Permeability of growing sea ice: Observations, modelling and some implications for thinning Arctic sea ice

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CR6.2 Rapid changes in sea ice: processes and implications
Overview

▶ Motivation
  ▶ Sparse observational basis of sea ice permeability
  ▶ Understand/ model the dependence of permeability on porosity

▶ Methods
  ▶ Centrifuge study of sea ice
  ▶ X-ray micro-tomography ($\mu$CT): 3-d sea ice microstructure
  ▶ CFD simulations to obtain permeability from $\mu$CT images

▶ Key results
  ▶ Relationship between effective and total porosity
  ▶ Revised permeability threshold (2-3% vs widely assumed 5%)
  ▶ Relationship between permeability and porosity
Centrifuging sea ice core segments yields a relationship between effective and total porosity of the form $\phi_{\text{eff}} = \text{const}.(\phi - \phi_c)^\beta$.

$\phi_c = 2.4 \pm 0.3\%$ is smaller than the widely assumed 5%.

$\beta = 0.83 \pm 0.03$ is consistent with the critical exponent expected for 3-D directed percolation (0.81).
Key Result 2: Permeability versus brine porosity

In a log-log robust fit we exclude the shaded transition regime, where both permeable and impermeable samples are present. We obtain a relationship $K \sim \phi^{4.1}$, with larger exponent than 3.1 reported by Freitag (1999).

The best percolation fit gives $K \sim (\phi - \phi_c)^{2.6}$ with $\phi_c = 2.4\%$. 
Connected versus disconnected porosity: 3-D XRT image

XRT image 2 cm from the ice-ocean interface, highlighting connected brine versus disconnected brine (ice invisible)
Connected versus disconnected porosity: 2-D XRT slices

Most connected brine

More disconnected brine

XRT imagery based on centrifuged samples reveals disconnected and connected pores and their transition.
Present work flow:

1. Rapid sectioning of sea ice cores
2. Transport samples at *in situ* temperatures
3. Centrifugation of brine at *in situ* temperatures
4. (Cooling sequence: centrifugation at lowered temperatures)
5. Storage below eutectic temperature (-80 °C) - stable samples
6. Absorption tomography: distinguishes air, ice and solid salts
   Air: connected network ↔ salt: disconnected inclusions
7. 3-d image postprocessing (filtering, segmentation)
8. Pore space analysis and permeability simulation
Work Flow from Field to CT Image Analysis

1. Field Sampling

2. Computed Tomography

3. Refrigerated Centrifuge

4. Analysis/simulations with GeoDICT

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Sea Ice Permeability - S. Maus
Field Conditions, April 2011, Longyearbyen

Location in Adventbay, Svalbard

Meteorological conditions at Longyearbyen airport

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**Temperature, Salinity, Brine Volume Fraction**

*In situ* ice temperature and salinity

**Note:** $S_{\text{water}} \approx 35 \text{ g/kg}$

**Cooling sequence:**

temperature and brine volume fraction
Computed Tomography and Permeability Simulations

Computed Tomography

- MicroCT 40 and MicroCT 80, Scanco Medical AG
- 37 mm FOV (horizontal image width), 18 μm resolution
- ≈ 1 hour scanning time per centimeter sample height
- ≈ 5 Gigabyte raw data per centimeter
- Imaging at -20 °C

Simulations with GeoDICT

- X × Y × Z ≈ 1200 × 1200 × 1500 voxels
- 18 μm voxel size ⇒ 2 × 2 × 2.5 cm
- Flow simulation in stacks (≈ 1200 × 1200 × 300 voxels)
- Hardware: 32 GB RAM, 1 cm ≈ 4 days on 3 Ghz Quadcore PC
- Stokes-Solver, Darcy flow (low Re): \( V = \frac{K}{\mu} \frac{dP}{dz} \)
- Vertical permeability \( K \)
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