Snow stratigraphy measured by snow hardness and compared to surface section images

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Abstract: Snow hardness is one of the most important parameters in the study of snow. Hand, ram and micro penetrometer hardness measurements were taken in seven snow pits. The snow profiles are analysed in terms of the three hardness tests and surface section images are used as an objective reference. From the images we established the stratigraphy in terms of layers and layer boundaries at high spatial resolution and compared the stratigraphy to the hardness profiles. The hand hardness test captured 80 % of all layers and layer boundaries and the ram hardness test 60 %. The micro penetrometer captured the stratigraphy more complete than hand and ram profiles. The hand and ram profiles are a generalization of the effective snow hardness and stratigraphy. Important details are missed, for example thin hard and soft layers which are highly relevant to avalanche formation. Differences in soft snow are resolved by the micro penetrometer, which is problematic or impossible with hand and ram tests. The surface sections and micro penetrometer profile show a much more stratified snowpack than revealed in a classical snow profile. Quantitative evaluation of mechanical and textural snowpack properties requires methods that have a spatial resolution of at least 1 mm. Since the main heat and mass fluxes are perpendicular to the snow surface, the much stronger stratification now revealed has a large impact on vapour transport. Electromagnetic models (microwave emission and radar), hydrology (water flow), avalanche formation (metamorphism in thin layers) are examples where a highly resolved snowpack stratigraphy will be important.

Keywords: snow cover, snow stratigraphy, snow hardness, mechanical properties, spatial variability

1. Introduction

The snowpack consists of numerous layers and layer boundaries that are related to the different snowfall, melting, wind erosion and deposition periods as well as to the metamorphic processes within the snow cover. A layer is a stratum of snow that is different in at least one respect from the strata above and below (Colbeck et al., 1990). A layer boundary is an interface or a transition between two adjacent layers (Colbeck, 1991). Snow stratigraphic profiles represent the varying properties of layers and layer boundaries in a snowpack. Layers are therefore the representative elementary volume (Bear, 1972), assumed to have "infinite" horizontal extension and homogeneous physical and mechanical properties.

To measure the mechanical hardness of a snowpack, Haefeli (Bader et al., 1939) developed the Swiss ramsonde from penetrometers used in soil mechanics. This was the first method to gain objective mechanical data from the snowpack. Due to its relatively large tip (4 cm diameter) the ramsonde is unable to detect thin and soft layers often responsible for the formation of avalanches. Abele (1963) showed the relationship of ram hardness and unconfined compressive strength in hard, processed snow and compressive strength is related to snow density. Geldsetzer and Jamieson (2001) showed the relationship of hand hardness and density. The International Classification for Seasonal Snow on the Ground (Colbeck et al., 1990) is the standard in describing the most important features of seasonal snow covers. It is the basis for the snowpack interpretation methods used by snow researchers and operational avalanche warning services. Depending on the aim of the snowpack investigation, the classification is focused on different properties. A classification of snow grains yields a representation of the metamorphic state of the snowpack. Sturm et al. (1995) developed a snowpack classification system according to climatic parameters and physical snow parameters. Hardness profiles were characterised for stability evaluation by deQuervain and Meister (1987) and this classification was extended by Stoffel et al. (1998) and Schweizer and Lütschg (2001).

A snow profile is a one-dimensional observation and record of the snow stratigraphy in a snow pit. Measured hand hardness and obvious textural variations are the criteria to establish the snow stratigraphy. The stratigraphy is central to all processes acting within the snowpack such as the main heat and mass fluxes. Thin hard and soft layers are highly relevant to avalanche formation. We propose that it is necessary to capture

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the snow stratigraphy based on highly resolved and objective mechanical hardness measurements that entail additional information on the snow texture. By measuring snow hardness with the newly developed SnowMicroPen (Schneebeli and Johnson, 1998) these requirements can be fulfilled (Johnson and Schneebeli, 1999, Schneebeli et al., 1999). The SnowMicroPen is applied the first time to natural snowpacks along with the classical methods. Hand hardness, ram hardness and micro penetrometer hardness profiles are compared. We show the fundamental differences of the three methods. The stratigraphy is compared and the hardness profiles are correlated. The suitability of the methods to capture the snowpack properties and the hardness and texture variations in a snow profile is discussed.

2. Data

Hand hardness, ram hardness and micro penetrometer hardness profiles were taken adjacent to one another in seven snow pits during the winters of 2000/01 and 2001/02. The measurements were done in winter (dry) and spring (moist/wet) snowpacks. Two slope profiles were taken in the area of Choerbschhorn, nearby Davos, Switzerland on January 9 and 15, 2002. Two flat field profiles were taken on February 8 and March 1, 2002 at the study plot Weissfluhjoch, Davos. The harder spring profiles were measured during the winter 2000/01 on May 15, June 1 and June 19, 2001 at the study plot Weissfluhjoch, Davos. For the four profiles of the winter 2001/02, 18 casted samples for serial section analysis were taken from sub-areas of the profile and transferred to the cold laboratory for processing and analysis.

3. Methods

3.1. Snow hardness

Snow hardness is the resistance to penetration that has the dimension of a force. It is given by the penetration of a material that is harder than snow. We are comparing three hardness measurement methods for snow: hand hardness, ram hardness and micro penetrometer hardness. Tab. 1 summarizes the resolution and operating characteristics of each method.

Hand hardness is a somewhat subjective, observer dependent manual penetration test that is used to establish the snowpack stratigraphy in a snow pit. The observer measures hand hardness by pushing the fist or 4 fingers or 1 finger or pencil or knife with a given force (about 50 N) and parallel to the layer into the snow and by sensing the resistance by hand (Colbeck et al., 1990). The hardness resolution of the hand hardness test is not constant. It depends on the elementary area of the measuring device and ranges from 0.3 to 7 cm, where knife blade is 0.3 cm, pencil is 1 cm, 4 fingers and 1 finger is 2 cm and fist is 7 cm. The values of the hand hardness are on an ordinal scale. Captured are primarily the hardness differences of the layers in the one profile under investigation. Hardness itself can vary greatly between observers since the pushing force and elementary area are subjective. There is no absolute hardness reference. The hand hardness levels were correlated to ram hardness by deQuervain (1950) and this correlation was modified in the International Classification for Seasonal Snow on the Ground (Colbeck et al., 1990). The latter correlation is used for the conversion of hand hardness to ram hardness.

Table 1: Characteristics of hand, ram and micro penetrometer hardness methods.

	Vertical layer resolution: [cm]	**Hardness resolution [N]**	**Elementary area of measurement: [mm^2]**	**Deformation velocity [m s^{-1}]**	**Penetration direction**
Hand hardness	0.3 to 7	10^1	variable 2 to 5000	variable 0.01 to 0.02	horizontal
Ram hardness	1.5 to 5	10^1 to 10^2	constant 1250	variable 0.068×10^{-3} to 0.7	vertical
SnowMicro Pen hardness	0.1	10^4	constant 20	constant 0.02	vertical

Ram hardness is tested with the Swiss ramsonde (Bader et al., 1939), which is the classical instrument to objectively measure snow hardness. However, Bader et al. (1939) stated that the classical snow profile and mechanical ram test can provide a characterization of the mechanical properties, but they are not suited to record the data at the needed spatial resolution. The ramsonde is driven into the snow by mechanical hammer blows on top of the probe. The vertical layer resolution of the ram test is limited by the size of the measuring cone (4 cm diameter) and is at best 1 cm. It is well known but was never published that there is a positional lag in the vertical distances in the ram profile. The hardness resolution is limited by the weight of the probe itself and the weight of the hammer. Gubler (1975) showed the dependency of the ram hardness on the speed of deformation, which is not constant during the ram hardness measurement. Gubler (1975) also pointed to the problem of the considerable energy loss at the connections of the individual parts of the ramsonde and developed a new ram hardness equation that partially accounts for these energy losses.

Micro penetrometer hardness is measured with the SnowMicroPen. It measures the snow hardness and snow texture at the millimeter scale (Schneebeli and Johnson, 1998, Schneebeli et al., 1999). The instrument records the penetration resistance on a small tip with high vertical resolution (4 μm) and high force resolution (0.005 N). The fundamental idea is that a quasi-continuous recording, small diameter penetrometer will connect more directly to the snow micro properties than large diameter cone penetrometers do (Johnson and Schneebeli, 1999).

3.2. Snow samples and snow microstructure images

To analyse the undisturbed snow stratigraphy and snow microstructure, 18 snow samples (7 cm x 7 cm x 5 cm) were taken from sub-areas of the four profiles taken during the winter 2001/02. To conserve the fragile snow structures during transportation and laboratory processing, the snow samples were filled with dimethyl phthalate and frozen. The surface section method described by Good (1987) was improved to yield better contrast and higher effective resolution (10 μm) in the digital images. Still higher resolution is obtained by producing image-mosaics, where a sample surface is photographed in 5 sections, which are later reassembled digitally. The images document the actual stratigraphy and the grain properties of the 7 cm x 7 cm area covered by each sample. The position of the samples in the snow profile is marked with horizontal black bars in Figure 1.

3.3. Comparison of methods

The comparison of the hardness profiles is based on the stratigraphy reconstructed from the highly resolved surface images of the snow samples. The surface images serve as an enlargement of the snow profile sub-areas. The position and number of layers and layer boundaries are determined from the surface images by visual inspection of changes in snow density and grain properties. Figure 2 shows an example of this classification on the left of the graph where the black vertical bars indicate the layers and the interruptions of the bars indicate the layer boundaries. The presence or absence of these features in the hardness profiles is determined and the occurrences are counted and compared. The hardness differences at layer boundaries that are present amongst the three hardness profiles are correlated. Selected layers marked with letters A thru L in Figure 1 are compared in detail.

4. Results

4.1. Comparison of hardness profiles

The seven profiles are shown in terms of their converted hand, ram and micro penetrometer hardness profiles in Figure 1. The hardness values are plotted on logarithmic y-axes. Differing one order of magnitude, the hardness values are shown on the same graph and can be compared at these scales. The logarithmic y-axes are chosen to get a better resolution at lower hardness values. The hardness profiles from each method are very different in such that ram hardness is more variable than hand hardness and micro penetrometer hardness is even more variable than the other two. The hand profile has a higher vertical layer resolution than the ram profile and it contains more extreme values than the ram profile. Hand hardness is not objective because the observer focuses subjectively on interesting layers, which has proven practical for the observation of potential fracture layers. The differences in the hardness profiles also stem from the underlying, different deformation processes inherent in each method. Hand hardness is measured with devices with variable reference areas and shapes but at roughly constant deformation velocity. This results in different deformation processes even amongst the hand hardness classes. Ram hardness is measured with a constant reference area but at variable deformation velocities. Because the SnowMicroPen has both a constant reference area and a constant deformation velocity, and it also has the highest spatial and hardness resolution it is considered the most reliable hardness profile. The results of the following comparison of layers and layer boundaries in the hardness profiles support this proposition.

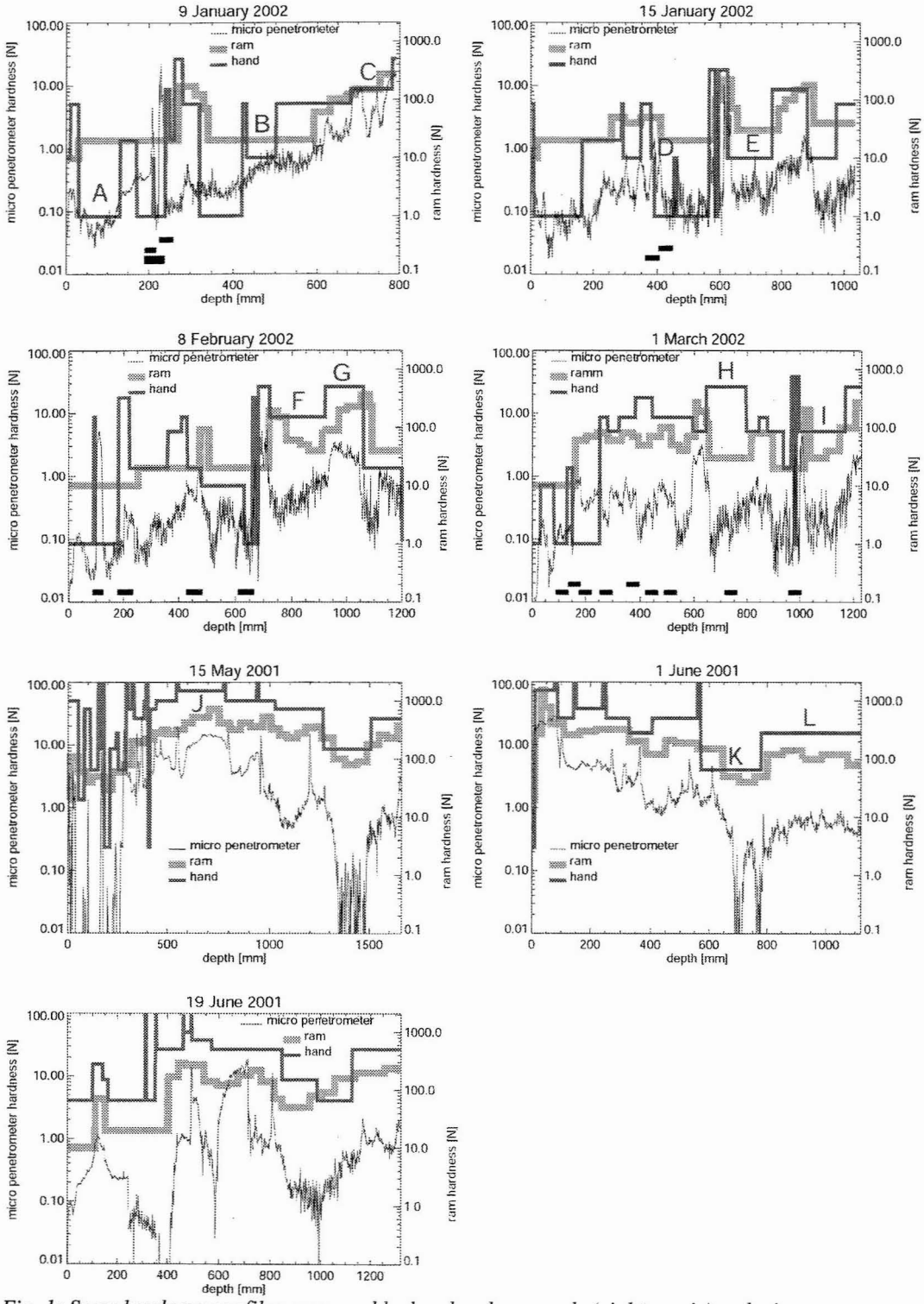

Fig. 1: Snow hardness profiles measured by hand and ramsonde (right y-axis) and micro penetrometer (left y-axis, smoothed with a moving average over 1 mm window). The logarithmic y-axes are chosen to get a better resolution in the lower hardness values. Differing in about one order of magnitude, the three hardness profiles are drawn on the same graph and can be approximately compared at these scales. The horizontal black bars above the x-axes mark the positions where the snow samples were taken. The letters A thru L mark layers discussed in the text.

4.2. Representation of layers and layer boundaries

In the surface images of the 18 snow samples we determined 41 snow layers and 17 layer boundaries. We compare this count to the occurrences in the different hardness profiles. Of all 41 layers, 25 (61 %) were recorded in the ram hardness profiles, 31 (76 %) in the hand hardness profiles and all were recorded in the micro penetrometer profile. Of all 17 layer boundaries, 9 (53 %) were recorded in the ram hardness profiles, 14 (82 %) were recorded in the hand hardness profiles. From the micro penetrometer hardness profile all layers and layer boundaries could be identified. In the case of three layer boundaries, the sign of the hardness difference was opposite in micro penetrometer and hand hardness profiles. A possible explanation is a recording error in the manual profile. Of all 17 determined layer boundaries, 14 coincide in the hand and micro penetrometer profiles, 9 coincide in the micro penetrometer and ram profiles, and only 5 coincide in the hand and ram profiles. An example where the stratigraphy is in agreement with the surface images is shown in Figure 2. An example where they are in disagreement is shown in Figure 3 where within a soft layer a thin, slightly harder layer exists that does not appear in the stratigraphy. The according micro penetrometer profile shows a layer with a hardness difference of 0.4 N.

The correlations of hardness differences at layer boundaries between hand and micro penetrometer hardness, between ram and micro penetrometer hardness and between ram and hand hardness are shown in Figure 4. Only the correlation between the hardness differences in hand and micro penetrometer profiles are statistically significant. This indicates, that the ram hardness measurement method produces significantly different hardness discontinuities at layer boundaries than hand and micro penetrometer. The layer boundaries in the hand hardness profiles are predefined discrete steps of the hardness classes. Ram hardness resolution at layer boundaries is better than hand hardness resolution. However, ram hardness resolution is dependent on the operator and on the snow hardness itself. Generally, the ram hardness resolution is low in soft snow. Gradually changing properties at layer boundaries are impossible to capture by hand hardness and difficult by ram hardness. Sharp hardness discontinuities in a snowpack are one of the controlling factors in avalanche formation (Schweizer and Luetschg, 2001). The SnowMicroPen has enough resolution to account for the gradient of a hardness discontinuity at the millimeter scale. For two exemplary layer boundaries, on top and below the crust, this is shown in Figure 2. The gradient of the force increase at the upper boundary of the crust and decrease at the lower boundary of the crust are calculated. From a linear fit to the micro penetrometer force data over a distance of 1 mm (250 data points) the average force gradient is calculated. The average force gradient in the millimeter above the crust to the first peak of the crust is 17.7 N mm^{-1} and for the discontinuity from the last peak of the crust to the millimeter below the average force gradient is -5.1 N mm^{-1}. With this method the magnitude of the hardness differences at layer boundaries can be quantified from micro penetrometer profiles. The absolute force record and the micro texture preceding or following a hardness discontinuity are also important factors when evaluating hardness discontinuities.

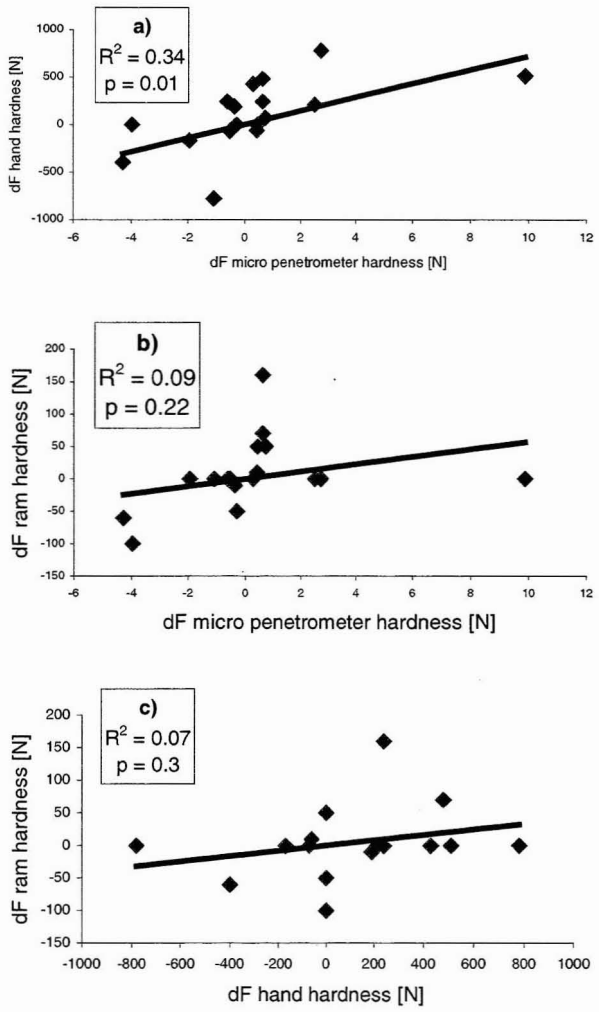

Fig. 4: The hardness differences (dF) at layer boundaries between: a) hand and micro penetrometer are correlated (p=0.01); b) ram and micro penetrometer and c) ram and hand are uncorrelated (p-values at 95 % confidence level).

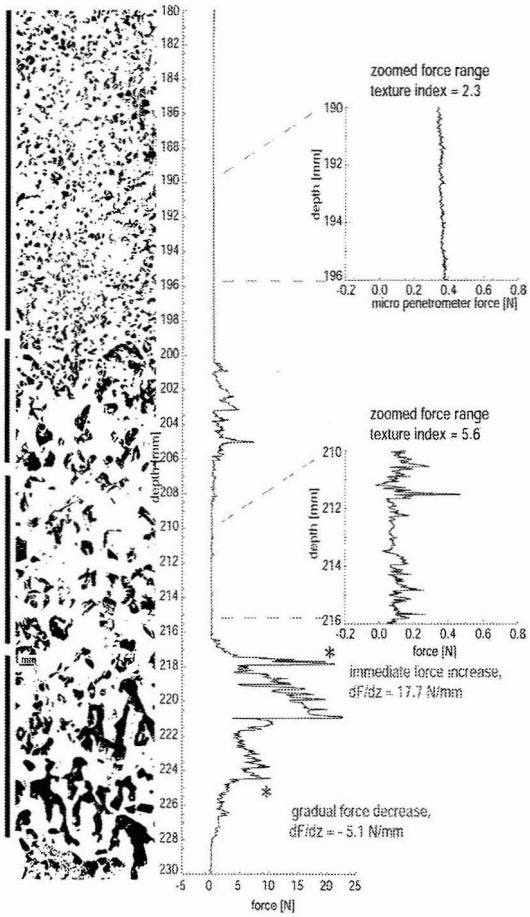

Fig. 2: Snow profile from 9 Jan. 2002: snow sample containing two crusts (black is ice). The black vertical bars on the left mark the layers as they are depicted from the surface image. Their interruptions mark the layer boundaries. This is an example where the stratigraphy established by hand hardness agrees with the surface image. Snow texture and hardness gradients at layer boundaries are calculated from the micro penetrometer hardness signal.

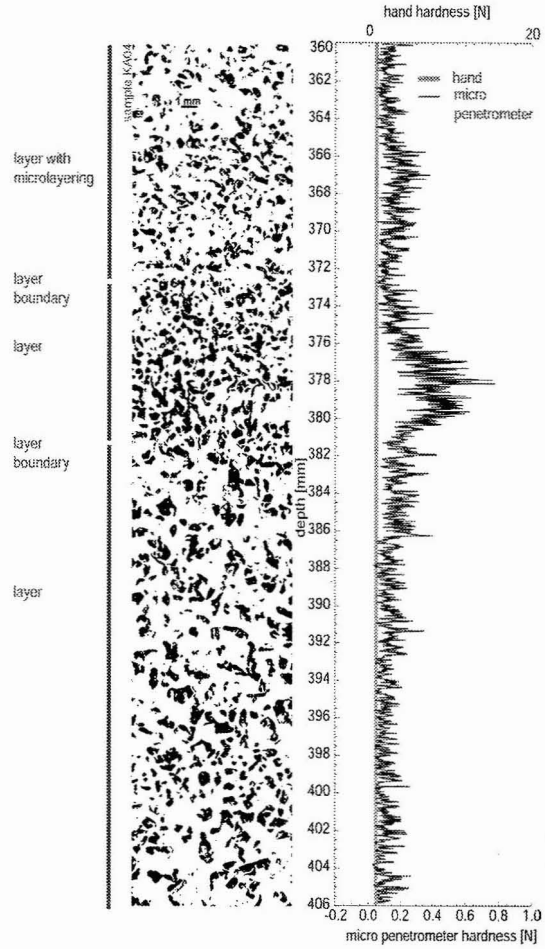

Fig. 3: Snow profile from 15 Jan. 2002: surface image containing a thin, harder layer and micro layering (black is ice). This is an example where the stratigraphy established by hand hardness disagrees with the surface image because the thin, harder layer is missing.

In Figure 2, two exemplary profile sections are zoomed and the texture index is calculated for each section. The texture change can be observed in the surface images and is reproduced in the calculated texture index. The higher texture index is an indication for lower textural stability (Schneebeli et al., 1999).

4.3. Homogeneity of layers compared to the micro penetrometer hardness

A selection of stratigraphically homogenous layers is exemplarily compared to the micro penetrometer hardness. These layers are marked in Figure 1 by the capital letters "A" thru "L" above the hand hardness. Layer A varies between 0.03 to 0.11 N around a mean value of 0.06 N. Here, the signal is superimposed by a higher frequency signal with a wavelength of a few millimeters, with similar amplitude as the main increase. This pattern is typical for wind influence during snow deposition. Thus, the micro penetrometer hardness varies by a factor of 4 within this stratigraphic layer. Layer B shows a consistent increase in hardness from 0.11 N to 0.8 N, an increase by a factor 8. Layer C entails two hardness increases and two decreases between 1 N and 8 N. Layer D shows a harder layer with a difference of 0.9 N to the layer below that does not appear in the hand hardness. This layer is captured in the surface image in Figure 3. Layer E is similar to layer A, but at a higher hardness level. Layer F and layer G show the positional lag in the ram profile. Layer F has a gradual force decrease in the ram hardness and a sudden force decrease followed by a gradual force increase in the micro penetrometer hardness. Layer H is contradictory to the ram hardness. The homogeneous stratigraphic layer contains a gradual hardness increase by a factor 10, from 0.06 to 0.6 N. Layer I varies between 0.06 N and 0.6 N in the micro penetrometer where micro layers become apparent.

The following layers are from the spring profiles that contain wet and refrozen layers that are on average much harder than the layers of the mid winter profiles. In layer J, a thin layer, which is softer by a factor 4, is missed in the hand and ram hardness. Layer K contains two layers with extreme mechanical softness, which are slush horizons measured by the SnowMicroPen fast enough before the water could drain into lower parts of the profile. After the opening of a snow pit the water can drain downward and re-strengthening can occur in these layers. This is shown in the systematically greater hand hardness than ram hardness in the spring profiles. Layer L is a rather homogeneous layer with small hardness variations.

Classical stratigraphical layers in the investigated profiles show often an increase or decrease in micro penetrometer hardness, and are not uniform. Most layers, except a few layers in wet snow, show a strong fluctuation between 20 to 50 %. In wet snow the SnowMicroPen measures the profile fast enough to capture the properties before the water can drain from the saturated layers.

5. Conclusions

Hand hardness, ram hardness and micro penetrometer hardness profiles are different records of the same snowpack. Each method is based on a different measuring process and has a different resolution in terms of space and hardness. From the comparison of the hardness profiles to highly resolved surface images of snow samples it results that the micro penetrometer profile captures the stratigraphic features most completely. Hand hardness profiles capture 80 % of the stratigraphic features and ram hardness profiles only 60 %. Besides the mean snow hardness, the hardness variation and micro textural information can be extracted from the SnowMicroPen force signal. No stratigraphic layer thinner than 1 mm could be found in the surface sections. Classical stratigraphic layers show considerable hardness variations. In many cases a consistent trend over a large (factor 2-10) range in hardness was detected. This feature has not been measured, but was known to exist from translucent profiles (Good and Kruesi, 1993). In the ram and hand profiles a considerable number of stratigraphic elements were missing, such as thin hard layers and soft layers. The hand hardness has better vertical layer resolution than the ram hardness. The hardness differences at layer boundaries are correlated between the hand hardness and the micro penetrometer hardness. However the hardness resolution of the hand test is limited by the elementary thickness of the measuring device. Customary solutions are known but not always applicable and not documented.

6. Discussion

Classical stratigraphic methods should be applied with great care to quantitative comparisons. This study shows that methods with high spatial and hardness resolution are necessary to detect the subtleties of the stratigraphy in the natural snow cover. Other high-resolution methods (surface sections, 3-D reconstruction, translucent profiles) are more time consuming than the micro penetrometer. The complexity of a snowpack measured with the SnowMicroPen is surprising. It will be necessary to develop improved algorithms to extract all the information and to quantitatively classify layers and layer boundaries in a micro penetrometer hardness profile. Process studies will get a much more detailed input from SnowMicroPen measurements and model runs can be compared with more complete stratigraphic data. The classical concept of layers, which is valuable for operational avalanche warning purposes must be

used with caution when applied to the simulation of snowpacks and the simulation of snowpack stability. Further physical interpretation of the micro penetrometer hardness will be a next step. This could widen the use of micro penetrometer hardness measurements. A further step is to correlate the micro penetrometer hardness and texture of failure layers to the layer stability.

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