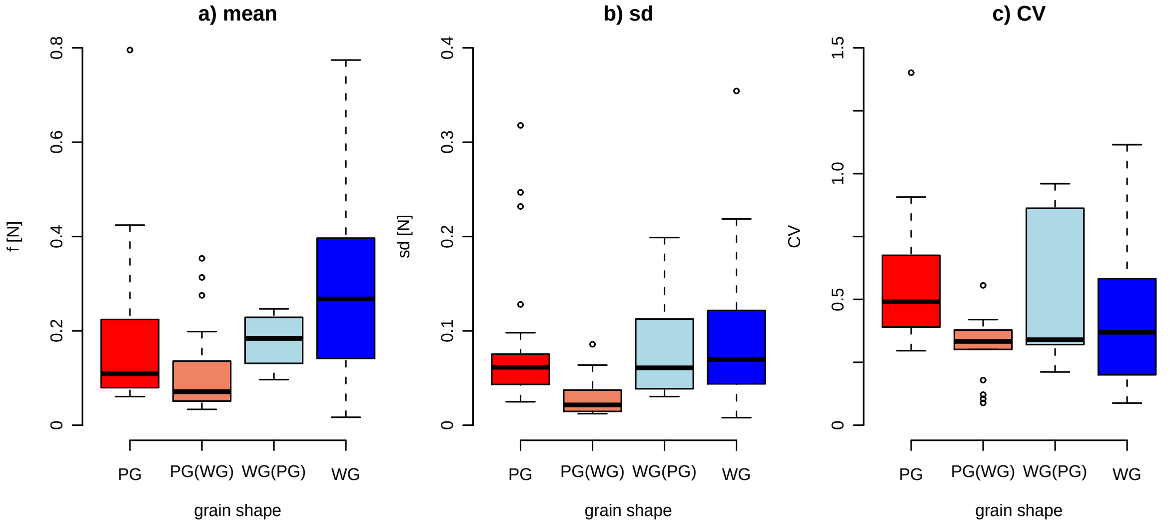

Figure 5.11: Box-plots showing a) mean penetration resistance (f), b) standard deviation (sd) and coefficient of variation (CV) for selected layers consisting of wet grains (WG) or persistent grains (PG) or transitions between those (secondary grain shape in brackets). PG data is all dry, the remaining data is all wet. The data-set consists of 31 different layers with each 2 - 5 SMP profiles (N=88), including also three artificially wetted PG layers.

previous studies in dry snow (Pielmeier, 2003). Surprisingly, for non-persistent grains, best fits were achieved when dry and wet data was included in the same regression model. This might be an indication that grain shape had not changed completely to wet grains during these experiments. With equi-temperature metamorphism decomposing precipitation particles (DF) would transform to small round grains (RG), which was probably the case, as measured liquid water content in these layers was often low. The obtained regression line seems similar to previous results (f=0.0033e$^{0.018\rho}$, Pielmeier (2003)), though this has not been tested statistically. However, it was also noted that dry and wet persistent grains (PG) can not be described using one regression model, but must be dealt with separately. Contrary to the non-persistent models, the persistent grain models can be further improved by using different models for dry and wet snow to describe the relationship between ρ and f. The low correlation coefficients ($r^2 \leq 0.3$) and the less inclined slope of the PG functions indicate that changes in density play a lesser role in persistent than non-persistent grains.
One major difference between the two grain type groups is the size of the particles. Crystal sizes observed for persistent grains varied between 1 and 6 mm, while non-persistent grains were much smaller (0.25 - 1 mm). Coarse grained snow has fewer bonds than fine-grained snow of the same density (Schneebeli et al., 1999). This explains the much lower penetration resistance for PG with similar densities than for NP snow. It also supports the need to fit different regression functions to the two grain form groups. Previously, Jamieson and Johnston (2001) presented shear strength measurements for dry snow and showed that different regression functions should be applied when deriving shear strength based on snow density for persistent and non-persistent grains.
The presence and amount of **water** has varying effects on penetration resistance, depending

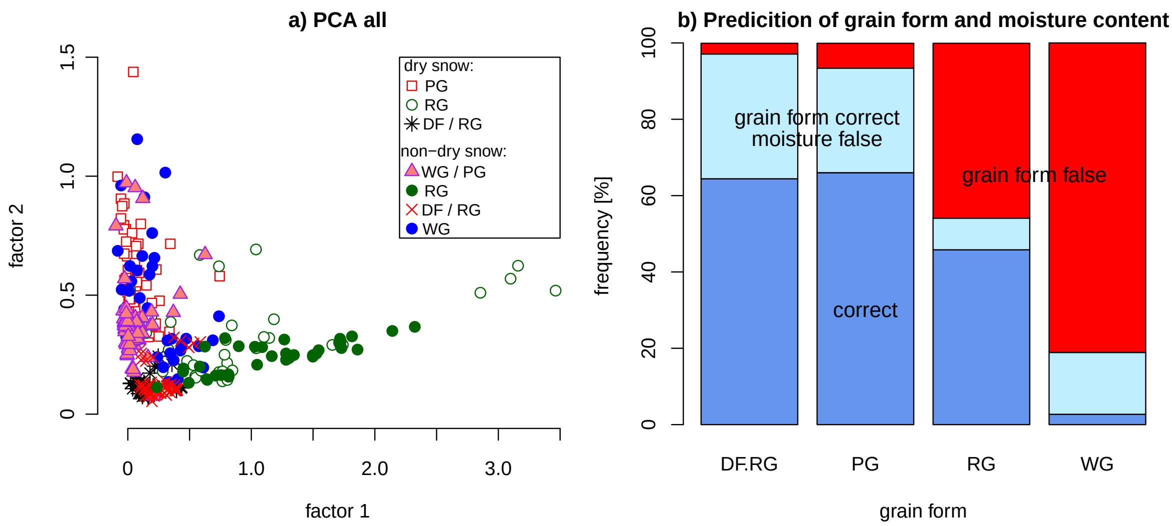

Figure 5.12: Grain shape characterization based on (a) two-factor principal component analysis (PCA) and (b) linear discriminant analysis (LDA). a) Grain shape plotted following two-factor PCA for 366 layers (natural wet snowpack) or 50 mm thick sub-layers (artificial wetting experiments [initial and final measurements]). Grain shape is grouped into persistent grains (PG), wet grains (WG), transitional forms between those (WG / PG), small round grains (RG) and low-density layers consisting of a mix of decomposing precipitation particles and small round grains (DF/RG) for dry and non-dry layers (LWC>0.5vol.%). Factor 1 has strong loading of mean penetration strength (f), factor 2 contains information on coefficient of variation (CV) and, to a lesser part, on standard deviation (sd). b) application of linear discriminant analysis on snow layers described in (a) shows frequency that observed grain shapes and moisture content could be correctly predicted by LDA. The full data-set was included in construction of linear terms.

on **grain shapes**. Persistent grains and wet grains show decreasing penetration resistance with increasing water content. Not surprisingly, this change is most prominent in the case of frozen **wet grains** (for instance a melt-freeze crust, MF) which softened with day-time warming, and associated increase in LWC, by about one magnitude. Very similar observations were made by Trautmann et al. (2006), who monitored the day-time transition of surface melt-freeze snow to wet snow. Shear strength decreased by more than 50%, often within short time spans. In their study, Trautmann et al. (2006) noted a linear correlation between shear strength and SMP penetration resistance in wet snow. Previously, Izumi and Akitaya (1985) reported that an exponential relationship exists between hardness and liquid water content of wet snow for a given dry snow density. They show further, that the number of inter-ice bonds and the total bond area between grains decreases proportionally to the logarithm of hardness. However, their observations were done in snow wetter than in this study (LWC 6. . .12 vol.%).

Persistent grains seem to loose little strength at very low LWC (<1 vol.%), but penetration resistance decreases once the water content is higher than approximately 1. . .2 vol.%. These results are confirmed by data obtained during my BSc thesis (Techel, 2007; Techel et al., 2008b). Here, in this study, the median decrease in PG layers is by a factor of approximately

1.5 to 3 at water contents of up to 4 vol.%. The magnitude of change in Techel et al. (2008b), was by a factor of more than 5 in a depth hoar layer (compare to Fig. 5.1c in the introductory section).

Non-persistent grains show a positive correlation between water content and penetration resistance. However, this observation may only be valid for low water content. Measured water content was often low with very few sub-layers being wetter than 3 vol.%. When dry snow is first wetted, grain clusters quickly form (Colbeck, 1982, 1997). At low LWC, the liquid is held by capillary forces in veins and junctions of the grain clusters (Colbeck, 1997). In soil, small amounts of water increase cohesion between sand grains, giving the soil additional strength (Rose, 2004). However, this is not the case between ice grains, where strong ice-to-ice contacts tightly bond crystals (Colbeck, 1997). These clustered ice grains have considerable strength at low LWC (Colbeck, 1997). This might be one explanation for the increase in penetration resistance at low LWC in layers consisting of small rounded snow (RG).

The limited number of observations at high LWC hint at a different influence of LWC on penetration resistance depending on grain shape. A further aspect of changes in **penetration strength** involves the **variability** within the same layer (and several SMP profiles). Persistent grains showed much more homogenously decreasing penetration resistance. The standard deviation σ of f in each layer decreased significantly from σ_{init}=0.035 to σ_{fin}=0.015 N ($p \leq 0.001$, Wilcoxon rank-sum test). DF/RG and RG layers showed higher variability in the final than in initial measurements (significant for DF/RG, σ_{init}=0.06, σ_{fin}=0.10, not significant for RG σ_{init}=0.30, σ_{fin}=0.40). The preferential infiltration pattern of liquid water resulted in very wet and completely dry areas. Measured LWC and density was more variable in non-persistent than persistent layers (if taken relative to the mean value for each layer). This might be a reason for the increase in variability.

5.4.2 Grain form characterization

Following the grain form characterization scheme based on SMP measurements (Satyawali et al., 2009), the three parameters mean penetration force (f), the standard deviation (sd) and the coefficient of variation (CV) were calculated for non-overlapping 1 mm-windows of the SMP signal.

In a first step, three grain shape groups, persistent grains (PG), small round grains (RG) and low-density mix of decomposing precipitation particles and small round grains (DF/RG) were used for testing the grain shape characterization approach introduced by Satyawali et al. (2009). Following artificial wetting, wetness increased in five of these layers, while four remained predominantly dry. The three grain shape parameters f, sd and CV changed for most of these layers during the course of the wetting experiments. Applying principal component analysis (PCA) for either the initial, the final or the combined data-set resulted in a good discrimination between grain shape groups. However, the difference between the initial and final SMP signal properties is less clear than between grain shape groups. The successful characterization does not come too surprising as the three groups had distinctly different

values for either snow density, grain size or penetration resistance.
In a second step, relatively similar groups, such as dry persistent grains (PG), wet wet grains (WG) and wet transitional forms between those (PG/WG) are compared. Typically, these three grain shape groups consist of coarse-grained snow with little strength. It shows that using single parameters, such as the CV can be suitable to distinguish between PG and the other groups, but there is hardly any difference between mixed forms and WG. Thus, the texture index for dry snow (based solely on CV, Schneebeli et al. (1999)) seems to be a useful discriminator between dry PG and wet WG. Mean penetration resistance and sd are lowest for transitional forms where persistent grains are still dominant. It is unclear, if this mirrors the fact that initial wetting of persistent grains significantly reduces hardness (reduction in grain bonds?) without a significant increase in densification (which would imply more inter ice-grain contact points). The data implies a hardness increase with continued wet grain metamorphism (and likely densification).
If, finally both data-sets are combined it shows that the proposed grain shape characterization scheme has its limits. While many shapes can be predicted, the wet WG could not be identified using the SMP signal. It might be necessary to apply a more extended model, such as the micro-mechanical model (Johnson and Schneebeli, 1999) to the SMP signal to be able to derive different grain shapes. However, when judging the quality of predicting these very similar grain shapes (PG, WG, WG/PG), it must be kept in mind, that the observed grain shapes are based on manual snow profiles and are prone to a, at least partially, an observer-dependent classification.

5.4.3 Limitations and problems

Several uncertainties must be considered when analyzing and discussing the presented results:

1. Measurement uncertainties
2. Spatial variability of snow structure and water flow
3. Layer definition
4. Time delay between SMP and LWC measurements
5. Data and data-quality

Measurement uncertainties include measured snow density, grain shape classification and grain size estimation in the field, measurement errors using SMP and Snow Fork. Snow densities measured within the same layer varied by approximately ±6% (546 layers, 1733 samples). Grain shape classification and size estimation is much more observer-dependent. Grain size should therefore be seen as an indication of size. It is certainly safe to say that it allows a classification into fine or coarse. It is much more difficult with grain shapes. While the observers were very experienced in the observation of manual snow profiles, false grain shape

classification can not be totally excluded as an error source. The Snow Micro Penetrometer measures highly resolved data, with a measurement error of ±0.005 N (Schneebeli and Johnson, 1998) and provides certainly the most accurate of the investigated data. However, it is of note to mention the often negative linear trend in the SMP signal resulting in negative force-values in very soft snow. Liquid water content measured using the Snow Fork normally lies within ± 1 vol.% in wet snow (Chapter 4). Main error source may be spatially heterogenous water distribution rather than inaccurate measurements. However, it must be noted that water content measured using the Snow Fork is approximately 1.4 times higher than using the Denoth wetness meter (Chapter 4).
Spatial aspects must be considered. Mountain snowpack layering and water infiltration into a layered snowpack can be highly heterogenous (Conway and Benedict, 1994). SMP measurements are sensitive to small changes in force and provide highly resolved data. While this provides information on micro-structure of snow, it also allows to observe the, sometimes, high spatial variability between measurements in close proximity (compare Fig. 5.5, for example layer F). Local differences in snow structure (clusters of refrozen snow or local ice bodies) can cause considerable differences between adjacent profiles. This complicated the alignment of SMP profiles to hand-hardness profiles, which was the basis for parts of the data-analysis discussed in the grain shape characterization. Here, about half the slope-profiles were excluded from further analysis due to these complications to reduce the subjectivity when defining layers. However, small-scale spatial aspects may have been slightly reduced by always using several SMP profiles for each layer (normally 3. . .5 SMP profiles).
The **distribution of liquid water** was observed to be highly variable (see also Chapter 4). To make water content measurements more robust, the median of 3. . .12 measurements was always given preference over the mean.
With water responding almost immediately to disturbances in the snowpack (as digging a snow-pit or taking measurements), the **time delay** between LWC observations, SMP measurements and manual profiles might also play a role when taking measurements in wet snow. However, the impact of this on measurements is not clear.
The **data-set** consists of more than 300 SMP profiles. However, these were observed in only nine different layers (artificial wetting) and ten different locations (naturally wet snow-pack).
Data-quality had to be considered with measurement errors being noted in the majority of the SMP profiles. Most frequent error was a drift, probably caused by temperature differences. This drift was semi-automatically corrected in all profiles in the same way by de-trending data based on the SMP signal in air. In most cases, the slope of the trend was about 10^{-5} N mm^{-2}. This may seem relatively insignificant, but can have an influence on changes in penetration strength of very soft layers. An observed decrease from 0.1 N to 0.05 N (factor 0.5) would contrast with 0.12 to 0.07 N (factor 0.58, assuming a similar correction of +0.02 N). Applying the same consistent de-trending procedure to all data, is believed to have eliminated the main error source.

5.5 Conclusion and further research

The introduction of liquid water into snow and its effect on micro-structural penetration resistance and snow density was investigated and a grain shape characterization based on the SMP force signal tested for wet snow conditions.

The rapid decrease of micro-structural **penetration resistance** at low liquid water content in layers consisting of persistent grains, as presented by Techel et al. (2008a), can be confirmed (hypothesis 1). The impact, the introduction of liquid water has on micro-structural penetration resistance, depends also on grain shape and size (hypothesis 2). Penetration resistance:

- decreased with increasing liquid water content in layers consisting of **persistent grains** at water contents less than 3 vol.% by a factor of about 1.5...3
- in layers consisting of **wet grains** decreases at LWC< 3 vol.% and remains low at volumetric water contents between 3...8 vol.%
- increases at water contents <3 vol.% in **non-persistent layers**

These observations lead to the conclusion that the strength of snow undergoing first wetting may depend more on dry snow structure (grain shape, size, density) than the actual liquid water content.

Assuming that micro-structural snow texture can be explained by the three micro-structural grain-shape parameters (penetration resistance f, standard deviation sd and coefficient of variation CV, Satyawali et al., 2009), then changes in snow texture following first wetting can be observed within the time-span of several hours (hypothesis 3).

Hypothesis 4, "the snow characterization, as introduced by Satyawali et al. (2009), can be applied to wet snow", can not be confirmed based on the presented data-set. While many grain shapes could be correctly detected using Principal Component Analysis (PCA) with the three parameters f, sd, CV, the PCA does not sufficiently discriminate between coarse-grained, soft wet snow and soft, coarse, persistent grain shapes or soft layers containing decomposing precipitation particles. Therefore, at present, the important distinction between wet grains and persistent grains can not be carried out using solely the SMP signal.

Future research should expand the limited knowledge concerning the influence water has on wet snow stability. For practical purposes it would be valuable to derive snow stability information based on the SMP signal. For this, future research sould

- incorporate a more detailed analysis of the available data from the artificial wetting experiments applying the micro-mechanical model (Johnson and Schneebeli, 1999; Marshall and Johnson, 2009)

- expand the principal component analysis for naturally wet layers by including measured liquid water content
- specifically aim at collecting micro-structural measurements of naturally wet snow-packs to enlarge the limited data-set used for analysis
- investigate typical micro-structural failure layer properties in wet snow

The Snow Micro Pen, in combination with the Snow Fork, is a very valuable tool to quickly measure snowpack structure and water content in wet snow-packs. For this, automatic grain characterization and failure layer detection in wet snow would be very valuable tools. Also, it would be of advantage, if the SMP itself would be more robust making it easier to handle in the field.

5.6 Acknowledgements

Field experiments using the Snow Micro Pen would not have been possible without the great support by Christine Pielmeier and Adrian Räz. Christine Pielmeier and Martin Schneebeli provided valuable feed-back concerning the data-analysis and interpretation of the results of this chapter.

Chapter 6

Assessing wet snow stability - survey

Information on snow stability is important for avalanche forecasting. Standard stability tests, like the Rutschblock (Föhn, 1987), are known to correlate to dry snow stability (Schweizer, 2002). Very limited research work exists on the applicability and interpretation of snow stability tests in wet snow situations.
Experienced avalanche forecasters in North America, Europe and New Zealand were approached with a questionnaire concerning their experience with a) snow stability tests in wet snow and b) forecasting wet snow avalanches. The intention of this survey is to provide a theoretical basis for the field experiments conducted in spring 2009 (Chapter 8).
Some of the results of this survey have been presented in a conference paper (Techel and Pielmeier, 2009).

Research questions:

1. What are the main forecasting problems practitioners are confronted with?
2. What role play stability test observations for wet snow avalanche forecasting?
3. What are the primary difficulties to overcome for the successful application of shear and stability tests in wet snow?
4. Are shear and stability tests a help for assessing wet snow stability?
5. Is there a certain test more suitable than others?
6. Which part of the test result is considered most important by avalanche professionals?

6.1 Introduction

Wet snow avalanches may threaten populated areas or infrastructure. Active avalanche hazard mitigation measures, like avalanche release by explosives, are difficult in wet snow. Thus, passive measures, like closures of threatened areas, are frequently applied. The correct prediction of size and timing of naturally occurring wet snow avalanches is very important to minimize economic losses caused by these closures. Wet snow stability is particularly hard to predict as it may change within hours (Tremper, 2001), or even minutes (Trautmann et al., 2006).
Certain meteorological settings are necessary for the formation of wet snow (such as rain, solar radiation, warm air temperatures). However, using these variables alone is insufficient to differentiate between stable and unstable days (Trautmann, 2008). Wet slab avalanching has been linked to the presence of persistent weak layers in the snowpack (Reardon and Lundy, 2004; Reardon, 2008; Baggi and Schweizer, 2009). Thus, snow-pack characteristics need to be incorporated into the forecast. Most direct information on snow stability are naturally occurring avalanches, signs of instability or loading tests (like stability tests, Tremper, 2001). Stability tests are a useful tool to assess dry snow stability, particularly in the absence of other signs of instability. In wet snow, stability tests are often considered as difficult to interpret or unreliable (Birkeland and Johnson, 1999; Schweizer, 2002; Reardon and Lundy, 2004). Very few studies exist, which specifically investigate the applicability of these tests in wet snow. Brown (2008) compared different shear and stability tests during spring melt of a continental snowpack with basal depth hoar. His data indicates that the diurnal weakening of the snowpack may be observed. In unstable slopes, test scores (Compression Test) were significantly lower and observed fracture propagation (Extended Column Test) higher than in stable slopes [1].
Avalanche forecasting must consider all of the stability, snowpack and weather information available. However, this survey focuses specifically on the role of shear and stability tests in the assessment of wet snow stability.

A more detailed introduction on wet snow avalanches, stability assessment and avalanche forecasting, is given in Chapter 2, Sections 2.2 and 2.3.

6.2 Methods

Qualitative analysis (like surveys) are especially suitable for developing hypothesis and formulating research questions (Mayring, 2007).
Primary objectives of this survey were a) to investigate the experience practitioners have made with stability tests in wet snow and b) to stimulate comments on wet snow stability assessment.

[1] based on data provided by Brown (2009), statistical by myself

Table 6.1: Overview of received vs. sent questionnaires.

Country	**Received**	**Contacted**
Switzerland	13	15
Austria	4	6
Norway	4	10
New Zealand	6	23
United States	9	11
Canada	4	15
France	0	1
Iceland	0	1

6.2.1 The questionnaire

A brief questionnaire consisting of 15 questions was developed (App. C, p. 156ff).
The structure of the questions was either closed (offering several choices) or semi-closed (Porst, 2008), allowing supplementary information. Ample space was left for additional comments to invite further input. The only open question dealt with difficulties forecasters are faced with when assessing wet snow stability.
Eight of the questions intended to gain a brief overview of the respective avalanche organization, weather and snow climate of that region. The remaining questions targeted the experience with stability tests in wet snow and assessing the wet snow avalanche hazard.
The questionnaire was distributed per Email-attachment in English, German and French to reach a wide audience.
Experienced forecasters and some researchers were approached in Austria, France, Iceland, New Zealand, Norway, Switzerland, the United States and Canada (Tab. 6.1). Pre-requisite for the participation in the survey was experience with stability tests. Experts were recommended by respective national avalanche organization (Norway: NGI, Switzerland: SLF, Canada: CAA, New Zealand: NZMSC[2]). Several US forecasters were approached personally at the 2008 ISSW snow conference (through C. Pielmeier). Some contacts were established by the author. Austrian forecasters were recommended by M. Oberhammer. Unfortunately, members of the French and Icelandic avalanche warning service could not be contacted.

6.2.2 Data

In total 41 completed surveys were received, which equals a return rate of more than 50% (Tab. 6.1). However, one survey was discarded as the respondents claimed to have very little knowledge of snow stability tests.
The approached avalanche professionals are involved in a wide rim of snow safety work (Fig. 6.1a). On average they are responsible in two different types of avalanche work. Half of the respondents are involved in national- or regional-scale avalanche forecasting. A large

[2]NGI - Norwegian Geotechnical Institute, SLF - WSL Institute for Snow and Avalanche Research SLF, CAA - Canadian Avalanche Association, NZMSC - New Zealand Mountain Safety Council

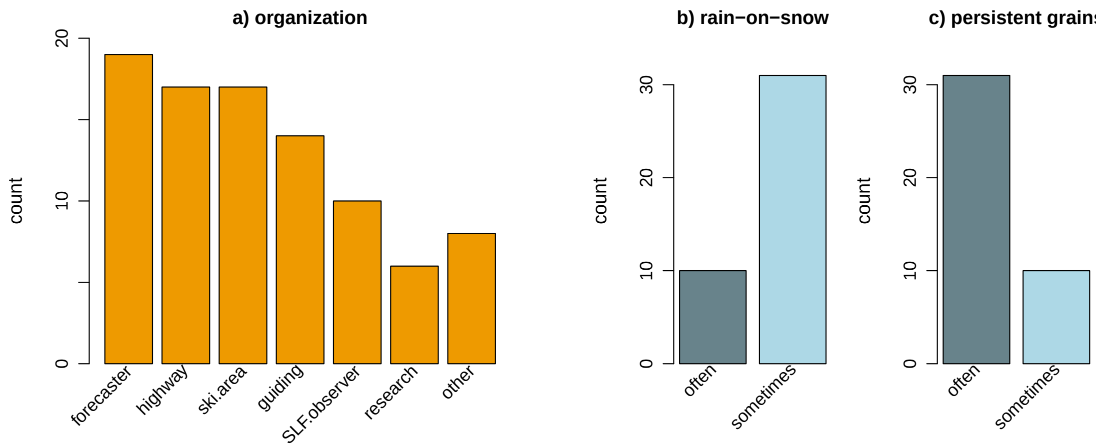

Figure 6.1: Respondents involvement in snow safety work (a, multiple answers were possible), (b) the frequency of winter rain-on-snow events occurring and (c) the frequency that persistent weak layers are present in the snowpack at the beginning of the melt-season.

number forecasts in ski areas, for highways or mining operations, or works as mountain- or ski-guide. Six respondents are (also) researchers. All have worked many winter seasons in their respective areas, or like many New Zealanders, have done several back-to-back winter seasons in New Zealand and North America.
The respondents from six countries (Tab. 6.1), work in a diverse variety of snow climates, in extremely maritime climates, transitional or continental mountain regions, or at the Arctic circle. About one quarter of the respondents indicate that winter rain is common (Fig. 6.1b). Despite these snow climatic differences, most respondents state that persistent weaknesses are frequently observed in the snowpack (Fig. 6.1c).

6.2.3 Data analysis

Analysis of closed and semi-closed questions

In fourteen of the fifteen questions a choice of answers could be selected. These answers were either counted (yes / no - type of answer) or, ordinal answers, were weighted according to their ranks. A typical choice of ordinal answer is *frequently, sometimes, never*, for which assigned weights would be *1*, *0.5*, *0*. These weights have no specific meaning but are necessary to calculate index sums or to apply rank-sum statistics. An overview of the assigned index weights can be found in App. C, Tab. C.1.
For the purpose of this survey, fracture quality (Rutschblock), fracture character (Compression Test) and shear quality were counted as belonging to one group (Hendrikx, 2005, Tab. C.2). Rutschblock release type and Extended Column Test (ECT) fracture propagation indicate fracture propagation propensity (Winkler and Schweizer, 2009) and are therefore grouped together.

Statistical methods

Nominal and ordinal data was analyzed using descriptive statistics, contingency tables, histograms and bar plots. Due to the small sample sizes, hypothesis testing using χ^2-based statistics could lead to false conclusions (Boslaugh and Watters, 2008). Therefore, the Fisher exact test for count data was used to analyze contingency tables (Agresti, 2007). The interpretation of probabilities needs caution due to the small numbers of the data-set, where one answer more or less could influence the p-value significantly. If a significant association between two variables was detected, contingency tables were visually analyzed to check whether the association was negative or positive.
Rank-based statistics, like the Mann-Whitney test or the Kruskall-Wallis H-test were used to compare two, or more than two groups (Ross, 2006; Boslaugh and Watters, 2008; R Development Core Team, 2008).
Spreadsheets (*Microsoft EXCEL*) and the statistics software *R* (R Development Core Team, 2008) were utilized to analyze data.

Analysis of comments

35 respondents offered additional feedback when asked what forecasting problems they are facing (open question). 30 surveys contained information to other questions as well, totalling 14 A-4 pages of comments. All comments were qualitatively investigated.
The three basic principles of qualitative interpretation according to Mayring (2007) are:

- summarizing - reducing material by assigning categories
- explaining - narrow (within the text) and wide context analysis (using additional sources of information) for clarification of certain points
- structuring - content based structure

The process of investigating the text-based answers orients itself on (Mayring, 2007; Dey, 1993)):

1. development of preliminary inductive codes while investigating the data-base
2. revision of code list (after about 20% of comments),
3. comparison and adjustment of existing categories with research objectives (survey questions, theory)
4. coding of available data
5. first analysis of codes, frequencies and possible links to each other
6. analysis of text sections not yet coded but marked important - mostly these are considered explaining comments

7. categories were spliced into families to structure the data
8. verification of appropriate assignment of categories and families (complete data-set)

To facilitate the investigation process the qualitative analysis software *atlas.ti* was used.

6.3 Results

6.3.1 Forecasting wet snow avalanches: problems, common practice and stability assessment

Wet snow avalanche forecasting is difficult. Most respondents indicated problematic wet snow avalanche situations or discussed factors difficult to interpret:

- **Meteorological causes** are most frequently mentioned. In particular precipitation-related situations like rain-on-snow events (18)[3] or snow-loading on a wet snowpack (4) are of concern.
- **Timing**: One of the key problems is associated with the timing of avalanche release (15), in particular the onset of avalanching is considered particularly difficult to forecast (4). Once an avalanche cycle has started, it becomes more predictable.
- **Avalanche type**: If considering the avalanche type, glide avalanches (7) are considered a major threat as they seem even more unpredictable than other wet snow avalanches. These were most often mentioned by Swiss respondents ($p \leq 0.01$). Also noted was the potential of loose slides triggering wet slab avalanches. In some regions wet loose snow avalanches are considered a large threat.
- **Snowpack, deep instabilities**: The majority of respondents (about 65%) is most concerned about wet slab avalanches failing in basal snowpack layers. The failure of deep instabilities (9), potentially resulting in large destructive avalanches, is considered particularly difficult to forecast.
- **Surface processes**, like (rapid) refreezing of the snow surface (4) or surface warming / wetting (3), are also challenges to forecasting. While many large slab avalanches have been observed to fail with the surface refreezing, the surface warming may trigger moist or mixed avalanches where the failure plane is still dry. These events are often extremely short-lived, and therefore difficult to predict.

Forecasters and researchers alike agree that **direct stability information** (Class I data), and in particular natural avalanche observations (8), are by far the the best indicator of wet snow instability ($p \leq 0.01$, Fig. 6.2). However, observing avalanches is a little late for forecasting the onset of avalanching. A relatively small role play regional or national avalanche

[3]this number indicates how often a similar remark was noted in the respondents comments

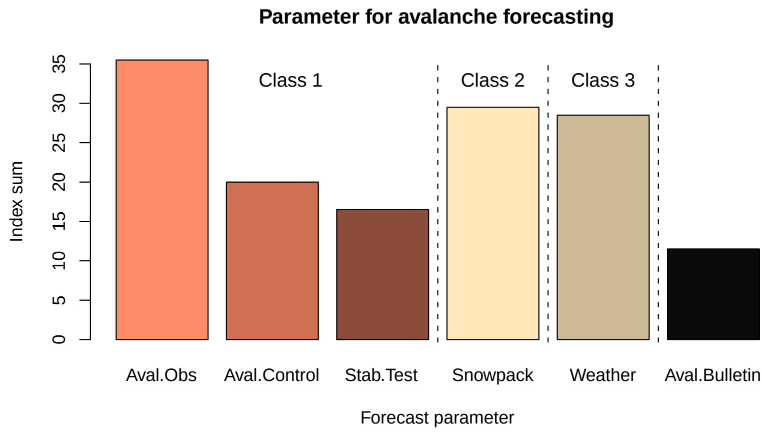

Figure 6.2: Weighted index sum of forecast parameters. Respondents ranked Class I observations first, followed by Class II and III. Within Class I observations *avalanche activity* observation are considered most important. Avalanche observations - Aval.Obs, artificially released avalanches - Aval.Control, stability tests - Stab.Test, avalanche bulletin - Aval.Bulletin.

forecasts. Within Class I observations, the role of stability tests in wet snow avalanche forecasting is relatively minor ranking third in importance ($p \leq 0.001$).
Weather observation and weather forecast are generally available and are considered very important (8).
Observed **snowpack** parameters include the advance of the wetting front, flow fingers or the general liquid water content (8), snow temperatures (7), resistance / penetration (5) or grain form (1). Increasing the frequency of snowpack observations with quick test pits (3) is also practiced. Several forecasters point out that avalanche forecasting must always consider all available information (6), even though single contributing factors can be difficult to interpret. Further significant associations relate to the frequency of facet formation in the snowpack and the type and depth of avalanche failure: full-depth avalanche failures are more of a concern if faceted grain forms are present ($p \leq 0.05$). On the other hand, surface avalanches are negatively correlated to frequency of facet formation ($p \leq 0.01$) and positively correlated to the loose snow avalanche type ($p \leq 0.001$). The role of persistent grain forms (be it a depth hoar base, facets above/below crusts) is often commented on (6) and believed to play a role in wet snow avalanche formation.
Critical snow conditions are often associated with the initial transition from a dry to moist/wet snowpack (7), especially if this transition is rapid (4). Avalanche activity is often expected, if snowfall turns to rain (4) or if warming is rapid (Fig. 6.3). Rain is one of the most effective avalanche triggers, (a lot of) rain also destroys weaknesses and 'resets' the snowpack.

6.3.2 Stability tests in wet snow

All respondents use stability tests in dry snow, which was a pre-requisite for participating in this survey. On average, participants use one or two different tests "most often" and another

Figure 6.3: Wet slab avalanche following a cold spring with frequent snow falls and subsequent very rapid warming. A situation that lead to these wet slab avalanches in an area where generally only loose snow avalanches are observed, Flute Basin, Whistler Mountain, Canada. Photo: Sittlinger, 2008.

test is "also used". This shows the experience with different stability and shear tests. Most popular are the Compression Test (CT, Jamieson, 1999), the Rutschblock Test (RB) and Shovel Shear Test (ST, see Fig. 6.4). Other tests include the Extended Column Test (ECT, Simenhois and Birkeland, 2006), the Propagation Saw Test (Gauthier et al., 2008) and the Stuffblock Test (Birkeland and Johnson, 1999). Non-standardized tests like hand shears were also mentioned. A number of practitioners use ski-cutting and explosives-testing of suspect slopes. While they are very helpful in testing (and removing) instabilities, these will not be further considered in this study.

Information from stability tests, which are direct information on snow stability, were ranked as less important than natural avalanche observations ($p \leq 0.001$) or results from artificial slope testing. Analyzing the three most frequently used tests (CT, RB, ST) shows that if a test is used in dry snow it most likely will be used in wet snow too (62.5 % of cases). However, there is a reasonably large percentage when these tests are used less frequently in wet snow conditions (32.5 %). In three cases (2.5 %), respondents indicated increasing the frequency a test is used (ST - twice, CT - once). Four respondents do not use any of the standard tests in wet snow. Of those, three normally use the CT in dry snow. A large number of respondents have some limitations concerning the applicability of stability tests in wet snow (almost 50%). Remarks range from "relatively useless", "hard to interpret" or "unreliable in wet snow" (7). Timing of observation (7) and the temporal validity is considered the main problem when observing wet snow stability. Moisture content and snowpack temperatures, both drivers of wet snow stability evolution, were noted to change extremely fast (8).

When asked, which of the test results properties (score, release type, quality of the failure plane, see p. 16) contains the most useful information for wet snow stability, release type (including fracture potential [ECT], $p \leq 0.001$) and the quality of the failure plane ($p \leq 0.05$) ranked higher than the score.

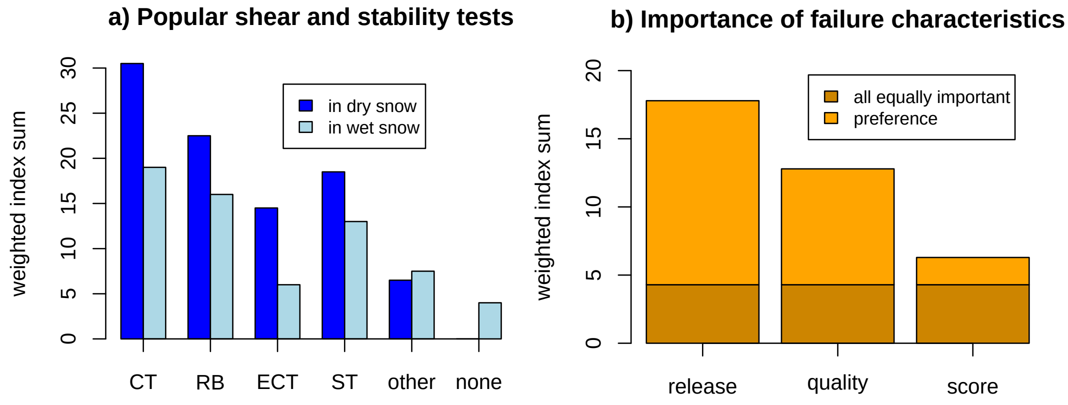

Figure 6.4: a): Index sum of most frequently applied shear and stability tests in dry snow (dark blue bars) and in wet snow (light blue bars). Compression Test (CT), Rutschblock test (RB), Extended Column Test (ECT9 , Shovel Shear Test (ST), other include stuff-block test, propagation saw test, ski cutting, explosives testing). b) Weighted index sum of test result properties. Respondents answer "consider all equally" has been split equally between the three test properties (lower section of the bars). Group *release* contains RB release type and ECT fracture potential, *quality* any of the failure quality ratings (Tab. C.2, App. C). All tests are used less frequently in wet snow. *Release type* is ranked higher than the other test properties.

Further significant correlations between tests and other variables include:

- The **Rutschblock**, in dry or wet snow, is most frequently practiced in Switzerland ($p \leq 0.05$). The **Compression Test**, on the other hand, is widely accepted in countries other than Switzerland.
- The **Shovel Shear Test** is the only test positively correlated to the usefulness of the test for stability assessment ($p \leq 0.05$). In wet snow, the ST is more frequently used in snow climates where winter rain is more frequent ($p \leq 0.001$).

6.4 Discussion

Forty, undoubtedly very experienced avalanche professionals from six countries, many different snow climates and forecasting operations have been addressed with a survey. The number of returned surveys indicates the interest in, and need to, research the subject. It is unclear if the forty respondents are a representative selection for forecaster's regularly using shear and stability tests to assess snow stability.

The **questionnaire** itself, seemed to pose few problems. However, there were some issues mentioned:

- **Language-related problems** generally seemed to cause minimal problems (one Italian speaking Swiss respondent)

- **Definition and identification of wet snow avalanches.** Wet snow avalanches were not sufficiently defined, in particular the difference between moist and wet avalanches (2x CH[4]). This truly is a weak point. However, as two other comments (CH, USA) indicated, defining avalanches according to their liquid water content is not as trivial as it seems. Both stated that the identification of a wet snow avalanche is difficult in the field. Often, the liquid water content of an avalanche is based on the avalanche deposit, even though an avalanche may have started as a dry (or mixed) avalanche and reached the valley floor as a wet looking slide. This is the case when wet snow was entrained. The classification is further complicated as Swiss guidelines (SLF, 2008) classify according to the deposit (dry, mixed, wet) and American guidelines (Greene et al., 2004) do not specify where the liquid water content is observed (dry, wet). The New Zealand avalanche classification scheme (Weir and Schreiber, 2000) seems to be the most complete: an observer records three classes of moisture content (dry, moist, wet) and indicates whether this was observed in the start zone or the deposit area.

- **Selection of choices**. "Almost never" and "sometimes (once or twice during winter)" was felt as being too similar to offer a real choice. (1 CH)

- **Most threatening avalanche**. This question was sometimes understood as the most frequent avalanche type, sometimes as the avalanche type causing most problems. Here, a better definition would have been advantageous.

The data-set is small and answers of a qualitative nature. Rank-based statistics contain many ties. Thus hypothesis testing is of limited value. Still, it may help filter associations between variables.
These limitations must be kept in mind, when further discussing the results of the survey:

- Direct **instability information** is of enormous value when assessing and forecasting wet snow avalanche hazard. However, these signs of instability often come too late for the *fore*casting of wet snow avalanches (Reardon and Lundy, 2004).

- Observed **snowpack** parameters, like decrease in penetration strength or snow temperatures were already described in Armstrong (1976) as tools to monitor wet snow stability. The influence of liquid water content on snow stability has been discussed in several studies (i.e. Kattelmann (1985), Conway et al. (1988)). Further important observations include snowpack structure and the advance of the wetting front. A snowpack, which has fully transformed into wet grains and where flow channels are fully developed, is considered relatively stable, while the presence of persistent weaknesses is associated with a more frequent occurrence of wet slab avalanches.

[4] indicates the number and country of respondents. CH - Switzerland

- The **temporal aspect of wet snow stability** is one of the key problems for the successful interpretation of snow stability tests. Trautmann et al. (2006) suggested 15-minute intervals might be necessary to observe changes in wet snow stability. As this is often operationally not possible, stability tests need to be temporally interpreted. This is particularly difficult, as neither the effect of increasing water content on weak layer strength, nor when infiltrating water will reach weak layers or where capillary barriers may form, are known.

- The **Shovel Shear Test** seems to promise some useful information. So far most positive feedback (survey, previous research) has come from maritime or low-elevation snow climates. Thus, it is unclear if the shovel shear test would also be a suitable test in more transitional or continental climates.

- Practitioners rank **release type** highest. In dry snow, studies have shown that Rutschblock release type or ECT fracture potential differentiate between stable and unstable slopes (Winkler and Schweizer, 2009; Schweizer et al., 2008). However, none of the returned surveys contained remarks why this may also hold true for wet snow.

6.5 Conclusion and further research

The survey aimed at establishing common practice among avalanche professionals when assessing wet snow stability.
There is general agreement that wet snow stability assessment must consider all available information, including direct stability information, snowpack and weather conditions. Concerning the role of shear and stability tests, no common practice seems to exits.
The key message from the survey, and previous research, is related to *timing* of wet snow instability and therefore the temporal interpretation of observations. It seems necessary to expand the knowledge on how to interpret snowpack properties and stability test results before warming, for instance based on early morning observations.
The survey leads to the following research questions, which were tested during the spring field campaign. These questions will be the focus of Chapter 8.

- In how far can snow stability and snowpack observations prior to melt-events aid in the assessment of snow stability following wetting?

- What information can be drawn from observing release type and fracture potential in snow stability tests in wet snow?

- What is the effect of changing liquid water content on stability test results?

- Can snow stability test observations be correlated to signs of instability in the field?

- What is the particular advantage of the Shovel shear test in wet snow? Does the shovel shear test have a practical application in the Swiss snow climate?

6.6 Acknowledgements

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in Norway: Jo Ellevold, Kalle Kronholm, Markus Landro, Albert Lunde;
in New Zealand: Peter Bilous, Russell Braddock, Penny Goddard, Andy Hoyle, George Robbi, Mark Sedon;
in the United States: Jon Andrews, Karl Birkeland, Bob Comey, Howard Conway, Janet Kelham, Chris Landry, John Stimberis, Craig Wilbour, Bruce Tremper;
in Canada: Clair Israelson, Mike Rubenstein, Jan Tindle, Ian Tomm, John Tweedy.

Chapter 7

Avalanche failure planes and the Rutschblock test in wet snow - investigating a seven year data-base

As outlined in the previous Chapter, no established correlation exists between snow stability tests in wet snow and its relevance in regard to wet snow stability or wet avalanche release. In winter, snowpack observations are carried out on a regular basis throughout the Swiss Alps by SLF observers and other practitioners. Many of these slope profile observations include Rutschblock tests to assess the local snow stability. Here, this diverse and long-term snow-profile data-base is searched for wet snow avalanche fracture line profiles and Rutschblock tests failing in wet snow layers.

Primary aim:

1. Establish a wet snow avalanche fracture line data-set.

Research hypothesis:

1. Typical parameters of wet snow avalanche failure planes exist.
2. The Rutschblock test provides useful information on fracture initiation and fracture propagation in wet snow.
3. The Rutschblock effectively tests weak layers to a similar depth in wet snow as in dry snow.
4. Similarities exist between failure planes where low Rutschblock scores are observed and wet snow avalanche failure planes.

Figure 7.1: Wet slab avalanche triggered by numerous point releases, Flüelapass, Davos region. The lower part of the snowpack consisted of very soft, moist or wet persistent grains. Photo: Mitterer/SLF, 2009.

7.1 Introduction

Snowpack structure plays an important role in the formation of dry slab avalanches (Schweizer et al., 2008), but also for wet slab avalanches (Reardon and Lundy, 2004; Reardon, 2008). However, many aspects on wet slab avalanche release are insufficiently understood. Previous studies have shown that critical conditions at beginning of melt, or presence of persistent weaknesses may play a role in immediate avalanche release or climax avalanche formation (Conway and Wilbour, 1999; Reardon and Lundy, 2004, Fig. 7.1, see Chapter 2.3).
In dry snow, shear or stability tests are one useful tool to assess current snow stability. Results from the survey indicate that the applicability and usefulness of these tests is rather limited in wet snow conditions (refer to Section 6.4).

The **Rutschblock** test (RB)[1] has been used for research and slope-stability observations in Switzerland since the 1960's (Föhn, 1987). The Rutschblock test can be regarded as a mini-slab avalanche (Föhn, 1987; Schweizer, 2002).
The RB provides valuable information on snow stability in dry snow. In particular, information on fracture initiation (RB score) and fracture propagation potential (RB release type) can be obtained (Fig. 7.2, Schweizer et al., 2008; Winkler and Schweizer, 2009, Ch.2.3). However, so far the applicability of the RB in wet snow situations has not been investigated.

A more extensive introduction on wet snow avalanches is given in Chapter 2.2 (p. 12ff) and on shear and stability tests in Chapter 2.3 (p. 15ff).

[1] additional information on RB can be found in Sec. 3, p. 23

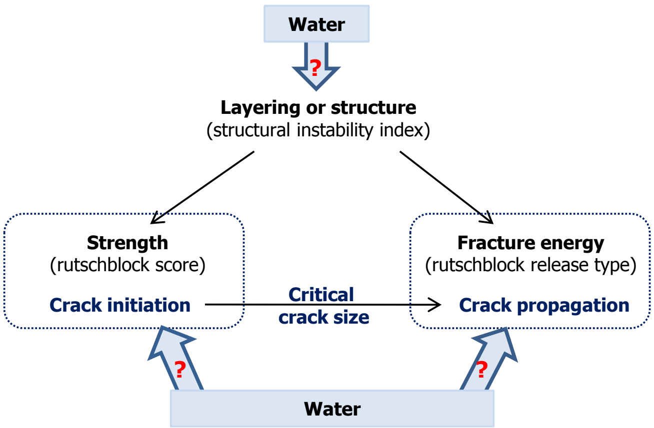

Figure 7.2: Schematic of dry avalanche release and interpretation Rutschblock test (RB), based on Schweizer et al. (2008), expanded by author. Crack initiation depends on strength, while crack propagation is driven by fracture energy. Layering or snowpack structure (investigated with the structural instability index, Tab. 3.5) influences both strength and fracture energy. Both can be observed in the field using the Rutschblock stability test. Water influences strength, fracture energy and snowpack layering, though many aspects are still poorly understood.

7.2 Methods

7.2.1 Data-base search

The SLF snow profile data-base was searched with the aim of finding avalanche fracture line profiles (Aval) and Rutschblock tests (RB) failing in wet snow layers. Initial search criteria were:

1. Failure plane (Rutschblock or Avalanche)
2. AND failure plane with water content estimation (mWC) at least moist (mWC$\geq$2)
3. AND profile observation after 1998

The search was programmed by Matthias Gerber (SLF).
The search resulted in more than 500 snow profiles in pdf-format. A first investigation showed that many failure planes were in fact in dry snow above or below ice-layers (mWC - code = 6), which reduced the data-set significantly. Further, there was a large number of profiles where layers had sub-zero temperatures, but mWC was given to be moist. These profiles also needed to be excluded.
Profiles were kept for further analysis, if the following failure plane criteria were fulfilled:

1. an avalanche or Rutschblock failure plane was noted (RB score 1…6)
2. failure plane not immediately below the surface melt-freeze crust

3. at least one layer adjacent to failure plane with an estimated water content equal or larger than(dry - moist, mWC$\geq$1.5), but not 6 (ice)

4. the snow temperature at the failure plane of more than -0.5°C (allowing for snow thermometer offset)

5. profile observation after 2002 (introduction of release type and fracture quality scheme)

Additionally, three fracture line profiles from before 2002 were also selected (1994, 1997, 2000) to increase the small number of avalanche fracture line profiles. Profiles taken at glide-avalanche fractures, on the other hand, were excluded (several observed by C. Mitterer, spring 2009).
All profiles observed during the spring field campaign were omitted from the data-set. They will be investigated separately in chapter 8.

7.2.2 Data

The data-set consists of 159 Rutschblock failure planes (RB), most of which contain RB score (RBsc), RB release type (RBrel) and RB fracture type (RBfrac). Additionally to the RB data, there were also 26 profiles when compression tests (CT) were performed. The extended column test (ECT, N=8) was rather infrequently used. Neither CT nor ECT data were analyzed in this study.
The avalanche fracture line data-set is much smaller (N=9). The failure plane was not always clearly indicated. In those cases the observers were contacted for further details. If no further information was available, it was assumed that the RB failure plane corresponds to the avalanche failure plane (N=2).
Available profile information contains observer identification, canton, slope aspect, elevation and slope angle, Rutschblock information (RBsc, RBrel RBfrac). For all layers adjacent to the failure plane, manual water content observations (mWC), grain form and size, and hand hardness (HH) were recorded (Tab. 3.1).

7.2.3 Data analysis

Failure plane characteristics were investigated. Absolute differences (.diff), mean (.mean), maximum (.max) and minimum (.min) of layers adjacent to failure plane (.above and .below) were calculated for hand hardness (HH), estimated water content (mWC) and grain size (see Tab. 3.1). For the avalanche data-set selected slab-properties overlying the failure plane were calculated. These included the weighted mean of the estimated water content and hand hardness. As profile data was only available in pdf-format, the large number of layers and profiles did not allow an easy extraction of slab-properties for the Rutschblock data-set.

Table 7.1: Investigated snowpack variables and Rutschblock observations for layers adjacent to failure plane, to slab overlying failure plane, according to recording standards as outlined in SLF (2008). Additionally, the presence of persistent weak layers and two index variables were calculated (structural index, capillary barrier index, section 3.2.1).

Parameter	
Failure plane (Aval, RB)	
Depth [cm]	
Hand hardness	HH
Liquid water content	mWC
Grain form	GF
Grain size [mm]	size
Capillary barrier index	cap.barr
Structural index	struct.index
Persistent weak layer	pWL
Grain form	GF
Slab above failure plane (Aval)	
Hand hardness	HH
Liquid water content	mWC
Rutschblock	
Score	RBsc
Release type	RBrel
Fracture quality	RBfrac

Grain form (GF) was analyzed and grouped according to the grain form classification (Chapter 3, Tab. 3.3) into persistent (PG, such as factes or depth hoar) and non-persistent (NP, such as precipitation particles and small round grains) grains. Melt-freeze-forms were split into frozen (MF) and melted forms (WG). Main grain shape was extracted for layers above and below the failure plane. The grain form combination (GF.comb) across the failure plane was grouped according to these four sub-groups. To further investigate the role of persistent grains, layers with PG as secondary grain form were also considered ((PG)). For these three groups, index-values (PG.index, WG.index, NP.index) were calculated where the main grain form is weighted by 1 and the secondary grain form by 0.5. Thus, a layer consisting PG(PG) would have an index of 1.5, while a PG(WG) layer would have index values of 1 for PG and 0.5 for WG. These index-values are thought to provide a simple overview of grain shape parameters of the full profile by

- taking the maximum of the PG.index (or the NP.index), this is thought as an index indicating if fully developed PG- or NP layers are present if the index is equal to 1.5
- the weighted mean of the WG.index, where WG.index=0 would indicate a snowpack which has not seen any wet snow metamorphism and where WG.index=1.5 is a fully wet-snow metamorphosed snowpack.

Index variables like the capillary barrier index (cap.barr, Baggi and Schweizer 2009, Tab. 3.4) and the structural instability index for dry snow (struct.index, Schweizer et al. 2008, Tab. 3.5) were calculated.
Soft layers containing persistent grains have been linked to the occurrence of wet slab

Table 7.2: Results: selected variables for Avalanche failure planes (Aval, N = 9) and Rutschblock failure planes (RB, N = 159). Shown is either median or mode. Significant differences between Aval and RB data are marked by: p≤0.01 = **, p≤0.05 = *, p≤0.1 = (*) and not significant p>0.1 = −. (Wilcoxon rank-sum test, Fisher Exact test for categorical variables). The full table is shown in App. D, Tab. D.1. Definition of variables in Tab. 7.1).

Structural variable	**Aval** (N=9)	**RB** (N=159)	**p**
depth [cm]	55	38	(*)
RB.sc	3, 4, 6	4 (31%)	−
RB.rel (mode)	pBr (3/3)	pBr (46%)	−
RB.frac (mode)	rou (2/3)	smo (47%)	−
HH.above	1.0	2.0	*
HH.below	1.0	2.0	(*)
HH.diff	0	1.0	(*)
HH.min	1.0	1.5	*
HH.mean	1.25	2.25	**
size.below [mm]	2.25	1.5	*
GF.comb	WG-WG (33%) PG-PG (33%)	WG-WG (23%)	*
pWL (yes/no)	6/3 (67%)	29/130 (18%)	*
struct.index	4	3	(*)
struct.index (PG)	4	3	(*)

avalanches (Reardon and Lundy, 2004; Reardon, 2008), thus a persistent weak layer index (pWL) including these two variables was calculated. It is defined by HH≤1.5 and PG present as primary or secondary grain form.

Statistical methods included rank-sum statistics (Wilcoxon rank sum test, Mann-Whitney U-test), χ^2-based hypothesis tests and, if expected or observed frequencies were smaller than five, the Fisher Exact test for Count Data (refer to Section 3.2.2 for details). The chosen level of significance was $\alpha \leq 0.05$.

7.3 Results

Both, RB and Aval were observed at similar elevation, slope angle and snow depth (Tab. 7.2[2]). 53% of RB were observed on northerly aspects (NW-N-NE) and 26% in southerly aspects (SE-S-SW). Aval were predominantly observed in southerly aspects (66%, including ESE and WSW aspects). 85% of slope profiles were observed in potential avalanche slopes (slope angle >30°). RB profiles have been observed in ten different cantons and Liechtenstein (47% in Grison). The majority of Aval profiles were observed in the canton of Grison (77%).

[2] the full table can be found in App. D

7.3.1 Avalanche failure planes

Based on the very limited number of available avalanche fracture line profiles, wet snow avalanches typically fail in, or adjacent to very soft layers (HH=1, 89%). The failure planes are between 20 and 101 cm below the snow surface. Layers adjacent to the sliding plane consist often of large grains (67% with size.max≥1.5 mm) where remnants of persistent grain forms are still visible (67%, Tab. 7.2).
Three of the avalanche fracture lines did not fail adjacent to persistent weak layers (pWL). These three failure planes had significantly smaller grain sizes. Grain size and shape are included in the structural instability index; thus it is not surprising that the index is significantly lower in these profiles than the remaining six.
Testing the avalanche data-set with the structural instability index for dry snow shows that only the maximum size, the minimum hand hardness and depth are more than half the time observed at wet snow fracture lines. If the grain shape criteria is reduced to remnants of persistent grains, then this criteria would also be fulfilled often (67%).
Considering the full profile (and not just the failure plane, which was not always clearly indicated), snowpack characteristics are:

- the snowpack is generally soft (median HH=2.2) and moist (mWC=2.1), where all layers are moist or wet
- persistent weak layers are present in 7 of the 9 profiles
- structural instabilities exist (struct.index=5)

7.3.2 Rutschblock failure planes

Most of the Rutschblock (RB) tests failed at the moderate score 4 (31%), with a smooth failure plane. Frequently, a partial failure was recorded (almost 50%). 93% of the Rutschblock failures occurred within the upper meter of the snowpack.
The strongest, and most significant correlation exists between RBsc and RBrel (r_s=-0.43, p=10^{-8}, Fig. 7.3a). Irregular failures are more frequently observed when only an edge of the block fails (Fig. 7.3b). If larger parts of the block fail, RBfrac is often smooth (Fisher test, p=10^{-5}, Tab.7.3, Fig. 7.3c).
Snow depth and **failure plane depth** have an influence on both RBsc and RBrel. A weak, but significant correlation exists between RBsc and depth (r_s <0.3, Tab.7.3). Failure of larger parts of the block (RBrel) is more frequently observed with increasing failure depth and decreasing snow depth. In particular, the median failure plane depth of whole block failures is significantly deeper than if edge or partial break failures occur (p≤0.01, Kruskall-Wallis test).
Grain shape has no significant effect on RBsc, though failure planes consisting of non-persistent grains have a slightly higher median score (Fig. D.1, App.D). Whole block failures are frequent if the grain shape above and below the failure are PG (p≤0.01, Kruskal-Wallis test, Fig.7.4a). If a failure occurs in WG-WG, then the failure tends to be irregular. Grain

Table 7.3: Summary table indicating significant positive ↗ and negative ↘ Spearman rank-order correlation r_s for RB score (RBsc, N=159) and RB release type (RBrel). With the exception of RBsc∼RBrel (r_s=-0.43) all correlations are weak (r_s <0.3). For RB fracture quality, significant differences between the three types of failure were tested using the Kruskall-Wallis-Test or the Fisher Exact test for pWL. Significance values are indicated with *. p≤0.001 = ***, p≤0.01 = **, p≤0.05 = *, p≤0.1 = (*) and not significant variables p>0.1 = –.

Variable	RBsc	RBrel	RBfrac
hs	–	↘	–
depth	↗	↗	–
RBsc	NA	↘	(*)
RBrel	↘	NA	***
mWC.below	–	–	*
pWL	–	(*)	*
GF.comb	–	**	*

size has little influence on the Rutschblock results.
With decreasing **hardness** difference between layers and decreasing hardness of the layer below the failure plane, whole block failures become more frequent (p≤0.1, Kruskal-Wallis test).
Irregular failures occur more frequently when the layer below the failure plane is **wetter** (p<0.05, Kruskall-Wallis test).
The **structural instability index for dry snow** (struct.index) is not correlated to Rutschblock failures in wet snow (Spearman rank-order correlation). Applying the critical ranges for the structural instability index to the Rutschblock failure planes shows that the size.max (73%) and the depth criteria (71%) are most frequently within the critical range (Tab. 3.5, Schweizer et al. 2008). Very soft layers and remnants of persistent grain forms were recorded in less than 50% of the cases.
The **capillary barrier index**, based on grain size and grain size differences between adjacent layers (Baggi and Schweizer, 2009), has no correlation to either RBsc or RBrel.
Persistent weak layers (pWL), adjacent to failure planes, were observed in less than 20% of cases. The RB score tends to be lower if the failure occurs at a moist persistent weak layer. Rough failures occur more frequently if the layer below is a pWL (p<0.05, Fisher test, Tab.7.3, Fig.7.4b).

7.4 Discussion

In this chapter, the failure plane of wet avalanches and Rutschblock tests has been investigated by exploring the SLF's snow-profile data-base.
Primarily, the data-base search aimed at finding wet snow avalanche fracture line profiles. Unfortunately, the data-base contained only very few profiles (N=9). This certainly presents the largest limitation to the interpretation of the obtained results. There are several additional questions before discussing the data-set: The majority of these profiles was observed

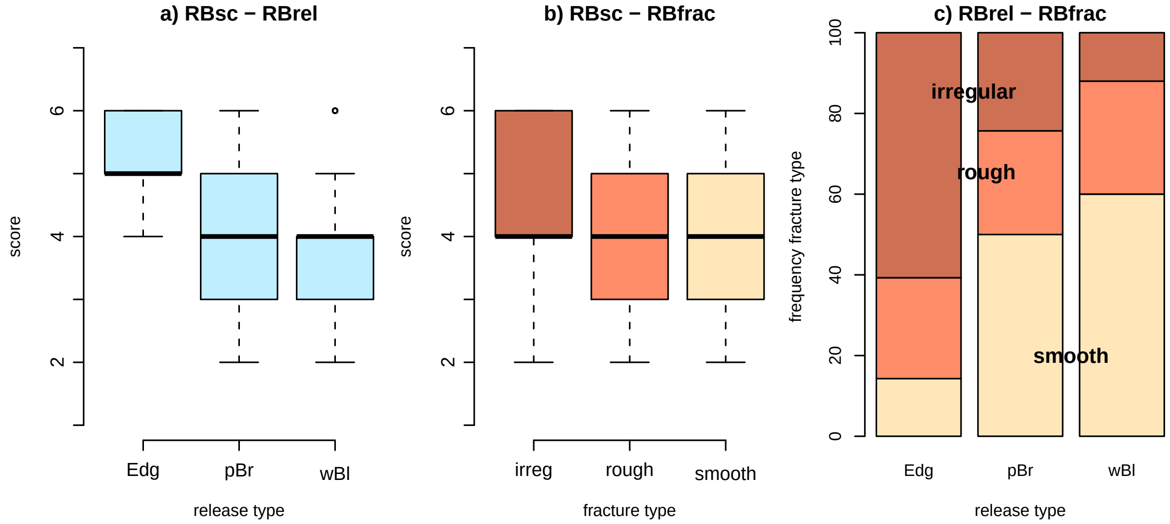

Figure 7.3: Rutschblock test properties: box-plots showing Rutschblock score (RBsc) to a) RB release type (RBrel) and b) to RB fracture quality (RBfrac). Bar-plot c) shows frequency of RBrel and RBfrac. RBrel consists of whole Block (wBl, n=54), partial break(pBr, n=72) and edge only (Edg, n=29) failures. RBfrac is classified into smooth (N=70), rough (N=40) and irregular (irreg, N=40) failure planes.

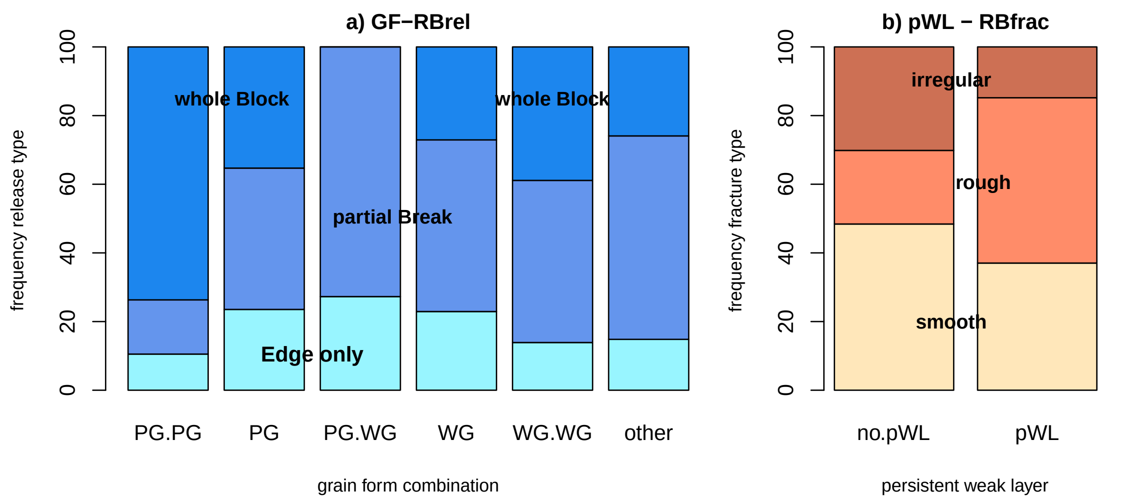

Figure 7.4: Relevance of grain shape on Rutschblock test (release type and fracture quality). a) grain form combination and observed RB release type frequency. Grain type is grouped into persistent grains (PG), wet grains (WG) and other forms (other). PG and WG indicate other grain shape combinations (like with melt-freeze or non-persistent grains). b) Presence or absence of persistent weak layer (no.pWL, pWL) and observed frequency of Rutschblock fracture quality.

in the canton of Grison. Thus, observed snowpack parameters may differ from those in regions with a generally deeper snowpack. Often, no indication was given if the profile was observed at a slab avalanche (which I assume was predominantly the case). Sometimes the failure plane was not clearly indicated and it had to be assumed that RB failure plane and avalanche failure plane were identical. Due to the time delay between profile observation and avalanche release, snowpack properties may have altered.
Keeping these numerous limitations in mind, the fracture line profiles suggest that **wet snow avalanches** fail:

- less than 1 m deep
- in or adjacent to very soft layers (hand hardness $\leq$1.5)
- in layers consisting of large grain (often $\geq$ 1.5 mm)
- in layers where remnants of persistent grain forms are still present

The **Rutschblock** data-set is very diverse with data from many different regions, elevations and aspects. Data has been collected by many different observers.
Rutschblock failure planes occur mostly within the upper meter of the snowpack (>90%) and within the critical ranges for skier triggering (>70%). This is consistent with previous studies (Schweizer et al., 2008; Winkler and Schweizer, 2009). The median failure plane depth (38 cm) is less than observed in dry skier-triggered avalanches (46 cm, Schweizer and Jamieson 2001) or in Winkler and Schweizer (2009) with 43 cm. Increasing RB scores with increasing depth and larger depth of whole block failures, were also noted by Schweizer et al. (2008).
Layers, consisting of large grains, were frequently observed above or below the failure plane (>70%). This is not too surprising as all failure planes were at least dry-moist and wet snow metamorphism generally leads to an increase in grain size (McClung and Schaerer, 2006). Failure layers consisting of persistent grains as main grain form are sometimes observed (20%). In the dry snow data-set analyzed by Winkler and Schweizer (2009), the majority of Rutschblock failure planes consisted of persistent grain forms. Due to snow metamorphism it can be expected that many of the PG has transformed to wet grain forms. If a failure occurs within PG, or of two layers where PG are the main grain form, then fracture propagation is significantly better (whole block). It is unclear, if this may be attributed to a high fracture propagation potential in snowpack layers consisting of well-developed PG undergoing first wetting. Wet slab instability has been linked to the presence of PG during spring warming (Reardon and Lundy, 2004; Hartmann and Borgeson, 2008; Baggi and Schweizer, 2009). However, factors, like a surface melt-freeze crust or slab properties, were not investigated, but may influence RB release type.
The significant correlation between score and release type confirms observations in dry snow (Schweizer et al., 2008).
None of the calculated index variables (structural instability index, capillary barrier index, persistent weak layer index) is correlated to, or differs significantly, between Rutschblock observations. In dry snow, Schweizer et al. (2008) reported significant correlations between the

structural index and both the RBs score as well as RB release type. Based on the wet snow data-set, the struct.index is not suitable to explain fracture initiation or fracture propagation in wet snow. The capillary barrier index, proposed by Baggi and Schweizer (2009), provided little useful information.
Correlations exist between layer properties. So is the estimated water content weakly, but significantly correlated to the layer's hand hardness (r_s=-0.25, p≤0.01) and grain size (r_s=0.26, p≤0.01).
PG.PG interfaces are generally very soft and consist of large grains. These criteria are also noted for WG.WG failure planes. Liquid water content in both failure plane groups is similarly high and higher than in the other failure plane groups (Fig. D.1, App. D). While high water contents can be expected in WG.WG layers, it is somewhat surprising that this is also the case in well-developed PG.PG-interfaces. Once water enters snow, metamorphism is rapid and grain shape alters. The higher the liquid water content, the faster the process (Brun, 1989). It would therefore be expected that wet layers transform to WG, with PG being secondary grain form. During the spring field campaign, less than 4% of the layers were classified wet (n=164), which is comparable to the quantitative water content measurements using the Snow Fork in these PG-layers (less than 5% had more than 3 vol.%, none wetter than 6%, see also Fig. A.2 in App. A). Therefore, it remains unclear, if these relatively high estimated water contents mirror natural conditions, or if the somewhat subjective and difficult estimation of the liquid water content in the field is the reason for this anomaly.
Unfortunately, the RB data-set did not include information on snow stability at the time of observation in the same slope. Thus, data can not be compared to existing snow stability. If the Rutschblock (RB) and avalanche (Aval) data-sets are compared, several differences can be noted:

- Failure layers are very soft in Aval (median HH=1), softer than RB, but very similar to dry unstable RB failure planes (Winkler and Schweizer, 2009)
- Grain size is larger in Aval than in RB and very similar to dry unstable RB failure planes (Winkler and Schweizer, 2009)
- persistent weak layers are frequently observed in Aval (67%), but seldom in RB failure planes (<20%), in dry unstable failure planes persistent grain forms are even more frequently observed than in Aval (>80%)
- Rutschblock-results can not be compared between RB and Aval, as only three RB tests were carried out at fracture line profiles
- the structural instability index is higher in Aval than in RB, however it is lower than in dry, unstable profiles (Winkler and Schweizer, 2009)

Further questions, which remain unanswered are:

- Are Rutschblock failure planes identical to, or representative for avalanche failure planes?

- What role do temporal changes play in regard to Rutschblock observations, but also on changes which occurred since avalanche release?

7.5 Conclusion and further research

In this chapter avalanche fracture line profiles and Rutschblock failure planes in wet snow were investigated.

Typical parameters of wet snow avalanche failure planes exist (hypothesis 1). Based on the small set of **wet snow avalanche failure planes**, structural instabilities observed at avalanche failure planes are:

- very soft layers (hand hardness $\leq$1.5),
- large grain sizes (often $\geq$1.5 mm),
- remnants of persistent grain forms may be observed,
- less than 1 m depth.

The information on fracture initiation and fracture propagation in wet snow gained by the Rutschblock test is limited and does not supoprt hypothesis 2. The **Rutschblock** test effectively tests the snowpack to approximately one meter depth in wet snow (hypothesis 3). The interpretation of the RB result (score, release type, fracture type) in wet snow is still unclear. The three variables were generally correlated to very few snowpack parameters:

- **Score** (fracture initiation) decreases with increasing failure plane depth. Score shows no correlation to snowpack variables.

- **Release type** (fracture propagation potential) is influenced by:
  - slope angle
  - depth (whole block at larger depth)
  - fracture initiation energy (score)
  - grain form combination across the failure plane (whole block failure if persistent grains are present)
- **Fracture quality** seems to be influenced by failure plane characteristics. Often a significant difference between irregular breaks and smooth / rough failures could be noted. So far, the interpretation of fracture quality observations in relation to the slab release mechanism is unclear (for dry and wet snow). Fracture quality is influenced by:

  - fracture initiation energy (score)
  - fracture propagation (release type)
  - water content
  - depth (slab thickness)

Some similarities exist between avalanche failure planes and Rutschblock failure planes (hypothesis 4). However, as generally no (or very limited) stability information is available for Rutschblock failure planes, the results do not allow conclusive comments on the correlation of Rutschblock results to avalanche release or snow stability.
The data-base search and analysis failed in establishing a sufficiently large enough data-set of unstable wet snow profiles. Therefore, this must be seen as a very first investigation of wet snow avalanche fracture lines and Rutschblock tests in wet snow.

Therefore, **further research** should focus on:

- investigating wet snow avalanche failure planes including stability test observations
- standard slope profiles should include detailed information on current snow stability in the same slope and similar aspects and elevations
- the role of fracture initiation and fracture propagation in wet snow
- the time dependence of observations
- the slab properties, the properties of the snow layers above the failure plane

The last two of these points will be investigated during the spring field campaign discussed in the following Chapter 8.

7.6 Acknowledgements

Matthias Gerber programmed the profile-data-base search. Christine Pielmeier, Martin Schneebeli, Christoph Mitterer and Jürg Schweizer gave valuable feedback concerning the interpretation of the RB results.

Chapter 8

Shear and stability tests in wet snow - field observations

The survey (Chapter 6) and previous research (for example Trautmann et al., 2006; Tremper, 2001) have shown that one of the key problems when assessing wet snow stability is the rapid temporal evolution of the snowpack following wetting. These rapid changes may be one reason for the limited applicability of snow stability tests in wet snow.
The focus of this chapter is on the diurnal evolution of wet snow stability, expanding the knowledge gained in the survey (Chapter 6), and comparing it to the data-base analysis (Chapter 7). In particular, information from stability tests and snowpack structure are investigated.
Some of the results have been presented in a conference paper (Techel and Pielmeier, 2009).

Research hypothesis:

1. Not all shear and stability tests are suitable for testing wet snow.
2. The shovel shear test is advantageous in wet snow (one result from the survey).
3. The information which can be drawn from snow stability tests is relevant for wet snow stability assessment.
4. Typical snowpack properties of unstable wet snow slopes exist.
5. Snow stability and snowpack observations prior to melt-events can aid in the assessment of snow stability following wetting.

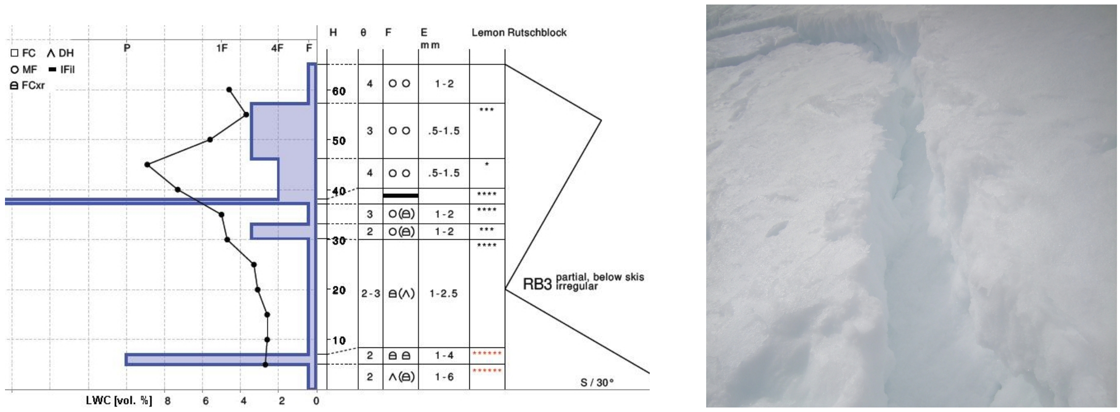

Figure 8.1: Snow profile (left) at a skier-triggered collapse (right). The slope cracked and slid approximately 20 cm, but did not release as an avalanche. 04 April 2009, Weissfluhjoch, S, 2662 m, 30°. Liquid water content was measured using the Snow Fork (blue line, in vol. %) less than 15 minutes after cracking and collapse. Hand hardness (shaded profile) and RB failure depth are indicated. Sliding plane of the slab and RB were identical.

8.1 Introduction

Wet snow stability evolves very rapidly. Trautmann et al. (2006) suggested 15 minute intervals might be necessary to monitor changes in wet snow stability. If wet snow stability is critical, snow profile observations in potential avalanche slopes may become dangerous (see example in Fig. 8.1).
Wet snow stability assessment is further complicated as the advancement of water infiltration in the snowpack is not known and very heterogeneous. Additionally, the interpretation of snowpack properties in regard to wet slab avalanche formation is insufficiently understood. The interpretation of stability test results is based on dry snow conditions. It is unclear, if these tests are applicable to wet snow stability assessment and how they may be interpreted. In this chapter, the focus has been on the assessment of wet snow stability with the help of shear and snow stability tests.

A more detailed introduction on shear and stability tests and their role in avalanche forecasting is given in Chapter 2.3.

8.2 Methods

8.2.1 Field methods and observations

Suitable slopes were selected allowing sufficient space for repeated observations in the immediate vicinity of morning observations to investigate diurnal changes in snow stability. Depending on expected warming, criteria for site selection were aspect, elevation and slope angle, as well as snow depth. The intention was to select sites which became unstable during

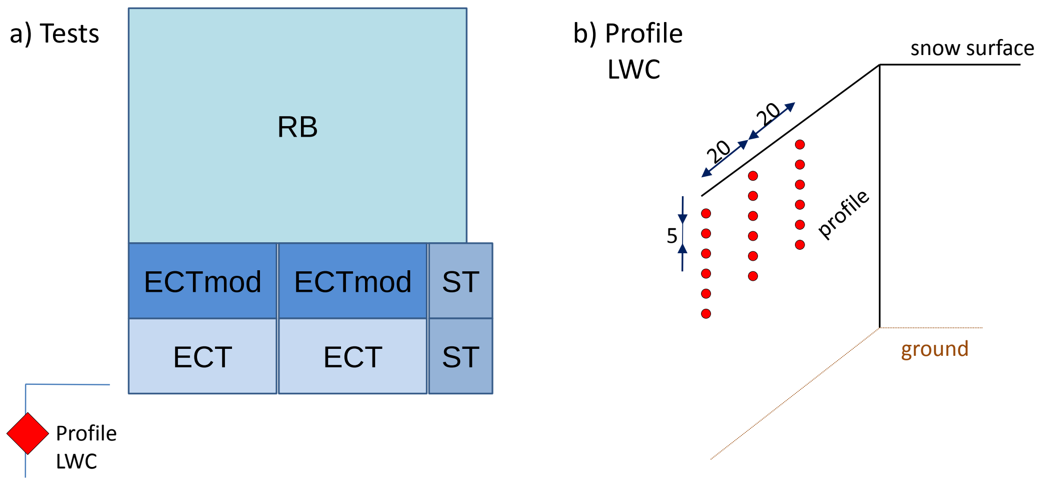

Figure 8.2: Layout of field experiments. a) One Rutschblock test RB, two Extended Column tests ECT and two Shovel shear tests ST were carried out. If a melt-freeze-crust was present, two additional modified ECT were carried out (ECTmod). In these the surface crust was removed. The snow profile was observed on a shaded side wall of the pit. Afternoon observations were very few meters from morning observations (beside or above, but within the same slope). b) Three vertical rows of liquid water content measurements were carried out beside the snow layering observation (profile). Distance between rows: 20 cm, vertical spacing between measurements: 5 cm.

the day. However, while unstable slopes were targeted, access to, and work in these slopes had to be avalanche-safe.

- **Snow profile**: Manual snow profile observations followed general procedures (chapter 3.1), or as described in SLF (2008). The layout is shown in Fig. 8.2. A snow profiles was always observed in the morning. On few occasions, when time allowed or on days when also SMP measurements were carried out, profile observation were repeated in the afternoon.

- **Liquid water content**: Beside standard snow profile observations, liquid water content (LWC) was measured using the Snow Fork (Sihvola and Tiuri, 1986). Accompanying morning and afternoon observations, liquid water content was measured before digging the snow pit, as well as following manual profile observations. The vertical distance between measurements was 5 cm (Fig. 8.2b). In each profile three vertical profiles were recorded with a horizontal distance of 20 cm. A detailed description of LWC measurement procedures is given in section 3.1.

- **Shear and stability tests**: Stability tests were performed adjacent to the snow profile (Fig. 8.2, Tab. 8.1). These included one Rutschblock test (RB, SLF, 2008), two Extended Column tests (ECT, Simenhois and Birkeland, 2006) and two shovel shear tests (ST, Greene et al., 2004). During morning observations, when a melt-freeze crust

Table 8.1: Shear and stability test observations. The same parameters were recorded for ECT and modified ECT (ECTmod) Fig. 8.2).

Test parameter	
Rutschblock	RB
score	RBsc
release type	RBrel
fracture quality	RBfrac
Extended Column Test	ECT
score	ECTsc
release type	ECTprop
Shovel Shear Test score	ST

existed, two modified ECT (ECTmod) were performed. For those, the surface melt-freeze crust was removed to approximate the expected diurnal loss in surface strength due to melting of the surface crust. Shear and stability tests were repeated in the afternoon, generally only two or three meters away from morning observations (Fig. 8.2).

- **Additional observations** included avalanche observations, signs of instability and hazard assessment. On very few days, micro-structural hardness was measured using the SMP (chapter 5).

8.2.2 Data

49 slopes were investigated on twenty field days. Many of these slopes were in potential avalanche terrain (median slope angle 32°). The median snow depth was 117 cm. Of those, fourteen locations were observed in the cantons of Berne and Fribourg, the remaining in the canton Grisons. Almost all field days (18) were carried out in March and April 2009. Eighteen of the locations were sampled during the intense avalanche cycle (1 April - 7 April, see also Fig. 1.1).

For eight slopes a snow profile was recorded in the morning and in the afternoon. Shear and stability tests were carried out in all of them in the morning, but only 35 slopes were tested in the afternoon (due to insufficient day-time warming). In total 32 sets (morning and afternoon) of Rutschblock, and 35 sets of two ECT and two ST were carried out. Additionally, for twenty locations two modified ECT were done.

Liquid water content measurements using the Snow Fork were carried out whenever possible, in 44 slopes in the morning and 34 slopes in the afternoon. Some information was lost due to false handling of the measuring device.

Five of the seven as unstable classified profiles were recorded during the intense wet snow avalanche period with avalanches reaching the valley floor (Davos region, between 1 April and 7 April).

Table 8.2: Investigated snowpack and shear and stability test observations for layers adjacent to failure plane and slab overlying failure plane or the full profile (*). Recording standards as outlined in SLF (2008), index variables as defined in Chapter 3.2.1.

Parameter		**Failure plane**	**Full profile**
depth [cm]		x	
hand hardness	HH*	x	
liquid water content	mWC*	x	
grain form	GF	x	x
wet grain index	WG.index		x
persistent grain index	PG.index		x
non-persistent grain index	NP.index		x
grain size [mm]	size	x	
capillary barrier index	cap.barr	x	x
structural index	struct.ind	x	
persistent weak layer	pWL	x	x
wetness class			x
decisive test			x
snow stability		x	x

8.2.3 Data Analysis

Failure plane

Failure plane criteria investigated for the different stability tests include the estimated water content (mWC), hand hardness index (HH) and grain size (size) (Tab. 8.2). For these, several variables were calculated (min, max, mean, diff). The effect of capillary barriers (Baggi and Schweizer, 2009, Tab. 3.4) and the threshold sum approach for dry snow (Schweizer et al., 2008, Tab. 3.5) were calculated. Grain form above and below the failure plane were grouped into the main grain forms persistent grains PG, non-persistent grains (NP) and wet grains (WG) or frozen wet grains (MF). Index variables and the GF classification are explained in detail in chapter 3.2.1 (p. 3).
Evaluated criteria considering the **slab overlying the failure plane** are the depth of the failure plane, and the weighted mean for HH and mWC (Tab. 8.2).

Full snow profile

In many cases, stability test failures may not be identical to avalanche failure planes. Therefore, it is necessary to investigate typical parameters of the full snow profile. Explored variables are the maximum of the structural instability index, the maximum of the capillary barrier index, the presence or absence of persistent weak layers (Tab. 8.2) and the median liquid water content for three different sub-layers (LWC, Tab. 8.3). The treatment of LWC data is discussed in detail in Chapter 4. Volumetric liquid water content values (LWC) always refers to the corrected liquid water content measured with the Snow Fork.

Grain form was incorporated using grain form index-values for the three main grain shape groups (persistent grains: PG.index, non-persistent grains: NP.index and melt-freeze-forms: WG.index). The main grain form is weighted by 1 and the secondary grain form by 0.5. Thus, a layer consisting PG(PG) would have an index of 1.5, while a PG(WG) layer would have index values of 1 for PG and 0.5 for WG. These index-values are thought to provide a simple overview of grain shape parameters of the full profile by:

- taking the maximum of the PG.index (or the NP.index), this is thought as an index indicating if fully developed PG- or NP layers are present if the index is equal to 1.5
- the weighted mean of the WG.index, where WG.index=0 would indicate a snowpack which has not seen any wet snow metamorphism and where WG.index=1.5 is a fully wet-snow metamorphosed snowpack.

Profiles were classified according to the **wetness classification** introduced in Chapter 4. In summary, the classification attempts to simplify the wetness profile by considering the median water content in three sub-layers. Surface water content was not considered for this classification, as it changes significantly during the day. The four wetness groups can be summarized (in their order of testing the data):

- *4-wet* - all layers at least wet (LWC>3 vol.%)
- *3-moist* - all layers at least moist (LWC>0 vol.%)
- *2-dry-moist* - at least one layer not dry (LWC>0 vol.%)
- *1-dry* - all layers are dry (LWC=0 vol.%)

No **stability classification** scheme exists for wet snow profiles. For this analysis, slopes were classified *stable* or *unstable* depending on the presence or absence of signs of instability. A similar approach was used by Brown (2008). Considered signs of instability are (in dry snow, Tremper (2001)):

- triggering of avalanches
- collapsing of snowpack
- whoompf-sounds
- crack formation

At least one of these signs had to be observed in the same slope and at the time of profile observation.
Information gained by shear and stability tests, in particular the decisive test result, is discussed in the next section.

Table 8.3: Liquid water content (LWC) measured with the Snow Fork (SnF). Depth below surface. n indicates the maximum number of measurements for each layer.

depth	layer	n
0...17.5 cm	LWC_{sfce}	9
17.5...52.5 cm	LWC_{mid}	21
52.5...102.5 cm	LWC_{low}	30

Table 8.4: Treatment of ordinal variables Rutschblock release type (RBrel) and ECT fracture propagation (ECTprop) for data-analysis. Index approximates the part of the block which failed. Index values are used for rank-order correlation analysis. ECTprop is always mean of two tests.

test	type of failure		index
RBrel	whole block	wBl	1
	partial break	pBr	0.5
	edge only	Edg	0.33
	no failure	NF	0
ECTprop	twice fp	fp	1
(two tests)	once fp	pp	0.66
	no fp	np	0.33
	no failure	NF	0

Shear and stability tests

Failures of Rutschblock, ECT, Shovel shear test and the modified ECT (ECTmod) were considered for analysis if

- the failure was at least 15 cm below the snow surface
- and not immediately below a surficial melt-freeze crust

Test scores (sc) were treated like ordinal variables. ECT and ST scores are always the mean of two neighboring tests. Fracture propagation potential (ECTprop) and release type (RBrel) were assigned with values according to the approximate area of the failure (Tab. 8.4).
Decisive failures are the failure which is relevant for snow stability assessment. Typically, these would be the lowest score and / or the best fracture propagation (RB, ECT). If, in one profile, twice the same score or the same fracture propagation was recorded for different failure planes, the upper of the two failure planes was considered as the relevant failure (similar to Winkler and Schweizer 2009).
Spatial variability of decisive test scores was investigated comparing the score between two adjacent ECT and ST tests, in the morning and in the afternoon, and for the full data-set. For the RB, spatial variability is considered to be ±1 score, which is similar to Campbell and Jamieson (2007). If ECTsc or STsc changed more than ± the median difference of the whole data-set (ECT: ±5.5 taps, ST: ±0.5 steps) or the RB score changed more than ±1 score from morning to afternoon, changes are considered significant. This led to three groups of test results:

- stability decrease

- no change in stability
- stability increase

Statistical analysis

Statistical analysis followed the procedures described in chapter 3.2.2 .
Correlations between ordinal variables was tested using the Spearman rank-order correlation r_s. Differences between data groups were investigated using rank-sum statistics (Wilcoxon rank sum, Mann-Whitney U test, Kruskall-Wallis test). The sign test was applied to test if changes were significantly different from a certain value (here: zero).

8.3 Results

8.3.1 Diurnal changes in liquid water content

Most of the 34 slopes, for which afternoon liquid water content measurements (LWC) are available, had warmed sufficiently by the time afternoon observations were carried out to have a moist or wet snow surface (LWC_{sfce} 2.4 vol.%, Fig. 8.3a). Layers in the middle of the snowpack were often dry or moist (LWC_{mid} 0.2 vol.%). The increase in LWC in the uppermost layers (LWC_{sfce}) was significant with +1.9 vol.% ($p \leq 0.001$, sign-test, Fig. 8.3b).

8.3.2 Shear and stability tests

The number of detected failure planes varied between tests: 99 failure planes were detected using the ECT, 27 with the ECTmod, 69 with the ST and 62 with the RB. Of those, more than half were dry failure planes. Despite using the same test to assess the snowpack, a failure plane detected in the morning was often not a failure plane in the afternoon (Tab. 8.5). ECT and ST tests always consisted of sets of two tests. The same failure plane was detected by both tests in more than two thirds of the cases. The median difference in the score between the first and second test is ±5.5 for the ECT and ±0.5 for the ST. If test results between different tests are compared, it shows that RB failure planes were in half the cases also detected using the ECT or ST, while ECT or ST often failed in different layers (about $^2/_3$ of the time).

8.3.3 Snowpack properties of failure planes

The median **failure plane depth** increased from morning to afternoon observations. This is highly significant for RB (+8 cm, $p \leq 0.01$, Mann-Whitney test) and ECT (+7 cm, $p \leq 0.05$), but not for the ST (+6 cm). The ST fails significantly deeper than the other tests ($p \leq 0.001$, Kruskall-Wallis test, Fig. 8.3c, Tab. E.2).

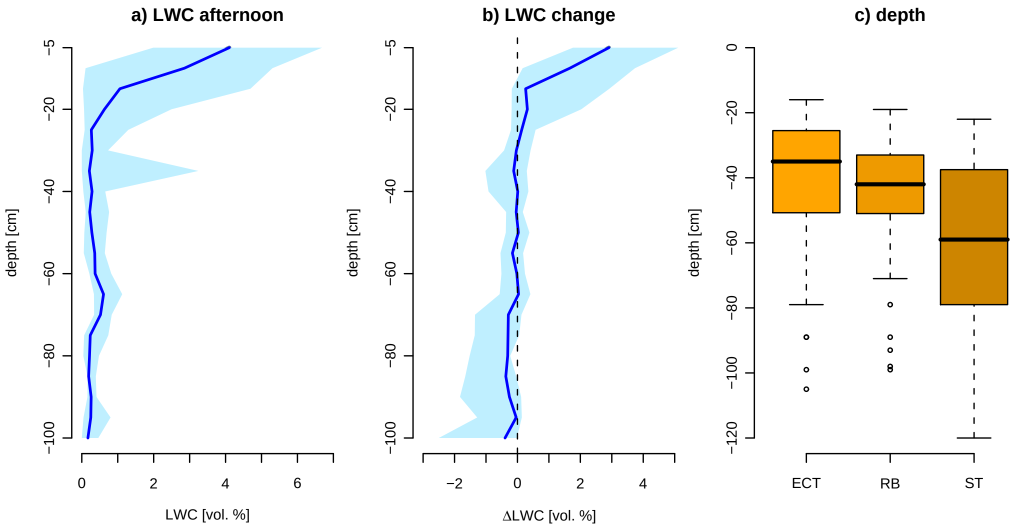

Figure 8.3: In a) Liquid water content (LWC) for afternoon measurements is shown, while in b) the increase in LWC from morning to afternoon is plotted. The blue line marks the Median, the shaded area represents the first to third quartiles. With increasing depth the number of available measurement decreases (less than 50% below 75 cm). c) Box-plot showing failure plane depth (in cm below surface) of all not dry failure planes for Extended Column Test (ECT, n=36), Rutschblock test (RB, n=24) and Shovel shear test (ST, n=38).

Failure plane properties for all not-dry failure planes were generally very similar between the different tests (Tab. E.2). Not surprisingly, most failure planes consisted of wet grain forms (WG). However, differences can be observed between tests: the ST failed most frequently in or at a WG-PG layers/interfaces, while many of the ECT failed in WG-WG failure planes (Tab. E.2). Typically, one of the adjacent layers to the failure plane consists of large grains (size≥1.25 mm) and is very soft (HH≤1.5). The failure plane is normally estimated as being moist (mWC=2). Neither water content, grain size nor hand hardness gradients seem to play a role in shear or stability test failure in wet snow. In 25…30% of the cases, a persistent weak layer (pWL) was found at the failure plane. Most failures occurred at interfaces where three of the structural instability criteria were fulfilled. Most often, these were the depth, maximum grain size, the minimal hand hardness and the grain form criteria.

Table 8.5: Comparison of failure plane (FP) detection between a) morning and afternoon observations, between b) first and second test (ECT, ST) and c) between different tests. Shown are frequencies for the detection of same failure plane. RB - Rutschblock test, ECT - Extended column test, ST - Shovel shear test.

Detection of same failure plane in...		**RB**	**ECT**	**ST**
a) morning and afternoon	FP=all	41%	33%	43%
b) first and second test	FP=all	-	57%	77%
	FP≠dry	-	63%	73%
c) different tests	RB	-	34%	38%
	ECT	50%	-	32%
	ST	58%	33%	-

Capillary barriers seem to play absolutely no role in test failure planes. The slab, overlying the weakness, was generally moist (mWC 1.69 - 1.84) and of medium hardness (HH 2.44 - 2.59).
Investigating the correlation ($p \leq 0.05$) between **all test results** failing in or adjacent to not-dry layers and snowpack characteristics shows that the

- **Rutschblock** score is higher with increasing failure plane hardness, and lower with increasing grain size or if the structural instability index increases. RB release type is strongly influenced by grain size, but also by hand hardness. Whole block failures occur more often when the weakness is soft and the grains are large (Tab. 8.6). Failure planes consisting of non-persistent grains produced higher scores than the other grain shape combinations. Whole block failures occur more frequently if the failure plane consists of PG-PG or PG-WG grains.

- **ECT** score is correlated to failure plane hardness with higher scores being observed if the failure plane is harder. None of the other variables are influential. Full propagation occurs more frequently if grain sizes are large, if persistent weak layers are present or if the overlying slab is dry. ECTsc and ECTprop are negatively correlated (Tab. 8.6).

- **Shovel shear test** score is strongly correlated to grain size and hand hardness. PG-PG and PG-WG interfaces produce lower scores. The same is true for failures in or adjacent to persistent weak layers. The structural instability index is negatively correlated to STsc (Tab. 8.6).

Investigating the relationship between **decisive test results** and measured water content of the sub-layers shows that

- **ECT fracture propagation potential** (ECTprop) and **RB release type** are significantly lower with higher LWC_{sfce} ($p \leq 0.05$). This effect is stronger visible for the ECTprop (r_s=-0.34).

- **RB score** is marginally influenced by surficial water content. Scores are higher with higher water content (p=0.05, r_s=0.26). **ST scores** are lower if the middle part of the snow-pack is wetter (LWC_{mid}, $p \leq 0.05$, r_s=-0.28). No effect of water content on the ECT score is observable.

Variability in decisive test results

The variability of the test score between two adjacent tests was compared for ECT and ST. The median difference between ECT's was ±5.5 taps and ±0.5 for the ST. The variability did not change significantly during the day.
From morning to afternoon:

Table 8.6: Significant correlation of snowpack variables to Rutschblock (RB), Extended Column Test (ECT) and Shovel Shear Test (ST) results. Correlations are shown if more than one variable was significantly correlated to the test result: positive correlations are indicated using $\nearrow$ and negative correlations with $\searrow$ ($p \leq 0.05$). If several variables were calculated for each parameter, the number of significant correlations is indicated by the small subsript. Categorical variables were compared using either the Kruskal-Wallis test or the Fisher test. Significant differences between groups are marked by: $p \leq 0.01 = ^{**}$, $p \leq 0.05 = ^{*}$, $p \leq 0.1 = (^{*})$ and not significant $p > 0.1 = -$. Only failure planes are considered, which are not dry. The full table with all variables can be found in App. E, Tab. E.1.

Variable	RBsc	RBrel	ECTsc	ECTprop	STsc
mWC	-	-	-	$\searrow^{1}$	-
HH	$\nearrow^{3}$	$\searrow^{2}$	$\nearrow^{3}$	-	$\nearrow^{5}$
size	$\searrow^{1}$	$\nearrow^{4}$	-	$\nearrow^{3}$	$\searrow^{3}$
GF	$*$	$(*)$	-	-	$*$
depth	-	-	-	$\searrow$	-
cap.barr	-	-	-	-	-
struct.index	$\searrow$	-	-	-	$\searrow$
pWL	$(*)$	-	-	$**$	$**$
score (RB / ECT)	NA	-	NA	$\searrow$	NA

- the **Rutschblock** score changed in 30% of the cases more than ±1 step. Overall, no significant diurnal trend was noticeable. Six times the score decreased and five times it increased. In six of those eleven cases there was no failure observed in the morning or afternoon. In the remaining five cases, the failure depth always changed indicating failure occurring in a different layer. Increasing RBsc were observed when the ΔLWC_{mid} decreased (by 2 vol.%) resulting in a predominantly dry-moist mid-pack (median LWC_{mid} 0.5 vol.%). Decreasing RBsc showed very little change in mid-pack LWC, but were similarly dry-moist (median LWC_{mid} 0.5 vol.%). Persistent weak layers were present in almost all slopes with changing scores.

- the score of almost half the **ECT** tests changed more than ±5.5 taps. A weak, but not significant increasing diurnal trend can be noted (+1.5 taps, sign-test). Changes in water content can not explain changing ECT scores.

- the **shovel shear test** score changed in 50% of the cases more than ±0.5 steps. No trend was observable. Decreasing scores are more frequently observed with increasing LWC_{mid} (and vice versa), but this is not significant.

The diurnal variability (mean of two tests) was not significantly different than the variability between the same two adjacent tests (ST, ECT).

8.3.4 Influence of melt-freeze crust on stability test results

On mornings, when a melt-freeze-crust (mfc) capped the snow surface, standard ECT's and ECT's with the surface crust removed (ECTmod), were conducted. The thickness of the mfc varied between 1 and 15 cm (n=20). Removing the mfc significantly reduced the fracture propagation potential for both dry and non-dry failure planes (ECTprop, $p \leq 0.05$, Mann

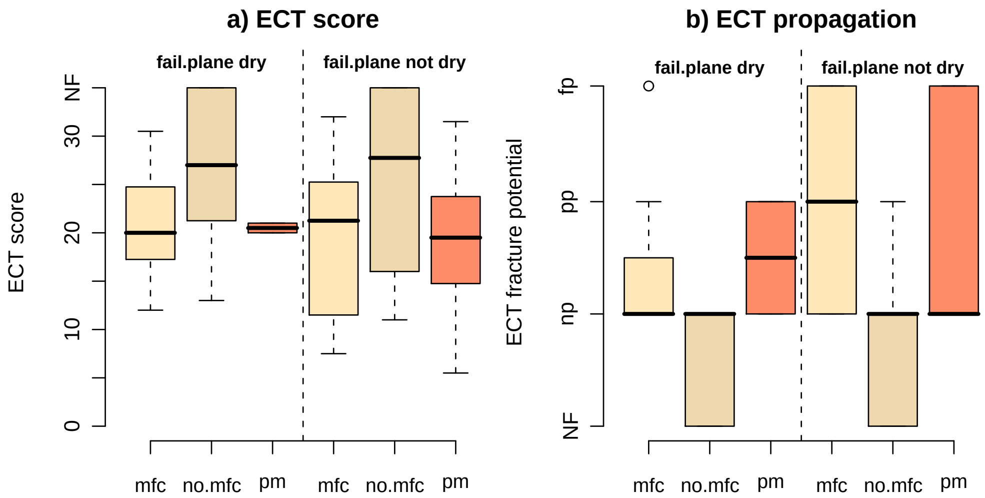

Figure 8.4: Effect of surface melt-freeze crust (mfc) observed in standard ECT (*mfc*) and in modified ECT (crust removed - *no.mfc*) in the morning and compared to ECT in the afternoon (*pm*) for a) ECT score (ECTsc) and b) ECT fracture propagation potential (ECTprop). Data is split into dry failure planes (morning N=7, afternoon N=2) and not-dry failure planes (morning N=20, afternoon N=19). Only test results are shown for which both ECT and ECTmod were observed and where the surface was moist in the afternoon (LWC_{sfce} >2 vol. %). Score is mean of two tests. ECTprop: fp - both tests with full propagation, pp - one of two tests with full propagation, np - no full propagation, NF - twice no failure.

Whitney U-test). The score (ECTsc) significantly increased when the surface crust was removed for non-dry failure planes ($p \leq 0.05$). For dry failure planes, the same trend was observed. However, this was not significant ($p < 0.1$, Fig. 8.4). Standard ECTsc and ECTprop did not significantly differ between morning and afternoon.

The change in decisive score (ECT, ECTmod) may be attributed to the **thickness of the crust** ($p < 0.01$, Spearman rank-order correlation). If a thin crust was removed (less than 5 cm), scores tended to decrease, while the removal of thick crusts increased the score. There is also a correlation between the reduction in propagation potential and the thickness of the removed crust ($p < 0.05$). In only two cases, when the crust was very thin, the ECTmod propagation potential slightly increased.

No correlation was noted between the thickness of the crust and decisive **Rutschblock** scores or RB release type.

8.3.5 Comparing stable and unstable slopes

Based on the stability-classification scheme introduced on p. 106, seven slopes were classified as unstable and 28 as being stable in the afternoon. In the morning all slopes were considered stable. Here, stable - unstable always refers to afternoon stability.

Comparing the **decisive shear and stability test results** showed that

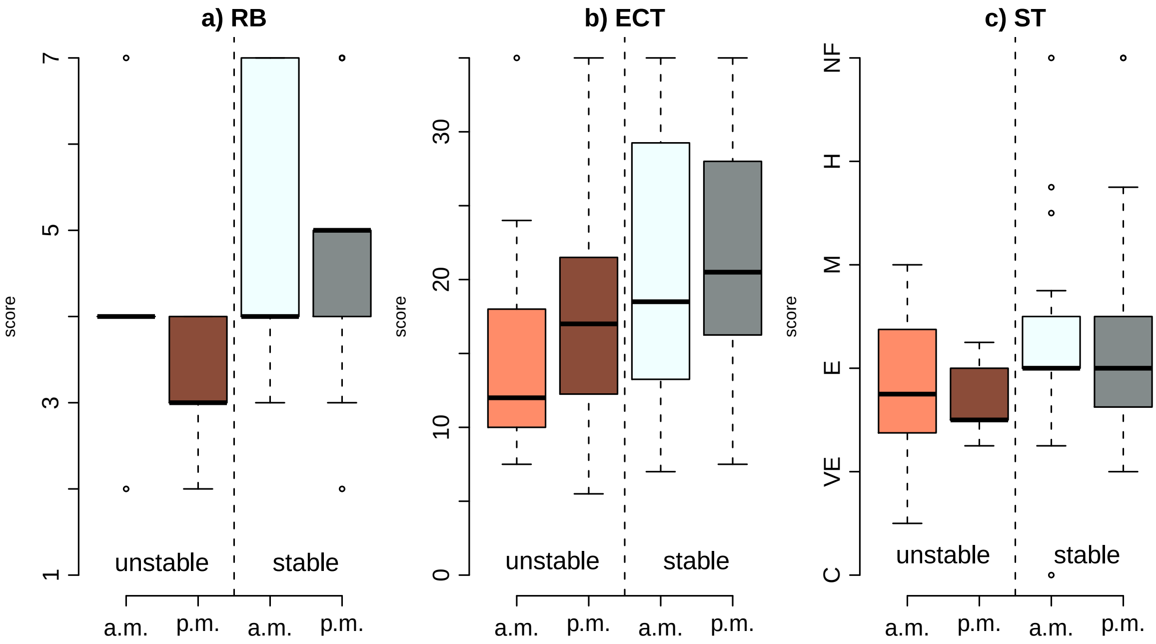

Figure 8.5: Morning (a.m.) and afternoon (p.m.) Rutschblock RB, Extended Column test (ECT) and shovel shear test (ST) scores. Weakest score for each profile shown if more than one failure plane for unstable (N = 7) and stable (N = 28) profiles.

- the **Rutschblock** differs significantly between stable and unstable slopes in the afternoon. Scores were lower ($p \leq 0.01$, Mann Whitney test) and release type was more often whole block or partial break, whereas stable slopes often failed edge only ($p \leq 0.05$, Fisher test). Morning RB results, however, did not substantially distinguish between stable and unstable slopes (Fig. 8.5a, Tab. E.3, App. E).

- the **ECT** has some potential. Morning scores in unstable slopes were lower than in stable slopes ($p < 0.1$). However, neither propagation potential nor afternoon score yielded significant differences (Fig. 8.5b).

- the **ST** frequently failed with low scores. Afternoon STsc were lower than morning scores, though this is not significant ($p < 0.1$, Fig. 8.5c).

In stable slopes, ECT and RB scores increased from morning to afternoon (although this is not significant). Unstable RB and ST scores show a slight diurnal decrease, however, none of these diurnal changes is significant (sign test).
A number of **snowpack** parameters (based on the full profile, not just the failure plane) differed significantly between stable and unstable slopes (Tab. E.3 in App. E):

- the **structural instability index** (for dry snow) was significantly higher in unstable than stable slopes (unstable median 5, stable 4, $p < 0.05$, Wilcoxon rank-sum test)

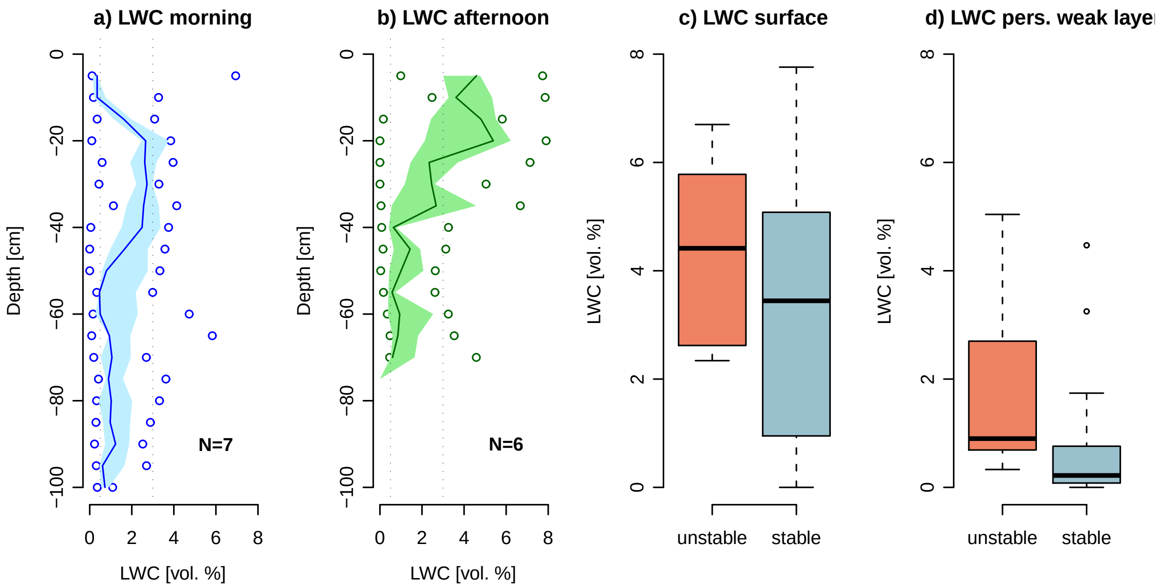

Figure 8.6: a) and b) show liquid water content (LWC) profiles of slopes which were unstable in the afternoon (morning, N=7, afternoon, N=6). The line represents the median, the shaded area the inter-quartile range and the dots the extreme values. LWC measured in surface layers (c) and persistent weak layers (d) is compared for stable and unstable slopes.

- **persistent weak layers** (pWL, with HH$\leq$1.5 and persistent grain forms still observable) were present in all of the unstable slopes, but only in some of the stable slopes ($p<0.05$, Fisher test)

- surficial **LWC** increased in most stable and unstable slopes (shown for unstable slopes in Fig. 8.6a, b). Afternoon LWC_{sfce} was at least moist or wet (LWC_{sfce} >2.2 vol.%) in unstable slopes (Fig. A.1c).

- the unstable profiles were wetter than the stable profiles (minimum of the weighted mean mWC-index in unstable slopes 1.5, $p\leq0.1$)

- despite LWC being only in the dry-moist range, higher LWC were measured in existing pWL in unstable than stable slopes (Fig. 8.6d)

- **melt-forms** (MF, WG) were present in all the unstable profiles, stable profiles had a wide range of snow crystals

8.4 Discussion

8.4.1 Slope selection: location and timing

Thirty-five slopes were investigated. Slope selection criteria were primarily based on expected warming. Unstable locations were targeted. For this, observations were often carried out in steep or very steep slopes, adjacent to rocky areas with thinner than average snow depth. This approach seems appropriate as wet snow avalanches typically release in very steep start zones with slope angles often much greater than 35° (Wiesinger, 2004; McCammon, 2009). Snow-balling and loose slides often initiates in rocky areas where persistent weaknesses may be better developed (due to temperature gradient metamorphism) and warming is enhanced due to the rocks. In these shallow, rocky locations, water infiltration leads to a more rapid decrease in stability. At the same time, locations in mid-slope and at lower angle may still be largely dry and relatively stable.
Slope stability was rated on obvious unstable signs in the same slope and at the time of observation. All profiles classified unstable, were observed on days when many (large) natural avalanches released in similar aspects and elevations.
Avalanche activity was wide-spread during the April 2009 period. The peak of the activity was late in the afternoon, often even later than our snowpack observations (between 1 and 5 pm). This might be one explanation why only seven slopes were classified unstable.

8.4.2 Stability tests and snowpack properties

The shovel shear test and two stability tests, the Rutschblock test and the ECT, were compared in wet snow conditions. The three tests often failed in different layers, though the failure plane properties are very similar (App. E, Tab. E.2). This is consistent with dry snow observations. Winkler and Schweizer (2009), who compared different stability tests, noted that in about half the cases the failure plane was different. The good news is that despite these differences, the decisive test result in each profile (lowest score, best fracture propagation) is moderately correlated between tests (r_s <0.6, $p \leq 0.05$). This indicates that stability ratings based on these tests would be similar.
The **water content** observed (mWC) at the failure plane had no visible influence on test scores or fracture propagation. Changes in surficial water content, on the other hand, had an effect on propagation potential (ECTprop, RBrel). If the snow surface was wet, fracture potential was lower. This hints at the possible influence of **surface melt-freeze crusts** on stability test results. Their effect on test results has been investigated for the ECT: if the crust was removed (ECTmod), the score increased and fracture propagation decreased. The increase in score might be explained by the reduction of load on the column (which has also been observed in dry snow, Lutz et al., 2009). Afternoon ECT observations seemed more similar to standard morning ECT observations than ECTmod results. However, differences are not statistically significant. It is unclear, if afternoon observations later in the day would have been more similar to ECTmod results. Thus, it is debatable if removing the surface-crust is counter-productive or a good approximation of afternoon surface conditions. In this

study, the ECT propagation potential was not a good indicator of unstable slopes. However, observations by Brown (Brown 2008, 2009) indicated the usefulness of ECTprop as a reliable indicator of wet snow stability.
In some circumstances, temporary water ponding may be caused at layer interfaces. This effect, the capillary barrier effect, was investigated using the cap.barr index introduced by Baggi and Schweizer (2009). The index did not correlate in any way to test results which is also mirrored by field observations: in several of the afternoon snow profiles, thin **water-saturated layers** above layer interfaces were observed. However, standard tests did not fail on these layers. This indicates that these tests are either not suitable for this type of failure or saturated layers are not relevant failure planes. If the latter would indeed be the case, this would contradict existing knowledge: water ponding above layer interfaces (capillary barriers) is believed to be one factor in the release of wet slab avalanches (Peitzsch, 2008; McClung and Schaerer, 2006).

The **score**, understood as an indicator of strength or **fracture initiation** (i.e. Schweizer et al., 2008; Winkler and Schweizer, 2009), is typically lowest

- in very soft layers consisting of large, persistent grains.

These effects are best seen for the STsc and the RBsc, much less so for the ECTsc. Many wet slab avalanches are triggered by snowballing (Fig. 8.7) or small loose snow avalanches (Conway and Wilbour 1999, see survey Ch. 6). It is questionable if the load applied by stability tests is comparable to wet snow avalanche triggers. In particular, the force applied to the ECT column (tapping on the back of the shovel blade) is relatively small. This might also explain the generally relatively shallow ECT failures.
RB release type and ECT fracture propagation are considered indicators for **fracture propagation propensity** in dry snow (Winkler and Schweizer, 2009). In wet snow, whole block failures (RBrel) or full propagation (ECTprop) was observed more frequently when the failure plane consisted of

- large, persistent grains

This is very consistent with observations of wet slab avalanches. These are known to fail if persistent, large-grained weaknesses exist at the beginning of the melt season (Reardon and Lundy, 2004; Reardon, 2008). Thus, ECTprop and RBrel can be thought of as indicators of wet slab propagation. However, when interpreting these tests, it should be kept in mind that surface conditions also influence the propagation (see above).
The **shovel shear test** effectively tests deep instabilities. In our slopes, these weaknesses were often very soft, large grained moist persistent layers, easily identifiable by eye and hand test. In maritime climates, where persistent weak layers are less developed, or if the failure plane is very thin, the ST may be of advantage. Here, it did not truly supply additional information (like on fracture propagation). Further set-backs are the very subjective nature of estimating the strength needed to cause failure and the small test area. Therefore, many

Figure 8.7: Many wet snow avalanches are triggered by small wet sluffs or roller-balls (as above) putting locally considerable weight onto the snowpack. This large roller-ball likely weighs more than 1000 kg. In contrast, stability tests are loaded by a skier's weight or by tapping on a shovel blade.... Photo: Techel, 2009.

repetitions are necessary for a reliable estimate of strength (Schaerer, 1988; Greene et al., 2004).
The **Rutschblock** test provides interesting information on fracture propagation and initiation in wet snow. It tests a relatively large area and is loaded by a comparatively large weight, which is of advantage. The **Extended Column test** tests surface layers well. It is very susceptible to the presence of a surface crust. For both, RB and ECT, it is too early for conclusive statements on their applicability in wet snow.

8.4.3 Assessing wet snow stability

In this study, criteria deciding whether a slope was stable or unstable were based on signs of (dry snow) instability (Tremper, 2001). A slope was called unstable if these signs were observed in the same slope at the time of observation. Deep ski penetration, which is also considered a sign of wet snow instability (Tremper, 2001) was not considered, as this information was not consistently gathered.
After only one season, the data set is small and unbalanced between stable (n=28) and unstable cases (n=7).
For **deep instabilities**, stability tests have the potential to provide additional information. The single best criteria to distinguish between stable and **unstable slopes** is the **afternoon Rutschblock score**. A RBsc threshold $\leq$4 would correctly eliminate 68% of the stable slopes and recognize all unstable slopes. The disadvantage is that observing the RB score

in the afternoon would require accessing potentially avalanche-prone slopes at a time when avalanche activity might be high. ECT (am) and ST scores (pm) were lower in unstable slopes. However, these results were not significant.
The slight increase in ECT (stable, unstable) and RB (stable) scores from morning to afternoon is surprising, though not significant, and may possibly be attributed to spatial variability. With the exception of the afternoon RB score, none of the tests truly performed better, including the ST. The latter contradicts the feedback from the survey.
Snowpack observations can often be safely carried out in the morning. The most significant snowpack criteria is the presence of persistent weak layers (pWL). pWL were observed in all unstable slopes. Further, all unstable slopes had a moist or wet snow surface ($LWC_{sfce} > 2$ vol.%). If both these parameters are considered as indicators of instability, and the 35 slopes are classified on either one of these criteria, then 50% of the stable slopes would be correctly detected. If both parameters are combined, all unstable slopes and 82% of the stable slopes are correctly classified.
If all test and snowpack observations (morning and afternoon) are available, afternoon RBsc is by far the best predictor. A combination of snowpack variables may also successfully classify stable and unstable slopes. Shear and stability test results are generally not good discriminators (Fig. 8.8a). If only morning observations are available (test and snowpack), classification is more successful using snowpack variables than shear or stability test results (Fig. 8.8b).
The regression tree analysis hints at the short temporal and spatial validity of shear and stability tests in wet snow. The RB confirmed snow stability observations in the same slope and at the time of observing signs of instability. In the morning RB scores were also generally low in unstable slopes. However, in one case, no failure occurred implying very stable conditions! The other tests did not provide clear indications on wet snow stability, which in part contradicts earlier findings (Brown, 2008, see also Fig. 2.7, p.18).
The snowpack factors successfully predicting slope stability are very similar to the conceptual model presented by Reardon (2008). In his model, three factors were discussed as relevant for wet slab instability: the water factory (the wet snow surface), the slab and the weak layer. With the exception of the slab criteria (HH.profile), which did not clearly differ between stable and unstable slopes, these parameters are significant indicators of wet snow instability. These are very hopeful results. But it must be kept in mind that the data-set is very small and not very diverse. Additionally, this will apply only to failure of deep, persistent instabilities. Surface instabilities are not considered.

8.4.4 Snowpack characteristics of unstable slopes

Combining the wet snow avalanche fracture line profiles (Chapter 7) and the seven profiles classified as unstable, results in a still small, but somewhat more diverse data-set. If these sixteen profiles are compared to the twenty-eight profiles classified as stable, it shows that the unstable profiles are significantly wetter and softer (Tab. E.3). In these unstable slopes, moist, persistent weak layers are observed and structural instabilities (as defined with the

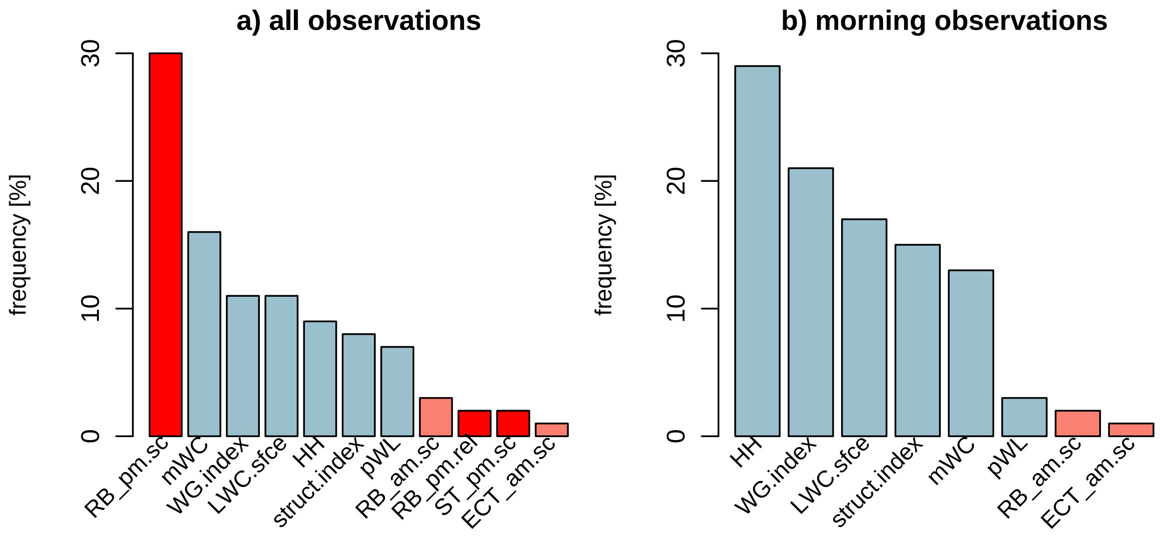

Figure 8.8: Regression tree analysis. Variables discriminating best between stable and unstable (n=7). data including a) all available information (snowpack, tests, morning and afternoon observations) and b) only information gained in the morning (snowpack, test). Shown is the frequency of the splitting variable for 100 runs with random selection of an equal number of unstable and stable profiles (n=7). Misclassification accuracy was 8.7% for a) and 17.8% for b). Variables are: $RB_{am.sc}$, $RB_{pm.sc}$, $ECT_{pm.sc}$, $ST_{pm.sc}$: respective scores for Rutschblock, ECT or Shovel Shear Test, observed in the morning and afternoon, $RB_{pm.rel}$ - RB release type in the afternoon, mWC - weighted mean estimated water content of snow profile, HH - weighted mean hand hardness, LWC.sfce - liquid water content measured at the snow surface. Index variables include the wet grain index (WG.index), the structural instability index (struct.index) and presence of persistent weak layers (pWL). Variables are listed in Tab. 8.1 and Tab. 8.2.

structural instability index (Schweizer et al., 2008)) exist. Unstable slopes have undergone considerable wet snow metamorphism (expressed using the WG.index) with many layers, especially above the failure plane, consisting of wet grains. The presence of non-persistent layers or well-developed persistent layers are poor discriminators between these slopes.
If these variables are tested using regression tree analysis for balanced data-sets (by randomly selecting an equal number of stable and unstable profiles) it shows that the above mentioned hand hardness and wetness criteria are the best discriminators between stable and unstable slopes (Fig. 8.9). Useful additional information was most often the structural instability index or the WG.index.

Table 8.7: Snowpack properties of unstable (n=16, avalanche fracture line profiles, spring field campaign) and stable (n=28, spring field campaign) profiles. Median values are shown for ordinal variables. For nominal variables the most frequent observation is indicated. Variables were tested using the Wilcoxon rank-sum test or the Fisher test. Significant differences between stable and unstable groups are marked by: p≤0.001 = ***, p≤0.01 = **, p≤0.05 = *, p≤0.1 = (*).

Variable	**unstable**	**stable**	**p**
HH.profile	1.76	2.54	***
mWC.profile	2.11	1.41	***
pWL [yes]	88%	50%	*
struct.index	5	4	*
WG.index	0.74	0.5	*
NP.index	0.5	1.5	(*)
PG.index	1.5	1.5	-

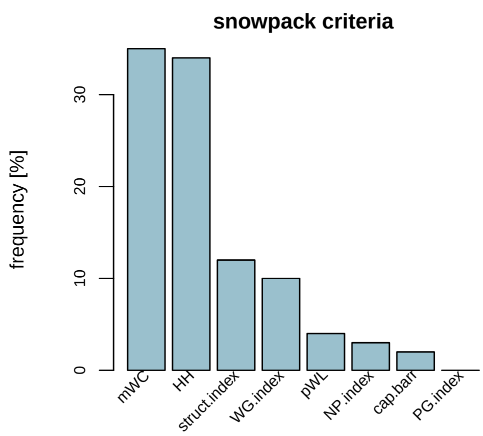

Figure 8.9: Importance of snowpack parameters for wet snow stability analysis. Regression tree analysis for 16 unstable profiles (spring field campaign, avalanche fracture line profiles) and equal number of randomly selected stable profiles (spring field campaign). Frequency of splitting variable is shown. Misclassification accuracy was 12.3%. If variable occurred at first split then weighted with 1, if variable was second split then weighted with 0.5. Variables are: mWC - weighted mean estimated water content of full snow profile, HH - weighted mean hand hardness of full snow profile, LWC.sfce - liquid water content measured at the snow surface. Index variables include the wet grain index (WG.index), the structural instability index (struct.index) and presence of persistent weak layers (pWL).

8.5 Conclusion and further research

In this chapter, the general applicability of the Rutschblock test, the Extended Column Test and the Shovel Shear Test in wet snow situation were explored and compared to existing snow stability.

Not all shear and stability tests are suitable for testing wet snow (hypothesis 1). Indeed, the results indicate that for wet snow conditions typically observed in the Swiss Alps, the Rutschblock test may be the most suitable of the three tests. The second hypothesis, "The shovel shear test is advantageous in wet snow" was based on the results from the survey (Chapter 6). However, this can not be confirmed. The Shovel Shear test failed consistently in weak, persistent layers but provides little additional information (like on fracture propagation). It is also hard to judge the strength required to cause failure. The information which can be drawn from snow stability tests is relevant for wet snow stability assessment (hypothesis 3), also has many limitations. The Rutschblock test was by far the best indicator of current slope stability if the instability criteria used is

- afternoon RB score $\leq$4.

For deep instabilities, stability tests provide some additional information (low to moderate scores, high fracture propagation potential). One helpful indication of instability could be the failure type of the test. Though, this was not consistently looked at, collapse-type failures may indicate very high instability. Unfortunately, in most cases, interpreting shear and stability tests in wet snow remains unclear. Temporal aspects, as well as surface conditions, must be considered.
Typical snowpack properties of unstable wet snow slopes exist (hypothesis 4). Based on this small data-set, the following indicators may assist in the estimation of afternoon wet snow instability:

- presence of moist, persistent weak layers
- AND/OR large parts of the snowpack are moist (weighted mean wetness of the profile mWC.profile=1.4) and very soft (mean weighted hardness HH.profile=1.9)
- AND/OR presence of structural weaknesses (struct.index$\geq$4)
- AND sufficient day-time heating to reduce the strength of the surface melt-freeze crust (LWC_{sfce} $\geq$2 vol. %)

Snow stability and snowpack observations prior to melt-events can aid in the assessment of snow stability following wetting (hypothesis 5). Applying the above snowpack criteria to representative profile observations prior to day-time melting, at a time when the snow surface is often still frozen and stable, can provide very good information on afternoon snow stability in regard to deep instabilities. Snowpack observations may best be undertaken in steep slopes

(>35°) with less than average snow-depth and relatively close to rocks. In these slopes, water may infiltrate faster and snow stability may decrease more rapidly than in other locations. Many wet snow avalanches are triggered by snow releasing from such start zones.
In conclusion: if moist, persistent weak layers are present, and if the weather forecast indicates sufficient heating to reduce the strength of the surface melt-freeze crust, unstable conditions may be encountered.

Further research should imply

- focus on collecting more data in unstable (and stable) slopes in diverse snowpack conditions
- target slope stability at the onset of wetting, when only surface layers are wet and the failure plane is still dry
- improve energy balance models to predict water production rates at the snow surface.

8.6 Acknowledgements

The data collection in the field campaign would not have been possible without the tremendous help of Adrian Räz and Christine Pielmeier. Part of the results discussed in this chapter have been presented in a small conference proceedings paper (Techel and Pielmeier, 2009, ISSW conference, Davos). Valuable feedback to this paper provided Thomas Stucki and Martin Schneebeli. Additional valuable feedback has been given by Jürg Schweizer and Christoph Mitterer.

Chapter 9

Conclusion

The introduction of liquid water into snow has a major impact on snow stability. Unfortunately, so far, mechanical properties of wet snow are poorly known. Forecasting the onset, or peak, of wet snow avalanche activity is difficult - on a slope-scale, but also on a regional scale.
Here, in this report, the focus has been on the role of liquid water on snow stability and wet snow stability assessment. For this, avalanche experts have been questioned, a data-base has been explored and field experiments were conducted.

The strength of wet snow: the role of water content and grain shape

In spring, when most of the wet snow avalanches occur in the Swiss Alps, snow stability is driven mainly by the reduction in strength rather than by changing stress patterns (Armstrong, 1976).

Indicators for the strength of snow are the hand hardness index (Colbeck et al., 1990; Höller and Fromm, 2010) and the shear strength (Jamieson and Johnston, 2001; Höller and Fromm, 2010). Micro-structural penetration resistance is correlated to shear strength (Trautmann et al., 2006). The Rutschblock score (Schweizer et al., 2008) and the Shovel Shear Test score also provide an estimate of failure layer strength (Schaerer, 1988). The strength of snow depends on snow density and grain form (Jamieson and Johnston, 2001). If density remains constant, but grain size increases, the number of inter-granular bonds must decrease (Schneebeli et al., 1999). In wet snow with increasing liquid water content, Izumi (1989) notes that decreasing snow hardness implies a reduction in the total bond area and number between ice grains.
Investigating these indicators of wet snow strength shows that grain shape, size, density, and liquid water content play a role:

- Micro-structural penetration resistance decreases at low liquid water content (>2…3 vol.%) in coarse, persistent grains (such as facets or depth hoar), but shows a slight increasing trend in fine-grained non-persistent layers (such as small round grains or precipitation particles) at low liquid water content (<3 vol.%).

- Micro-structural penetration resistance is strongly correlated to snow density for layers consisting of non-persistent grains (independent of water content). This relationship is much weaker for persistent grains, where water content plays a more significant role than snow density.

- Hand hardness, despite being a very rough estimate of strength, mirrors many of the micro-structural observations: it is consistently very low in *wet* persistent grains.

These results imply that weak persistent layers undergoing first wetting (or repeated wetting when the facetted grain shape is still well developed) don't require much liquid water to become very weak. These observations are in part supported by shear and stability test results:

- The Shovel Shear Test score is lowest in moist, very soft layers consisting of coarse persistent grains.

- The Rutschblock test score is higher in layers consisting of non-persistent grains.

This may suggest that the Shovel Shear Test is the most suitable of the tests to investigate the strength of deep, persistent weaknesses. However, the test score must be considered as a rather subjective estimation of strength (Schaerer, 1988). Also, the information gained is difficult to interpret in view of assessing wet snow stability. Collapse-type failure, sometimes observed when a moist, weak facetted base of the snowpack failed, may be a strong indicator for very low wet snow stability.
The data suggests that the decrease in strength following wetting of snow, is grain shape dependent and occurs already at liquid water contents much lower than 8 vol.%. This is consistent with first results from my BSc thesis (Techel, 2007; Techel et al., 2008b), but is in contradiction to previous research. The transition from the pendular to the funicular regime (about 8 vol.%) was noted to be the critical threshold for snow to loose strength (Bhutiyani, 1994; Brun and Rey, 1987; Kattelmann, 1985). However, already Conway et al. 1988, p. 10 observed "that the weakest layers were not always those with the highest water content". Not just water content but also grain shape must be considered when trying to anticipate changes in strength (Conway et al., 1988).
Water-saturated layers are characterized by high liquid water content and have the lowest strength (Colbeck, 1997). Such lubricated layer interfaces are considered one likely cause for the failure of wet slab avalanches (McClung and Schaerer, 2006; Peitzsch, 2008). Surprisingly, in this study shear and stability tests did not fail in, or above water-saturated layers. An observation which was also noted by Mitterer (2009) during his field campaign last spring. This contradiction leads to some questions:
Are shear and stability tests not suitable to investigate this type of failure? What role does layer-parallel capillary flow play in the formation of wet slab avalanches?

Fracture propagation in wet snow

Very little is known on fracture propagation in wet snow. Here, based on stability tests providing some information on fracture propagation, snowpack properties and their influence on fracture initiation and propagation in wet snow were investigated. To achieve this, a snow profile data-base was explored and field observations conducted. The results obtained by these two methods were not always consistent. Thus, the outcome indicates a direction rather than a conclusive statement on fracture propagation in wet snow: A fracture which can easily be initiated (for instance a low Rutschblock score), tends to propagate better than fractures requiring a lot of energy to fail. This is consistent with observations in dry snow (Schweizer et al., 2008). Fracture propagation potential is highest when these failure planes are composed of facets or depth hoar and is lower in well-developed wet grains. The few observations available for moist, non-persistent failure planes, such as small rounds or precipitation particles, indicate that fracture propagation is generally poor.
What implications has this on wet slab avalanche formation? Does this imply that: Wet slab avalanches release when the snowpack structure is still relatively intact, while large loose avalanches fail when snow is very soft, cohesionless and wet?

Snowpack properties of unstable wet slopes

For a first time, the snowpack properties of a set of unstable wet snow profiles from the Swiss Alps has been studied. These included nine wet snow avalanche fracture line profiles (years 1994...2009) and seven profiles classified as unstable (spring 2009).
Typically, avalanche failure planes are in, or adjacent to, very soft, coarse grained layers consisting of persisting grain forms or wet grains with remnants of persistent grains still recognizable. These failure layer properties are very similar to the characteristics of layers having the lowest strength and highest fracture propagation potential.
Unstable profiles are generally very soft and moist or wet (refer to Tab. E.3). Very soft, moist, persistent weak layers are present in almost all of these profiles. Further, the spring-data implies that unstable slopes have a moist or wet snow surface (melting surface-crust).

Discussing wet snow stability evolution

Applying the results discussed in the previous sections, may explain the conceptual model developed for wet snow avalanches (Tremper, 2001, Fig. 9.1e, dotted line) including information on failure layer strength and fracture propagation potential.
It is known that initial dry snow conditions depend mostly on snow structure (grain shape, size, density, Conway et al., 1988). Low density, fresh new snow, for instance, is intricately shaped. Warming and wetting will cause major alterations in grain shape and size (Conway et al., 1988). These grain re-arrangements cause a rapid increase in density (Marshall et al., 1999, Fig. 9.1a). These rapid changes are thought to be a cause for snow instability following

the onset of rain (Conway et al., 1988). The data indicates that failure planes consisting of moist non-persistent grains tend to fail with higher Rutschblock scores and that at low water content these layers exhibit significant strength (SMP: penetration resistance). Failure of non-persistent weaknesses would therefore be expected before considerable densification (and also wetting?) has occurred resulting in the failure of mixed avalanches rather than wet avalanches [1]. The role of temporary water ponding above capillary barriers, may also be a failure mechanism (Peitzsch, 2008).
Persistent grains, such as depth hoar or facets, on the other hand, had very little strength once they became wet, while fracture propagation potential remained still relatively high (Fig. 9.1b, c). This implies, that failure may occur before wetting of the failure plane occurs (if snow stability is already close to critical, Conway and Raymond, 1993, mixed avalanches), or once a persistent weakness becomes wet (wet avalanches, Fig. 9.1e).
Despite high densities, wet grains can have very little strength if the water content is high (Colbeck, 1997). Therefore, I conclude that the amount of liquid water is the key driver of stability in a fully wet-grain metamorphosed snowpack (Fig. 9.1d)
This leads to the question, if snowpack structure and failure layer characteristics are initially more important than actual liquid water content, while with prolonged wetting, it may be the wetness and associated loss of cohesion of the snowpack (Fig. 9.1d). However, the question in-how-far saturated layers at capillary barriers cause slope instability can not be answered from the data presented.

9.1 Practical implications

Methodology

The manual snow profiles, observed during the field campaign, provided good, though time-consuming and only point-specific information. The spatial interpretation of observed phenomena like snowpack structure or water content distribution is very difficult. Tools to quantitatively measure the micro-structure (Snow Micro Pen, Schneebeli and Johnson, 1998) and the wetness of the snowpack (Snow Fork, Toikka, 2009) provided very valuable information. In particular, a tool such as the Snow Fork, but of significantly lesser weight and size, would be a useful addition to improve the quality of manual snow profile observations during the melt season. Similar applies to the Snow Micro Pen: it provides highly resolved snowpack data, but ameliorations are necessary to make it more robust to handle in the field.
The approach to explore the SLF's snow profile data-base showed that generally much less data is collected in wet snow. This was especially evident in the case of wet snow avalanche fracture line profiles, with only a small number of these profiles being recorded over the years. Closer inspection of the recorded snow profiles showed some of the problems practitioners are confronted with when observing manual snow profiles: the classification of grain shape and the estimation of liquid water content. Repeatedly, inconsistencies were noted. This leads to

[1] The term mixed avalanches is used for failure of avalanches before the failure plane has been wetted, while wet avalanches refers to avalanches failing after the failure plane has become wet.

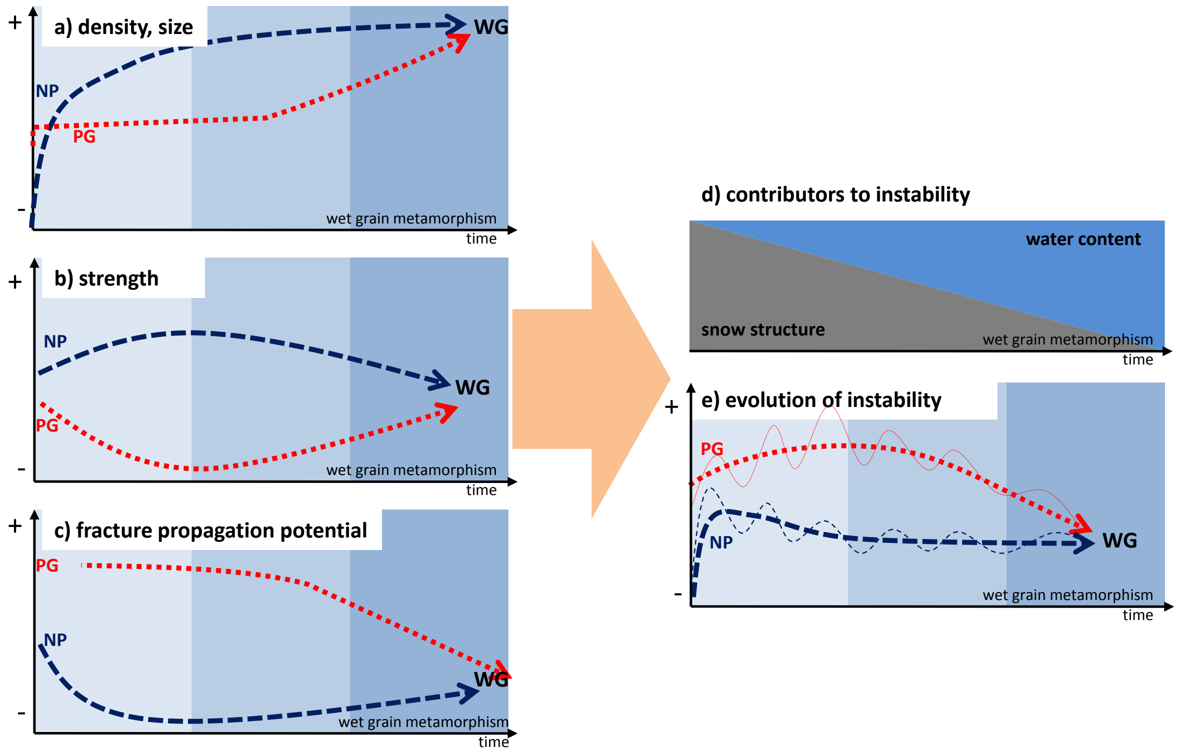

Figure 9.1: Conceptual model of wet snow metamorphism and its impact on strength (fracture initiation) and fracture propagation potential for an isothermal persistent weakness (PG, grain shapes such as facets or depth hoar) and non-persistent weakness (NP, such as precipitation particles or small round grains). a) evolution of snow density and grain size, b) evolution of layer strength and c) fracture propagation potential. d) Initial stability conditions depend mostly on snow structure, while final conditions are mostly driven by liquid water content. e) evolution of instability based on b) and c) (bold line) and the conceptual model by Tremper (2001, p. 199, thin line, representing diurnal variations).

some questions: how can incorrect observations be reliably filtered, but also, in-how-far can such a data-base be used for research purposes.

Wet snow stability assessment

Wet snow stability assessment was the main objective of this report. For this, a survey among avalanche experts was carried out, the SLF snow-profile data-base investigated and field experiments conducted.
Avalanche forecasting incorporates all available information. Most important for avalanche professionals are:

- direct signs of instability
- snowpack

- meteorological information

However, the information has varying ease of interpretability in regard of snow stability assessment. Also, the temporal validity of observations must be considered.

Signs of instability are the best observation for current stability assessment. However, if avalanches are observed, it is too late to forecast the onset of avalanching. If conditions remain similar (snowpack, meteorological information), unstable signs would indicate future poor wet snow stability. It is questionable, however, how valid these signs are for longer term forecasting. In wet snow, signs of instability are:

- avalanching
- cracking and collapsing snowpack, settlement noises (whoompf)
- large foot penetration (Tremper, 2001)

Meteorological information, which was not investigated in this report, is very important: for the formation of wet snow, and hence water infiltration and secondly, the weather forecast may be the best tool to forecast the trend in wet snow avalanche activity (Tremper, 2001). Major advantages with meteorological information are reliable real-time measurements and a relatively high-quality weather forecast. Meteorological information requires a lot of interpretation, by itself it is not sufficient to explain stable or unstable conditions (Armstrong, 1976; Trautmann, 2008).

The **snowpack** is the key to wet snow avalanche forecasting (Conway and Raymond, 1993; Fierz and Föhn, 1994). Immediate avalanching at onset of melt or rain has been observed if snow stability was critical (Conway and Raymond, 1993, mixed avalanches). Often this is the case following new snow falls (Heywood, 1988; Conway and Raymond, 1993). Delayed avalanching depends very much on snowpack structure. Of particular interest are the presence or absence of persistent weak layers (Reardon and Lundy, 2004; Reardon, 2008; Tremper, 2001). Snowpack variables were investigated in detail based on observations in the Swiss Alps. Snowpack criteria, which may indicate an unstable snowpack, are:

- The **wetness and hardness of the snowpack** were often the best predictors of instability. The data indicates that an unstable snowpack is moist or wet and very soft to soft. This speaks more for instability following considerable weakening of slab and base, rather than the very first introduction of water into weak layers (Techel et al., 2008b) or the presence of a strong slab. Reardon (2008) hypothesized that slab-like properties must still exist for the occurrence of wet slab avalanches.
- The **presence of moist, persistent weak layers** is one of the most prominent features of unstable wet snowpacks and has been addressed previously (for instance Reardon and Lundy, 2004; Techel et al., 2008b). Avalanche forecasters indicated that wet

slab avalanche occurrences are more frequently observed when persistent weaknesses are present. These weaknesses were observed in the majority of unstable profiles, but they are not a sole good discriminator between stable and unstable slopes.

- The **presence of structural instabilities** was investigated by applying the structural instability index for dry snow (Schweizer et al., 2008) to the snow profile data. The failure planes of avalanches were generally less than 1 m deep and were adjacent to, or failed in, moist or wet layers consisting of large persistent grains (such as facets or depth hoar) with very low hardness. Two criteria played little role: the difference in hardness and grain size between the layer above and below the failure plane. The structural instability index alone is not a good discriminator of stable and unstable slopes.

- **Surface wetness** indicating a melted surface-crust is one important criteria of instability.

The above criteria must be interpreted with caution: the data-set is small and not very diverse (snowpack of the Swiss Alps only). Also, this interpretation may only be used for delayed avalanching (wet avalanches), not for immediate releases with the onset of melt or rain (mixed avalanches).

Shear and stability tests as tools for wet snow stability assessment were in the focus of this project. The avalanche experts had limitations on the applicability of shear and stability tests in wet snow. Consequently, they ranked the tests last as a forecast parameter. The field experiments, however, gave a somewhat mixed picture: to assess current stability, the Rutschblock score was the most significant variable. As forecast tools (for instance using morning observations for afternoon conditions), shear and stability tests ranked last, behind all the snowpack variables. This temporal limitation is a major set-back when interpreting stability test results in wet snow.

9.2 Recommendations for future research

With the unstable profile data-set being very small, it should be a priority to observe more fracture line profiles of wet loose or wet slab avalanches, preferably very soon after failure. Also, avalanche failure right at the onset of melt or rain (mixed avalanches) has not been investigated and should be included in future research. Snow-climatic, regional differences certainly exist. Therefore, future field data should also be collected in other areas of the Swiss Alps, or even maritime or continental snowpacks. The data also lacks information on stable conditions following an unstable phase (like late in the melt season).
The Rutschblock showed some potential when assessing unstable wet snow stability. However, more data must be collected, with special regard to a temporal interpretation of the test result. The development of a new method to test wet snow stability should be explored.
The Snow Fork and the Snow Micro Pen were found to be valuable tools to quickly record

water content and highly resolved penetration resistance profiles in wet snow. If an emphasis in future research lies on using these, or similar, tools in wet snow, it would be very important to automatically derive wet snow stability from such data. For practical purposes, it should be considered if improvements could be made to both tools to facilitate the use in the field. Future research should consider the application of remote sensing technology to monitor surface wetness. One option may include using these at automatic weather stations. Such information, combined with meteorological observations, would allow real-time monitoring of surface wetness. This again could be used to improve snowpack models.

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Appendix A

Liquid water content - observations and measurements

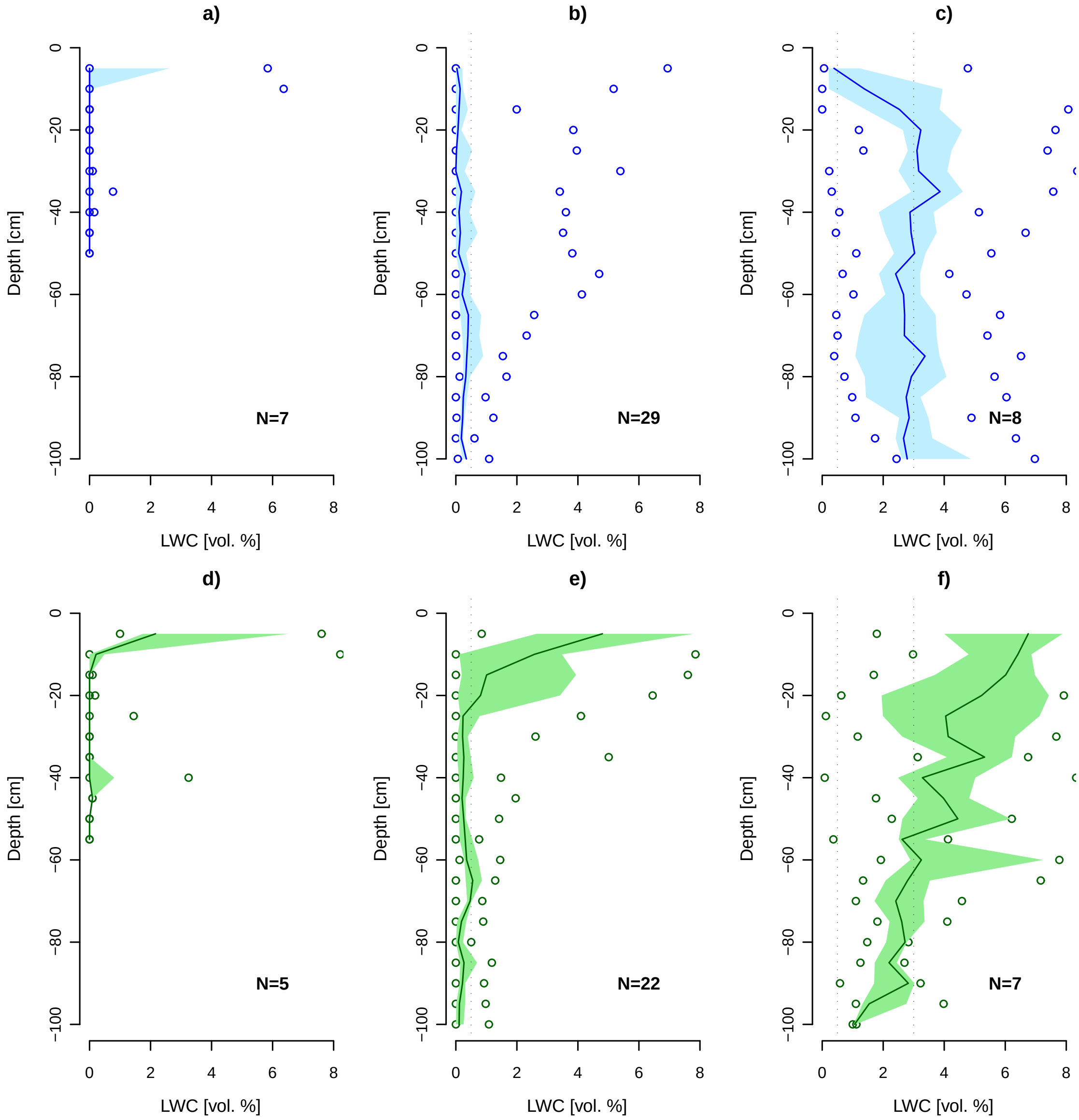

Figure A.1: a) to c) showing morning LWC, d) to f) showing afternoon LWC. The line represents the median, the shaded area the inter-quartile range and the dots the extreme values. Four groups: *1-dry* (a, d), *2-dry-moist* (b, e), *3-moist* (c, f). The last group *4-wet* has been incorporated in plot c as only two observations were in this group (Both in morning).

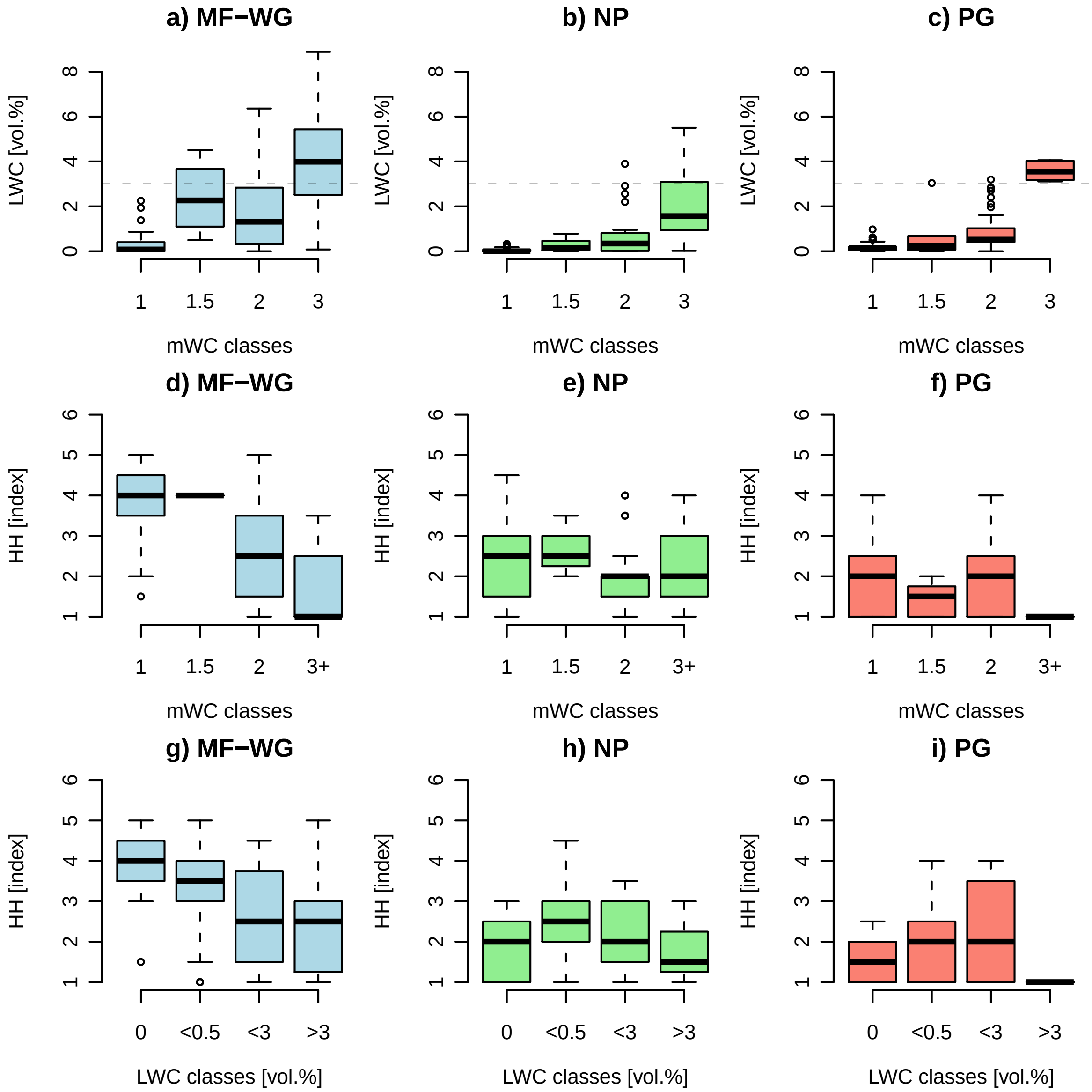

Figure A.2: Plots a to c showing estimated water content classes (mWC) to measured liquid water content (LWC) of 315 layers, plots show hand hardness to mWC classes (d to f, n=550) or to LWC classes (g to h, n=315) depending on each layers primary grain form. MF-WG - melt-freeze - wet grains, NP - non-persistent grains, PG - persistent grains. mWC classes are defined as: 1 - dry, 1.5 - dry-moist, 2 - moist (excluding moist-wet), 3+ - wet (including moist - wet and very wet) Sample sizes for the mWC class 1.5 (all grain forms) is less than 10, for PG and NP layers less than 10 observations fell into mWC class 3 or LWC class > vol.%.

Appendix B

SMP

Table B.1: Data-set 1: overview of layers during artificial wetting experiments. Layers A1, A2 and A3 were observed for the BSc thesis (Techel, 2007). Layer properties are grain form and size (SLF, 2008) as well as initial liquid water content (LWC_{init}). For all layers the number of repeated wetting and measurement is indicated (wetting, for instance dry (d) + 3 times artificial wetting), the approximate water flow rate and the number of measurements taken (micro-structure: SMP, LWC: SnF - Snow Fork, density). * - the Denoth measurement device was used to measure LWC during the 2007 experiments. Data from 2007 is only used for comparison in the discussion section.

date	**aspect elevation angle**	**layer**	**grain form size** [mm]	$\mathbf{LWC}_{init}$ [vol.%]	**wetting** (n)	**duration** [h]	**flow rate** [l m^{-2}]	**SMP** (n)	**SnF** (n)	**density** (n)
12 March 2007	S, 2660 m, 30°	A1	FC, DH, .5-3	dry	d + 3	4.5	2.0	42	33*	66
13 March 2007	S, 2660 m, 30°	A2	FC, FCxr, .5-1	dry	d + 2	2.0	3.0	21	14*	28
13 March 2007	S, 2660 m, 30°	A3	RG, .25	dry	d + 2	5.0	2.2	28	23*	46
15 March 2008	S, 2660 m, 30°	B	DF, RG, .25 -.75	dry	d + 3	3.6	1.5	20	72	36
15 March 2008	S, 2660 m, 30°	C	RG, DF, .25 -.75	dry	d + 3	3.6	1.5	20	96	48
13 April 2008	N, 2300 m, 21°	D	DH, FC, 1 - 4	dry	d + 6	4.1	3.8	35	142	117
13 March 2009	N, 1560 m, 8°	E	PP, DF, RG, .25 - 1	dry	d + 8	4.5	5.8	27	144	72
13 March 2009	N, 1560 m, 8°	F	RG, MF, .25-1	dry	d + 8	4.5	5.8	27	144	72
16 March 2009	SW, 1970 m, 23°	G	RG, .25	dry	7	4	4.8	21	63	42
16 March 2009	SW, 1970 m, 23°	H	RG, .25	< 0.5	7	4	4.8	21	84	56
10 April 2009	NE, 2665 m, 38°	J	FCxr, 1-4	dry	d + 8	4.75	5	45	144	78
10 April 2009	NE, 2665 m, 38°	K	FCxr, DH, 1-6	dry	d + 8	5.25	5.4	45	144	76

Table B.2: Data-set 2: overview. Number (n) of layers with different grain forms is given. WG - wet grains (excluding melt-freeze crusts), PG - persistent grains, (PG) or (WG) is secondary grain form.

date	profile	aspect	elevation	slope angle	SMP	layers (n)			
			[m]		(n)	WG	WG (PG)	PG (WG)	PG
17 March 2009	18a	SW	2100	37°	3				
17 March 2009	17b	S	2100	30°	3				
17 March 2009	18b	SW	2100	35°	3				
18 March 2009	19				3				
18 March 2009	20				3				
7 April 2009	49a	NW	2410	38°	3	-	-	-	2
7 April 2009	50a	NW	2026	26°	3	2	-	2	-
7 April 2009	49b	NW	2410	38°	3	-	1	-	1
7 April 2009	50b	NW	2024	24°	3	2	2	-	-
11 April 2009	51a	NE	1950	22°	3	1	-	-	-
11 April 2009	52	E	1690	31°	3	7	-	-	-
11 April 2009	51b	NE	1950	22°	3	3	1	-	1

Table B.3: Initial $_{init}$ and final $_{fin}$ median values for the artificially wetted layers. GF - grain form, LWC - liquid water content, ρ - snow density, f - penetration resistance, sd - standard deviation, CV - coefficient of variation. Significant differences are shown (p$\leq$0.05, Mann-Whitney U-test).

layer	**GF**	**ΔLWC** [vol.%]	ρ_{init} [kg m^{-3}]	ρ_{fin} [kg m^{-3}]	$\Delta\rho$ [kg m^{-3}]	f_{init} [N]	f_{fin} [N]	Δf [N]	sd_{init} [N]	sd_{fin} [N]	Δsd [N]	**CV**$_{init}$	**CV**$_{fin}$	ΔCV
B	DF/RG	**0.6**	180	178		0.25	0.33		0.026	0.043		0.11	0.11	
C	DF/RG	0.1	191	198		0.17	0.22		0.011	0.012		0.07	0.06	
E	DF/RG	0	113	150	**37**	0.10	0.29	**0.19**	0.008	0.017	**0.008**	0.11	0.07	**-0.03**
F	RG	**2**	278	314		1.53	0.93		0.087	0.071		0.09	0.08	
G	RG	0	243	289		0.81	1.39	**0.58**	0.168	0.084		0.21	0.06	**-0.15**
H	RG	**2.9**	306	340	**34**	1.17	1.28		0.162	0.082		0.24	0.08	**-0.16**
D	PG	**3.3**	284	273		0.21	0.14	**-0.06**	0.066	0.061	**-0.005**	0.36	0.37	
J	PG	**3.2**	264	244		0.11	0.08	**-0.03**	0.047	0.025	**-0.022**	0.45	0.33	**-0.12**
K	PG	**3.1**	253	278	**25**	0.10	0.05	**-0.05**	0.062	0.014	**-0.047**	0.64	0.34	**-0.30**

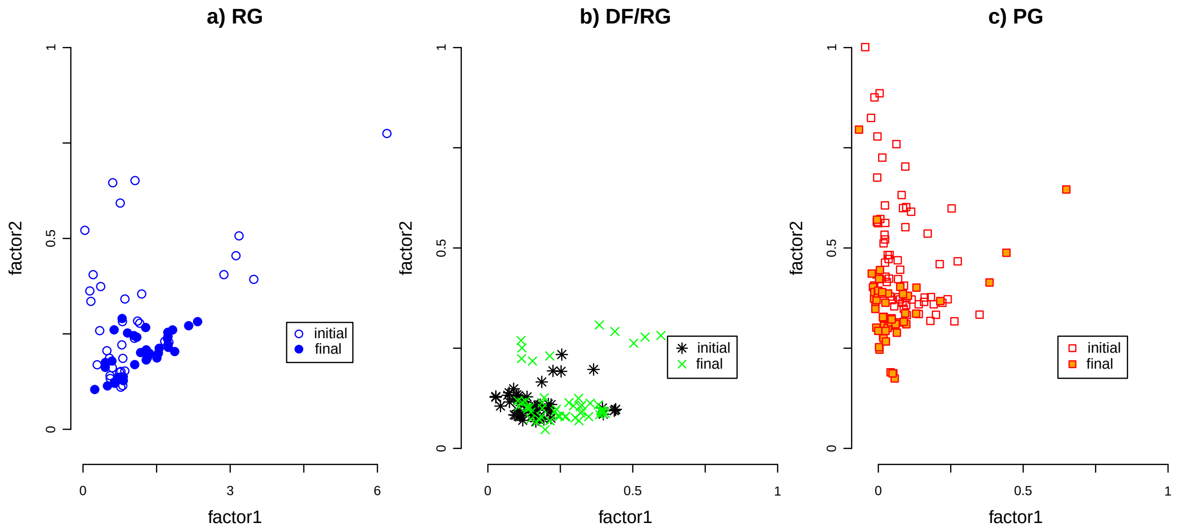

Figure B.1: Principal component analysis for artificially wetted layers, before and after wetting. Grain-shape specific plots are shown: a) small round grains (RG), b) lower-density layers consisting of decomposing precipitation particles and small round grains and c) persistent grains (facets, depth hoar, facets undergoing rounding). Initially, before the experiments, all layers were dry. After experiments (final measurements) layers consisting of persistent grains (PG) and round grains (RG) were wet with liquid water content larger than 2 vol.%, while layers initially consisting of decomposing precipitation particles and small round grains (DF/RG) remained predominantly dry, but showed densification. The mean penetration strength had strongest loadings in factor 1 and the coefficient of variation in factor 2.

Appendix C

Survey

Table C.1: Assigned weights for answers where index sums are calculated (questions 6, 9, 10, 12, 14 of the questionnaire).

index weight	**Q. 6**	**Q. 9, Q. 10**	**Q. 12**	**Q. 14**
1	one answer	often used	one preference	most important
0.5	two answers	also used	two preferences	also important
0.33	all equally	-	all important	less important

Table C.2: Overview of shear quality (Johnson and Birkeland, 2002), fracture character (van Herwijnen and Jamieson, 2003) and fracture quality (Schweizer, 2002), table based on Hendrikx (2005)

Fracture character	Typical shear quality	Likely fracture quality
Sudden Planar	Q1	Planar
Sudden Collapse	Q1	Planar
Resistant Planar	Q2	Planar or Rough
Progressive Compression	Q2	Rough
Non-planar Break	Q3	Irregular

Your forecasting area

1. **In which country / region / state / province / avalanche operation do you work?**

2. **For what kind of snow safety operation do you work?**

	(please tick all appropriate)
highway/community	
ski area	
research	
guiding (heli-ski, ski tour guiding, …)	
regional / national forecasting	
other (please name)	

Comments

If you work in several regions, please answer the following questions for your main forecasting area.

Your area's snow climate and snowpack

3. **What is the primary meteorological cause for…**
   a) … the formation of wet snow in your area?
   b) … arising concerns in relation to decreasing snowpack stability?

	a) formation of wet snow	b) decreasing snow stability
rain		
solar radiation/spring warming		
both equally		

4. **How frequently does your region experience rain-on-snow events during the main winter season (Jun., Jul., Aug.) at the elevation of typical avalanche start zones?**

frequently - about once a month or more frequently	
sometimes - once or twice during winter	
hardly ever	

5. **Are facets and depth hoar frequently observed in the snowpack prior to spring melt or rain-on-snow?**

frequently (almost every year)	
sometimes (maybe every second year or less often)	
hardly ever (maybe every fifth year or less often)	

Comments

Wet Snow Avalanches

For the purpose of this survey: a "wet snow avalanche" means all avalanches where the releasing snow is partially or fully moist or wet.

6. Are the most threatening wet snow avalanches in your area mostly…?

slab avalanches	
loose snow avalanches	
both equally	

Based on the depth of the failure plane…

full-depth avalanches (glide avalanches)	
full-depth avalanches (failure in basal layers)	
surface layer avalanches	
all	

Comments

Snow Stability Tests, Snow Stability Evaluation

A 'test' means snow stability test or shear test. "Wet snow" and "moist snow" are considered the same for the purpose of this survey.

7. **Do you use snow profile observations and snow stability tests mainly for…**

…operational purposes (i.e.: avalanche forecasting)	
…research	
both equally	

8. **Do you observe snow profiles and tests after rain or after wetting of the snowpack…**

…more frequently than in dry snow situations?	
…less frequently than in dry snow situations?	
…at the same frequency as in dry snow situations?	

Comments

9. Which test do you use most frequently in *<u>dry</u>* snow?

(please tick all appropriate)

	most often	also used
Rutschblock		
Compression Test		
Stuffblock Test		
Extended Colum Test		
others (please indicate)		
Shovel Shear Test		
I don't use any test		

10. Which test do you use most frequently in *<u>wet</u>* snow?

(please tick all appropriate)

	most often	also used
Rutschblock		
Compression Test		
Stuffblock Test		
Extended Colum Test		
others (please indicate)		
Shovel Shear Test		
I don't use any test		

Comments

11. **Do you weigh the test results in your assessment of the avalanche danger more in a dry or wet snowpack?**

more in dry snow	
more in wet snow	
both equally	
don't know	

12. **To which of the following do you give most importance in wet snow conditions?**

test score	
fracture character	
release type	
shear quality	
consider all	
don't know	

Comments

13. **Does the information you receive from your test (in wet snow) help you assess wet snow stability?**

yes	
no	
sometimes	

Comments

14. **Which of the following information do you consider** a) **important and** b) **do you have available when forecasting wet snow avalanche hazard?**

(please tick all appropriate)

	a) importance			b) availability	
	most important	also important	less important	not (or not regularly) available	regularly (daily) available
stability test results					
snowpack observations (i.e.: temperature, wetness, melt freeze crust, …)					
avalanche activity observations (i.e.: indicator avalanches)					
results from avalanche control by explosives or ski cutting					
Regional Avalanche Forecast issued by a Regional / National organization					
weather observations and forecast					
snowpack models					
other (please name)					

Comments

15. **In what situation is the wet snow avalanche hazard most difficult to forecast? Which weather and/or snowpack conditions have produced unexpected / surprising natural wet avalanches?**
    Please give one or more example situations, if possible including information to snowpack, weather, previous avalanche activity …

Bemerkungen:

Appendix D

Avalanche and Rutschblock failure planes

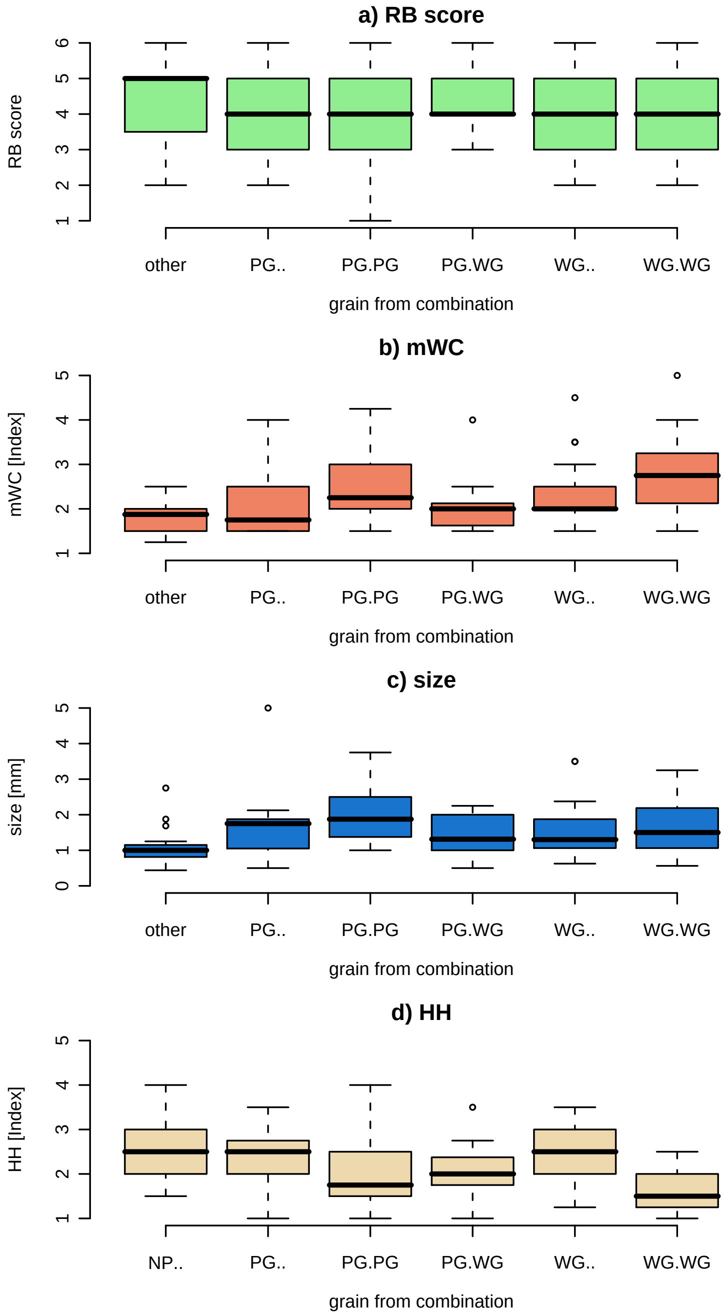

Figure D.1: Rutschblock failure plane properties. a) RB score depending on failure plane grain type combination. Failure plane properties of layers above and below RB failure planes by grain type combination. b) estimated water content (mWC), c) grain size and d) hand hardness (HH). PG.PG - persistent grains above and below, WG.WG - wet grains above and below, PG.WG - both grain forms adjacent to failure plane, WG... and PG... - these grain forms together with either (dry) melt-freeze grains (MF) or non-persistent grain-forms (NP). NP.. - grain form combination exclusively consisting of NP or MF, or mix of those.

Table D.1: Results: investigated variables for Avalanche failure planes (Aval, n = 9) and Rutschblock failure planes (RB, n = 159). Definition of variables in Tab. 7.1). Significant differences between Aval and RB data are marked by: $p \leq 0.001$ = ***, $p \leq 0.01$ = **, $p \leq 0.05$ = *, $p \leq 0.1$ = (*) and not significant $p > 0.1$ = −. (Wilcoxon rank-sum test)

Structural variable	Aval	RB	p
elevation [m]	2280	2200	–
slope angle [°]	37	35	–
hs [cm]	120	127	–
depth [cm]	55	38	(*)
RB.sc	3, 4, 6	4 (31%)	–
RB.rel (mode)	pBr (3/3)	pBr (46%)	–
RB.frac (mode)	rou (2/3)	smo (47%)	–
mWC.above	2.25	2.0	–
mWC.below	2.25	2.0	–
mWC.diff	0.0	0.5	–
mWC.max	3.0	2.5	–
mWC.mean	2.5	2.0	–
mWC.slab	2.7	NA	
HH.above	1.0	2.0	*
HH.below	1.0	2.0	(*)
HH.diff	0	1.0	(*)
HH.min	1.0	1.5	*
HH.mean	1.25	2.25	**
HH.slab	2.1	NA	
size.above [mm]	1.5	1.25	–
size.below [mm]	2.25	1.5	*
size.diff [mm]	0.25	0.25	–
size.max [mm]	2.25	1.5	–
size.mean [mm]	2.0	1.31	–
GF.comb	WG-WG (33%) PG-PG (33%)	WG-WG (23%)	*
GF.PG (yes/no)	4/5 (44%)	48/103 (30%)	
GF.(PG) (yes/no)	6/3 (67%)	71/88 (45%)	
pWL (yes/no)	6/3 (67%)	29/130 (18%)	
struct.index	4	3	(*)
struct.index (PG)	4	3	(*)
cap.barr	0	0 (64%)	–

Appendix E

Shear and stability tests

Table E.1: Significant Spearman rank-order correlations are indicated using $\nearrow$ for positive and $\searrow$ negative correlations ($p \leq 0.05$). Categorical variables were tested using either the Kruskal-Wallis test or the Fisher test. Significant differences between groups are marked by: $p \leq 0.001$ = ***, $p \leq 0.01$ = **, $p \leq 0.05$ = *, $p \leq 0.1$ = $*$ and not significant $p > 0.1$= $-$. Only failure planes are considered, which are not dry.

Variable		**RBsc** (n=24)	**RBrel** (n=24)	**ECTsc** (n=36)	**ECTprop** (n=36)	**STsc** (n=38)
Score	RB /ECT	NA	-	NA	$\nearrow$	NA
Water content	mWC.above	-	-	-	-	-
	mWC.below	-	-	-	-	-
	mWC.diff	-	-	-	-	-
	mWC.max	-	-	-	-	-
	mWC.mean	-	-	-	-	-
	mWC.slab	-	-	-	$\searrow$	-
Hand hardness	HH.above	-	-	$\nearrow$	-	$\nearrow$
	HH.below	$\nearrow$	$\searrow$	-	-	$\nearrow$
	HH.diff	-	-	-	-	-
	HH.min	$\nearrow$	$\searrow$	$\nearrow$	-	$\nearrow$
	HH.mean	$\nearrow$	-	$\nearrow$	-	$\nearrow$
	HH.slab	-	-	-	-	$\nearrow$
Grain size	size.above [mm]	$\searrow$	$\nearrow$	-	-	$\searrow$
	size.below [mm]	-	$\nearrow$	-	$\nearrow$	$\searrow$
	size.diff [mm]	-	-	-	$\nearrow$	-
	size.max [mm]	-	$\nearrow$	-	$\nearrow$	$\searrow$
	size.mean [mm]	-	$\nearrow$	-	$\nearrow$	$\searrow$
GF.comb		$*$	($*$)	-	-	$*$
depth		-	-	-	$\searrow$	-
cap.barr		-	-	-	-	-
struct.index		$\searrow$	-	-	-	$\searrow$
pWL		($*$)	-	-	**	**

Table E.2: Median values for all not-dry failure planes. Rutschblock (RB), Extended Column test (ECT) and Shovel shear test (ST). Significant differences between tests (p, Test: Kruskall-Wallis-test) are indicated with asterisk. p≤0.001 ***, not significant -. Critical range indicates the frequency of failure planes within the ranges as indicated for dry snow (Schweizer et al., 2008).

Structural variable		**RB** n=24	within critical range	**ECT** n=36	within critical range	**ST** n=38	within critical range	**p**
	depth	40	96%	33	100%	59	74%	***
Water content	mWC.above	2		2		2		-
	mWC.below	2		2		2		-
	mWC.diff	0.5		0.5		0.5		-
	mWC.max	2		2		2		-
	mWC.mean	2		2		2		-
	mWC.slab	1.69		1.86		1.84		-
Hand hardness	HH.above	2		2		2.5		-
	HH.below	1.5		1.5		1.5		-
	HH.diff	1	13%	1	25%	1	11%	-
	HH.min	1.5	46%	1	58%	1.5	42%	-
	HH.mean	1.88		1.75		2		-
	HH.slab	2.54		2.44		2.59		-
Grain size	size.above	1.25		1.125		1.5		-
	size.below	1.38		1.13		1.38		-
	size.diff	0.5	33%	0.5	25%	0.5	32%	-
	size.max	1.5	75%	1.25	64%	1.5	74%	-
	size.mean	1.19		1.03		1.31		-
Grain form	GF.above (mode)	mf (66%)		mf (72%)		mf (68%)		
	GF.below (mode)	mf/pg (46%)		mf (47%)		pg (58%)		
	GFpg yes/no	46%		39%		47%		
	GF(pg) yes/no	63%		56%		63%		
Index variables	capillary.barrier	0		0		0		-
	pWL	25%		31%		29%		-
	struct.index	3		3		3		-

Table E.3: Snowpack properties of unstable (n=7) and stable (n=28) slopes. Median values are shown for ordinal variables. For nominal variables the most frequent observation is indicated. Variables were tested using the Wilcoxon rank-sum test or the Fisher test. Significant differences between stable and unstable groups are marked by: p≤0.01 = **, p≤0.05 = *, p≤0.1 = $*$ and not significant p>0.1= $-$.

Variable		**unstable**	**stable**	**p**
Snowpack	HH.profile	1.75	2.54	*
	mWC.profile	1.94	1.41	*
	wetting.class	moist (71%)	moist (57%)	-
	LWC.sfce (min / median) [vol.%]	2.2 / 4.9	0.5 / 2.9	-
	pWL [yes/no]	100%	50%	*
	cap.barr	1.0	0.05	-
	struct.index	5	4	*
	PG.index	1.5	1.5	-
	NP.index	0.5	1.5	-
	WG.index	0.75	0.5	(*)
Tests	RBsc	4	4	-
a.m.	RBrel	wBl (43%)	pBr (32%)	-
	ECTsc	12	18.5	(*)
	ECTprop	fp (57%)	np / fp (32%)	-
	STsc	1.75	2	-
Tests	RBsc	3	5	**
p.m.	RBrel	pBr (57%)	nf / pBr (36%)	-
	ECTsc	17	20.5	-
	ECTprop	fp (57%)	np (46%)	-
	STsc	1.5	2	(*)