A directed percolation model for the permeability of young sea ice

Sönke Maus

Norwegian University of Science and Technology (NTNU)
Department of Civil and Environmental Engineering
Trondheim, Norway

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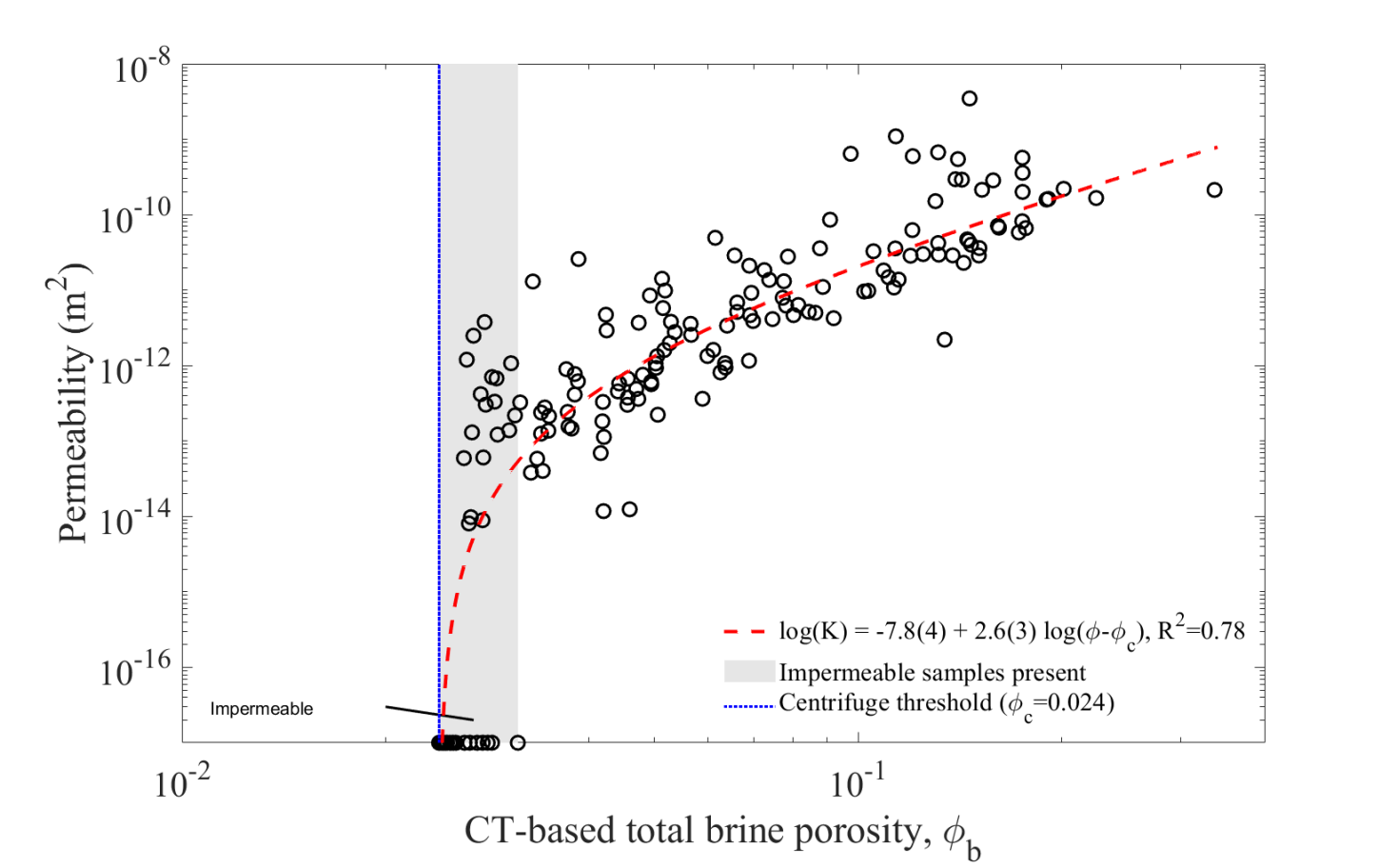
CR4.3 Rapid changes in sea ice: processes and implications

Overview

- Motivation
  - Sparse observational basis of sea ice permeability
  - Understand/ model the dependence of permeability on porosity
- Methods
  - CFD simulations to obtain permeability from 3D μCT images
  - 3D pore space analysis
  - Directed percolation modelling
- Key results
  - Critical throat size controls threshold porosity
  - Directed percolation model merged with high porosity permeability prediction from plate spacing
  - Predicted permeability threshold depends on plate spacing/growth rate
  - Most likely threshold range 1-4% for young sea ice

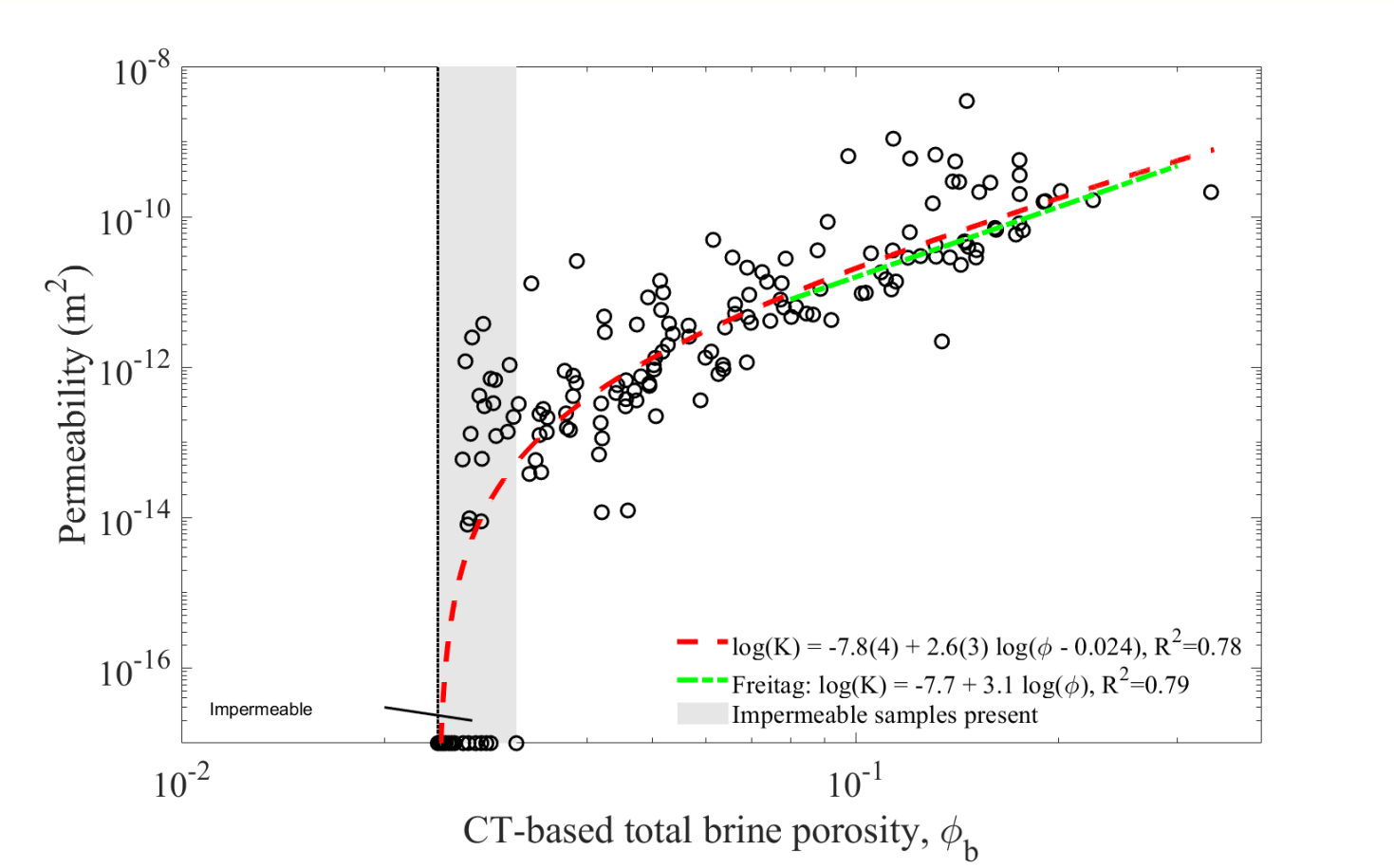
Recent results: permeability of young sea ice



Percolation behaviour of permeability: $K \sim (\phi - \phi_c)^{2.6}$
Threshold from centrifuging: $\phi_c = 2.4\%$

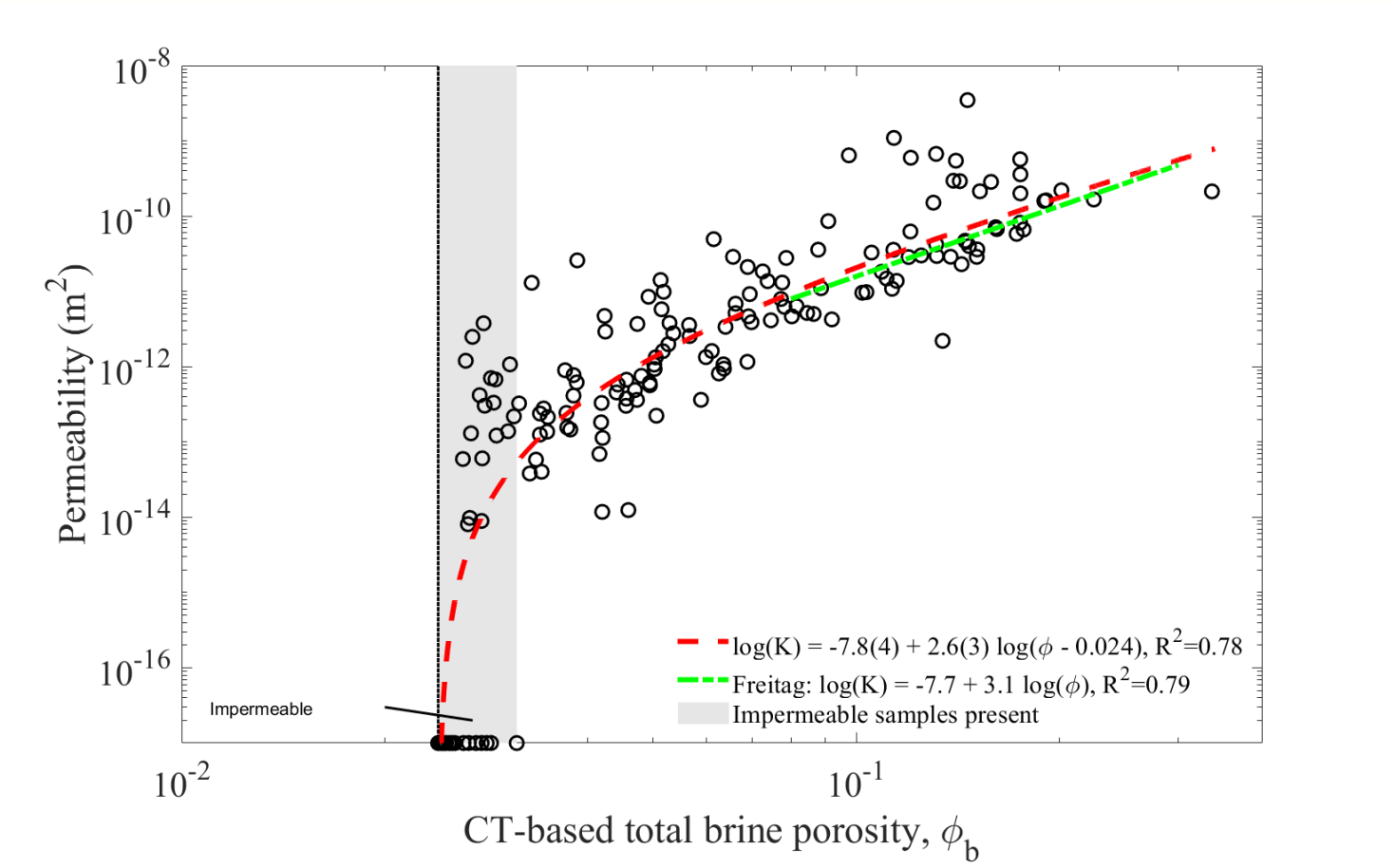
From Maus, Schneebeli and Wiegmann, TC-2020-288, 2020

Recent results: permeability of young sea ice



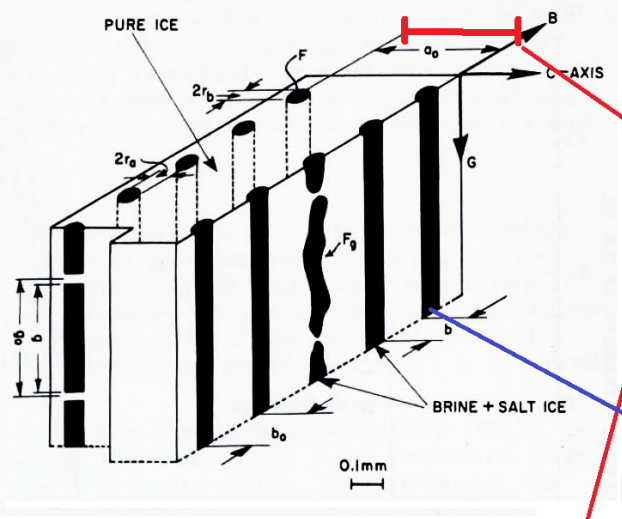
Extends the frequently used relationship $K \sim (\phi)^{3.1}$ (from Freitag, Ber. z. Polarforschung, 325, 1999) to low porosities

Recent results: permeability of young sea ice



1. What determines the percolation threshold in young ice?
2. How variable is the percolation threshold?

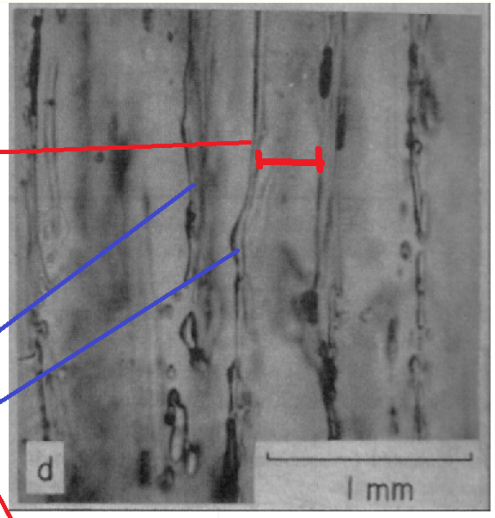
Pore splitting: early concepts and observations



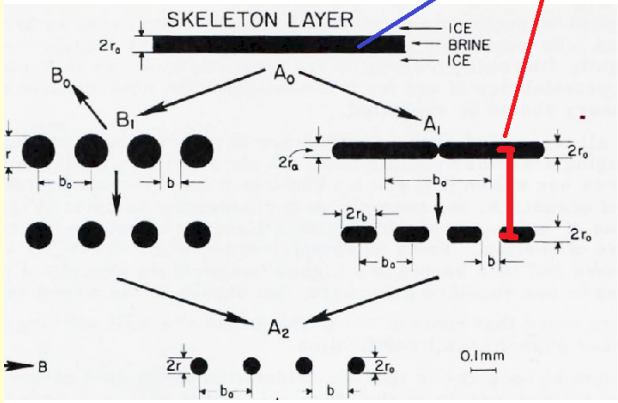
Assur (in: Arctic Sea Ice,US Nat Acad Scie, Pub 598, 1958)

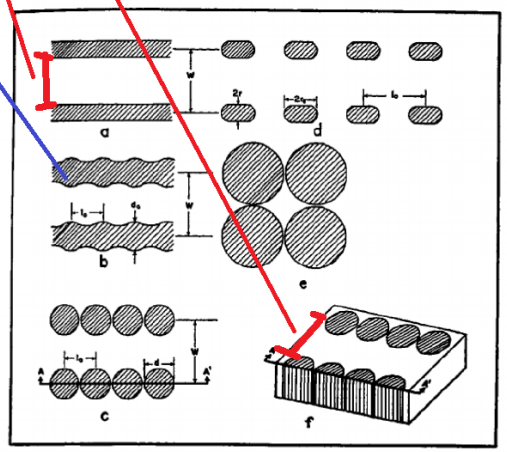
Plate spacing

Brine layer thickness

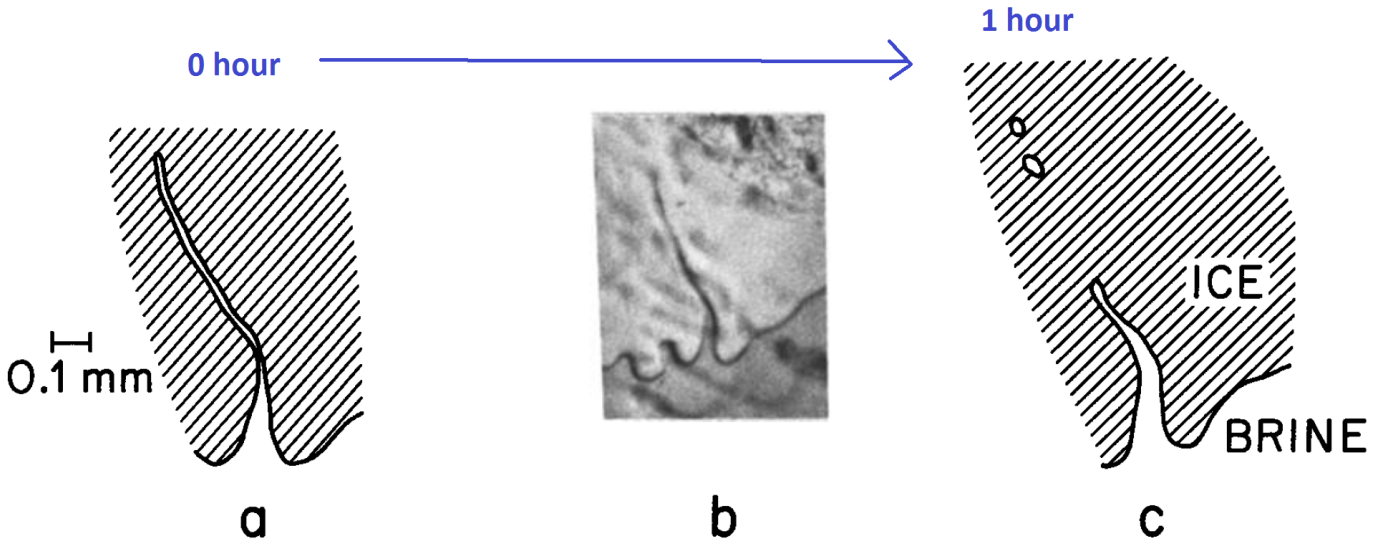


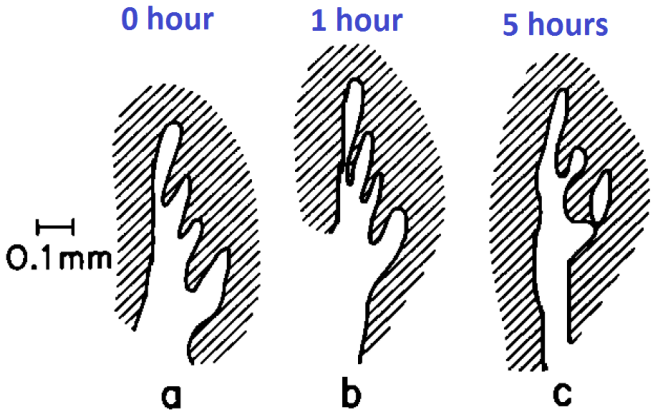
Anderson and Weeks (Trans. Amer. Geophys. Union, 39, 1958)





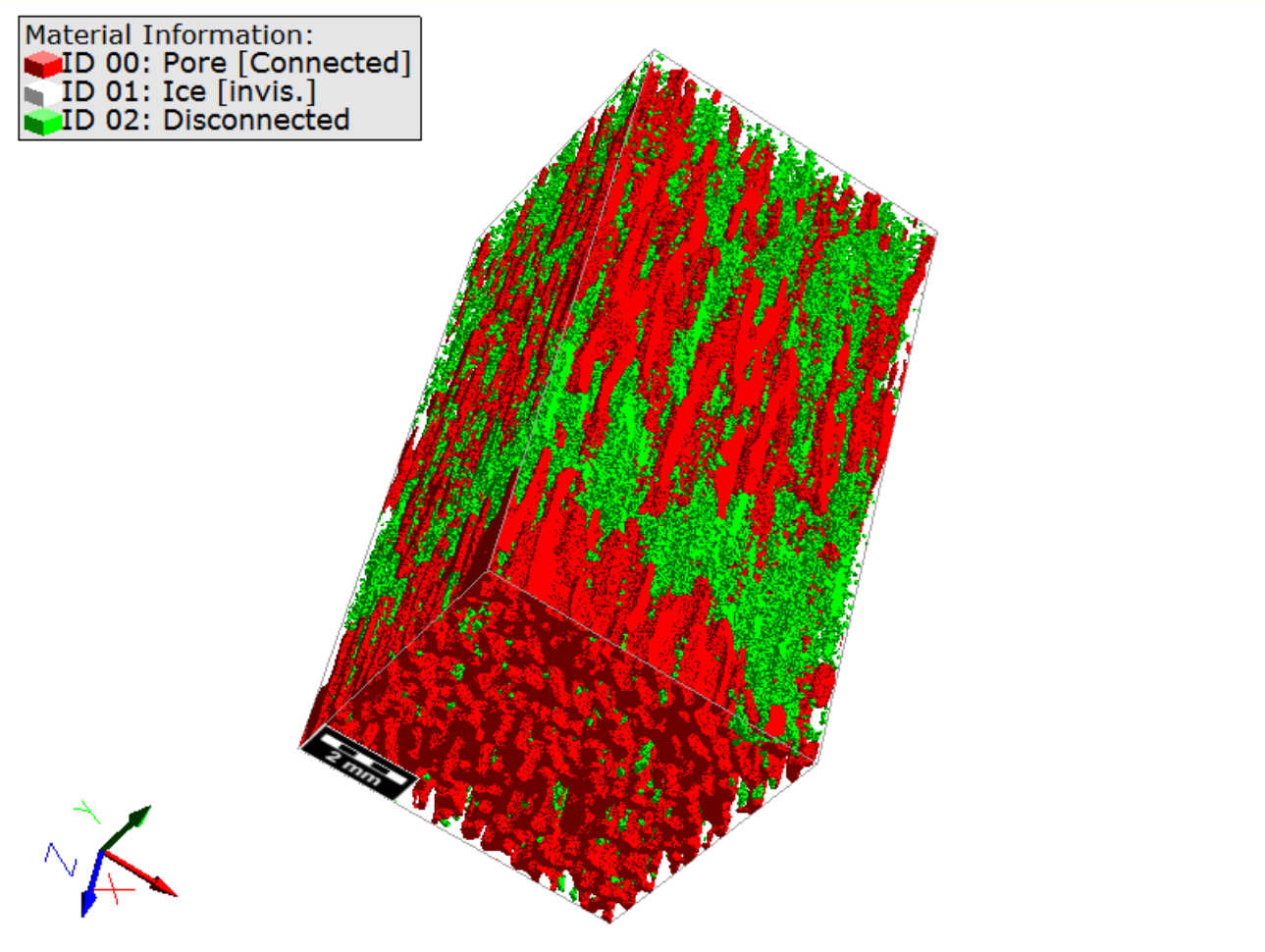
Pore splitting observations: below 0.1 mm pore width





Niedrauer and Martin (J. Geophys. Res., 84, C3, 1979,1176-1186)

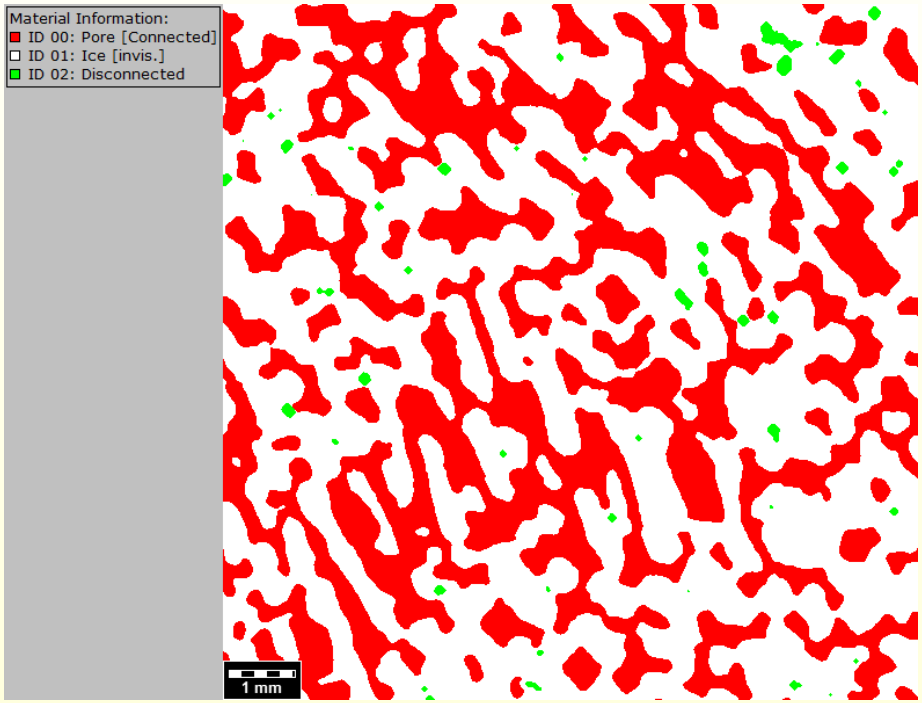
Connected porosity and critical pore sizes: 3-D XRT image

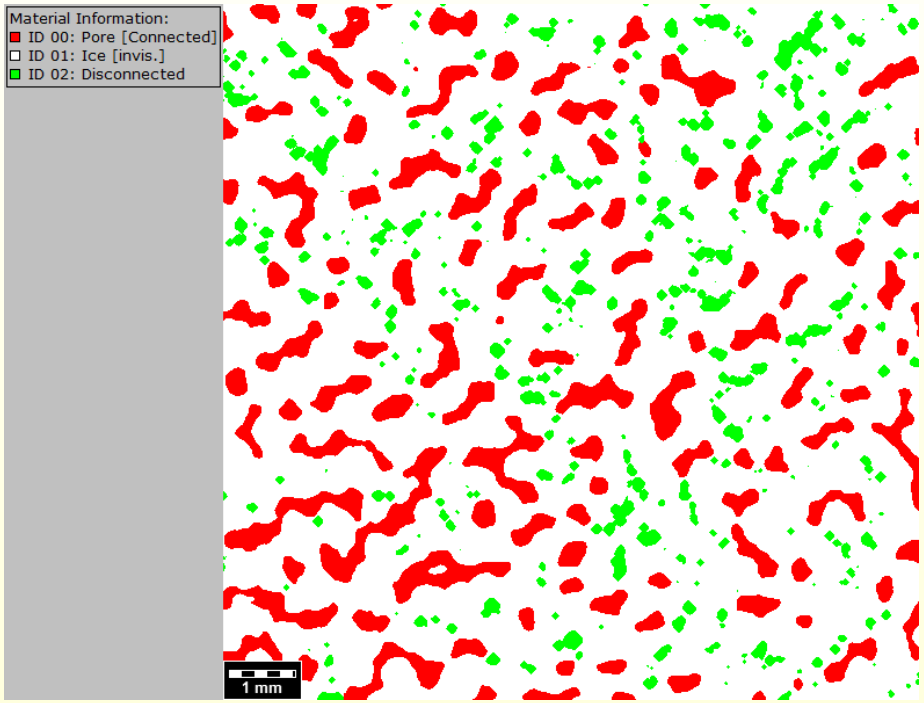


X-ray micro-tomograhy 2-4 cm from the ice-ocean inteface

Connected brine versus disconnected brine (ice invisible)

Connected porosity and critical pore sizes: 2-D XRT slices



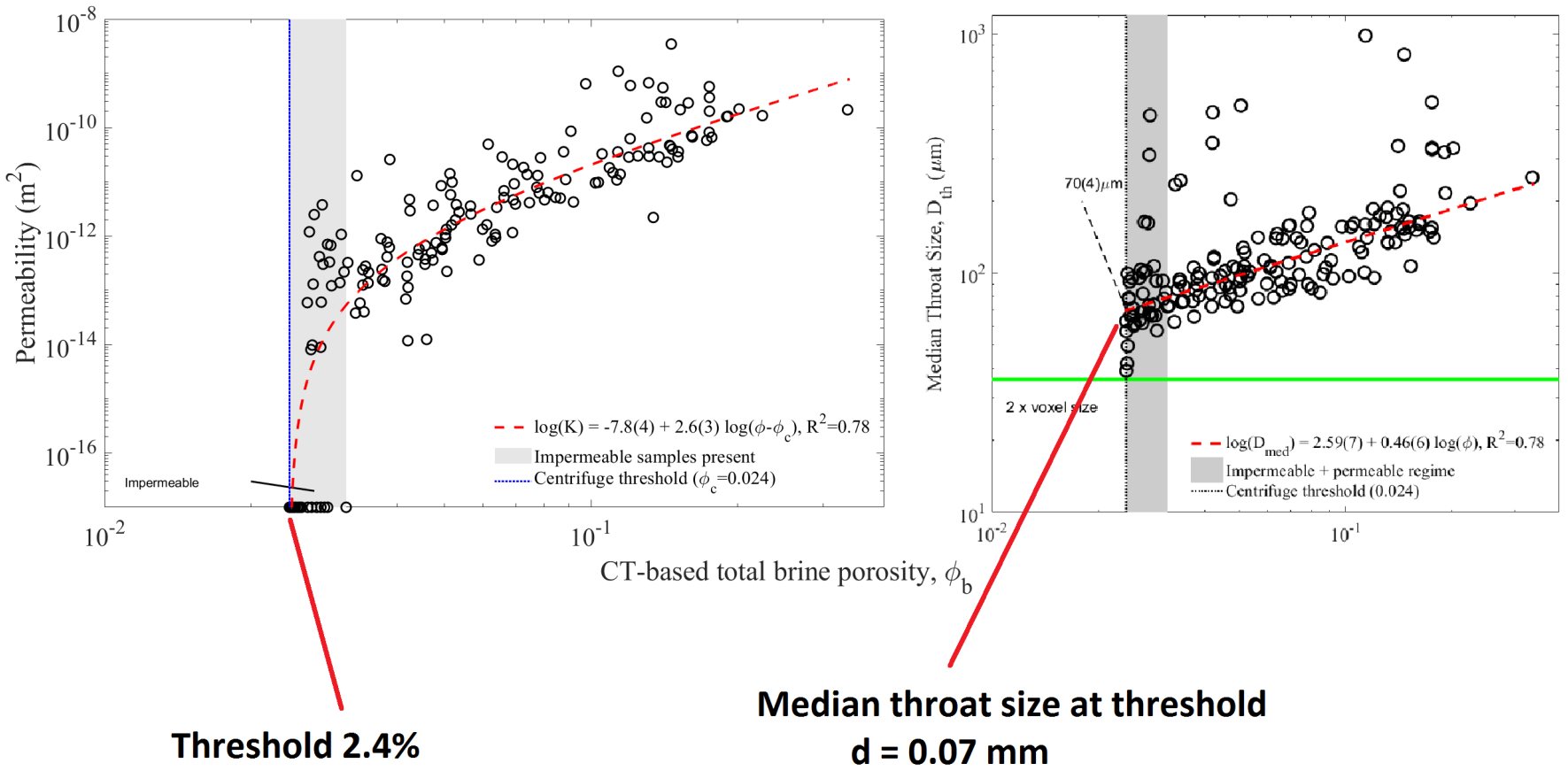


Most connected brine
Horizontal connectivity

More disconnected brine
Only vertical connectivity

Statistics of 3D connectivity give critical pore sizes for connectivity

Percolation threshold: critical throat size



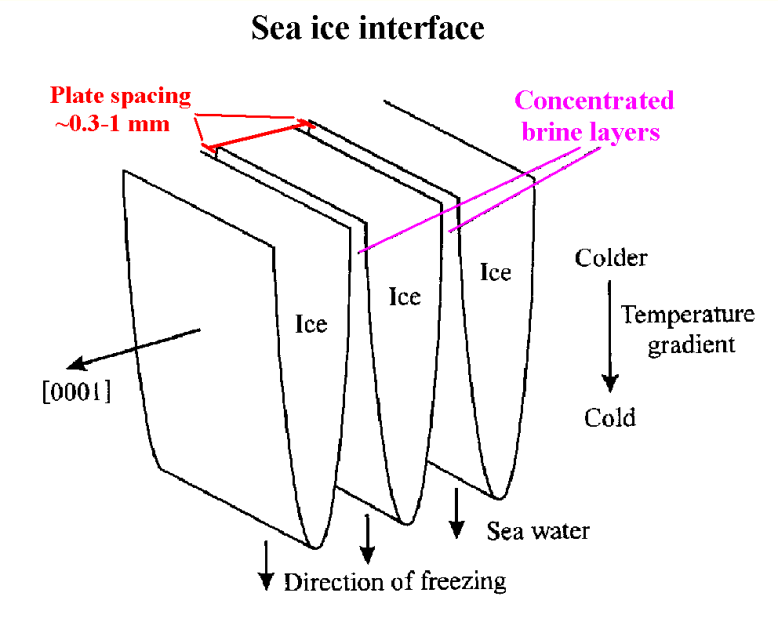
Threshold 2.4%

Median throat size at threshold
d = 0.07 mm

(From Maus, Schneebeli and Wiegmann, TC-2020-288, 2020)

See also Anderson and Weeks (Trans. Amer. Geophys. Un., 39, 1958)

Permeability dependence on plate spacing

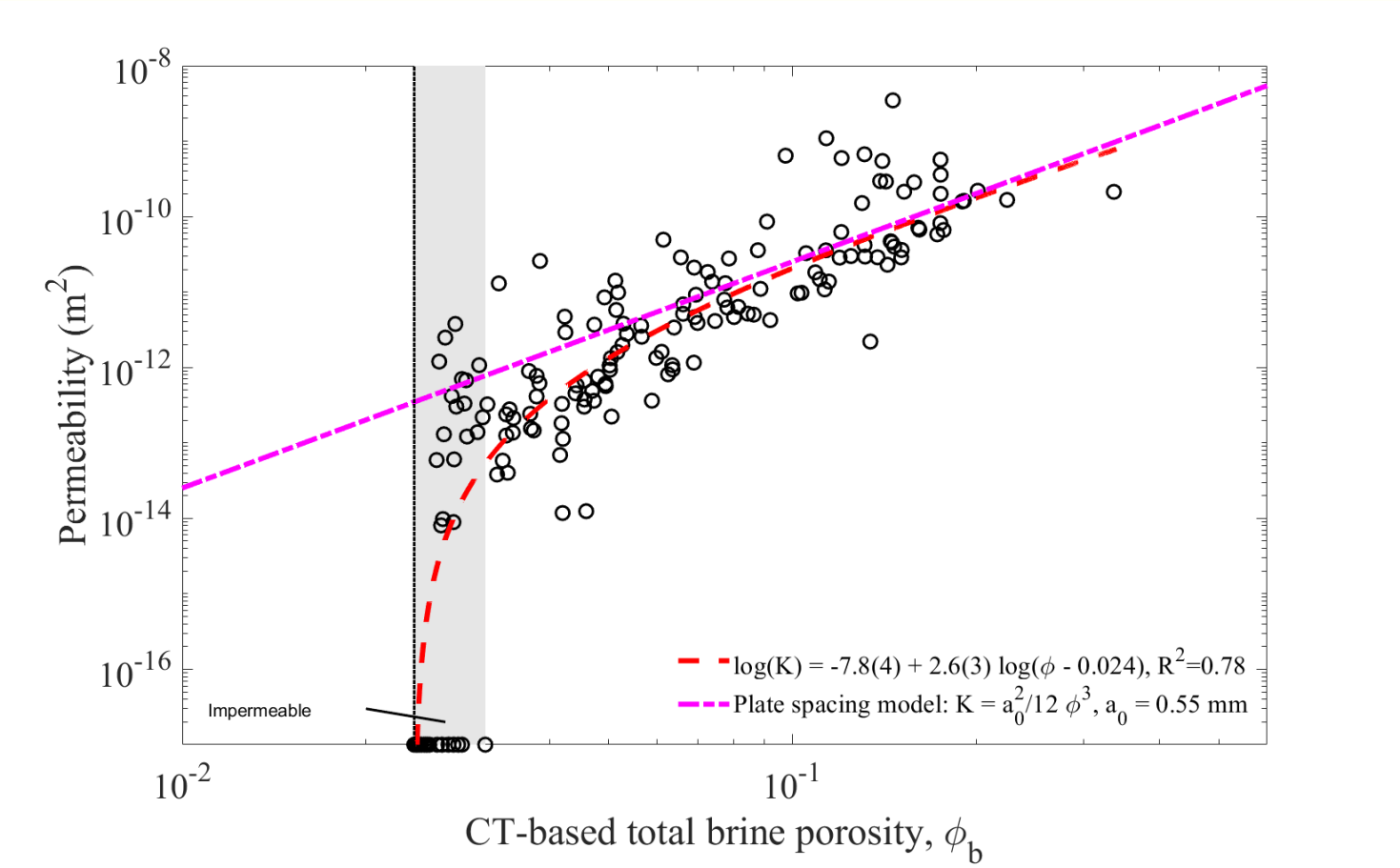


(from Petrenko and Whitworth, Physics of Ice, Oxford Univ. Press, 2002)

Plate spacing permeability model

- plate spacing: a_0
  brine layer width: d
  brine porosity: $\phi = d/a_0$
- single brine layer permeability:
  $K_d = d^2/12$
- Bulk permeability:
  $K = a_0^2 \phi^3$

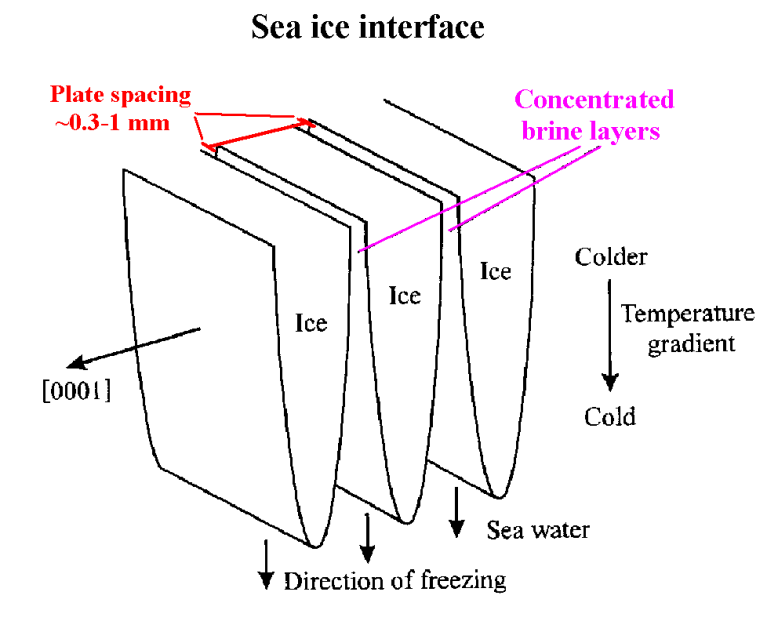
Plate spacing versus percolation model



The plate spacing permeability prediction matches the percolation model at high porosities.

(Average plate spacing for the young ice: $a_0 = 0.55mm$).

Porosity threshold dependence on plate spacing



(from Petrenko and Whitworth, Physics of Ice, Oxford Univ. Press, 2002)

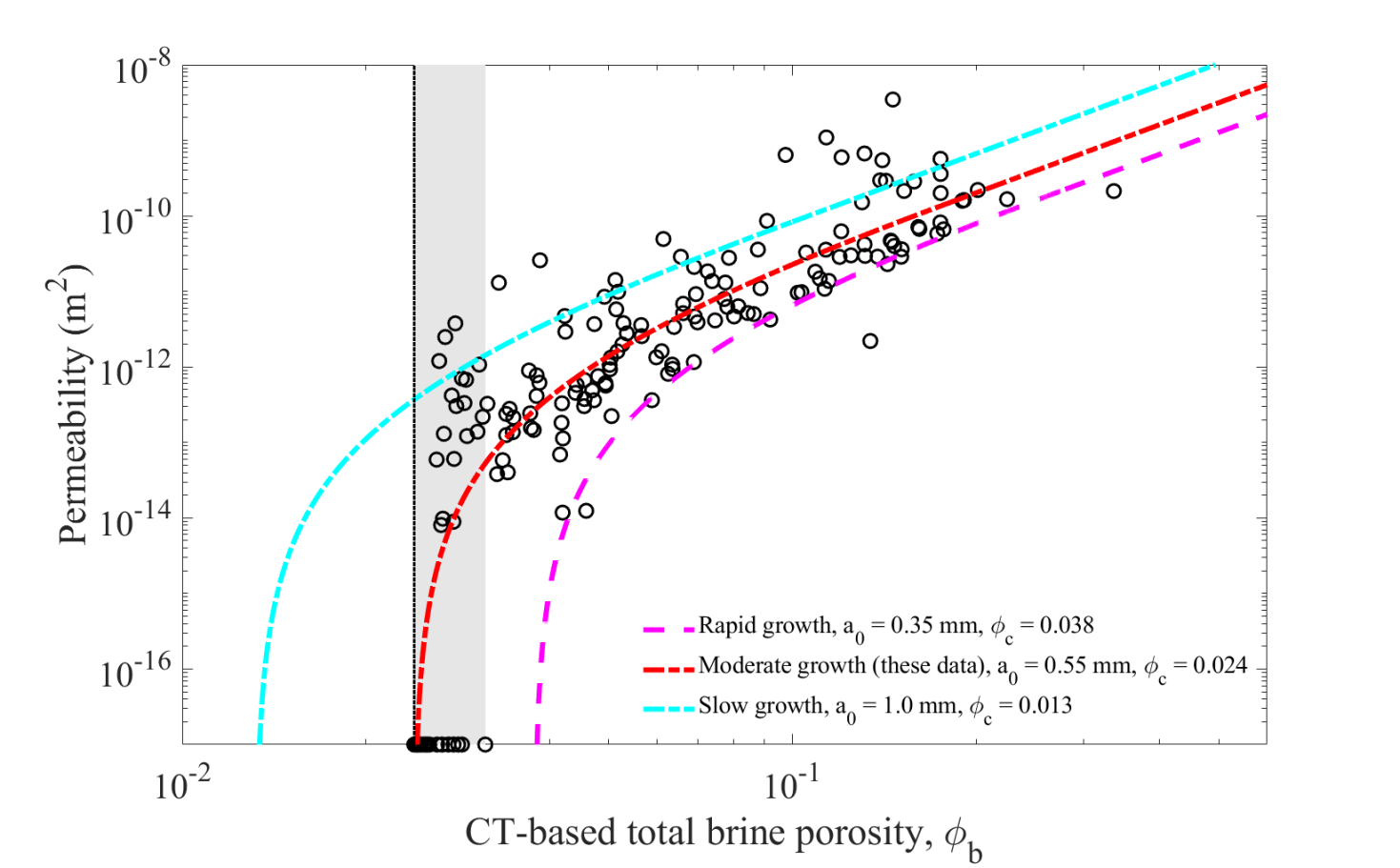
Hypothesis for plate spacing a_0

- pore close-off at critical pore width $d_0 = 0.07mm$
- pores located in original brine layers spaced by a_0
- number of brine layers $\propto a_0^{-1}$

$\rightarrow$ **Critical porosity** $\phi_c \propto a_0^{-1}$

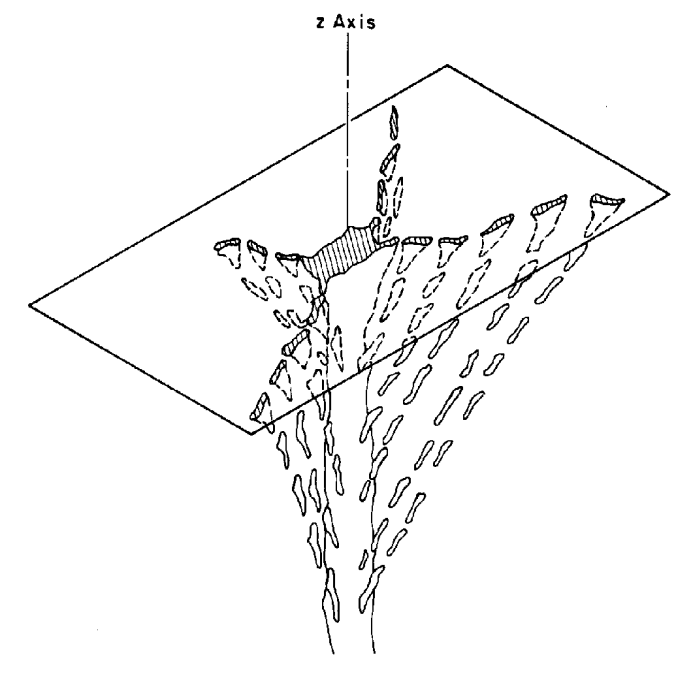
$\rightarrow$ **Critical porosity ϕ_c increases with growth velocity**

Permeability and percolation - dependence on plate spacing

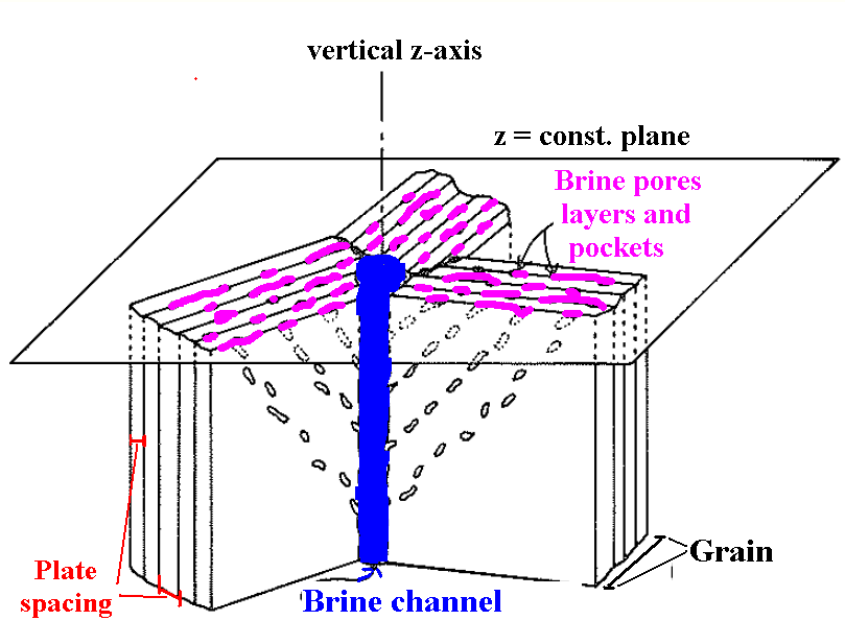


Extrapolating the present results ($\phi_c = 2.4\%$ and $a_0 \sim 0.55mm$):
The porosity threshold for natural sea ice (with $0.3 < a_0 < 1.0mm$) is estimated in the range $1 < \phi_c < 4\%$.

Porosity threshold dependence on plate spacing



(from Lake and Lewis, J. Geophys. Res., 75, 583, 1970)



(from Wakatsuchi, Inst. Low Temp. Sci, 33, 29, 1983)

The results apply to young sea ice dominated by primary pores within the planes of original brine layers.
Older sea ice with wide brine channels may behave differently.

Acknowledgements

I like to thank

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