3-D SNOW AND ICE IMAGES BY X-RAY MICROTOMOGRAPHY

C. COLÉOU[1] AND J.-M. BARNOLA[2]

1 MÉTÉO-FRANCE, CENTRE D'ETUDES DE LA NEIGE, GRENOBLE (FRANCE)
2 LABORATOIRE DE GLACIOLOGIE ET GÉOPHYSIQUE DE L'ENVIRONNEMENT, CNRS, GRENOBLE (FRANCE)

Presentation given at the ESRF-ILL Workshop "Environmental Studies Using Neutron and Synchrotron Facilities", 20-21 February 2001.

Evolution of snow in temperate as well as in polar regions is strongly dependent on its structural properties. We present 3-D imaging results obtained by X-ray absorption tomography, a technique that will allow the extraction of quantitative information about the structural parameters of snow and ice.

Snow is a porous medium. At negative temperatures it consists of ice and air with water vapour. Snow is constantly moving and its porosity decreases with time. It is slowly compacted into firn and then ice. A very wide range of porosity can be found: from more than 95% for fresh snow to around 40% for firn and then to less than 10% for ice. Changes in dry snow are caused by vapour diffusion among the grains - they are driven by temperature gradients and grain curvatures [1]. On polar ice caps, below a depth of 10 metres, the medium becomes isothermal although its porosity is still open. Then the porosity decreases more slowly, firn evolves into ice by a process similar to sintering under load. The transition from an open to a closed porosity is called close off and it occurs when firn becomes ice. During the transition, air is trapped in bubbles between the ice crystals.

Three-dimensional images of snow and ice with a spatial resolution of 10 μm were obtained using X-ray absorption tomography, an established technique used on the ID19 beamline [2]. 900 two-dimensional X-ray absorption images

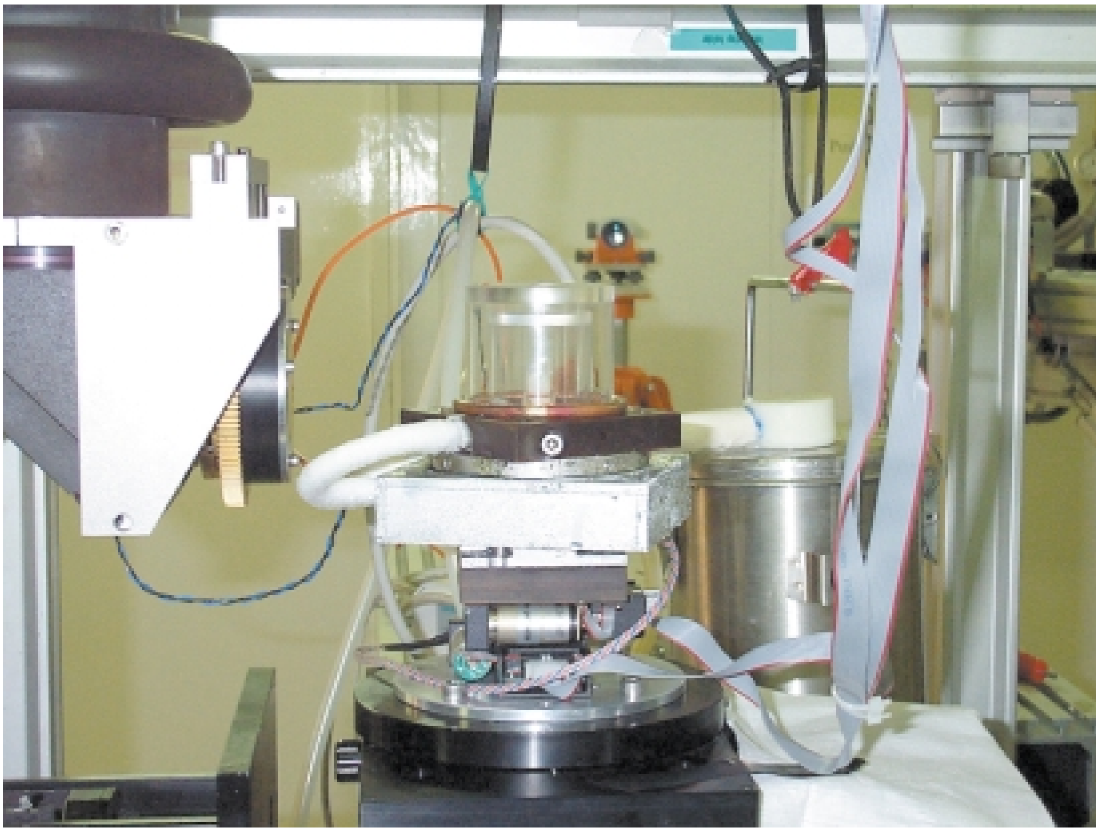

Fig. 1: View of the experimental setup used for snow and ice samples. The cryostat was mounted on a high-accuracy rotation and translation stage. Images were recorded with a Frelon CCD camera.

were recorded at angular positions of the object around an axis spanning 180°. An appropriate algorithm was then used to reconstruct a 3-D image from the data.

SAMPLE PREPARATION

Specificities of snow and ice need special requirements for sample preparation. Since firn and ice is rather hard, it was possible to carve out a cubic sample (edge about 15 mm). Ice and air offer a good level of contrast and so the images could be obtained by local absorption tomography at an energy of 18 keV. Snow needed strengthening prior to being machined into the shape of a cylinder (9 mm high, 9 mm diameter). Dense snow was cohesive enough to allow removal of the filling medium before imaging. X-ray absorption tomography at 10 keV was used. Snow with low density was too fragile to stand up to the rinsing stage. A selection of pure chemicals have been tested, examples being trans-1,2-dibromocyclohexane and cycloheptane. They fulfilled the required conditions regarding their melting point, reaction with ice, hardness and their attenuation coefficient which has to be different from that of ice. In all cases, a special device (a liquid-nitrogen cooled cell at about –50°C) was used to prevent both melting and metamorphism of the samples during the experiments (Figure 1).

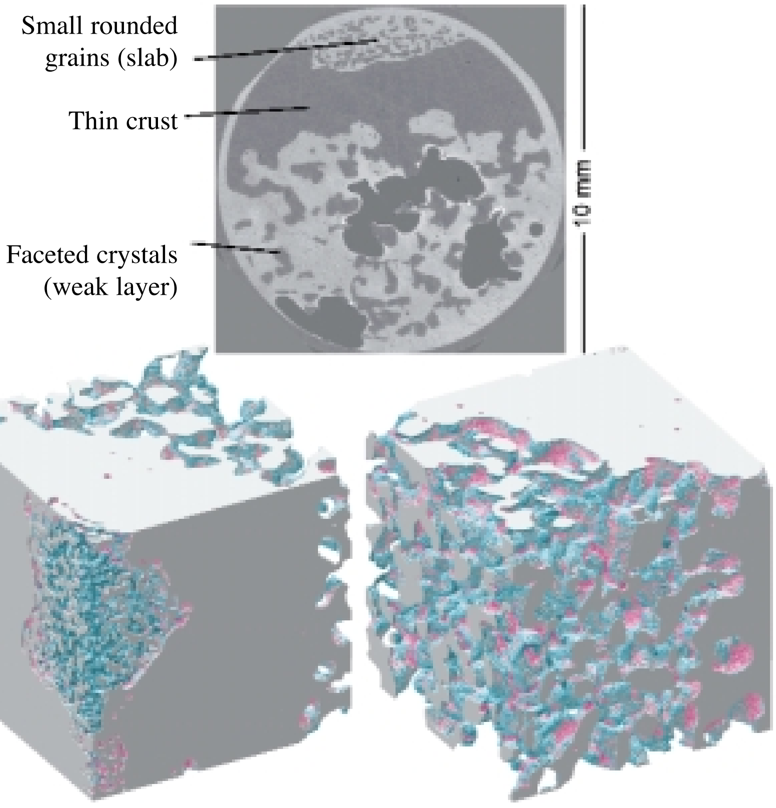

Fig. 2: Plane and 3-D reconstructed views from a snow sample collected at the failure of a slab avalanche.

RESULTS ON SNOW

From the grey level data files produced at the ESRF, a 3-D binary image was obtained by morphological processing on each image plane. The first 3-D images [3] have shown the feasibility of this technique which provides us with good quality images of the snow structure or grain assembly.

What is the interest of such images? Most physical properties and physical processes occurring inside snow are strictly linked to its microstructure. The aim was then to extract relevant information from these images. The two first geometrical parameters studied were porosity, which is the simplest descriptive parameter but often the most important for many of snows physical properties, and local curvature, which is a governing parameter of snow metamorphism. We have shown that the size of the sample studied is statistically representative for these parameters [4]. Another important geometrical parameter is surface area, which denotes the ability of a given snow to evolve. 3-D images will be used as a reference for the development of a snow metamorphism model at uniform temperature. Under such conditions, snow tends to minimise its specific area and should lead to a symmetric histogram of curvature peaked at zero.

A large area of interest where snow images could improve our knowledge is the study of avalanches and mechanical properties of snow. Snow stability on a slope is linked to the superposition of the different snow types. For instance, a cohesive layer above a weak layer is typical of most of the slab avalanches triggered by skiers. Figure 2 shows views from a snow sample collected at the failure of a slab avalanche. Classical observations describe the layering of the snow pack. X-ray microtomography is an interesting tool for visualising the bonding between different snow layers.

RESULTS ON FIRN AND ICE

The transformation of the snow into ice can be very slow in polar regions (up to 3000 years) and it is very important to know precisely when and how the gas was trapped in order to interpret the air archive (atmospheric information) compared to the ice archive (climatic information) [5]. Thus the aim of the firn and ice part of the project was to study the evolution of both open and closed porosity of the material and in a first step to test the feasibility of the method. Twelve samples have been analysed. They were taken at depths between 62 and 120 m on a Vostok (Antarctic) core, thus covering the entire range of the pore closure. The results were excellent: in Figure 3, two examples are shown and compared with the 2-D technique also used at the LGGE to study the firn structure [6]. This last method presents the advantage of revealing both pores and grain boundaries. However, it is obvious

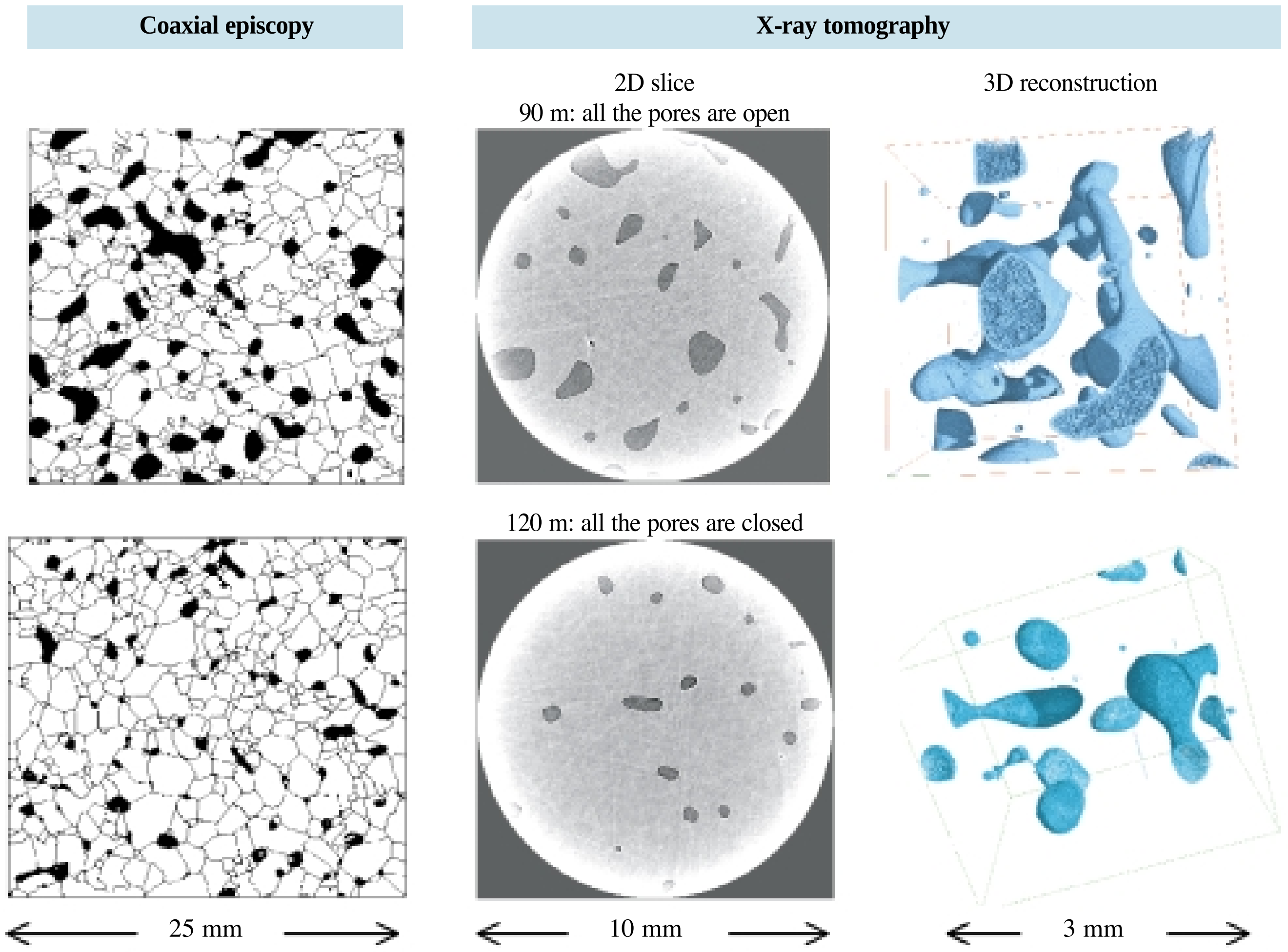

Fig. 3: 2- and 3-dimensional images of ice around the firn-ice transition: porosities appear in black in the 2-D images. The episcopy technique reveals that the pores are located at crystal boundaries. 3-D reconstructions from the 2-D slices give access to the real shape of the porosities.

from Figure 3 that the 2-D information alone is unable to give precise information on the open to closed porosity ratio. The detailed images of the shape of the pore phase near their closure show some particularities: at 90 m all the main pores are open, however very small bubbles, which are certainly formed well before the "close off", are visible. At 120 m, even if all the pores seem to be well isolated, some very small channels still exist and the gases can be fractionated when they diffuse through them.

Quantitative studies are in progress to look in particular at the influence of the sample size on the quality of the information given by such reconstructions.

CONCLUSION

X-ray microtomography appears as a very powerful tool for the study of snow microstructure and firn-ice porosities. Furthermore, 3-D imaging is gaining momentum in several domains dealing with the structure of materials. New ways to provide relevant information from the images and model development will certainly benefit from exchanges between the different research areas. ■

REFERENCES

*[1] S.C. Colbeck, Journal of Geophysical Research, **88**, 5475-5482 (1983).*

[2] J. Baruchel, J-Y. Buffière, E. Maire, P. Merle and G. Peix, X-Ray Tomography in Material Science, Hermes (2000).

*[3] J.B. Brzoska, C. Coléou, B. Lesaffre, S. Borel, O. Brissaud, W. Ludwig, E. Boller and J. Baruchel, ESRF Newsletter, **22-23** (April 1999).*

*[4] C. Coléou, B. Lesaffre, J-B. Brzoska, W. Ludwig and E. Boller, Ann.Glaciol. **32**, (2000), in press.*

*[5] L. Arnaud, M. Gay, J.-M. Barnola and P. Duval. Journal of Glaciology, **44**, 326-332, (1998).*

*[6] J.-R. Petit et al., Nature, **399**, 429- 436 (1999).*

ACKNOWLEDGEMENTS

We thank J.-B. Brzoska, B. Lesaffre, P. Duval, C. Goujon and F. Flin for their participation in the research and E. Boller, P. Cloetens and O. Brissaud for their help for the experimentation.