Visualization of three-dimensional snow: how to use it in snow education

Martin Heggli*, Matthias Jaggi, Bernd Pinzer, Stephen Steiner, Thiemo Theile, and Martin Schneebeli
WSL Institute for Snow and Avalanche Research, Davos, Switzerland

ABSTRACT: Traditionally, the shape of snow crystals is studied on a crystal screen. Therefore, snow is implicitly considered as a material composed of individual grains. However, doing this, the structural information is lost, comparable to trying to understand the significance of structure from a pile of rubble. Most mechanical and physical properties of the snow can only be explained by considering the three-dimensional (3D) architecture of the snow microstructure. We give an overview of the methods used to visualize the 3D structure of the snow, which can be easily used in a class room, as anaglyph images and animations. We will present and explain images of the major snow classes and several interfaces and weak layers. We also give an overview of current techniques which can be used to collect samples in the field and how they can be processed later using high-resolution micro-tomography (micro-CT). The imaging of layers at the scale of a few centimeters is now possible with the newly developed replica technique and fast computers. This makes the technique available to image layer transitions, as they often occur in weak layers.

KEYWORDS: microstructure, micro-CT, serial sections, surface rendering, anaglyph, replica method

1 INTRODUCTION

Traditionally, the shape of snow crystals is studied on a crystal screen. However, through the process of sampling and preparing the snow on the screen the information about the three-dimensional (3D) architecture and connectivity of the snow is lost and snow is implicitly considered as a material composed of individual grains. However, most mechanical and physical properties can only be understood and predicted by considering the 3D microstructure of the snow. Properties that are intrinsically dependent on the 3D structure are e.g. thermal conductivity (Pinzer and Schneebeli, 2009; Schneebeli and Sokratov, 2004), electromagnetic reflectance (Toure et al., 2008), mechanical strength (Schneebeli, 2004; Schneebeli et al., 1999) and permeability (Albert, 2002).

It is therefore important to measure and visualize the 3D structure of the snow. Such visualizations can contribute to a better understanding of the material snow and its properties. They should therefore also be used in “snow education” to demonstrate the true microstructure of snow. Furthermore, the 3D data can serve as starting structures for numerical simulations.

Corresponding author address: Martin Heggli, WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland;
tel: +41 81 417 0169; fax: +41 81 417 0110;
email: heggli@slf.ch

2 FIELD SAMPLING

Usually, snow is sampled in the field, sometimes in remote locations. Therefore, a lab with suitable instrumentation for microstructural analysis is often not nearby. The snow structure is susceptible to rapid changes due to snow metamorphism because of the high vapor pressure of ice near its melting point (Pinzer and Schneebeli, 2009). Hence it is often necessary to conserve the samples to prevent structural changes in the samples before they can be analyzed in the lab. To this purpose the snow samples are cast with a solidifying liquid. Several substances can be used such as 1-chloronaphthalene (Flin et al., 2003), dimethyl phthalate (Perla et al., 1986) and diethyl phthalate (Heggli et al., 2009). We prefer to use diethyl phthalate because it is least toxic, environmentally relatively well degradable, and comparatively cheap.

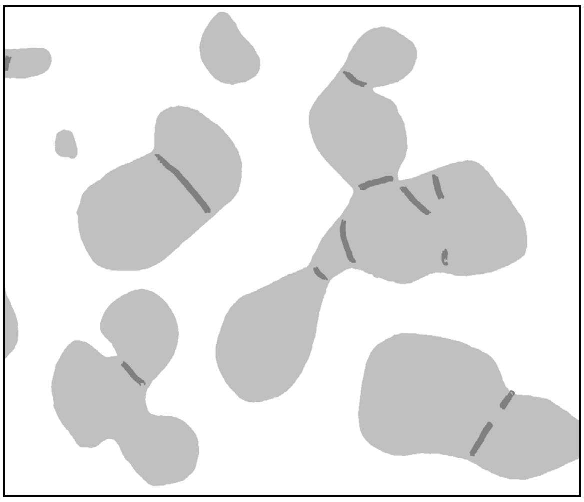
Briefly, the casting process is performed as follows: a snow sample is put in a sample collection box. The box is slowly filled with dyed diethyl phthalate that has been preconditioned to a temperature of -2°C to -5°C. When the snow sample is completely filled with the diethyl phthalate the sample box is put in an insulated container and packed with dry ice on all sides. After about 1 hour the diethyl phthalate has solidified and the samples can be stored at -20°C for several months. Details can be found online (http://tinyurl.com/nuzf34).

Until recently, diethyl phthalate cast snow samples could only be analyzed by serial sectioning because of the lack of X-ray contrast between ice and diethyl phthalate. This was often difficult because re-crystallization of the diethyl phthalate made automatic image analysis difficult if not impossible. However, recently we have presented a novel method that allows analyzing cast samples with micro computed tomography (micro-CT) (Heggli et al., 2009). For this replica method the cast snow samples are stored in a vacuum container for several days until all ice has sublimated. The resulting negative (replica) of the original structure can be analyzed with micro-CT. Inversion of the replica image by image processing in the computer yields an image of the original snow structure.

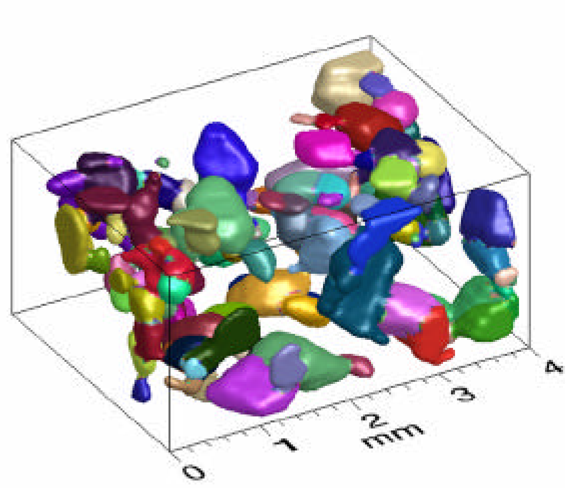
3 MEASURING 3D STRUCTURAL INFORMATION

Two methods are used to measure the 3D structure of snow: serial sectioning (Perla et al., 1986) and micro computed tomography (micro-CT) (Coléou et al., 2001; Schneebeli, 2004). Serial sectioning is a destructive process in which subsequent sections of a cast snow sample are produced with a microtome. Each surface section is imaged. The process of subsequent sectioning and imaging can be automated in order to increase the productivity of the process. A variation of the serial sectioning method allows detecting the crystallographic grain boundaries in the snow. To this end each section is left to sublimate for several minutes which leads to a preferential sublimation at the grain boundaries (grain boundary etching) because of the higher surface energy at the grain boundaries. Under coaxial (?) illumination the grain boundaries become visible (Arnaud et al., 1998). Fig. 1 a) shows an example of a section processed in this way. 3D reconstruction allows visualization of the crystallographic grains in a snow sample (Fig. 1 b).

Micro computed tomography (micro-CT) is a non-destructive method to measure the 3D structure of samples, which allows to scan the same sample multiple times and to follow changes of the microstructure due to isothermal metamorphism (Kaempfer and Schneebeli, 2007), temperature gradient metamorphism (Pinzer and Schneebeli, 2009) or mechanical deformation. In the micro-CT a large number of projections (usually 1000) are acquired using an X-ray beam transmitted through the sample. Image contrast is based on the different X-ray absorption of the different phases (ice and air) in the sample. Sophisticated algorithms make it possible to reconstruct virtual cross-sections of the sample. A stack of these cross-sections is a 3D data set that contains the full information on the 3D structure of the sample. Kerbrat et al. (2008) have shown that the effective resolution of the micro-CT is sufficient to resolve the features of the ice surface in most snow types.



(a)



(b)

Figure 1. When a surface section is sublimated for several minutes the crystallographic grain boundaries become visible (a). The structure can be divided into crystallographic grains, which can be displayed in a 3D reconstruction of the structure (b).

4 3D VISUALIZATION

Both serial sectioning and micro-CT yield stacks of two-dimensional slices in the first step. Such a stack of slices contains the full 3D information of a sample. The slices can be viewed as such, however it is often more instructive to generate 3D visualizations. There are several possibilities of doing so. They should be used depending on the intended use of the visualization. All methods require some image processing before the visualizations can be generated. In each case segmented data sets are needed. First, the data should be filtered to reduce noise in the images. Second, the images are segmented. This means that each volume element (voxel) of the image is assigned to either of the two phases ice or air. Such binary images can then be used to generate different kinds of 3D visualizations.

4.1 Surface renderings

3D surface renderings give an illusion of a 3D structure by using central perspective and only displaying parts of the structure that are visible to the observer (i.e. hiding parts that are covered by other parts closer to the observer). In a surface rendering a structure appears as it would appear in a conventional photograph (Fig. 3).

4.2 Anaglyphs

Anaglyph images are an interesting option to visualize 3D structures. Their advantage is to give a truly 3D visual impression. The generation of such images is relatively straight-forward: two surface renderings are needed the viewing angle of which differs by about 7°. One image is colored in red and the other in cyan. Then the two images are superimposed. There are several software packages that allow generating anaglyph images (e.g. ImageJ is free software with that option). For viewing red-cyan goggles are used that let each eye only view one of the two images. Anaglyphs can be used in presentations given that the audience can be equipped with red-cyan goggles. A disadvantage for printed products is that color print is required. is 10 × 10 × 10 µm. In the volume rendering we can recognize a number of different layers.

4.3 Animations

An appealing option for presentations are animations that show a structure from different viewing angles. Basically, such animations are composed of a series of surface renderings that are displayed one after the other. The parallax in such animations enhances the 3D impression.

4.4 Physical models

In a classroom or an exhibition, physical 3D models (Fig. 2) allow the students or visitors to experience the different snow structures “hands-on”. Specialized companies produce 3D models from a 3D dataset by rapid prototyping methods such as laser sintering.

5 EXAMPLES

In Fig. 3 we show examples of three typical snow types. The 3D structures are visualized as surface renderings (left) and as anaglyph images (right). Note that the surface renderings only give the illusion of 3D, whereas the anaglyphs generate truly 3D images. However, perceiving the anaglyphs correctly requires color print and the use of red-cyan stereo goggles.

As compared to the serial sectioning method micro-CT allows much faster acquisition of images of large samples. With serial sectioning several hundred slices can be measured at most. This corresponds to a few millimeters sample height. With micro-CT full 3D structural information from a sample which is several centimeters high can be acquired in about 24 h. It is hence possible to visualize a sample with several layers and to study the stacking of different layers. This is important to understand and model properties of a layered snow pack such as optical properties, thermal conductivity or mechanical strength of weak layers.

Fig. 4 shows a layered snow sample that was retrieved near the surface of the snow pack in Davos, Switzerland. The snow sample was cast with diethyl phthalate in the field and then processed according to the replica method, as described above. The 3D structure of the sample was measured with a table-top micro-CT (µCT40, Scanco Medical AG). A total of 6600 slices were measured corresponding to a sample height of 66 millimeters. The size of each voxel (volume element) is 10 × 10 × 10 µm. In the volume rendering we can recognize a number of different layers.

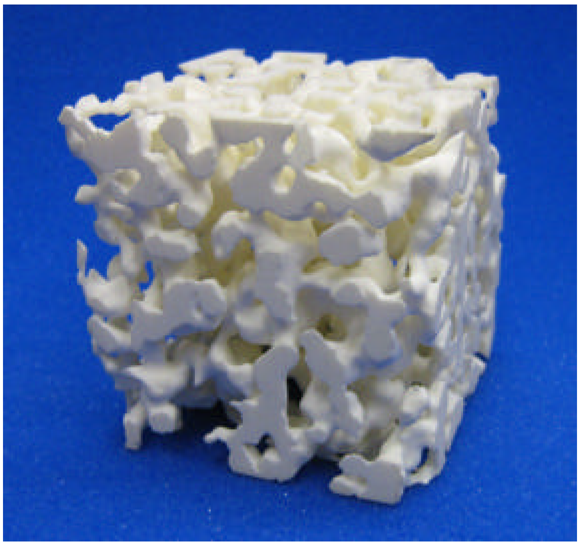
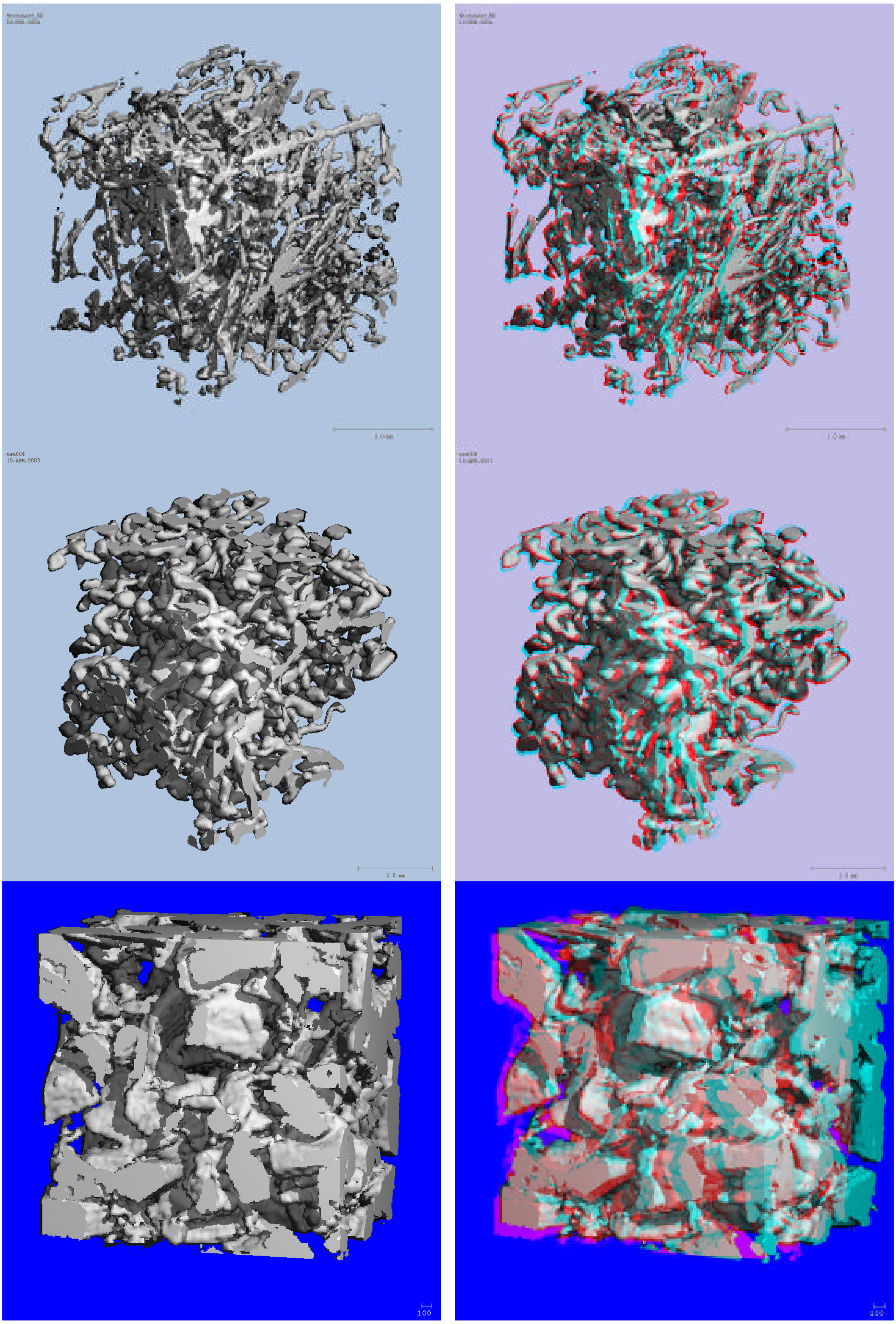


Figure 2. This 3D model of rounded snow with a density of 310 kg/m^3 was made by laser sintering. The magnification is 25× and the cube has a size of 10 × 10 × 10 cm corresponding to an original sample size of 4 × 4 × 4 mm.



(a)

(b)

(c)

Figure 3. Three typical snow types are visualized with volume renderings (left) and anaglyphs (right): new snow (a), small rounded grains (b), and depth hoar (c). Please use red-cyan stereo goggles to view the anaglyphs.

Figure 4. The top 66 mm of the snowpack were sampled in Davos, Switzerland. The 3D image was realized with the replica method described in section 2. Several different layers are visible in this sample. The sample cross section is 5 × 5 mm and the voxel size is 10 × 10 × 10 μm.

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