衛星系研究会 2017

冥王星地下海の安定性と進化

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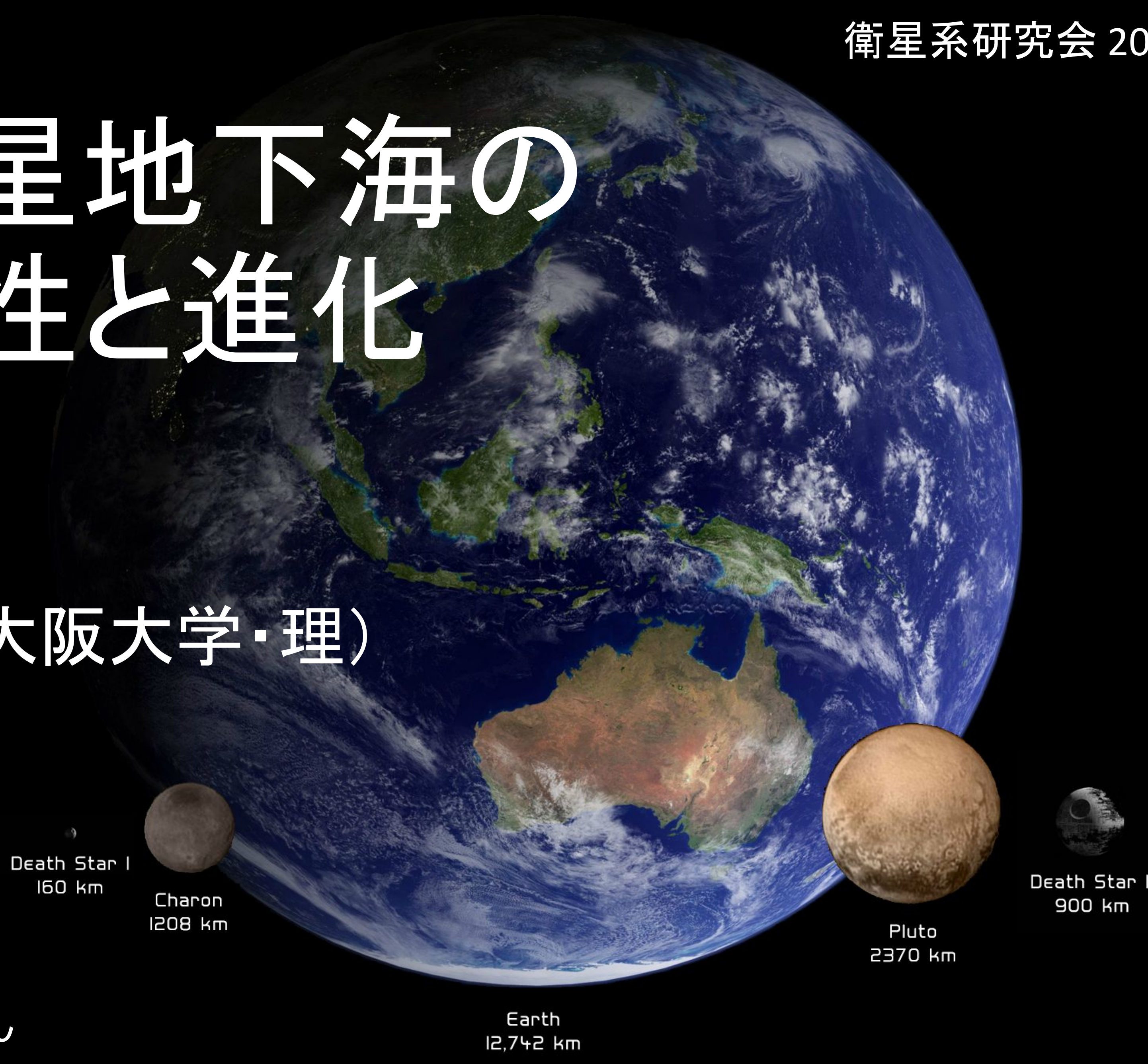

ACK for 鎌田さん

Background

- Pluto: icy dwarf planet
  - Radius = 1186 km
  - Bulk density = 1.88 g/cc (30-35 wt% of H_2O)
  - No detectable flattening implies warm/deformable interior (ocean?) [Nimmo+ 2016]
  - Extensional tectonics with strong H_2O spectral signature [Moore+ 2016, Grundy+ 2016]
  - Astrobiological/geophysical interests to investigate the conditions which Pluto may retain an ocean.

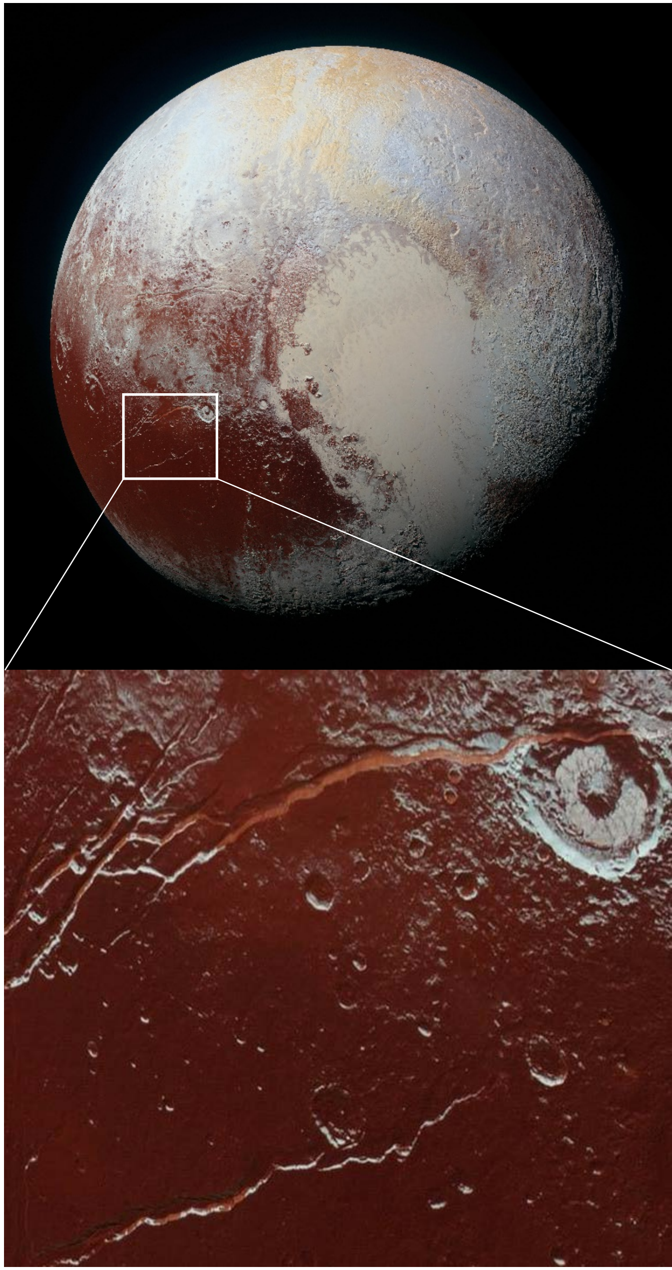

Image credit: NASA/JPL

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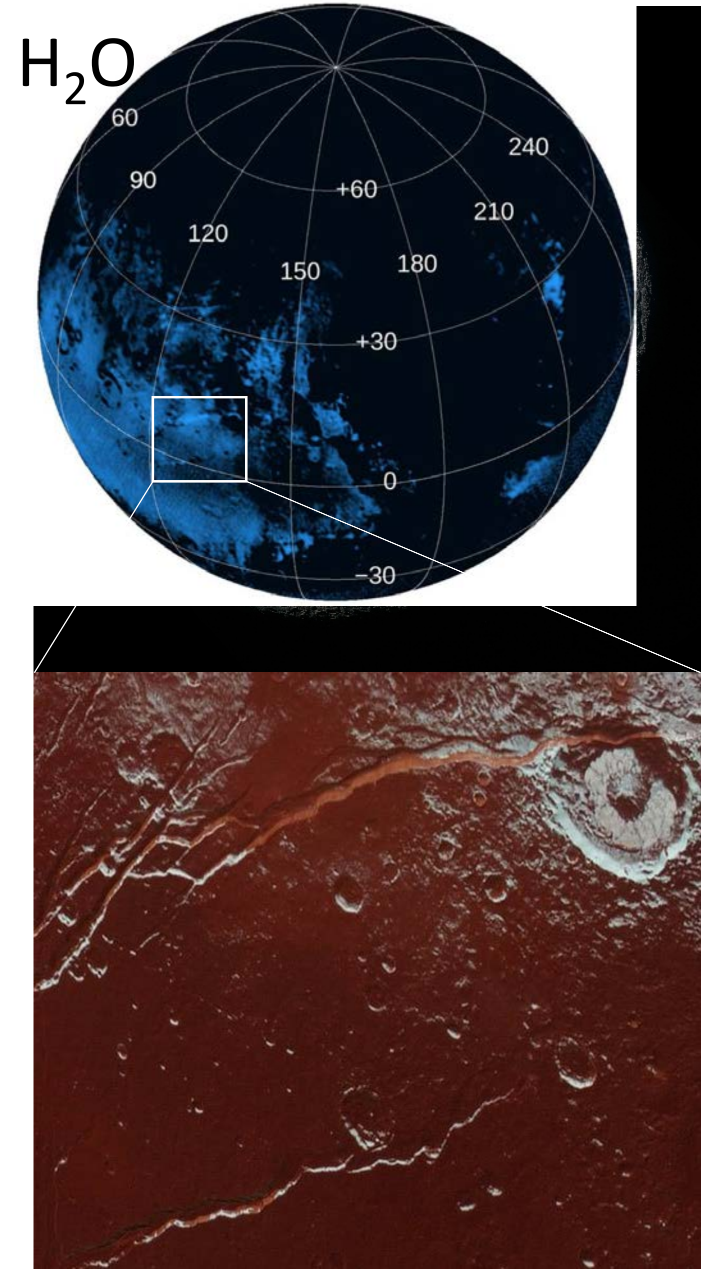
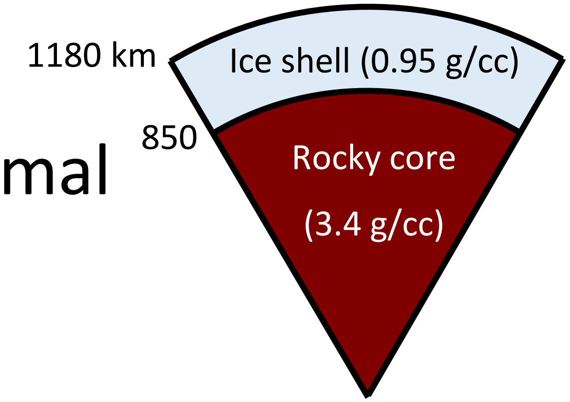


Image credit: NASA/JPL

Previous study for Pluto's evolution



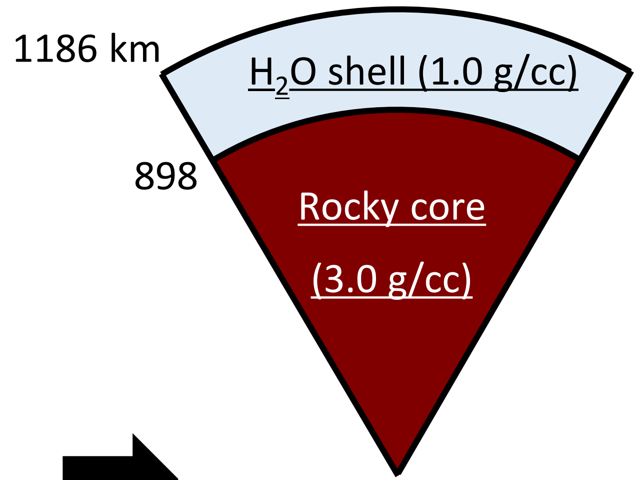
- Robuchon and Nimmo (2011)
  - Numerical simulation for interior thermal evolution w/ cold initial state using 2-layered interior model.
  - If the ice shell has a large viscosity (reference vis >5×10^{15} Pas), the ocean should be present.
  - Caveat
    - Only Ice-Ih appeared case is considered.
    - Assumed rocky core is conductive (no convection included)

→ Needs a further investigations under various structural settings (HP-ice appeared case) and different initial thermal states (cold and hot).

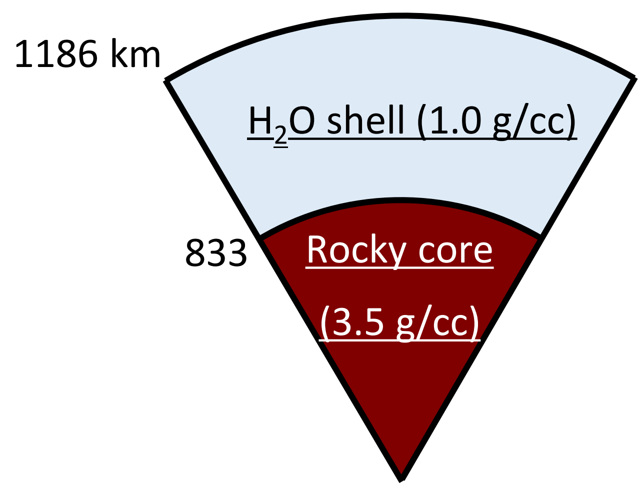
HP: high-pressure

Structural settings

- Mean Radius
  = 1186 km
- Mass
  = 1.305×10^{22} kg
- Bulk density
  = 1.88 g/cc



If 2-components are completely differentiated

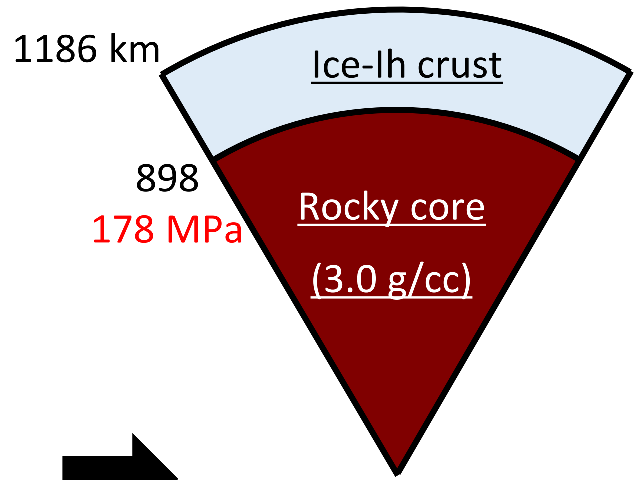


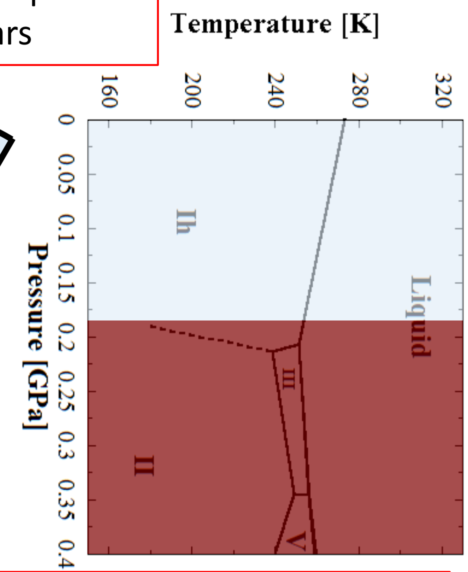
Structural settings

- Mean Radius
  = 1186 km
- Mass
  = 1.305×10^{22} kg
- Bulk density
  = 1.88 g/cc

→Considers
- a large core (only ice-Ih) case
- a small core (ice-Ih-III) case

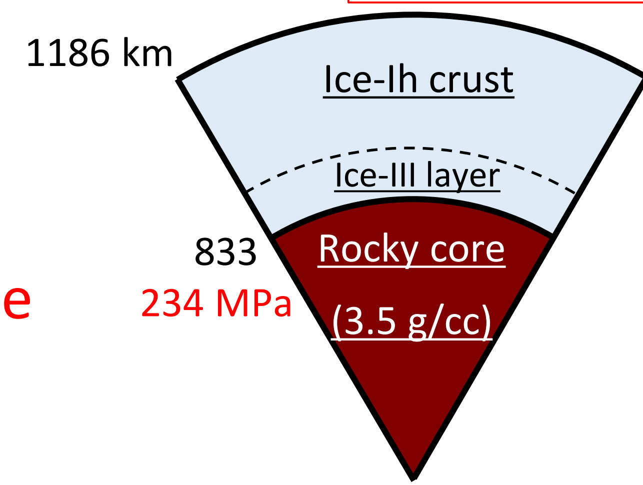
Only low-pressure phase ice (Ice-Ih) appears

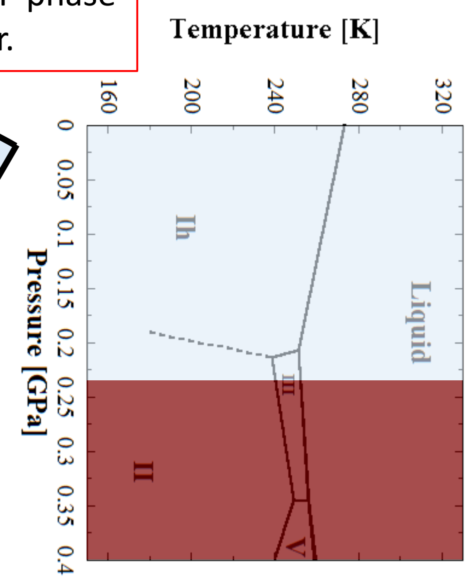




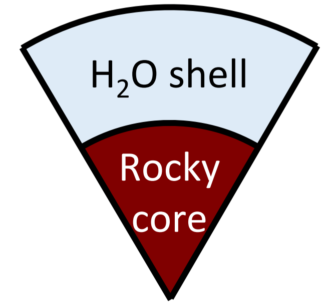
Ice Ih-III-Liquid triple point pressure= 207 MPa

Both ice-Ih and HP phase ice (Ice-III) appear.





Model



- 1-D thermal-structural evolution model
  - Mixing Length Theory for solid parts

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot \boldsymbol{F} + \rho Q$$

[e.g., Kimura+ 2009, Wagner+ 2011]

$$\boldsymbol{F} = F_{cond} + F_{conv}$$

$$F_{cond} = k_c \nabla T$$

$$F_{conv} = k_v(\nabla T - \nabla_{ad} T)$$

$$k_v = \begin{cases} 0 & \dfrac{\partial T}{\partial r} < \left(\dfrac{\partial T}{\partial r}\right)_{ad} \\ \dfrac{\rho C_p \alpha g l^4}{18\nu}\left[\dfrac{\partial T}{\partial r} - \left(\dfrac{\partial T}{\partial r}\right)_{ad}\right] & \dfrac{\partial T}{\partial r} > \left(\dfrac{\partial T}{\partial r}\right)_{ad} \end{cases}$$

  - Parametrized Convection Theory for liquid part

t: time
T: temperature
r: density
C_p: specific heat
Q: heat generation
k_c: thermal conductivity
n: kinetic viscosity
r: radius
a: thermal expansion coef.
l: mixing length
g: gravity

- conduction/convection, spherical symmetry

- Rheologies [Goldsby & Kohlstedt 2001; Karato+ 1986]
  - Liquid water, $\eta_w = 10^{-3}$ Pas
  - Solid ices, $\eta_{ice} = \eta_{ice0} \exp\left[25\left(\frac{T_m}{T} - 1\right)\right]$

$$\eta_{ice0} = 1 \times 10^{15}, 5 \times 10^{17}\ Pas$$

  - Rock, $\eta_{rock} = 4.9 \times 10^8 \exp(23.25 T_m/T)$

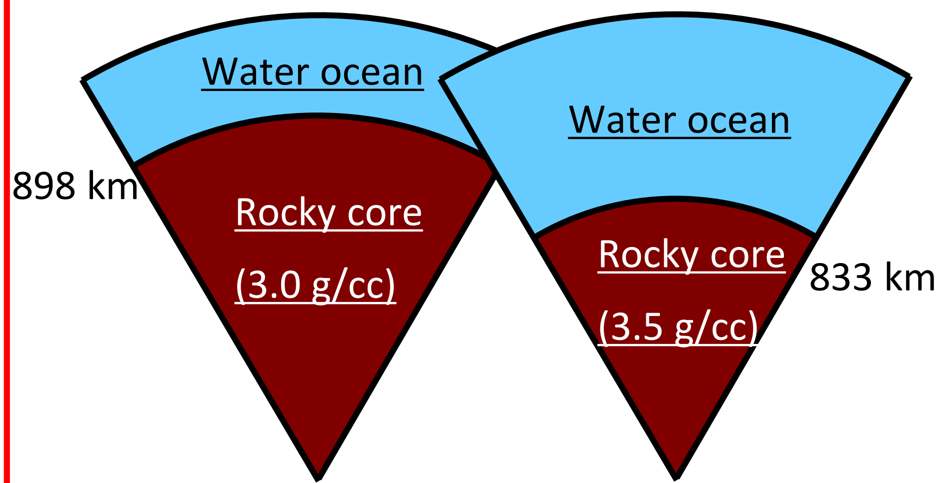
- Heat source
  - U = 12.0 ppb, Th/U = 3.3, K/U = 6.15×10^4

    (Carbonaceous chondritic)

Structural setting and initial state

- Hot (ocean) start

No solid ice shell and vast ocean

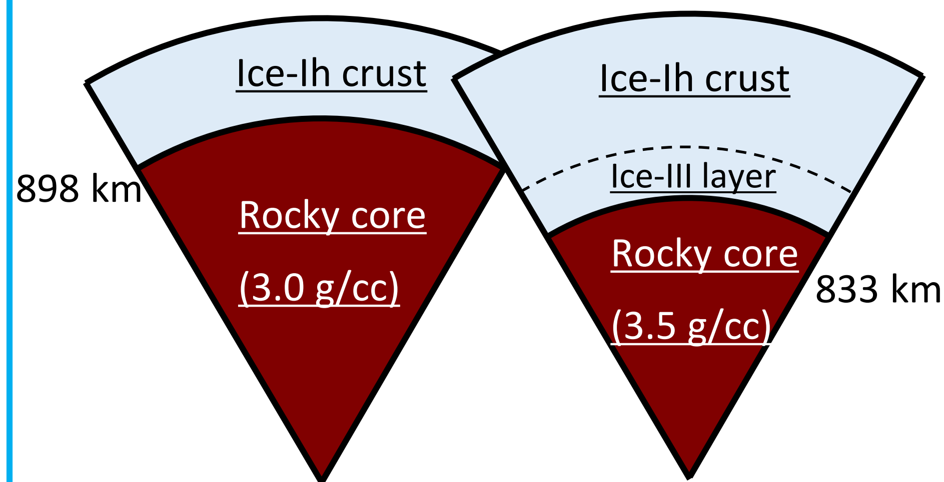


Large core   Small core

- Surface: 273.15 K → 44 K
- Ocean: adiabatic T-grad
- Core: iso-T of the ocean-core boundary

- Cold (icy) start

Initial H_2O layer is entirely frozen

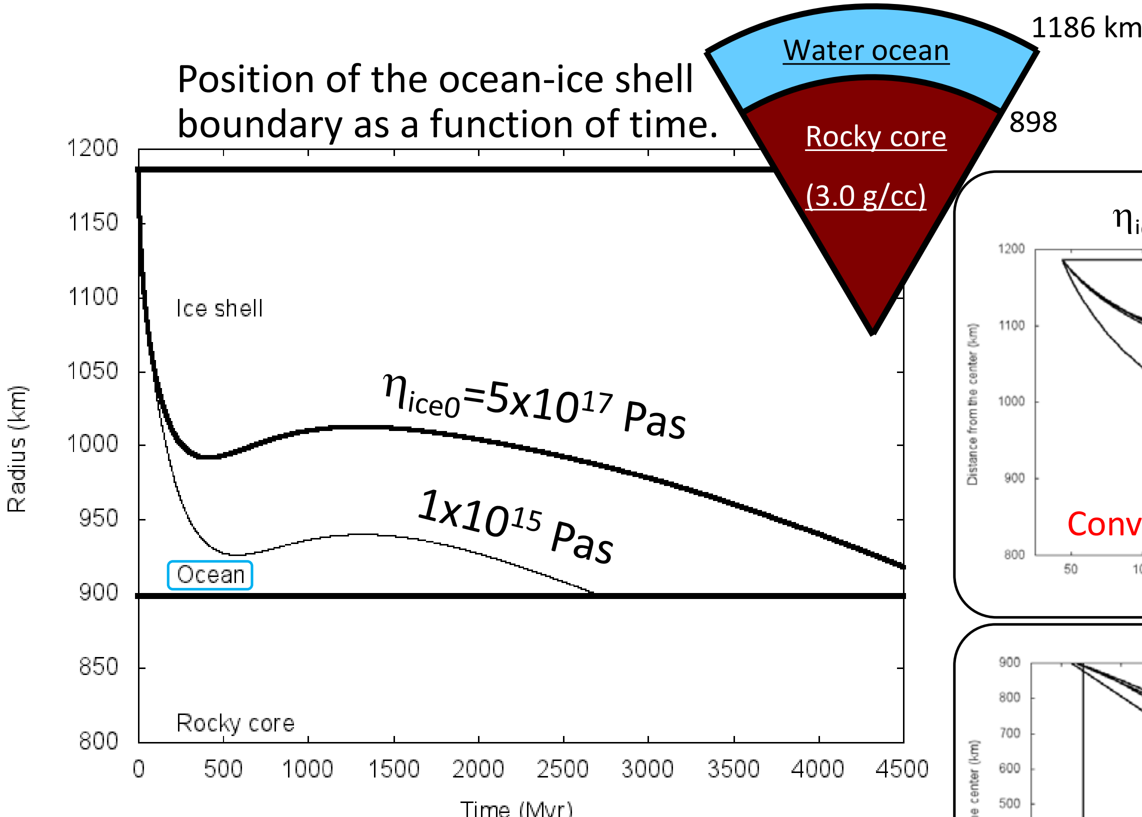


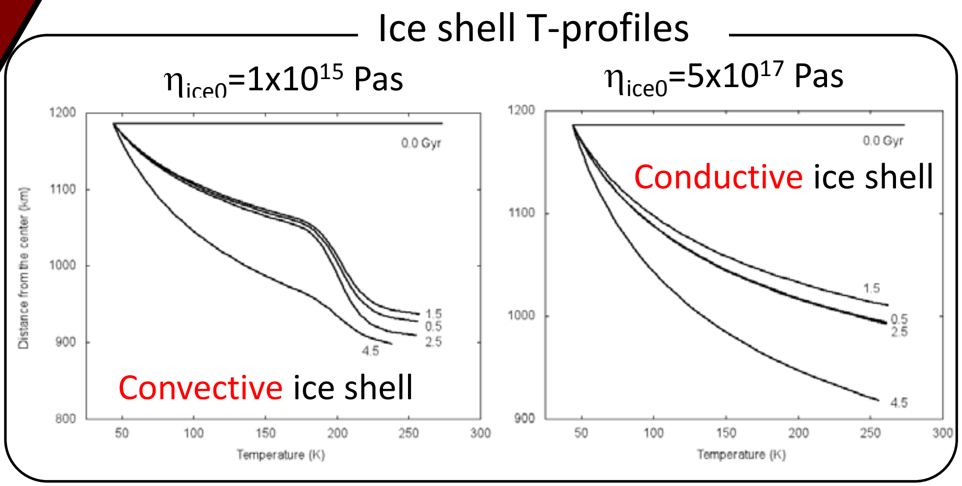
Large core   Small core

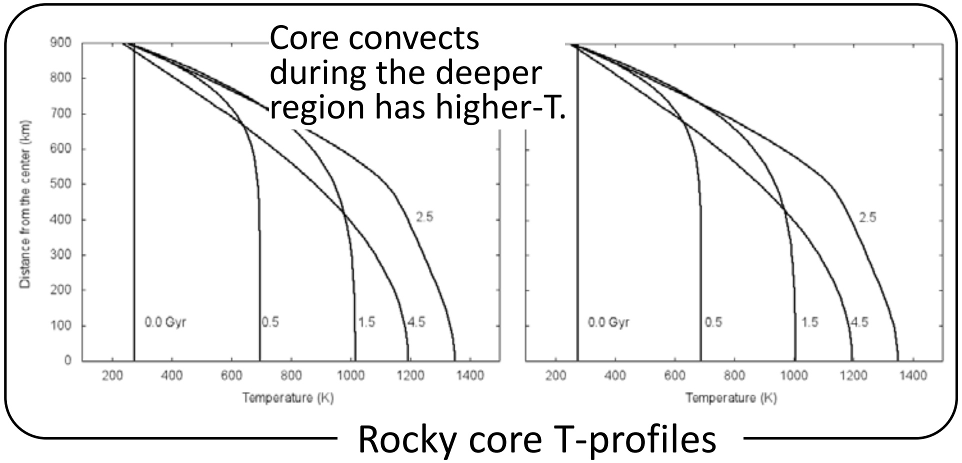
- Surface: 44 K
- Ice: iso-T of 250 K
- Core: iso-T of 250 K

Track the change of boundary position between ocean and ice layer(s) with time.

Results: ocean stability, hot start w/ large core

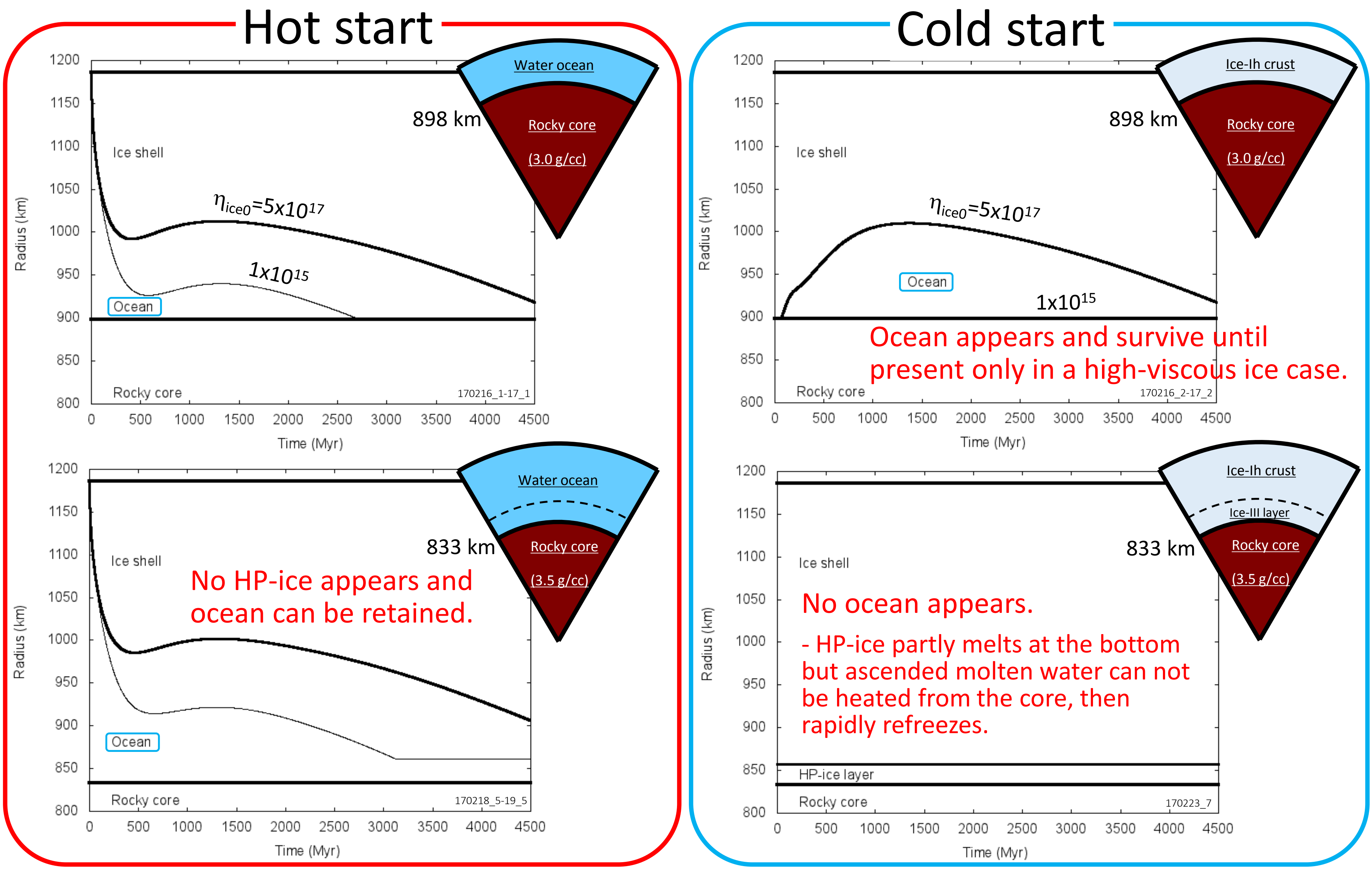




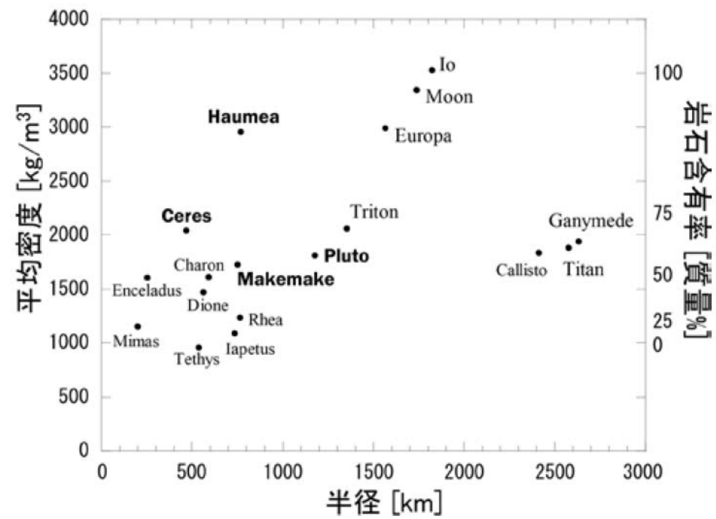


- If the solid ice has (extremely) large viscosity, the ocean can be survived by present.
- In the lower η_{ice0} case, the ocean can be retained until recently, but frozen at present.

CI chondritic heat source



Ice shell viscosity controls stability of subsurface ocean.



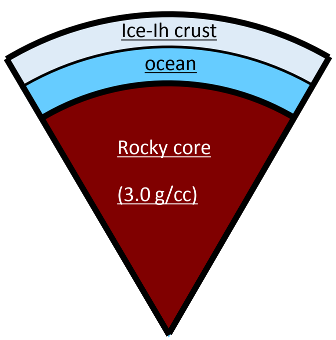
地下海が存在する

➔氷を融点以上に保つ

➔内部に熱を保持する

- たくさん発熱 ・・・ 熱源を多く(岩石量大 or 潮汐変形大)
- 熱を逃げにくく・・・ 冷却率を小さく

氷地殻の粘性率が大きいほど保温性は高い



$$\eta_{ice} = \boxed{\eta_{ice0}} \exp\left[\boxed{A}\left(\frac{T_m}{T} - 1\right)\right]$$

$$\eta_{ice0} = 1 \times 10^{15}, 5 \times 10^{17}\ Pas$$

A = 25

Ice shell viscosity

$$\eta_{ice} = \eta_{ice0} \exp\left[A\left(\frac{T_m}{T} - 1\right)\right]$$

- 氷地殻の粘性率が大きいほど保温性は高い

For $d_0 = 0.1$ to 1 mm,
$\eta_{ice0} = 10^{13-15}$Pas

$\eta_{ice0} = \eta(d_0, T_m)$, $A = Q_V / RT_m$

* Stress-strain rate relationship

$$\eta = \frac{1}{3^{\frac{n+1}{2}}} \frac{\sigma}{\dot{\varepsilon}}$$

* Diffusion creep = volume diffusion creep
(n=1)
+ grain boundary diffusion creep

$$\dot{\varepsilon} = \frac{42 V_m \sigma}{3RTd^2}\left(D_V + \frac{\pi\delta}{d} D_b\right)$$

$$D_V = D_{0,V} \exp(-Q_V/RT)$$

$$D_b = D_{0,b} \exp(-Q_b/RT)$$

$$\delta = 2b$$

$$\eta = \frac{RTd^2}{42 V_m D_{0,V}} \exp\left(\frac{Q_V}{RT}\right)$$

σ : stress	d : grain size
ε : strain rate	D_V : Vol. diffusion const.
V_m: molar vol.	Q_V : Vol. diffusion activation energy
R : gas const.	T_m : melting point

(by analogy with terrestrial ice sheets)
For reasonable grain sizes ~0.1 to 1 mm, the diffusion creep is overwhelmingly dominated by the vol. diffusion.

Ice shell viscosity

$$\eta_{ice} = \boxed{\eta_{ice0}} \exp\left[\boxed{A}\left(\frac{T_m}{T} - 1\right)\right]$$

- 氷地殻の粘性率はどうすれば決まるか

$$\eta_{ice0} = \frac{RT_m d_0^2}{42 V_m D_{0,V}} \exp\left(\frac{Q_V}{RT_m}\right)$$

σ : stress
ε : strain rate
V_m: molar vol.
R : gas const.
d : grain size
D_V : Vol. diffusion const.
Q_V : Vol. diffusion activation energy
T_m : melting point

For reasonable grain sizes d_0 = 0.1 to 1 mm, $\eta_{ice0} = 10^{13-15}$Pas.

For Pluto’s case and $\eta_{ice0} = 5 \times 10^{17}$Pas, d_0 ~ 20 mm

融点に近くても，数cm粒径はなかなか・・・

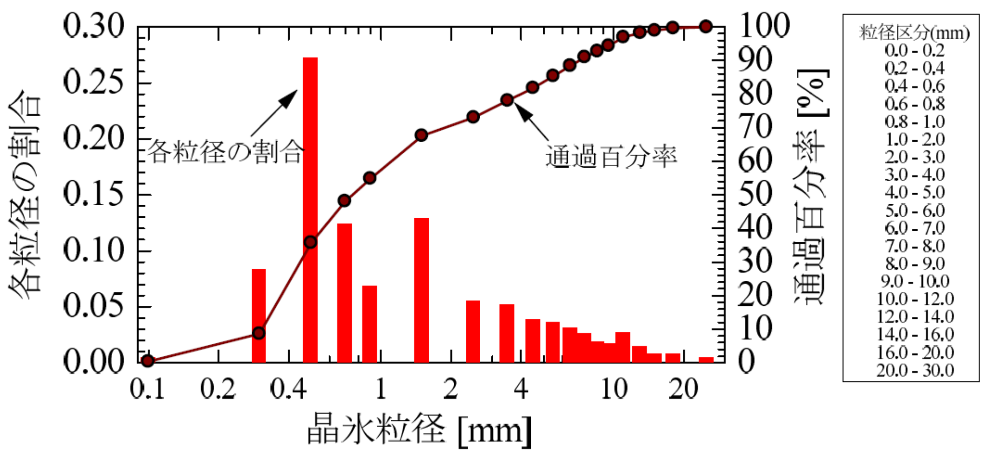
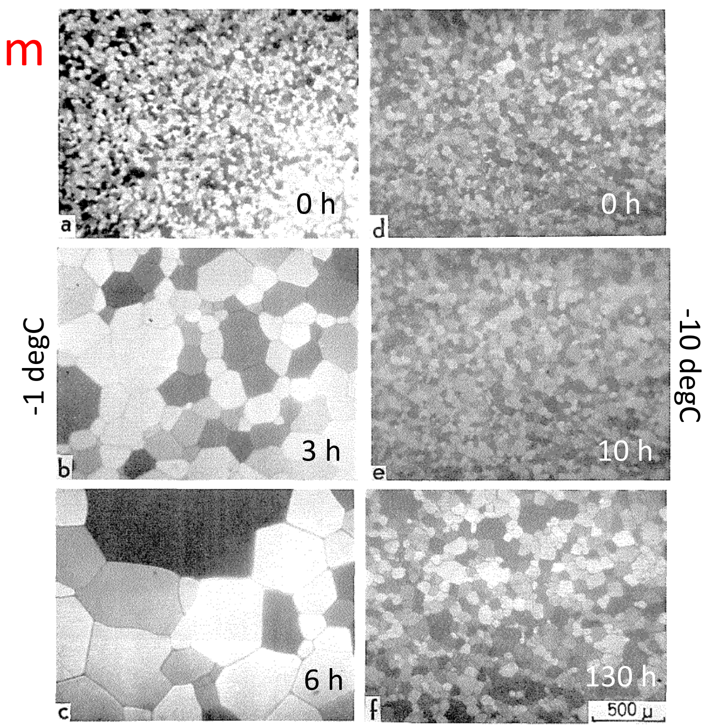


図-8 晶氷粒径の度数分布と加積曲線

吉川ら，土木学会論文集B1, 69 (2013).



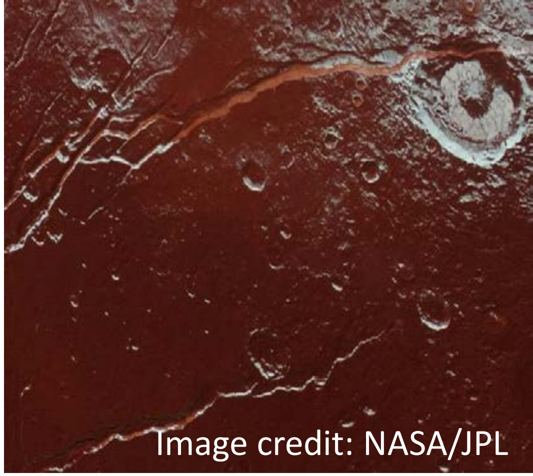
第2図　純氷の微結晶の粗大化

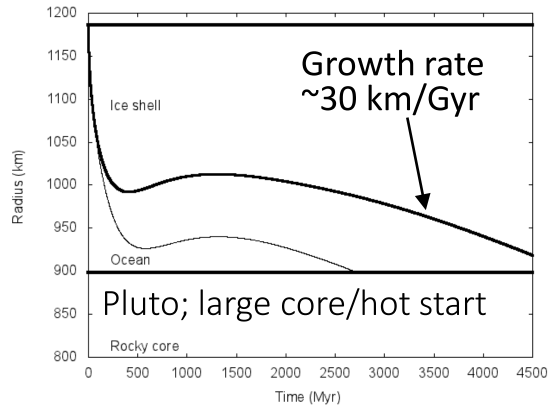
鈴木，低温科学, 27 (1970).

Discussion 1: Extensional tectonics

- Volume increase (e.g., from liq H_2O to ice-Ih) (Ice shell growth)
- Viscoelastic stress model for Europa
  - ex.) Ice shell growth at ~8 km/Gyr generates 1 MPa surface tensile stress for 0.5 Gyr [Kimura+, 2007]
  - Pluto's shell growth ~30 km/Gyr

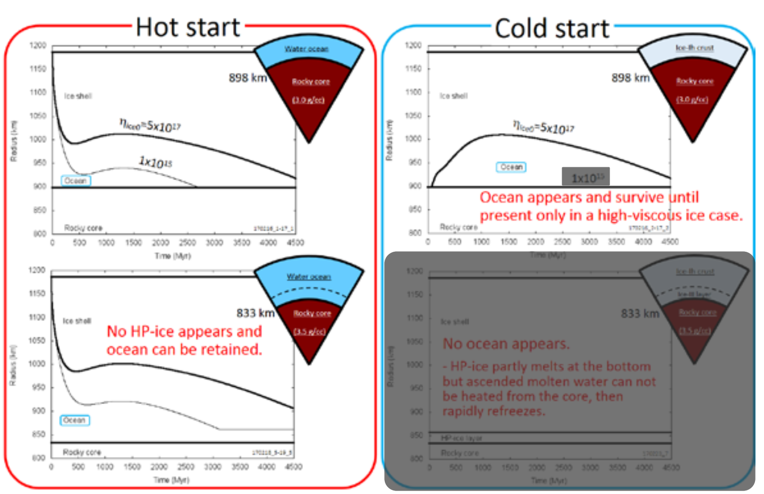
    → Sufficient stress could be generated.



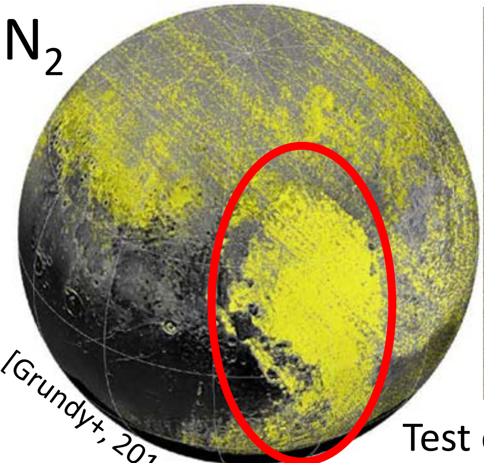


- No shell growth (no ocean appears) case can be ruled out.

- More precise estimation of tectonic age, better constraint to the interior evolution.



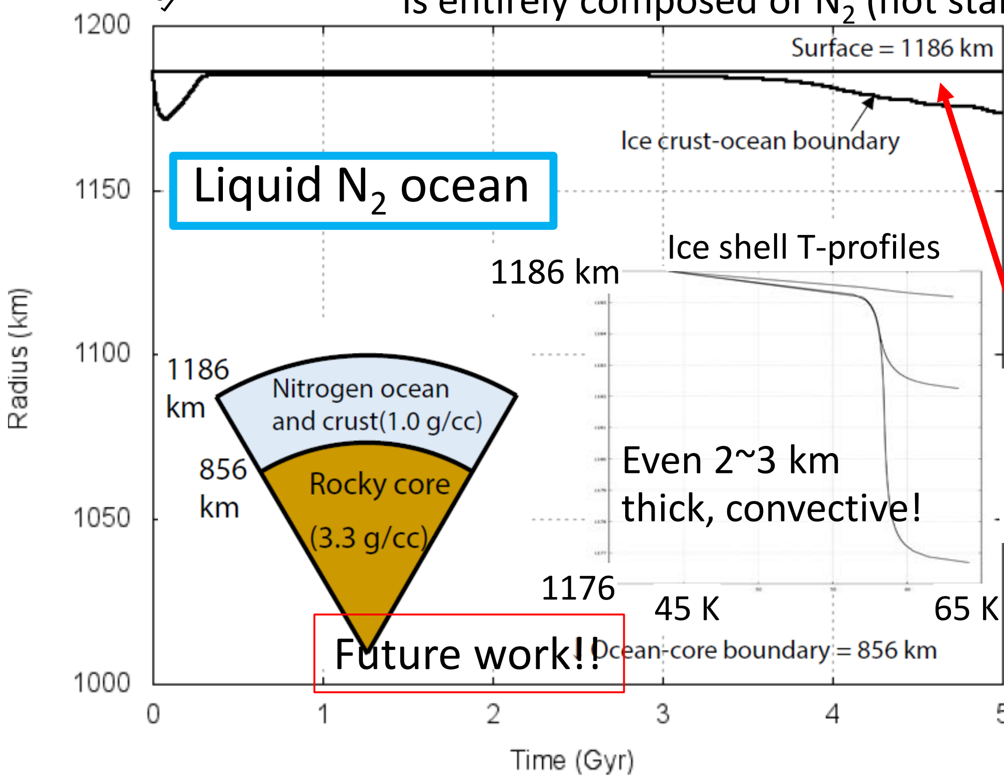
Discussion 2; Nitrogen contribution



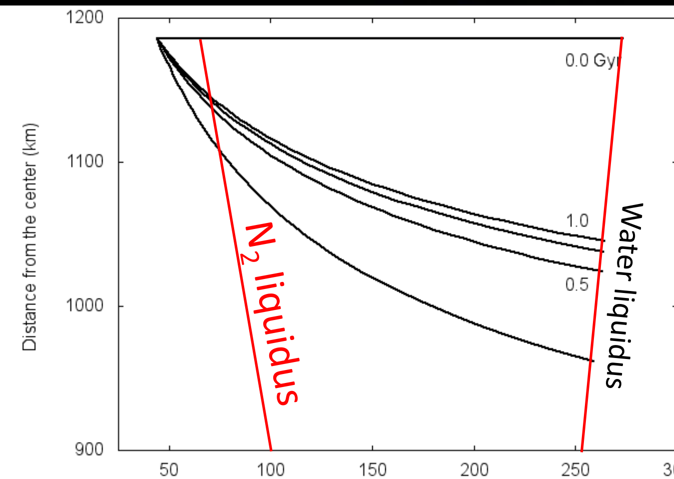
[Grundy+, 2016]

Smooth N_2 ice landscape showing polygons could be evidence of convection.

Test calculation assuming surficial layer is entirely composed of N_2 (hot start).



Future work!!



Huge N_2 ocean under the ~12 km thick solid convective N_2 shell exists at present.

$$\eta_{ice} = \eta_0 \exp\left[A\left(\frac{T_m}{T} - 1\right)\right]$$

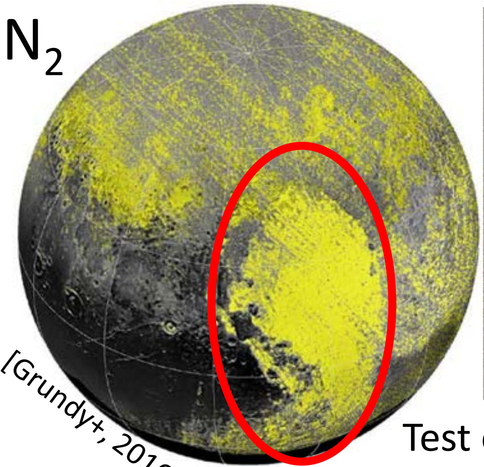
η_0 = 8.8x10^{10} (Pas), A=24.9, T_m=63.15 (K)

[Brown & Kirk, 1994]

Low melting point and viscosity.

Discussion 2; Nitrogen contribution

N_2



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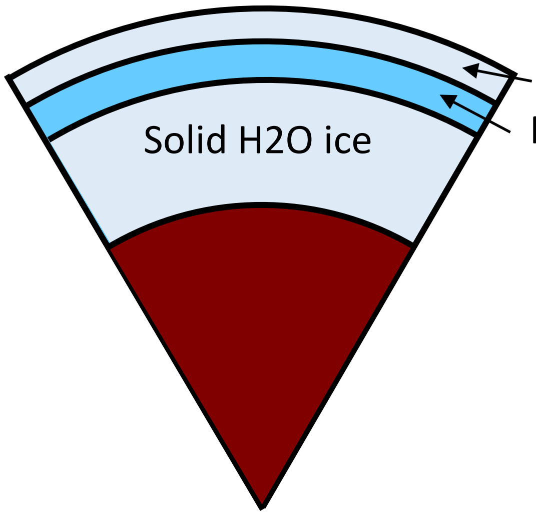

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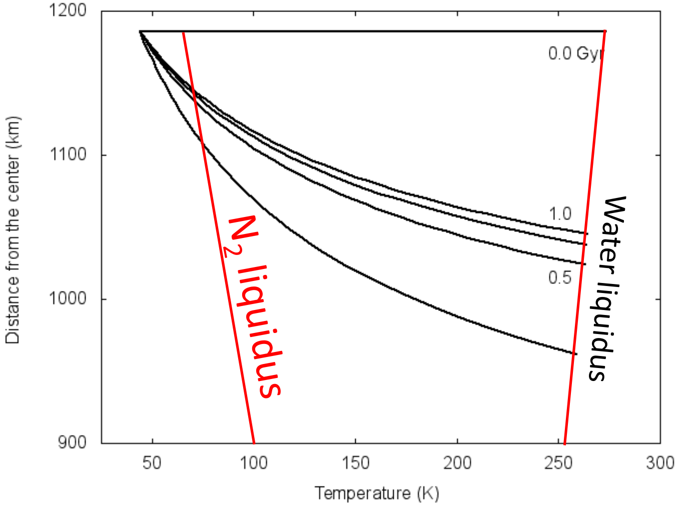

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$\eta_0 = 8.8 \times 10^{10}$ (Pas), A=24.9, T_m=63.15 (K)

[Brown & Kirk, 1994]

Low melting point and viscosity.

Summary

- We investigated stability of the ocean of Pluto using a thermal/structural evolution model.
- In a large core/thin water shell model (only ice Ih appears case), the ocean should be present if the ice has large viscosity (reference visc. $> 10^{17}$ Pas).
- In a small core/thick water shell model, the ocean should be present if the ocean presents from initial.
- If the initial Pluto was entirely frozen and HP ice covered the core, no ocean appears. It should be ruled out in terms of extensional tectonics.