Sea Ice microstructure
Oil migration through brine channels

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Outline

• Oil/sea ice interaction

• Sea-ice microstructure
  – Growth
  – Porosity & permeability
  – Brine movement

• Oil entrainment in ice

• Conclusions

Sea Ice Group (GI|UAF)

• Hajo Eicken
• Chris Petrich
• Jonas Karlsson
• Daniel Pringle
  .... and other collaborators
Oil & sea ice interactions

Oil encapsulation
- Under-ice spreading
- Encapsulation in growing ice
- Mobilization and migration in spring
- Surfacing and weathering
- Release with ice break-up

Potential mitigation
- Limited access
  - Both under- and in-ice
- Remediation
  - After oil have migrated toward the surface
Sea ice microstructure properties and structure profiles

- Textural classification
  - Granular
  - Columnar
  - Mixed columnar/granular

- Genetic classification
  - Snow ice
  - Frazil ice
  - Congelation ice

- Growth condition
  - Snow deposition
  - Flooding
  - Turbulent mixing

- Stratigraphy
  - Water column supercooling
  - Intergranular pores, isometric grains
  - Intrasea ice, intergranular pores, prismatic grains

- Depth [cm] Time scale
  - Temperature [°C]
  - Salinity [%]

- Time scale:
  - 10 days
  - 25 weeks
  - 50 months
  - 150 years
Sea ice microstructure

- Brine entrapped at the bottom of sea ice
- Constriction & segregation of pore space
  - During thickening & cooling
  - Brine layer > brine tube > brine pockets
  - Depends of salinity & temperature (porosity)

\[a \leq b < c\]
\[a \sim 0.1 \text{ to } 0.3 \text{ mm}; \ b \sim 1 \text{ to } 5 \times a; \ c > 5 \times a\]
\[d \sim 0.25 \text{ to } 1.25 \text{ mm (avg 0.7)}\]

[Assur, 1960]

[Kovacs, 1996]
Sea ice microstructure

Brine channel system (BCS)

- Winter (March)
  - Number density
    0.5±0.1 dm\(^{-2}\)
  - Aerial fraction
    0.10±0.04 cm\(^{-2}\)
  - Mean spacing
    11±4 cm

Eicken
Sea ice microstructure

- Host of multitude of organisms

- Release of extracellular polymeric substance (EPS)
  - Influence ice growth & microstructure

- Biota would be influence by oil spill

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BCS as an ecosystem

[Image: A: No EPS, B: EPS, C: Blue colored EPS]
Sea ice microstructure

- X-ray imaging
  - Multiple projections of a same object
  - Every projection at a slightly different angle
  - Contrast based on density

- Computed tomography
  - 2D slices
  - 3D model reconstruction
• Winter growth
  – Columnar sea ice
  – Brine channel
    • $V_f$: 2-3% in January
    • Segregated

• Spring
  – Warming event
  – Increasing porosity
    • Increasing channel diameter
    • Interconnection
  – Salinity change

• Volume occupied by brine
  – Dependant of temperature and salinity

Brine channel evolution
[Pringle, 2009]
Connectivity is function of temperature

The fractional connectivity is the proportion of inclusions intersecting the upper surface which are also connected to the lower surface.

Porosity

Connectivity

(a) $T = -15 ^\circ C$, $\phi = 0.033$
(b) $T = -6 ^\circ C$, $\phi = 0.075$
(c) $T = -3 ^\circ C$, $\phi = 0.143$

[b] Golden et al., 2007

[b] Golden et al., 2007
• Intrinsic permeability
  – Mathematical model (Golden et al., 2007)
  – Difference between cold & warm ice

• Percolation threshold $\phi_c = 0.05$
  – $T = -5^\circ C$
  – $S = 5$ PSU
Porosity

State variables and physical properties

Measurement
• Ice core data
• *In situ*

Calculated
• Simple relationship
• Mathematical model
Brine movement

- Ice core data from Barrow, Ak

- Higher salinity at bottom
  - Winter C-Shape curve

- Surface melting
  - Late May / early June
  - S-Shape curve

- Downward flushing of meltwater
  - Higher permeability
  - Brine drainage

[Petrich, 2013]
Brine movement

• Force balance
  – Driving force
    • Density difference $\frac{\partial \rho}{\partial z}$
    • Limited by
      – Medium permeability $K_z$
      – Fluid viscosity $\mu$
  – Retarding motion
    • Thermal diffusivity $\alpha_{si}$
    • Phase transition

• Porous medium
  – Rayleigh number
    $$Ra_p = g \frac{\frac{\partial \rho}{\partial z} K_z \Delta z}{\mu \alpha_{si}}$$
  – If $Ra > Ra_{p,c}$: convection
1st experimental study

Winter oil spill
- Landfast ice
- Oil spilled 15 February
- Migration to surface in April / early May

Spring oil spill
- Landfast ice
- Oil spilled 15 May
- Migration to surface within 1 hour

Ice surface prior to under-ice spill

Ice surface 2 h after under-ice spill

[Martin, 1979]
Oil movement in ice

• Ice tank
  – Mimic natural sea ice growth
  – Insulated ice tank
    • Prevent ice formation along the wall
  – Pressure release
    • Avoid tank deformation
  – Pump
    • Break saline convection cell
    • Provide similar ocean heat flux

• Oil entrainment & migration
  – Temperature & salinity data
  – Oil flow
  – Oil content & distribution

[Diagram with labels:
1: Salinometer
2: Pressure Release
3: Video Camera
4: Heating Pump
5: Tube
6: Shield
7: Thermistor Probe]

[Karlsson, 2011]
Oil movement in ice

Temperature profile

Events:
- Oil flow to surface
- Weak light
- Strong light
- Insolation on ice
- B: Bottom Heating off
- C: Core taken
- OR: Oil Release
- OT: Oil starts seeping up along tank

[Karlsson, 2011]
Oil movement in ice

**Growth season experiment**
- No warming event
- Oil confined at the bottom

**Melt experiment**
- Simulated warm spelt
- Oil migration within the ice

[Karlsson, 2011]
Oil movement in ice

- Brine movement
  - Critical threshold: $\phi_c = 0.05$

- Oil movement
  - Critical threshold $\phi_{c,oil} = 0.10-0.15$

[Diagram showing oil concentration vs. porosity (brine + oil) with data points for different temperatures and crude types. Source: Karlsson, 2009]
Conclusion

• Oil migration
  – Encapsulated into pore space
  – Entrained during spring

• Microstructure & brine inclusion morphology
  – Controlling factors of depth penetration
  – Determine entrainment and mobilization in Spring

• Fluid exchange with underlying ocean
  – Controlled growth rate
  – Interface morphology
  – Feedback biota-oil
Further work

- Linkage with biota
  - Ongoing work
  - Indoor experiment

- X-Ray observation of oil/ice
  - Similar density
    - $\rho_{\text{ice}} = 0.92 \, [\text{gcm}^{-3}]$
    - $\rho_{\text{oil}} \approx 0.87 \, [\text{gcm}^{-3}]$
  - Possible to distinguish oil layer
  - Possibility to follow
    - Oil distribution ?
    - Oil content ?

- Modeling
  - Simple 1D model
  - Fluid flow in porous media
References

AMAP, 2007. Arctic Oil and Gas 2007. Arctic Monitoring and Assessment Program (AMAP) Oslo, Norway


Thank you