DEVELOPMENTS IN THE STRATIGRAPHY OF SNOW

CHRISTINE PIELMEIER* and MARTIN SCHNEEBELI
Swiss Federal Institute for Snow and Avalanche Research, Flüelastrasse 11, CH-7260 Davos-Dorf, Switzerland
* *E-mail: pielmeier@slf.ch*

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Abstract. Snow on the ground can be regarded as aeolian sediment with rapidly changing properties. We explore the Swiss (Alpine) history of stratigraphy of snow to show the trends and developments. The observation of snow stratigraphy starts in the 18th and 19th century with a geologic focus, descriptions are superficial and only verbal. In the early 20th century, the scientific interest in snow stratigraphy increases. Detailed descriptions and drawings become available. Slope scale geomorphologic features and surface processes were observed and documented. Starting from the 1940s, a shift of interest to the physical and mechanical properties in "homogeneous" layers takes place, from a slope-centred approach to a sample-centred approach. Stratigraphic description becomes one-dimensional, and the concept of well-defined layers gets accepted and still predominates today. However, all physical and mechanical processes are strongly related to the spatial variability of the snow mechanical properties. New instrumental developments show that the perceived strict layering may be a too simple model. The requirements for modern snow stratigraphy, integrating different scales and modern technology, is discussed from an international viewpoint.

Keywords: mechanical properties, physical properties, profile, snow cover, snow properties, snow stratigraphy

1. Introduction

The stratigraphy of snow, though not a discipline by itself as in soil science (USDA, 1993) and sedimentology (Selley, 1988), is important in snow research because it is the framework used when knowledge about the properties, processes and dynamics of the natural snowpack is sought. The main goal of recording snowpack stratigraphy was always to capture a physically relevant representation of the snowpack at the appropriate resolution to derive processes acting within the snowpack. Snow stratigraphy is used today as a tool in avalanche warning, snow hydrology and snow research. The *in-situ* investigation of the snowpack is commonly achieved by opening a vertical profile wall and recording at a vertical line textural properties at a resolution of about 1 cm or more. The recent development of numerical models simulating the snowpack with layers (Bartelt and Lehning, 2002; Brun et al., 1989; Jordan, 1991) and the development of highly resolving instruments and sampling (Schneebeli, 2002) shows that the classical method is at its limit. Historically the developments in snow stratigraphy follow different directions. The developments show a mix of consistent and scattered research directions, with some directions

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consistently followed, some given up and some reinvented. We assemble the ideas and discuss the requirements for a strategy of future snow stratigraphical work. A modern snow stratigraphy could contribute much to the understanding of snow processes and to the development of snow models.

2. Chronology of Developments in Snow Stratigraphy

A chronological overview of snow stratigraphy with respect to the development of methods is given in Table I. It is divided into five time periods: Prior to 1900, 1900 until the 1930s, 1940 until the 1960s, 1970 until the 1980s and 1990 until present. The qualitative and quantitative developments are listed with the names of the first author of the contribution. The stratigraphic methods are grouped in five categories. The descriptive method is the verbal interpretation of the stratigraphy. Optical methods are analog and digital optical recordings of the stratigraphy. Morphological methods capture the grain size and grain shape of snow crystals. Mechanical methods focus on the mechanical properties of the whole snowpack or layers. Textural methods serve to interpret the snowpack with combined morphological and mechanical properties. Following the Table, the developments, major advancements and trends are then summarised for each period.

2.1. The 19th Century and Earlier

2.1.1. *Descriptive Methods*

During the early 18th century the first observations of the phenomena "snowpack and avalanches" are documented by Scheuchzer (1706) in Switzerland. Snow stratification in particular is observed by Agassiz (1840), who quoted Zumstein and de Saussure as having known about it before. Tyndall (1861) observes and mentions stratigraphy of snow. The Swiss forester Coaz (1881) first recognises the relationship between the stratigraphy of snow and avalanche formation. Heim (1885), a pioneer in glaciology, observes and physically explains the reasons for the stratified nature of the snowpack and of metamorphism, as well as the changing optical properties and hardness properties during the metamorphism from new snow to glacial ice.

2.1.2. *Summary of the Early Period (Before 1900)*

The earliest documentations of snow stratigraphy are purely descriptive. The close observation of the phenomena "snow" during expeditions to Greenland, polar and alpine regions begins, where large time and spatial scales are covered. This leads to a geomorphologic-sedimentologic perception of the snow cover. For the first time systematic methods for snow investigations and avalanche observations are developed.

TABLE I

Chronology of the developments in snow stratigraphy (“quant”. = quantitative)

Period	**Descriptive method**	**Optical method**	**Morphological method**	**Mechanical method**	**Textural method**
18–19th century	Observation and description of phenomena: Scheuchzer (1706), Agassiz (1840), Tyndall (1861), Coaz (1881), Heim (1885)				
1900–1930s	Observation and description snow texture and snow surface phenomena: Paulcke (1926,1938), Welzenbach (1930), Hess (1933), Seligman (1936)	Drawings and photographs of cross-sections: Paulcke (1926, 1938), Welzenbach (1930), Hess (1933), Seligman (1936), Eugster (1938) Dye method: Welzenbach (1930), Nakaya (1936)	Collection of grain shapes: Seligman (1936), Bader et al. (1939) Grain size, 3 grain size categories for field analysis, laboratory sieve analysis: Bader et al. (1939)	Density (quant.), 2 hardness: categories Welzenbach (1930) Pressure gauge, shear frame: Eugster (1938) Finger hardness test: Paulcke (1938)	Snow surface categories: Hess (1933 Paulcke (1938) Textural classification: Paulcke (1938), Bader et al. (1939) Textural analysis: Bader et al. (1939)
1900–1930s continued		Microscopy: Seligman (1936) Thin sections (quant.): Bader et al. (1939)		Hand hardness test, 4 hardness categories, ramsonde, hardness related to failure planes: Bader et al. (1939)	
1940–1960s		Thin section analysis (quant.): de Quervain (1948) Translucent profile: de Quervain (1948), Benson (quant.) (1962) Relation spectral extinction to grain size and density (quant.): Mellor (1966)	Measured grain size (quant.): EISLF (1951) Grain shape classification: EISLF (1951), LaChapelle (1969) Snow classification (quant.): Eugster (1952) First Int. Snow Classification: Schaefer et al. (1954)	Safety index: Bucher (1948) Measured tensile and compressive strength, cone pene-trometer, hand hardness scale (fist-knife), relation to ram hardness (quant.): de Quervain (1948) Relation hand and hand hardness: EISLF (1951) Snow resistograph: Bradley (1966) Shear, tensile and compressive strength, shear frame (quant.): Roch (1966)	Relation hardness and grain size to tensile strength (quant.): de Quervain (1948) Textural analysis (quant.): Eugster (1952) Snow surface classification: CRREL (1962)
1970–1980s	Description of mountain forest snow cover: In der Gand (1978)	Thin section analysis (quant.): Good (1974, 1982) Relation radar backscatter to snow properties (quant.): Ellerbruch et al. (1977), Boyne et al. (1979,1980), Gubler et al. (1984,1986) Mountain forest snow cover drawings: In der Gand (1978), Imbeck (1983, 1987); photography:	Near surface faceting: Armstrong (1977) Extension of snow classification by the degree of meta-morphism and riming: Ferguson (1984, 1985)	Improvement of ram hardness equation (quant.): Gubler (1975) Higher resolution density and temperature measurements (quant.): Ferguson (1984, 1985) Digital resistograph (quant.): Dowd et al. (1986) Cone penetrometer	Textural analysis (quant.): Keeler (1969), St. Lawrence (1974), Kry (1975a, b) Textural parameters from thin sections: Good (1974) Textural analysis (quant.): Gubler (1978) Relation distance

TABLE I
Continued

Period	**Descriptive method**	**Optical method**	**Morphological method**	**Mechanical method**	**Textural method**
1970–1980s continued		Imbeck (1983, 1987) Thick section: Harrison (1982)		(quant.): Schaap et al. (1987) Rutschblock test: Föhn (1987a, b) Stability classification (quant.) : de Quervain et al. (1987)	between grains to tensile strength (quant.): Good (1987) Classification for mountain forest snow cover: Imbeck (1983, 1987)
1990–present		Relation FMCW radar backscatter to snow properties: Gubler et al. (1991), Koh (quant.) (1993), Holmgren et al. (1998) Translucent profile method, improved: Good et al. (1992) Surface sections vertical and horizontal: Good et al. (1992) Surface sections (3D): Schneebeli (2000) X-ray micro tomography: Coleou et al. (2001), Schneebeli, (2002) NIR photography (quant.): Haddon et al. (1997), Schneebeli (2002)	Int. Classification for seasonal snow on the ground: Colbeck et al., 1990) Snowpack model (quant.): Brun et al. (1992), Lesaffre et al. (1998), Lehning et al. (1999) SnowPit, spatial or temporal snow profile: Shultz et al. (1998)	Penetrometers: digital resistograph improved (quant.): Brown et al. (1990); SnowMicroPen (quant.): Schneebeli et al. (1998,1999); Sabre (quant.): Mackenzie et al. (2002) Weak layer analysis with Rutschblock test: Föhn (1992) Stability tests: Loaded column test (quant.): McClung et al. (1993); Rammrutsch test, Schweizer et al. (1995); Compression test (tap test): CAA/NRCC (1995); Stuffblock test: Birkeland et al. (1996); Quantified loaded column test (quant.): Landry et al. (2001) Stability classification, advanced: Stoffel et al. (1998), Schweizer et al. (2001)	Surface sections of heterogeneous snow (quant.): Good et al. (1992) Relation image patterns to mechanical properties (quant.): Good et al. (1992) Climatic snow cover classification: Sturm et al. (1995) Texture analysis (quant.): Schneebeli et al. (1999) Micro structural and mechanical model (quant.): Johnson et al. (1999) Relation NIR to stratigraphy: Haddon et al. (1997), to grain size (quant.): Schneebeli (2002)

2.2. From 1900 to the 1930s

2.2.1. *Descriptive Methods*

The first systematic snow profile documentations in the Alps are recorded by Paulcke (1926, 1938), Welzenbach (1930) and Hess (1933). They observe and describe snow stratigraphy, snow texture and snow surface phenomena in terms of grain size, hardness and humidity and also document the first systematic methods and measurements.

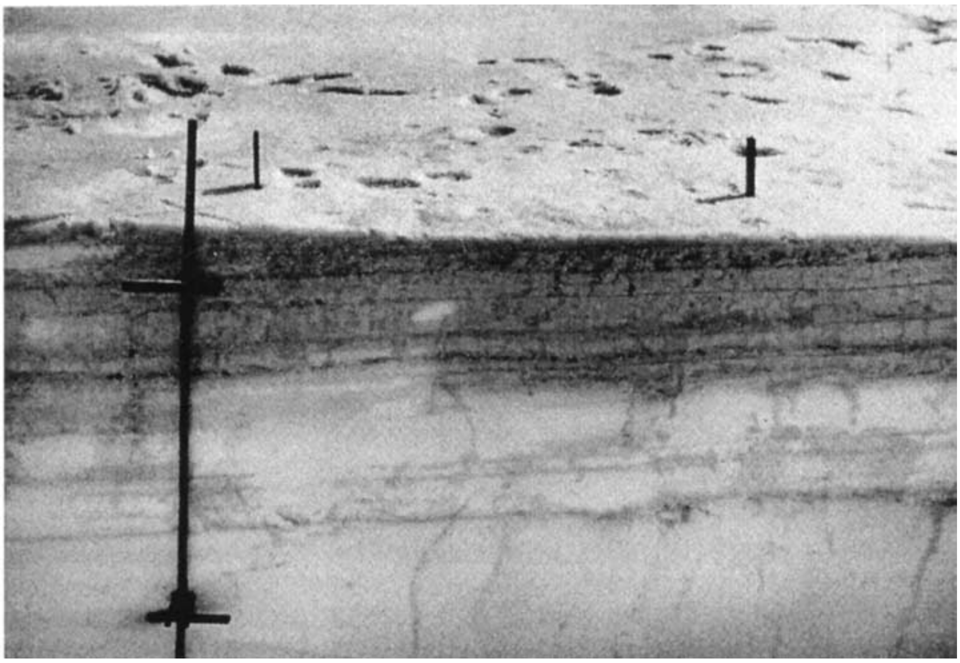
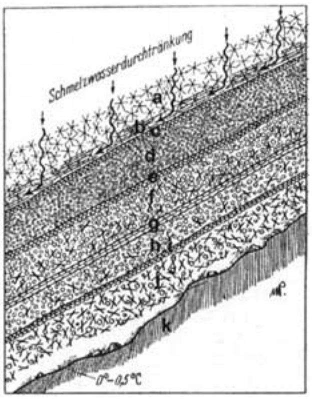


Figure 1. Snow stratigraphy proven by a dye tracer experiment (Welzenbach, 1930).

2.2.2. *Optical Methods*
Dye method: Welzenbach (1930) uses dye tracer experiments to visualise the stratigraphy of snow and its effect on water transport in the different layers (Figure 1). Nakaya et al. (1936) introduce the so-called bonfire method, where smoke is used to stain the snow profile for visualization of the snow stratigraphy. The method produces high contrast for black and white photography of snow stratigraphy.

Drawings, photography and microscopy: Welzenbach (1930) investigates cornices using two-dimensional snowpack cross sections. Paulcke (1926, 1938) deals with snow classification and stratigraphy using geological methods. He classifies the snowpack in terms of sedimented layers which may contain snow with homogeneous but also with heterogeneous properties (Figure 2), and he considers and draws the geomorphological settings of the snow cover. His snow classification is a two-dimensional approach to discrete layers and horizons with continuously changing properties. For him this information is fundamental to judge the avalanche danger on a slope. Hess (1933) detects thin separation planes in the snowpack and snow stratigraphy as suitable method to record them. His documentations are graphical and photographic, and he shows dividing planes as thin as 1 cm responsible for avalanche formation (Hess, 1933). Seligman (1932–1934) translates and expands Welzenbach's work on snow deposits. He also describes his stratigraphic methods, which are photography (cross sections of field profiles) and binocular microscopy (snow crystals). He observes and describes processes such as firnification,



a) "loose snow – new snow"
b) "slack flow, hydroplane on c) wind crust = avalanche danger!"
d) "firn, fine grained"
e) "wind crust"
f) "firn, medium grained, with singular facets"
g) "ice lamella from sun crust"
h) "firn with singular facets"
i) "crust"
j) "depth hoar with singular firn grains, development of voids = avalanche danger!"
k) "bedrock"

Figure 2. Snow stratigraphy shown in a descriptive cross section of the snowpack (Paulcke, 1938).

snow surface formation and avalanche formation based on his photographic and microscopic documents. Seligman (1936) provides a broad collection of ice forms and gives a comprehensive overview of available instruments and methods in snow research. From qualitative comparisons of cross section drawings and photographs he draws empirical conclusions about avalanche formation and metamorphism (Seligman, 1936).

Thin section: The method of thin sections and a quantified micro textural analysis of them are first introduced by Bader et al. (1939). This method preserves the texture of snow aggregates in small samples for later microscopic analyses.

2.2.3. *Morphological Methods*

From 1934 to 1938, Bader et al. (1939) carry out systematic snow and avalanche research. To record snow profiles they use mineralogical and crystallographic methods to characterise snow crystals by micro photography and microscopy. In laboratory experiments, Bader et al. (1939) focus on the detailed measurement and classification of homogeneous snow samples and isolated snow crystals. They provide a comprehensive collection of grain photographs and thin sections and lay the foundation for the analysis of snow micro structure (Bader et al., 1939). For grain size measurements they introduce the laboratory method of sieving and three grain size categories for field observations (fine, medium, coarse).

2.2.4. *Mechanical Methods*

Density, hardness and strength measurements: Welzenbach (1930) first documents measured density profiles of cornices and qualitatively distinguishes two hardness categories (packed snow and pressed snow) from visually observed textural differences. Paulcke's (1938) technique of snow profiling is visually to inspect the open profile wall before sensing the hardness differences by hand, measuring density and grain properties. He gives the first description of a hand hardness test, where snow hardness is described in terms of ease at which a layer can be penetrated by a finger. Eugster (1938) recognises the importance of thin layers and the limitations of the stratigraphic methods available. First, Eugster develops a new instrument, the shear frame, to measure the cohesive strength in layers and at layer interfaces. Then he develops the first penetrometer, a pressure gauge that measures the penetrability of snow and quantifies the cohesive strength of the snow profile. Figure 3 shows two examples of quantified and graphically documented snow profiles, including stratigraphy, morphology and mechanical strength which are amongst the first quantitative mechanical profiles that relate mechanical, stratigraphic and morphologic properties. The drawings of the morphology include gradually changing snow properties and textural variability within the stratigraphic layers. Haefeli (Bader et al., 1939) researches the mechanical properties that make a snow layer potentially avalanche active. He establishes an ordinal snow hand hardness scale with four classes (loose, soft, hard, very hard). For an objective measurement of snow hardness he develops the Swiss ramsonde from penetrometers used in soil mechanics. It has a 40 mm diameter measuring cone and a 60° included angle. Bader et al. (1939) describe the technique of snow profiles at a level study plot. The classical snow profile and mechanical ram profile can provide some characterisation of the physical snow properties but are not suited to record the data at the necessary spatial resolution. Thin and soft layers often responsible for the formation of avalanches cannot be resolved with the ramsonde. However, the advantage of in-situ tests is obvious because the handling of snow samples for laboratory analysis is difficult (Bader et al., 1939).

2.2.5. *Textural Methods*

Paulcke (1938) introduces a snow classification for homogeneous and heterogeneous layers according to grain size, grain morphology and the degree and pattern of packing, pressing and melting and gives snow surface categories. Bader et al. (1939) give a detailed description of snow profile recordings at a level study plot where the stratigraphy is established by placing a thread on the snowpack after each new snowfall to mark the layer boundaries. Temperature, density, water equivalent and vertical air permeability are determined for each layer. An example of a complex, quantified study plot profile is shown in Figure 4a. A complex slope profile where ram hardness is first related to an avalanche failure plane is shown in Figure 4b. Bader et al. (1939) develop the first systematic textural snow classification (Figure 5) which combines ordinal grain size and hardness classes. Bader et al. (1939) first document time-profiles, which show the seasonal development of the snowpack by graphically interpolating a series of bi-weekly snow profiles. A quantified micro-textural analysis from the thin section images is introduced by Bader et al. (1939), where principal axes are measured in the thin sections before and after deformation experiments. In laboratory experiments snow samples are exposed to compressive, shear and tensile deformation and the changes in snow micro-texture are analysed.

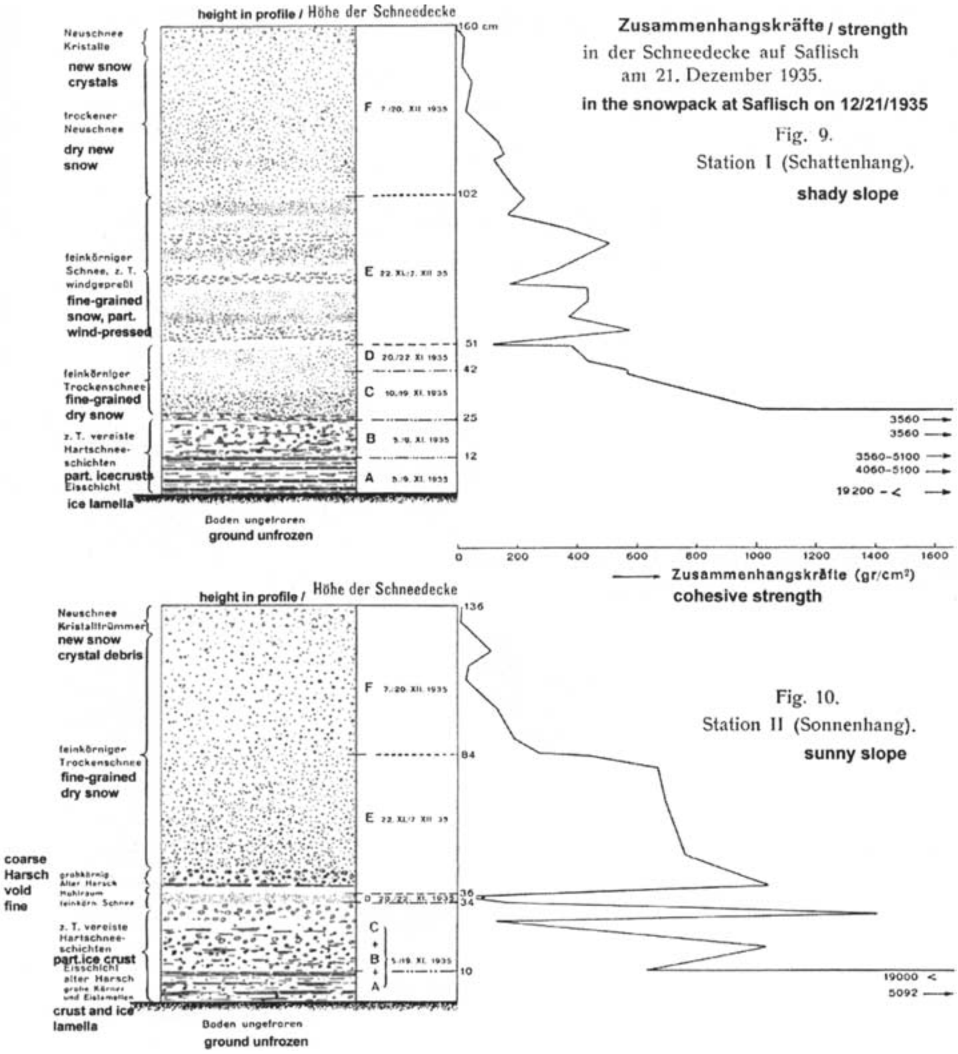


Figure 3. Two snow profiles in terms of morphology and cohesive strength by Eugster (1938).

2.2.6. *Summary of Period 1900–1930s*

In the beginnings of the 20th century different professionals, the Army and mountaineers begin systematic investigations of the seasonal snowpack. The observations and experiments are carried out during expeditions and in provisional laboratories during this period and prominent, extensive contributions are published during the 1930s. Snow morphological, mechanical textural properties become quantified and snow surface classifications are established. Special snow instruments and also analytical methods are developed to gain objective and quantitative data. A shift from large scale perception of the snowpack to a focus on the physical

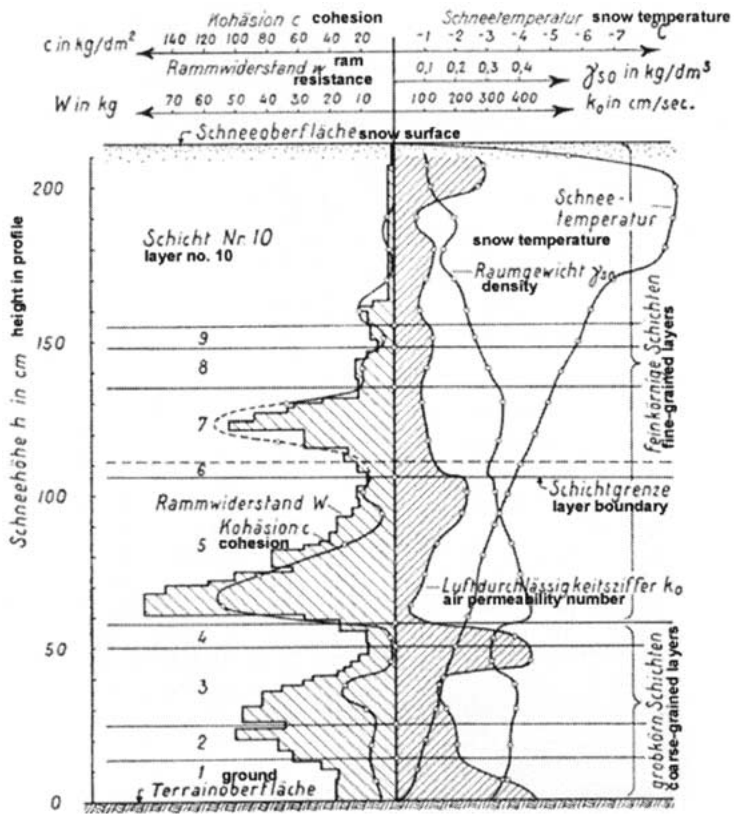


Figure 4a. Complex snow profile taken by Haefeli on 16 February 1937 at the flat study plot Weissfluhjoch, Davos (Bader et al., 1939). Measured parameters are the stratigraphy based on the threads, ram resistance, cohesion, air permeability, density, snow temperature and grain size categories.

properties of snow samples takes place. The need for objective methods with higher resolution than those available arises.

2.3. From 1940 to the 1960s

2.3.1. *Optical Methods*

Thin section, translucent profile: De Quervain (1948) uses thin sections of snow samples to analyse snow texture. De Quervain (1950) shows the first translucent snow profile in correlation to classical snow stratigraphy and different snow hardness measurements (Figure 6). Benson (1962) uses pit wall and thin section photography to establish a correlation of the strata of high and low density with dark and light strata on the thin section photos.

Spectral extinction: Studies on optical properties of snow and their relationship to grain size and density are presented by Mellor (1966). The spectral extinction in

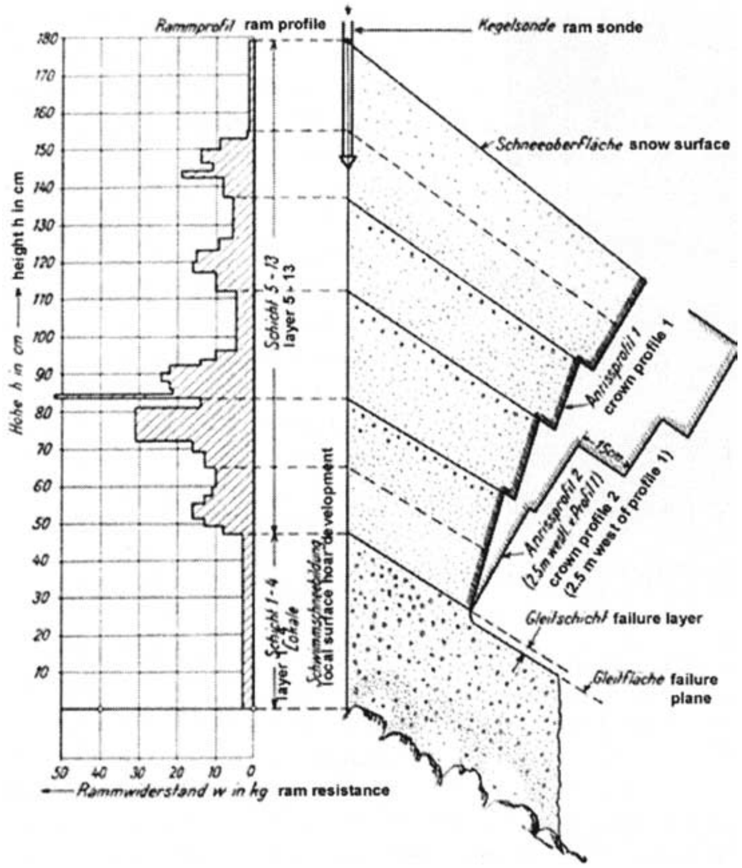


Figure 4b. Complex slope profile taken by Haefeli above an avalanche crown (Bader et al., 1939). Measured parameters are the stratigraphy based hardness differences and ram resistance. Grain size and morphology are only drawn.

snow is applied to the measurements of snow structure and for the remote sensing of snow-covered terrain.

2.3.2. *Morphological Methods*

Measured grain size and grain shape symbols are included in the snow profiles at the level study plot Weissfluhjoch, Davos (EISLF, 1951). Eugster (1952) recognises that grain diversity is important and introduces a morphological classification accounting for the actual variability of the grain shapes within one stratigraphic layer. Figure 7 illustrates this system where a grain shape distribution in quantiles of tenths is given (Eugster, 1952). This advanced snow morphological stratigraphy is not followed today. The first international snow classification (Schaefer et al., 1954) is a morphological classification for solid precipitation as well as the first standard method to measure and describe snow on the ground. It defines standard units and classes for rational and ordinal parameters of the seasonal snowpack. The

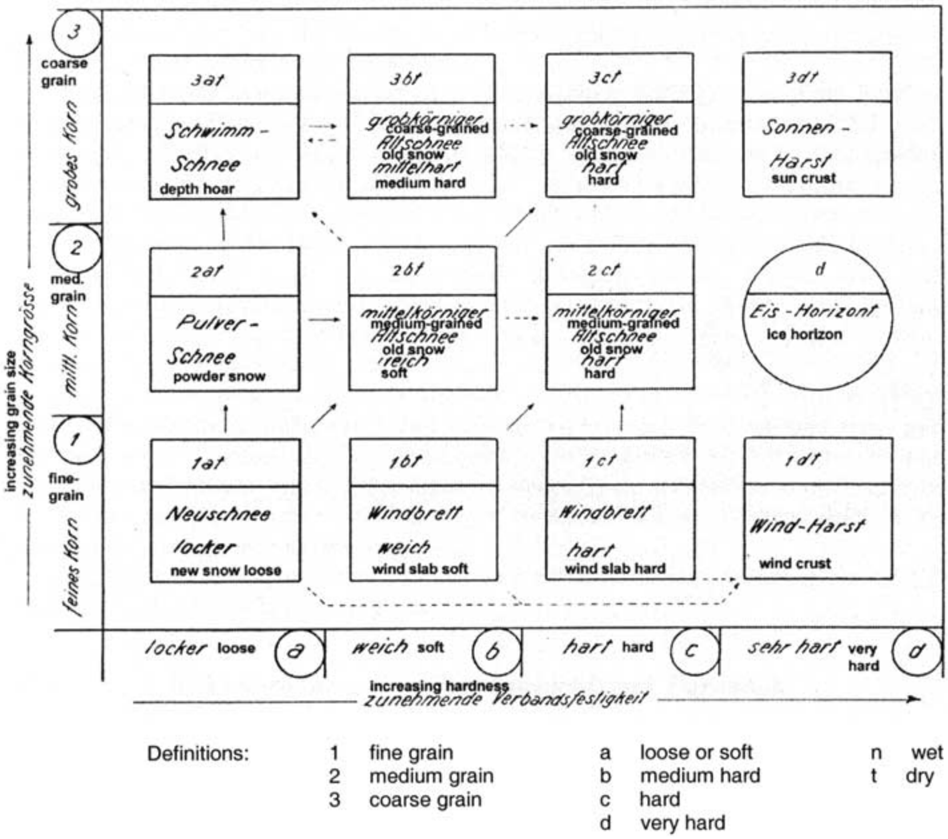


Figure 5. Snow classification system field profiles by Bader, Haefeli et al. (1939). The classification combines categories of sieved grain size and hand hardness (manual observation). Wetness and dryness are also indexed.

ordinal classes for wetness, grain shape and hand hardness are refined as compared to the previously applied schemes. Temperature and density profiles are taken in 10 cm intervals from the snow surface to the ground. International symbols for grain shape, grain size wetness and surface conditions are introduced (Figure 8). This standard reduces the snow stratigraphy to a one-dimensional record, which presupposes discrete layers with homogeneous snow properties and surface parallel layer boundaries. Only the temperature profile is drawn continuously with interpolated values between the 10 cm interval measurements. LaChapelle (1969) presents a field guide to snow crystals, which includes a photographic collection of crystal types and describes his photographic technique. Furthermore, LaChapelle (1969) shows and discusses the main systems of snow classification available: after Nakaya (1954), Magono and Lee (1966), Sommerfeld (1970) and the International Snow Classification (Schaefer et al., 1954), which are all centred on snow crystals and their individual properties.

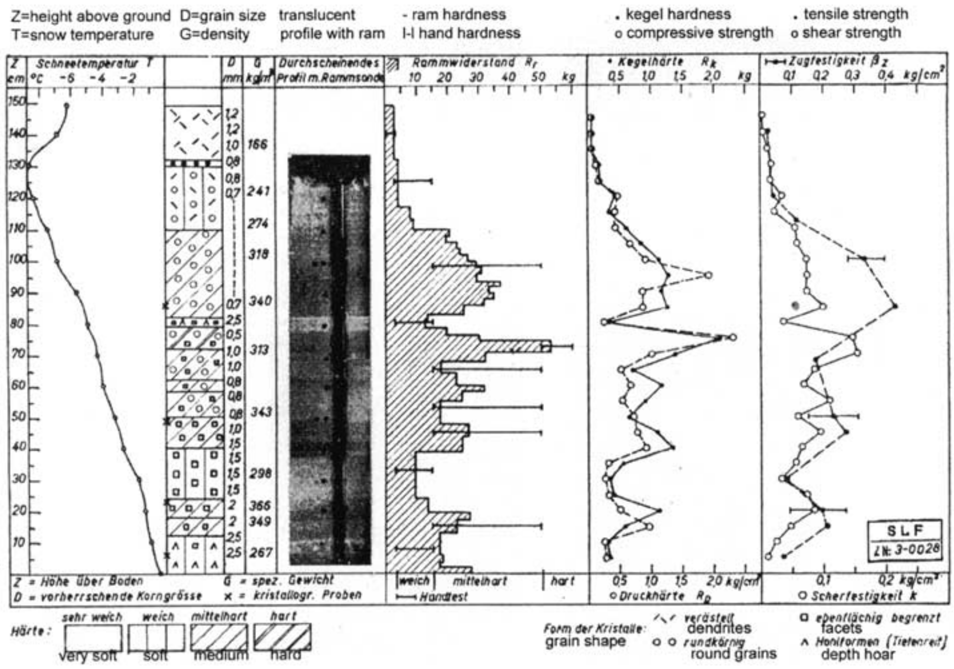


Figure 6. Snow profile taken on 1 February 1950 with a translucent profile and a comparison of hardness measurements (De Quervain, 1950).

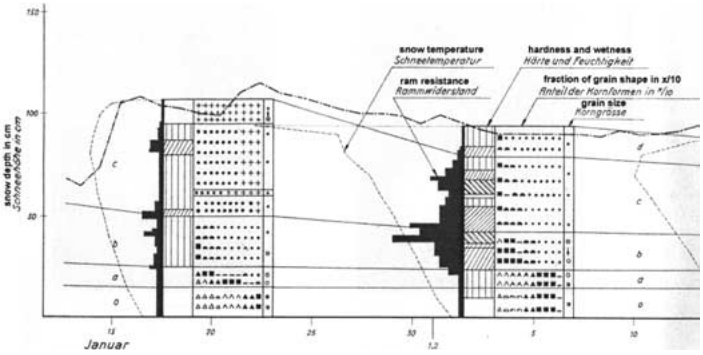


Figure 7. Vertical snow profile section according to Eugster's (1952) expanded morphological classification where fractions (in tenths) of grain shapes are given for each layer.

2.3.3. *Mechanical Methods*

Hardness and strength measurements: Bucher (1948) develops a safety index from laboratory shear experiments. The safety index relates the stresses in snow to the snow stability and gives information about the snow stability. De Quervain (1950) develops the "Kegelsonde", a small hand-held indenter with a cone diameter of 10 mm and a cone angle of 60° for individual layers. De Quervain compares three different penetrometers: The ramsonde (vertical measurement), the "Kegelsonde"

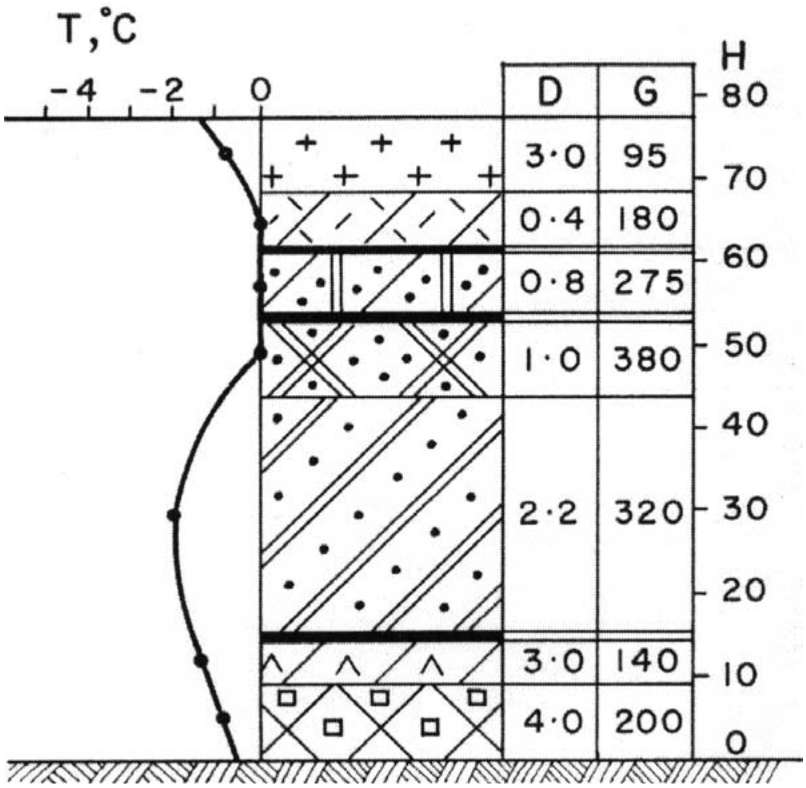


Figure 8. Vertical snow profile section according to the International Snow Classification (Schaefer et al., 1954). *T* is the snow temperature in °C, *D* is the grain diameter in mm, *G* is the gravimetric density in kg m^{-3}, and *H* is the profile height in cm.

and the pressure gauge (Eugster, 1938). The correlation of the resulting profiles to the absolute scale determined from tensile and shear strength of snow is not satisfying and only crude comparisons can be made (Figure 6). De Quervain finds that at equal ram hardness coarse grained snow has a lower tensile strength than fine grained snow. Hence, a better correlation can be achieved when grain size is included into the analysis. The parallel translucent profile photography supports this proposition. At the same time, de Quervain (1950) proposes the use of an extended hand hardness test with five classes that correlate to ram hardness. His hand hardness classification is still used today. To improve the shortcomings of the ramsonde and to assess snow stability, Bradley (1966) develops the snow resistograph with an upward moving snow blade. It records the resistance on the blade and gives a immediate graphical output of the hardness profile. The angle of the blade is about 10° and the surface area is 6.7 cm^2. Despite its clear advantages over the ramsonde it never became widely used, perhaps due to the weight and cost of the new instrument. Roch (1966) documents field tests in tension and shear to study the ratio between shear and tensile strength of snow. He also analyses the relationship of the tensile strength of snow with varying temperature, time, overload and metamorphism.

2.3.4. *Textural Methods*

De Quervain (1948) analyses snow texture, the arrangement of grains in the snow aggregate, by determining the spatial orientation of the grains in thin sections of snow samples but cannot establish a good relationship of the texture data and the snow mechanical properties with the methods available (ram hardness, tensile and compressive strength). He proposes to continue to focus on grain shape as an important factor for snow strength. Eugster (1952) applies a quantitative texture analysis method to snow that was originally designed for the textural analysis of geological bodies (Sander, 1950). Eugster shows that the relative bond diameter is correlated with the tensile strength of snow. This approach combines snow mechanical behaviour and snow textural properties. Eugster attributes the scatter of the data to his assumption of idealised spheres in his theoretical model underlying the textural parameters. This analytical snow textural approach was later readopted by Keeler (1969) and Kry (1975a, b). In 1962, instructions for making and recording snow observations are issued in the United States (CRREL, 1962) which provide guidelines for recording the physical features of Arctic snow covers. Snow cover magnitude, distribution and variability are important aspects. The defined layers represent major storm-precipitation or high wind drift periods and annual accumulation boundaries. The stratigraphy is established by the observation of textural and hardness differences. Snow properties are recorded according to the International Snow Classification (Schaefer et al., 1954). A classification for snow surface conditions is newly introduced (CRREL, 1962). Benson (1962) traverses Greenland and uses snow and firn stratigraphy to establish the state of the mass balance of the ice sheet. He uses the spatial variability of the snowpack to reconstruct storm events. For large scale observations (20–40 km) Benson (1962) develops a specific glacial climate snowpack classification system, which is based on altitude and climate on the ice sheet.

2.3.5. *Summary of Period 1940 to 1960s*

This period brings about the first International snow classification, which focuses on the grain size and shape of disaggregated snow crystals. A collection of international grain shape classifications is issued as a field guide to snow crystals. It is also the period when the systematic analysis of physical and mechanical properties of homogeneous snow samples starts and many laboratory experiments are carried out. Snow surface characterisation is advanced and a snow surface classification is presented. New instruments to capture snow hardness and snow strength are developed and compared and the ram and hand test are combined. Translucent snow profiles illustrate the high variability of snow stratigraphy and snow properties in natural snow profiles and show that stratigraphic description is incomplete.

2.4. From 1970 to the 1980s

2.4.1. *Descriptive Methods*

Systematic investigations of the mountain forest snow cover are carried out and documented (In der Gand, 1978). He empirically relates the increased stability of the snowpack on forested slopes to the textural inhomogeneity inherent in these profiles. Mountain forest snow cover variability is further described by Imbeck (1983, 1987).

2.4.2. *Optical methods*

Drawing, photography: Cross section drawings are used by In der Gand (1978) to document snow profiles of mountain forest snow covers. He illustrates the large vertical and horizontal variability of the mountain forest snow stratigraphy. Imbeck (1987) uses cross section drawings and photography to record mountain forest snow covers.

Thin section, serial section, thick section: Good (1970) develops an automatic laboratory method to photograph and analyse snow structure from thin sections via the optical properties of the samples and presented numerical parameters to identify snow structure (Good, 1974, 1982). Good (1987) uses thin sections, serial planar sections three-dimensional analysis in his image analytical work. The distance between grains is the best single parameter to characterise the micro structure of different snow types and a relation to tensile strength is established (Good, 1987). For irregular grain shapes, a three-dimensional analysis of the geometry of the snow structure is necessary (Good, 1989). Harrison (1982) develops a thick section sampler for large snow profile samples. With this technique, bulk profile sections up to 1 m height are prepared for photography on a light table. A comparison to the bonfire and dye-techniques shows improvements in the layer resolution of the snow profiles.

Radar: The relationship between the electromagnetic scattering properties and the physical properties of the snowpack is first presented by Ellerbruch, Little et al. (1977) and Boyne and Ellerbruch (1979, 1980). With a ground-based FMCW active microwave radar system (8–12 GHz) stratigraphy is observed and snowpack water equivalent is measured with $\pm 5\%$ accuracy. Gubler and Hiller (1984) develop a ground-based microwave FMCW radar system and interpret density discontinuities from the backscatter. Continuously changing properties cause refractions that are difficult to interpret. Figure 9 (Gubler and Weilenmann, 1986) illustrates the problem of correlating the physical radar spectra with the classical stratigraphic parameters. In snowpacks with homogeneous density, such as polar snowpacks or wet alpine snowpacks, water equivalent estimations are possible (Fujino and Wakahama, 1985; Gubler and Hiller, 1984). The method has potential use for snowpack monitoring, but improvements in four areas are necessary: the relation of physical

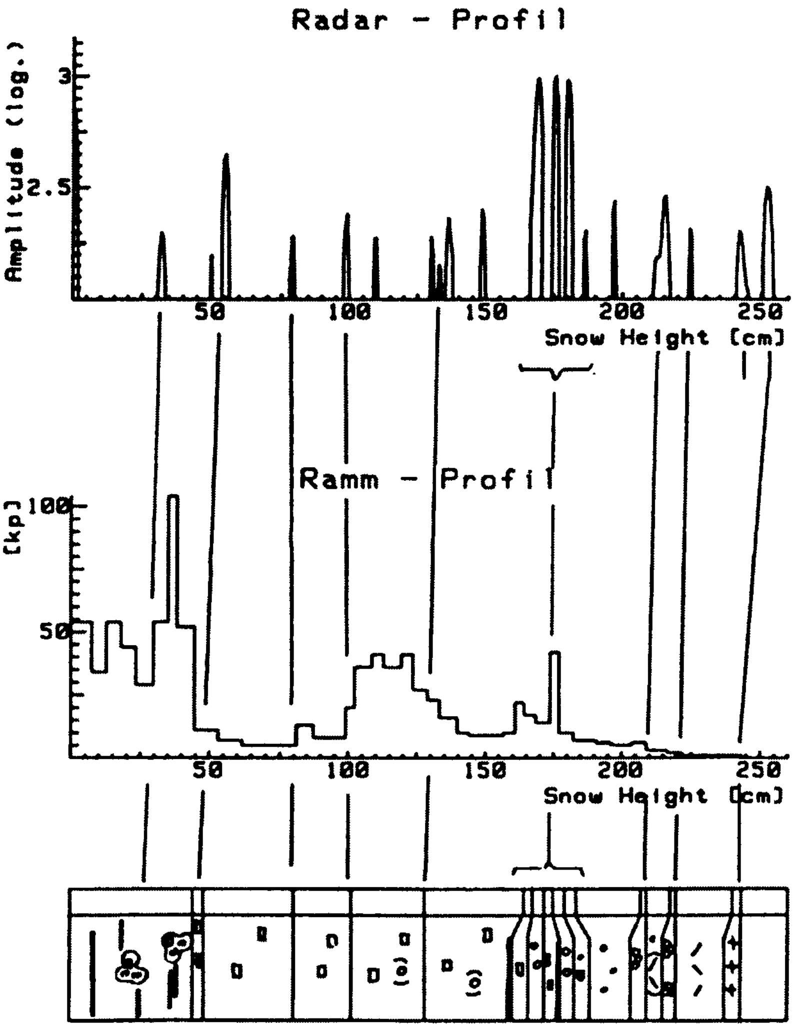


Figure 9. A comparison on radar spectra to classical snow stratigraphic parameters (Gubler and Weilenmann, 1986).

snow parameters to microwave frequency, the development of theoretical models as a function of snow parameters, improvements in the measurements and elimination of ambiguities from the analysis, simultaneous analysis of hardness profiles (Fujino and Wakahama, 1985).

2.4.3. *Morphological Methods*

UNESCO (1970) issues guidelines on seasonal snow cover observations, which are later published in handbook form (UNESCO, 1981). The method of stratigraphic snow pit records is based on the International Snow Classification (Schaefer et al., 1954). Armstrong (1977) studies snowpack characteristics and its relationship to avalanche release and is first to report on sub-surface metamorphism driven by solar radiation, that produces persistent weak layers in the snowpack. These layers were mainly responsible for failures when new snow loads accumulated. Ferguson (1984; 1985) investigates the relationship of snow stratigraphy to avalanche formation. Her snow profiles are based on the guidelines of the International Snow Classification (UNESCO, 1981) but she extended her records to ratio level data wherever possible to improve the quantification of the snow stratigraphy. Ferguson (1984) extends the grain shape classification by including information on the general metamorphic state, the degree of riming, the degree of rounding (destructive metamorphism), of building (constructive metamorphism) and of bonding (wet metamorphism). Her quantitative snow profiles are a successful method to assess the avalanche potential of a slope, but direct mechanical measurements are necessary to improve the assessment of snowpack stability.

2.4.4. *Mechanical Methods*

Hardness and stability measurements: Gubler (1975) improves the ram hardness equation, but ram hardness still cannot be correlated to the strength properties of the snow because its low resolution and it is incapable to account for the inter-granular snow structure, which is responsible for the tensile strength. De Quervain and Meister (1987) present the first stability classification system from ram hardness profiles, which consists of six ram profiles types with specific stability attributes (Figure 10). Föhn (1987a) quantifies the rutschblock stability test, a practical field test developed by the Swiss Army in the 1970s, to gain an index of the stability of the weakest area in an isolated snow column (3 m^2). He correlates the rutschblock index with stability index gained from the shear frame test and with empirical avalanche activity observations. Föhn (1987b) describes special shear frame procedures and analytical methods to prove the validity of the stability index approach. St. Lawrence and Bradley (1973) compare the resistograph to the ramsonde and find a good correlation, but a much better resolution of soft and thin layers is possible with the resistograph. It is advanced in the digital resistograph by Dowd and Brown (1986), which has higher resolution (5 mm), is faster and operates at variable speed. Frequent malfunctions and lack of durability in the field are probably the reasons why only a prototype was built. Brown and Birkeland (1990) developed another prototype of the digital resistograph, with better resolution and digital data storage. The durability of the force sensor and the electronics are problematic and it was not further developed since then. Schaap and Föhn (1987) test a geotechnical penetrometer with a cone diameter of 11.3 mm and a 60° included angle and high resolution (1 mm in hard snow) and digital data storage. The signal of the probe reveals much greater variability of the snow stratigraphy and snow hardness than the classical methods, which makes the comparison of the two methods difficult. The complex signal is also not directly suited for practical avalanche warning applications, and the signal interpretation is not further advanced. Systematic investigations of the spatial variability of the snowpack and in particular its

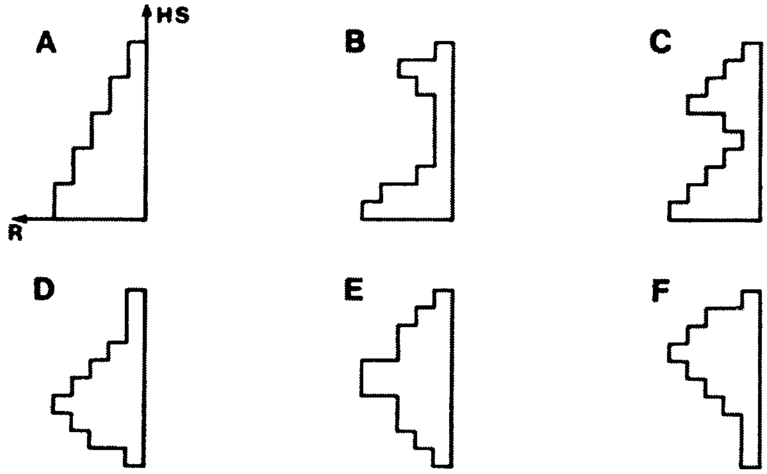


Figure 10. Stability classification based on ram profiles with stability attributes (De Quervain and Meister, 1987).

relation to snow cover stability are carried out by Conway and Abrahamson (1988) and Föhn (1988). Conway and Abrahamson (1988) find many small deficit areas (layers of small spatial extent with little strength) in the snowpack on slopes, which are related to avalanche formation. Föhn (1988) finds that many small or few large deficit areas are needed for slab avalanche formation. These two studies are the start of the investigation of the spatial variability of mountain snowpacks.

2.4.5. *Textural Methods*

The relation of snow textural parameters with snow mechanical parameters regains attention by Keeler (1969), St. Lawrence (1974), Kry (1975a, b) and Gubler (1978) who recognise that snow density only partially explains mechanical strength, because very different snow structures can exist at equal snow densities. Imbeck (1983, 1987) records forest snow covers and the effect of snow interception by trees, which causes increased textural variability and a non-parallel stratification of forest snow covers. He introduces a specialised snow classification that differentiates continuous and discontinuous layer boundaries and includes disturbances in the profile.

2.4.6. *Summary of Period 1970–1980s*

The undisturbed snow texture, which consists of the grains, the inter-granular bonds and their spatial arrangement gains larger scientific interest. Seismic, optic and electromagnetic methods are introduced to snow science in order to investigate snow mechanics and snow metamorphism in the textural context and highly variable snow stratigraphy and snow properties are measured. Due to the lack of reference profiles or their lower resolution the increased variability is difficult to interpret. The availability of faster computers is very useful in the advancement of image analytical methods. The importance of the spatial variability of snow stratigraphy and snow properties is reconsidered but most available methods are only suited for point measurements and the local information needs much interpretation to describe the continuous state of the snowpack.

2.5. From 1990 to present

2.5.1. *Optical Methods*

Translucent profile: Good and Krüsi (1992) refine the method of preparing translucent snow profiles by cutting it with a heated wire. They analyse the binary images with pattern recognition and linear structure analytical tools. While time consuming and delicate to prepare, translucent profiles are so far the only objective record of the complete and undisturbed stratigraphy of the snowpack. Also, an insight into the small-scale spatial variability of the snowpack properties is possible. An attempt to correlate transmissivity to snow properties fails (Good and Krüsi, 1992).

Surface section, Micro CT: The three-dimensional snow micro structure is measured and visualised by optical computer tomography (CT) from planar sections and X-ray micro-tomography (Coleou et al., 2001; Schneebeli, 2000). The methods are suitable to quantify the undisturbed snow micro structure, yet the samples are small and the measurements are costly. Schneebeli (2002) introduces a method of snow micro-tomography, where three-dimensional micro-structure of snow and snow properties are measured continuously.

Radar: FMCW radar technology is used by Gubler and Rychetnik (1991) to investigate mountain forest snow covers, but the typical irregular snowpack disturbances described by Imbeck (1987) do not appear in the radar profiles. Irregular shapes and properties produce multiple scattering of the electromagnetic waves within the snowpack, which makes such structures invisible in the resulting profile. In strongly stratified antarctic snowpack clear reflections are gained with this method (Foster et al., 1991) but a correlation to the manual snow profile is not possible. The vertical resolution is relatively low (dm – m) but the inter-annual accumulation and layer thickness on glacial ice can be reconciled from the radar profiles. Koh (1993) also partially explains snowpack stratigraphy and spatial and temporal variability from FMWC radar signals (26.5–40 GHz) but he cautions that a complete snow stratigraphy is not possible so far. Koh (1993) suggests to use multi-frequency FMCW radars to determine its usefulness in snow stratigraphy. With improved FMCW radar technology, Holmgren et al. (1998) approach the investigation of snowpack stratigraphy and show the shallow arctic snowpack in a two-dimensional radar signal cross-section. Only large density continuities produce a distinct radar backscatter. Increased resolution leads to a loss of penetration depth and ground information. Holmgren et al. (1998) conclude that snow stratigraphy cannot be resolved with the currently available radar technology.

NIR photography: Haddon et al. (1997) introduce analogue near-infrared photography (NIR) to snow stratigraphic research. Using quantitative image analytical procedures, layer boundaries are retrieved from the NIR images. Matzl and Schneebeli (2002) advance the profile preparation method and introduce digital NIR photography. From the advanced images it is possible to retrieve snow stratigraphy and a correlation of reflectivity with optical grain size is established.

2.5.2. *Morphological Methods*

The new International Classification for Seasonal Snow on the Ground (Colbeck et al., 1990) focuses on the physical snow properties in discrete, homogeneous snow layers. Measured parameters are mean grain size, grain size distribution, snow crystal morphology, bulk snow structure, and density. The classification of the snow properties is refined and new instruments and methods are taken into consideration. Lesaffre et al. (1998) determine objective grain shape characteristics from images of snow grains. The influence of snow stratigraphy on snowmelt infiltration and wet snow metamorphism is observed by Albert and Hardy (1993) who compare differences between flat open sites and deciduous forest sites on slopes. Shultz and Albert (1998) present an automated procedure for plotting the snow stratigraphy, that is based the International Classification (Colbeck et al., 1990). It is unique because of the simultaneous display of many profiles, which facilitates the qualitative analysis of temporal and spatial variability.

2.5.3. *Mechanical Methods*

Hardness and stability measurements: Föhn (1992) carries out a systematic investigation of weak layers and weak interfaces at fresh avalanche fracture lines by taking rutschblock tests, shear tests and classical snow profiles. 40% of all detected weak zones are layers with a thickness of 1–60 mm, and 60% are weak interfaces where no distinct layer texture could be recorded with the classical methods (Föhn, 1992). Birkeland et al. (1995) investigate the spatial variability of snowpack stability. Depth and average snow resistance measurements by the digital resistograph are related to terrain features on slopes. Terrain features only partially explain the spatial snowpack variability. Snow over rocks is found to be significantly weaker than in adjacent areas. Birkeland (1997) investigates snow stability and snow properties throughout a small mountain range. He finds that stability is only weakly linked to terrain, snowpack and snow strength variables after relatively homogeneous weather conditions, but strongly linked after heterogeneous weather conditions. Generally, stability decreases on high elevation and northerly facing slopes. Kronholm et al. (2002) present a method for the systematic investigation of the spatial variability of snow stability and relate it to avalanche formation. To detect and measure fracture layers and their mechanical properties a variety of stability tests are introduced. The loaded column test is introduced by McClung and Schaerer (1993), the compression test (tap test) by CAA/NRCC (1995), the rammrutsch test by Schweizer et al. (1995) and the stuffblock test by Birkeland

and Johnson (1996). Birkeland and Johnson (1999) find a correlation of rutschblock and stuffblock results. Landry et al. (2001) introduce the quantified loaded column stability test. Stoffel et al. (1998) and Schweizer and Lütschg (2001) extend the stability classification: however, this classification is still limited because it is based on the ram hardness profile and does not include thin layers. Schneebeli and Johnson (1998) develop a snow micro-penetrometer, the SnowMicroPen, for field and laboratory measurements. Its high measuring frequency and small tip yield a measurement of single bond fractures (Schneebeli and Johnson, 1998). It captures the snow stratigraphy and the snow properties more completely than the ram and hand hardness tests do (Pielmeier and Schneebeli, 2002). MacKenzie and Payten (2002) develop a field snow penetrometer.

2.5.4. *Textural Methods*

Colbeck (1991) reviews the formation and effects of the layered snowpack, describes layer formation processes and the effects which layers have on the physical and chemical processes within the snowpack. Mean properties of the whole snowpack or of the bulk structure are not sufficient. Rather the smallest element in snow stratigraphy, like a thin crust, is the controlling component for fluxes and forces within the snowpack (Colbeck, 1991). The geometric parameters gained from image analysis of translucent profiles are related to snow mechanical properties (Good and Krüsi, 1992). However, the link to a direct mechanical measurement is not made in this approach. Nohguchi et al. (1993) consider the endlessly repeated finer structure in the stratified snowpack from the viewpoint of fractals. Conway and Benedict (1994) show that a complex snow stratigraphy and spatial variability of the snow properties influences the channelling of snowmelt. Water penetration into a layered snowpack is delayed in comparison to an idealized, homogeneous snowpack. Sturm et al. (1995) introduce a climatic snow classification with six classes for the distribution of northern hemisphere snowpacks and their properties. The classification combines information on snowpack stratigraphy and on snow texture. The classes can be derived from climate variables and classified snowpacks can be mapped for the use in regional and global climate modelling from climate data. Johnson and Schneebeli (1999) develop a theory of penetration, which is used to recover micro structural and micro mechanical parameters from the SnowMicroPen force measurements. Laboratory experiments show that snow strength can be interpreted with a resolution of 1 mm and snow texture with a resolution of 4 mm from the SnowMicroPen force signal (Schneebeli et al., 1999). A comparison of simulated (Lehning et al., 1999) and measured snow properties shows that the SnowMicroPen can facilitate the verification of snowpack models (Pielmeier et al., 2000).

2.5.5. *Summary of Period 1990 to Present*

A new international snow classification is introduced, which is based on a morphological classification of snow in homogenous layers. Sophisticated earlier quantifications and classifications of snow textural parameters are not advanced. The newly developed methods are more or less successful in the quantitative, highly resolved representation of the snow stratigraphy. Radar investigations cannot readily capture the snow stratigraphy and properties; translucent profiles can, but the physical interpretation is difficult. X-ray and three-dimensional reconstruction from serial sections allow a three-dimensional quantification of snow micro-texture and the relation of micro textural to micro-mechanical properties is possible. For field applications, several stability tests are introduced to gain stratigraphic and mechanical information about the weakest layer in a snowpack. This information is still lacking in classical snow stratigraphy. Modern micro penetrometers are introduced and the SnowMicroPen is successfully applied in laboratory and field investigations. With the method of digital near-infrared photography of snow profiles, the snow stratigraphy and grain size can be quantified from the images. The investigation of the spatial variability is readopted; methods for a systematic investigation are now available and become used.

3. Summary

There are different requirements in snow stratigraphy: (1) a representation of the snowpack properties for climate change studies on polar snow and firn; (2) a representation for slope stability assessment in avalanche warning applications; and (3) a physically relevant snowpack representation for the research of complex snow processes and for development and validation of snowpack models. In the first application the stratigraphy and water- and gas-transport properties of the polar snowpack have to be reconstructed in great detail. Secondly, the weakest layer has to be identified in a mountain snowpack. This is achieved by a stability test and the snow profile documents the gross snowpack structure and weak layer properties. The third application requires a comprehensive and physically relevant snowpack representation. The classical snow profile only partly fulfils these requirements. It is based on expert knowledge, and its reproducibility is unclear because no comparative studies are available. The available comparisons of classical snow profiles with translucent profiles show that the two methods yield different stratigraphies with greater variability in the translucent profile.

It is not possible to draw physically relevant parameters from the classical snow profile. The record is reduced to a point measurement and its spatial representativeness is unclear. Snow stratigraphy, however, is a highly complex system and it has to cover different spatial and temporal scales. The most promising efforts today are the instrumental and analytical developments that yield relevant physical, quantitative and verifiable snow parameters and take into account the high vertical, lateral and temporal variability of the snowpack. Such an approach can greatly improve process studies and process simulations of the snowpack. The spatial scale at the surface can be covered by near-infrared photography and remote sensing, but the costs may be quite high. Typical digital cameras now have a resolution of more than 2000^2 pixels: the grain and eventually the grain type distribution of a snow field of 100 × 100 m can be resolved with a spatial resolution of 0.05 m, and a small scale plot (10 × 10 m) down to some tens of grain clusters. Vertical snow profiles can be done with a speed of 0.5 m/min, with a spatial resolution of 0.5 mm and texture recognition. Undisturbed surface imaging by radar will be a challenge by using new very high frequency radars (30 GHz), where a theoretical resolution of 0.005 m should be possible, at least in dry low density snow. However, radar will never measure properties like the strengths of bonds, and may develop in the near future to be a help to track layers, but not their texture. In the future snow stratigraphy should focus on sensor integration, combining several high resolution methods digitally. This will also require the use of new positioning techniques such that the properties can be geo-referenced. Additional spatial variability investigations will show whether scaling laws can be established, and whether the snowpack can be modelled spatially. The recent developments in snow stratigraphy challenge the general assumption of a snowpack consisting of discrete layers with homogeneous properties. The classical qualitative and gross sampling could be replaced by a quantitative and detailed sampling, giving more insight into the mechanical, thermal and hydrologic behaviour of snow. A combination of the physical approach developed during the last century with the geomorphologic-sedimentologic approach from the beginnings of snow stratigraphic research could greatly enhance the understanding and interpretation of snow stratigraphy and snowpack properties. Numerical modelling of snowpacks can now move to more objective and more physical methods for reference snow profiles.

4. Additional Material

An extended version of this review is available upon request (Pielmeier, 2003).

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