STUDY OF NETWORK IMAGE OF A SNOWPACK MICROSTRUCTURE FOR QUANTIFICATION USING A MORPHOROMETRICAL METHOD

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ABSTRACT: Computer tomography has advanced with respect to diagnostic imaging over the last several years in terms of the increasing capacity of computers. The technique of tomography is also useful to quantify the three-dimensional microstructure of snow. In this study, several methods were introduced to analyze the microstructure of snow in order to parameterize the network image of a snowpack. We used a three-dimensional NMR imaging data set of four snow types: artificial ice spheres, large rounded polycrystals, small rounded monocrystals, and depth hoar crystals. A three-dimensional gradient-echo sequence (image matrix = 128^3; voxel size = $(200\ \mu m)^3$ or image matrix = 256^3; voxel size = $(120\ \mu m)^3$) was used for the three-dimensional imaging. We measured the porosity and number of terminus of the samples and carried out the node-strut analysis. The structure model index (platelike, rodlike, or spherelike) and trabecular bone pattern factor (concave or convex in three dimensions) were also calculated. By using each parameter, it was possible to distinguish between the four types of test snowpacks. Therefore, snow network analysis may be a useful method to characterize the microstructure of a snowpack.

KEYWORDS: snow structure, morphometry, structural classification, structure parameters, MRI

1. INTRODUCTION

The microstructure of a snowpack affects its mechanical and physical properties. However, it is difficult to measure the microstructural features of a snowpack, especially in field observations. In this study, we determine the snow type of the snowpack on the basis of the density and microarchtecture.

The specific surface area (SSA)—total surface area per unit mass or unit volume—is an important parameter that is used to describe the microstructure of porous media; therefore, the SSAs of snowpacks have been investigated by several researchers (e.g., Narita, 1971; Legagneux *et al*., 2002). In several recent studies, attempts have been made to measure the SSA directly using X-ray tomography in order to investigate the 3D microstructure of snow (e.g., Col'eou *et al*., 2001; Matzl and Schneebeli, 2006; Kerbrat *et al*., 2007). SSA have rilations to chemical reaction, light schattering of snowpack, and useful to descrive snow metamorphism.

This study introduces several methods that can be used to analyze the microstructure of snow in order to parameterize the network image of a snowpack. Since the snow strength depends on the density and microarchitecture of a snowpack, it is important to be able to quantify the architectural features of the network image of a snowpack.

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2. THREE-DIMENSIONAL MR DATA

Four types of ice particles were tested: spheres of approximately 3-mm diameter, large rounded polycrystals, small rounded monocrystals, and depth hoar crystals. The ice spheres were formed by dropping water droplets into liquid nitrogen. The other three types were sampled from a natural snowpack in Hokkaido, Japan.

Three-dimensional structural data of the snowpack was obtained using NMR images (Ozeki et al., 2003). Because ice produces a negligible NMR signal, we imaged the pore space between the snow grains by filling it with dodecane doped with iron acetylacetonate. The diameter and length of the snow sample were 24 mm and 100 mm, respectively. We used two spatial resolutions with the following sets of matrix and voxel sizes: 256^3 matrix with 120-μm voxels on a side, and 128^3 with 200-μm voxels. The higher resolution was used to image the small rounded monocrystals, and the lower resolution was used for the other samples. The field of view of the higher resolution was

approximately (30.7 mm)^3, and that of the lower resolution was approximately (25.6 mm)^3. We used three-dimensional gradient echoes for the imaging sequence in all our images. Figure 2 shows a two-dimensional cross section of large rounded polycrystals. The threshold was decided using the P-tile method, which was based on the bulk density.

3. NETWORK IMAGE ANALYSIS

Combined with developments in computer tomography, studies on bone histomorphometry have advanced significantly in recent years. The trabecular bone strength depends not only on the bone volume density but also on the microarchitectural features of the bone. Several parameters other than the bone volume density have been established for the classification of bone structures. The snowpack strength depends on the microarchtectural features of snow, and the anisotoropy of a snowpack suructure is an effective parameter to classify snow types. In this study, we applied the structure model index (*SMI*) and trabecular bone pattern factor (*TBPf*) to the network image of a snowpack structure in order to attempt the structural classification of a snowpack. We also measured the porosity and number of termini in the samples, and carried out node-strut analysis.

The *SMI* is calculated by means of three-dimensional image analysis based on a differential analysis of the triangulated structure surface (Hilderbrand and Rüegsegger, 1997). The structure volume V depends on a linear measure r, and the structure surface S is the derivative of the volume with respect to r.

$$V = f(r), \quad S = \frac{\partial V}{\partial r} = f'(r) \qquad (1)$$

r is taken as the half-thickness or the radius. SMI is defined as

$$SMI = 6 \cdot \frac{S' \cdot V}{S^2} \qquad (2)$$

where S' is the surface area derivative. For an ideal plate and rod structure, the SMI value is 0 and 3, respectively (Figure 3). For a structure with plates and rods that both had equal thicknesses, the value lies between 0 and 3 depending on the volume ratio of the rods and plates.

TBPf is used to quantify the connectedness of trabecular bone patterns. The basic concept is that the connectedness of

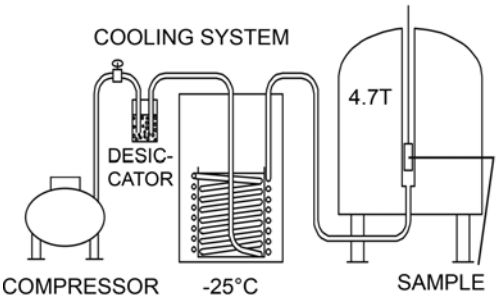


Figure 1. Apparatus used for the NMR imaging of a snowpack structure.

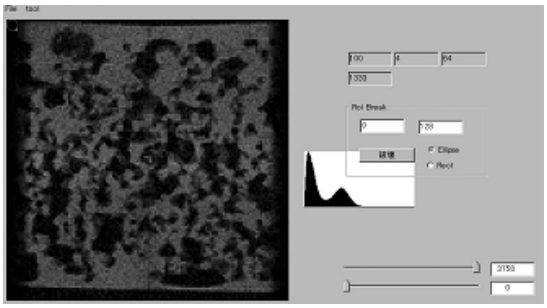


Figure 2. Two-dimensional cross section image obtained from the three-dimensional data on large rounded polycrystals. Image sequence: 3D-GE, TR = 100 ms, FOV = (25.6 mm)^3, voxel size = (200 μm)^3, image matrix = $128 \times 128 \times 128$.

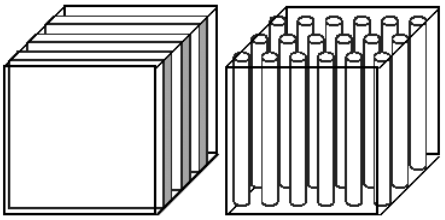


Figure 3. An ideal plate and rod structure for *SMI*. Models A and B indicate *SMI* values of 0 and 3, respectively.

structures can be described by the relation of convex surfaces to concave ones (Hahn *et al*. 1992). Many concave surfaces represent a well-connected spongy lattice, whereas many convex surfaces indicate a badly connected trabecular lattice in two-dimensional sections. The concept of *TBPf* can be employed for the determination of the connectedness of snowpacks. The *TBPf* of a well-connected structure is positive, whereas that of a badly connected one is negative. We used a trabecular bone analyze system

(TRI/3D-BON: RATOC System Engineering) to analyze the network structure of snowpack.

4. RESULTS

Figure 4 shows the relation between *SMI* and *SV/TV*. In this study, we use *SV/TV* instead of the snow density ρ_S. It is defined as the volume of the snow grains divided by the total volume. ρ_I simply relates the snow density ρ_S to $\rho_S = \rho_I \cdot SV/TV$. There is not a definite correlation between SMI and SV/TV. In fact, the plots in the figure indicated that the distributions depend on the snow types.

Figure 5 shows the relation between *TBPf* and *SV/TV*. The value of *TBPf* decreased with an increase in *SV/TV*. Remarkably, the value of the ice spheres was almost zero.

5. CONCLUSIONS

In order to describe the network image of a snowpack, the structure model index (*SMI*) and trabecular bone pattern factor (*TBPf*) were introduced to analyze the microarchitectural features of snow. *SMI* can be used to indicate whether the structural features are platelike, rodlike, or spherelike. *TBPf* can be used to indicate the connectedness of a snowpack. The result of the relationship between *SMI* and *SV/TV* showed that the distributions depend on the snow type. The result of the relationship between *TBPf* and *SV/TV* showed that *TBPf* decreased with an increase in *SV/TV*. Snow network analysis may be a useful method to characterize the microstructure of a snowpack and effectively classify snow types.

6. REFERENCES

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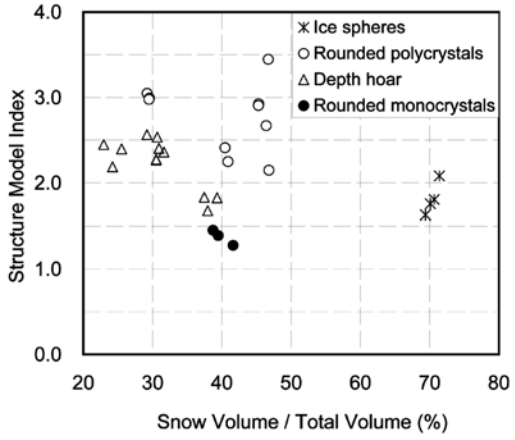


Figure 4. relation between *SMI* and *SV/TV*.

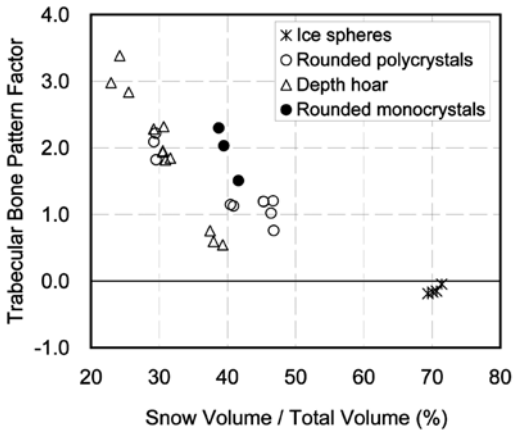


Figure 5. relation between *TBPf* and *SV/TV*.