Transfer of heat and liquids through the high-pressure ice layer of Ganymede

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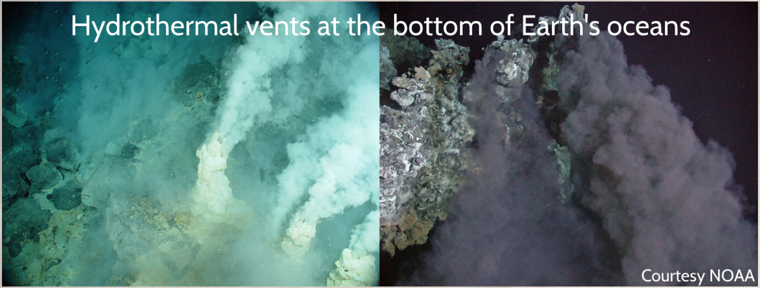
Outline

1. **Ocean worlds**
2. **Model & numerical implementation**
3. **Results**
4. **Conclusions & perspectives**

Ocean worlds

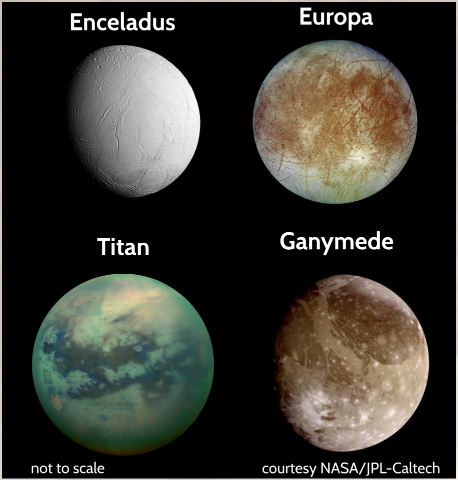
- water-rock interactions → rich communities of organisms



- leaching of volatiles (Ar, methane, ...) from the silicates

Ocean worlds

- water-rock interactions → rich communities of organisms
- Galileo & Cassini: deep oceans within the icy moons → ocean worlds



Formation and evolution of Ocean Worlds in the Solar System and beyond

Christophe Sotin
(JPL-Caltech/NASA)

úterý 7. listopadu v 18 hodin
Matematicko-fyzikální fakulta UK
V Holešovičkách 2, posluchárna T1

Vodní světy jsou planety/měsíce, které hostí velké množství kapalné vody na povrchu nebo v nitru. Jejich výzkum je motivován především otázkou možnosti vzniku života mimo Zemi. Ve Sluneční soustavě jsou vodní světy zastoupeny několika ledovými měsíci velkých planet a pozorování mise Kepler přinesla důkazy o existenci mnoha dalších vodních světů i mimo naši soustavu. Přednáška prof. Sotina se zaměří na otázky týkající se formace a evoluce vodních světů. Přednášející, který je jedním z řídících pracovníků JPL-Caltech/NASA, také představí projekty, které NASA v souvislosti s vodními světy plánuje v příštích letech a rád zodpoví i další dotazy. Profesor Sotin přijíždí na pozvání Katedry geofyziky MFF UK.

Ocean worlds

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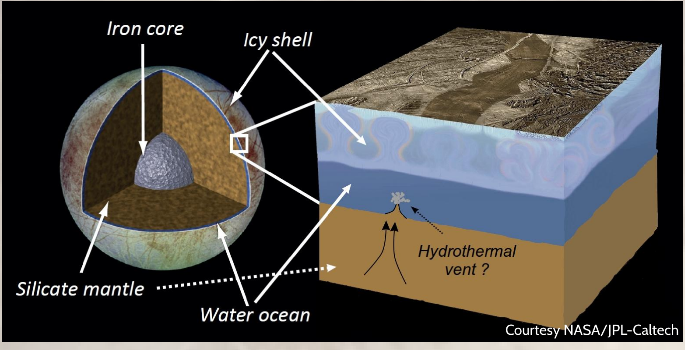
- Galileo & Cassini: deep oceans within the icy moons → ocean worlds
- Europa & Enceladus: direct contact of silicates with the ocean



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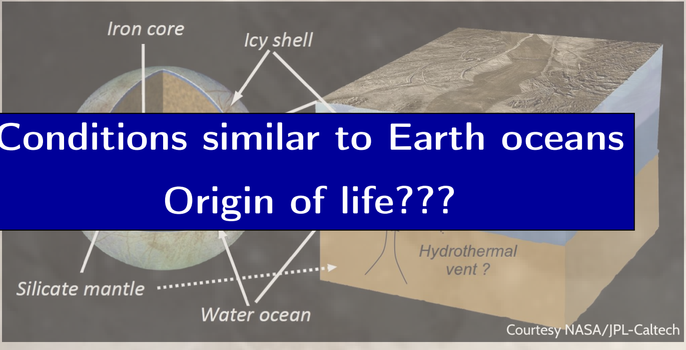
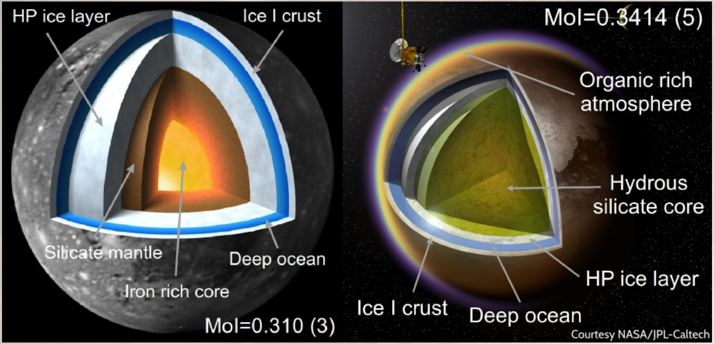


Conditions similar to Earth oceans

Origin of life???

Ocean worlds

- water-rock interactions → rich communities of organisms
- Galileo & Cassini: deep oceans within the icy moons → ocean worlds
- Europa & Enceladus: direct contact of silicates with the ocean
- Ganymede & Titan: thick HP ice layer between silicates and ocean



Ocean worlds

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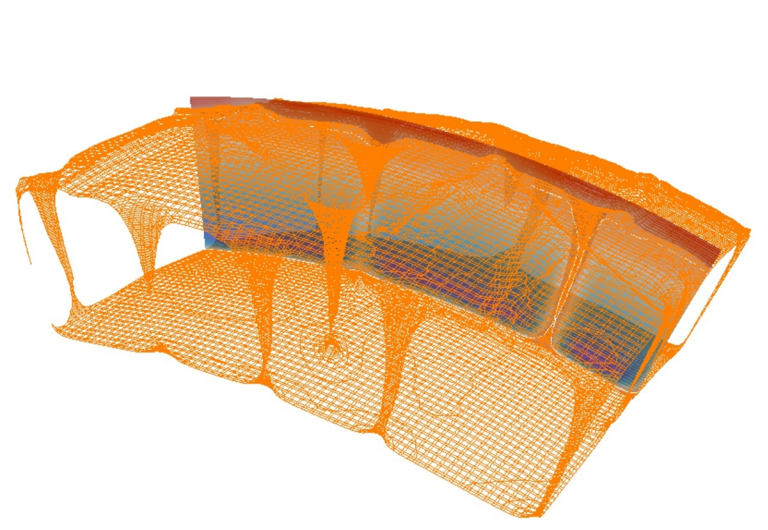
Is water/volatiles exchange between silicates and ocean still possible?

Heat transfer through HP ice layer

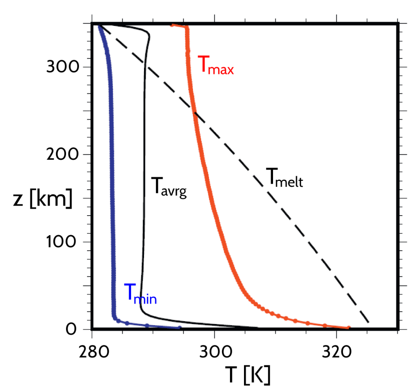
- *Choblet et al.* (2017): solid-state thermal convection



Heat transfer through HP ice layer

- *Choblet et al.* (2017): solid-state thermal convection
- max (red) and avrg (black) temperature exceeds the melting curve in the upper part

→ cold thermal boundary layer cannot exist in a solid state



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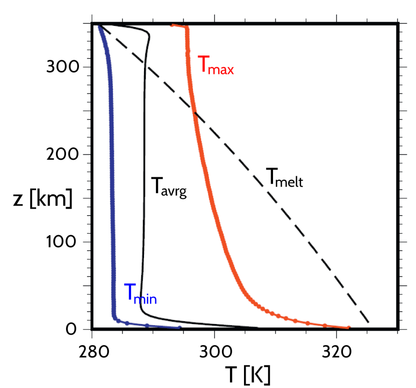
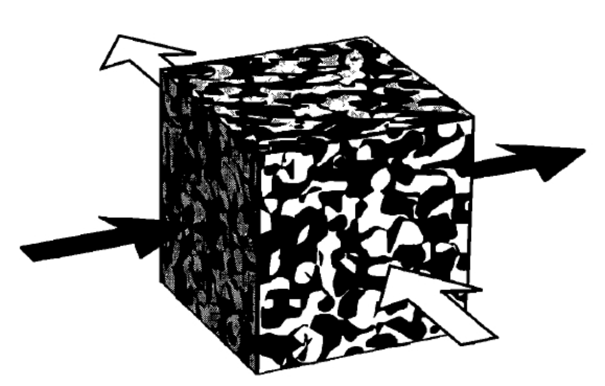


→ **two-phase mixture model**

Two-phase mixture model

- coexisting phases: solid ice matrix (i) + liquid water (w)
- volume fraction of water in the mixture: porosity $\phi = \frac{V_\mathrm{w}}{V_\mathrm{i} + V_\mathrm{w}}$
- amount of ice: $1 - \phi$
- cold ice ($\phi = 0$) vs. temperate ice ($\phi \sim$ few percents)
- assumption of thermal equilibrium in the temperate ice: $T_\mathrm{i} = T_\mathrm{w} = T_\mathrm{m}$



***Bercovici et al.*, 2001**

Governing equations

- Stokes system $$\nabla \cdot \mathbf{v}_{\mathrm{i}} = \frac{\Delta\rho}{\rho_{\mathrm{w}}\rho_{\mathrm{i}}} r$$

$$\begin{aligned}
\nabla\Pi \quad = \quad & -(1-\phi)\rho_{\mathrm{i}}\alpha_{\mathrm{i}}(T-T_{\mathrm{m}})\mathbf{g} - \phi\Delta\rho\mathbf{g} + \nabla\left(\frac{(1-\phi)\mu_{\mathrm{i}}}{\phi}(\nabla\cdot\mathbf{v}_{\mathrm{i}})\right) \\
+ \quad & \nabla\cdot\left((1-\phi)\mu_{\mathrm{i}}\left[\nabla\mathbf{v}_{\mathrm{i}}+(\nabla\mathbf{v}_{\mathrm{i}})^{\mathrm{T}}-\frac{2}{3}(\nabla\cdot\mathbf{v}_{\mathrm{i}})\mathbf{I}\right]\right)
\end{aligned}$$

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- extension ($r>0$)
  compaction ($r<0$)

Governing equations

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- extension/ /compaction
- thermal & phase-change buoyancy

Governing equations

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- extension/ /compaction
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- bulk & shear viscous deformation

Governing equations

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- energy balance

$$\rho_\mathrm{i}c_\mathrm{i}\frac{\partial T}{\partial t} + \rho_\mathrm{i}c_\mathrm{i}\mathbf{v}_\mathrm{i}\cdot\nabla T + Lr = k_\mathrm{i}\nabla^2 T$$

- extension/ /compaction
- thermal & phase-change buoyancy
- bulk & shear viscous deformation
- heat consumption ($r>0$) release ($r<0$)

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- advection of porosity

$$\frac{\partial\phi}{\partial t} + \nabla\cdot(\phi\mathbf{v}_\mathrm{w}) = \frac{r}{\rho_\mathrm{w}}$$

- extension/ /compaction
- thermal & phase-change buoyancy
- bulk & shear viscous deformation
- heat consumption/ /release
- melting ($r>0$) freezing ($r<0$)

Governing equations

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$$\frac{\partial\phi}{\partial t} + \nabla\cdot(\phi\mathbf{v}_\mathrm{w}) = \frac{r}{\rho_\mathrm{w}}$$

- water velocity

$$\mathbf{v}_\mathrm{w} = \mathbf{v}_\mathrm{i}$$

- extension/ /compaction
- thermal & phase-change buoyancy
- bulk & shear viscous deformation
- heat consumption/ /release
- melting/ /freezing
- water advected by ice

Governing equations

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$$\mathbf{v}_\mathrm{w} = \mathbf{v}_\mathrm{i} - \frac{k(\phi)}{\mu_\mathrm{w}\phi}(1-\phi)\Delta\rho\mathbf{g}$$

- extension/ /compaction
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- heat consumption/ /release
- melting/ /freezing
- $k(\phi)=0$: water advected by ice
- $k(\phi)>0$: water percolates through ice

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- extension/ /compaction
- thermal & phase-change buoyancy
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- heat consumption/ /release
- melting/ /freezing
- $k(\phi)=0$: water advected by ice
- $k(\phi)>0$: water percolates through ice
- $\Delta\rho>0$: water migrates upwards

Boundary conditions

- Stokes problem
  - free slip (Γ_{T} & Γ_{S}): $\mathbf{v}_{\mathrm{i}} \cdot \mathbf{n} = 0$

$$\left[(1-\phi)\mu_{\mathrm{i}} \left(\frac{1}{\phi}(\nabla \cdot \mathbf{v}_{\mathrm{i}})\mathbf{I} + \nabla \mathbf{v}_{\mathrm{i}} + (\nabla \mathbf{v}_{\mathrm{i}})^{\mathrm{T}} - \frac{2}{3}(\nabla \cdot \mathbf{v}_{\mathrm{i}})\mathbf{I}\right) \cdot \mathbf{n}\right]_{\mathrm{t}} = \mathbf{0}$$

  - no slip (Γ_{B}): $\mathbf{v}_{\mathrm{i}} = \mathbf{0}$
- energy balance
  - fixed temperature (Γ_{T}): $T = T_{\mathrm{m}}$
  - prescribed heat flux from silicates (Γ_{B}): $\nabla T = \mathbf{q}_{\mathrm{s}}$
  - insulating (Γ_{S}): $\nabla T \cdot \mathbf{n} = 0$
- water transport
  - free outflow (Γ_{T} = interface with the ocean)
  - impermeable (Γ_{B} & Γ_{S}): $\mathbf{v}_{\mathrm{w}} \cdot \mathbf{n} = 0$

Model parameters

- ice permeable to water transport above a threshold porosity ϕ_c

$$k(\phi) = \begin{cases} k_0(\phi - \phi_c)^2 & \phi \geq \phi_c \\ 0 & \phi < \phi_c \end{cases}$$

- temperature and pressure dependent ice viscosity

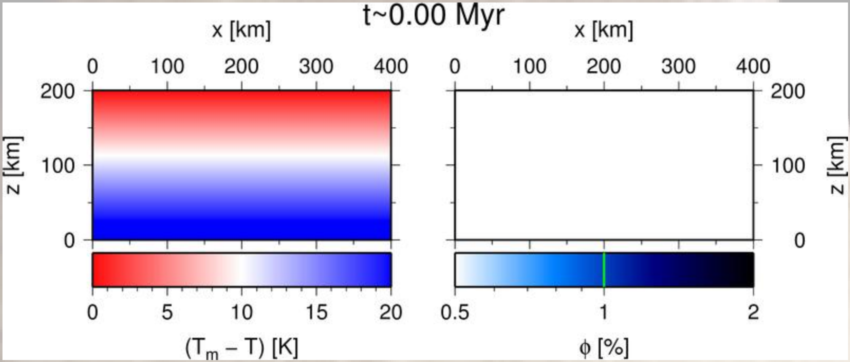
$$\mu_i = \mu_0 \exp\left[\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_m(P)}\right)\right]$$

Numerical implementation

- 2d Finite Element code in cartesian box with λ=2
- FEniCS (http://fenicsproject.org), MPI parallelization
- problem split into 3 partially decoupled subproblems:
  (1) energy balance: P2, SUPG regularization, Crank-Nicolson scheme
  (2) porosity transport: discontinuous Galerkin, implicit Euler scheme
  (3) Stokes problem: Taylor-Hood (P1-P2 for pressure-velocity)
- linear (1, 3): PETSc mumps, nonlinear (2): Newton
- mesh: 200×100 crossed diagonal triangular elements, refined at bottom and top, $\sim 10^5$ elements (best resolution less than 1km)
- adaptive time-stepping, two problems with different timescales:
  - convection: $\Delta\, t_{\mathrm{c}} \sim \mathbf{v}_{\mathrm{i}}^{-1}$
  - percolation: $\Delta\, t_{\mathrm{p}} \sim \mathbf{v}_{\mathrm{w}}^{-1}$
- computed times: ∼10–40 Myr, $\Delta t \sim 10$ y, $\sim 10^6$ time steps
- typical calculation on Salomon cluster: 24 cores, 400-600 hours (depending on model parameters)
- we acknowledge support by IT4Innovations projects OPEN-10-1, OPEN-11-21

Reference simulation

H=200 km, μ_0=10^{15} Pa s, q_s=20 mW m^{-2}, ϕ_c=1%



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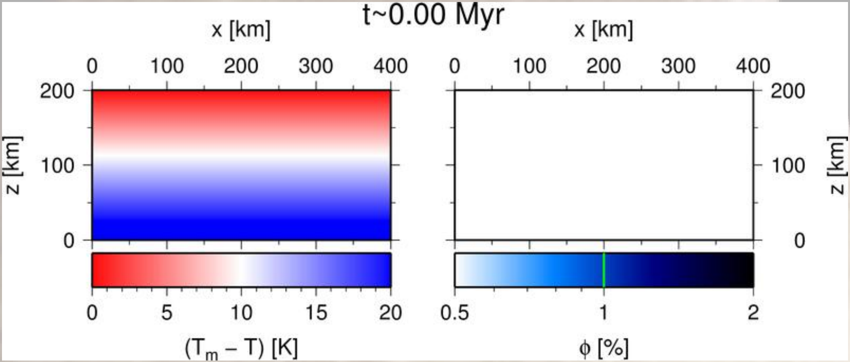
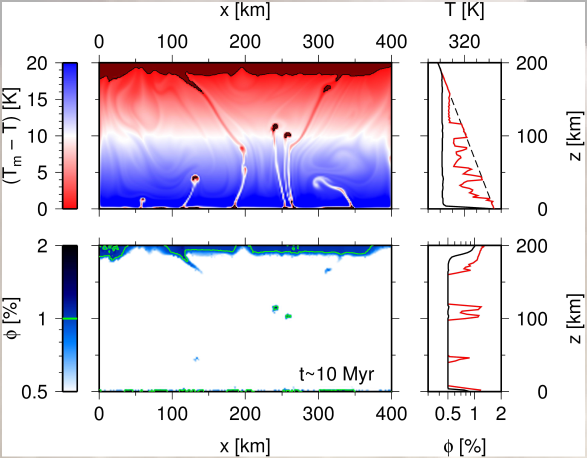


Reference simulation - statistical steady-state



- silicates: $T = T_{\rm m}$, $\phi_{\rm av} \sim \phi_{\rm c}$, volatiles leaching

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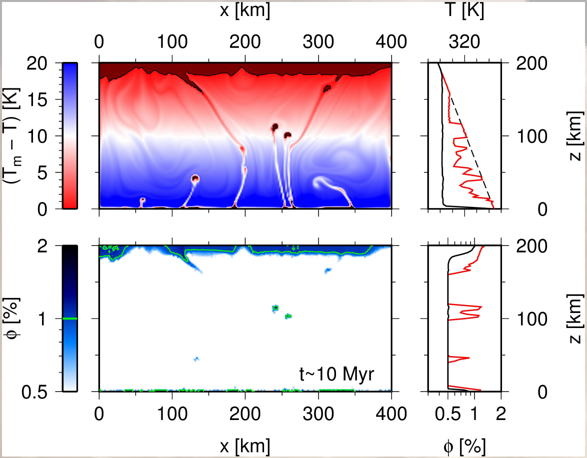
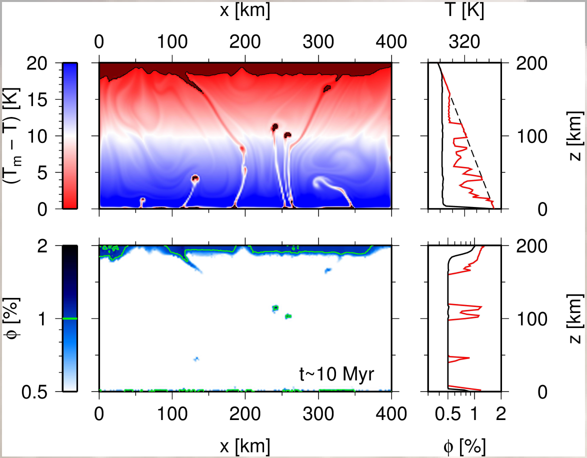


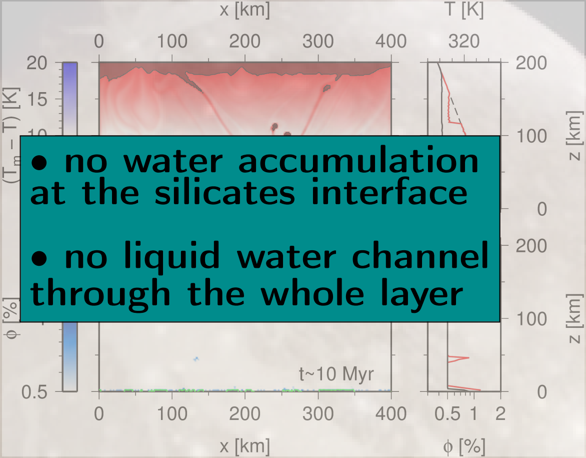
- silicates: $T = T_{\mathrm{m}}$, $\phi_{\mathrm{av}} \sim \phi_{\mathrm{c}}$, volatiles leaching
- interior: $T_{\mathrm{av}} < T_{\mathrm{m}}$, hot plumes: $\phi_{\mathrm{max}} \sim \phi_{\mathrm{c}}$, volatiles transfer

Reference simulation - statistical steady-state



- silicates: $T = T_\mathrm{m}$, $\phi_\mathrm{av} \sim \phi_\mathrm{c}$, volatiles leaching
- interior: $T_\mathrm{av} < T_\mathrm{m}$, hot plumes: $\phi_\mathrm{max} \sim \phi_\mathrm{c}$, volatiles transfer
- ocean: $T = T_\mathrm{m}$ & $\phi_\mathrm{av} \sim \phi_\mathrm{c}$, volatiles dissolution into the ocean

Reference simulation - statistical steady-state

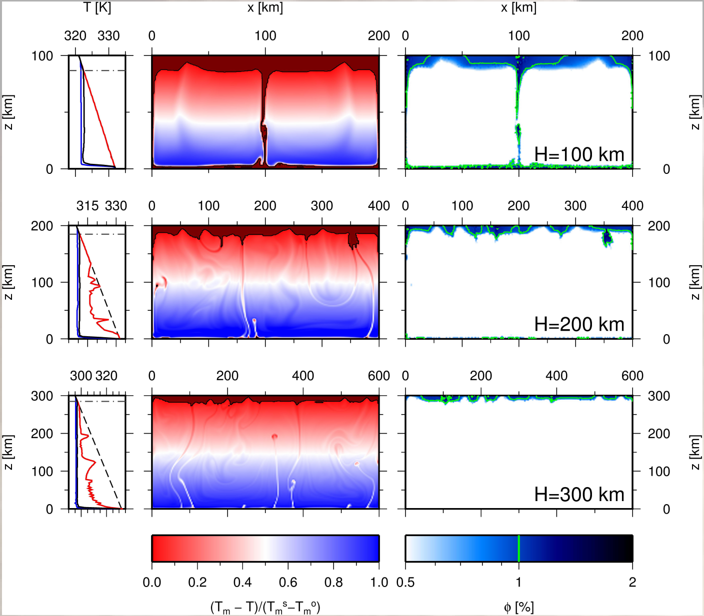


• no water accumulation at the silicates interface

• no liquid water channel through the whole layer

- silicates: $T = T_{\rm m}$, $\phi_{\rm av} \sim \phi_{\rm c}$, volatiles leaching
- interior: $T_{\rm av} < T_{\rm m}$, hot plumes: $\phi_{\rm max} \sim \phi_{\rm c}$, volatiles transfer
- ocean: $T = T_{\rm m}$ & $\phi_{\rm av} \sim \phi_{\rm c}$, volatiles dissolution into the ocean

Increasing HP ice layer thickness H ($\sim$ increasing Ra)



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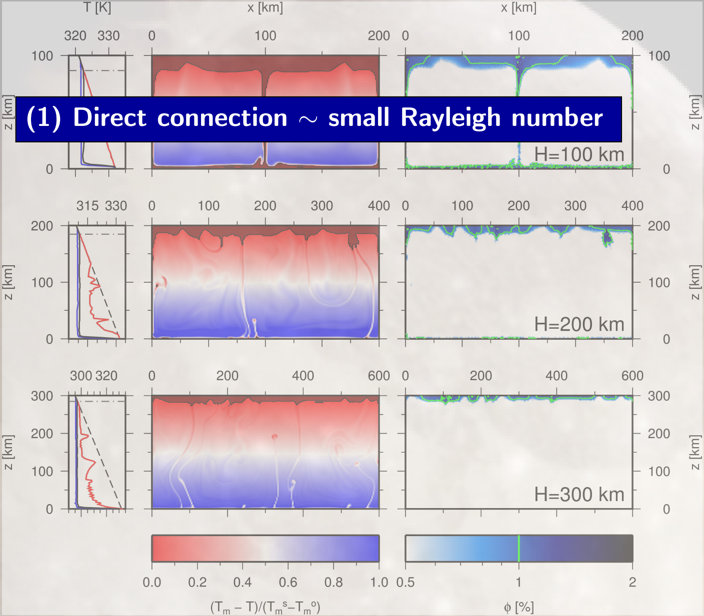
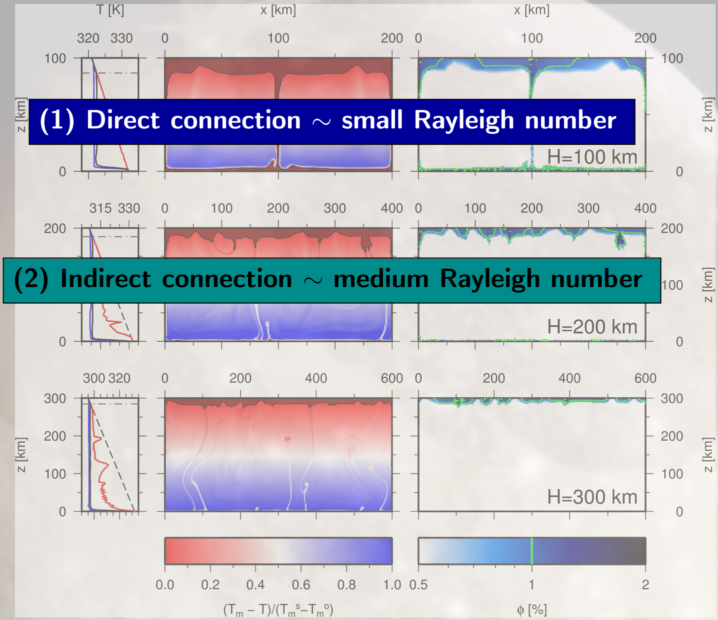


(1) Direct connection $\sim$ small Rayleigh number

Increasing HP ice layer thickness H ($\sim$ increasing Ra)



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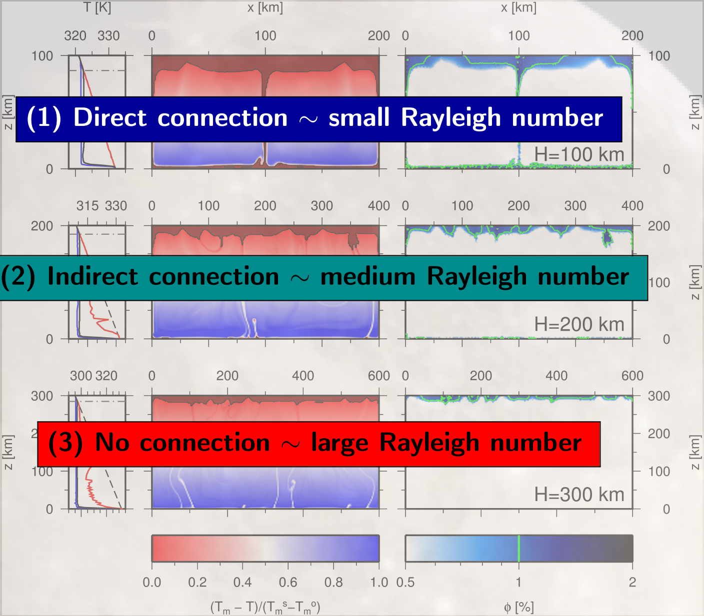
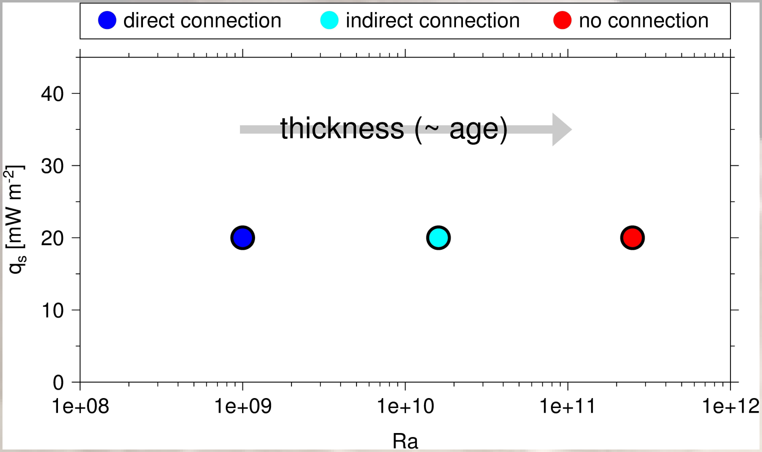


(1) Direct connection $\sim$ small Rayleigh number

(2) Indirect connection $\sim$ medium Rayleigh number

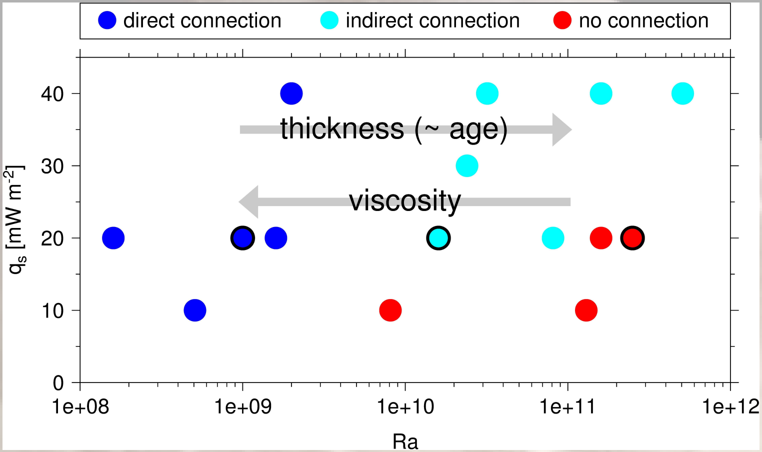
(3) No connection $\sim$ large Rayleigh number

Ganymede's global thermal evolution



- HP ice layer became less permeable as Ganymede cooled down

Ganymede's global thermal evolution



- HP ice layer became less permeable as Ganymede cooled down
- larger viscosity → connection even later in Ganymede's evolution
- larger silicates heat flux → more bottom melting

Conclusions

- melting at the interface with silicates → volatiles leaching
- melt & volatiles transfer by upwelling plumes → extraction into ocean
- exchange of water and volatiles between silicate interior and ocean more probable during the early stages of Ganymede's evolution

Kalousova et al. (2018), Two-phase convection in Ganymede's high-pressure ice layer - Implications for its geological evolution, *Icarus*, **299**, 133–147.

Conclusions & perspectives

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- scaling laws + thermal evolution model → interpretation of JUICE observations (ocean density, H_2O layers thicknesses, ...)

juice

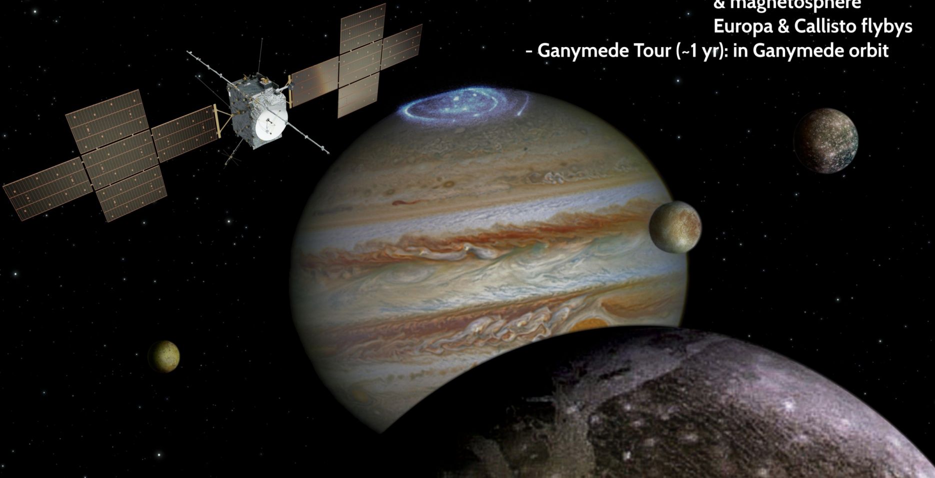
esa

→ JUPITER ICY MOONS EXPLORER

Exploring the emergence of habitable worlds around gas giants

Two mission phases:

- Jupiter Tour (~2.5 yr): Jovian atmophere & magnetosphere Europa & Callisto flybys
- Ganymede Tour (~1 yr): in Ganymede orbit



Conclusions & perspectives

- melting at the interface with silicates → volatiles leaching
- melt & volatiles transfer by upwelling hot plumes → ocean
- exchange of water and volatiles between silicate interior and ocean more probable during the early stages of Ganymede's evolution

Kalousova et al. (2018), Two-phase convection in Ganymede's high-pressure ice layer - Implications for its geological evolution, *Icarus*, **299**, 133–147.

- scaling laws + thermal evolution model → interpretation of JUICE observations (ocean density, H_2O layers thicknesses, ...)
- Titan - thinner HP ice layer - did exchange of volatiles occur longer throughout its evolution? - work in progress

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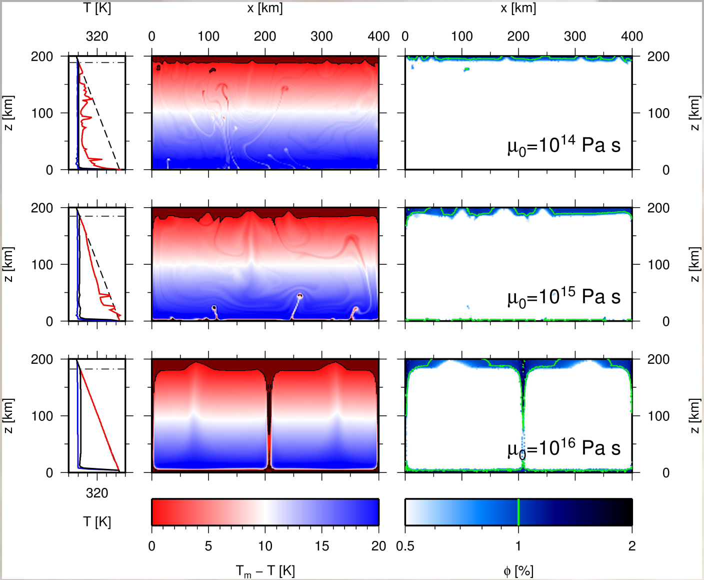
Thank you for your attention!

Increasing melting point viscosity μ_0 ($\sim$ decreasing Ra)



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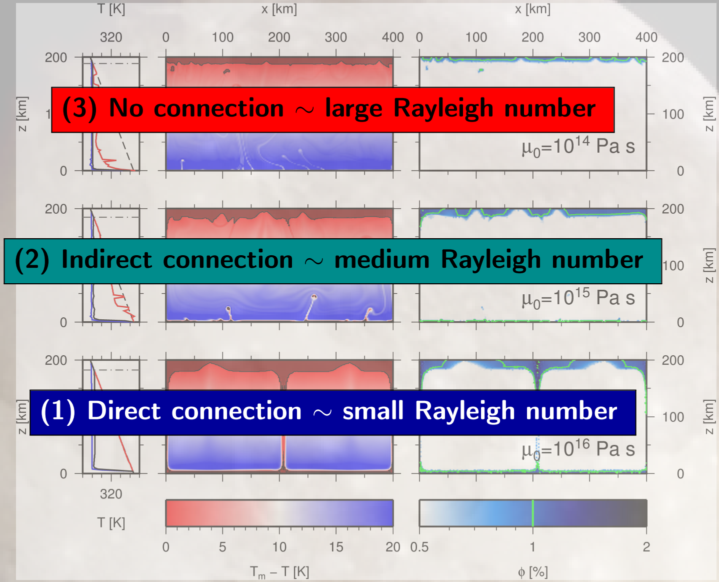
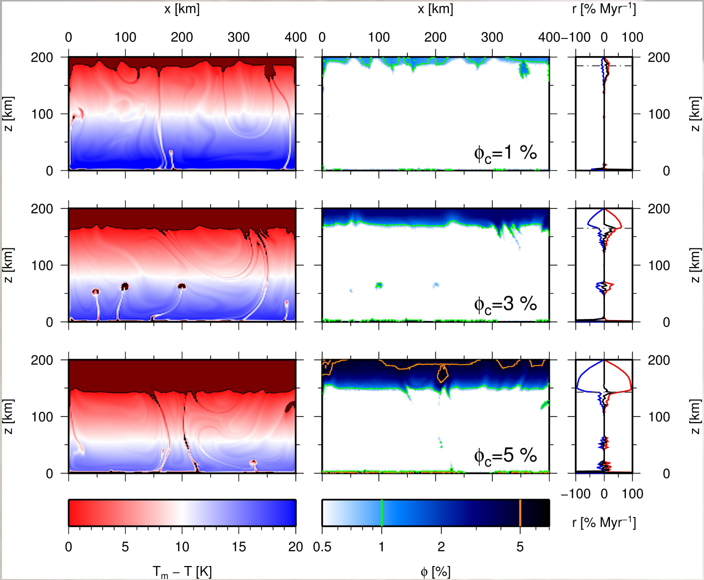


Increasing percolation threshold ϕ_c (top to bottom)

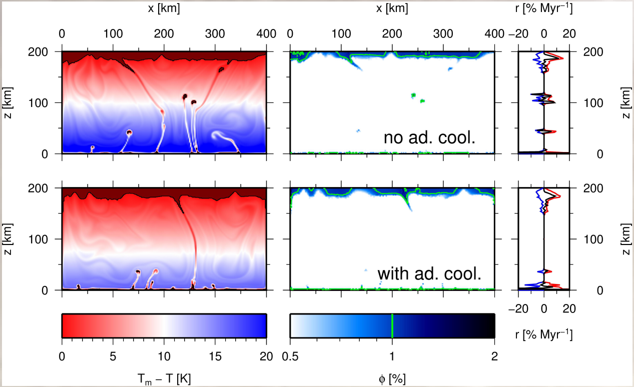
→ **thicker top temperate layer**

→ **more melt at the interface with ocean**



Effects of adiabatic heating/cooling

- adiabatic gradient: $(\frac{\partial T}{\partial r})_s = -\frac{\alpha T g}{c_p} \sim -0.026$ K km^{-1}
- temperature gradient accross the layer: $(\frac{\partial T}{\partial r}) \sim -0.115$ K km^{-1}



- cooling due to decompression → less melting in the upwelling plumes
- warming up of descending material due to compression

→ warmer interior ∼ enhanced potential for melting at the silicates interface