MEASURING SNOW PROFILES WITH HIGH RESOLUTION: INTERPRETATION OF THE FORCE-DISTANCE SIGNAL FROM A SNOW MICRO PENETROMETER

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ABSTRACT: The classification of snow profiles is traditionally based on the discrete interpretation of snow layers in a snow pack. The layers are discriminated according to the physical properties of the snow. To account for the micro-mechanical behaviour of snow in deformation, the classification needs to be extended to the micro-structure of snow. A new instrument, the high-resolution snow penetrometer "SnowMicroPen" has been introduced. It is a new instrument to continuously measure the snow hardness at the micro-scale. The new method of snow interpretation is described. Different quantitative approaches to interpret the penetrometer force-distance signal are shown. The penetrometer force signal reveals the great variability of the micro- and meso-properties in a snow pack. A comparison of the physical characterization of snow and the new, mechancial characterization is shown. Being able to measure the complexity of the micro-properties of snow is the basis for a snow classification that includes the deformational behaviour of snow. It is also the basis to investigate scale and spatial variability questions.

KEYWORDS: snow pack, snow profile, snow classification, penetrometer, scale, spatial variability

1. INTRODUCTION

The discrimination and classification of snow layers is the classical method to investigate the snow cover. La Chapelle (1992) reviewed various systems of classifications of snow. All the classifications described there are based on the description of types of snow crystals, how they are formed, and how they change after they have been deposited.

The International Classification for Seasonal Snow on the Ground (Colbeck et al., 1990) is also a physical interpretation of discrete snow layers. Measures are mean grain size, grain size distribution, snow crystal morphology, bulk snow structure, and density. As Colbeck et al. (1990) state, "Automated texture analysis could not be included into the International Classification due to the lack of a standard and unambiguous set of parameter definitions".

A climatic classification system was developed by Sturm et al. (1995). This classification can be derived from climate variables. Snow packs are also classified according to the textural and stratigraphic characteristics of the layers. These are the sequence of the layers, the thickness, density, crystal morphology and grain characteristics within each layer.

The physical description of snow and snow packs does not include information on the micro-structure and the bonding of snow. Bader et al. (1954) recognized that the classical snow profile and traditional mechanical tests can provide some characterization of the mechanical properties, but often are not suited to record the data at the needed resolution, i.e. at the micro-level. Subjectivity of the interpretation and lack of standard of parameters are further problems at hand. Shapiro et al. (1997) made this claim more recently. They stated that the measurement and interpretation of the snow micro-structure is necessary to study the deformational processes in snow under loading. Knowledge of the behaviour of snow in deformation is fundamental to understand the processes of avalanche release and many snow engineering questions. Therefore, Shapiro et al. (1997) see the need to extend the physical characterization to micro-structural properties that most influence deformational processes. Such a deformational classification requires a method to measure suitable properties of the micro-structure of snow, such as stress, strain and strength. With this data, constitutive

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relationships of snow deformation could be established.

In soil research, Meigh (1987) and Huang et al. (1993) showed that penetration strength is correlated to soil mechancial properties. Fukue (1979) showed this correlation in snow. Schneebeli and Johnson (1998) concerted their efforts to develop a snow micro-penetrometer, the SnowMicroPen, that measures micro-level snow grain bond ruptures. This new instrument is a constant-speed, small tip, high resolution snow penetrometer that samples the penetration force at a resolution of every 4 μm. It provides a unique force-distance signal for different snow types and Johnson and Schneebeli (1999) developed a statistical theory of penetration that recovers micro-properties of these snow types from the signal. Schneebeli et al. (1999) showed that the signal of the penetrometer can be correlated to micro-mechanical and micro-textural properties of snow. They developed a semi-empirical model to predict the micro-texture of snow from the penetration force-distance signal. Pielmeier et al. (2000) suggested that penetration tests with the SnowMicroPen will greatly enhance the snow pack model verifications.

Several quantitative methods to interpret the force-distance signal have been developed. After we give a brief overview of the new instrument, the signal interpretation methods are illustrated. The definitions of the scales at which the 1-dimensional snow profile is investigated are the:

- *micro-scale*: snow bonds and grains
- *meso-scale*: snow layers
- *macro-scale*: snow profile

At all scales, geostatistical analysis is used to analyze spatial continuity. The texture index (Schneebeli et al., 1999) delivers a micro-mechanical and micro-textural classification at the micro- and meso-scale. The original force-distance signal is analyzed on all scales. Spectral analysis of the force-distance signal is a tool for the quality control of the measurement.

A direct comparison between the classic and the new method of snow profile interpretation is not possible. This is due to the quasi-continuous nature of the penetrometer measurement, where the sampling distance is significantly shorter than the size of the smallest unit in snow. A comparison of methods is made to show the additional information gained from the force-distance signal about snow micro-structure and its variability.

Finally, an outlook on the 2- and 3-dimensional measurement and analysis of the micro-penetrometer measurements is given.

2. THE SNOWMICROPEN

Starting in 1995 Johnson and Schneebeli worked independently to develop a penetrometer with high spatial resolution that could detect fine layering and micro-structural effects. Their independent efforts have been combined to eventually develop the SnowMicroPen, seen in Fig. 1. The instrument can measure snow at very high resolution and it gives information on the mechanical properties at the micro-scale. The fundamental concept is that a continuously recording, small diameter penetrometer will make a more direct connection to micro-properties than do large diameter cone penetrometers (Johnson and Schneebeli, 1999).

The maximum length of a penetrometer measurement is 160 cm and the measuring speed is 20 mm s^{-1}. The penetration resistance is recorded dynamically at a sampling distance of 4 μm. The force sensor has a very high measuring range (-500 N to 500 N), which allows to cover the whole spectrum of hardnesses that may occur in a natural snow pack.

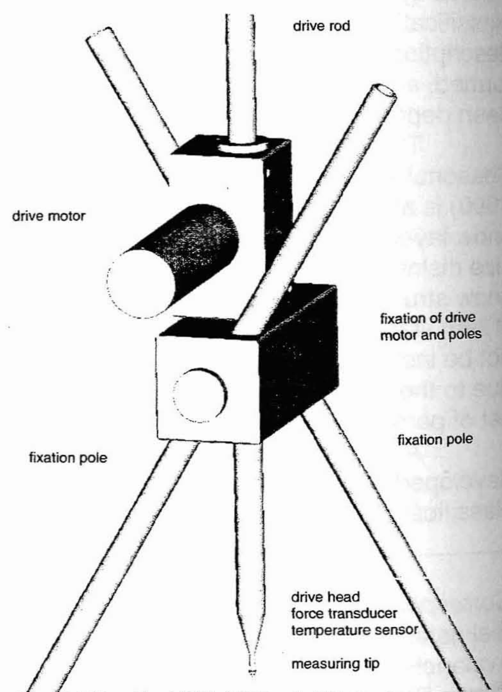

Figure 1: View of the SnowMicroPen

During the last year, the SnowMicroPen for field applications has been advanced and the device was built more robust. Also, the operational software has been improved. A temperature correction is used to offset the drift of the force signal that occurs if the sensor experiences a temperature gradient during the measurement (Schneebeli, unpublished).

3. INTERPRETATION OF THE PENETROMETER FORCE-DISTANCE SIGNAL

In the following, the signal interpretation methods that have been developed are illustrated and the applicable scales are mentioned. The penetrometer force-distance signal is analyzed here for 1-dimensional snow profiles.

3.1 Analysis of micro-scale texture using the original force signal

The micro-penetrometer provides a unique signal for different snow types. The force signal in Fig. 2 and Fig. 3 are illustrated over a range of 4 mm. The measurement in Fig. 2 was taken in round-grained, decomposed snow. Statistical analysis of the signal gives a mean of 0.25 N. The distribution of the force values is symmetric about the mean and the signal is always above zero force. In contrast, Fig. 3 is an example of a force signal measured in faceted, temperature gradient metamorphosed snow. The mean force in this snow is at about 0.1 N, the distribution is negatively skewed and zero force values reoccur throughout the measurement.

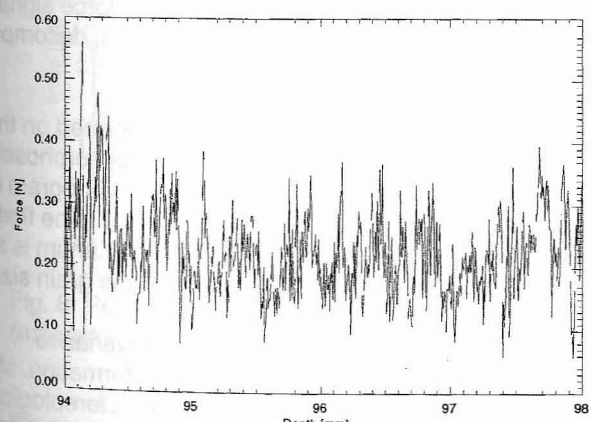

Figure 2: Force signal measured in round-grained decomposed snow.

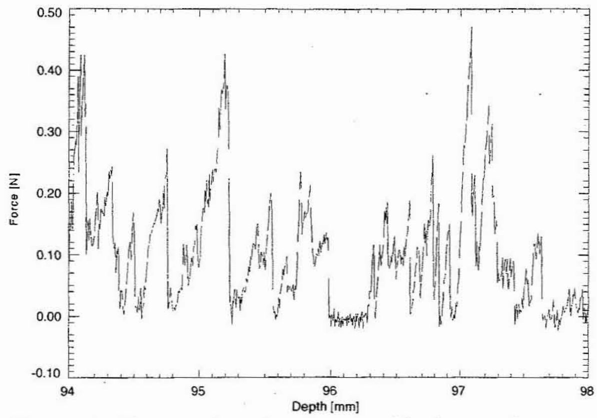

Figure 3: Force signal measured in faceted temperature gradient metamorphosed.

The high resolution of the measurements provides information about the snow grain bond ruptures during the measurement. The different micro-texture of the two snow types is clearly represented in their penetrometer force-distance records.

3.2 Analysis micro- and meso-scale spatial continuity using semivariance analysis

A tool to quantify spatial continuity in a measurement is the semivariance analysis. The the force signal reveals the spatial continuity at the micro-and meso-scale. It is shown, how we can retrieve micro- and meso-textural information from this geostatistical signal analysis. Fig. 4 is the h-scatterplot for the round-grained, decomposed snow sample in Fig. 2. The h-scatter plot is the force record at a distance x+h (h=1 mm) as a function of the force record at a distance x (Isaaks and Srivastava, 1989). The distance between the spatially related force values is called the lag-distance or the lag. As the lag distance is increased, the similarity between pairs of values decreases and the points on the h-scatter plot spread out further from the diagonal line, where h=0.

The semivariogram summarizes the relationships between all possible pairs of force separated by distances from 0 to a defined maximum distance, i.e. it is the summary of all possible h-scatter plots. As the paired force values on the h-scatterplot become less spatially related, the semivariance $\gamma(h)$ increases. The semivariance at a certain lag is calculated from the following:

$$\gamma[N^2] = \frac{1}{2n} \sum (x_i - y_i)^2 \quad \text{for } i=1,....n$$

It is half the squared difference between force values at the x and y coordinates on the h-scatter plot measured at the lag distance to the 45-degree line, where x=y.

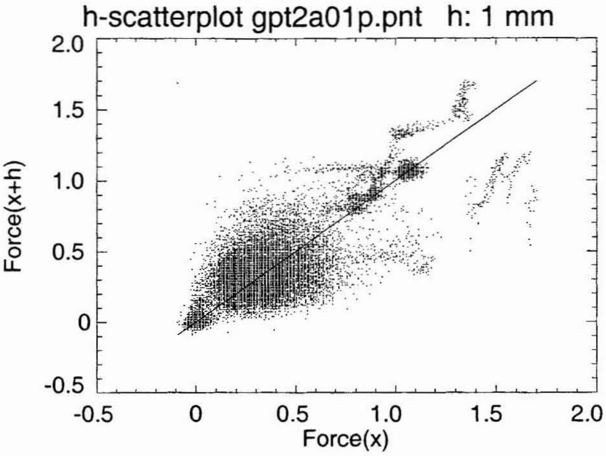

Fig. 4: H-scatterplot with a lag distance (h) of 1 mm. It shows the spatial relationship of the force values at the location x to the force value at the location separated by the distance h.

Eventually, an increase in the lag distance no longer causes a corresponding increase in the semivariance and the curve reaches a plateau, called the sill. Although the semivariogram for a lag=0 is theoretically 0, extremely short scale variability such as the noise of the force signal cause the vertical jump from the origin of the semivariogram to the value of it at extremely small distances. This is called the nugget effect. Fig. 5 shows the semivariogram for the unfiltered signal of a round-grained decomposed snow sample also shown in Fig. 2.

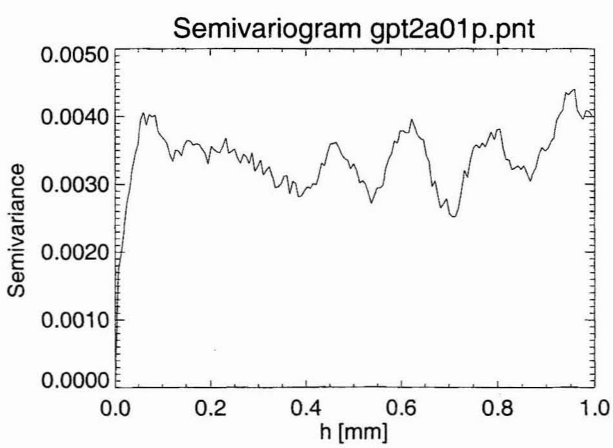

Fig. 5: Semivariogram showing spatial continuity up to a lag distance of 0.075 mm.

The semivariance is calculated with a lag distance of 1 point (which is equivalent to the sampling distance). The semivariogram is shown for a range of 1 mm.

Spatial continuity at the microscale exists in this snow type up to a lag distance of 0.075 mm, which is equivalent to 33 force readings of the penetrometer. The noise of the signal is contained in this range. The sill of the variogram is reached at 0.0035 N^2. At a lag distance of 0.8 mm a minimum variance is reached. This corresponds to the interbond distance which is assumed to correspond to the grains size in this well defined snow sample. When filtering the noise of the signal with a boxcar average filter with a length of 0.2 mm, the semivariogram reveals a larger scale of spatial continuity at about 4 mm which can be attributed to some fine layering in the snow sample. Fig. 6 shows this second sill at about 0.001 N^2. The reduction of variance by a factor of about 10 by filtering the force signal shows that most of the variability stems from the noise.

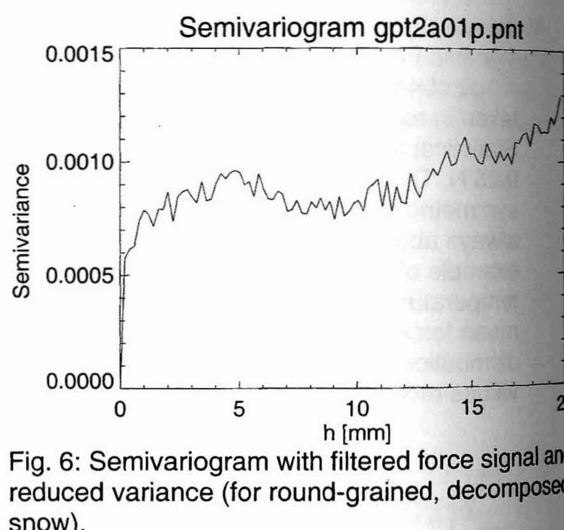

Fig. 6: Semivariogram with filtered force signal and reduced variance (for round-grained, decomposed snow).

The same analysis is performed on the faceted, temperature gradient metamorphosed snow as shown in Fig. 3. The semivariogram of the unfiltered signal is show in Fig. 7. The first sill is at about 0.75 mm and the first minimum is at 2 mm, which again corresponds to the grain size in this sample.

The results from the semivariance analysis indicate micro-textural information. More samples need to be analyzed and stereological analysis of bond properties need to be correlated to this signal analysis.

Semivariance analysis of the force-distance signal are a new method to retrieve micro-textural information of the snow as well as about meso-scale layering in a snow sample.

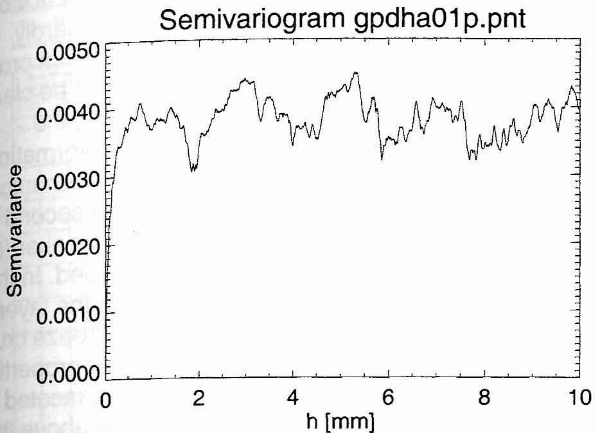

Fig. 7: Semivariogram with unfiltered force signal of faceted, temperature gradient metamorphosed snow.

3.3 Analysis of micro- and meso-scale snow hardness and texture using the texture index, and of discontinuities using the force signal

Based on the statistical signal analysis of the force signal, Schneebeli et al. (1999) developed a semi-empirical model to classify different snow types according to their micro-mechanical and micro-textural properties. Building on this classification of homogeneous snow samples, the interpretation is extended to natural, stratified snow profiles.

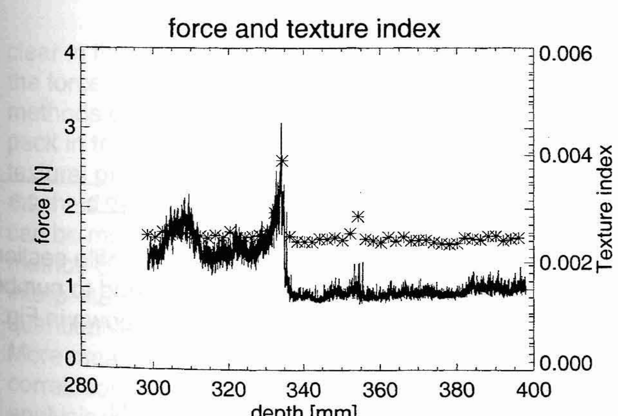

Fig. 8: Penetrometer force signal and texture index (asterisks) of a section of a natural snow profile .

Fig. 8 is the penetrometer force signal with the superposed texture index (asterisks) of a section of a natural snow profile. The profile section is of 100 mm and contains the interface of two bulk snow layers with a melt-freeze crust in the middle. The texture index (Schneebeli et al., 1999) classifies the snow hardness at a resolution of 1 mm and the snow texture at a resolution of 4 mm.

Abrupt discontinuities in the force signal also produce a high texture index, as seen in Fig. 4. However, this cannot be interpreted in terms of a snow. Such abrupt signal jumps must be classified as discontinuities in the snow texture. Therefore, the original force signal is evaluated simultaneously for abrupt force increases or decreases. The first derivative is calculated and if it exceeds a defined limit, it is classified as a discontinuity. The analysis also takes the snow hardness above and below the discontinuity into consideration.

3.4 Spectral analysis of force signal

The space-force signal is transformed into its space-frequency representation using Fast Fourier transformation (Oppenheim and Schafer, 1995). The Fourier transformation assumes an infinite, stationary signal. Since this is not the case, a small portion of the signal, i.e. a window function is used for the spectral analysis. The spectra of penetrometer measurements from 23 laboratory and natural snow samples have been analyzed. The spectral signatures of all snow types are not significantly different and it is not possible to draw a classification from this analysis. For all snow types, the highest energy lies in the the low frequencies.

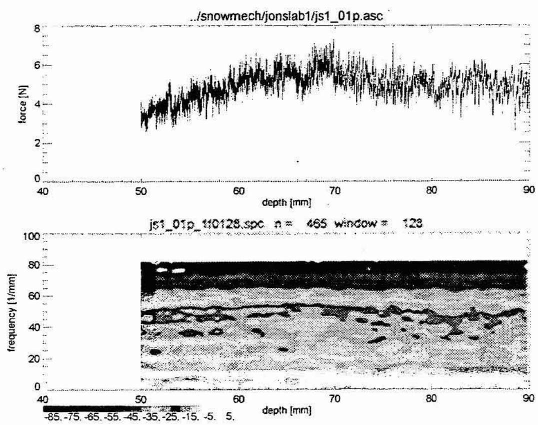

Fig. 9: Force signal and spectrum of a measurement where a failure occured at depth 65 mm. The spectral bands seen above 65 mm disappear at this depth.

However, the space-frequency representation of the signal gives insight into the quality of the signal. Failures of the sample or resonance frequencies that occurred during the measurement may be hidden in the original force signal but can be easily detected in the space-frequency representation. Fig. 9 is the force signal of a snow sample and its space-frequency representation. The sample had an internal failure during the measurement. The failure is not obvious in the original force signal. Yet, the space-frequency representation reveals the failure. The spectral bands visible at the frequencies of 10, 20 and 30 mm^{-1} disappear at a depth of 65 mm.

The spectral analysis of the force-distance signal provides a quality control tool at all scales.

4. COMPARISON OF METHODS: CLASSICAL SNOW PROFILE, PENETROMETER PROFILE, TRANSLUCENT PROFILE

In this comparison it is shown, how stratigraphy is viewed in the classical snow profile as opposed to the pentrometer profile. The way a profile is measured and interpreted by the two methods is fundamentally different. To illustrate the layer discrimination process in the classical profile a translucent profile is shown also. The translucent snow profile is an isolated thin wall of snow photographed against the setting sun.

On 1 February 2000, the classical snow profile shown in Fig. 11 was taken at the Weissfluhjoch test field by the avalanche warning service, independently from the penetrometer and translucent profile. Previous to that day a two day snow fall period brought about 60 cm of new snow that was deposited on a melt-freeze crust. Below the crust, faceted crystals developed. The upper part of the profile is used for an exemplary comparison of penetrometer, classical and translucent snow profile. In particular we look at the section of the three layers marked in Fig. 10 and Fig. 12 with numbers, new snow (1), melt-freeze crust (2), second crust (3) and faceted crystals (4) is . The box in the classical snow profile in Fig. 11 contains this profile section. Fig. 10 is the penetrometer force signal with the marked layers corresponding to Fig. 12. The penetrometer profile is shown for the section surrounding the melt-freeze crust. The depth 33 cm in the force profile corresponds to the snow height of 118 cm in the classical profile. The penetromter force above the melt-freeze crust (1) has a trend to increasing hardness from 0.25 N to 1 N. The alternation of harder and softer layers in this part of the profile can be seen in great detail. The layering is due to grain size and/or density differences that could be a result of wind influence during deposition. This layering is less obvious in the translucent profile in Fig. 12 and hardly obvious in the hand hardness and ramm profile in Fig. 11. The melt-freeze crust (2) can be clearly interpreted from all profiles, however, the penetrometer measurement gives information about the exact thickness and the mechanical hardness of this very thin layer. The second crust (3), 20 mm below the first, is much weaker (0.9 N). In the classical profile it is not recorded. In the translucent profile the brightness of the layer resembles the one of the first melt-freeze crust, which might wrongly suggest similar properties. The snow below the second crust is faceted and has a larger grain size than the one above the crusts. This is reflected in the greater variability of the force signal (4).

The comparison shows that the penetrometer profile agrees with the information from the snow profile and the translucent profile. Yet, the force signal gives much more precise information about the micro-properties of the snow and and it reveals the great variability in mechanical hardness and texture within the layers.

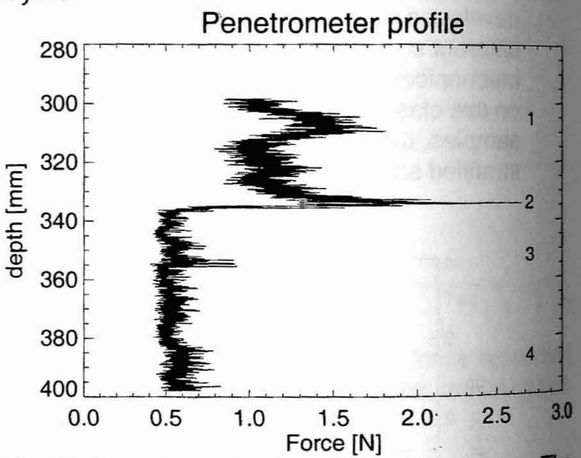

Fig. 10: Penetrometer signal of profile section. The position of the numbers correspond to numbered layers in the translucent profile shown in Fig. 12.

5. RESULTS AND DISCUSSION

The two different methods of snow profile interpretation are not directly comparable. Discrete layers that are defined in the classical profile are not always reproduced by the penetrometer. Moreover, the force signal shows the great variability in the mechanical and textural properties in a snow pack. Snow layers appear unequally

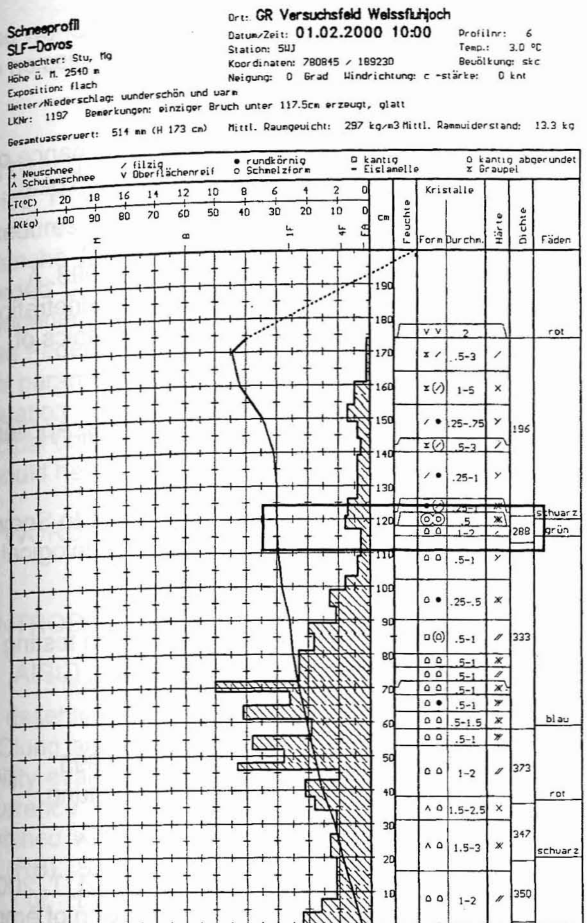

Fig. 11: Classical snow profile of test field profile. The profile section in comparison is contained in the black rectangle.

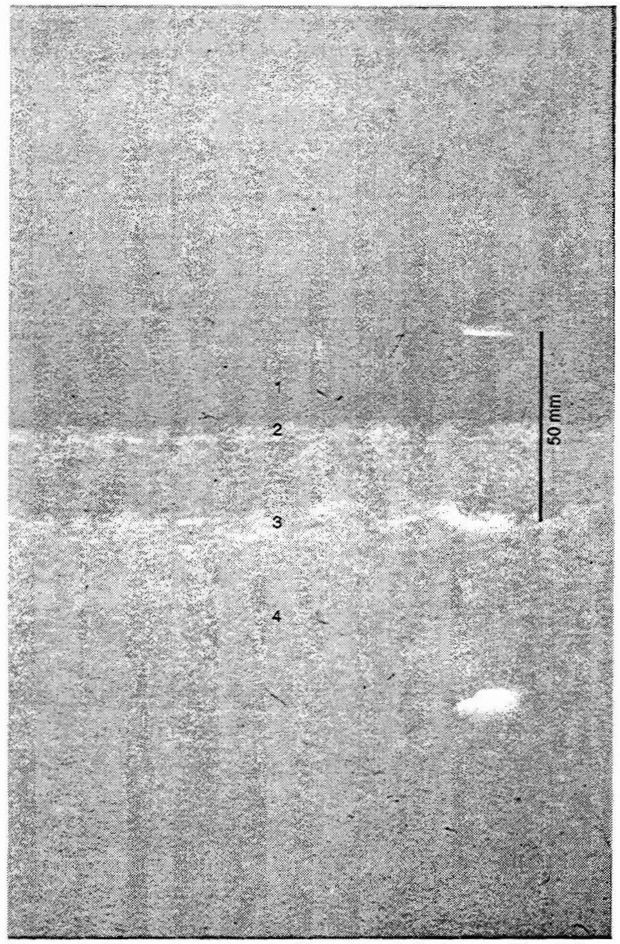

Fig. 12: Translucent profile of test field profile. The numbered layers correspond to the numbers on the penetrometer profile shown in Fig. 10.

clear in the penetrometer profile. The evaluation of the force-distance signal with the described methods provides a characterization of the snow pack in terms of its micro-mechanical and micro-textural properties. The precise magnitude and mechanical hardness of thin layers and interfaces can be measured by the penetrometer. This new method of objective and quantitative snow profile interpretation is the first step to facilitate a quantitative analysis of the snow in deformation. More measurements need to be taken and a correlation to bond properties from stereological analysis will enhance the signal interpretation.

The speed of the measurement allows to measure up to 120 snow profiles during a winter day. Hence, a systematic analysis of spatial variability at all scales is now possible. Systematic spatial measurements will be effected in the winter 2000/01. The analysis of spatial variability is combined with the analysis of snow pack stability and with the analysis of the micro properties of the snow pack.

Now that we can measure snow micro-structure it will be possible to manage the questions of micro-mechanical behaviour of snow in deformation and the spatial variability of the snow micro-properties.

6. OUTLOOK: VISUALIZATION OF 2- AND 3-DIMENSIONAL SPATIAL VARIABILITY

During the winter 1999/2000 the measurement of spatial variability of the seasonal snow pack with the SnowMicroPen has started. For the 2-dimensional analysis of small scale spatial variability (cm to m) measurements have been taken in lines at the flat Weissfluhjoch test field. Fig. 13 is the visualization of some of the 2-dimensional force measurements. The vertical lines represent the actual location of the measurements. The spacing was increased from 100 mm to 200 mm to 500 mm.

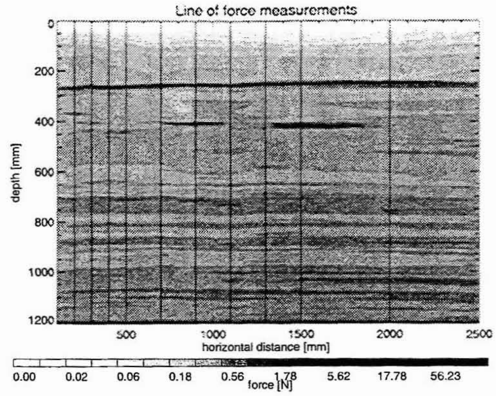

Fig. 13: Visualization of 2-dimensional spatial variability of a line of penetrometer snow profiles.

In Fig. 14 a 3-dimensional view into a small, 25 x 15 cm snow block is illustrated. Measurements were taken in a regular 5 x 5 cm grid. Analysis of 2- and 3-dimensional spatial variability of the micro-mechanical and micro-textural properties of snow packs can now be undertaken.

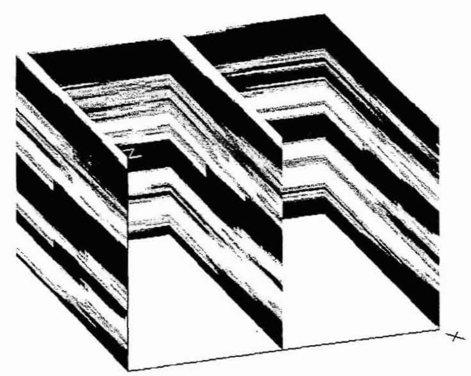

Fig. 14: Fence diagram of a small snow block and its stratigraphy.

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