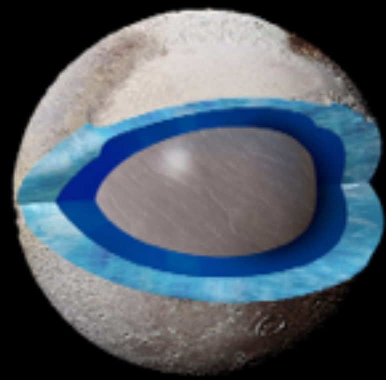
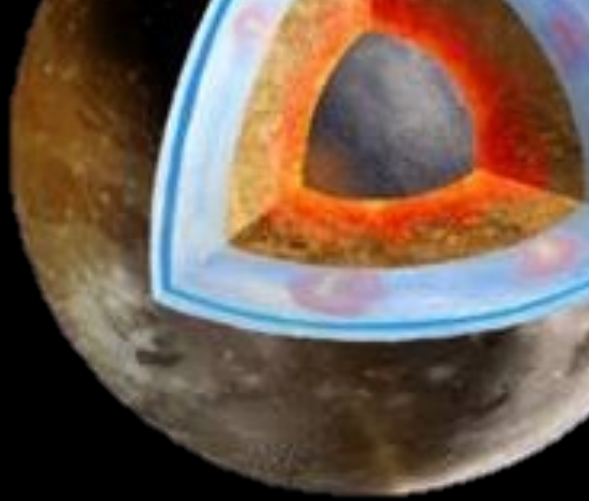
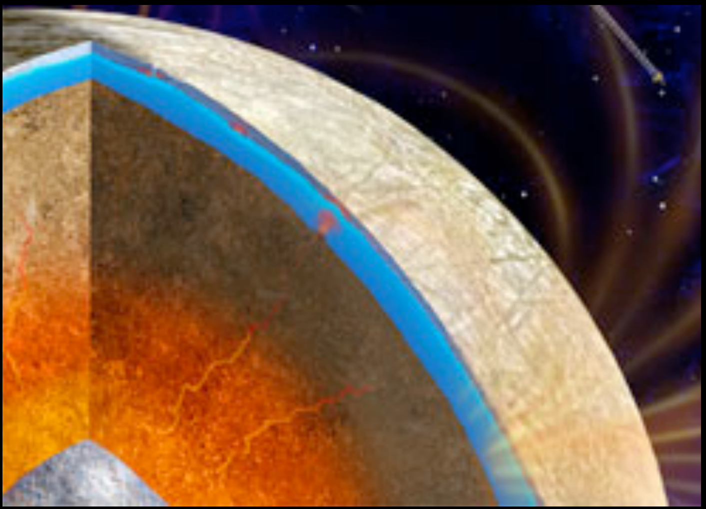


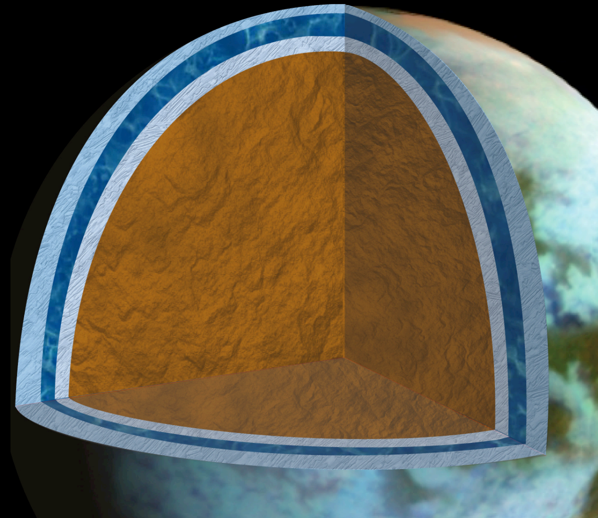


# Geodynamics of icy worlds: Context for water-rock interactions



**Gabriel TOBIE**

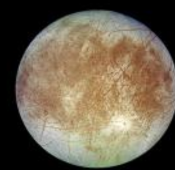
*Laboratoire de Planétologie et Géodynamique,*
*CNRS/ Université de Nantes*

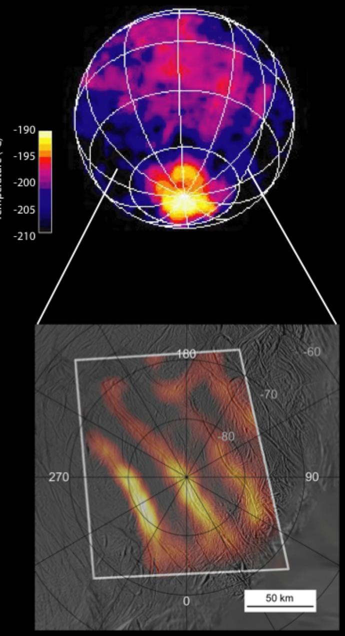


# Introduction

Enceladus | Pluto | Europa | Titan | Ganymede





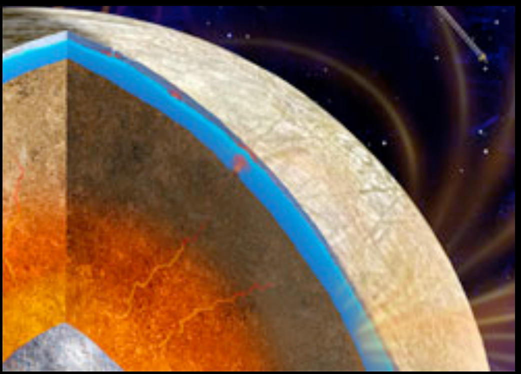
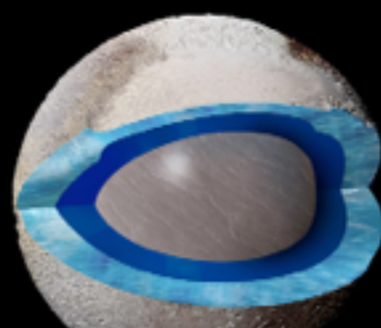
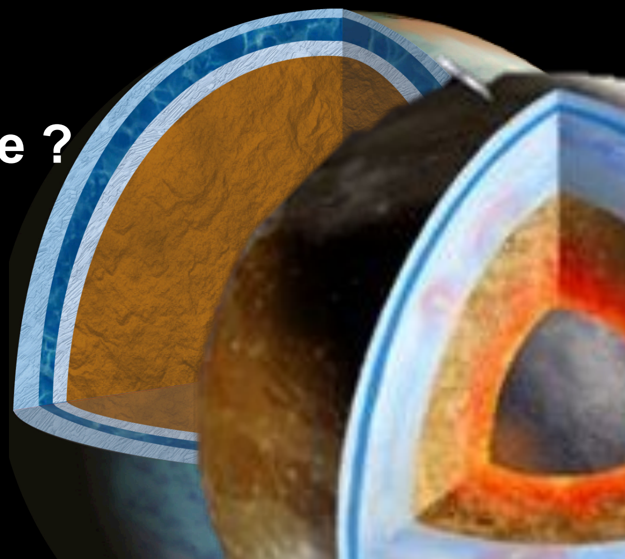



**Major questions about icy worlds :**

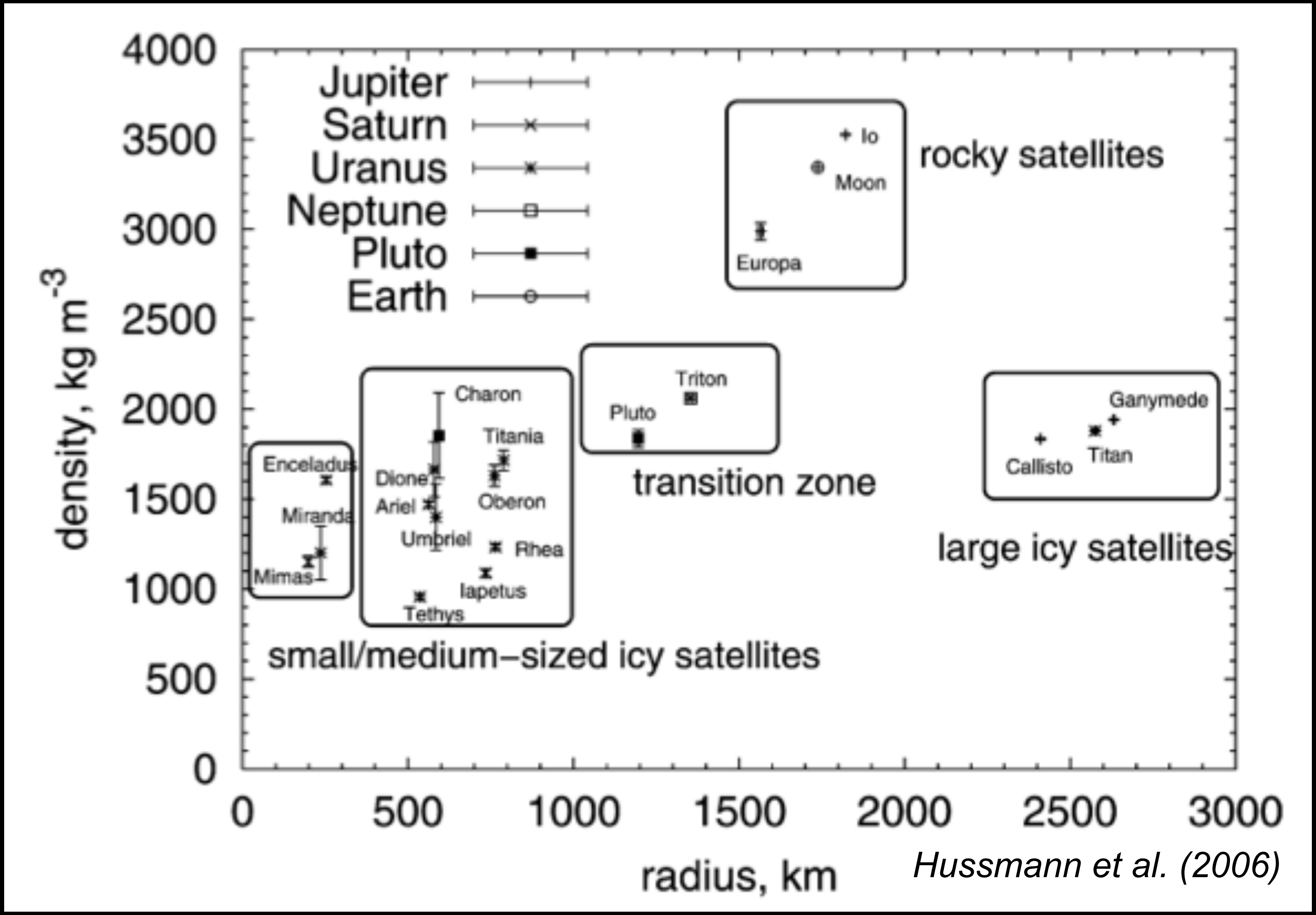
1- What are the structure and composition of their water-rich interiors ?

2- What are the source of energy that powered their endogenic activities ?

3- Are their subsurface oceans suitable for the emergence of life ?

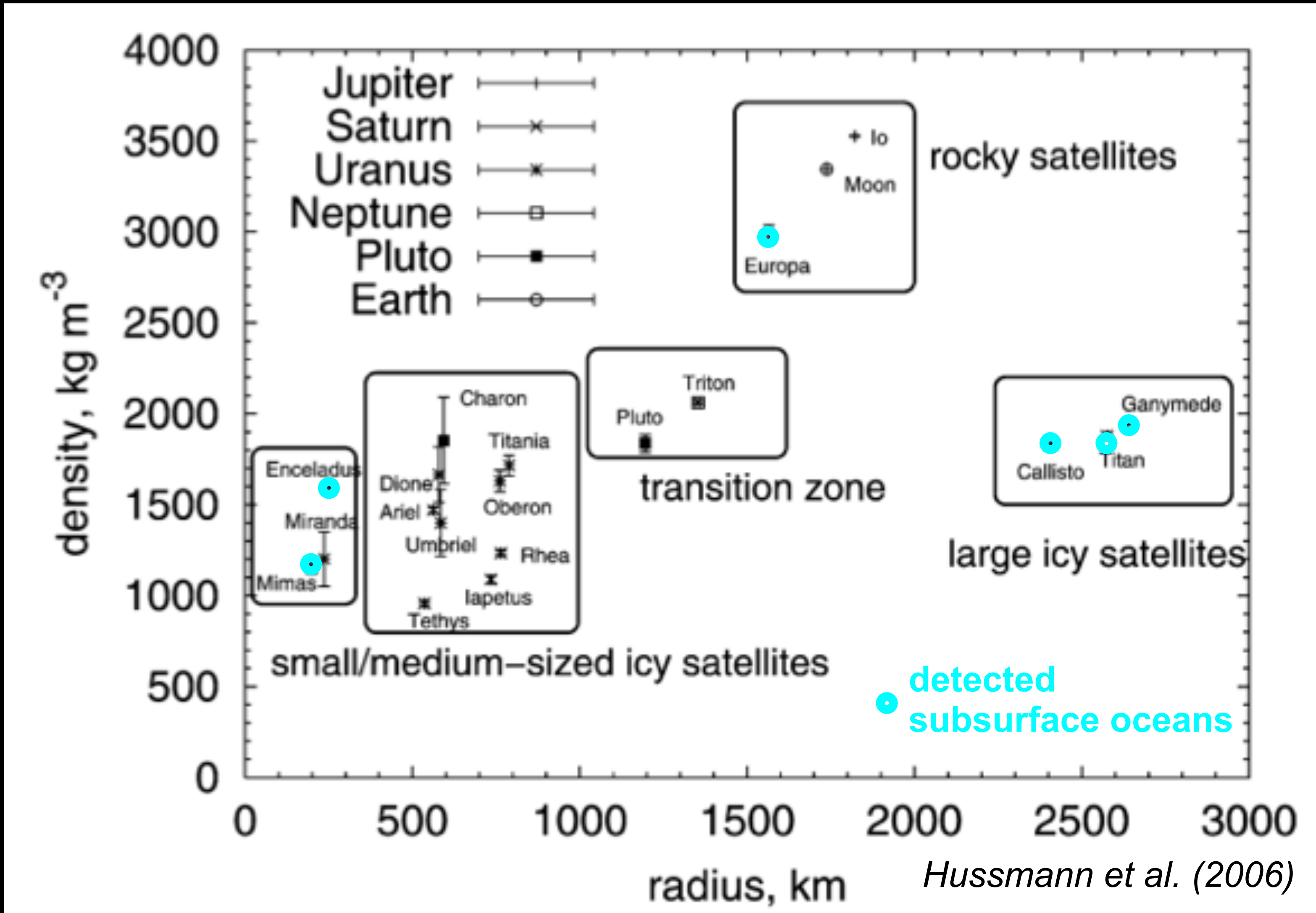




# Observational constraints on icy world interiors




Except for Io, those bodies consist of a mixture of silicate and water ice, with different fraction and degree of differentiation.

# Observational constraints on icy world interiors

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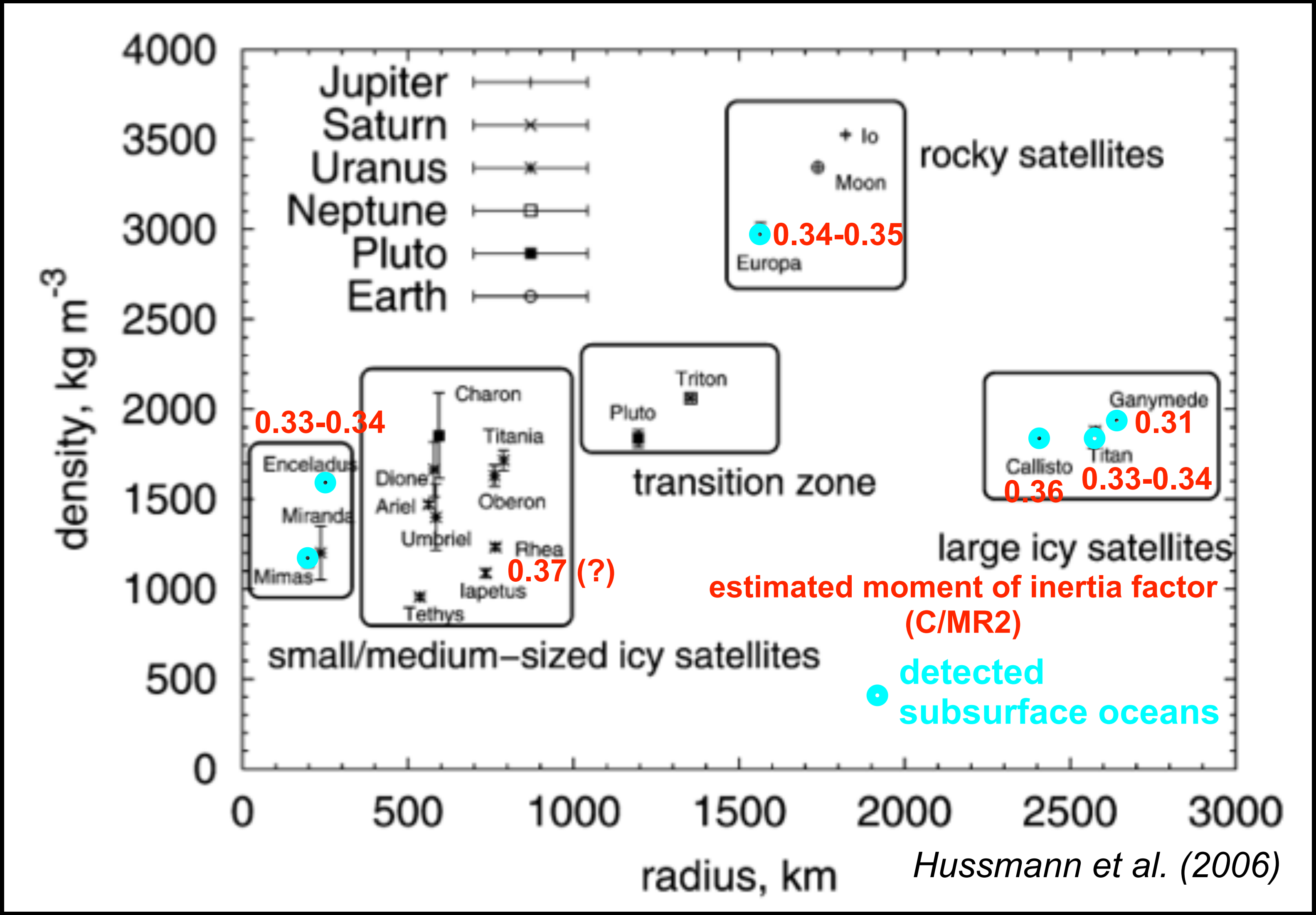
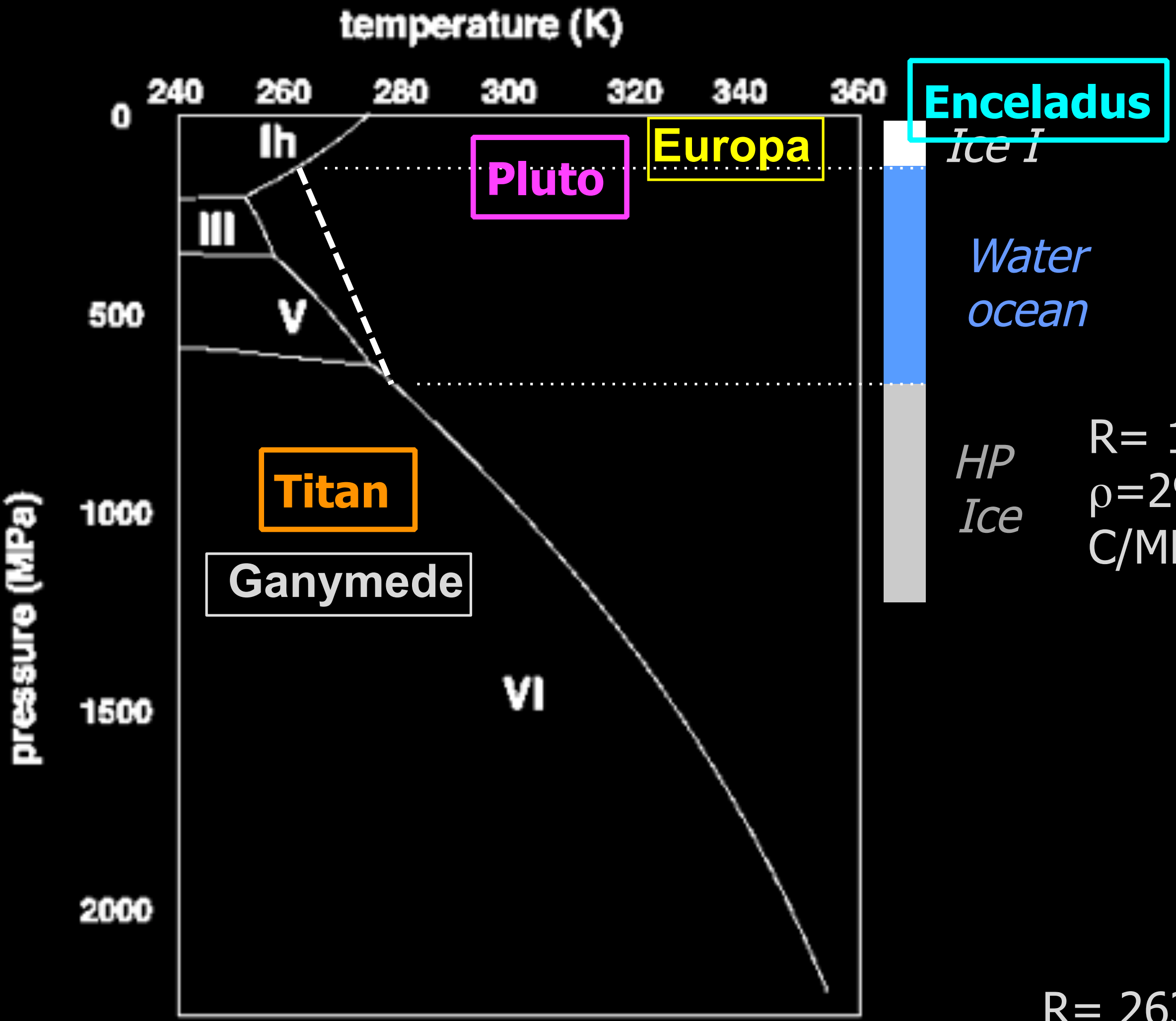
# Observational constraints on icy world interiors

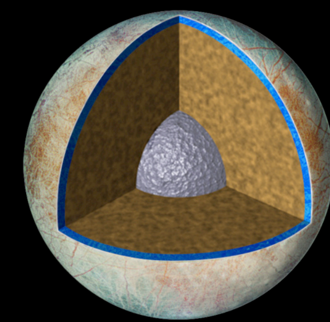



Except for Io, those bodies consist of a mixture of silicate and water ice, with different fraction and degree of differentiation.

# Water phase diagram and hydrosphere structure

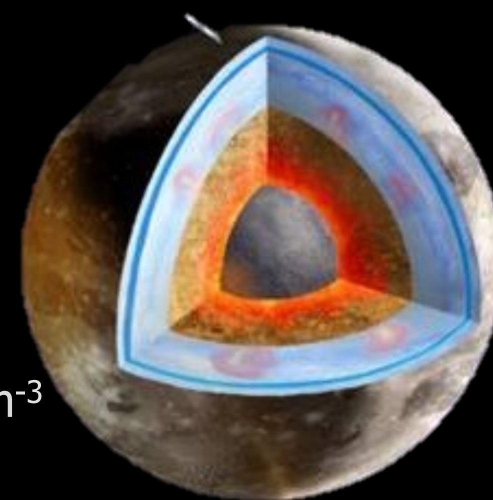



Europa



R= 1565 km,
$\rho$=2970 kg .m$^{-3}$
C/MR$^2$=0.347

Ganymede



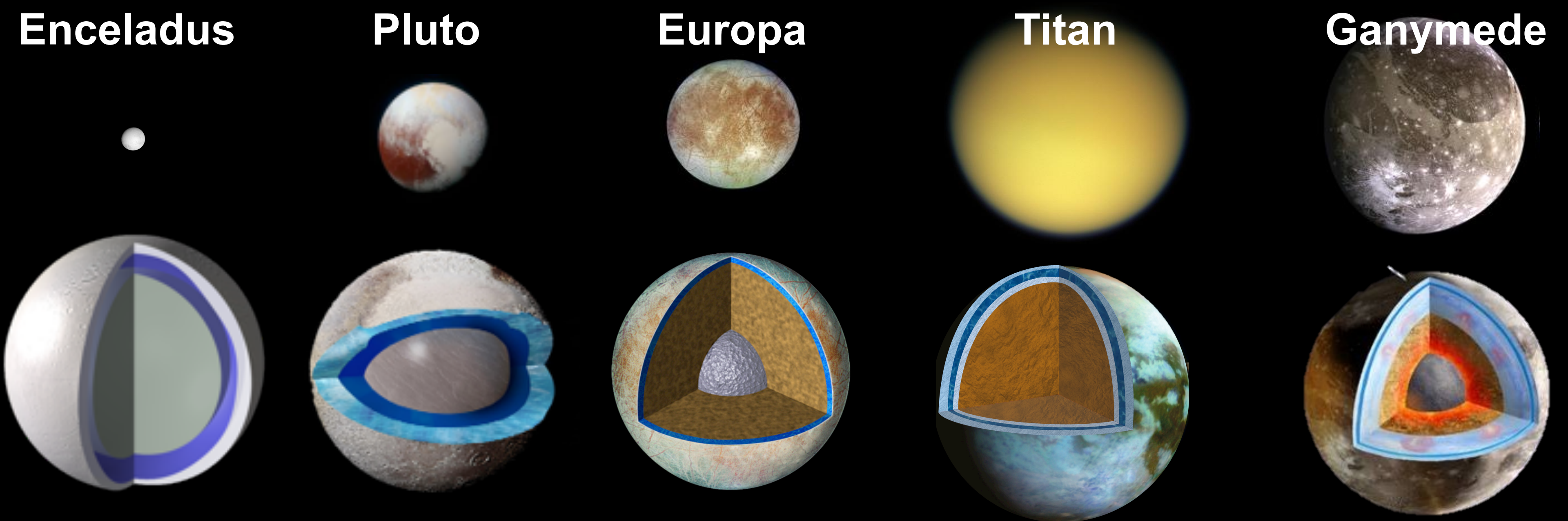
R= 2634 km,
$\rho$=1940 kg .m$^{-3}$
C/MR$^2$=0.311

**Rocky core and ocean separated by a thick high-pressure ice mantle.**

# Estimated hydrosphere characteristics

| | Enceladus | Pluto | Europa | Titan | Ganymede |
|---|---|---|---|---|---|
| Radius (km) | 252 | 1188 | 1561 | 2575 | 2641 |
| Ice shell thickness (km) | 5-35 | 200-250 | 10-30 | 50-70 | ~100 |
| Ocean volume x Earth's) | ~0.02 | ~0.4 | ~2 | ~10-12 | ~10-15 |
| Rock core radius (km) | ~185 | ~850 | ~1400 | ~2000-2100 | ~1750-1800 |
| Compositional constraints | Na/K-bearing salts (icy grains): low salinity Nano-silica, $H_2$: hydrotherm. vents Libration, topo, gravi: Global ocean/thin shell | Possibly $NH_3$, $CH_3OH$ | Mg-bearing salts (surface) Mag. induction: Moderate salinity | Electric field, Tides: High salinity; Topo/ Gravi | Mag. induction: Low-moderate salinity |
| **Confidence** | **++++** | **-** | **++** | **+++** | **+** |

# Role of size/pressure on the rock core properties




**Enceladus**

Lilmited compaction (P<40 MPa)

Porous core (20-30%, <500-700 K)

Efficient water flow through the core

**Pluto**

Porosity in the outer core

Rock core mostly hydrated (<1000 K)

**Europa**

Fractured/porous rock crust

Relatively hot mantle (>1400 K)

Iron core possible

**Titan**

Hydrated upper mantle

Anhydrous rock inner core

Iron core unlikely

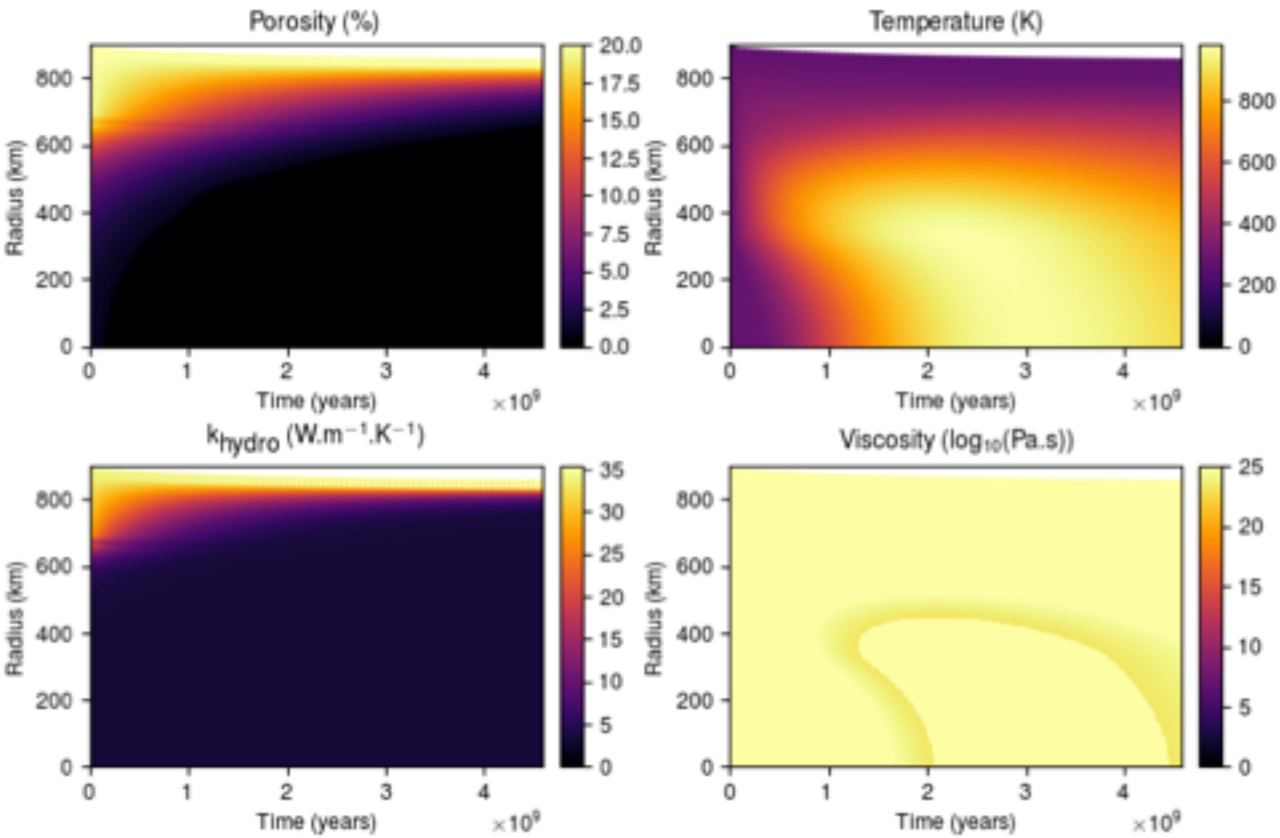
**Ganymede**

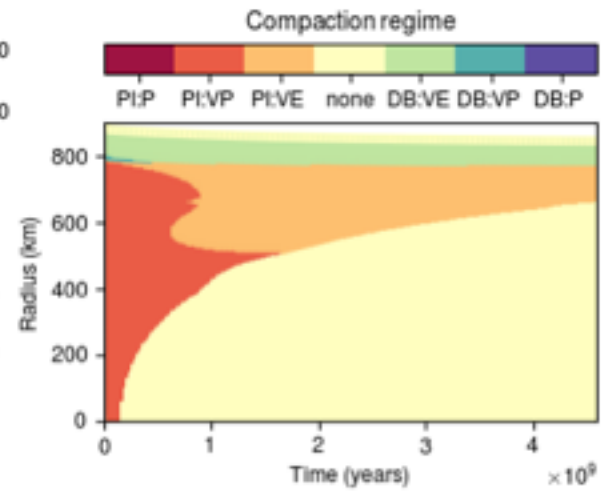
Mostly anhydrous rock mantle

Liquid iron core with active dynamo

# Evolution of core porosity: the example of Pluto

Nominal: tuff rheology, grain size $d_s = 5$ mm, initial porosity $\varphi_0$=0.2, viscosity threshold $\max(\eta_{sil}) = 10^{25}$ Pa.s

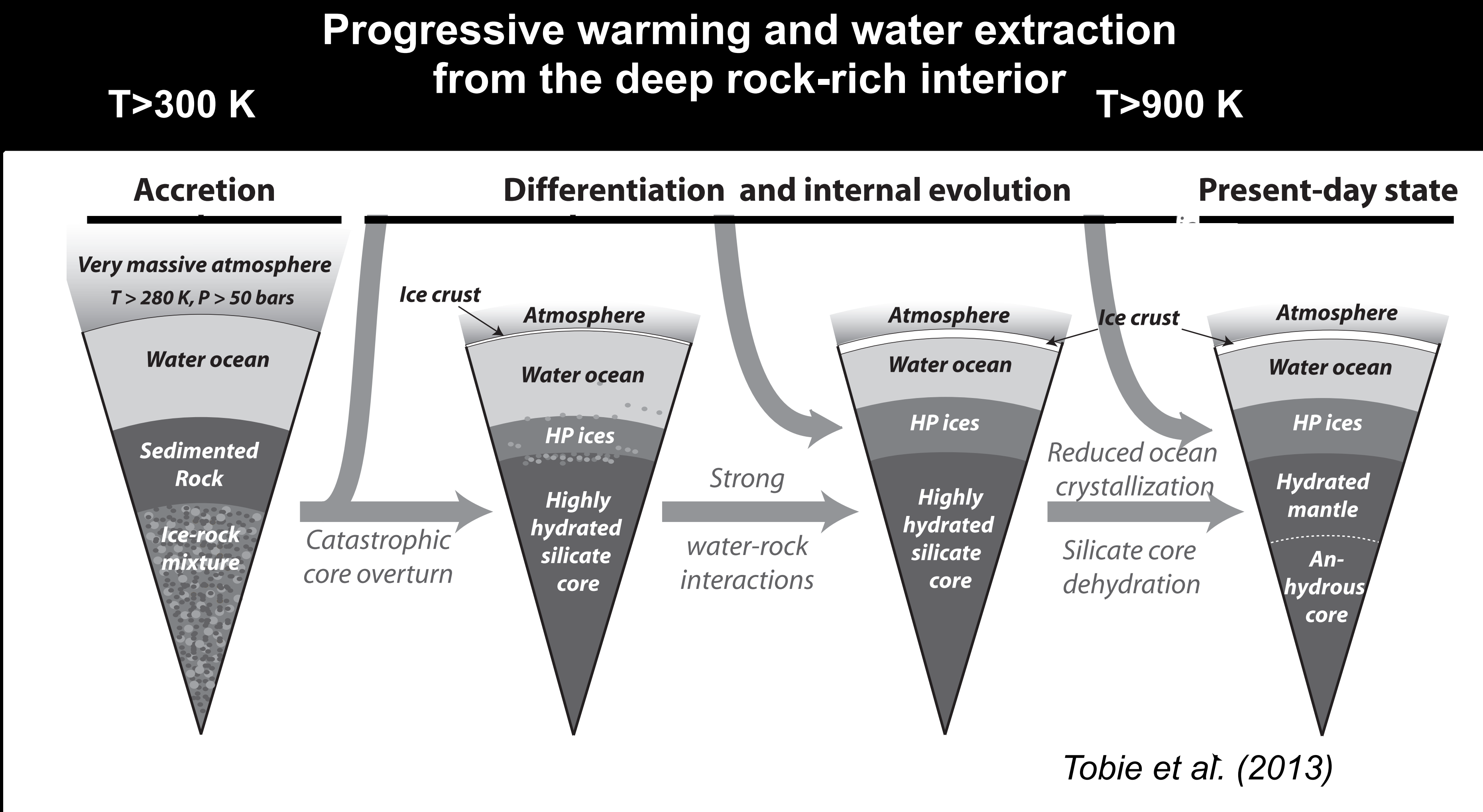



*L. Gabasova (Master Thesis, Nantes, 2017)*

- Water-rock interactions controlled by compaction timescale.
- Elevated primordial porosity (>20%) may be preserved in the outer part of the core during billions of year.

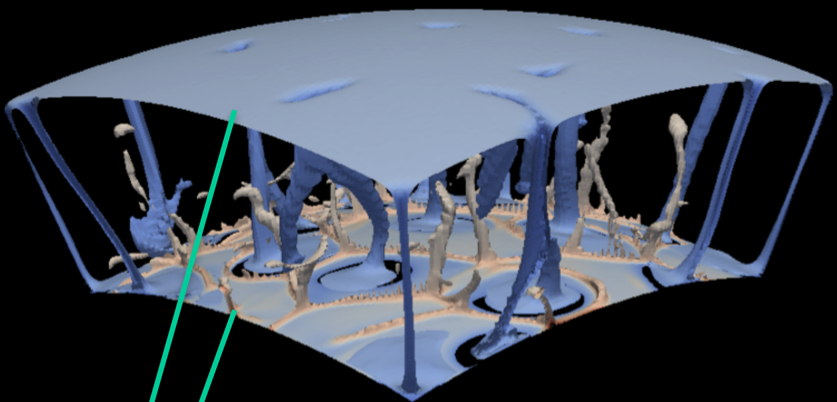
# Ice-water-rock segregation: The example of Titan

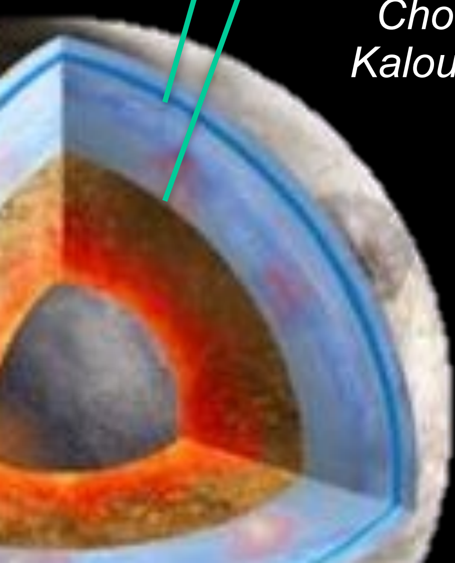



- **Large-scale melting, strong but brief water-rock interaction (0.5-1 Gyr)**
- **Water-rock interactions induced by core dehydration, possibly until present** *(Castillo-Rogez and Lunine 2010)*

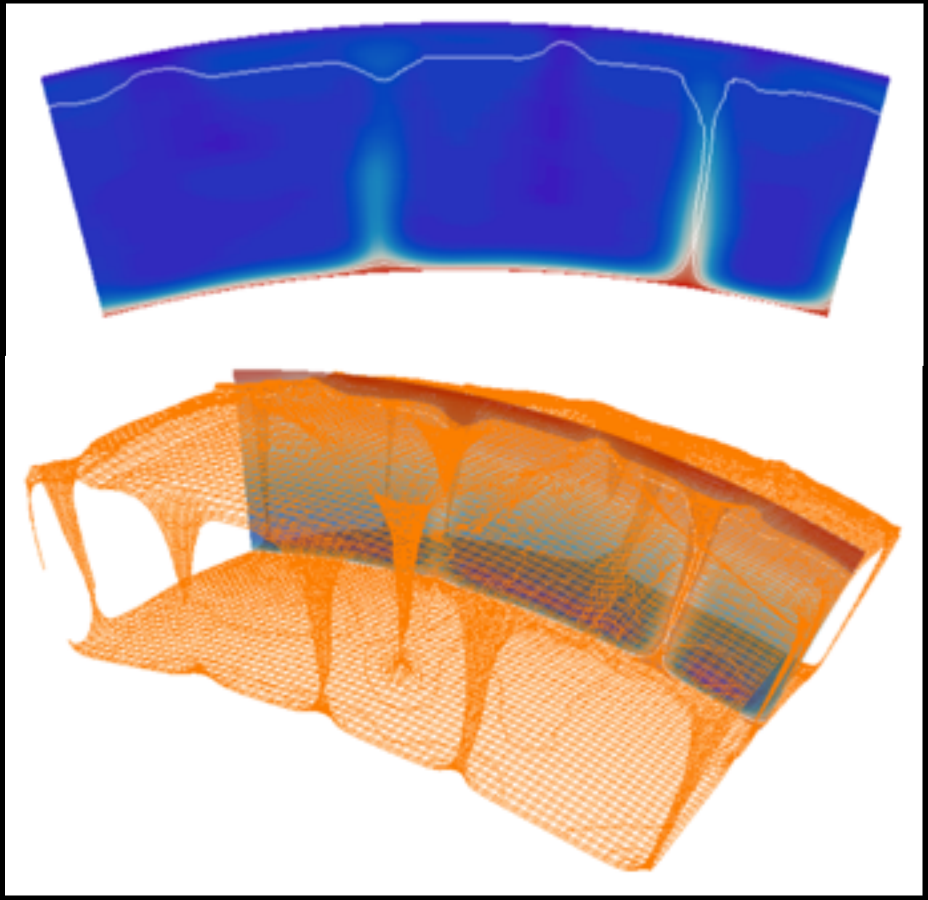
# Water-rock interactions at the base of the HP ice mantle

**2D/3D modeling of thermal convection in the HP ice mantle**





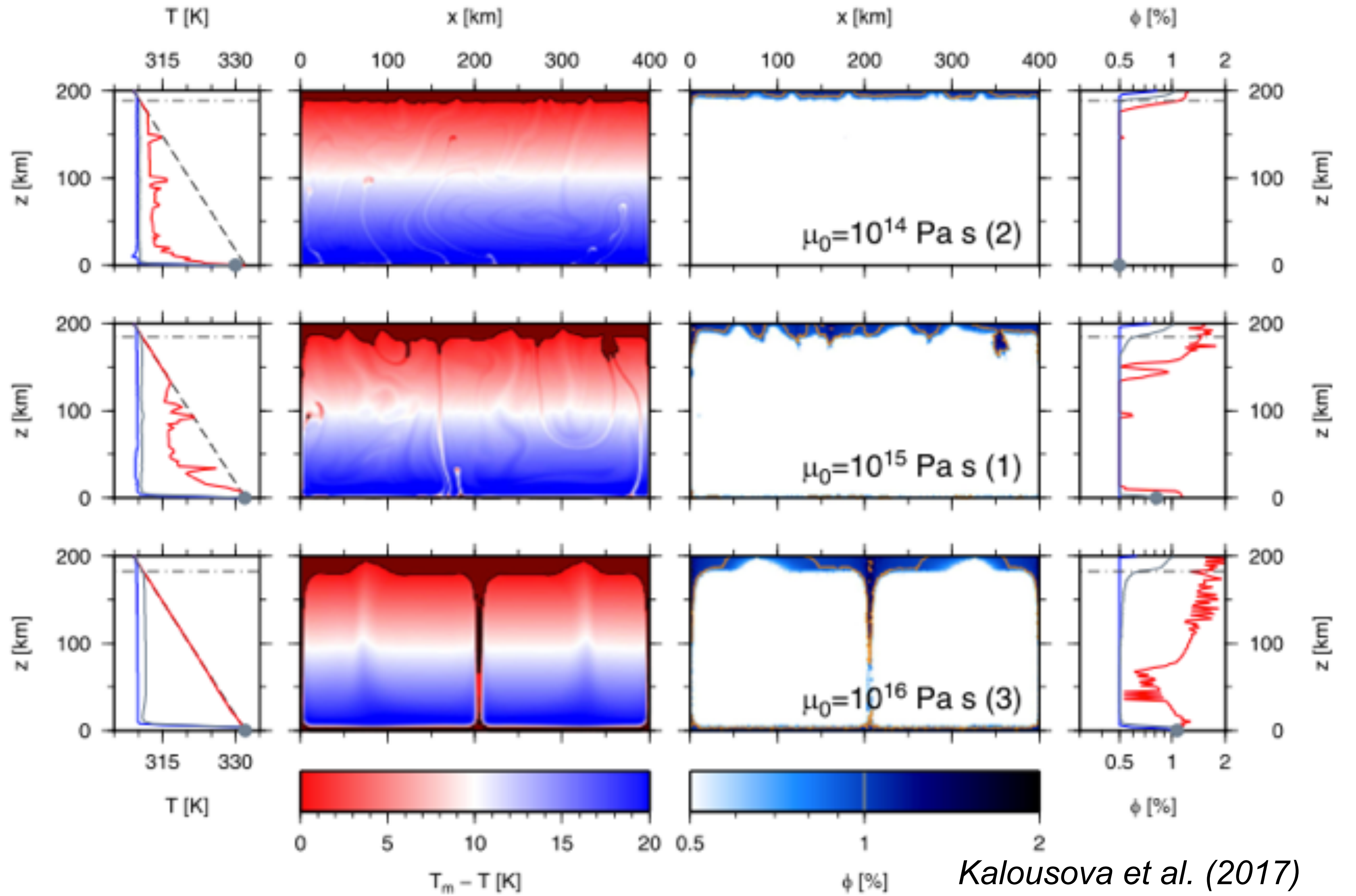
*Choblet et al., (2017)*
*Kalousova et al., (2017)*



> Efficient heat and mass transfer through the HP ice mantle through melt generation and extraction
> Ice melting in hot plumes and the base of the layer
> HP ice mantle does not preclude water-rock interactions

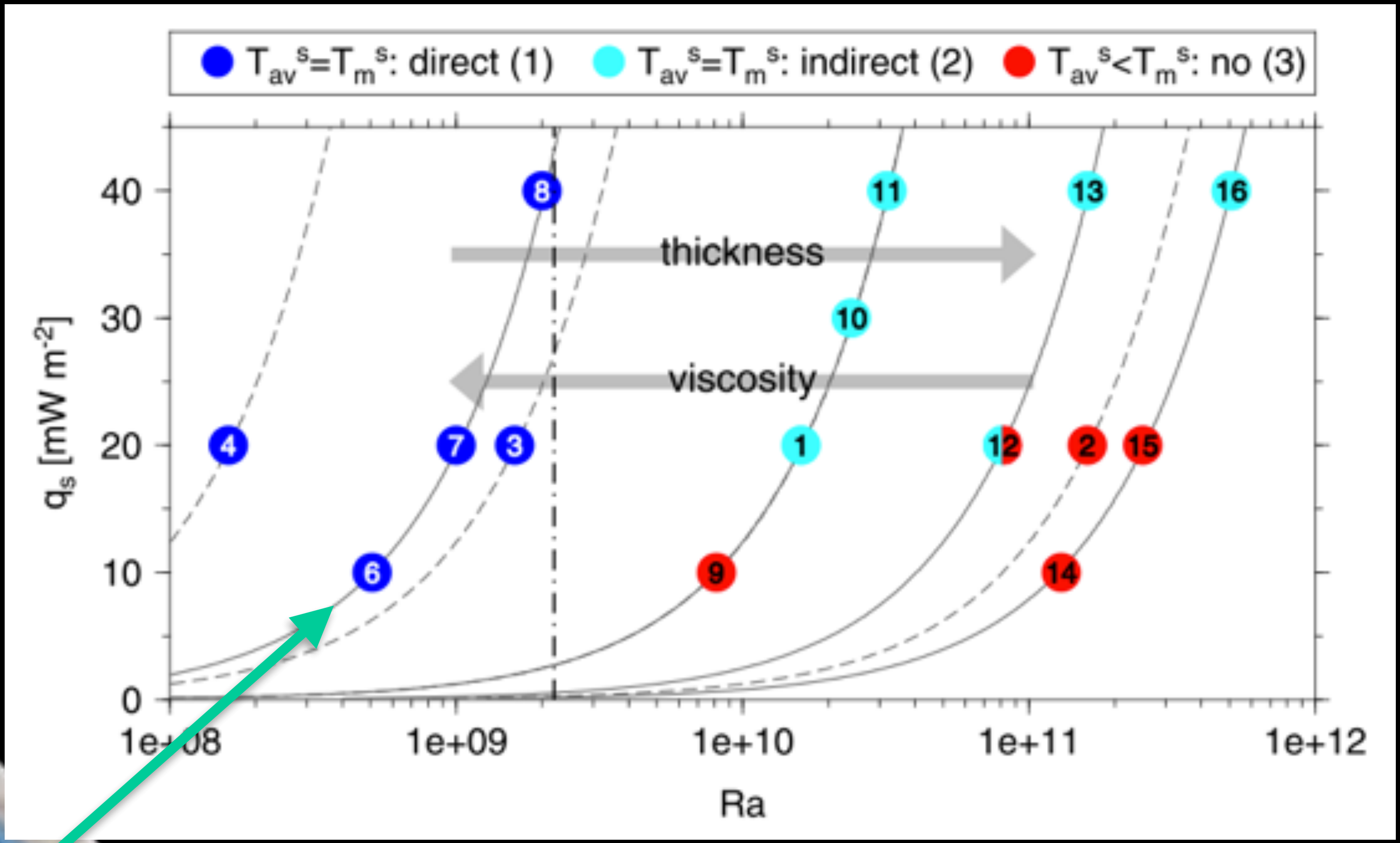
# Water-rock interactions at the base of the HP ice mantle

## 2D modeling of thermal convection in the HP ice mantle including water generation and transport

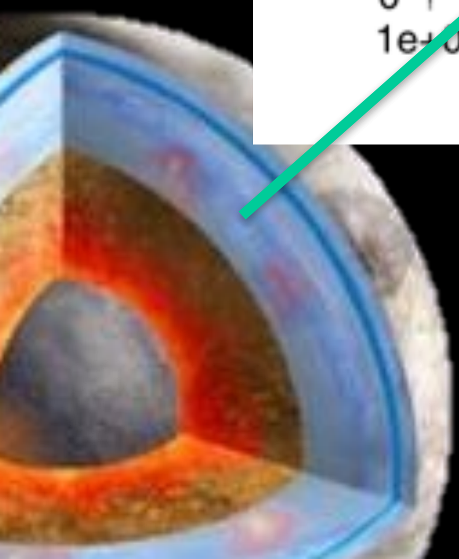



Kalousova et al. (2017)

# Water-rock interactions at the base of the HP ice mantle

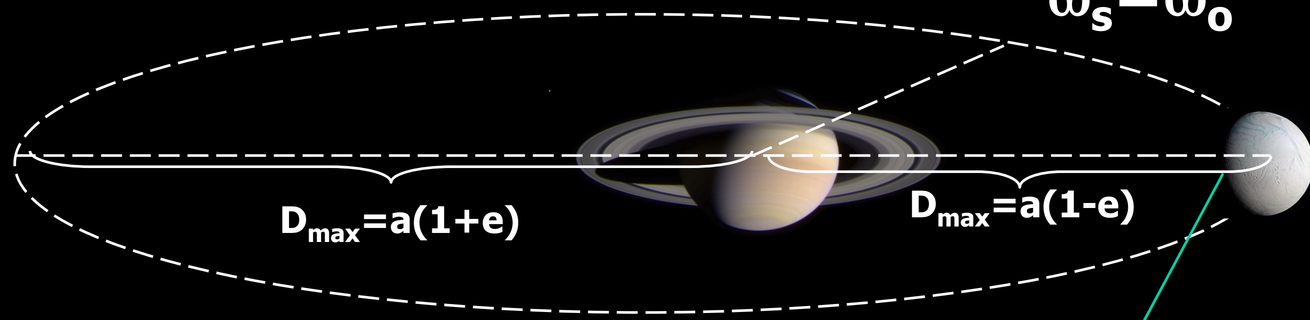



*Kalousova et al. (2017)*



> Ice melting in hot plumes and the base of the HP ice mantle depending on the vigor of convection (viscosity-mantle thickness)
> water-rock interactions at the base of the ice shell may be important during the early stage of evolution of **Ganymede** and possibly until present for **Titan**

# Tidal dissipation as a heat engine for icy worlds




Periodic fluctuation of tidal potential
(to the first order in eccentricity)

$$V_T(r,\theta,\phi,t) = \frac{3GM_J R_s^2}{2a^3}\left(\frac{r}{R_s}\right)^2 \left[T_* + T_0 + T_1 + T_2\right]$$

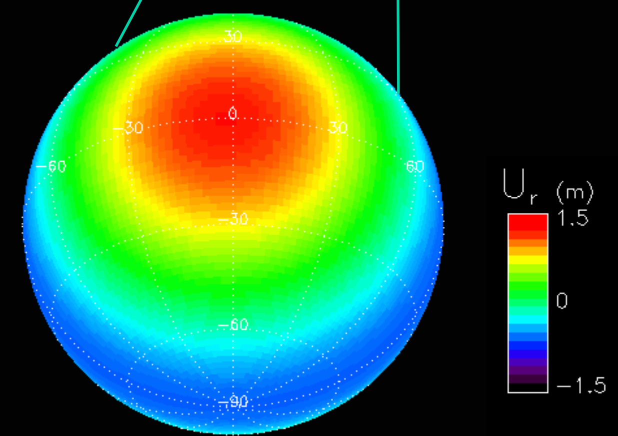
**flattening** $$T_* = \frac{1}{6}(1 - 3\cos^2\theta)$$

**elongation/alignment** $$T_0 = \frac{1}{2}\sin^2\theta\cos(2\phi + 2bt)$$

**flattening** $$T_1 = \frac{e}{2}(1 - 3\cos^2\theta)\cos(nt)$$

**elongation/alignment** $$T_2 = \frac{e}{2}\sin^2\theta\Big[3\cos(2\phi)\cos(nt) + 4\sin(2\phi)\sin(nt)\Big].$$

**Sotin et al. Europa after *Galileo***

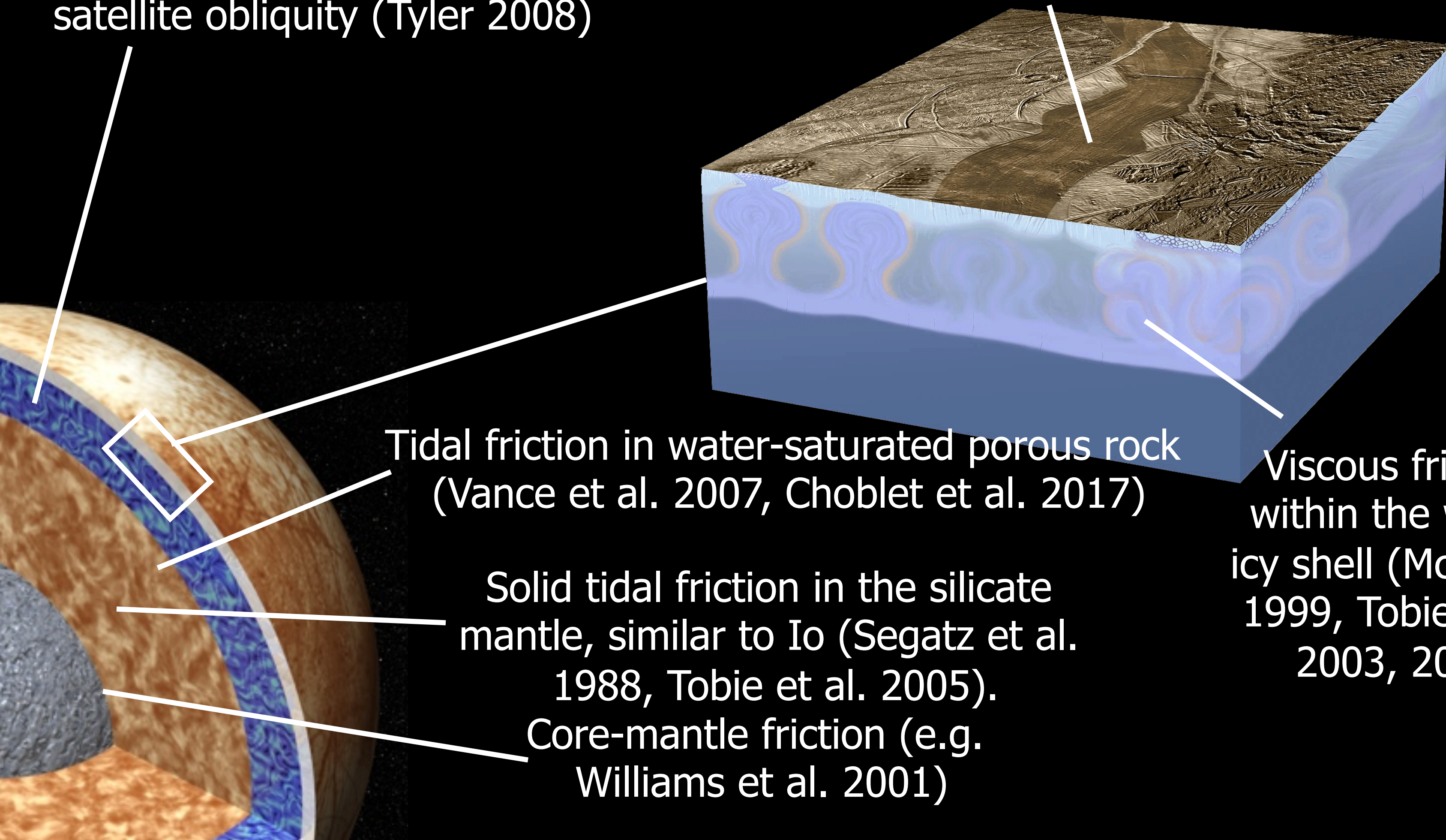


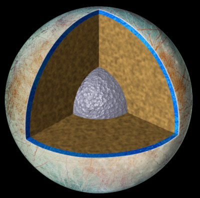

Radial displacement
due to tidal forcing

> periodic deformation of the satellite > internal friction > tidal heating

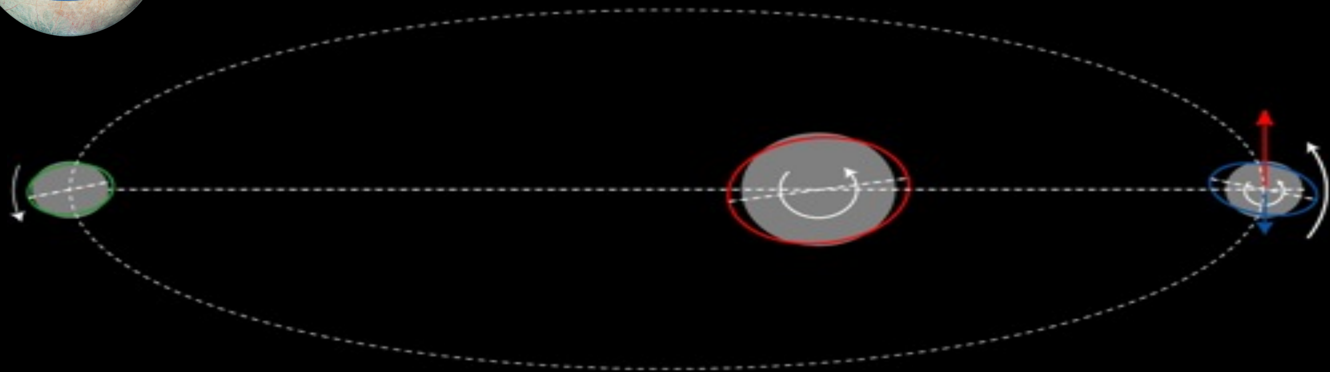
# Tidal dissipation as a heat engine for icy worlds

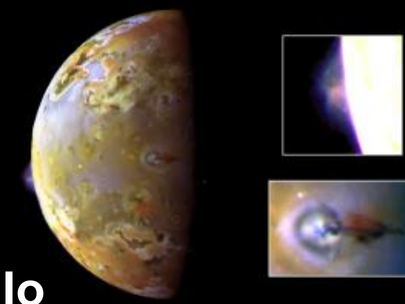
## Possible tidal friction mechanisms in icy world interiors





# Maximal tidal heating in Europa's rocky core





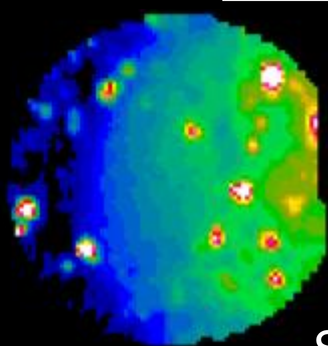
Io

**Likelihood of seafloor volcanic activities ?**

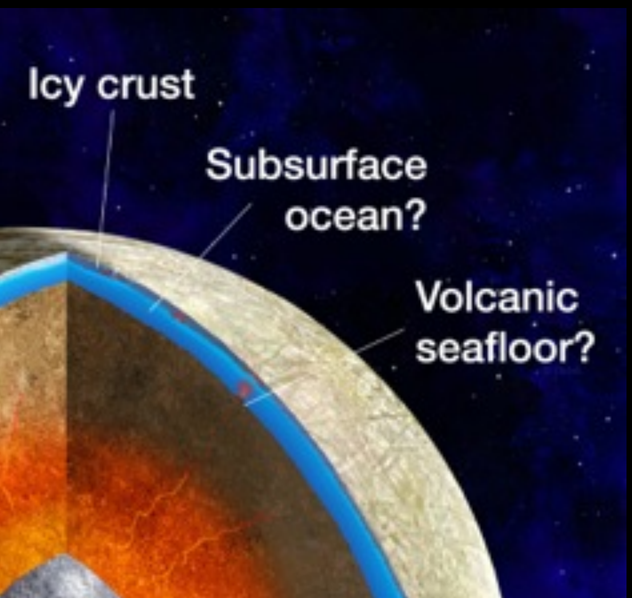
**Heat production by tidal friction in the rocky core ?**

**Global dissipation in the interior**

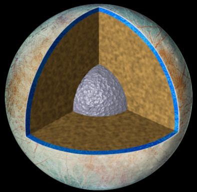
$$\dot{E}_{glob} = -\frac{21}{2} Im(k_2) \frac{(\omega R_s)^5}{G} e^2$$



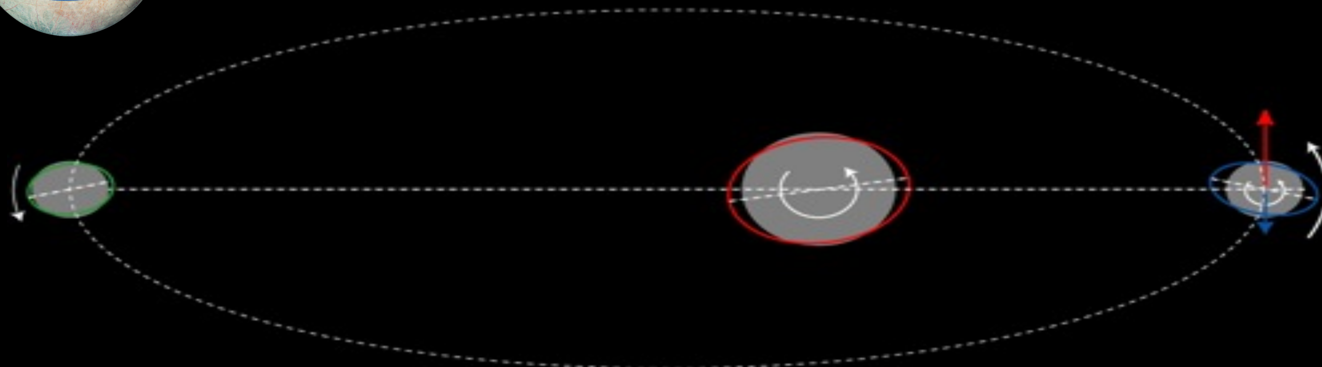
Global dissipation on Io estimated from thermal IR flux : ~100 TW (>100 x radiogenic power )

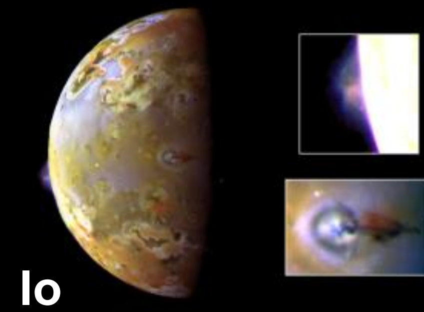



Scaling to Europa: $(P_I/P_E)5$ x $(R_E/R_I)5$ x $(e_E/e_I)2$ x 100 TW ~ 9 TW (> 10 x radiogenic power) assuming Im(k2) constant between Io and Europa



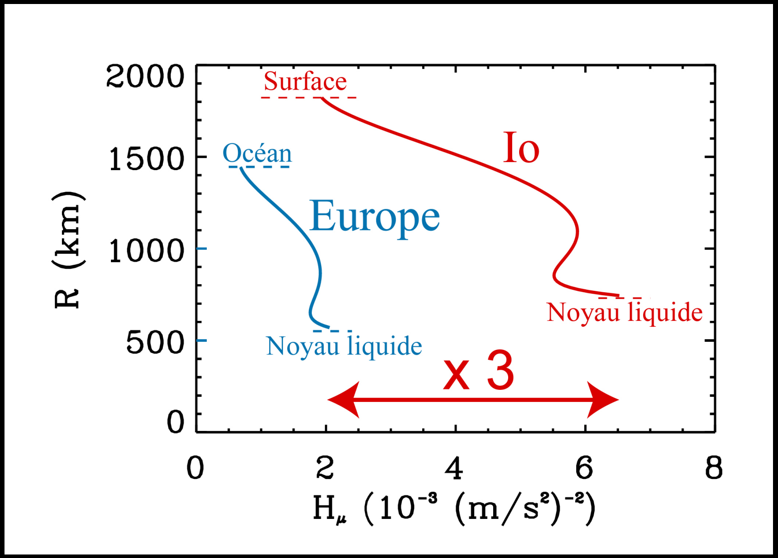
# Maximal tidal heating in Europa's rocky core

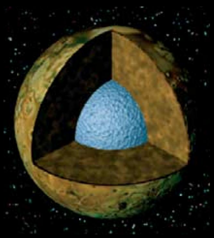


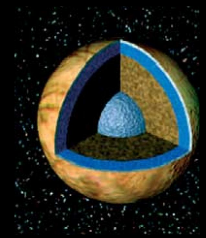


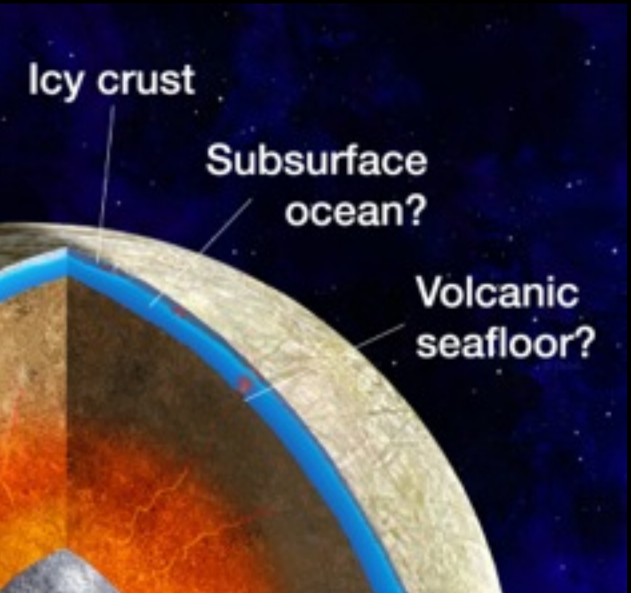

**Likelihood of seafloor volcanic activities ?**

**Heat production by tidal friction in the rocky core ?**





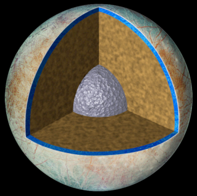


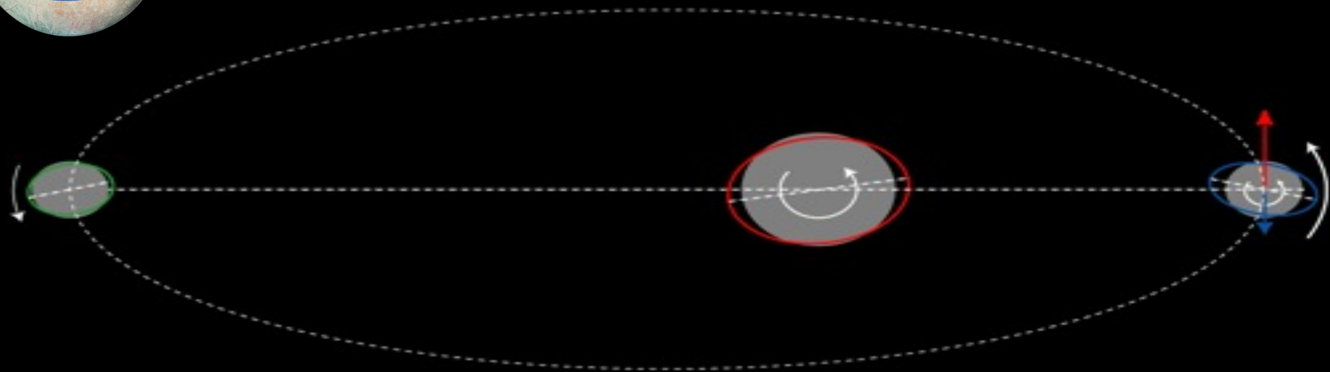

Owing to the decoupling effect of liquid water, Europa's mantle is less sensitive to tidal deformation.

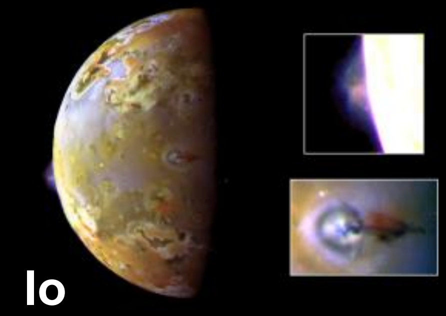
Im(k2)e < 3 x Im(k2)i -> Global dissipation < 3 TW.

*Tobie et al (2005)*

# Maximal tidal heating in Europa's rocky core



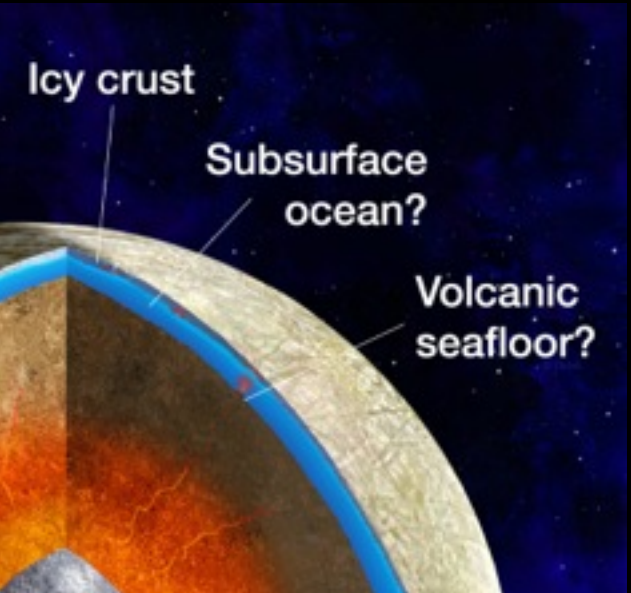





**Likelihood of seafloor volcanic activities ?**

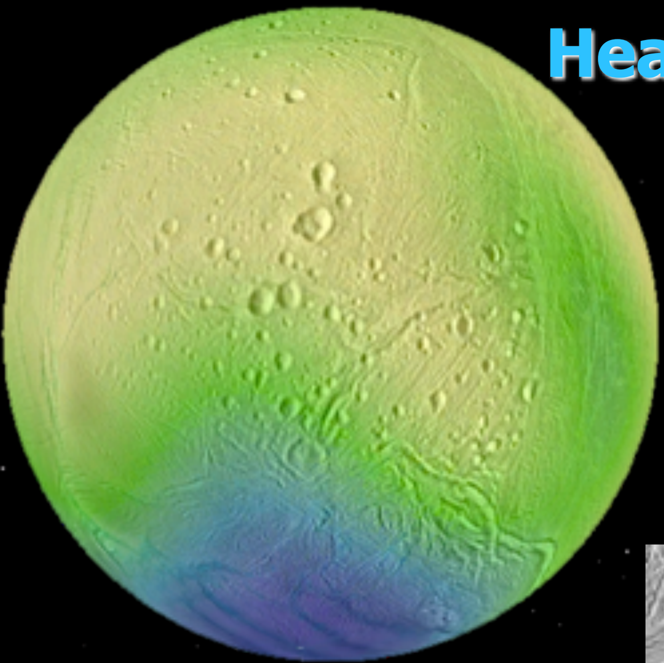
**Heat production by tidal friction in the rocky core ?**

**Silicate volcanism similar to Io > very unlikely**
Global dissipation similar to Io would require a very hot interior, even hotter than on Io.



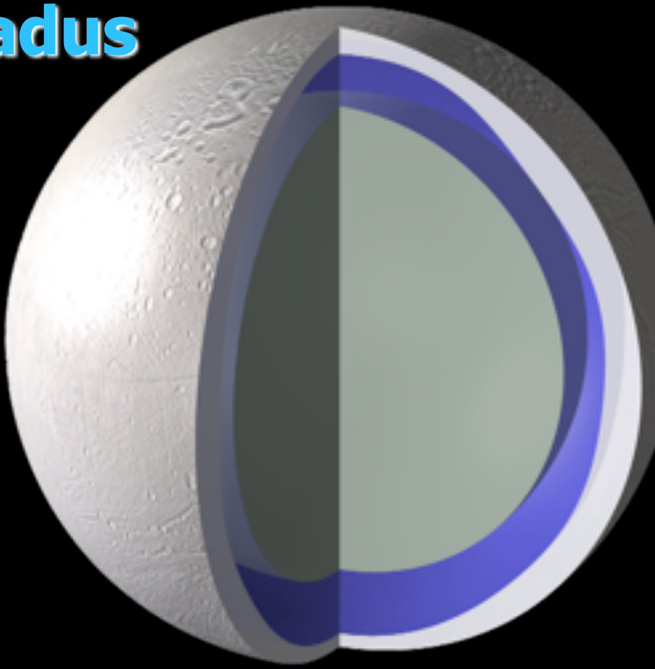

**Moderate volcanism > likely, especially in the past** when both radiogenic heating and tidal dissipation were high
total available power: up to 5 TW
mean heat flux : ~100-200 mW.m-2
similar to heat flow near mid-oceanic ridges on Earth

# Heat budget of Enceladus



Global ocean underneath an ice shell with thickness of 20-25 km on average from libration data

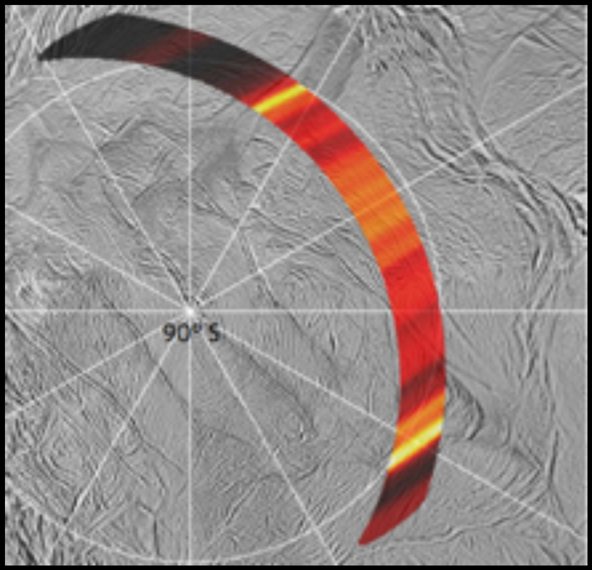
*Thomas et al. (2016)*



*Hemingway et al. (2017)*

Ice shell possibly as thin as 2-4 km at the south pole from gravi-topo analysis

*Cadek et al. (2016), Beuthe et al. (2017), Hemingway et al. (2017)*

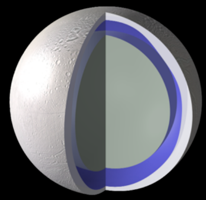



Abnormally high heat flux at the south pole, possibly as high as 1 W/m2 (> 10 x Earth's average heat flux)

*Le Gall et al. (2017)*

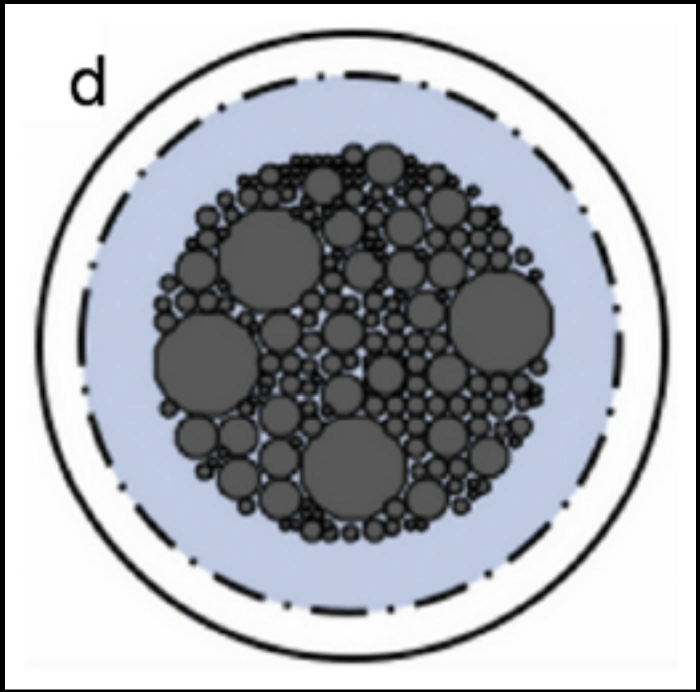
25-30 GW required to explain the present-day thermal state of Enceladus ( > 10 x radiogenic power)

Dissipation processes in Enceladus' interior ?



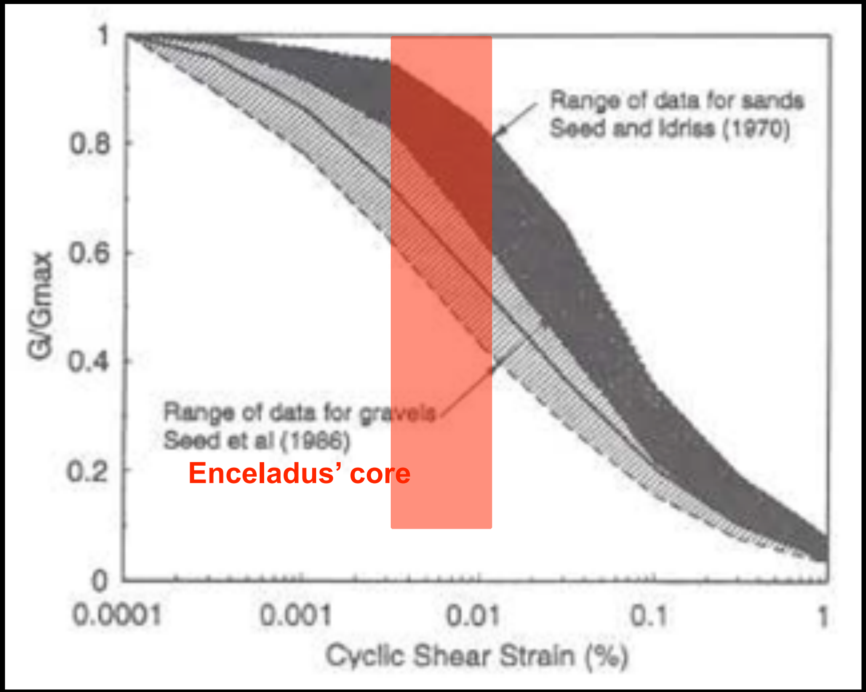
# Tidal heat production in the unconsolidated water-saturated core

Porosity in the core estimated between 20-30% based on Cassini's gravity data *(Iess et al. 2014)*




The core may be considered as a mixture of water-saturated sands and gravels.

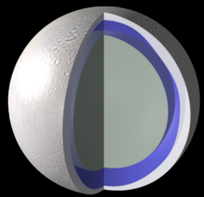
Strong decrease of effective shear modulus for cyclic strain exceeding ~ 0.01 %

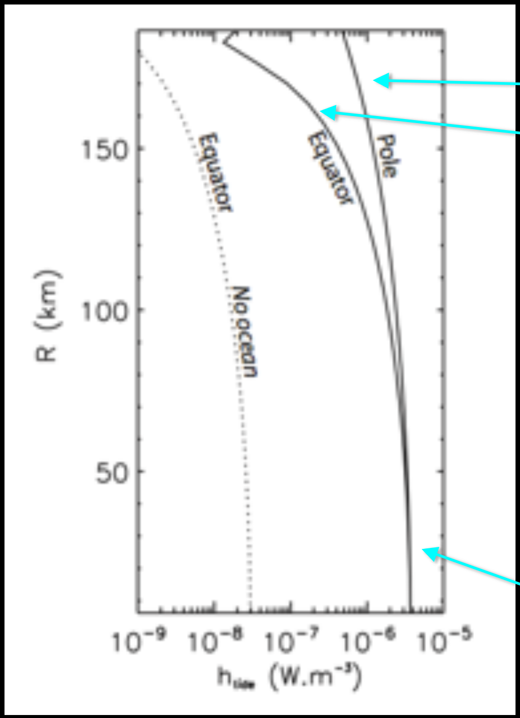



*Rollins et al. (1998)*

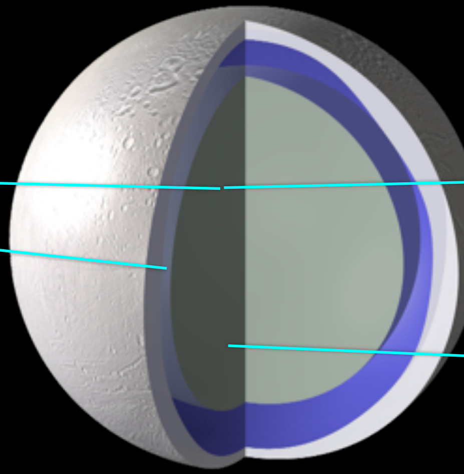
**Anelastic properties of such granular materials classically describe from the effective shear modulus and dissipation function.**

# Tidal heat production in the unconsolidated water-saturated core

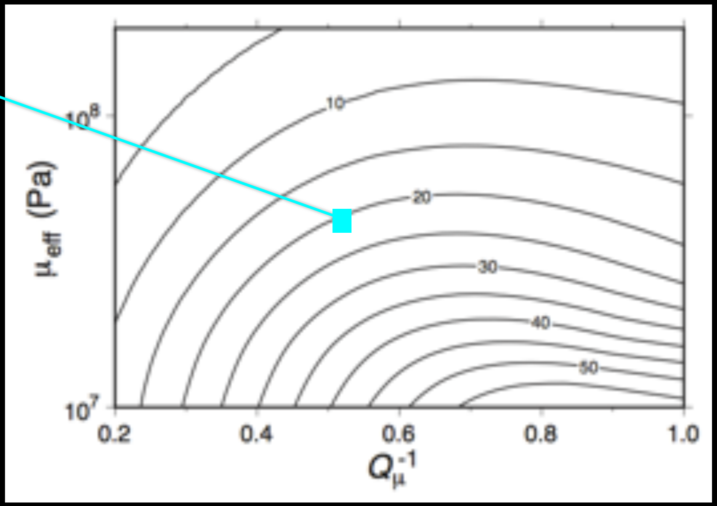


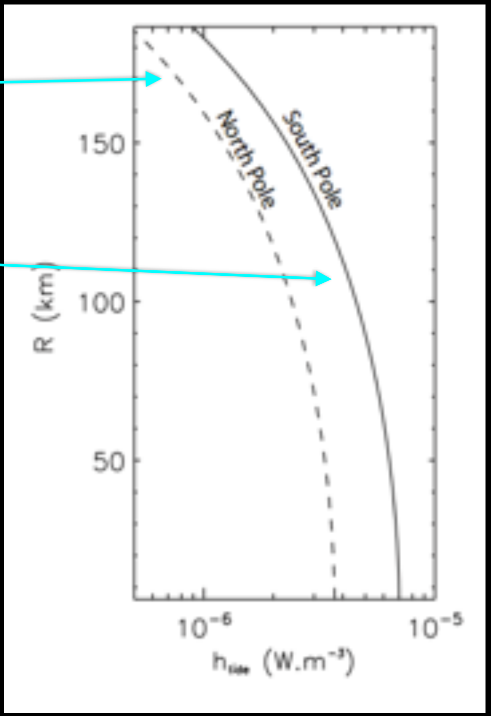



Tidal heating profile at the pole and the equator



Global heat production in the core (GW)

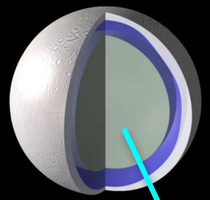


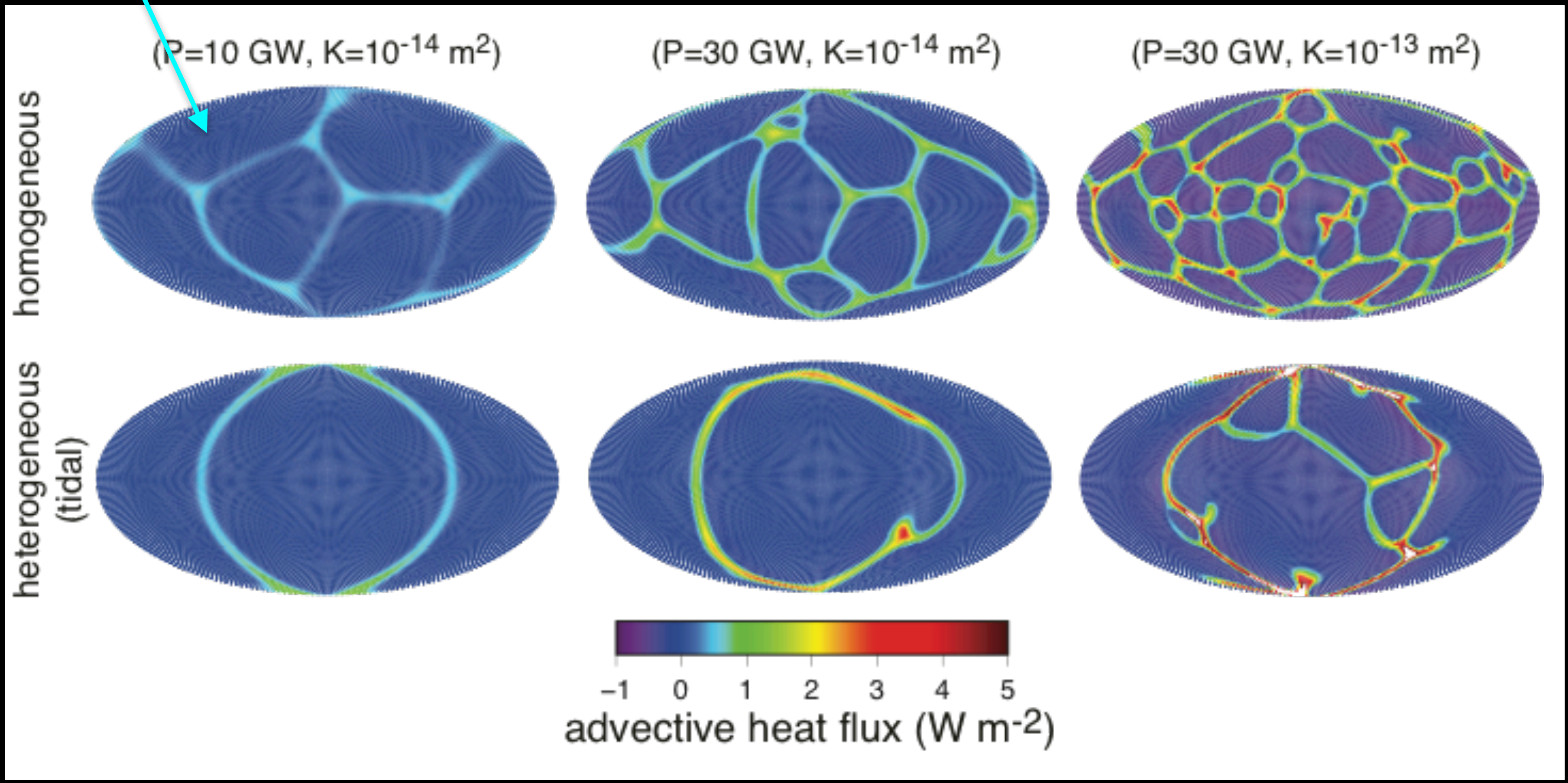

Increase of tidal heating at the south pole due to thinner and more deformable ice shell

*Choblet al. (2017)*

# Water flow in the tidally-heated porous core of Enceladus

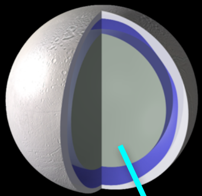


## Porous flow of liquid water in a 3D spherical model



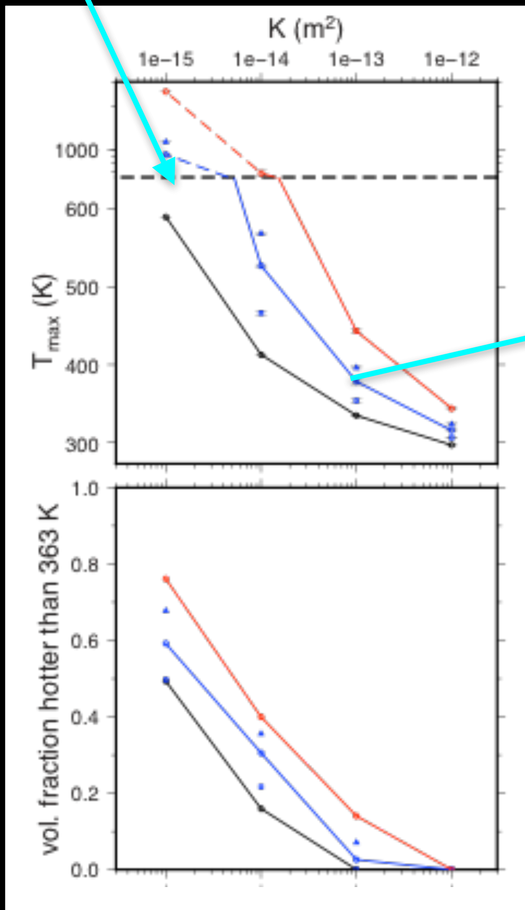

**Heat released by narrow upwelling of hot water (> 100 °C) concentrated to the poles and trailing/leading meridians where maximal dissipation occurs.**

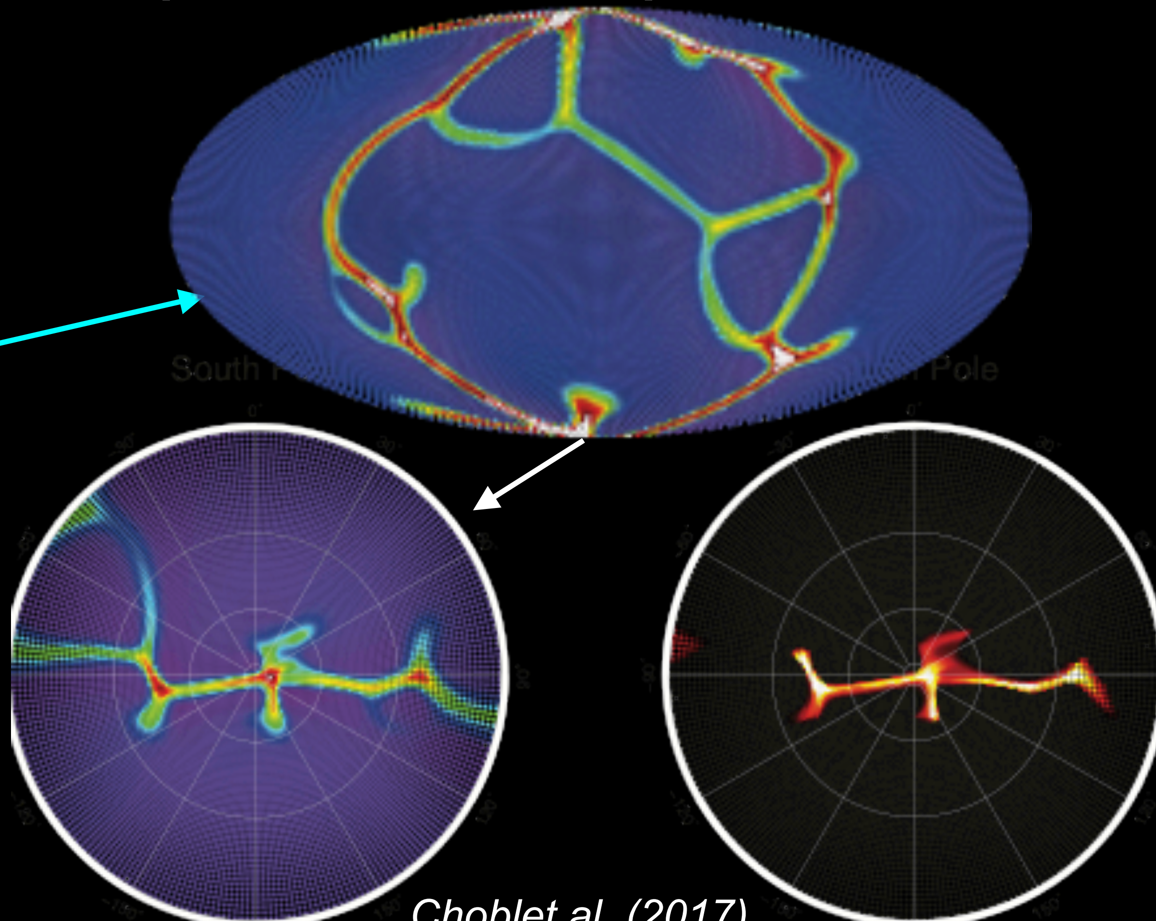
*Choblet al. (2017)*



# Water flow in the tidally-heated porous core of Enceladus

## Porous flow of liquid water in a 3D spherical model



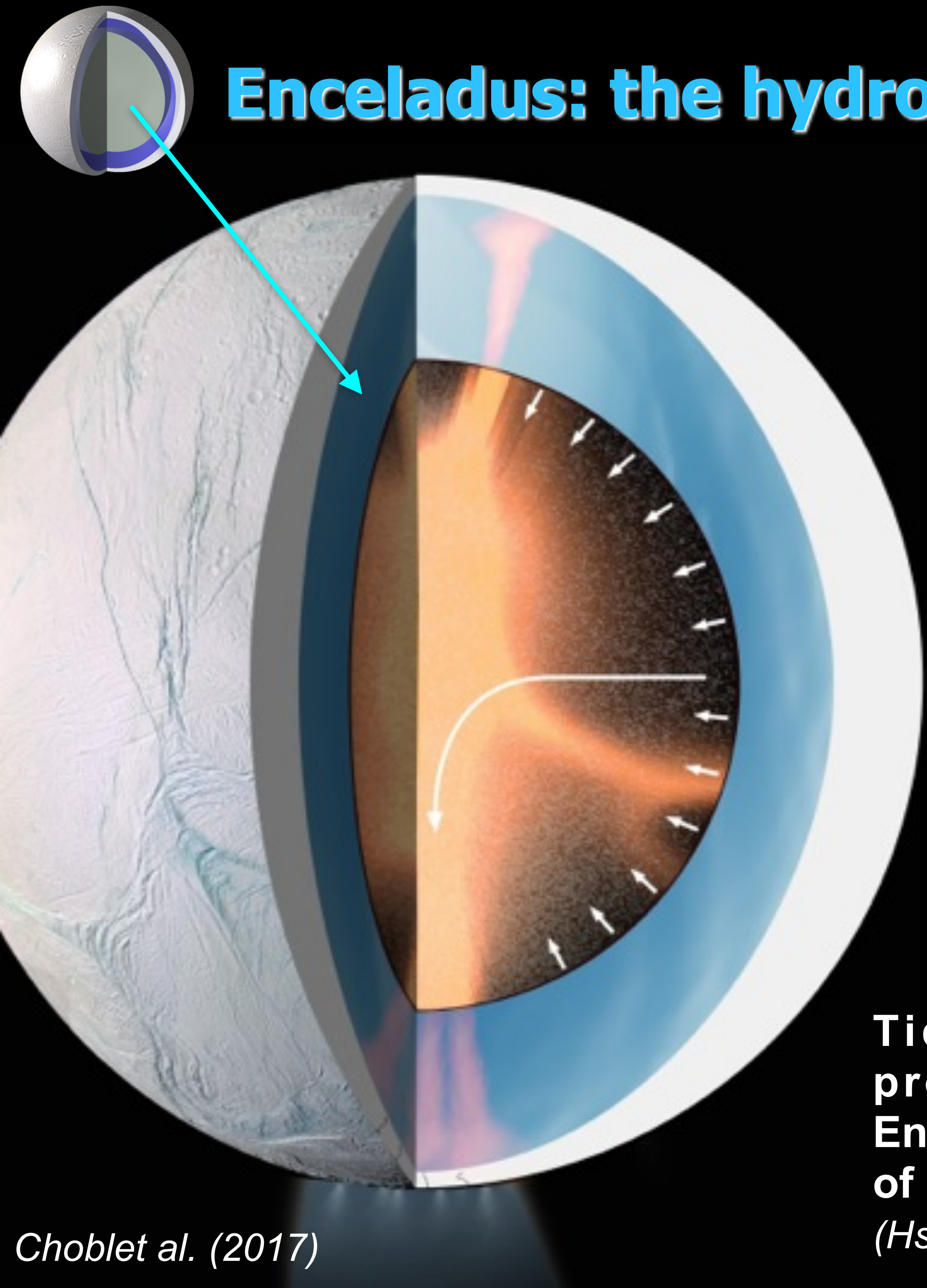



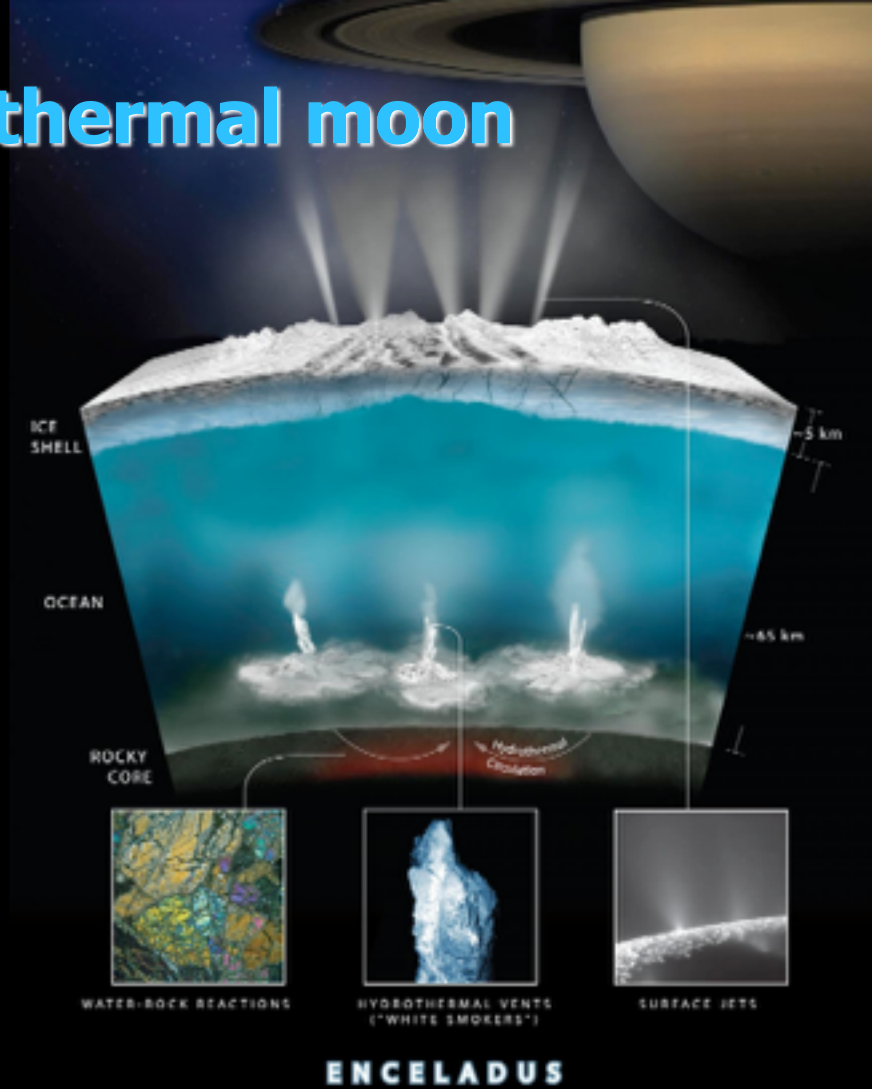
*Choblet et al. (2017)*

**-Temperature higher than 363 K observed in localized regions, for core permeability ranging between $10^{-14}$ and $10^{-13}$ $m^{-2}$.**

**-Most of the power released in a few hotspots (> 100 °C, > 5 $W.m^{-2}$).**

# Enceladus: the hydrothermal moon



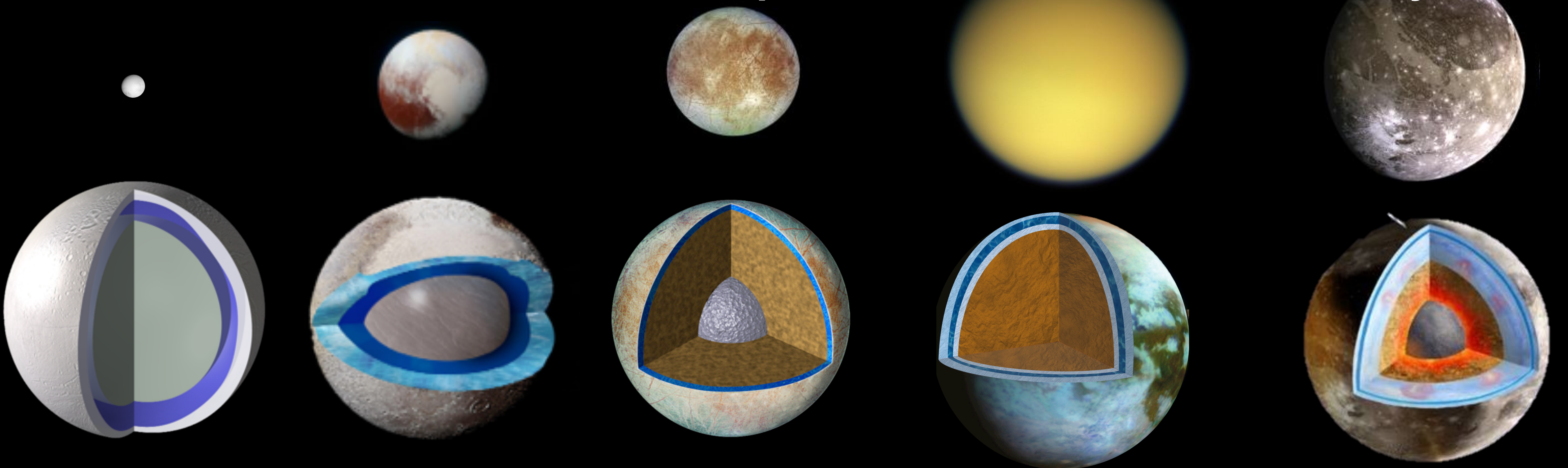



Tidally-controlled hydrothermal processes in the entire core of Enceladus consistent with the detection of nano-silica and of native hydrogen *(Hsu et al. 2015, Waite et al. 2017)*.

*Choblet al. (2017)*

# Geodynamical context for water-rock interactions: A synthesis

Enceladus Pluto Europa Titan Ganymede



**Moderate to low T fluid interactions**

Tidally-heated porous water flow

Compaction-controlled porous flow

*Mimas, Dione, Rhea, Tethys, Ariel, Titania, Umbriel, Oberon, Ceres, Eris, Sedna etc.*

*Triton*

**Moderate to high T fluid interactions**

Volcanically-driven water-rock interactions

*Earth, Early Mars*

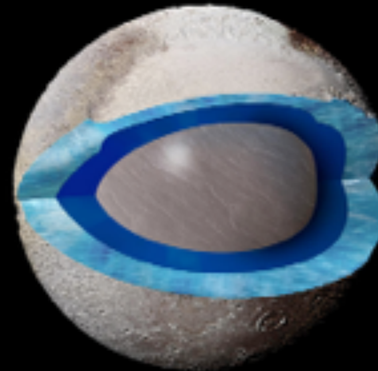
**High-pressure (> 1GPA) fluid interactions**

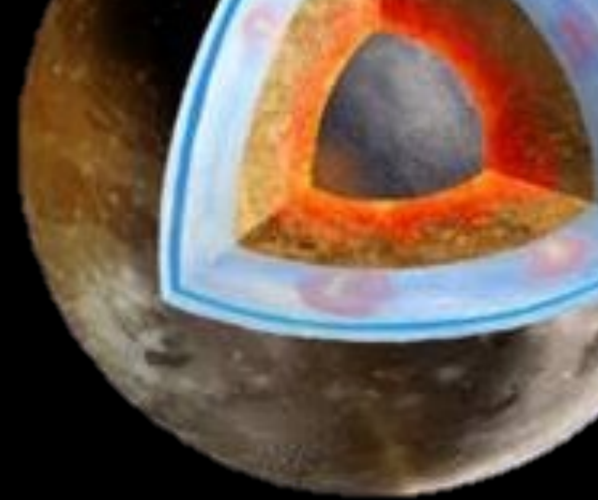
Massive water-rock interaction during core differentiation

Core dehydration

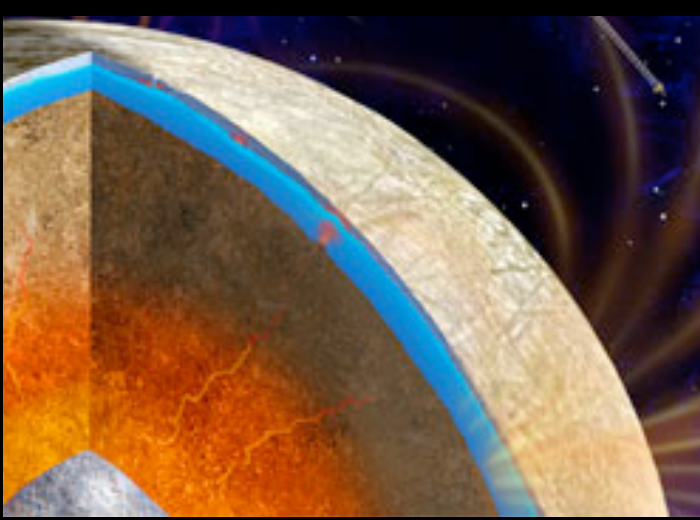
Water-rock interactions at the HI mantle-core interface

*Callisto*





# Thank you for your attention



ANR