Downward oxidant transport through Europa's ice shell in porosity waves

Marc Hesse[1,2], Steven Vance[3], Jacob Jordan[4]

[1] Department of Geological Sciences, University of Texas at Austin
[2] Institute for Computational Engineering and Sciences, University of Texas at Austin
[3] Jet Propulsion Laboratory, California Institute of Technology
[4] Department of Geology & Geophysics, Yale University

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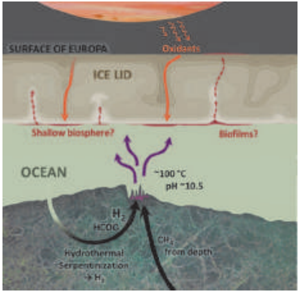
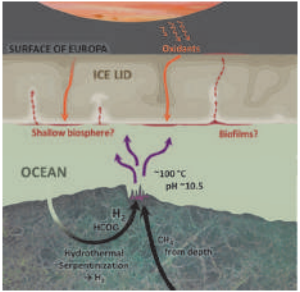
Redox disequilibria as energy source for life



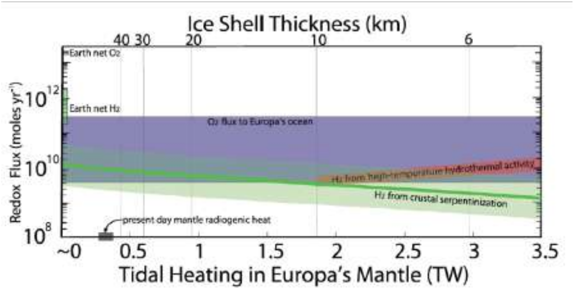
Russell et al. (2017)

- Requires downward oxidant transport through the ice-shell.

Redox disequilibria as energy source for life



Russell et al. (2017)

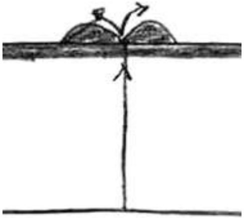


Vance et al. (2016)

- Requires downward oxidant transport through the ice-shell.
- What are the physics of the transfer processes?

Proposed ice-shell transfer processes

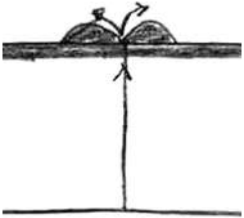
Resurfacing



Greenberg (2010)

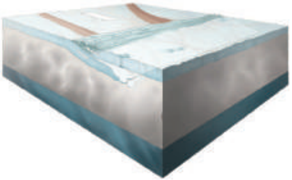
Proposed ice-shell transfer processes

Resurfacing



Greenberg (2010)

Subduction



Kattenhorn and Prockter (2014)

Proposed ice-shell transfer processes

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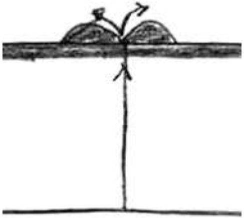

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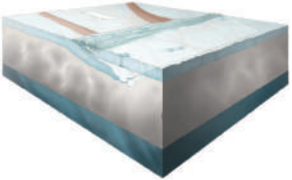
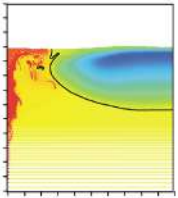


Kattenhorn and Prockter (2014)

Impact



Cox and Bauer (2015)

Proposed ice-shell transfer processes

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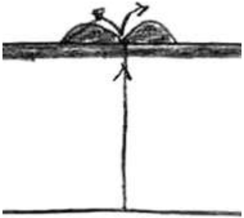

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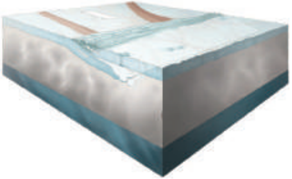

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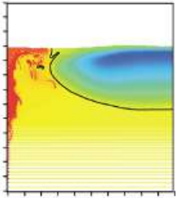
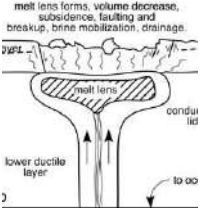


Cox and Bauer (2015)

Brine percolation



Sotin et al. (2002)

Proposed ice-shell transfer processes

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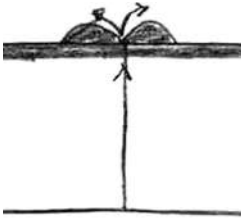

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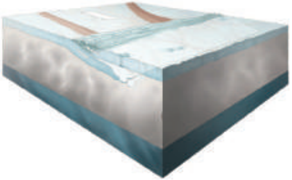

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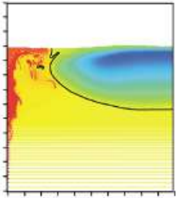

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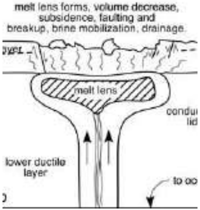
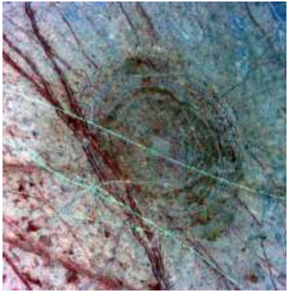


Sotin et al. (2002)

Here we focus on oxidant transport by downward brine percolation.

Surface features indicating near surface brines

Impact craters



NASA

Chaos terrains

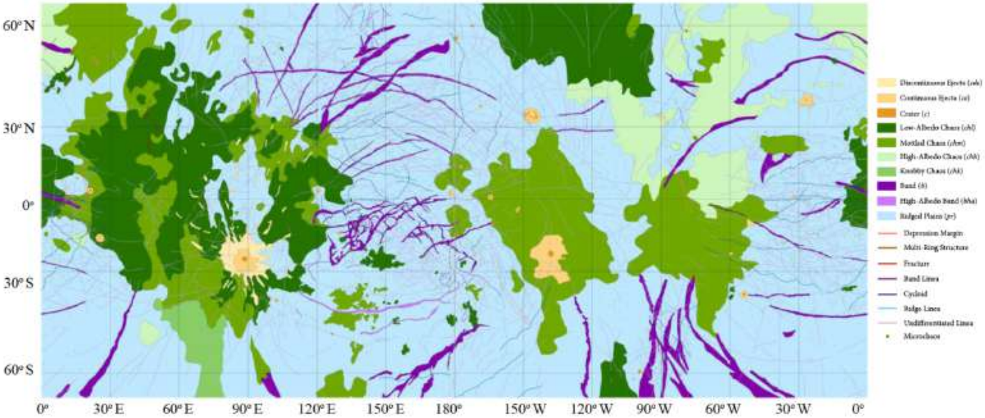
NASA

Lenticulae (domes)

NASA

Assume near-surface brines form in region saturated with oxidants.

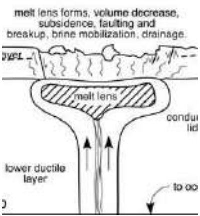
Distribution of chaotic terrains



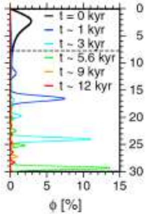
Senske et al. (2018)

Does brine percolate downward or not?

Efficient downward percolation



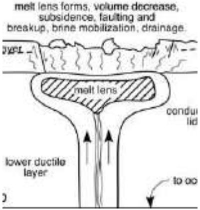
Sotin (2002)



Kalousová (2014)

Does brine percolate downward or not?

Efficient downward percolation **Formation of perched aquifers**



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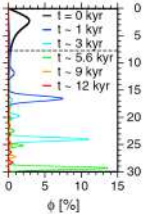

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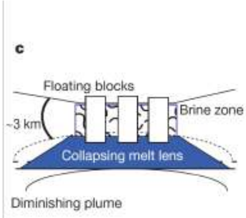
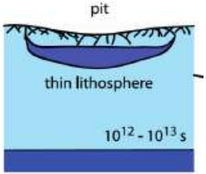


Schmidt (2011)



Manga (2017)

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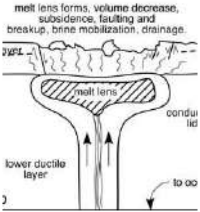
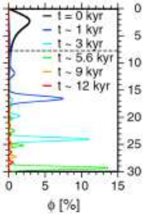


Sotin (2002)



Kalousová (2014)

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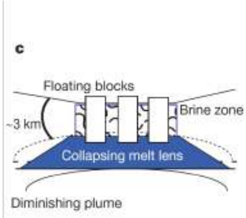

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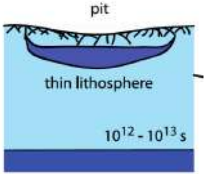


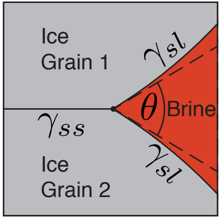
Manga (2017)

Type of behavior is determined by permeability of underlying crust.

- Are small amounts of partial melt present throughout the crust?
- Does this partial melt form a connected network?

Equilibrium melt percolation

Dihedral angle θ



$$\frac{\gamma_{ss}}{\gamma_{sl}} = \frac{\cos(\theta/2)}{2}$$

Equilibrium melt percolation

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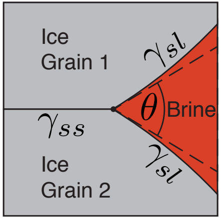

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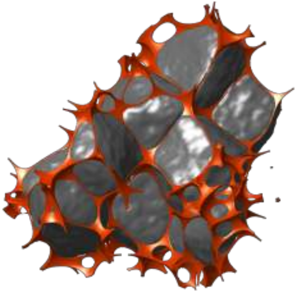
Wetting: $\theta \leq 60°$



Percolation

Equilibrium melt percolation

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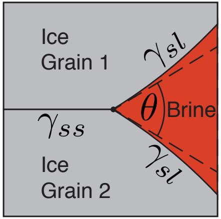

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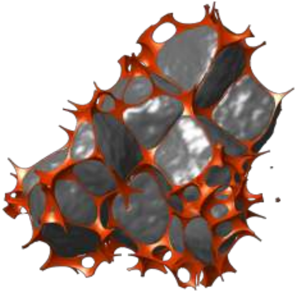
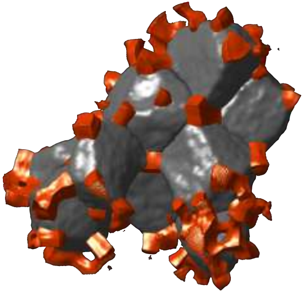


Percolation

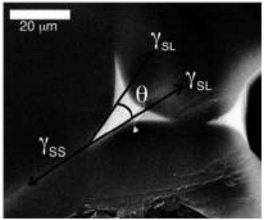
Non-wetting: $\theta > 60^\circ$



Disconnected

Does brine connect?

Ice-brine dihedral angle



McCarthy (2012)

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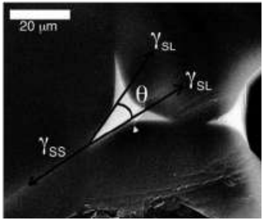
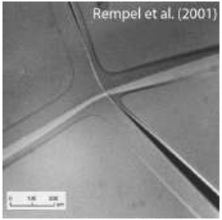


McCarthy (2012)

Brine pore network



Rempel (2001)

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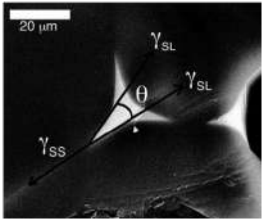

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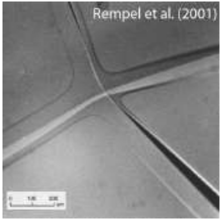

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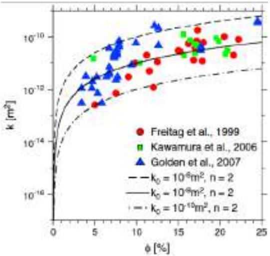
Permeability of ice



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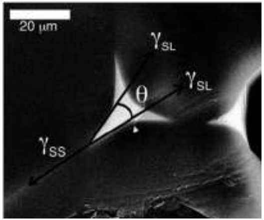

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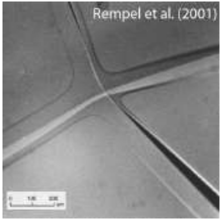

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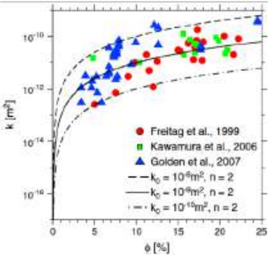

Kalousová (2014)

In a partially molten ice shell brine is mobile at low melt fraction.

Simple model for brine transport in ductile ice

Mass conservation:

Brine: $$(\rho_b\phi)_t + \nabla\cdot(\phi\rho_b\mathbf{v}_b) = 0$$

Ice: $$(\rho_i(1-\phi))_t + \nabla\cdot((1-\phi)\rho_i\mathbf{v}_i) = 0$$

where ϕ is the porosity, ρ_p and $\mathbf{v}_p$ are density and velocity of the p-phase.

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Constitutive laws:

Compaction relation: $$p = p_b - p_i = \xi_\phi \nabla\cdot\mathbf{v}_i$$

Darcy's law: $$\mathbf{q} = \phi(\mathbf{v}_b - \mathbf{v}_i) = -k_\phi/\mu\,(\nabla p + \Delta\rho g\hat{\mathbf{z}})$$

where k_ϕ is permeability and ξ_ϕ is bulk viscosity and $\Delta\rho$ is density difference

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Governing equations for ϕ and p are

Porosity evolution: $$\phi_t + \nabla\cdot[\phi\mathbf{v}_i] = \nabla\cdot\mathbf{v}_i$$

Two-phase continuity: $$-\nabla\cdot[\mathbf{q}+\mathbf{v}_i] = 0$$

Simple model for brine transport in ductile ice

THE UNIVERSITY OF TEXAS AT AUSTIN

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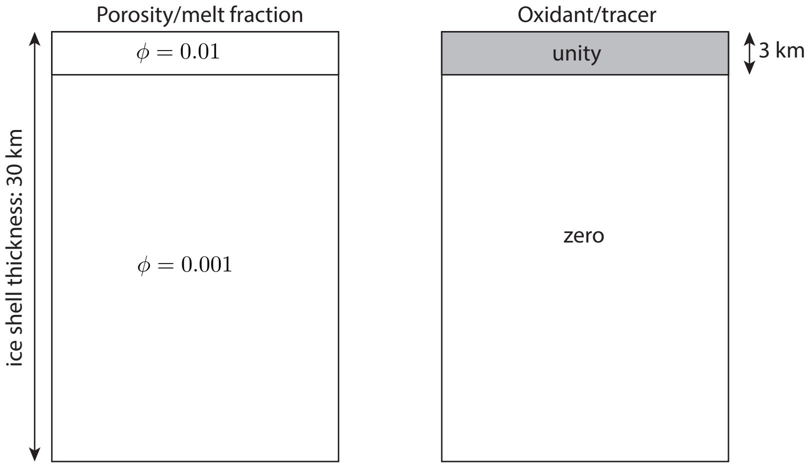
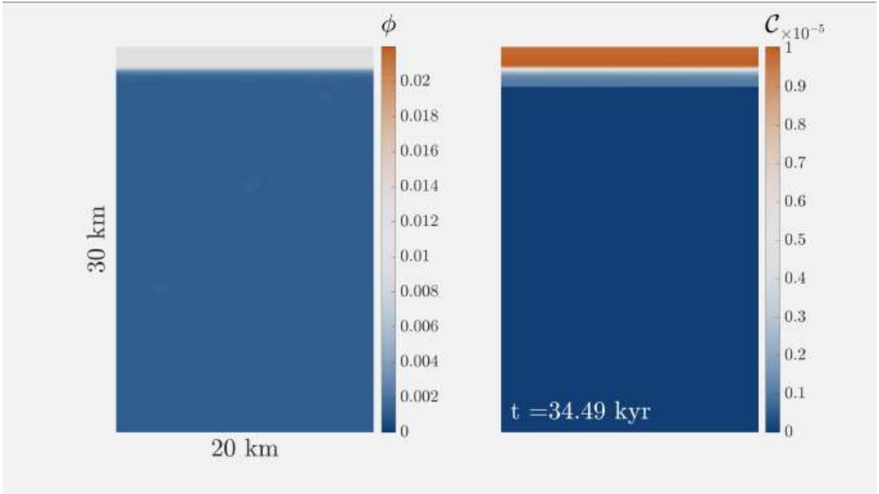
Internal length-scale: $\delta = \sqrt{k_\phi\xi_\phi/\mu}$ (compaction length)

Simple model problem for oxidant transport



Slow uniform transport: $\delta/H \sim 1$



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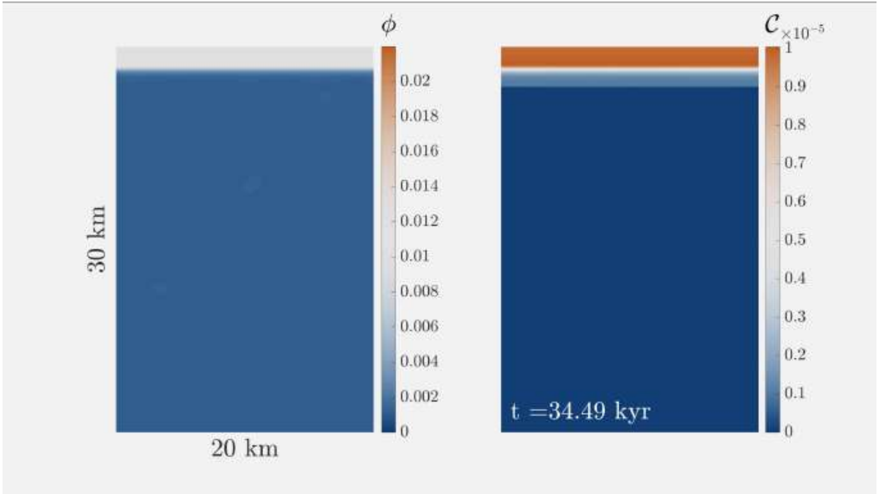
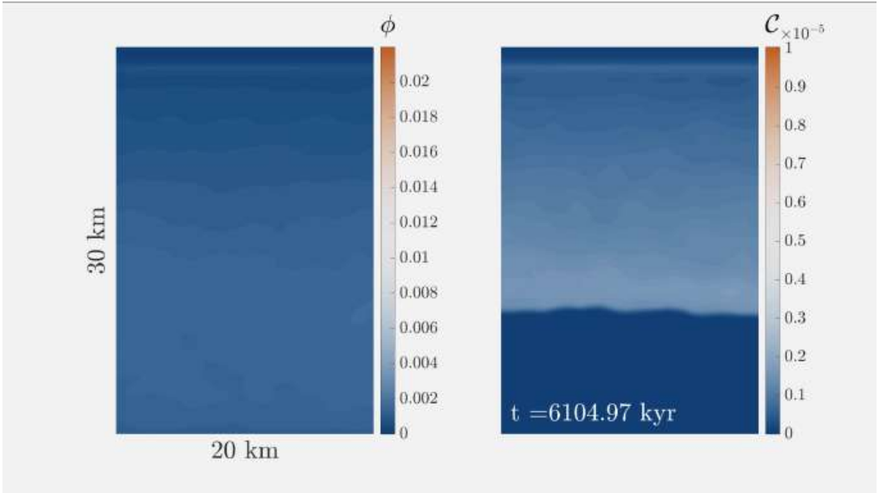


Slow oxidant transport in uniform front as entire crust is dilated.

Just in case the movie fails!



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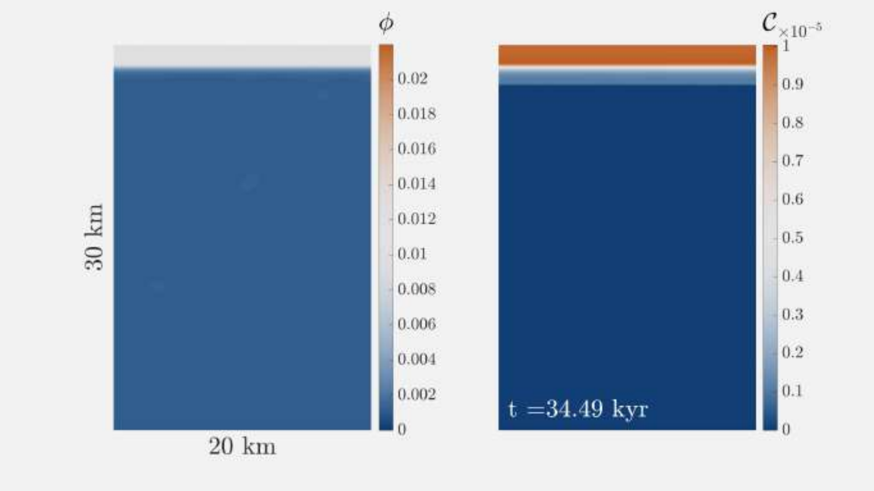
Fast localized transport: $\delta/H \ll 1$



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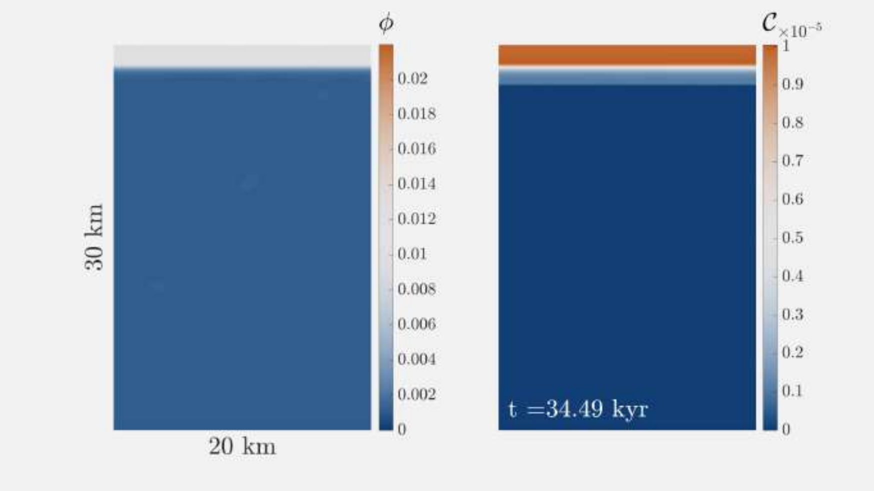

Faster oxidant transport that localizes into 2D porosity waves.

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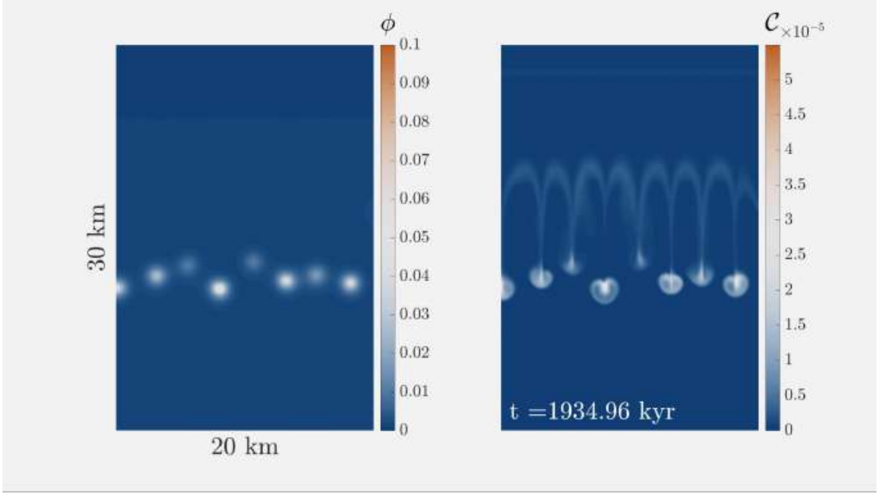
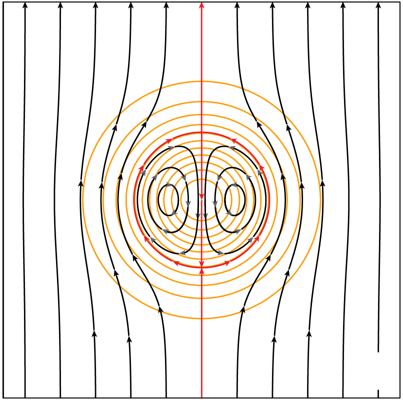


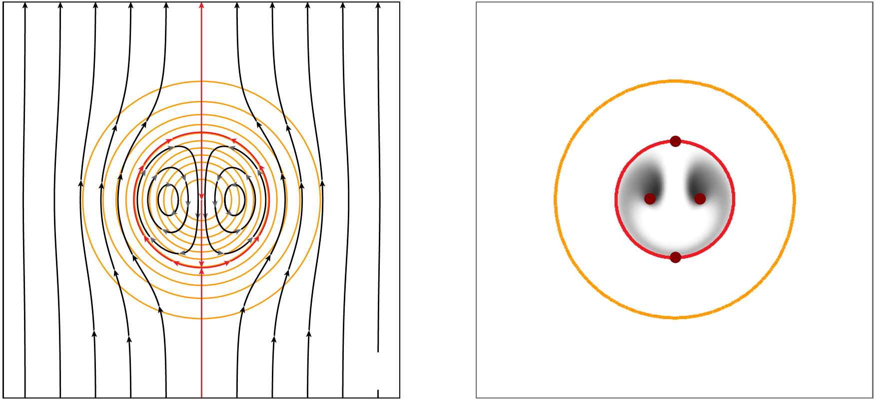
Faster oxidant transport that localizes into 2D porosity waves.

Fluid recirculation in 2D porosity waves



Jordan and Hesse (2018)

Fluid recirculation in 2D porosity waves



Jordan and Hesse (2018)

Changes in transport dynamics over time?

Dynamics are determined by:

$$\frac{\delta}{H} = \frac{\sqrt{k_\phi \xi_\phi}}{\sqrt{\mu} H}$$

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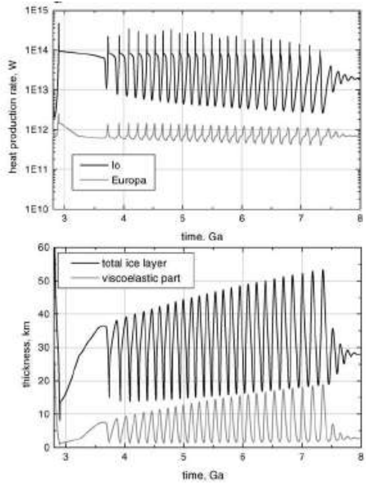
Thermo-orbital evolution leads to

- Large variation in H.
- Variation in heat production.
  - affects porosity, ϕ.
  - affects permeability, k_ϕ.
  - affects bulk viscosity, ξ_ϕ.



Hussmann and Spohn (2004)

Changes in transport dynamics over time?

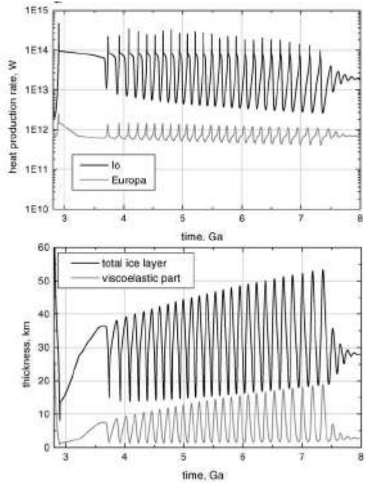
Dynamics are determined by:

$$\frac{\delta}{H} = \frac{\sqrt{k_\phi \xi_\phi}}{\sqrt{\mu H}}$$

Thermo-orbital evolution leads to

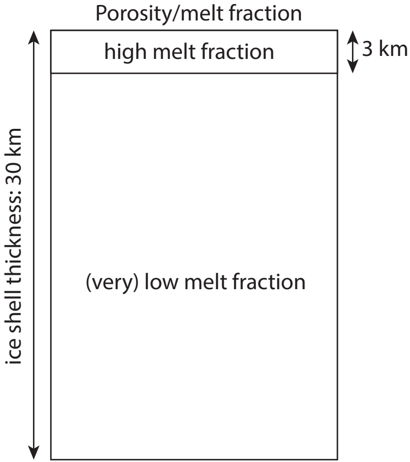
- Large variation in H.
- Variation in heat production.
  - affects porosity, ϕ.
  - affects permeability, k_ϕ.
  - affects bulk viscosity, ξ_ϕ.

Explore effect of thermo-orbital evolution on oxidant transport.



Hussmann and Spohn (2004)

What if the there is a layer of solid ice?



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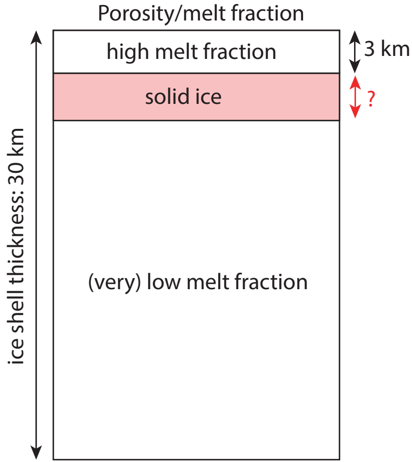

Does solid ice prevent brine drainage?

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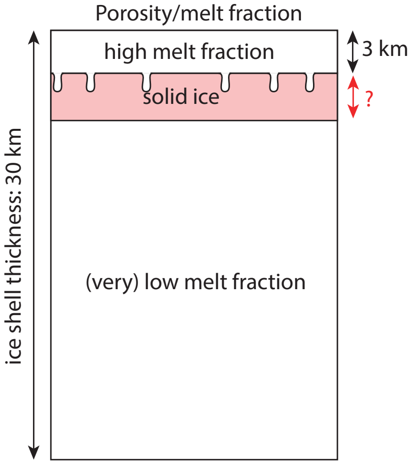
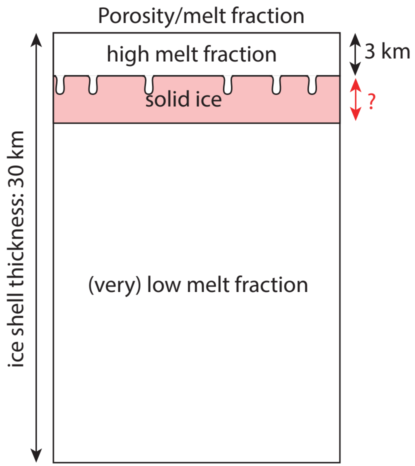


Does solid ice prevent brine drainage?

Possible penetration mechanisms:

- Brine wicks into ice by capillary forces.
- Partial melting induced by latent heat released from brine crystallization.
- Transfer of elastic stresses from the volume expansion of solidifying brine.

What if the there is a layer of solid ice?



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- Brine wicks into ice by capillary forces.
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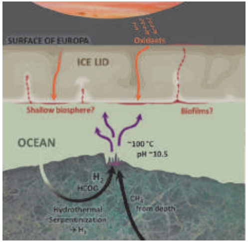
Likely a broad range of behaviors.

Summary and conclusions

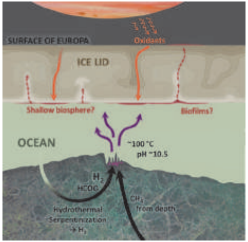
Redox disequilibria



Need O_2 transport.

Summary and conclusions

Redox disequilibria



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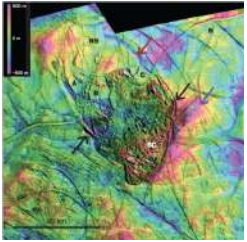
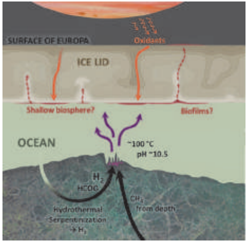
Near-surface melting



Brine percolation.

Summary and conclusions

Redox disequilibria



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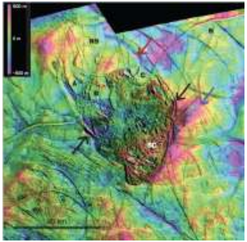
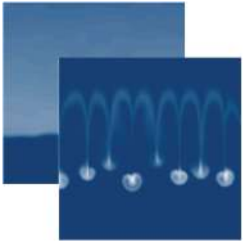


Brine percolation.

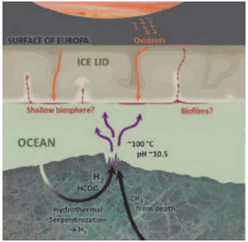
Transport Regimes



Change over time.

Summary and conclusions

Redox disequilibria



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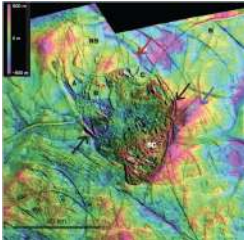

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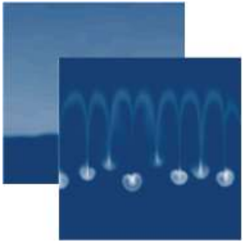

Change over time.

To percolate, or not to percolate:

That is the question.

Thank you for your attention.