Modelling oil entrapment in sea ice on the basis of 3d micro-tomographic images

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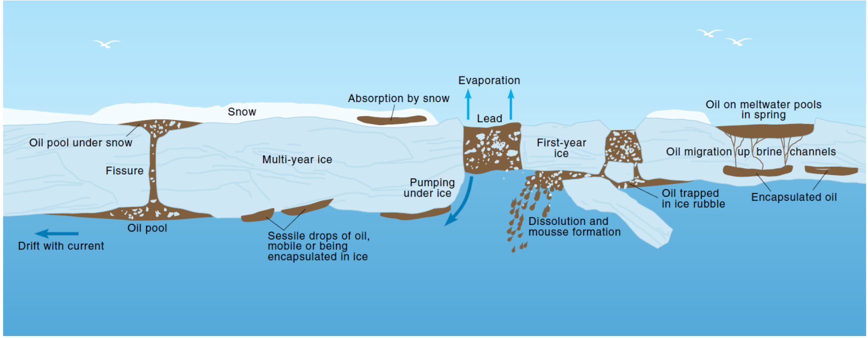
Overview

- Background
  - Oil-in-ice problems (sea ice)
  - Oil-through-ice movement: experiments and modelling
- Present approach/methods
  - Centrifuging sea ice
  - Computed micro-tomography (μCT): 3d sea ice microstructure
  - Numerical analysis/simulations (of 3-d μCT images)
- Results
  - Permeability, pore space
  - Oil uptake capacity of sea ice
- Conclusions

Interaction of Oil and Sea Ice



(AMAP, Arctic Pollution Issues, 1998)

1. Pooling under ice
2. Leads-ridges-brash
3. Uptake by pores

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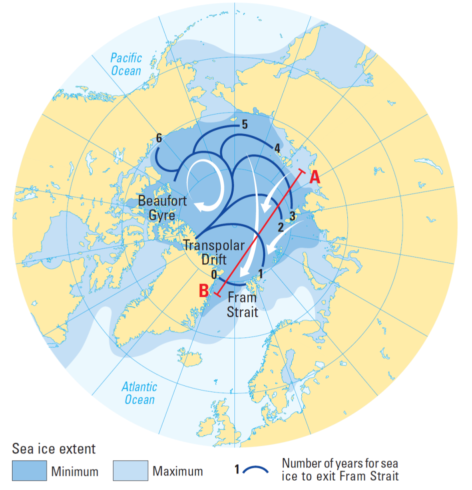
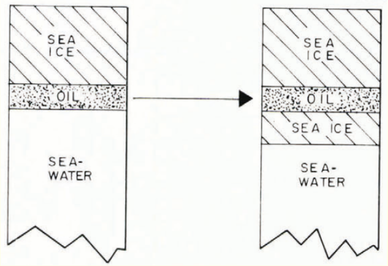


(AMAP, Arctic Pollution Issues, 1998

Where and when is spilled oil released from drifting sea ice?

Laboratory studies



(Wolfe and Holt, J. Glaciol., 1974)

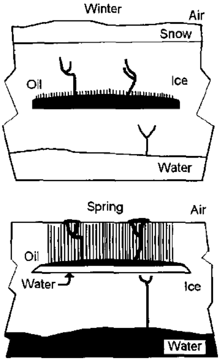
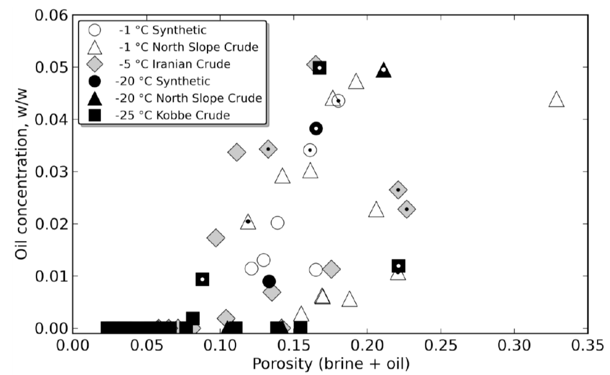


Fig. 1 Oil permeation into sea ice

(Otsuka et al., MTS/IEEE Oceans'04, 2004)

Results from mostly laboratory studies:
Winter: Oil becomes encapsulated
Spring/summer: Oil eventually migrates to surface

Oil uptake in laboratory



(Karlsson et al., POAC, 2011)

- by threshold brine porosity of 8-15%
- by distance from oil lens (3 cm - Karlsson; 10 cm - Otsuka et al.)
- by 30 % oil saturation of pore space

Previous Studies and Conjectures: oil storage capacity

- Under ice pooling capacity
  - 10 to 60 L/m^2 (Fingas and Hollebone, Mar. Poll. Bull. 2003)
  - 0.5 to 16 L/m^3 spreading model (Wilkinson et al., GRL, 2007)
- Uptake by pore space (based on porosity threshold 10-15 %)
  - Winter: < 2 L/m^2
  - Spring: 5 to 10 L/m^2
    (Petrich et al., Cold Reg. Sci. Technol., 2013)

$\Longrightarrow$ uptake by pore space is $\approx$ 20 % of under ice pooling capacity ?

Eytrapolation Issues: Laboratory to Field

(Karlsson et al., POAC, 2011

Do laboratory results reflect field conditions?

- thickness of oil pools/layers (lab: 3-8 mm)
- comparability of microstructure and permeability
- (boundary conditions: ocean, atmosphere, tank)

Present Approach

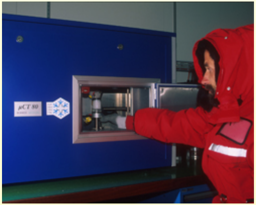
"*There are no mathematical algorithms to predict the movement of oil through ice. This aspect then requires extensive studies.*" (Fingas and Hollebone, 2003)

⟶ 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 ℃) - 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 ananlysis and permeability simulation

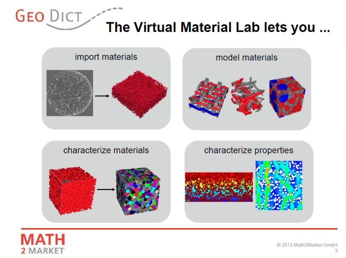
Work Flow from Field to CT Image Analysis

1. Field Sampling



2. Computed Tomography

3. Refrigerated Centrifuge



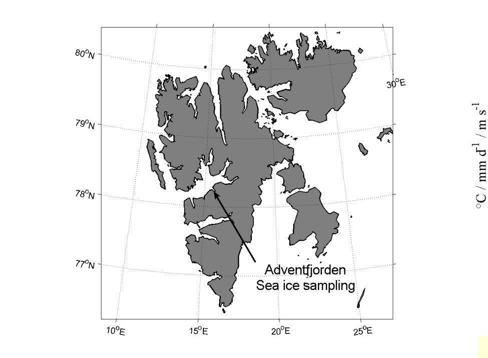
4. Analysis/simulations with GeoDICT

Sampling and Preparation

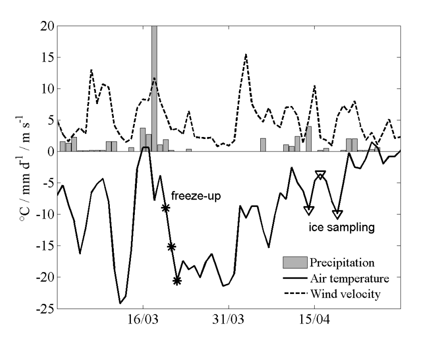
After sampling

After first cutting

Field Conditions, April 2011, Longyearbyen

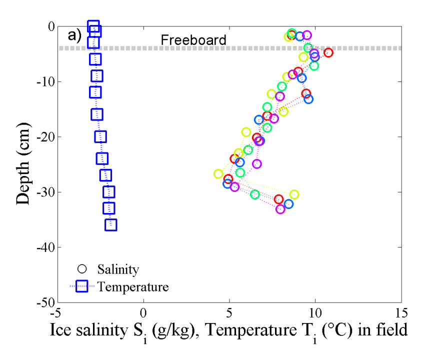


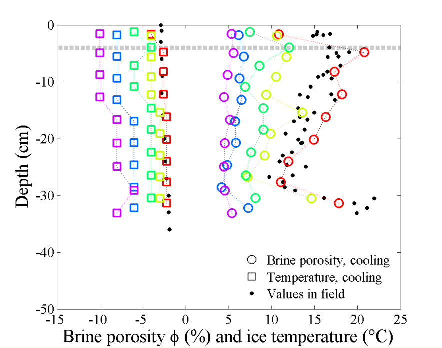
Location in Adventbay, Svalbard



Meteorological conditions at Longyearbyen airport

Temperature, Salinity, Brine Volume Fractionj



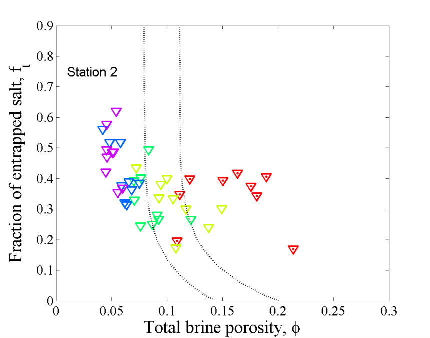


In situ ice temperature and salinity
Note: $S_{water} \approx 35$ g/kg

Cooling sequence:

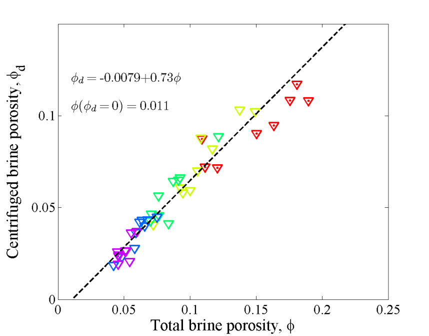
temperature and brine volume fraction

Interpretation of Centrifuging Results



Non-centrifugable brine volume fraction

"Saturation": $(1-\phi_d)/\phi$



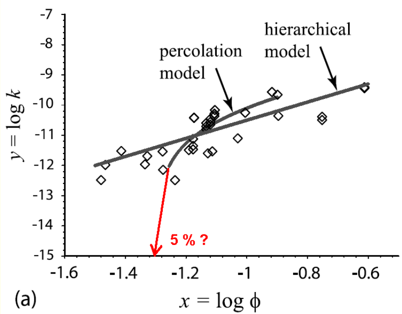
Centrifuged brine volume fraction ϕ_d

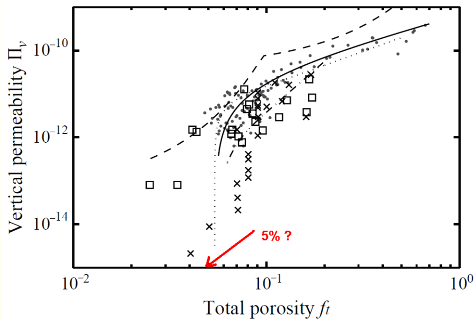
versus total brine volume ϕ

Trapped brine fraction increases with decreasing brine content

Linear fit indicates a threshold $\phi \approx 1$ %

Previous Work and Percolation Hypothesis





Borehole field data - proposed percolation threshold $\phi_c \approx 0.05$ has remained unconfirmed (Golden et al., 2007)

Laboratory experiments - different methods and ice types imply high scatter (Petrich et al., 2006, see also Maksym and Jeffries, 2000)

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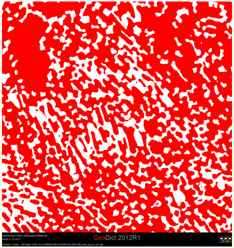
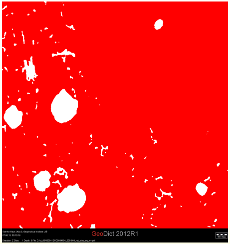
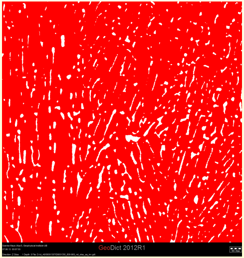


Young ice, 1 cm from bottom



Summer first-year ice, 40 cm f. interface



Young ice - 5 cm from bottom

Computed Tomography and Permeability Simulations

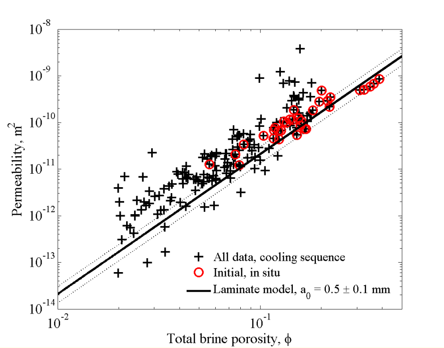
Computed Tomography

- MicroCT 40 and MicroCT 80, Scanco Medical AG
- 37 mm FOV (horizontal image width), 18 μm resolution
- $\approx$ 1 hour scanning time per centimeter sample height
- $\approx$ 5 Gigabyte raw data per centimeter
- imaging at -20 ℃

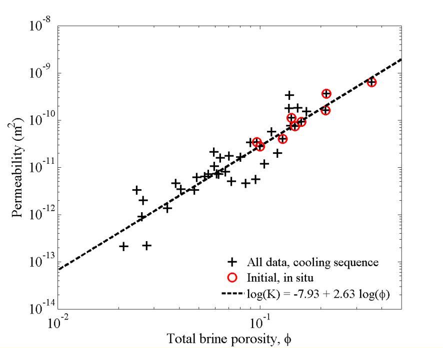
Simulations with GeoDICT

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

Permeability Simulations with GeoDict



Small stacks (2 x 2 x 0.55 cm)



From 4-5 stacks in series (1/K average)

No permeability threshold down to 2% porosity

Physics of Oil Entrainment - Capillary Pressure

Oil-brine buyancy has to overcome surface tension:

$$P_c = \sigma_{nw} cos(\theta) \left(\frac{1}{R_1} + \frac{1}{R_2} \right), \quad (1)$$

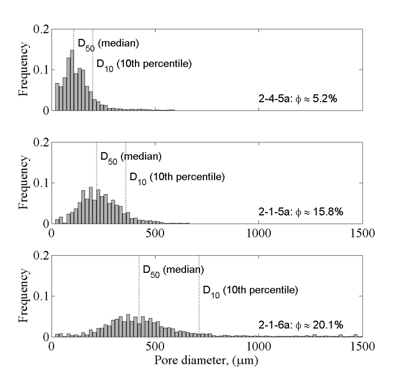
simplifies for circular cross sections to

$$H = \frac{2\sigma_{nw} cos(\theta)}{g \Delta\rho R}. \quad (2)$$

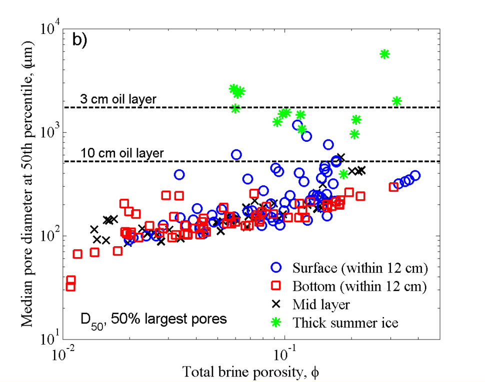
- σ_{nw} is oil-water surface tension, g gravity acceleration
- θ the oil-ice contact angle
- R pore radius
- $\Delta\rho$ oil brine density difference
- H oil pool or layer thickness

$\Longrightarrow$ Oil entrainment depends on pore sizes and pool thickness.

Pore Sizes and Capillary Pressure



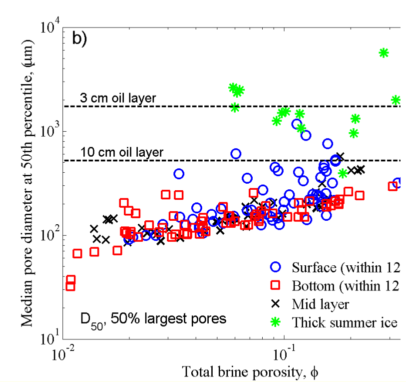
Typical pore sizes of young ice

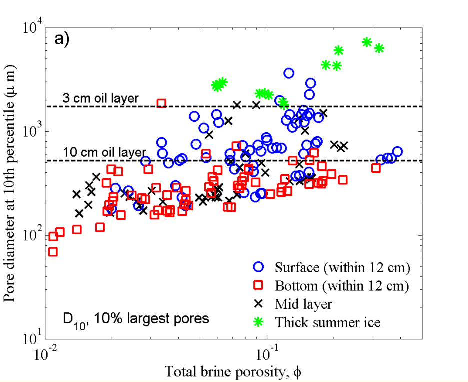


Median pore diameter D_{50}

Oil infiltration potential of sea ice (50% of pore space)

Pore Sizes and Capillary Pressure



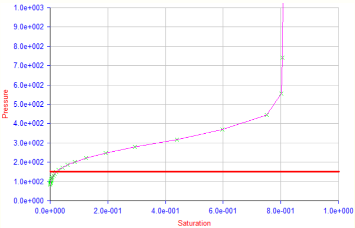


Median pore diameter D_{50}

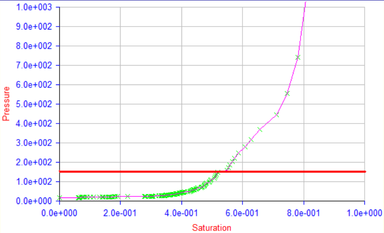
Pore diameter D_{10}, 10% of pores are larger

Oil infiltration potential of sea ice (10% versus 50% of pore space)

Displacement of brine by oil, simulation



Young ice, 1 cm from bottom



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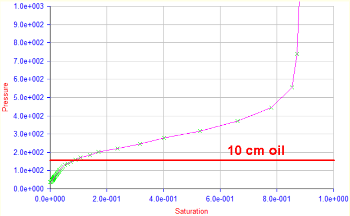
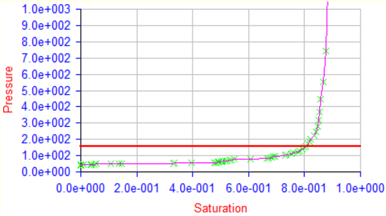


Young ice - 5 cm from surface



Summer first-year ice, 30 cm f. interface

160 Pa corresponds approximately to a $\approx$ 10 cm oil pool

Summary and Outlook

Sea ice permeability:

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Conclusions on oil uptake by sea ice:

- Depends on pool thickness and pore sizes - no threshold
- Older summer ice:
  - 10 cm oil pool sufficient for $> 50\%$ (of pore space) oil infiltration
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Outlook:

- μCT imaging, in particular of ice at different ages
- Validate spill experiments by μCT flow modelling
- Combine large scale transport with μCT flow modelling
- General: microstructure prediction + evaluation of physical properties by μCT (e.g. elastic modulus, electric and thermal conductivity; transport of particles/dissolved matter)