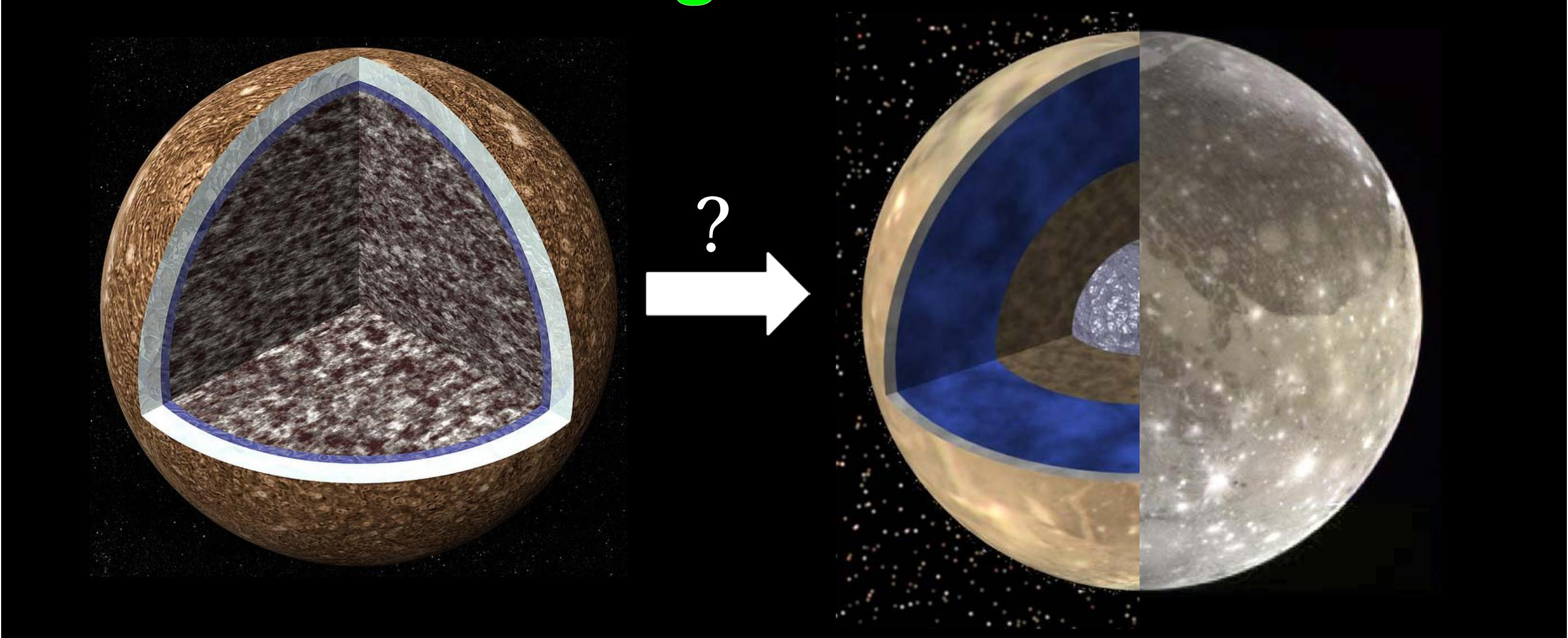
Dehydration of primordial hydrous rock in Ganymede: Formation of the conductive core and the grooved terrain



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Abstract

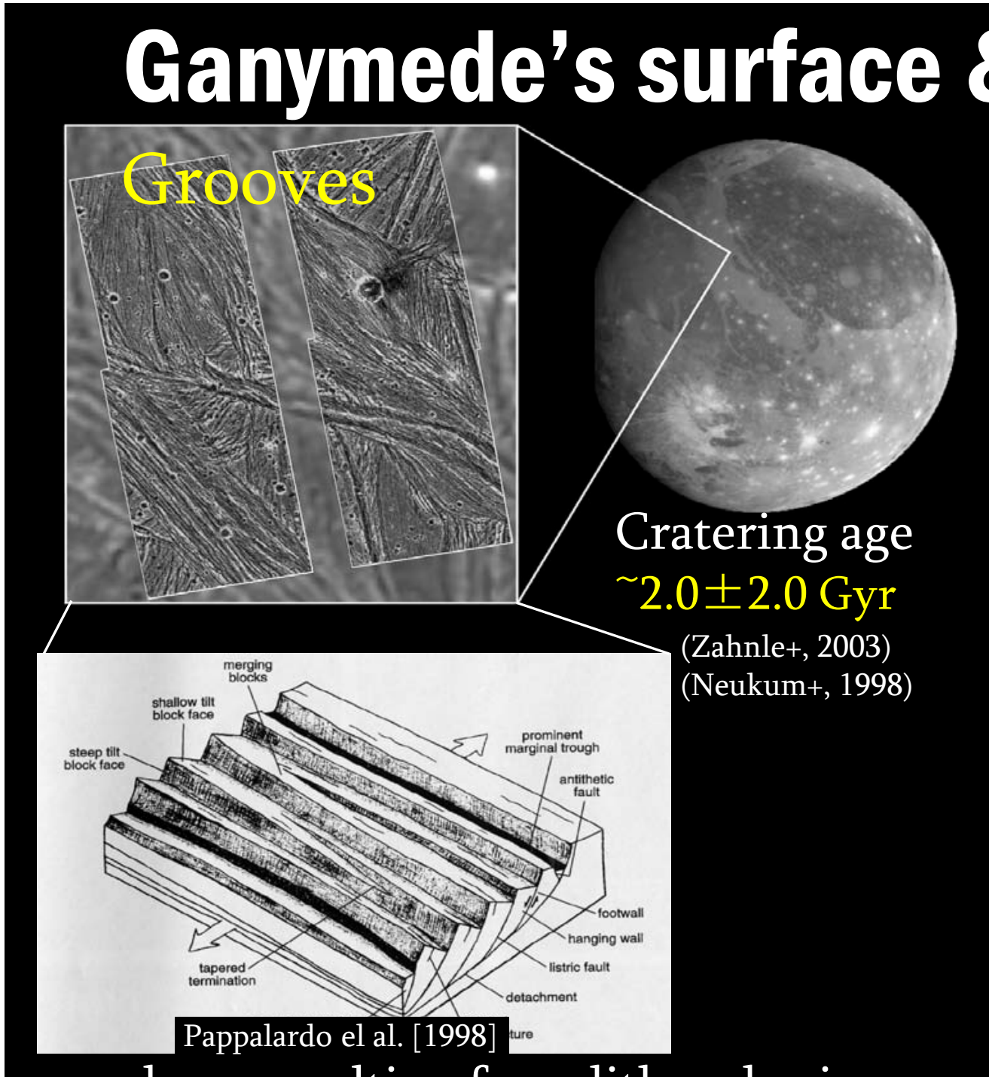
We propose a new hypothesis for the formation of the conductive core and the surface grooved terrains on Ganymede.

Numerical simulations for the interior thermal history are performed assuming that the primordial rocky core was initially hydrated. The primordial core is heated by the decay of long-lived radiogenic isotopes and becomes dehydrated if the temperature exceeds ~900 K. The volume expansion accompanying the dehydration is possibly enough large for the formation of the observed grooved terrains on Ganymede.

Dehydration also results in the sharp viscosity increase, and the central temperature possibly exceeds the eutectic point of troilite and iron oxide, allowing the formation of a conductive core. Given the reasonable silicate fraction (~45-52 wt %), Ganymede's interior can form a conductive core while slightly smaller Callisto can escape from sufficient heating for melting the conductive material.

This may explain the observed dichotomy in the surface geology and internal structure between the both giant icy satellites.

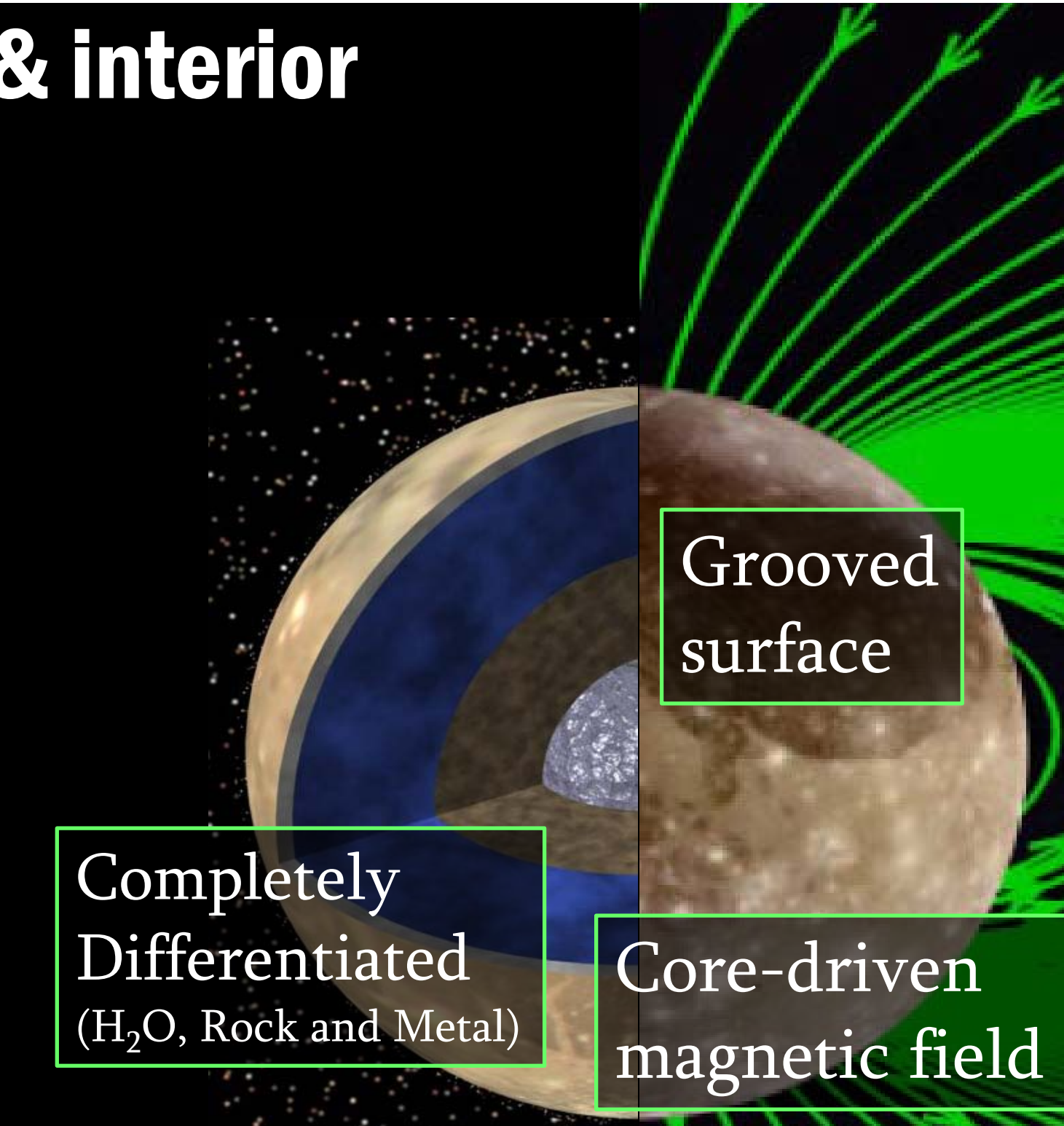
Ganymede's surface & interior



Pappalardo el al. [1998]

Cratering age
~2.0±2.0 Gyr
(Zahnle+, 2003)
(Neukum+, 1998)

- grabens resulting from lithospheric extension (global expansion).



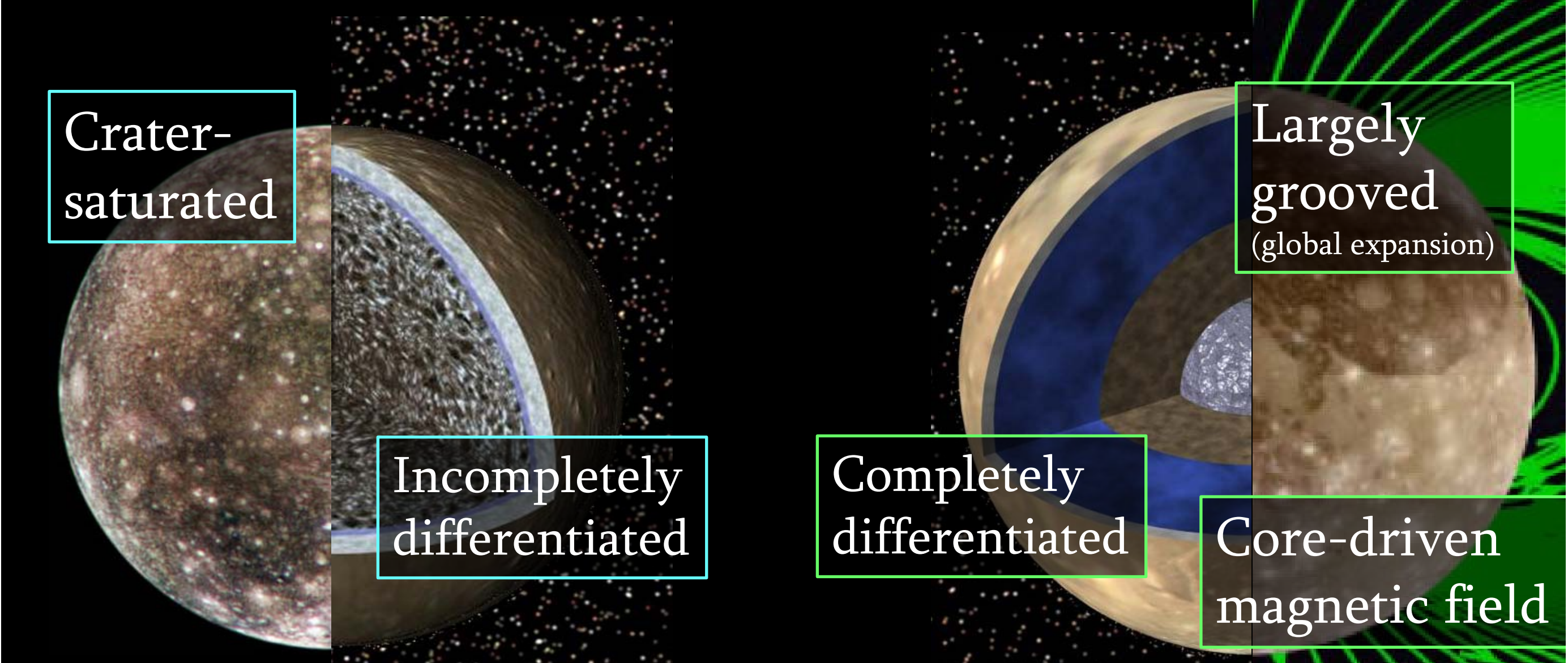
Grooved surface

Completely Differentiated
(H_2O, Rock and Metal)

Core-driven magnetic field

Internal heating allows the formation of a conductive core and global expansion during Ganymede's history. But their mechanisms still remain an open question.

Contrasting surface and interior between Callisto and Ganymede



Crater-saturated

Incompletely differentiated

Largely grooved
(global expansion)

Completely differentiated

Core-driven magnetic field

Focused points
- the metallic core formation
- the tectonic activity (global expansion)

} must be induced only on Ganymede

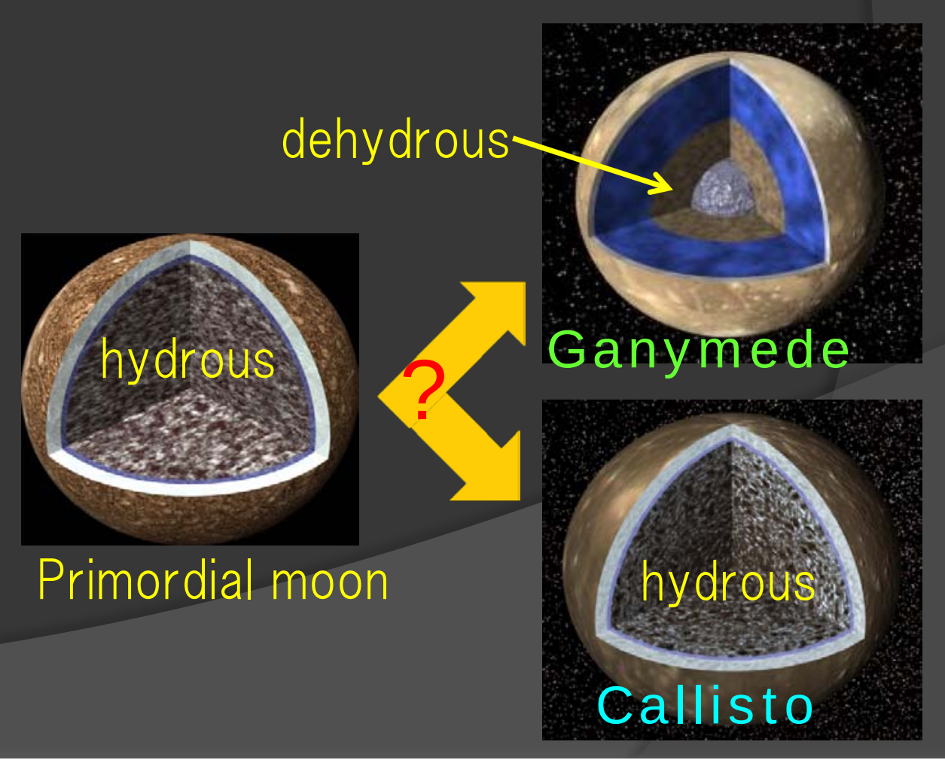
Origin for the formation of a conductive core and grooves of Ganymede still remain an open question.

- Previous works investigate the origin of surface/interior dichotomy between Ganymede and Callisto due to differences in,,,
  - accretional process (e.g., Lunine & Stevenson, 1982; Stevenson+, 1986; Mosqueira & Estrada, 2003) — - Too early to explain the grooves.
  - material property (Friedson & Stevenson, 1983) — - No considering to form the metallic core.
  - orbital history (Showman+, 1999; Bland+, 2009) — - Induced expansion is well short of the min. value of geologic estimate.
  - impact energy during LHB (Barr and Canup, 2010) — - Too early to explain the grooves.
- Thermal history of the core to be capable of the magnetic field generation in Ganymede (Hauck+, 2006; Kimura+, 2009) — - Assuming that the core has formed just after the end of Ganymede's accretion.

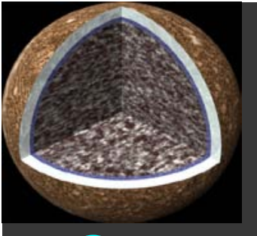
New viewpoint in this work: Dehydration of primordial hydrous rock.
→ Trying to explain both events of the formation of the conductive metallic core and the tectonics (global expansion) only on Ganymede in relatively young age.

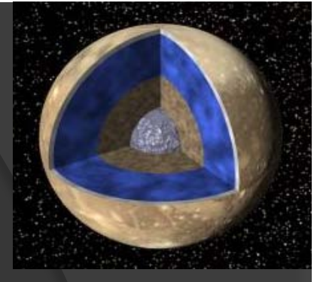
Aims of this work

- We numerically investigate the contribution of de-hydration of primordial hydrous rock on the evolution of the large icy moon(s).
  - Trying to explain both events of the formation of the conductive metallic core and the tectonics (global expansion) only on Ganymede in relatively young age.
  - Subsequent evolution of the primordial moon can be diverged to Ganymede and Callisto because of a small difference of size and mass?



Dehydration of hydrous rock





- Assuming that silicate rock will be initially hydrated.
  - similarity in reflectance spectra among hydrated carbonaceous chondrites and asteroids near Jovian orbit (e.g., Cruikshank+, 2001; Rivkin+, 2002, Karlsson+, 2009).
  - Deformation experiment of Serpentine: (Hilairet+, 2007)
    - @1 and 4 GPa, 200~500 deg C
    - Strain rate 10^{-6}~10^{-4} /s
  - Viscosity ~ 4×10^{19} Pas@10^{-13} /s (with small temperature dependency)

$$\eta_{eff} = A\dot{\varepsilon}^{-0.74}\exp\left(\frac{3.8\times10^{2}}{T}\right)$$

- Dehydration at 880 ~ 950 K (with small pressure dependency) (e.g., Song+, 1996; Escartin+, 1997)
  - Rock rheology drastically changes through dehydration.
  - Reaction (endothermic) heat ~4×10^{5} J/kg (Weber+, 1965).

Framework of the numerical simulation

1-D Model for thermal history

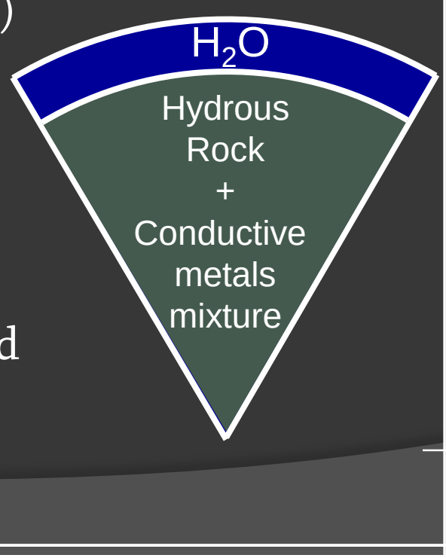
$$\rho c_p \frac{\partial T}{\partial t} = \nabla\cdot\left(F_{cond}+F_{conv}\right)+\rho Q$$

$$F_{cond} = k_c \nabla T \qquad F_{conv} = k_v\left(\nabla T - \nabla_{ad} T\right)$$

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

(e.g., Sasaki & Nakazawa, 1986; Abe, 1997; Kimura+, 2009)

- Phase change in the (pure) H_2O layer is considered.
- Ts = 100 K
- Initial T-profile:
  - H_2O shell is whole liquid with adiabatic T-grad.
  - H_2O ice solidus in the mixed-core.



Heat sources

- Radiogenic heating
  U: 12 ppb
  Th/U = 3.3, K/U = 7×10^{4}
  (e.g., Schubert+, 1986)
- no tidal heating
- dehydration heat = 4×10^{5} J/kg

Rheology

- Water ice

$$\eta_i = 10^{15}\exp\left[25\left(T_m/T-1\right)\right]$$

- Hydrous rock

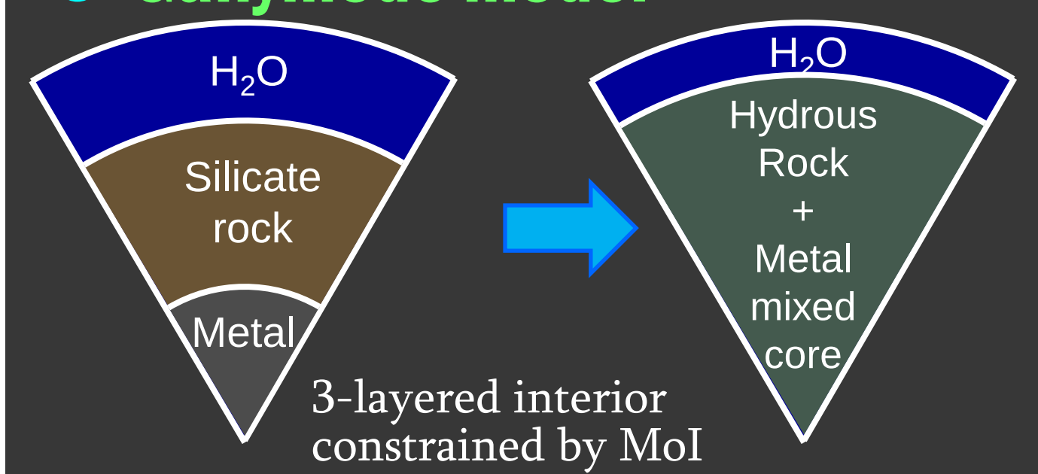
$$\eta_{hyde} = \left(4.0\times10^{19}\right)\exp\left(3.8\times10^{2}/T\right)$$

-> dehydrated (T>900 K)

$$\eta_{dehy} = 4.9\times10^{8}\exp\left(23.25T_m/T\right)$$

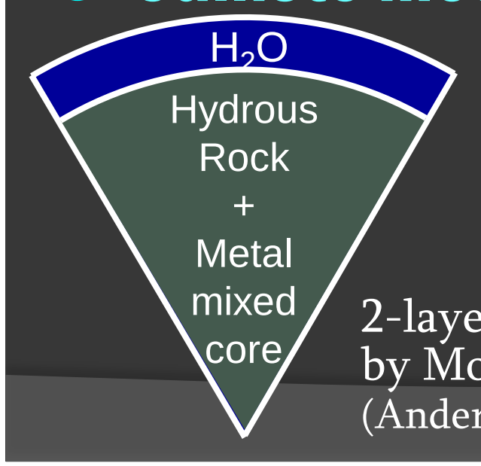
Structural settings

Ganymede model



3-layered interior constrained by MoI and bulk density (Anderson+, 1998)

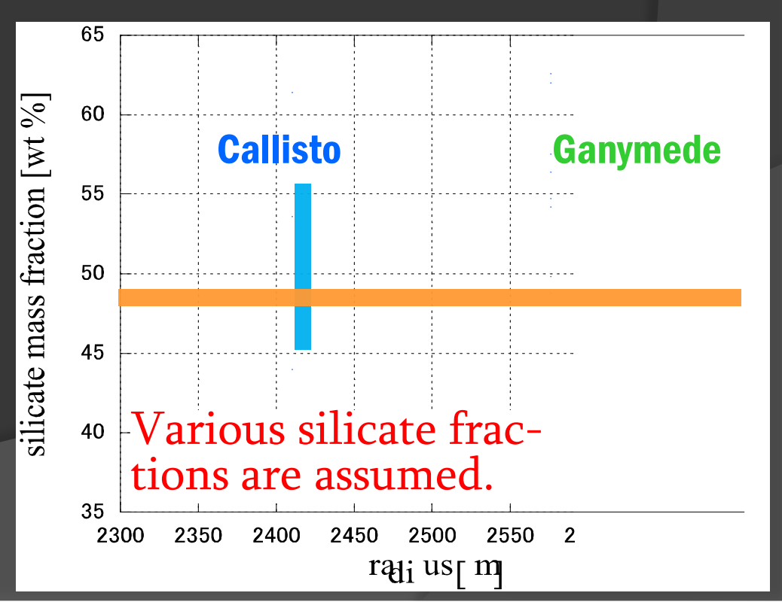
Callisto model



2-layered interior constrained by MoI and bulk density (Anderson+, 2001)

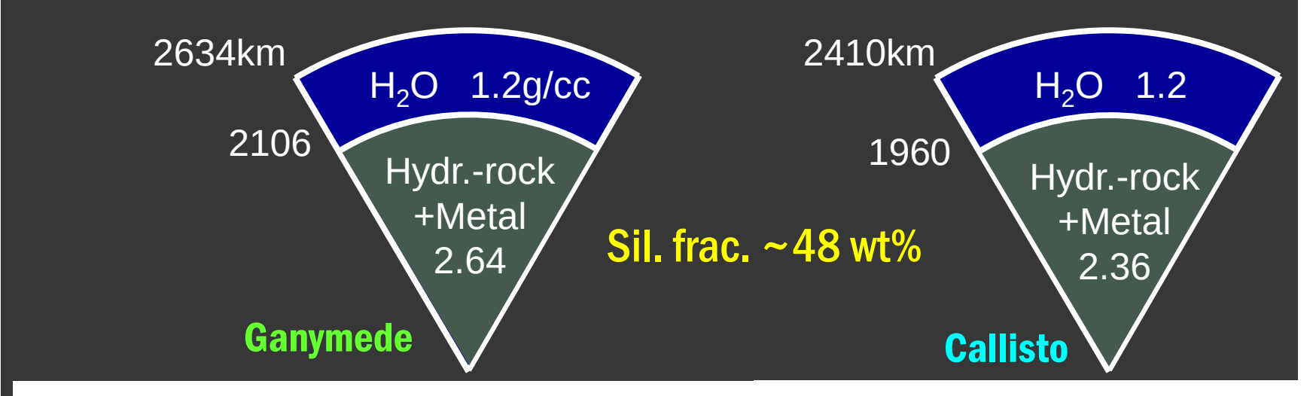
Parameters

Densities
- H_2O : 1200 kg/m^3
- Silicate : 3000-4000 kg/m^3
- Conductive Metal (e.g., FeS, Fe_3O_4) : 5150 kg/m^3

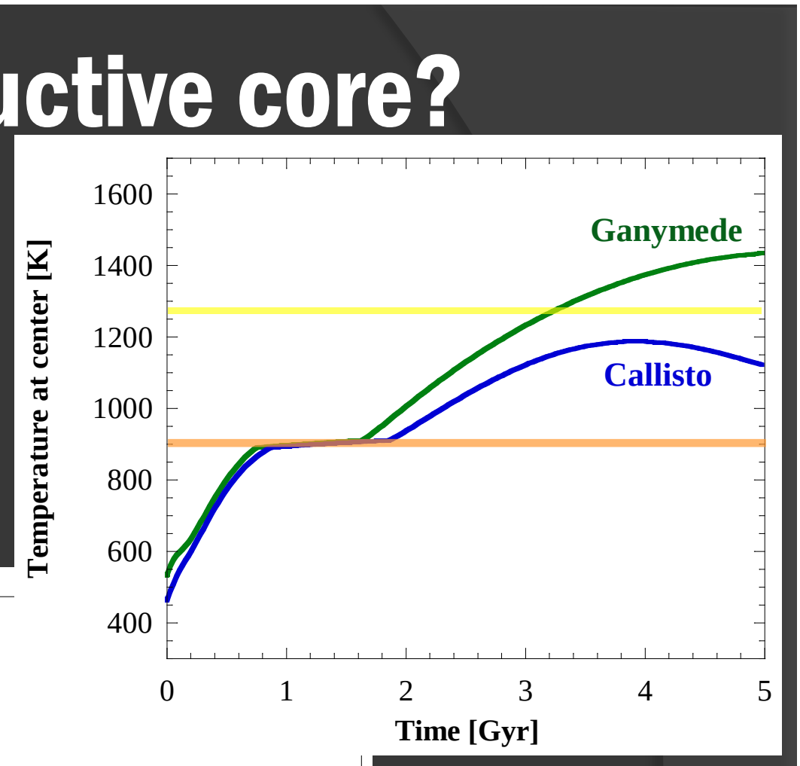


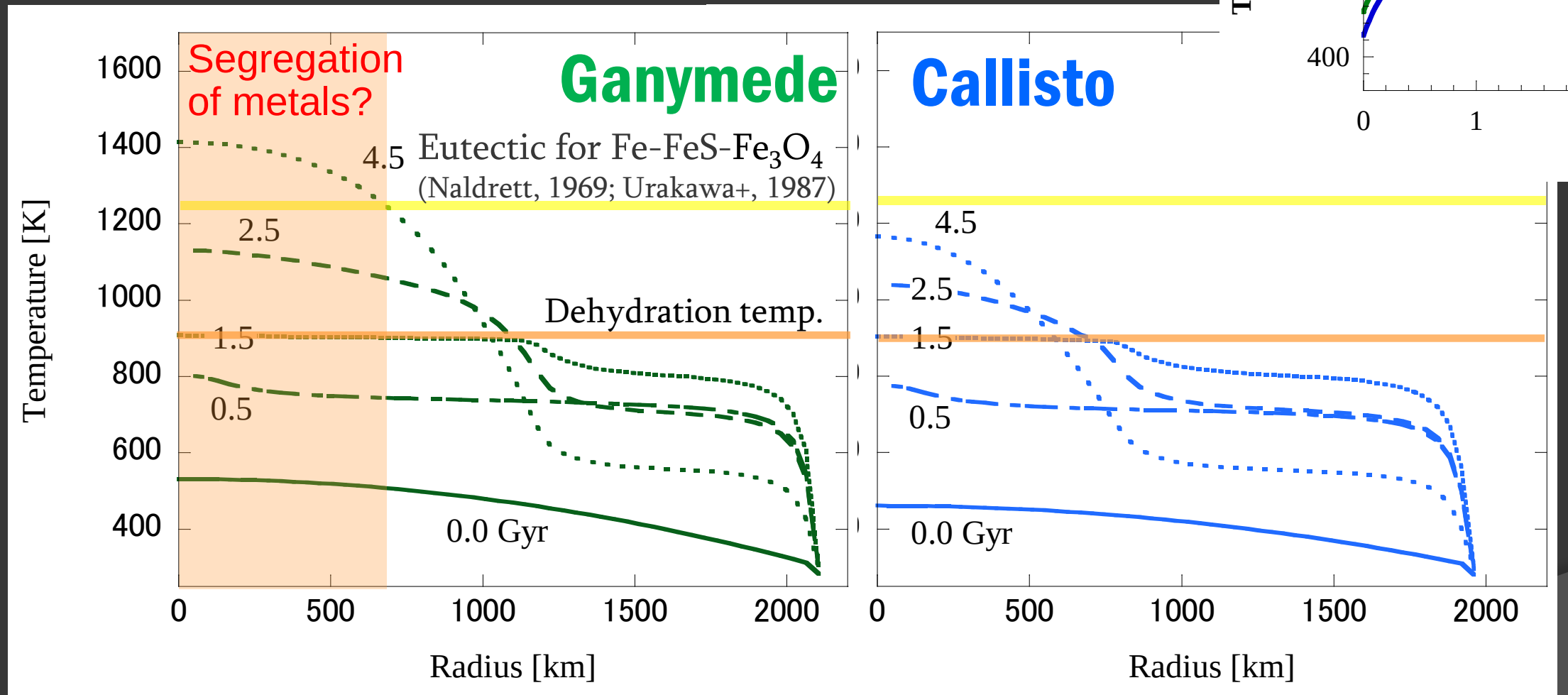
Various silicate fractions are assumed.

Result: Formation of the conductive core?



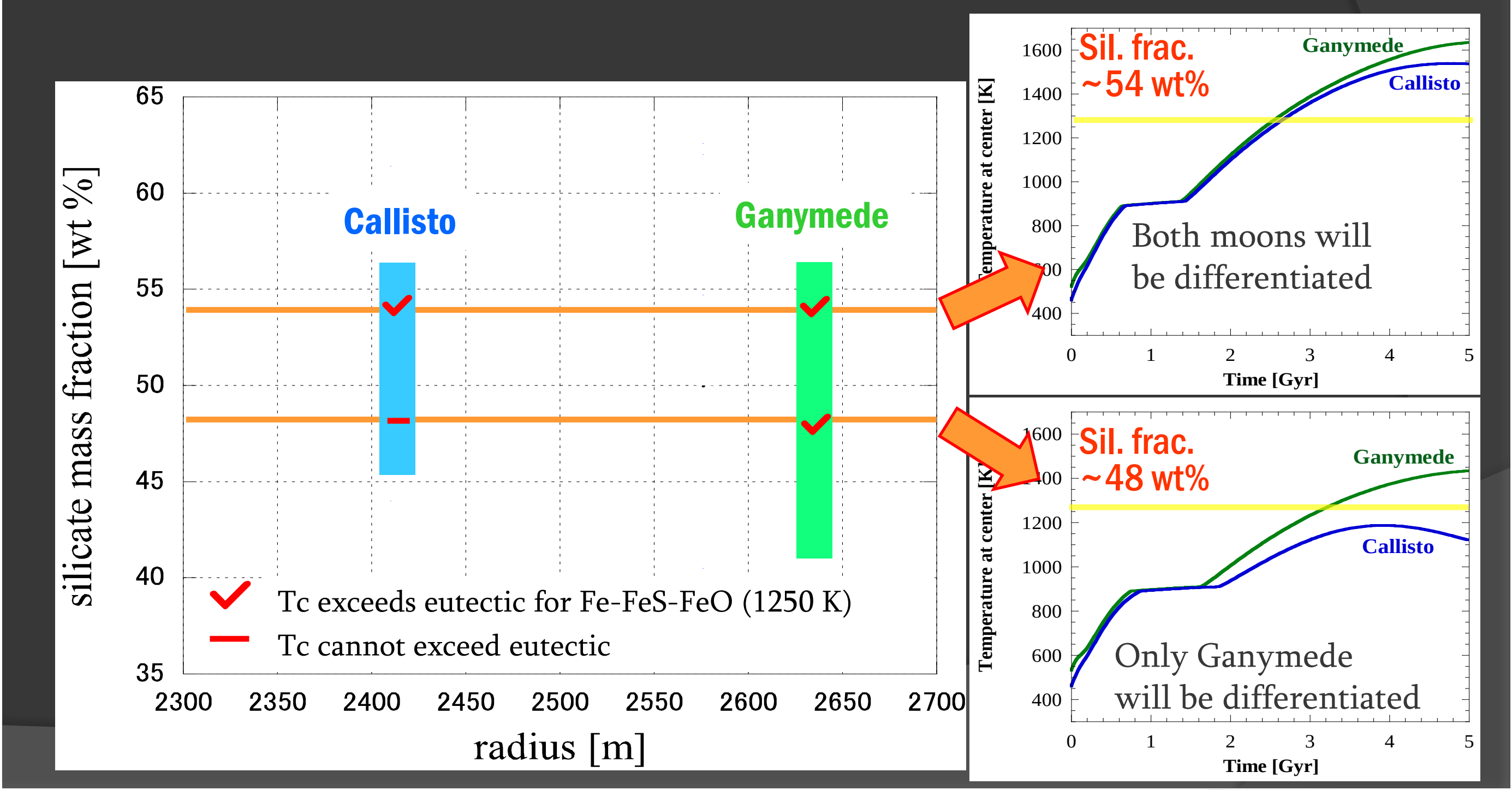
Sil. frac. ~48 wt%





- implying the formation of a conductive core only in Ganymede, an contrasting interior with Callisto

Systematic simulations with various silicate fractions

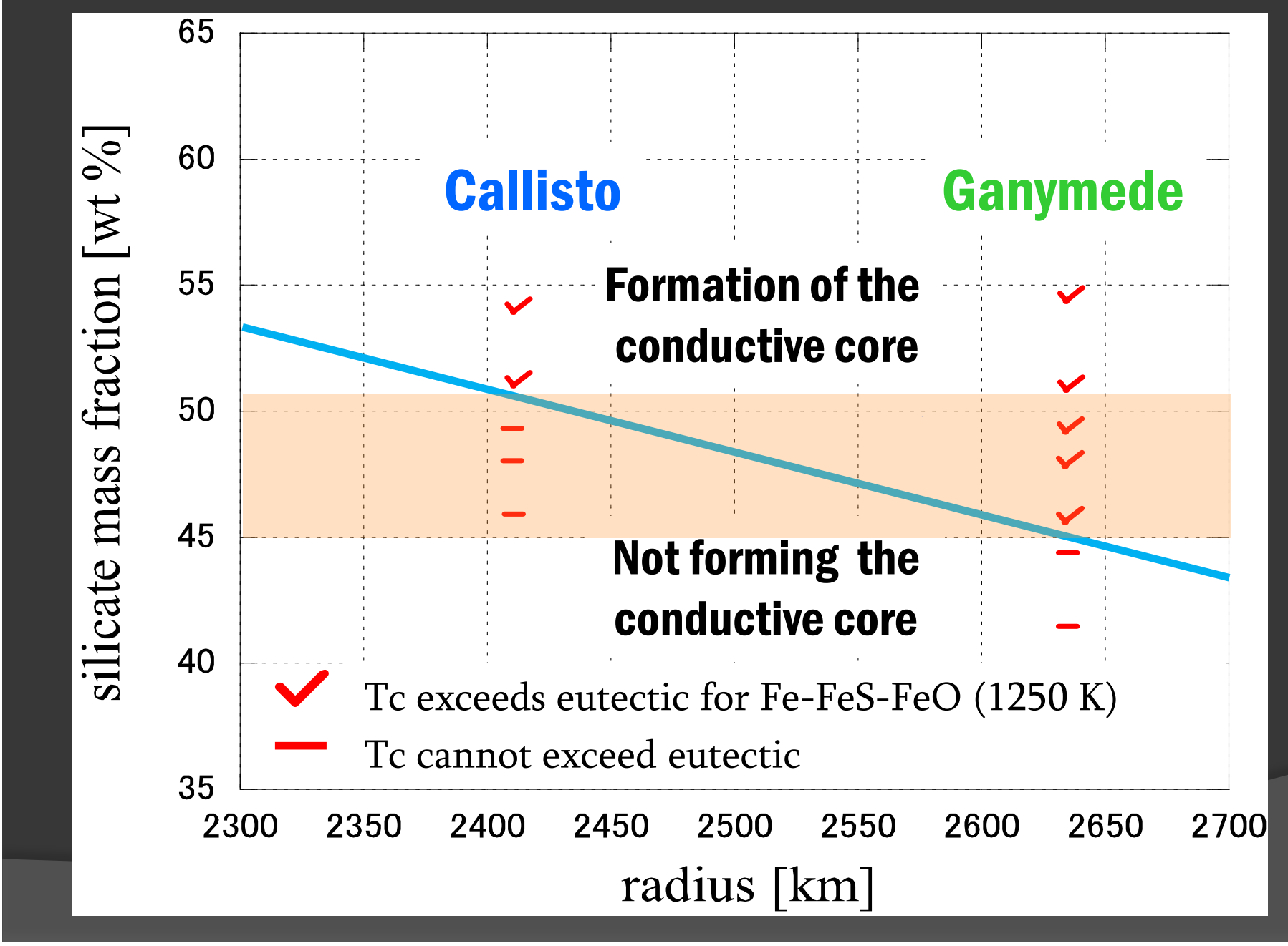


Both moons will be differentiated

Only Ganymede will be differentiated

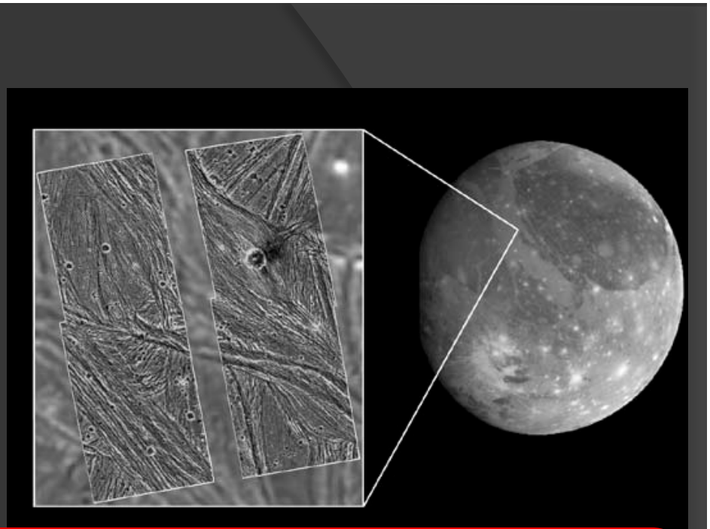
Contrasting interior with Callisto
- Structural regime that is capable of differentiation -

Specific range for the silicate fractions, that is capable of conductive core differentiating

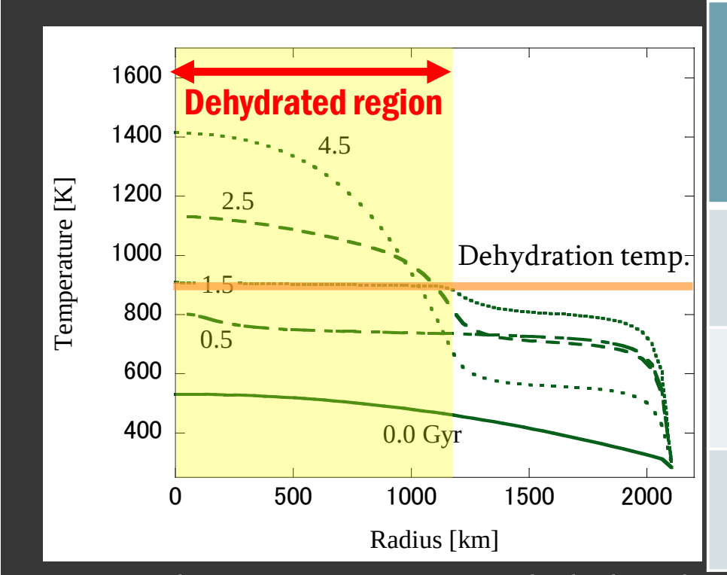


- Smaller moon needs larger silicate fraction to make it possible to form the conductive metallic core.
- For intermediate value of the silicate fraction (45-52 wt%), Ganymede can differentiate, while Callisto cannot.

Result: Formation of the surface extensional tectonics?

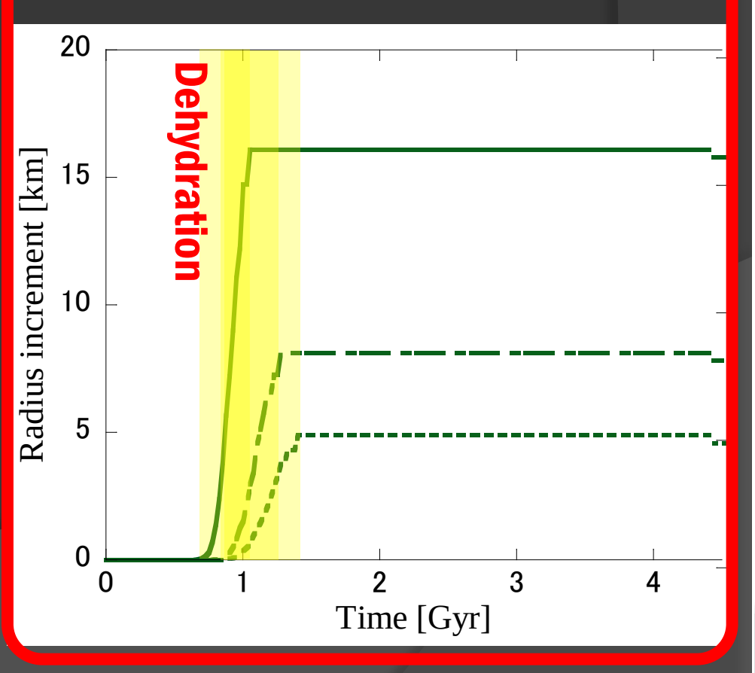


- Grooves on Ganymede - grabens resulting from lithspheric extension (global expansion).
- Required radius increase of 0.02-4 % (Golombek 1982, Collins+, 2008).
- Dehydration experiment - 10.3 vl% increase (Kono+, 2007).



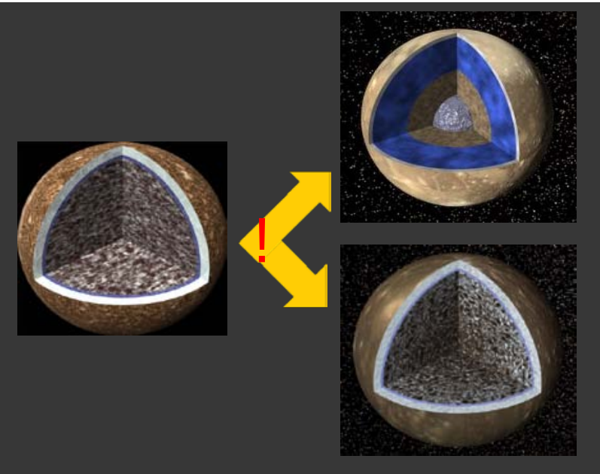
Dehydrated radius in the primordial core	Radius increase (ratio to the moon's radius)
1482 km (f_{sil}~54 %)	16.1 km (0.61 %)
1179 km (f_{sil}~48 %)	8.1 km (0.31 %)
995 km (f_{sil}~46 %)	4.9 km (0.19 %)

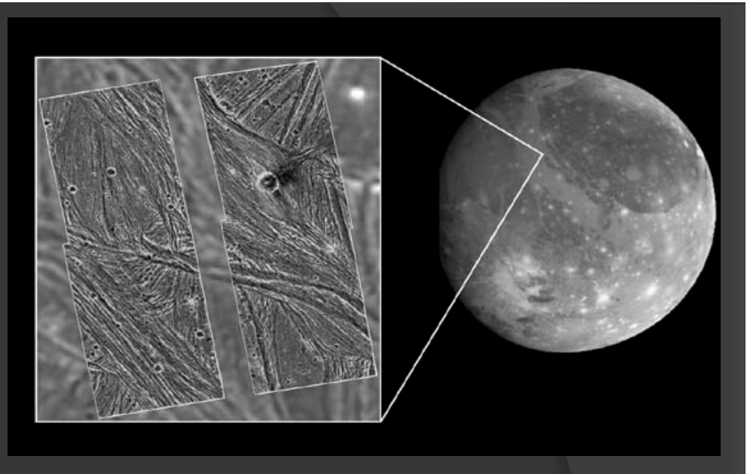
Cratering age:
~3.6Gyr? (Neukum+ 1998)
~2.0Gyr? (Zahnle+ 2003)



- Radius increase and dehydration age are consistent with the previous geological estimate and the cratering age, implying the dehydration of the primordial core in Ganymede has created the surface grooved terrain after LHB.

Summary





- Numerical simulations for the internal thermal history considering with the primordial hydrous core and its dehydration are performed.
- Dehydration results in the sharp viscosity increase, and the central temperature possibly exceeds the eutectic point of conductive materials, allowing the formation of a conductive core. And accompanying volume expansion is possibly enough large for the formation of the grooved terrains on Ganymede.
- This may explain the observed dichotomy in the surface geology and internal structure between the both giant icy satellites.