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X-ray microtomography of sea ice

Sönke Maus *[1]

[1]Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, NORWAY

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Summary: Two applications of X-ray microtomography to study the in situ microstructure of sea ice are described. The first approach is based on 3d imaging of centrifuged samples, revealing the morphology of natural *in situ* brine pore networks and their connectivity. Secondly, phase-sensitive time-lapse tomography of the seawater freezing process and short-term ice microstructure evolution, was performed at the ID19 beamline of the European Synchrotron Radiation Facility (ESRF), showing the feasibility of imaging in 4d.

1. INTRODUCTION

Sea ice is a porous medium that floats on its own melt, seawater. Fluid flow in and through sea ice determines the desalination of sea ice and thereby the evolution of its pore space and transport properties, being relevant for many scientific fields [1,]: (i) e.g., to which degree melting snow may drain through sea ice, creating a brighter surface and higher albedo, is relevant for the earth's climate system; (ii) sea ice microstructure also controls the mechanical properties of sea ice, affecting its large-scale dynamics, the way how it deforms and moves within the high latitude oceans, as well as its interaction with offshore structures; (iii) freezing of the multicomponent solution seawater in pore networks gives rise to complex bio-geochemical processes that shape a unique ecosystem of microorganisms and algae [2,] (iv) Recently, the interaction of oil with sea ice, i.e. oil migration into the sea ice pore space, has been pointed out as an important issue to evaluate the environmental risks of drilling and oil spills in ice-covered waters [3,]. Although the physical and geochemical properties of sea ice depend strongly on its microstructure, most of our knowledge is still based on destructive 2-dimensional thin section analysis, dating back more than 30 years [4, 5, 1,].

Both conventional X-ray tomography [6, 7, 8, 9,] as well as Synchrotron-based XRT [10, 11, 12, 13,] have been applied to image snow and polar firn, where the high air-ice absorption contrast allows microstructure observations. Two aspects make sea ice micro-tomographic imaging more challenging then for the ice snow system. First, as sea ice is a reactive medium, changing its temperature will strongly change its microstructure. Imaging sea ice at lower temperature than in the field [14,] thus does not necessarily yield relevant information on brine pore connectivity and transport properties. The second aspect is the relatively small absorption contrast between ice and water. This contrast increases with salt concentration in the brine, which in turn increases with decreasing temperature. Hence, to obtain good quality images, one needs again to image at low temperatures, which precludes observations of in situ brine channel connectivity. XRT imaging has thus recently been performed on ice grown from saltwater to which a contrast agent (CsCl) was added [15, 16,]. However, to what degree laboratory ice resembles natural sea ice is unclear.

2. EXPERIMENTAL METHOD

We applied two approaches to obtain micro-tomograhic images of the sea ice microstructure under in situ conditions. The first approach is to centrifuge the connected brine out of the samples prior to imaging [17,]. This procedure replaces the brine (high absorption) with low absorbing air and thus creates sufficient aborption contrast to ice in order to obtain high quality X-ray tomographic images of in situ brine pore networks. This approach is feasible with conventional CT imaging.

As the second approach for in-situ imaging of sea ice microstructure we performed *phase-sensitive imaging* at the ID19 beamline of the European Synchrotron Radiation Facility (ESRF), a technique that enhances image

*e-mail: sonke.maus@ntnu.no

contrast by incorporating the real part of the refractive index of ice and water [18, 19, 20,]. In addition to the enhanced contrast, short acquisition times (in our case 5 minutes per tomographic scan) made it possible to obtain time-lapse tomography images of the dendritic freezing process and evolving seawater-ice interface.

3. RESULTS

We present results from an experiment where natural arctic sea ice samples have been centrifuged at different temperatures and correspondingly different brine porosities. The centrifuged samples were imaged by X-ray microtomography (XRT) to obtain the 3-d details of characteristic pore scales and connectivity, as well as their variation with porosity. The results can be interpreted in terms of a connectivity phase transition at a porosity of 2%. This threshold is considerably lower than the frequently cited value of 5% suggested by an earlier X-ray tomography study of laboratory grown ice [15, 16,]. Our pore scale observations near the threshold indicate that this earlier estimate was limited by spatial resolution, supporting that our estimate of the critical porosity is more feasible and robust.

Our first phase-contrast time-lapse tomography in situ experiments were performed with seawater freezing upwards. While such ice growth is different from natural sea ice, where brine convection shapes the development of pore networks, the microstructures are analysed in terms of modern theories of crystal pattern formation [21,].

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