衛星系形成小研究会

衛星内部構造進化

Jun Kimura

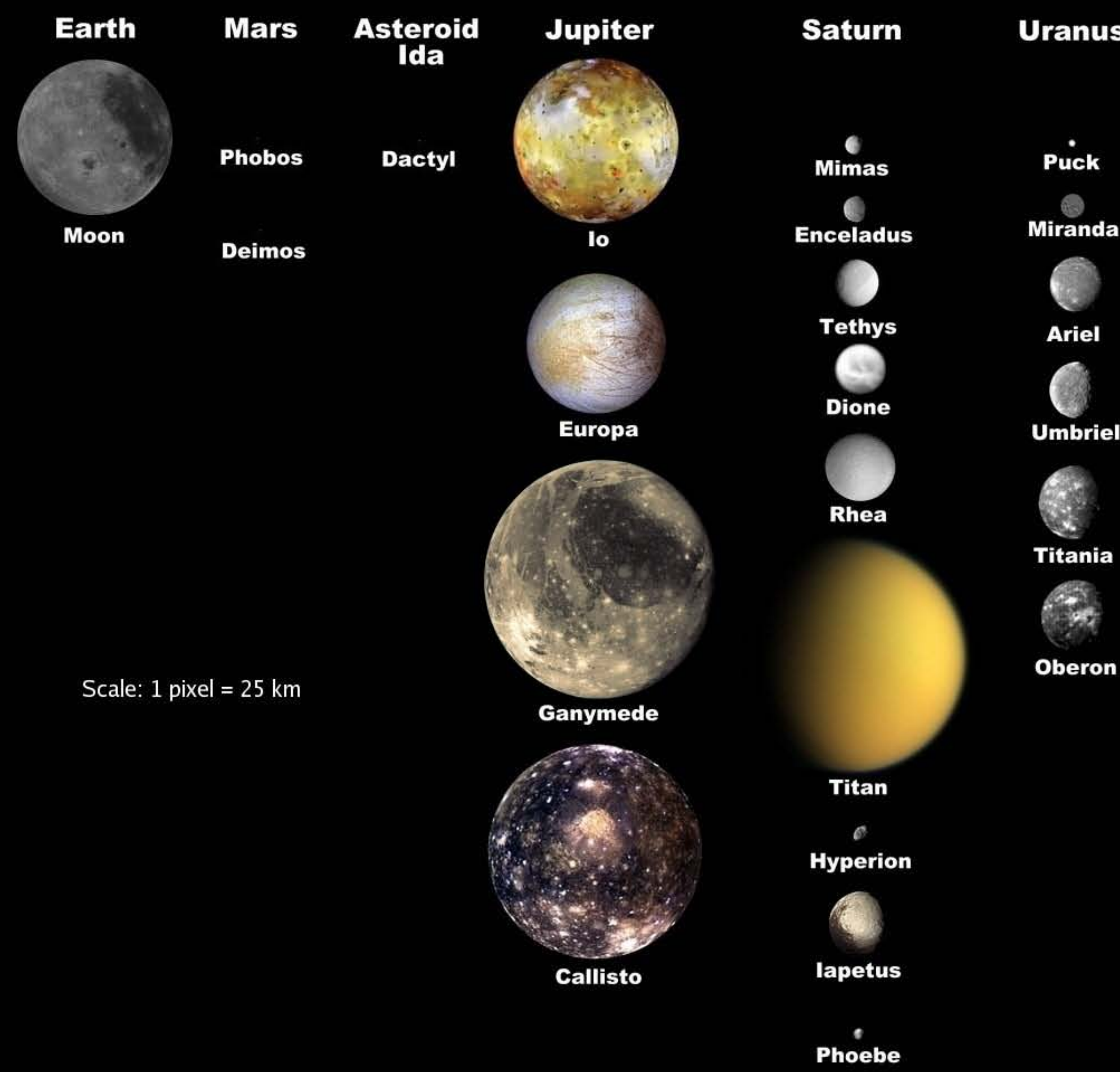
CPS/Hokudai

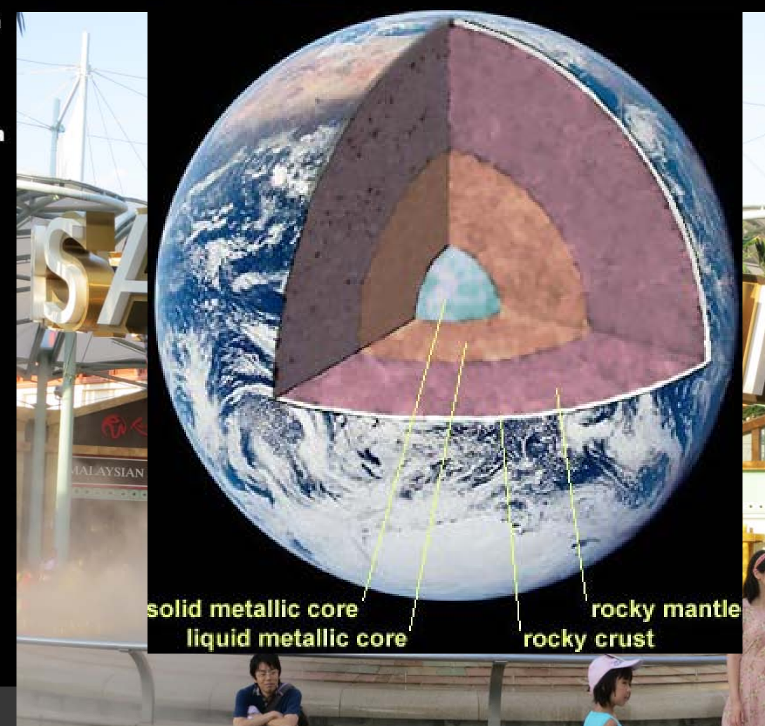
2012 08/22-24@小樽

衛星内部構造進化

- 衛星の半径·平均密度分布
- ガリルオ衛星の内部構造モデル
- 内部構造進化その1:
  - 地下海の進化(存続期間)
    - サイズと平均密度に依る3つの進化レジーム
- 内部構造進化その2:
  - 金属核の形成(for ガニメデ)
    - 表面地形の成因とリンクした仮説の提示

Selected Moons of the Solar System, with Earth for Scale

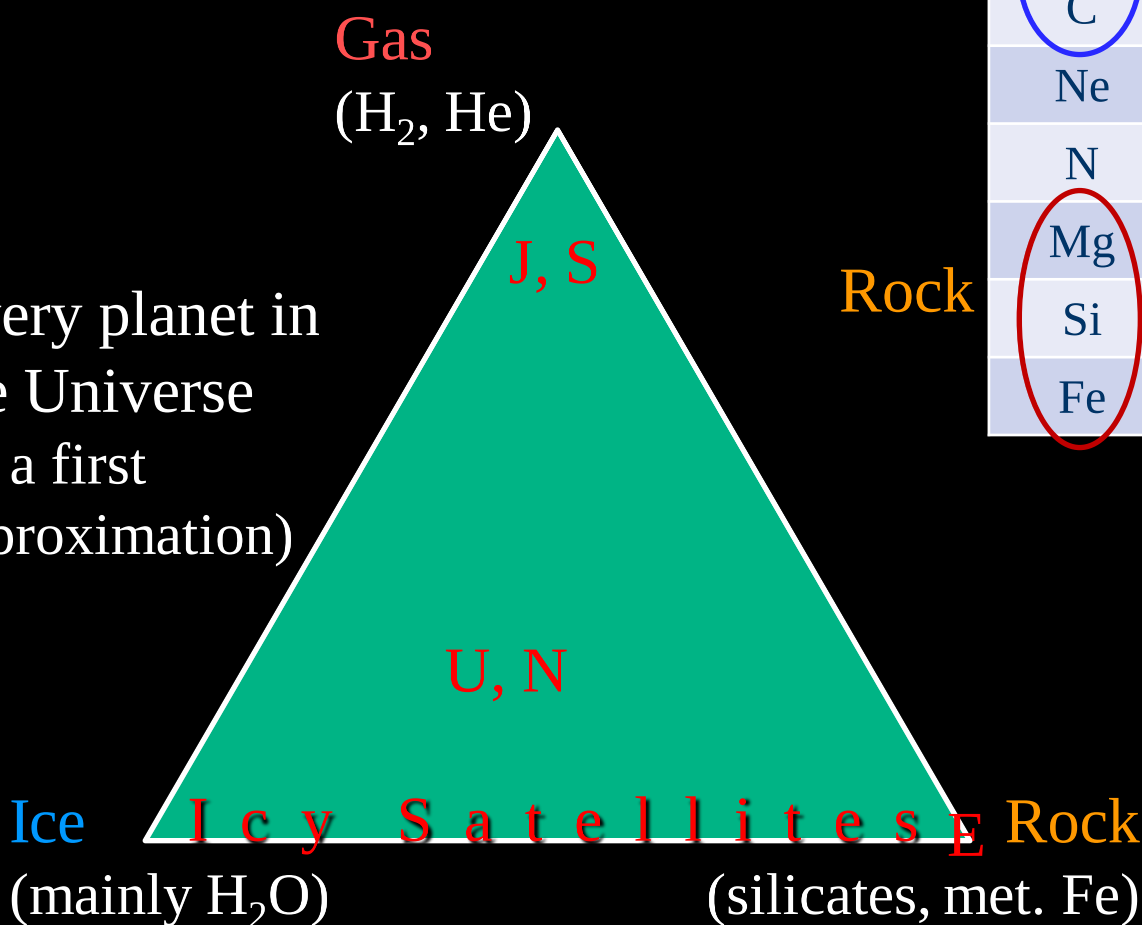




Element	Number Fraction	Mass Fraction
H	0.92	0.71
He	0.08	0.27
O	$7x10^{-4}$	0.011
C	$4x10^{-4}$	0.005
Ne	$1.2x10^{-4}$	0.002
N	$1x10^{-4}$	0.0015
Mg	$4x10^{-5}$	0.001
Si	$4x10^{-5}$	0.0011
Fe	$3x10^{-5}$	0.0016

Gas: H, He
Ice: O, C
Rock: Mg, Si, Fe

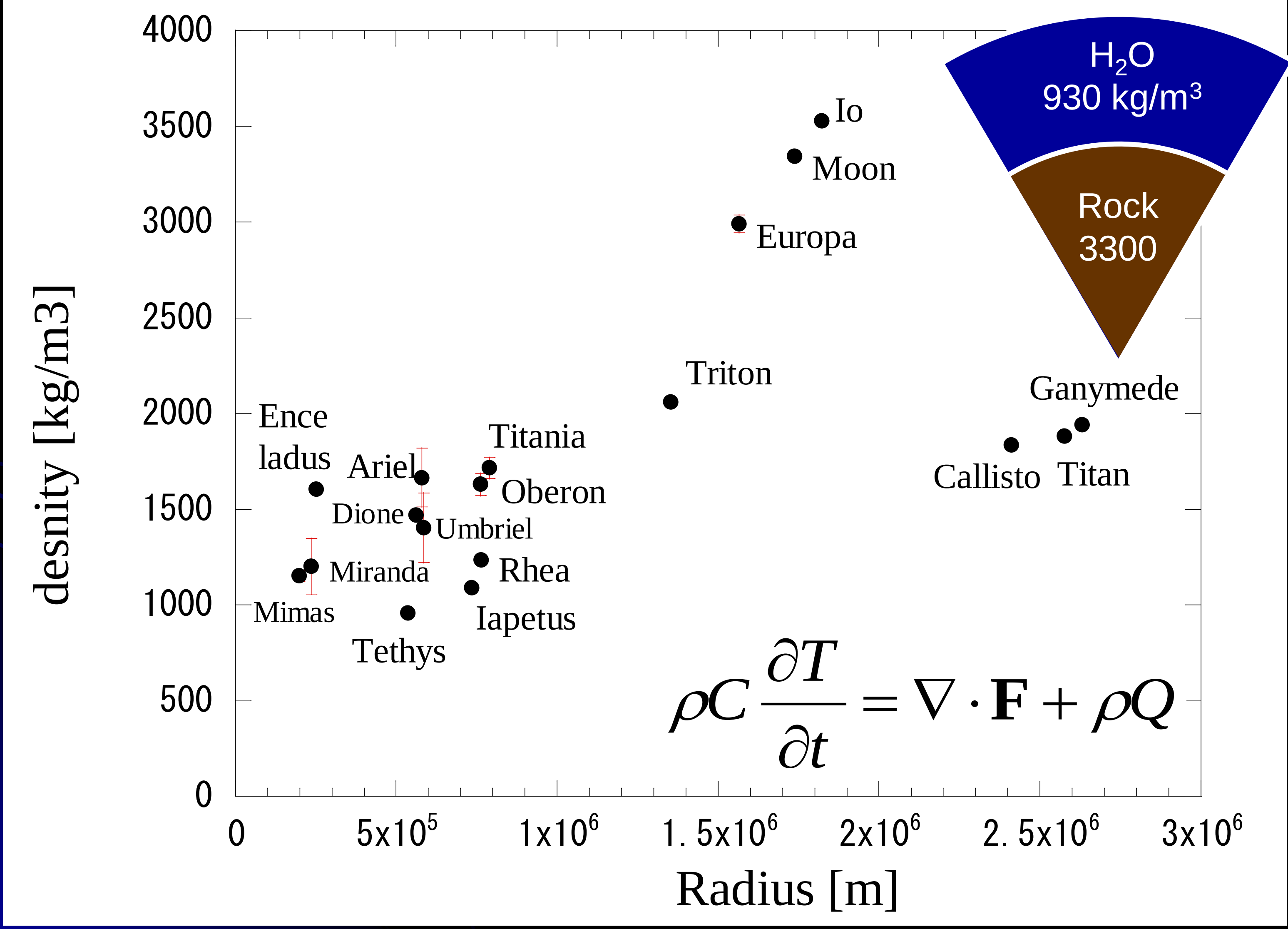
Every planet in the Universe (to a first approximation)



氷衛星の
Ice-Rock比は
さまざま

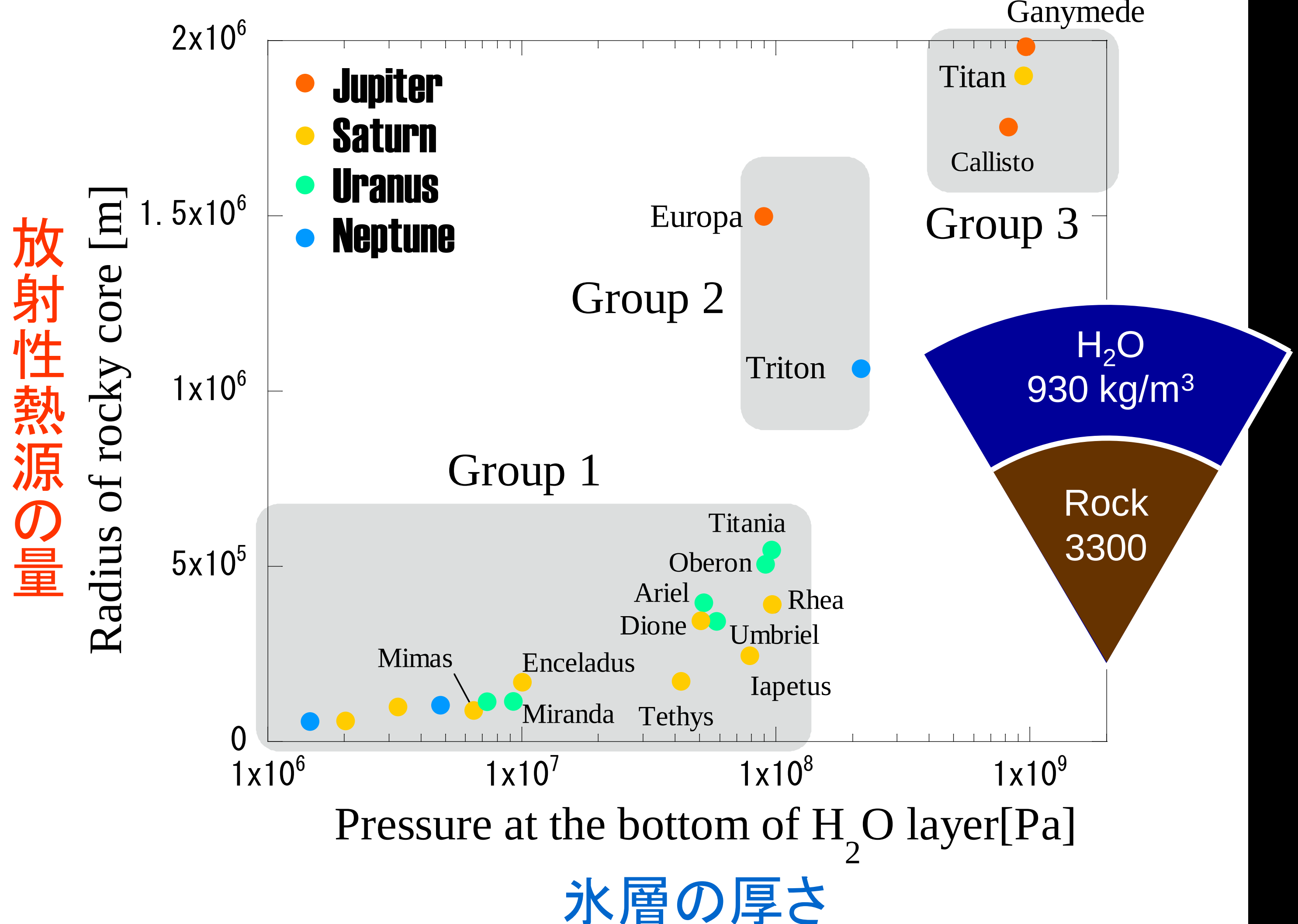
Stevenson, Proc. of CPS-Pschool, 2012

氷衛星の内部構造
（半径 vs. 密度）



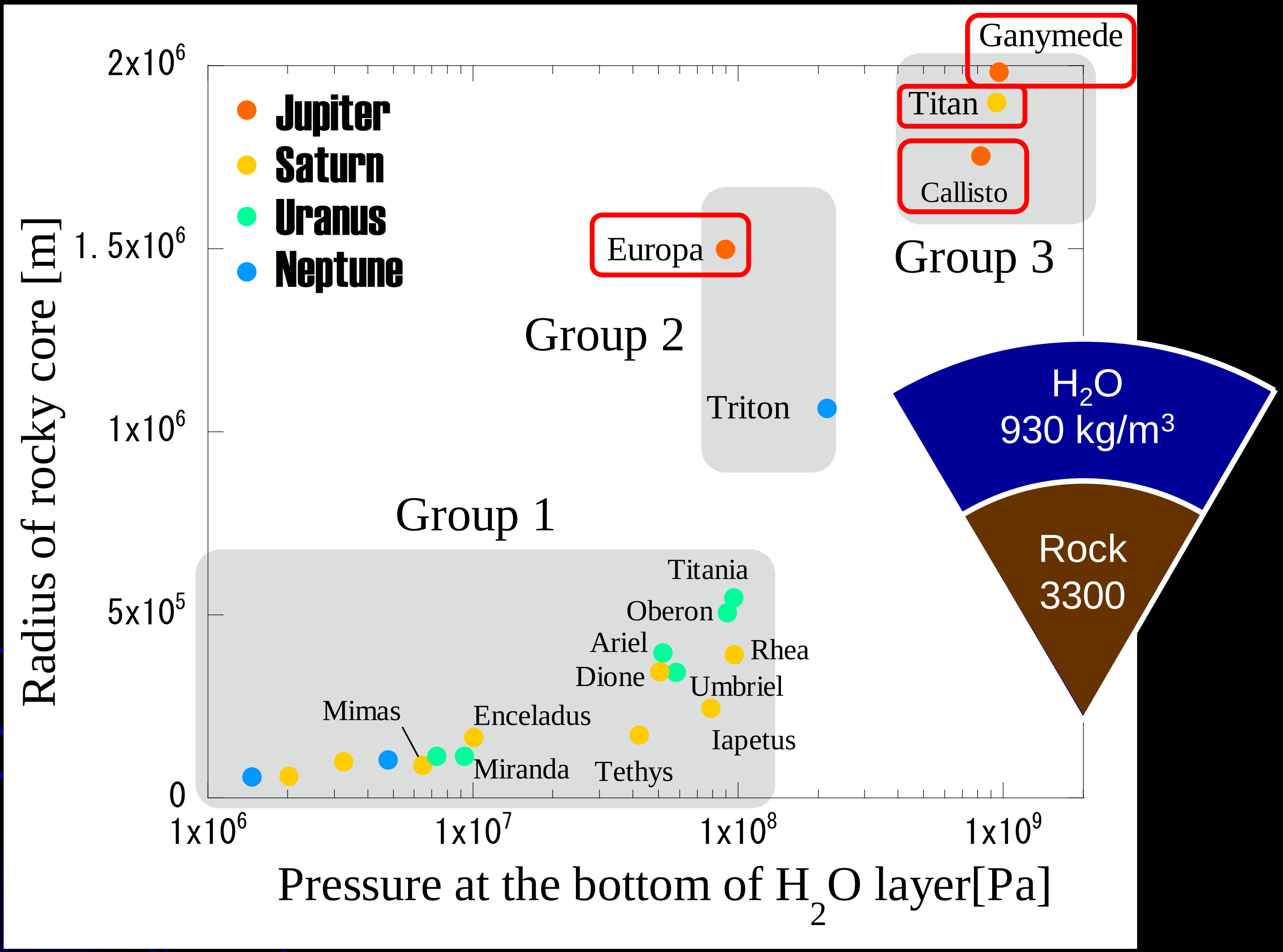
$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot \mathbf{F} + \rho Q$$

H_2O・岩石比と内部構造



木村・栗田（2006）を修正

H_2O・岩石比と内部構造



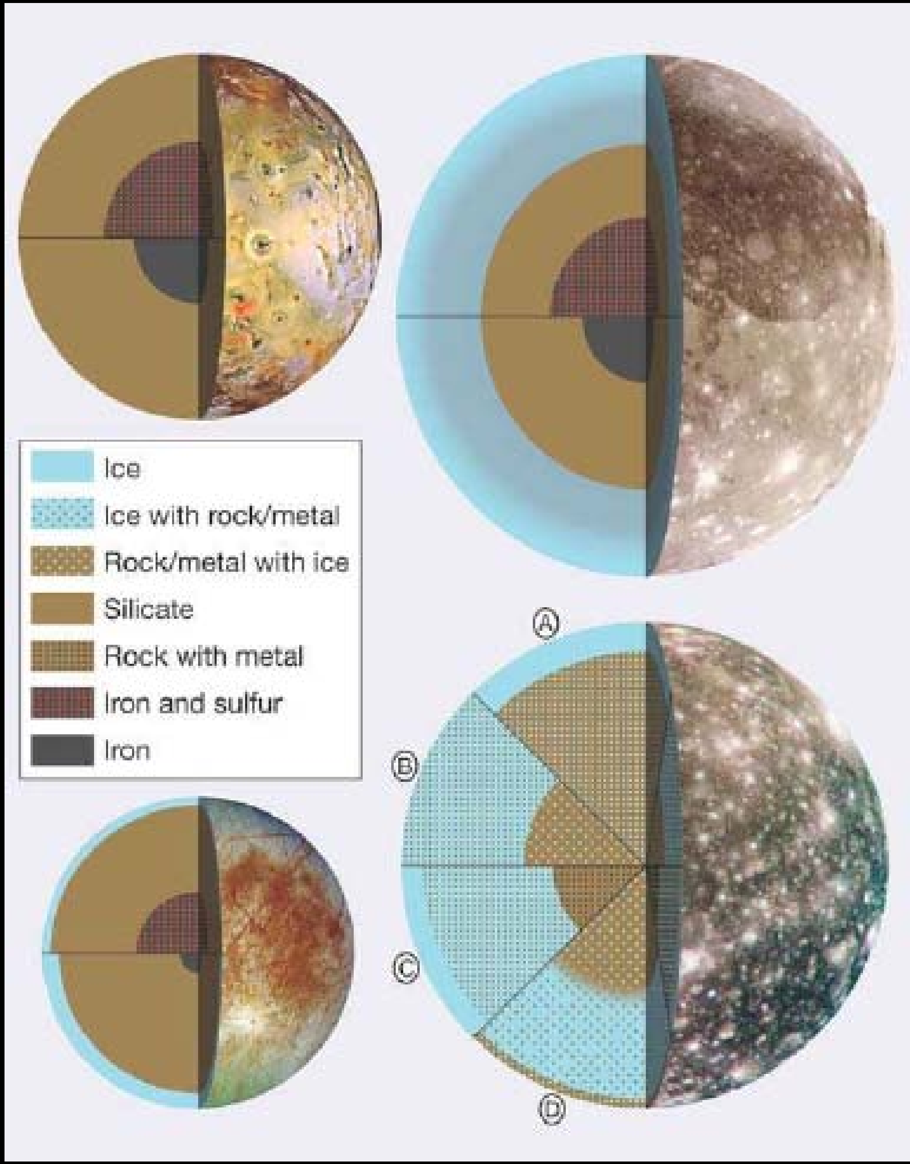
構成成分の分化度（成層度）は，慣性能率因子から.

木星の４大衛星：内部を知る情報

	mass (10^{20}kg)	radius (km)	density (kg/m^3)	MoI (C/MR^2)
Io	893.2	1822	3529.5	0.37685+-0.00035
Europa	478.0	1565	2989.5	0.346+-0.005
Ganymede	1481.7	2634	1935.6	0.3105+-0.0028
Callisto	1075.9	2410	1834.4	0.359+-0.005

Anderson+, 1996, 1998, 2001a,b

木星の４大衛星の内部構造モデル



Io

Ganymede

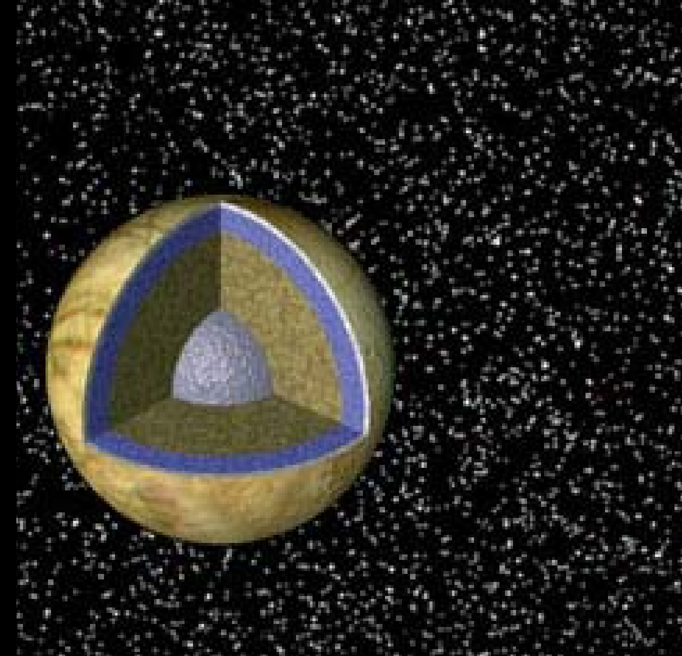
Europa

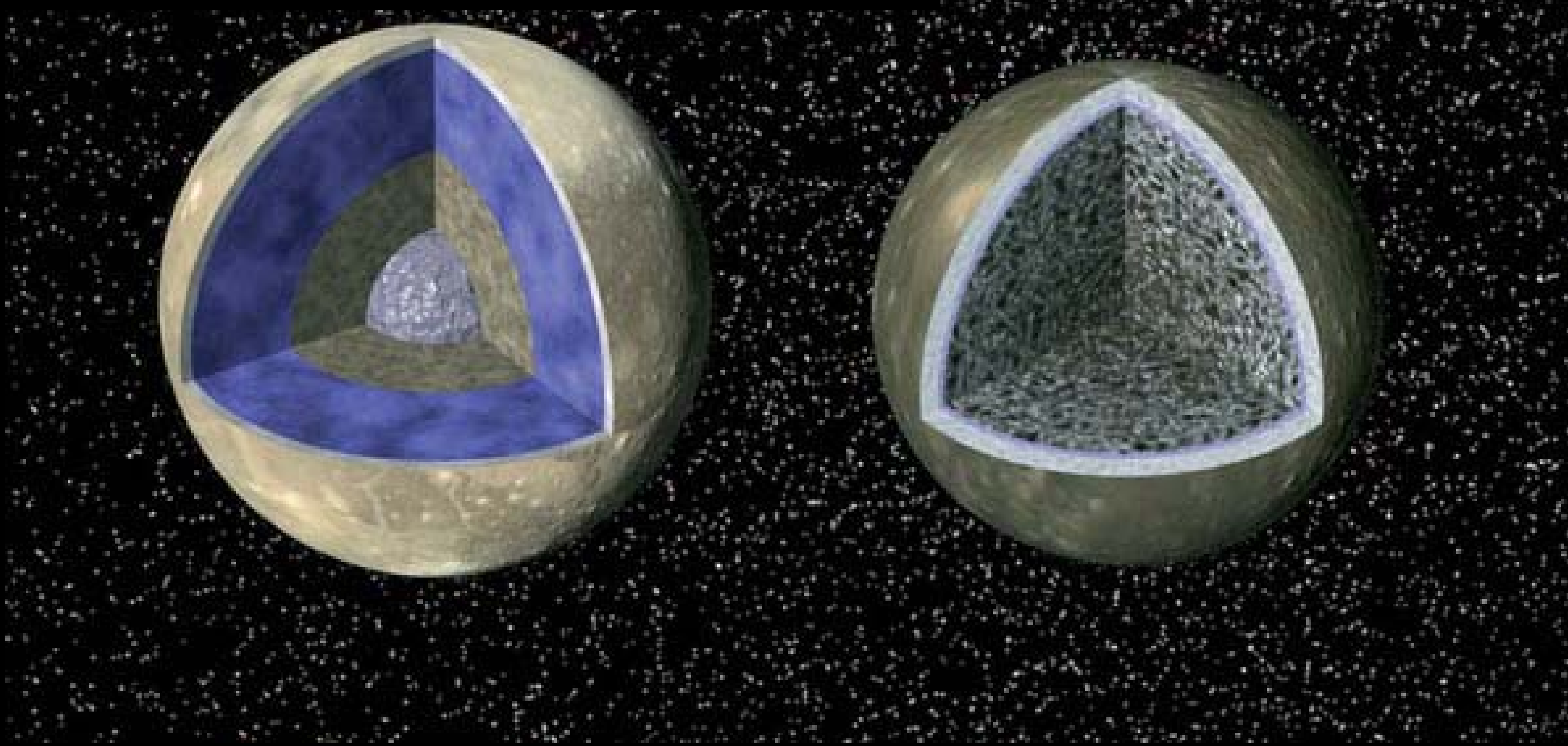
Callisto

Bagenal et al., 2004

氷衛星の内部構造進化

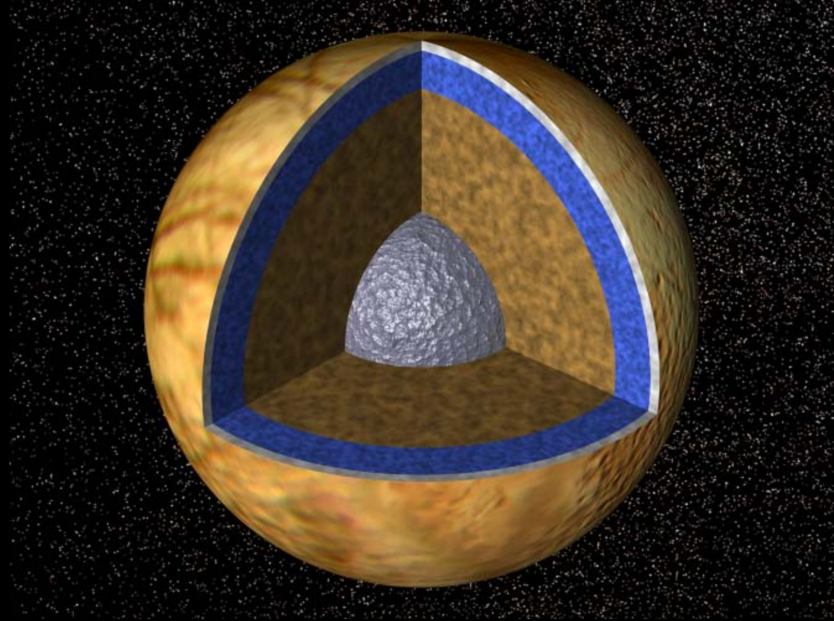
- H_2O層の進化
  - （地下）海の存続期間
- 金属核の形成

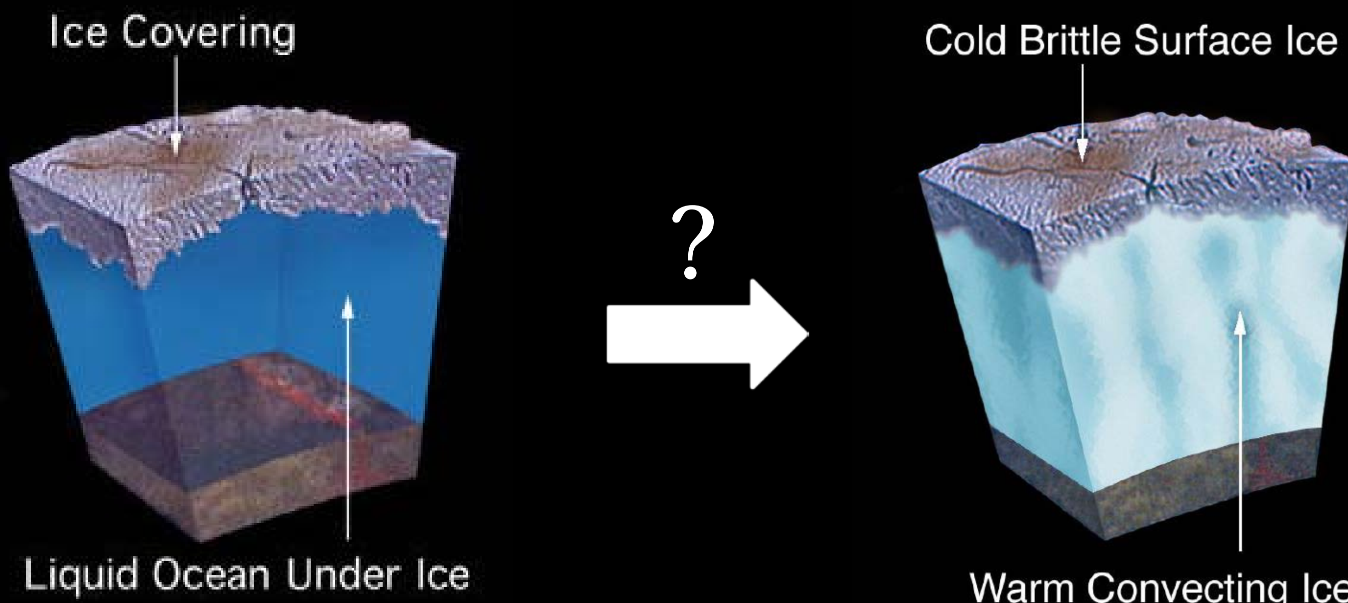




氷衛星の内部構造進化

- H_2O層の進化
  - （地下）海の存続期間



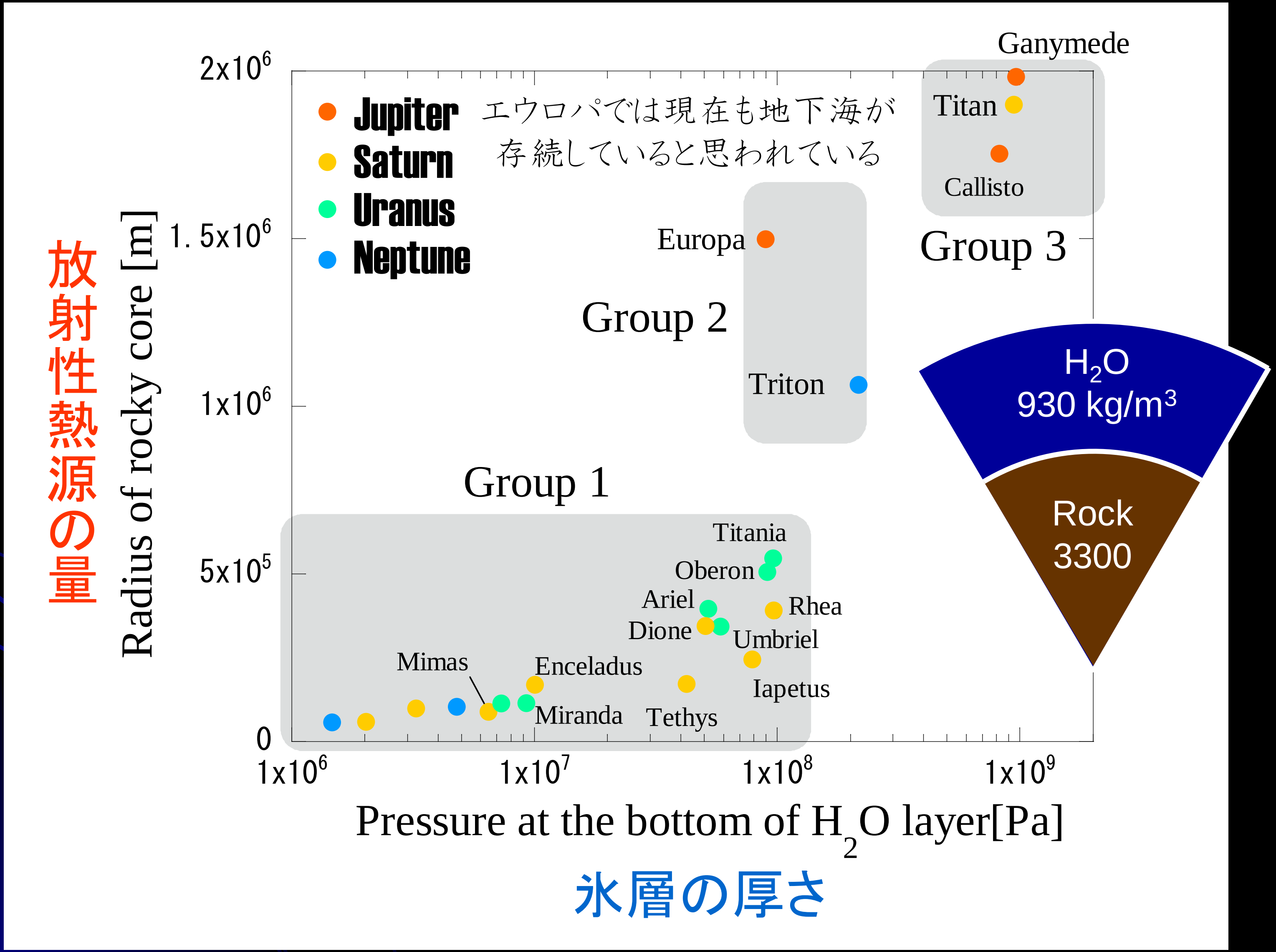


熱源

vs.

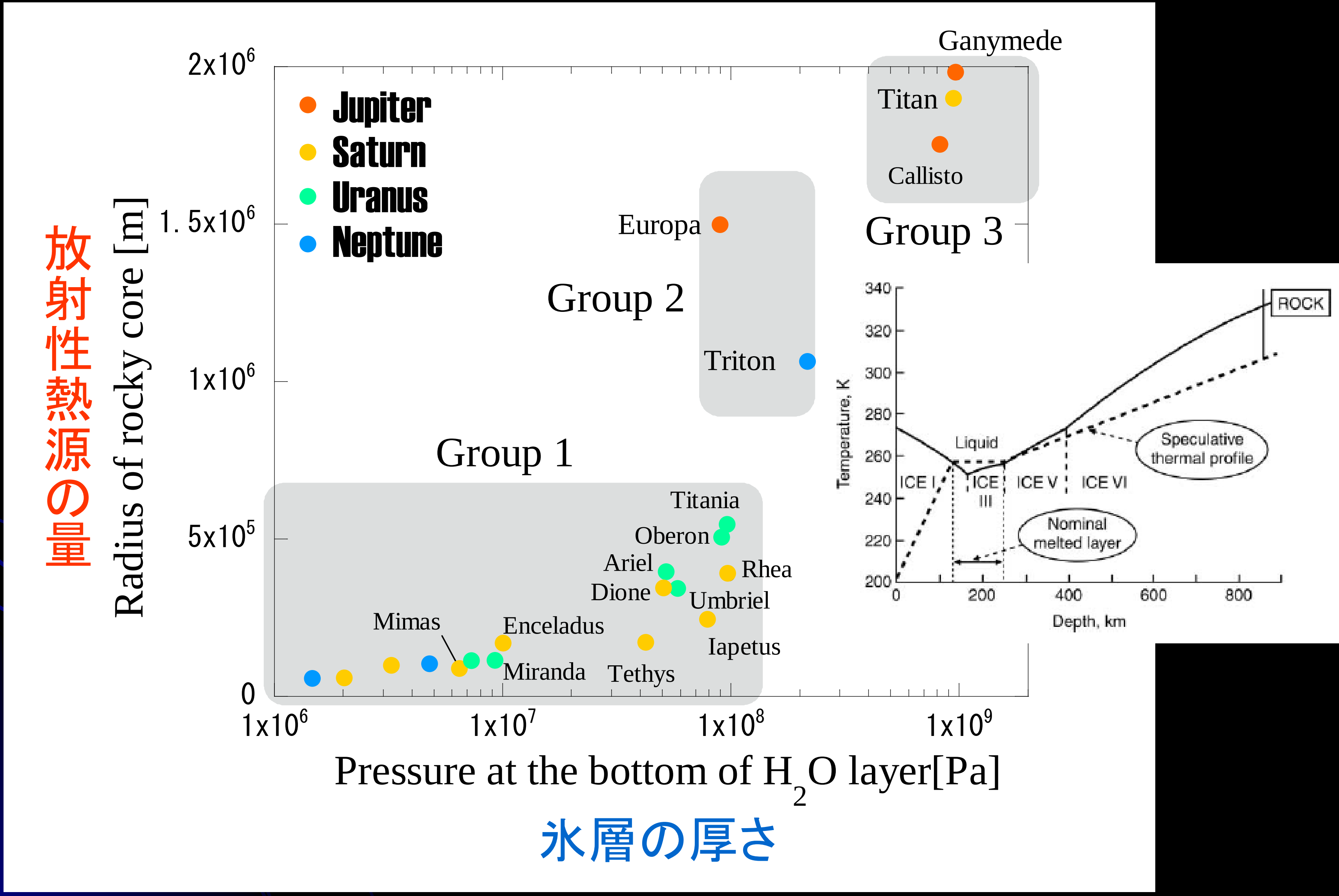
熱輸送

H_2O・岩石比と内部構造



木村・栗田（2006）を修正

H_2O・岩石比と内部構造



木村・栗田（2006）を修正

H_2O・岩石比と内部構造・進化

特集「太陽系天体の種別とその概念整理」

衛星の内部構造と分類学，準惑星への示唆

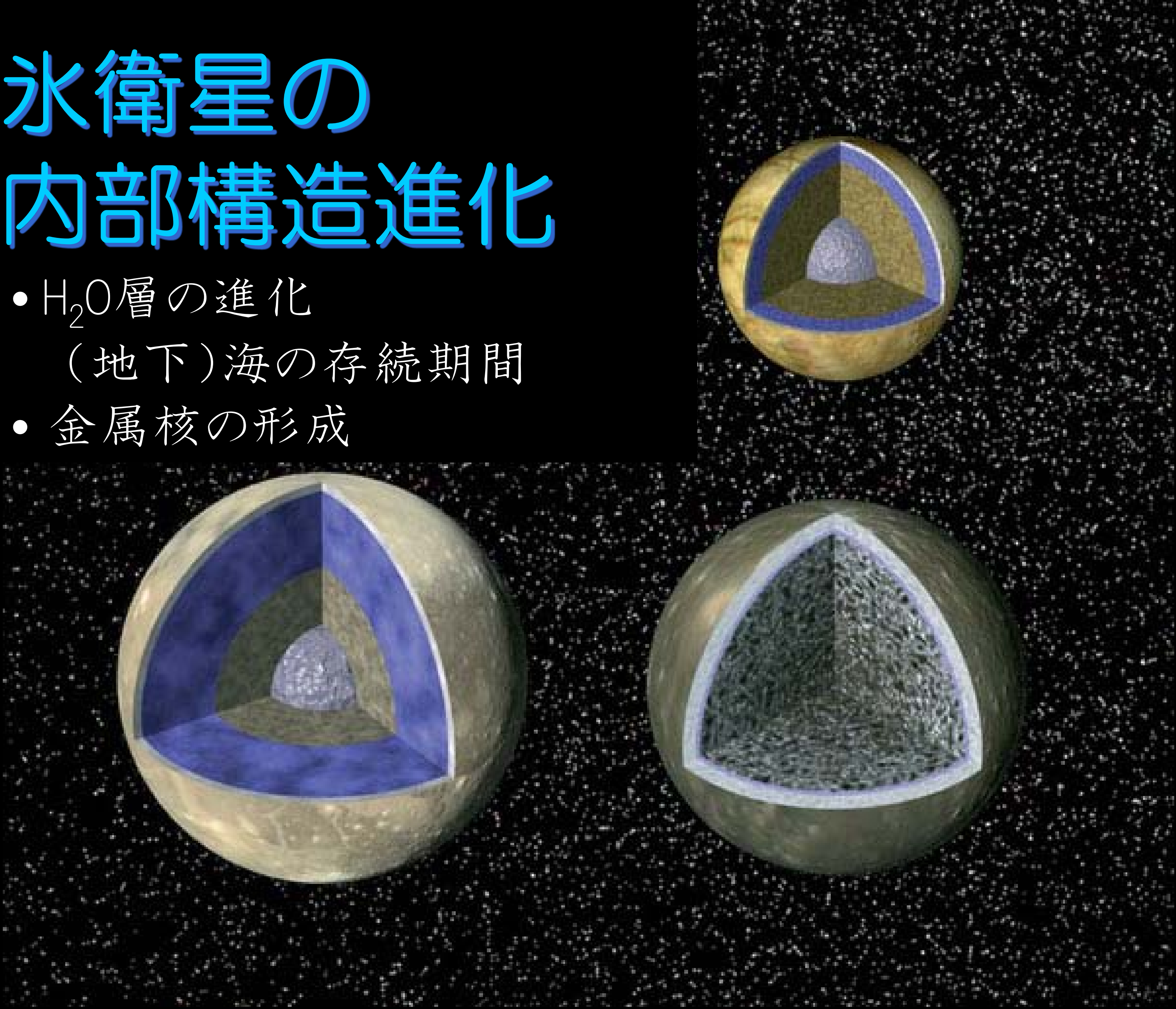
木村 淳[1]

（要旨）太陽系の構成メンバーは惑星や準惑星だけでなく，衛星も重要な要素のひとつである．"惑星の定義"に関する決議では直接は扱われなかったが，大きさでは惑星に匹敵するものもある衛星もまた，太陽系天体分類の観点から議論を欠くことはできない．サイズや外見において幅広い多様性を示す衛星だが，氷＋岩石の固体天体という共通性は天体分類上大きな特徴であり，同時に衛星間の個性や種別を生み出す重要な要素でもある．本稿ではこれまでの研究によって示された，サイズによる構造の違いや氷岩石比の違いが生み出す進化パターンをレビューするとともに，太陽系外縁天体への示唆や，どのような衛星の定義づけが適切かについて議論する．

木村，遊星人 vol. 17, no. 1, (2008)

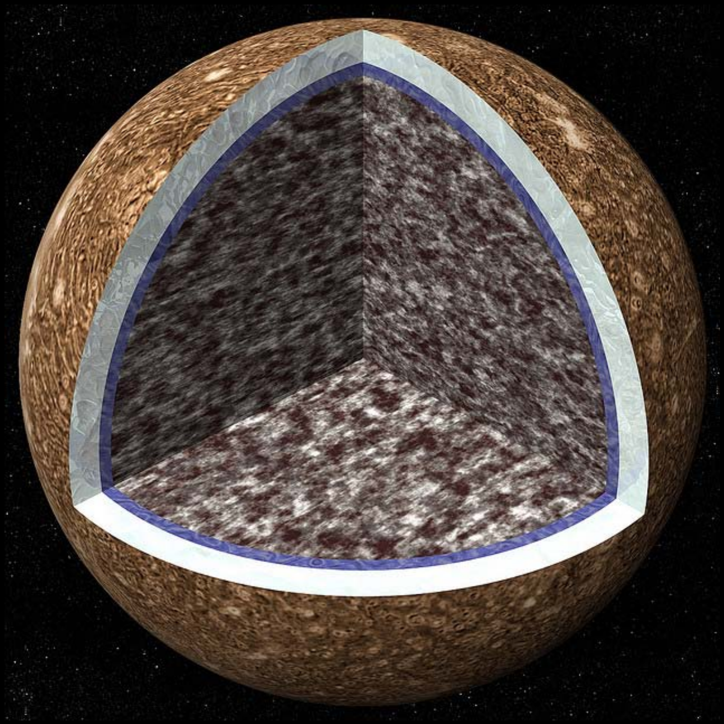
氷衛星の内部構造進化

- H_2O層の進化
  （地下）海の存続期間
- 金属核の形成

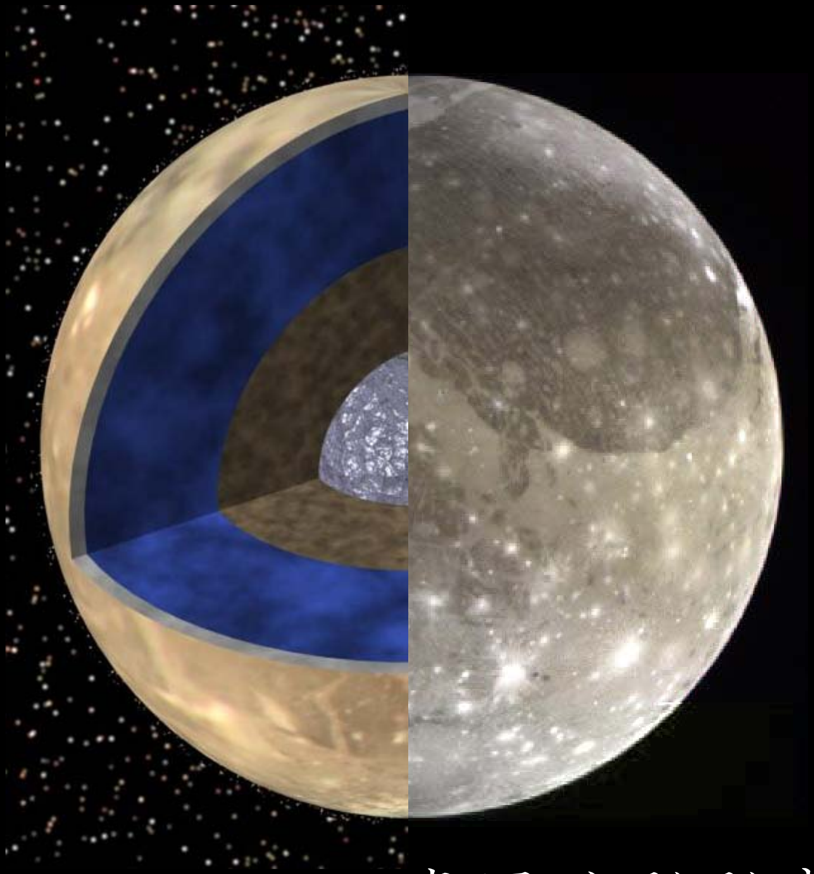


氷衛星の内部構造進化

- 金属核の形成



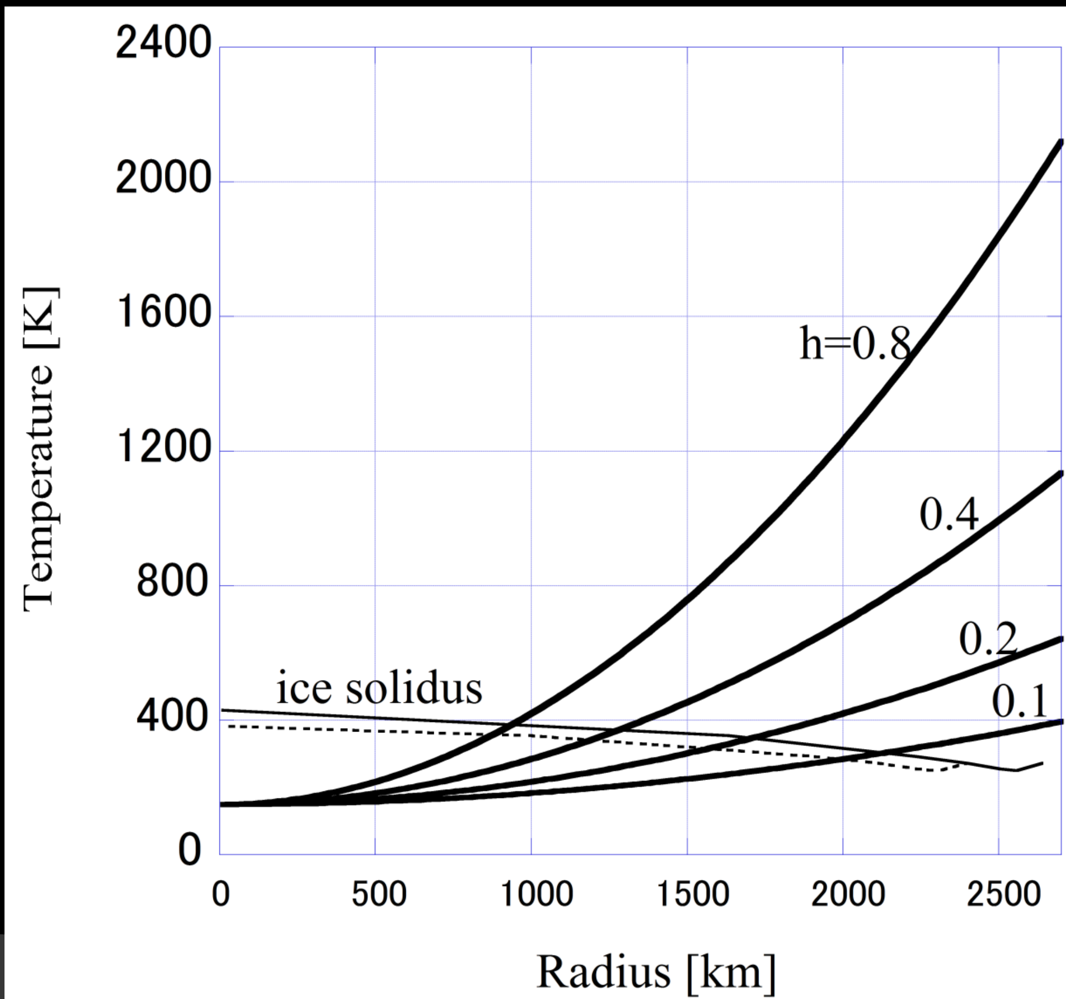
?



- 表面地形形成

Accretional temperature profile

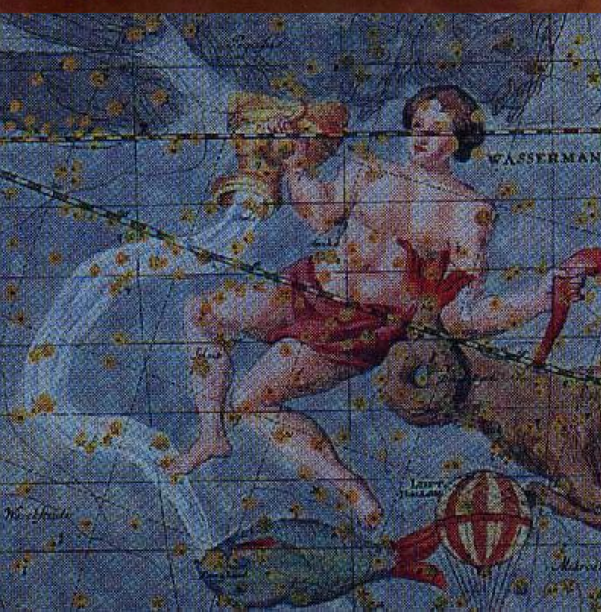
Safronov, 1969; Schubert+, 1986

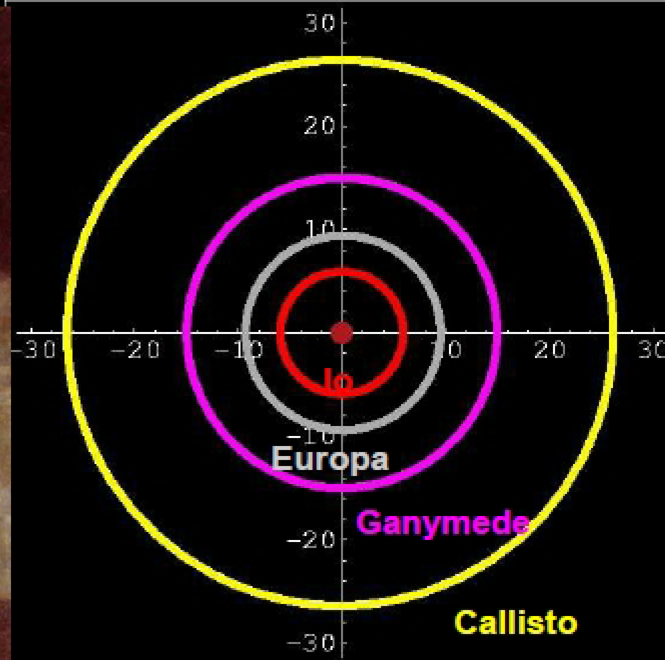


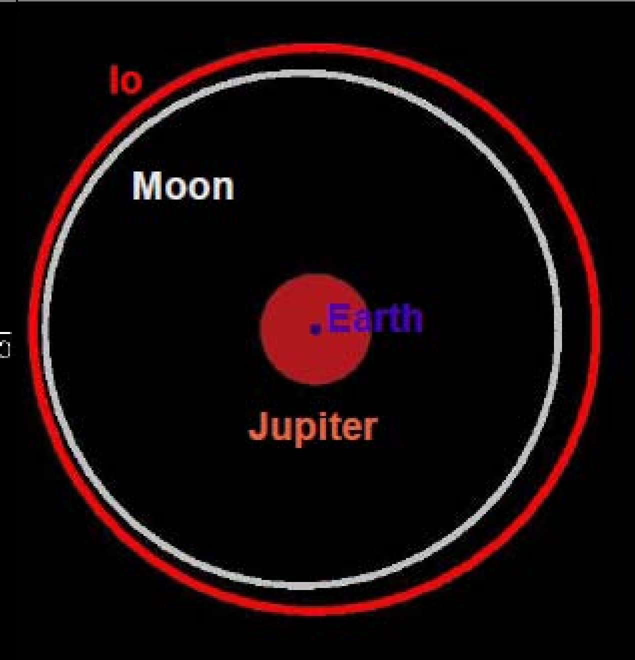
$$T_a(r) = h\frac{GM(r)}{cr}\left[1 + \frac{1}{2}\frac{ru^2}{GM(r)}\right] + T_e$$

$$T_e = 150\,\mathrm{K}, \quad c = 1800\,\mathrm{J/kgK}$$

$$\frac{GM(r)}{ru^2} = 4, \quad \rho_{sat} = 1930\,\mathrm{kg/m^3}$$







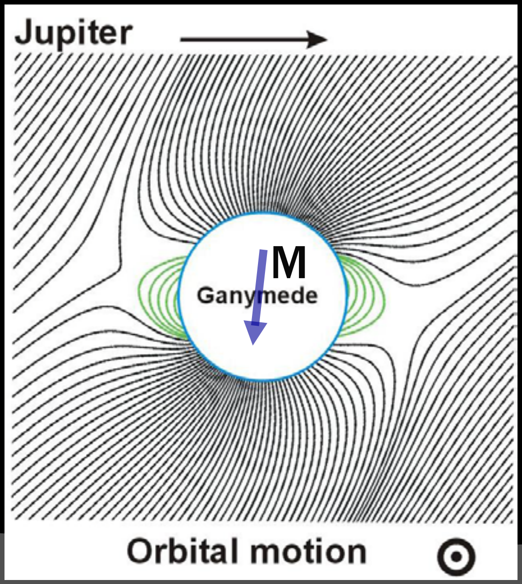
	mass (10^{20}kg)	radius (km)	density (kg/m^3)	MoI (C/MR^2)
Io	893.2	1822	3529.5	0.37685+-0.00035
Europa	478.0	1565	2989.5	0.346+-0.005
Ganymede	1481.7	2634	1935.6	0.3105+-0.0028
Callisto	1075.9	2410	1834.4	0.359+-0.005

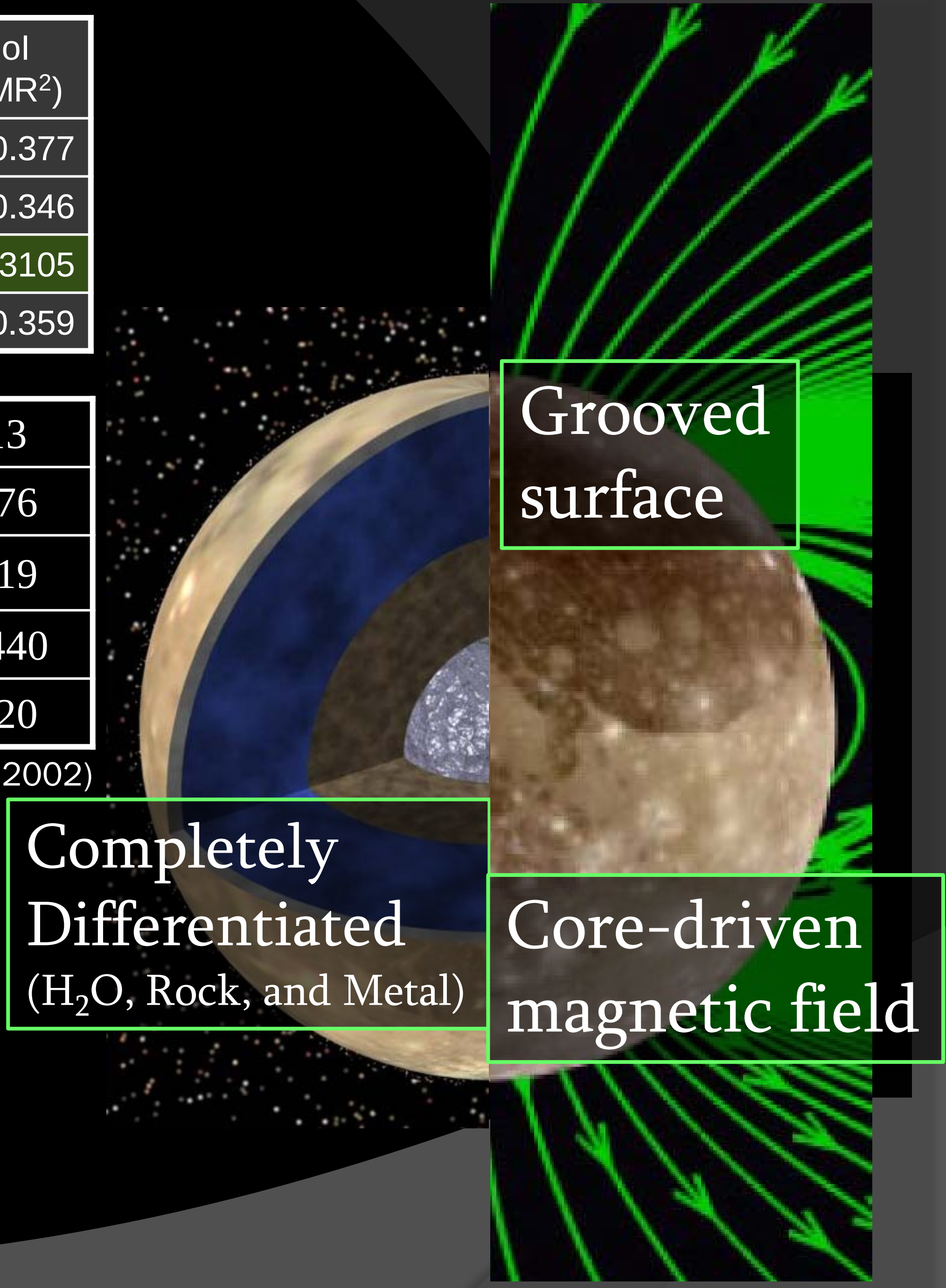
【Ganymede】トロイアの王子．その絶世の美しさに惚れたゼウスが誘拐し，永遠の若さと不死を与えた代わりにオリンポス十二神へ不死の酒ネクタールを給仕する任を押し付けた．

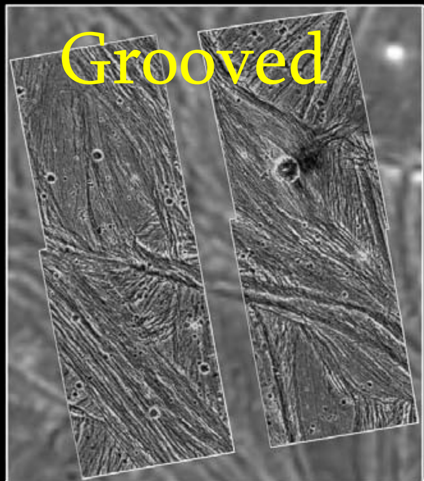
	mass (10^{20}kg)	radius (km)	density (kg/m^3)	MoI (C/MR^2)
Io	893.2	1822	3529.5	0.377
Europa	478.0	1565	2989.5	0.346
Ganymede	1481.7	2634	1935.6	0.3105
Callisto	1075.9	2410	1834.4	0.359

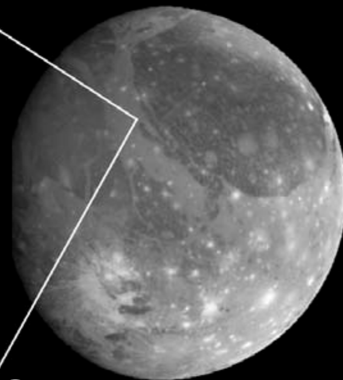
Dipole moment (10^{12} T m^3)	13
Tilt angle (degree)	176
Surface strength (nT) at the equator	719
Surface strength (nT) at the poles	1440
Ambient Jovian field (nT)	120

(Kivelson+ 2002)

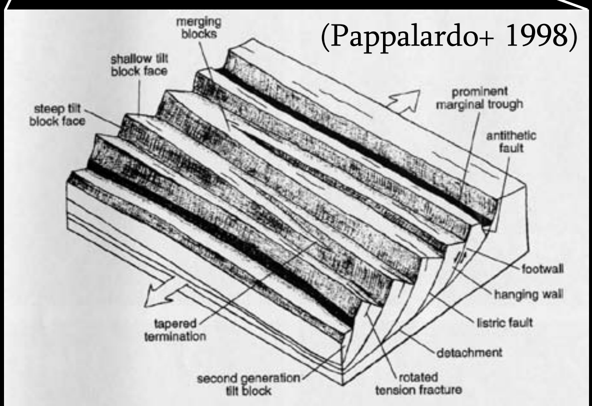




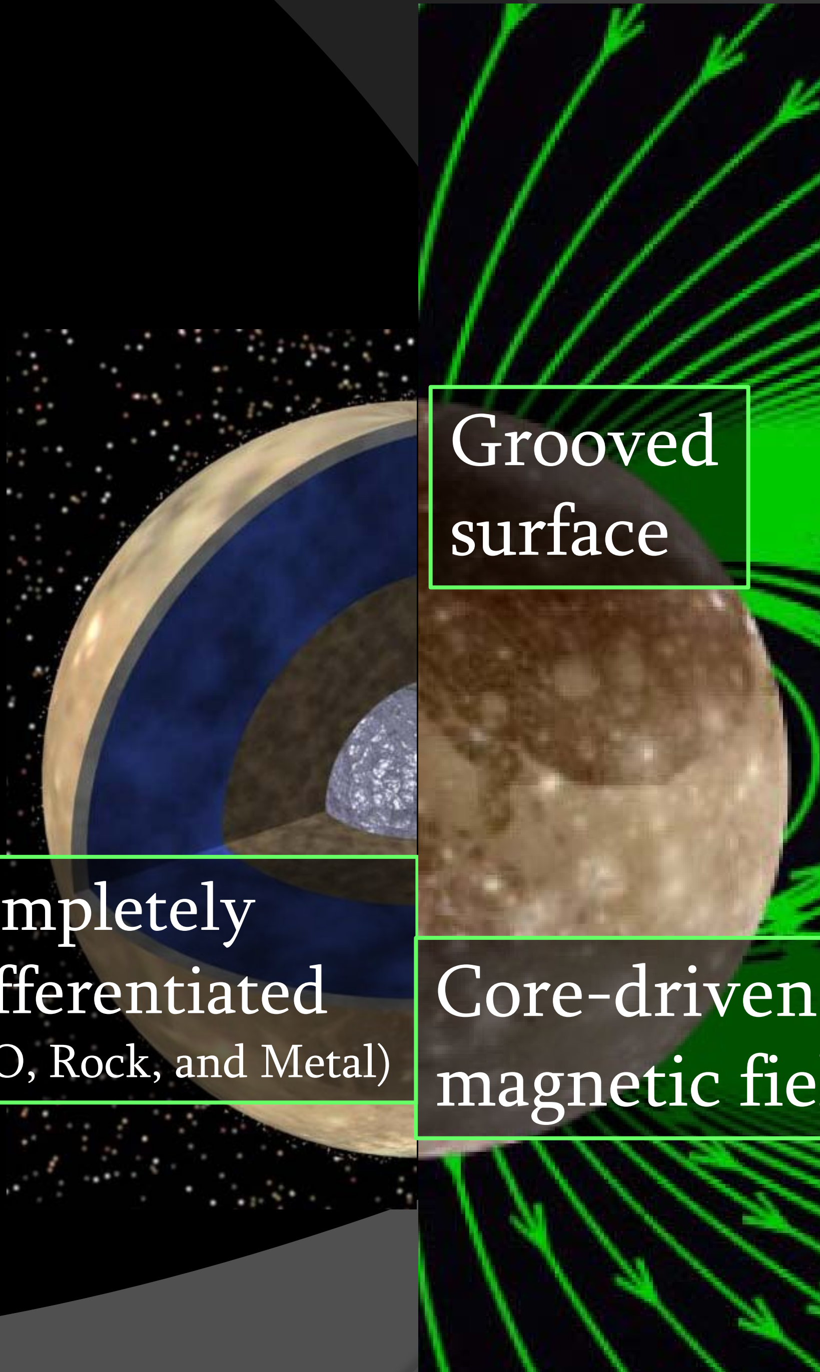




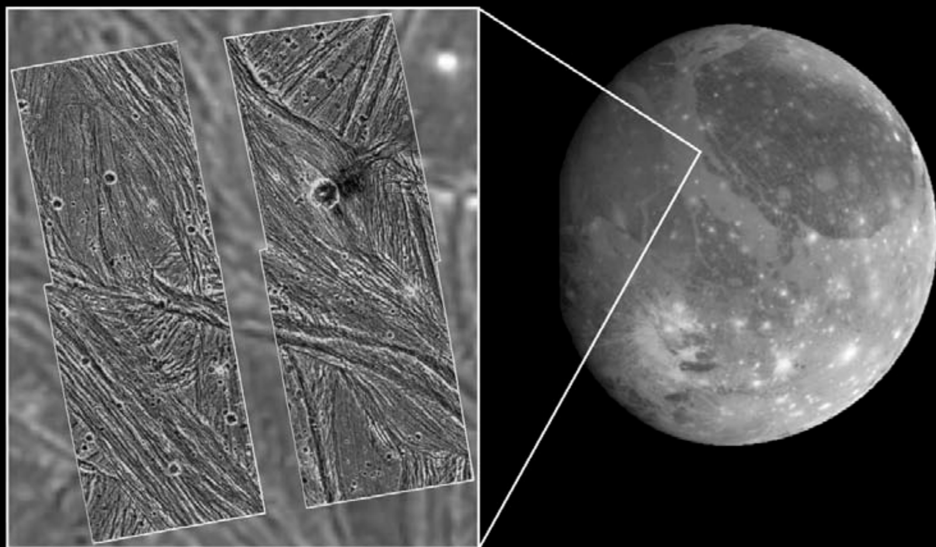
Cratering age
~2.0 Gyr (with large ambiguity)
(Zahnle+, 2003)

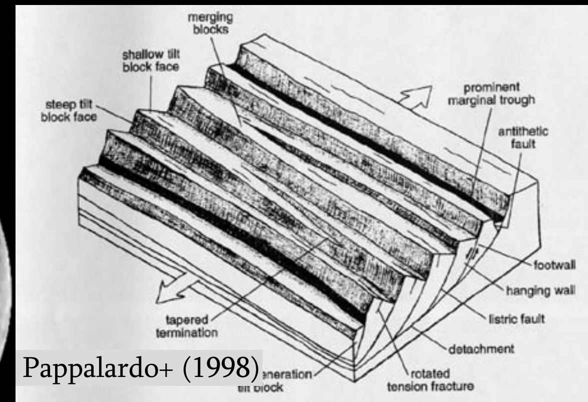


- grabens resulting from lithospheric extension (global expansion).

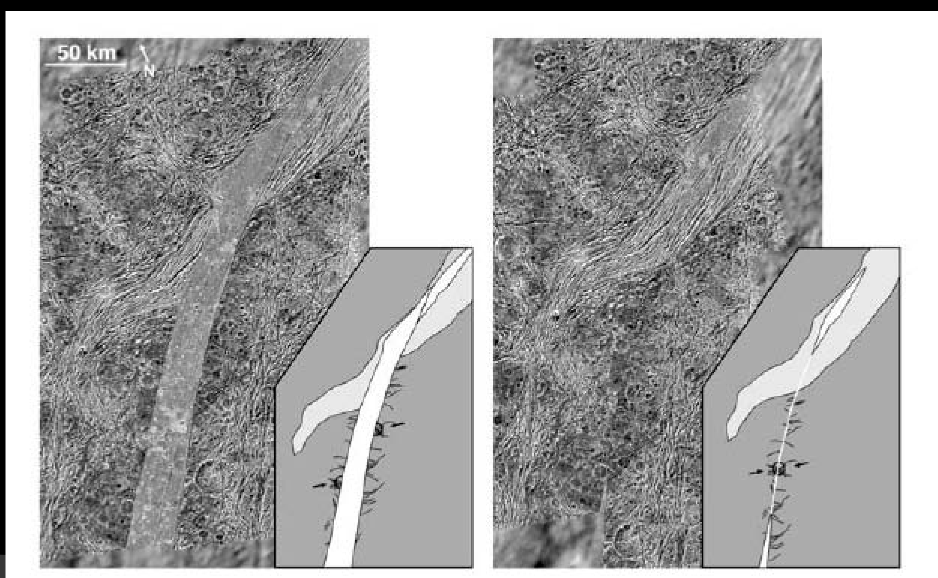


Surface geology on Ganymede



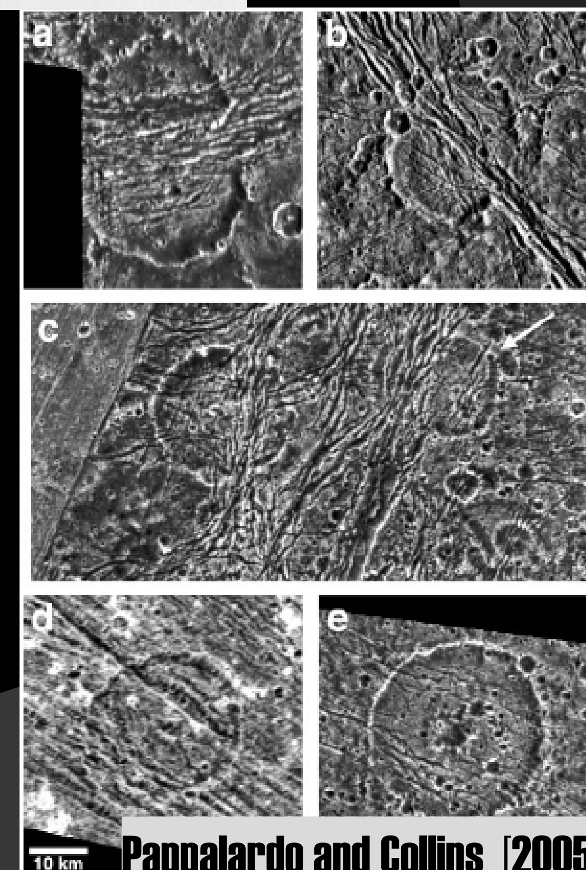


Pappalardo+ (1998)



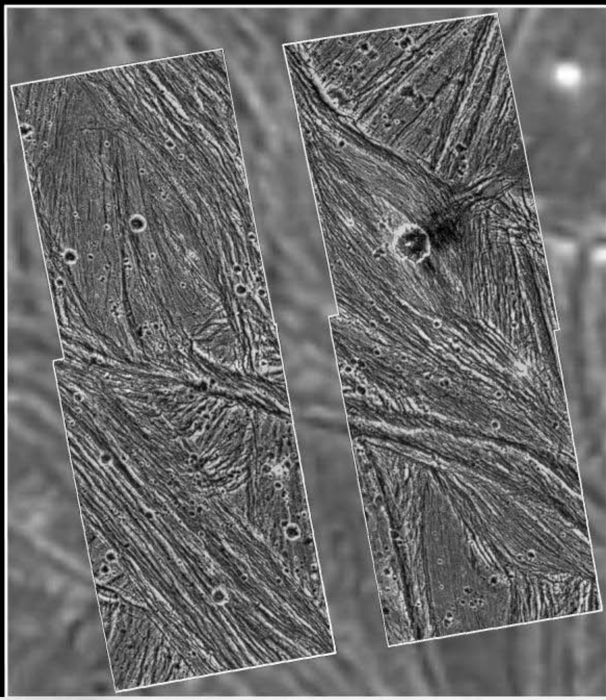
Head et al. [2002]

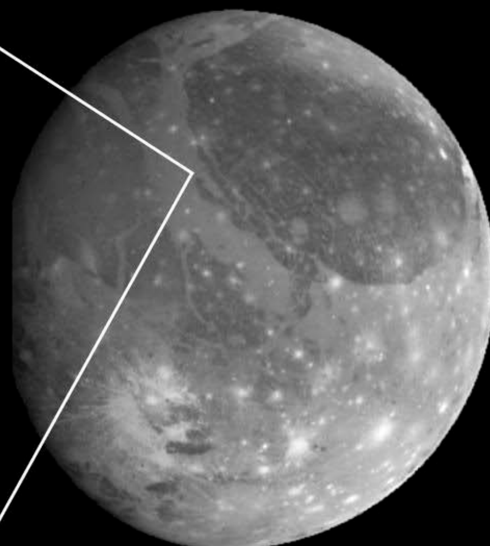
過去に全球的な
膨張イベントが
発生した痕跡か？

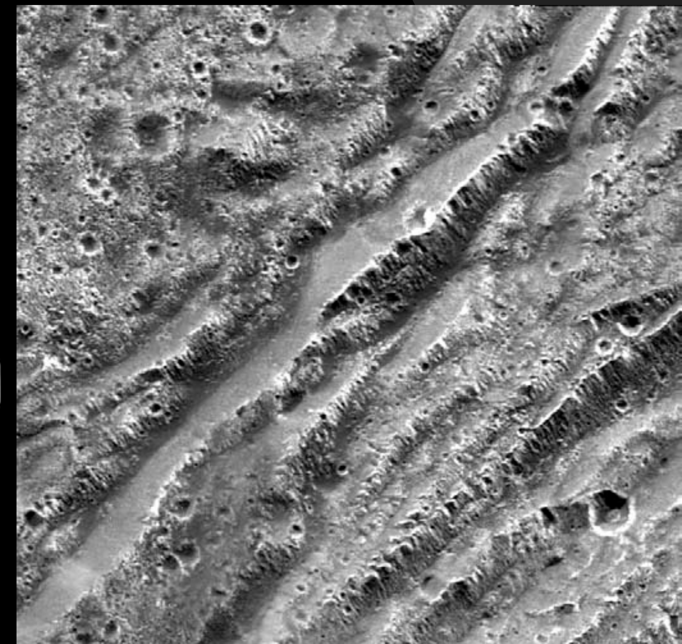


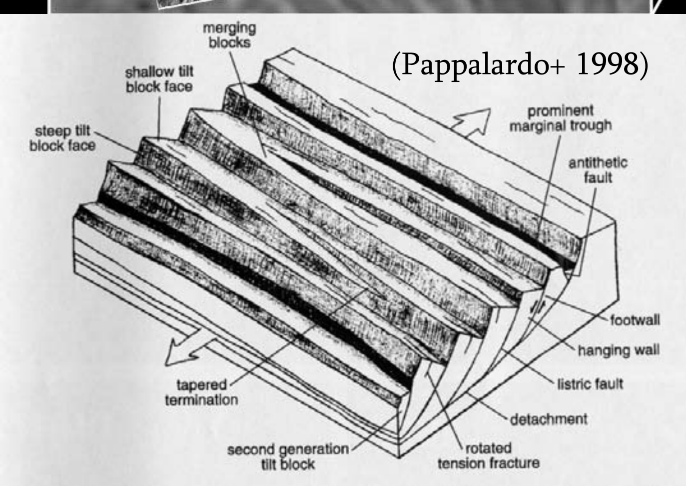
Pappalardo and Collins [2005]

Surface extensive tectonics on Ganymede



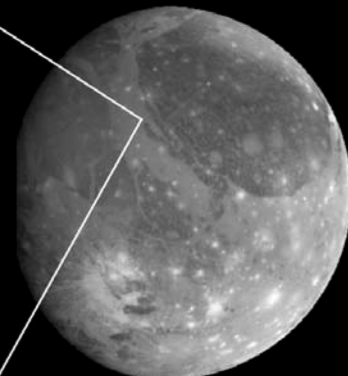




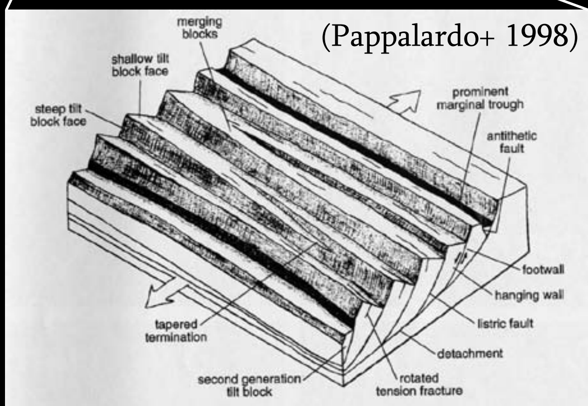


(Pappalardo+ 1998)

- Cratering age ~2 Ga (with extremely high ambiguity) (Zahnle+ 2003)
- Radius increase of 0.02-1% (Golombek 1982), 2.5-4 % (Collins 1998) is required to form all grooves.

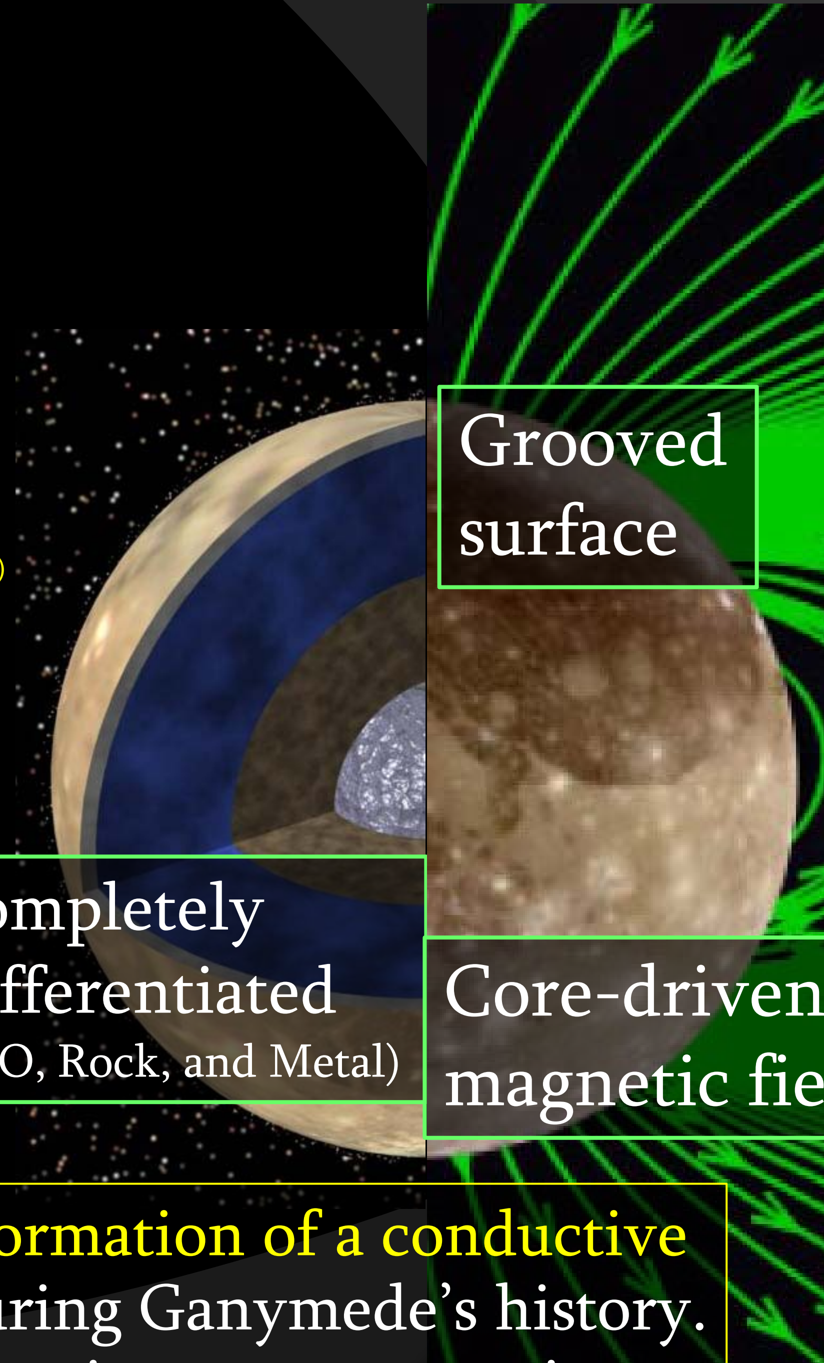


Cratering age
~2.0 Gyr (with large ambiguity)
(Zahnle+, 2003)



(Pappalardo+ 1998)

- grabens resulting from lithospheric extension (global expansion).



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

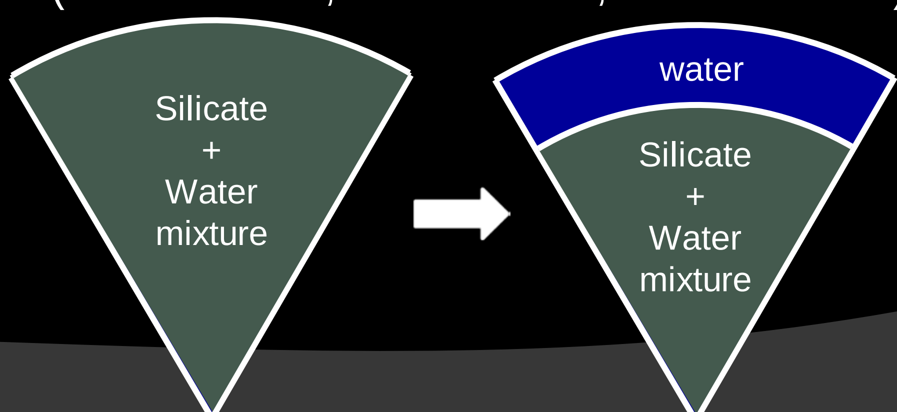
Previous works that focused on the tectonics and the metallic core of Ganymede

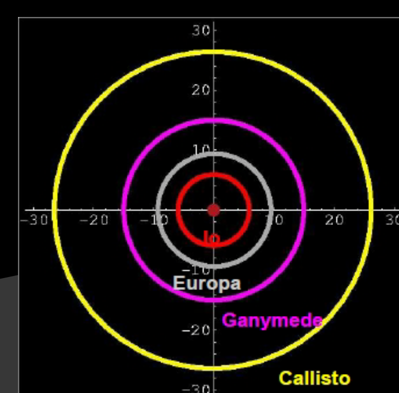
The surface tectonics (global expansion) originated from…

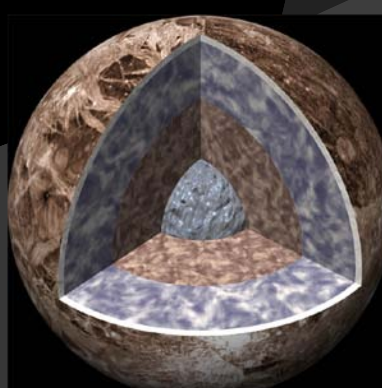
- post-accretional differentiation
  (Squyres 1980, Mueller & McKinnon 1988)
  - inconsistent with the apparent youth of the terrain ~ 2 Ga.
- differentiation during LHB
  (Barr & Canup, 2010)
  - inconsistent with the apparent youth of the terrain ~ 2 Ga.
- ice re-melting via orbital evolution
  (Showman+ 1999, Bland+ 2009).
  - Induced expansion is much lower than geological estimate.

The magnetic field originates from…

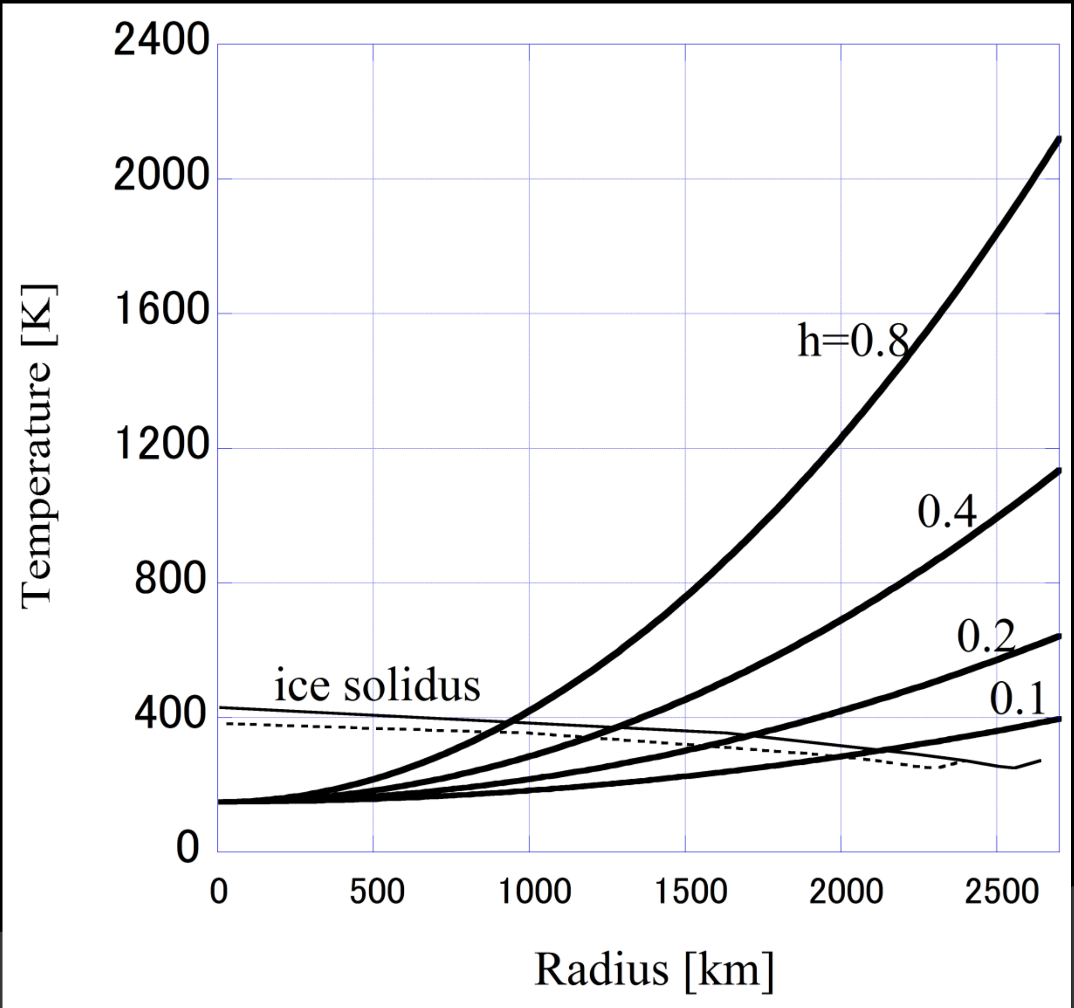
- convection in the molten metallic core
  (Hauck+ 2006, Bland+ 2008, Kimura+ 2009)
  - Assuming the core has formed just after the end of accretion. But accretional heating is insufficient to form the core.







Accretional temperature profile



Safronov, 1969; Schubert+, 1986

$$T_a(r) = h\frac{GM(r)}{cr}\left[1+\frac{1}{2}\frac{ru^2}{GM(r)}\right]+T_e$$

$$T_e = 150\,\mathrm{K}, \quad c = 1800\,\mathrm{J/kgK}$$

$$\frac{GM(r)}{ru^2} = 4, \quad \rho_{sat} = 1930\,\mathrm{kg/m^3}$$

Previous works that focused on the tectonics and the metallic core of Ganymede

The surface tectonics (global expansion) originated from…

- post-accretional differentiation
  (Squyres 1980, Mueller & McKinnon 1988)

  - inconsistent with the apparent youth of the terrain ~ 2 Ga.

- differentiation during LHB
  (Barr & Canup, 2010)

  - inconsistent with the apparent youth of the terrain ~ 2 Ga.

- ice re-melting via orbital evolution
  (Showman+ 1999, Bland+ 2009).

  - Induced expansion is much lower. than geological estimate.

The magnetic field originates from…

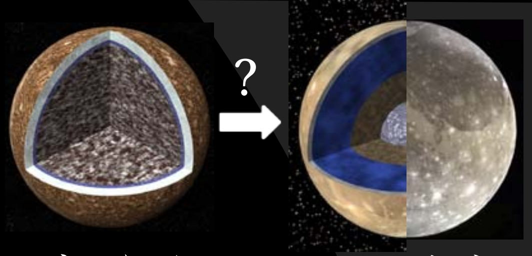
- convection in the molten metallic core
  (Hauck+ 2006, Bland+ 2008, Kimura+ 2009)

  - Assuming the core has formed just after the end of accretion. But accretional heating is insufficient to form the core.

New proposition in this work:

Contribution of dehydration of primordial hydrous rock.

→ Trying to explain both events of the formation of the metallic core and the tectonics (global expansion) on relatively young age



Motivation 1

- ガニメデの金属核はいつできたか？集積熱が高くないので誕生直後には作れないはず．
- ガニメデ表面の地溝帯形成（全球的膨張）はいつ起きたか？地形年代（～2Gyr）に合うモデルが先行研究にはない．

やったこと

- 木星衛星ガニメデにおける金属核形成と表面地形形成を同時に説明する進化モデルを構築．
- 初期ガニメデはH_2O＋岩石＋金属の混合体として集積し，岩石は含水鉱物であると仮定．
- 長寿命放射性核種壊変熱と伝導・対流熱輸送を考慮した熱史シミュレーションを実行．温度変化に伴う含水鉱物の脱水と，それによるレオロジーの変化と反応熱の発生を考慮．

Motivation 2

- 同程度のサイズと平均密度を持つカリストには，金属核も表面の地溝帯もない．なにゆえにこうも歴史を違えたのか？

Initially hydrous rock and its dehydration

➢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).

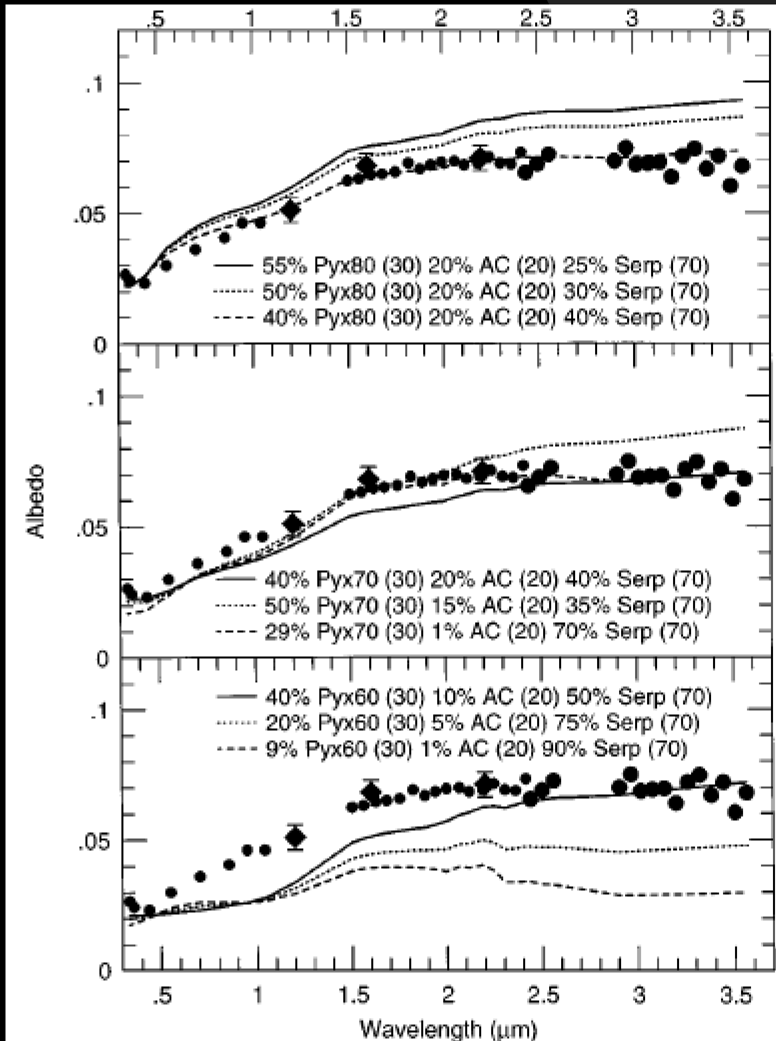


FIG. 4. Intimate mixture models of pyroxene, amorphous carbon, and serpentine with varying amounts of each component. The effect of the different Mg content of pyroxenes is shown. The top panel uses pyroxene with 80% Mg, the middle panel 70% Mg, and the lower panel 60% Mg; all optical constants for the pyroxenes were taken from the Jena group web site (see footnote to Table III).

Composite spectrum of Trojan asteroid Hektor from UKIRT, ECAS, and IRTF data, which shows that the hydrous silicate serpentine could exist on Hektor in concentrations up to about 40% (Cruikshank+ 2001 Icarus).

Dehydration of hydrous rock

- **Dehydration Temperature**

  720 C@2.0 GPa, 690 C@3.0 GPa, 620 C@5.0GPa (Ulmer & Trommsdorff, 1995)
  690 C@2.0 GPa, 610 C@5.0 GPa (Song+ 1996)
  550 C@0.3 GPa, 600 C@0.4 GPa (Hirose+ 2006)

(Ulmer & Trommsdorff, 1995 Science)

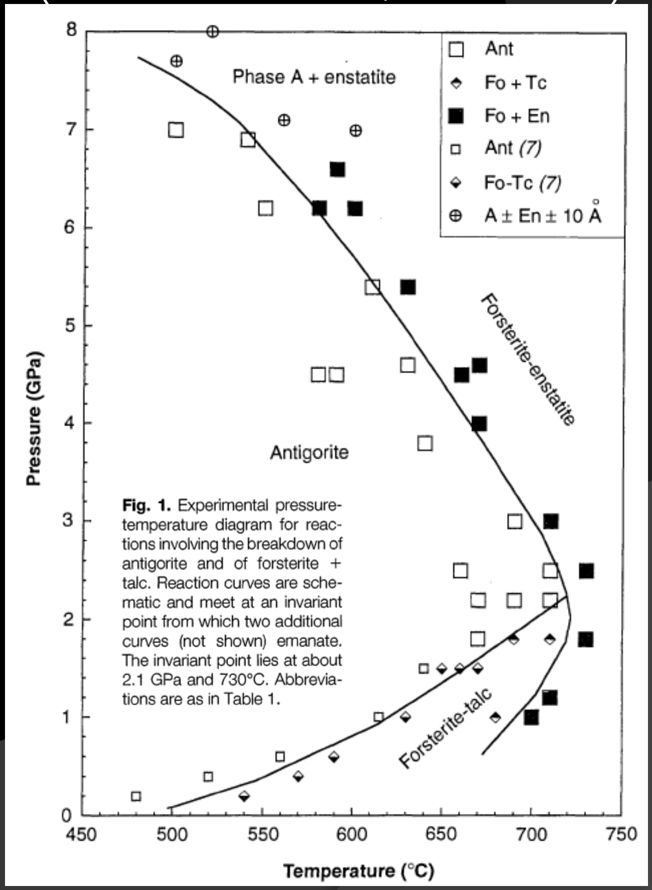


Fig. 1. Experimental pressure-temperature diagram for reactions involving the breakdown of antigorite and of forsterite + talc. Reaction curves are schematic and meet at an invariant point from which two additional curves (not shown) emanate. The invariant point lies at about 2.1 GPa and 730°C. Abbreviations are as in Table 1.

$(Mg, Fe)_3Si_2O_5(OH)_4 \longrightarrow (Mg, Fe)_2SiO_4 + (Mg, Fe)SiO_3 + 2H_2O$

- **Viscosity changing**
  - Deformation experiment of Serpentine: (Hilairet+ 2007)
    - @1 and 4 GPa, 200~500 C
    - Strain rate 10^{-6}~10^{-4} /s
  - Viscosity ~ 1x10^{20} Pas@10^{-14} /s

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

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

(Karato+ 1986)

- **Reaction (endothermic) heat**
  - ~4x10^5 J/kg (Weber+ 1965).

Framework of the numerical simulation

1-D Model for thermal history

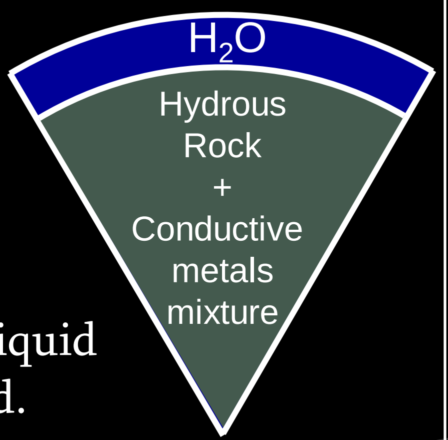
$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot \left(F_{cond} + F_{conv}\right) + \rho Q$$

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

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

(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

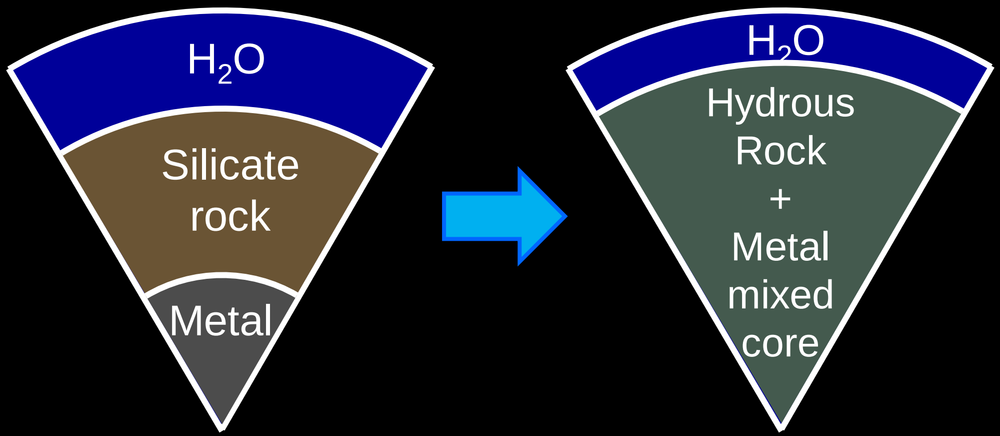
$$\eta_{hyde} = \left(1.0 \times 10^{20}\right) \exp\left(3.8 \times 10^2 / T\right)$$

-> if dehydrated (T>900 K),

$$\eta_{dehy} = 4.9 \times 10^8 \exp\left(23.25 T_m / T\right)$$

Structural settings

◎ Ganymede model



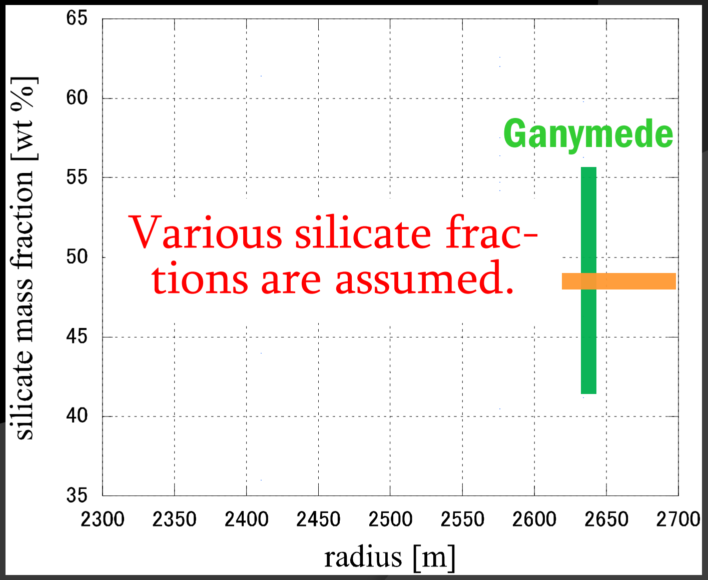
3-layered interior constrained by MoI and bulk density (Anderson+, 1998)

2-layered interior model as initial condition for the thermal history

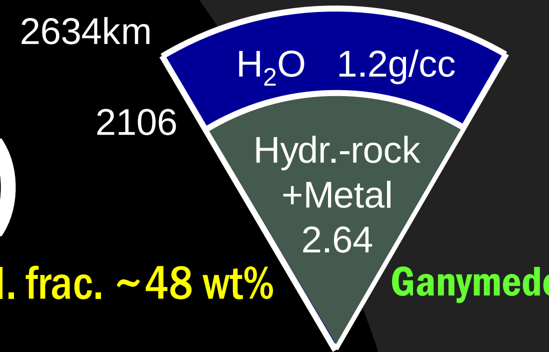
◎ Parameters

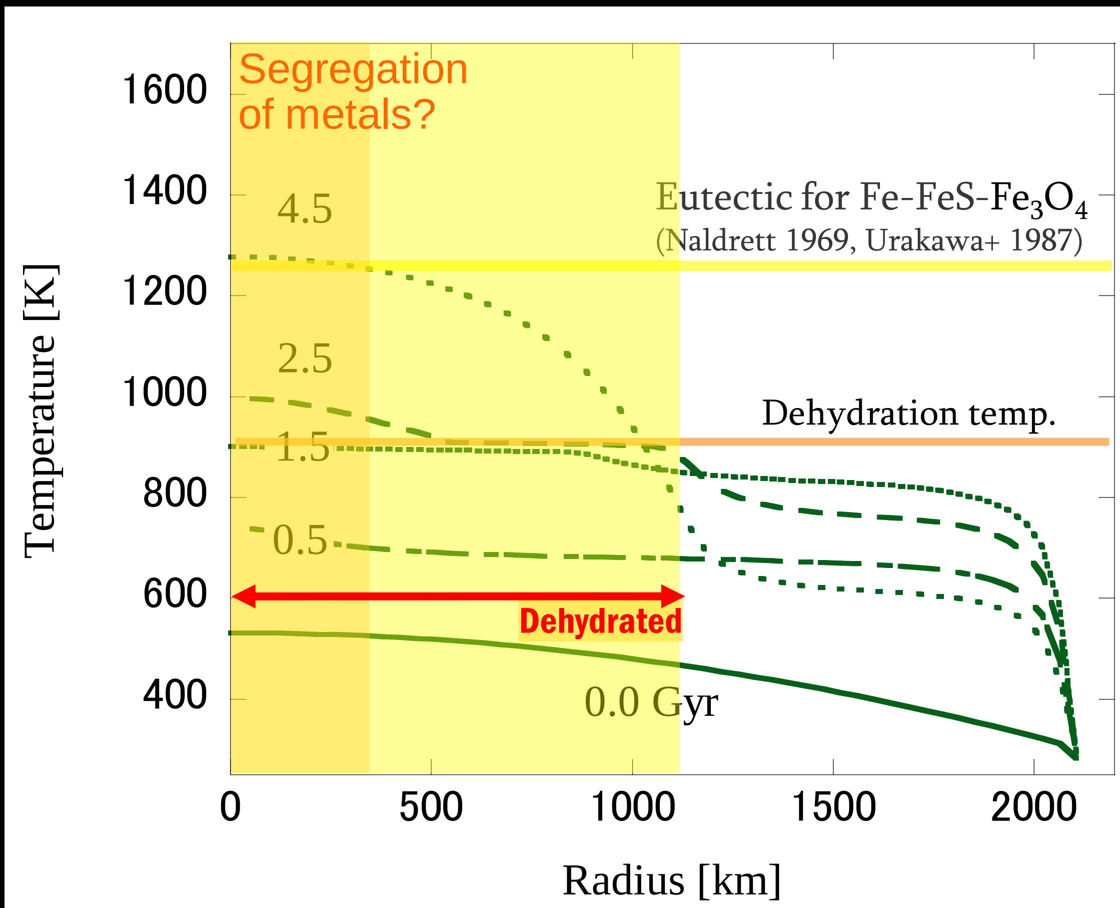
Densities

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



Results: Temperature profiles (primordial core)



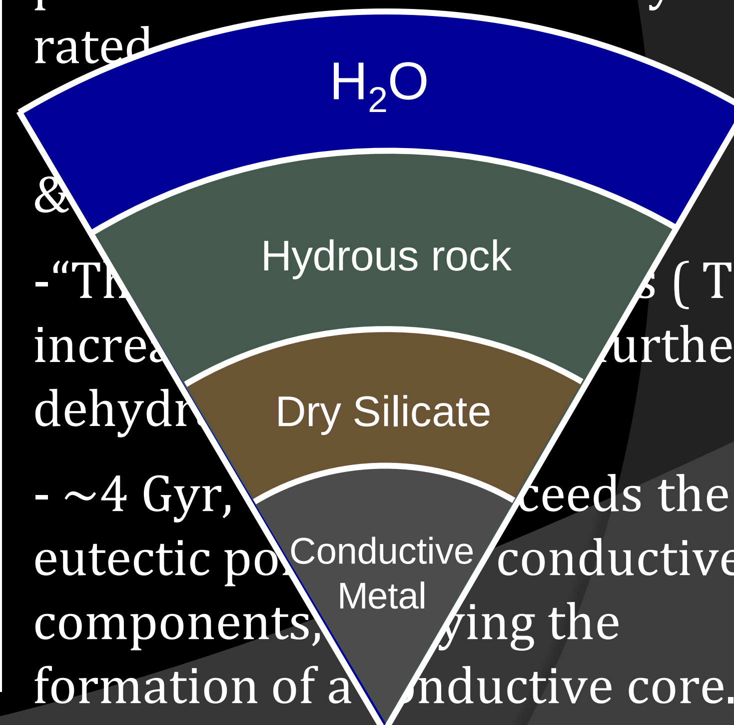


- ~1.0-1.5 Gyr, deeper region in primordial core will be dehyd-rated

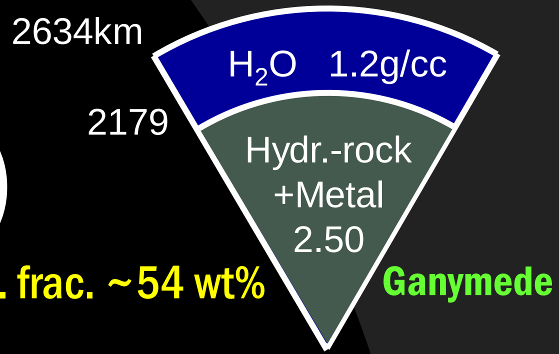
&

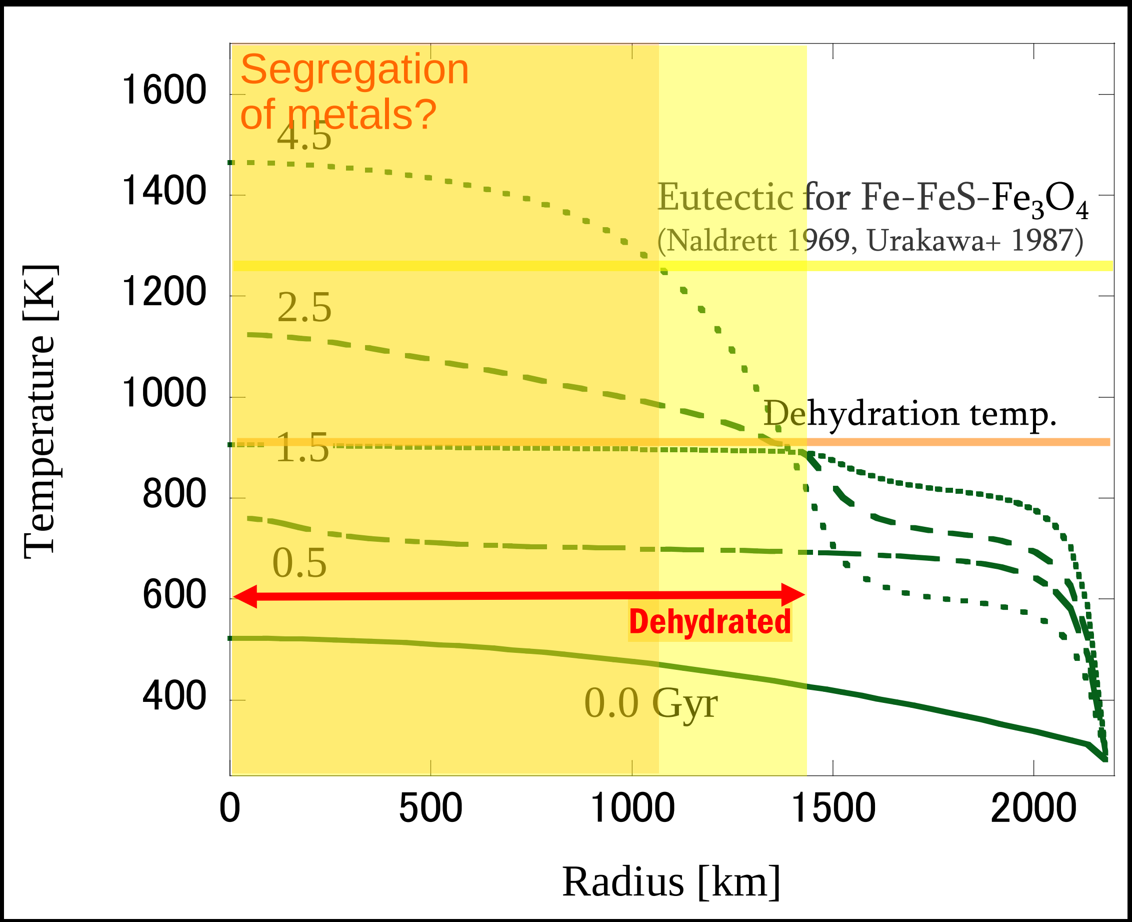
-“Th… s (T increa… urther dehydr…

- ~4 Gyr, … ceeds the eutectic po… conductive components, … ying the formation of a … nductive core.

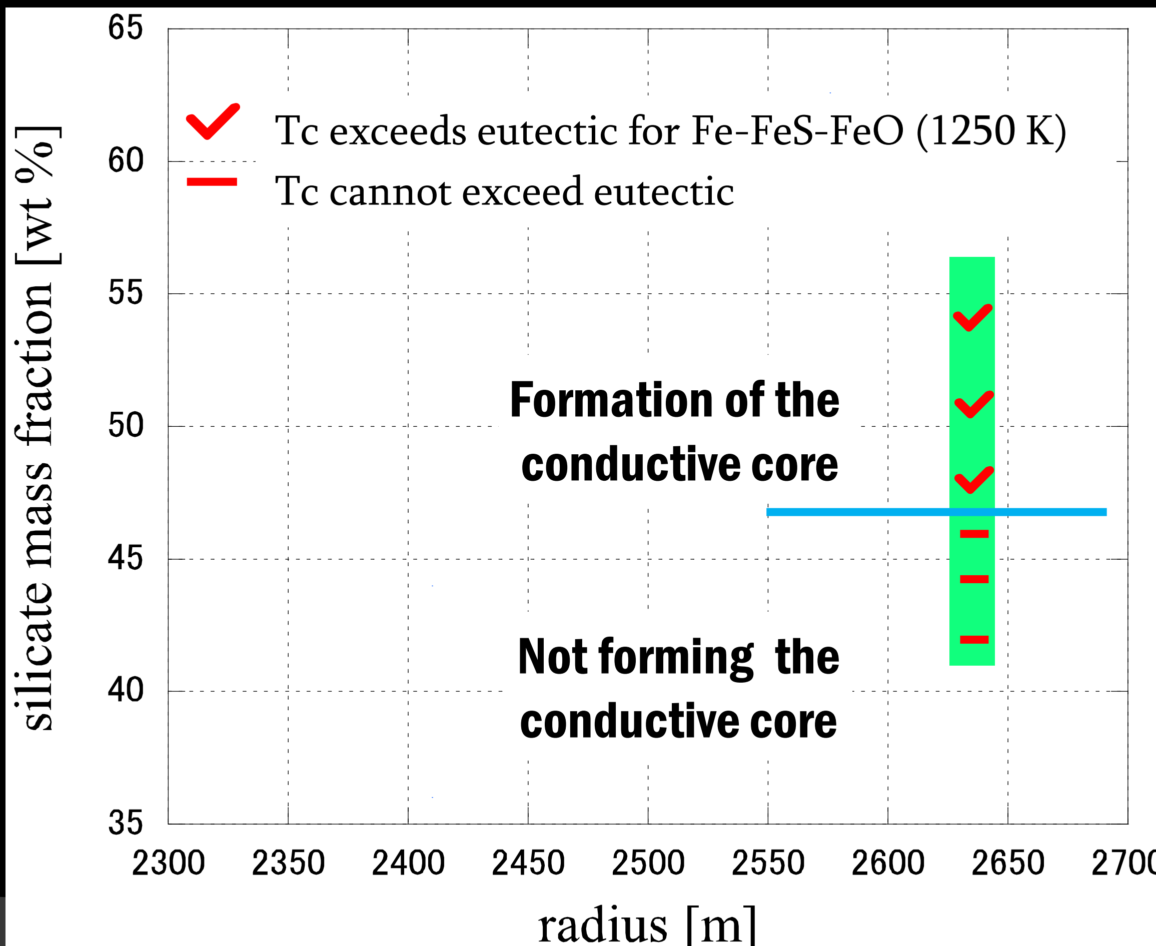


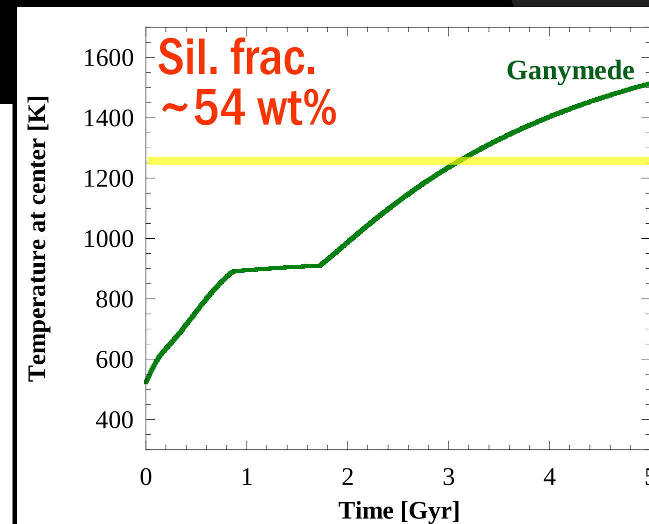
Results: Temperature profiles (primordial core)

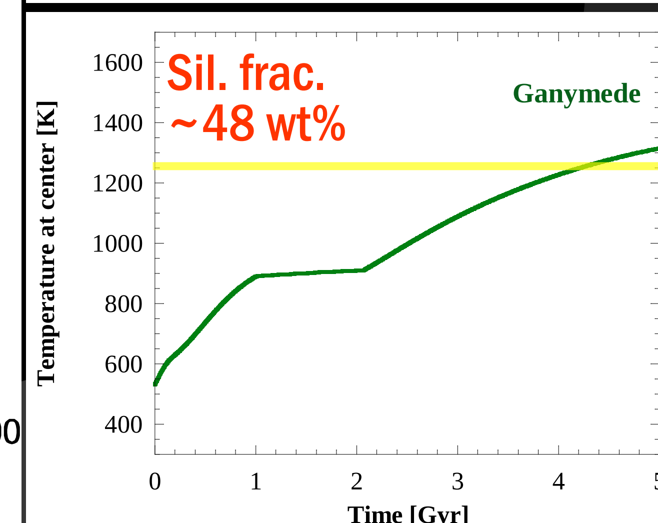




Systematic simulations with various silicate fractions (core forming-diagram)

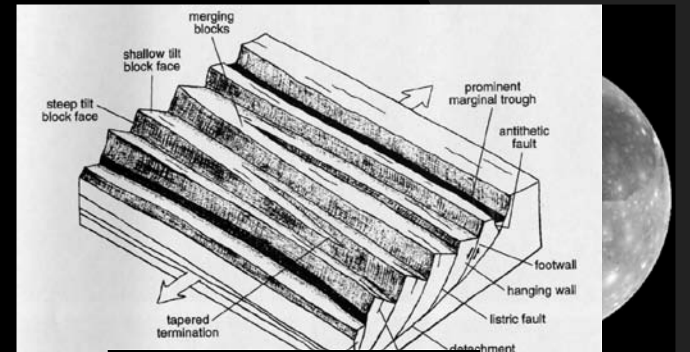




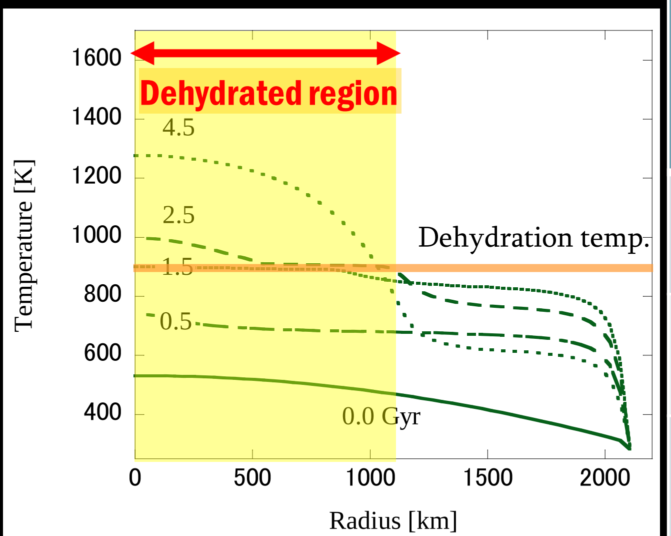


Dehydration could explain to induce surface extensional tectonics?

- Grooves on Ganymede - grabens resulting from lithspheric extension (global expansion).
- Required radius increase of 0.02-1% (Golombek 1982), 2.5-4 % (Collins 2008).
- Dehydr. of serpentine -- 10.3 vl% incr. (Kono+ 2007).

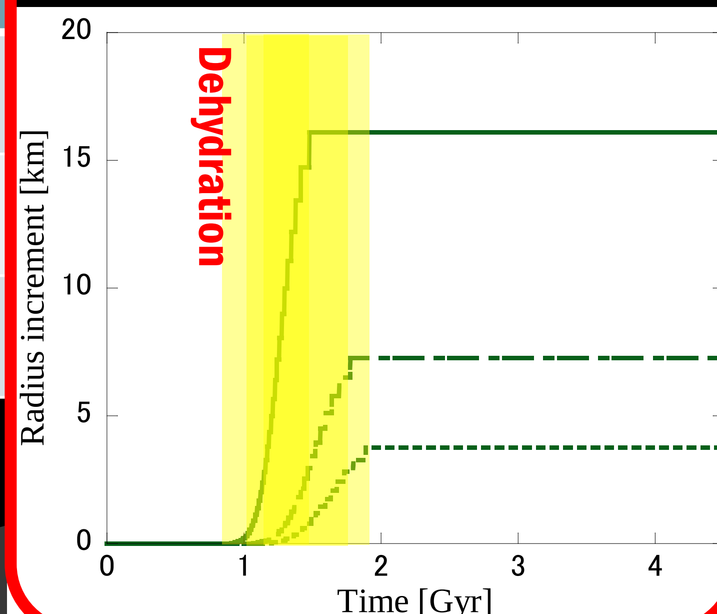


Pappalardo el al. [1998]



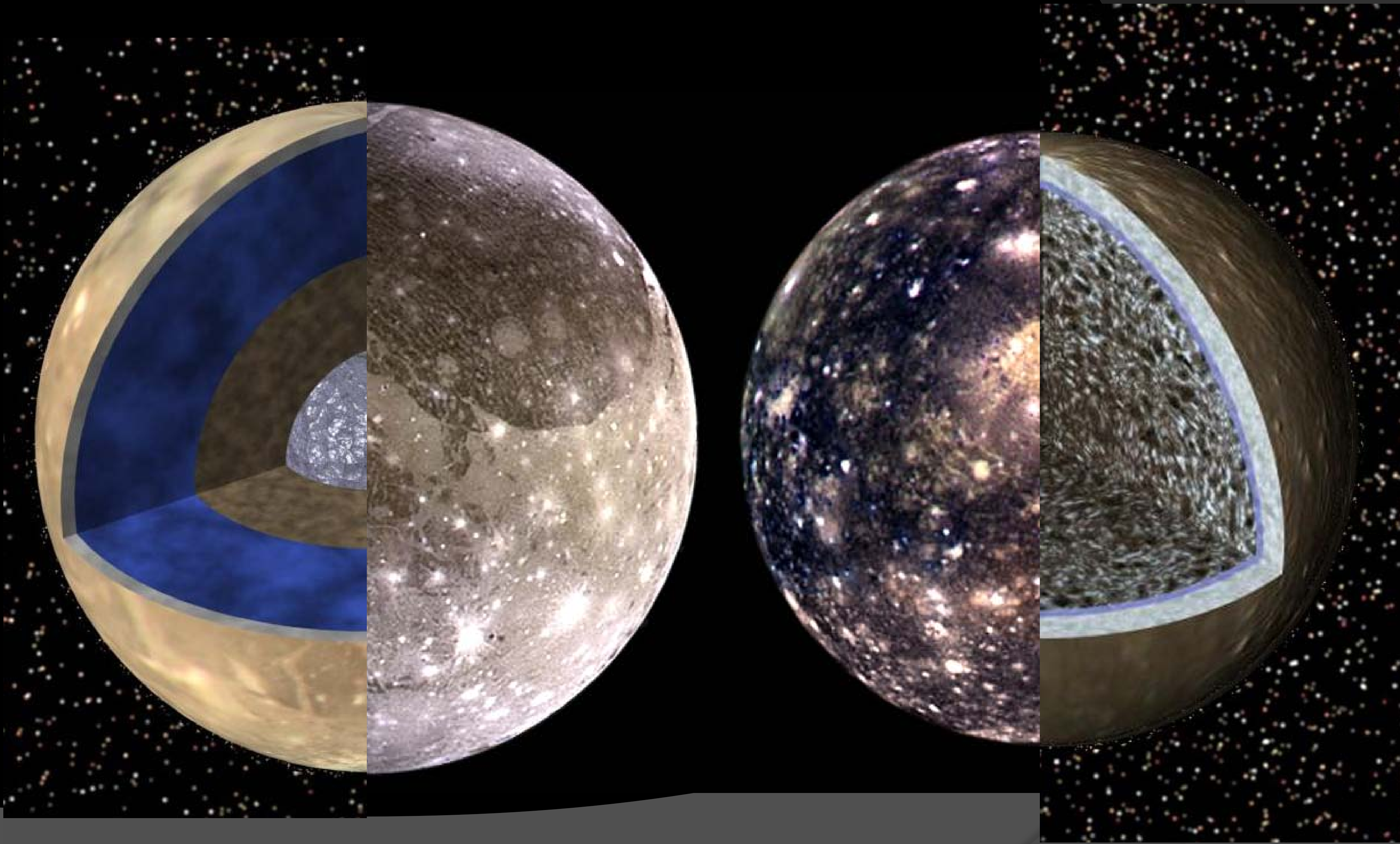
Dehydrated radius in the primordial core	Radius increase (ratio to the moon's radius)
1482 km (f_{sil}~54 %)	16.1 km (0.61 %)
1137 km (f_{sil}~48 %)	7.3 km (0.28 %)
912 km (f_{sil}~46 %)	3.8 km (0.14 %)

Cratering age ~2.0 Ga? (Zahnle+ 2003)

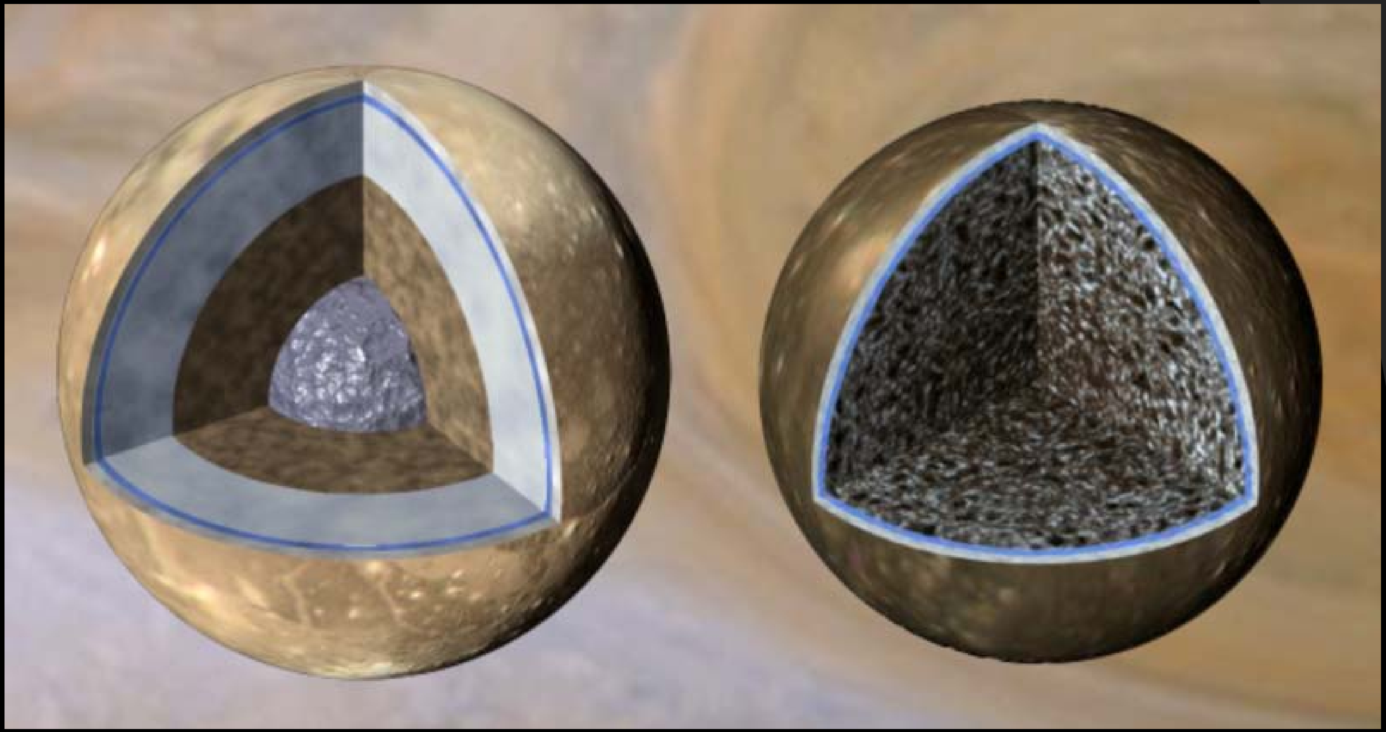


- Radius increase and dehydration age are roughly consistent with the previous geological estimate and the cratering age.

じゃあ，カリストは？



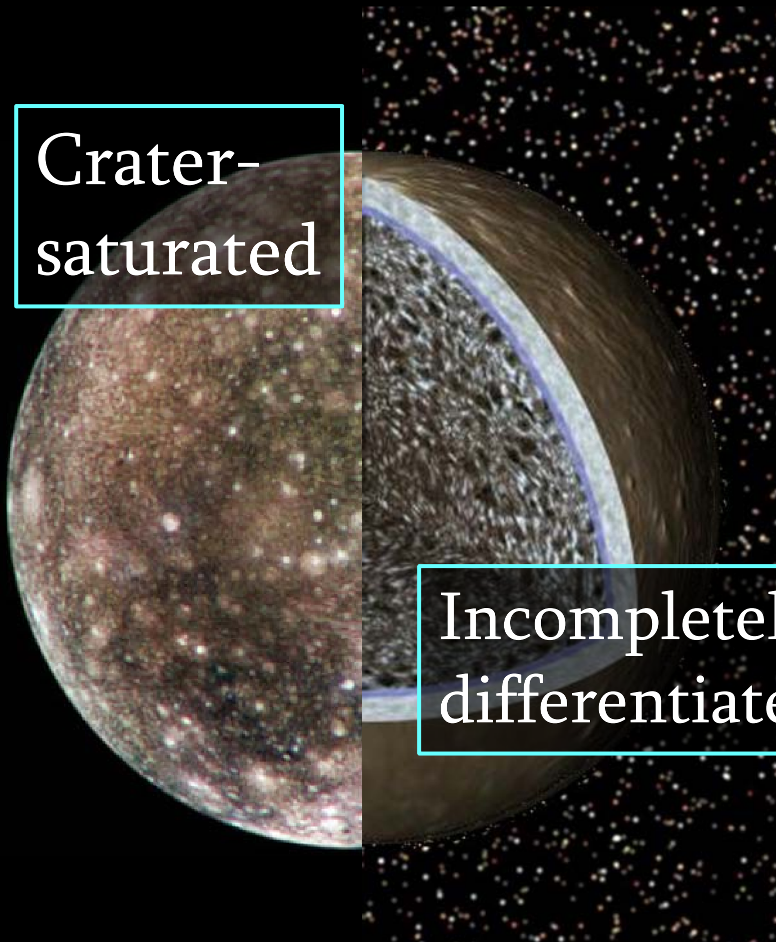
Ganymede and Callisto



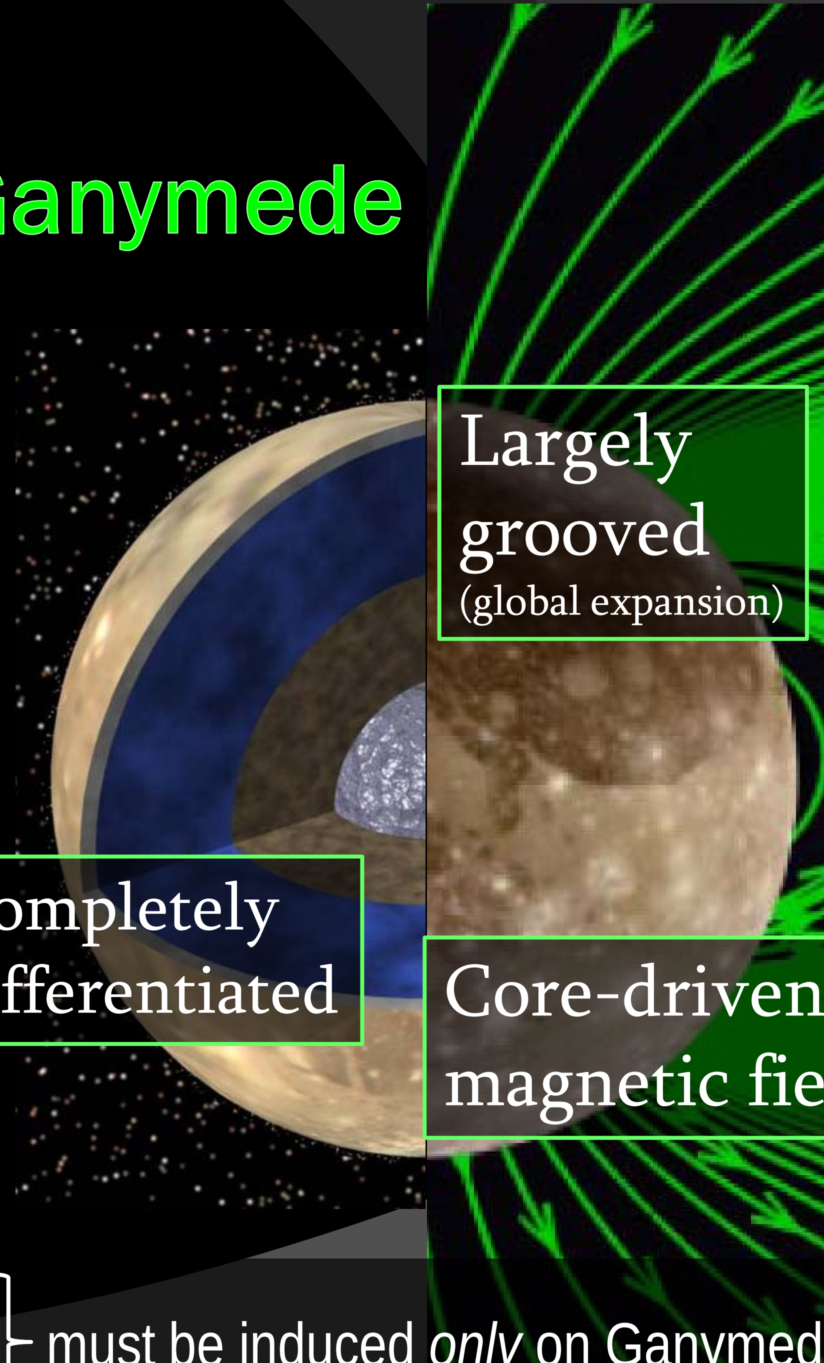
Radius	2634 km	2403 km
Mean density	1.936 g/cc	1.834 g/cc
Surface	Tectonic	Heavily cratered
Interior	Clearly differentiated	Incompletely

Ganymede and Callisto have similar size and mean density, but they have remarkably different interiors.

Callisto



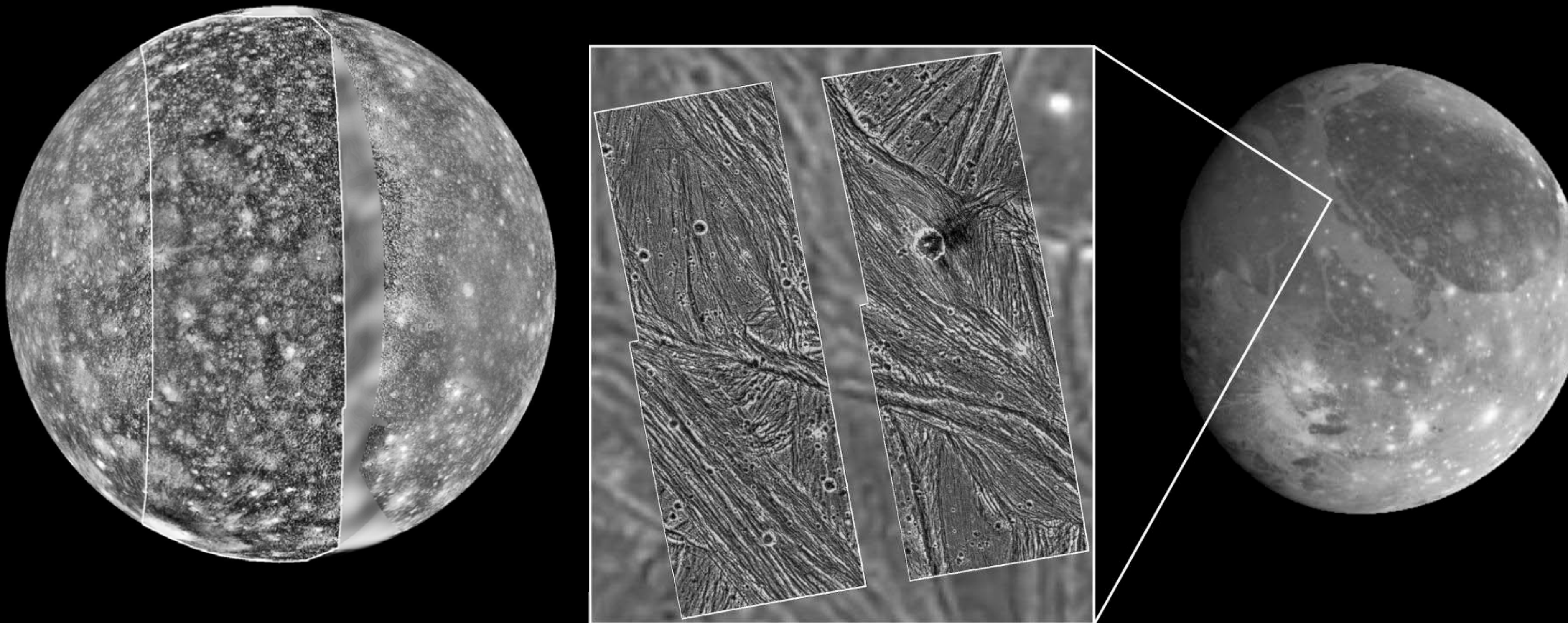
Ganymede



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

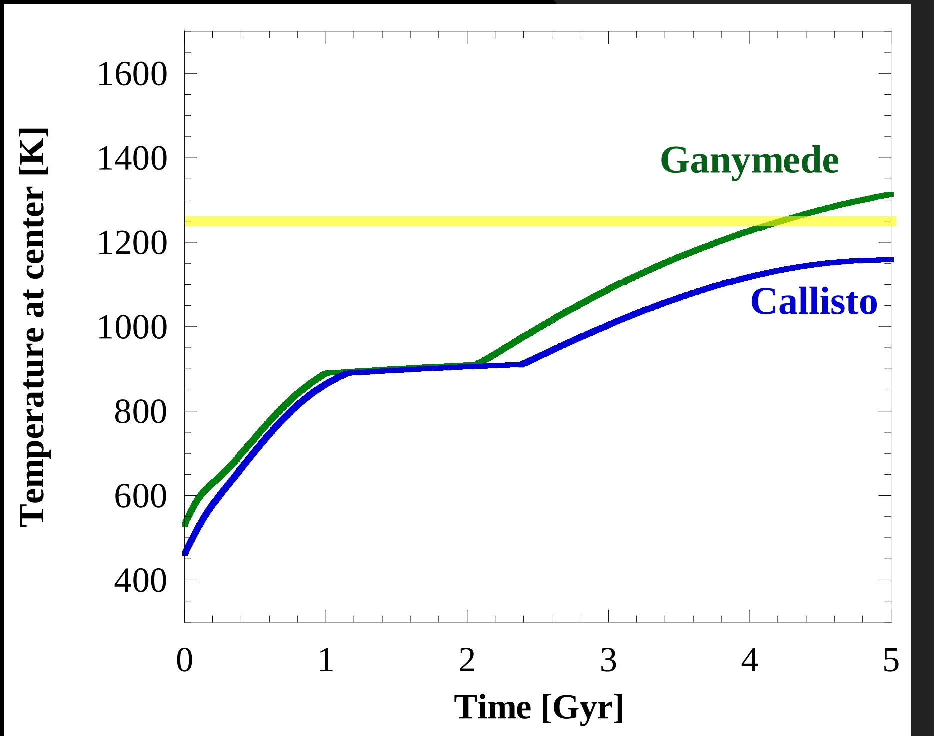
} must be induced *only* on Ganymede

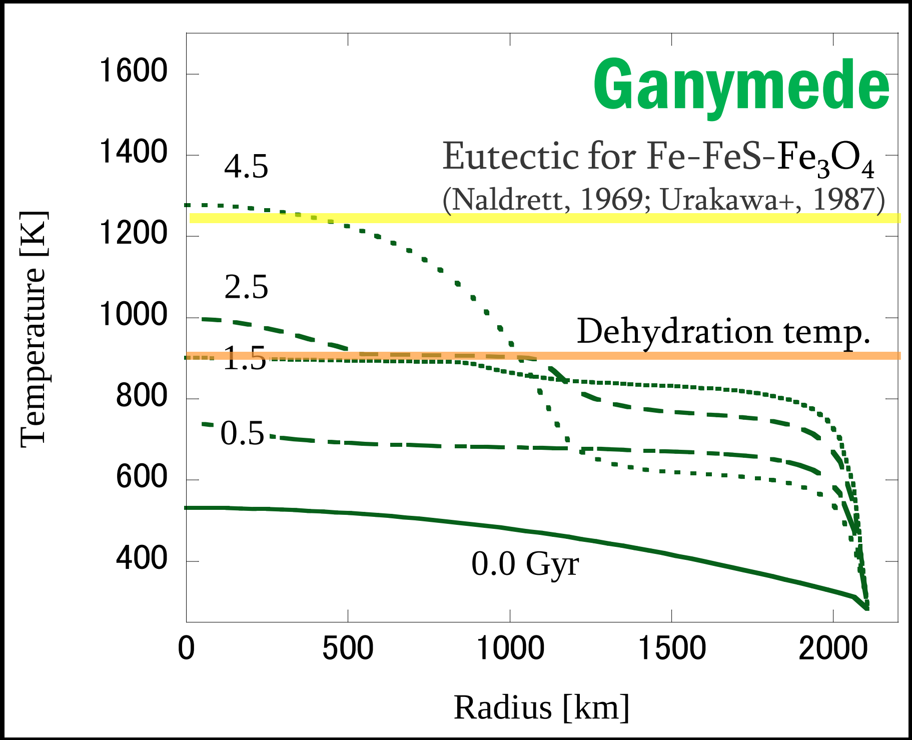
Surface contrasting morphology between Ganymede and Callisto

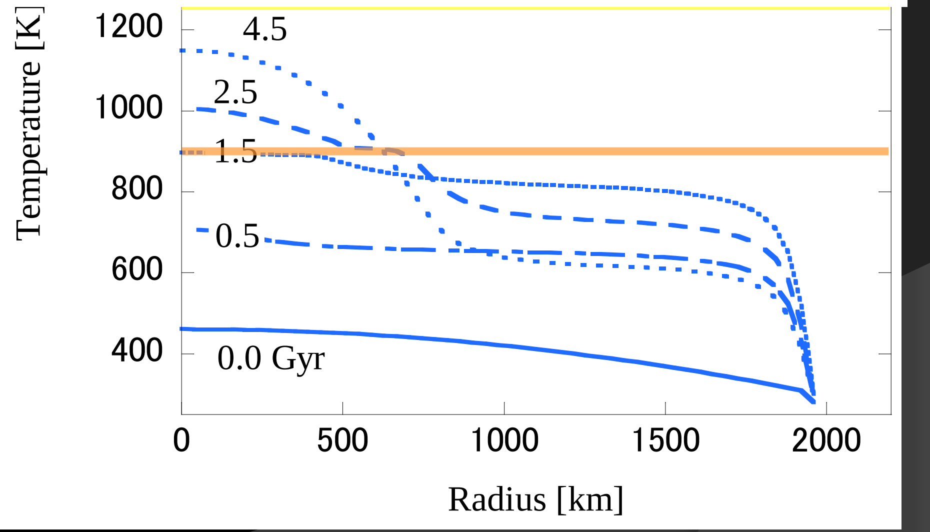


- Ganymede - tectonic & cratered surface (~2 Ga)
- Callisto - crater-saturated surface (~4 Ga)

Results: Temperature profiles

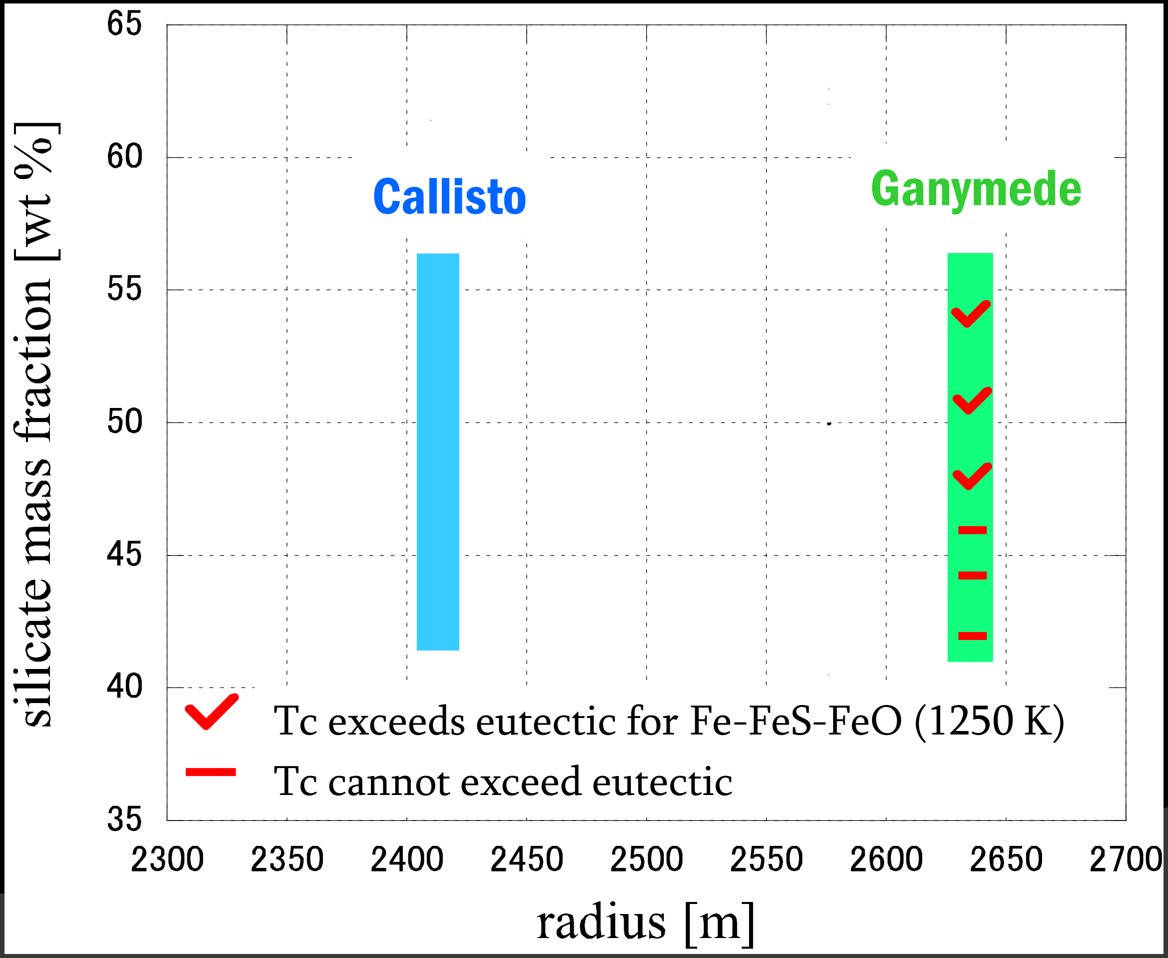




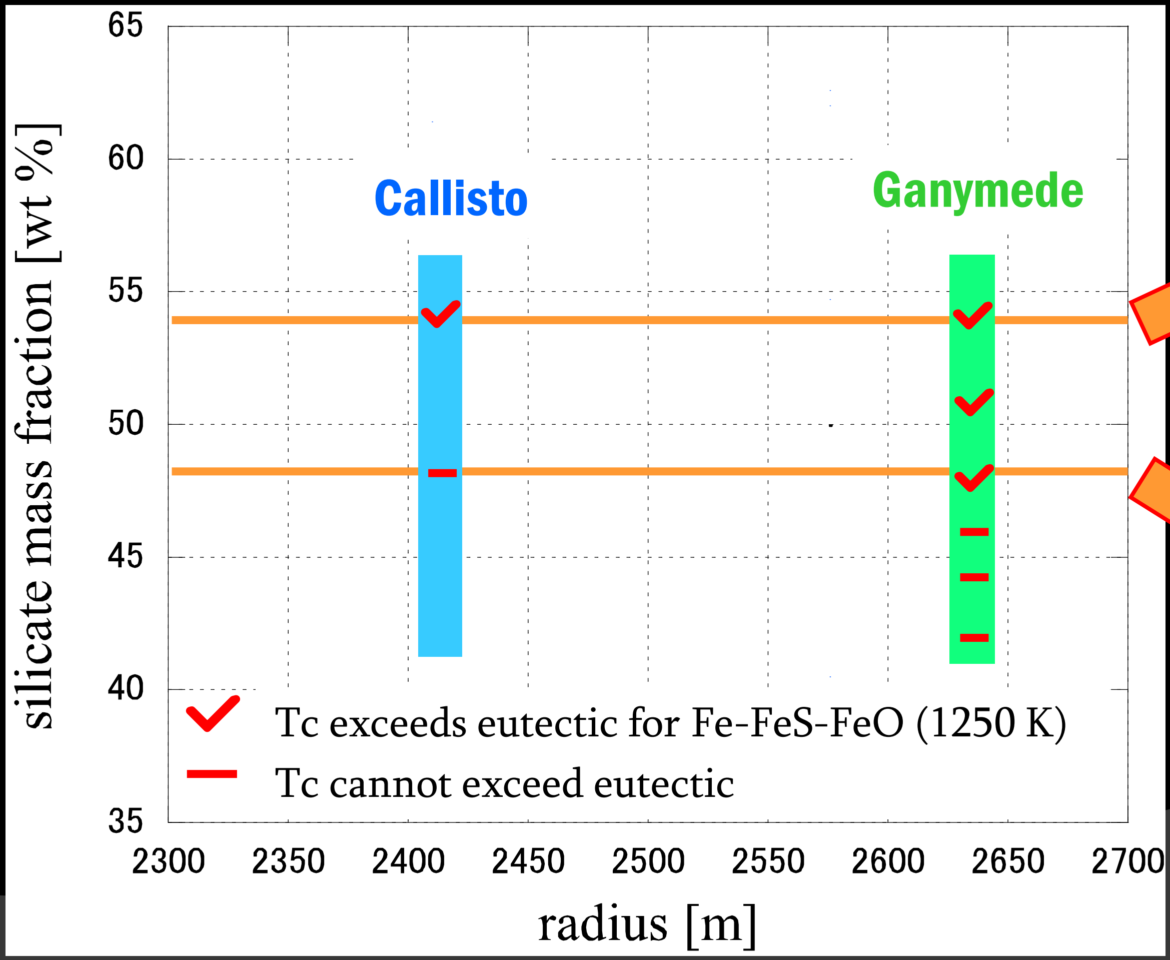


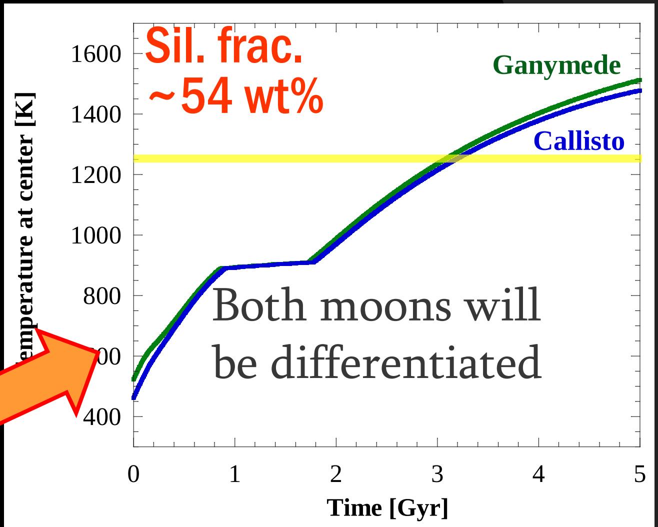
- implying the formation of a conductive core only in Ganymede, and the creation of an interior dichotomy.

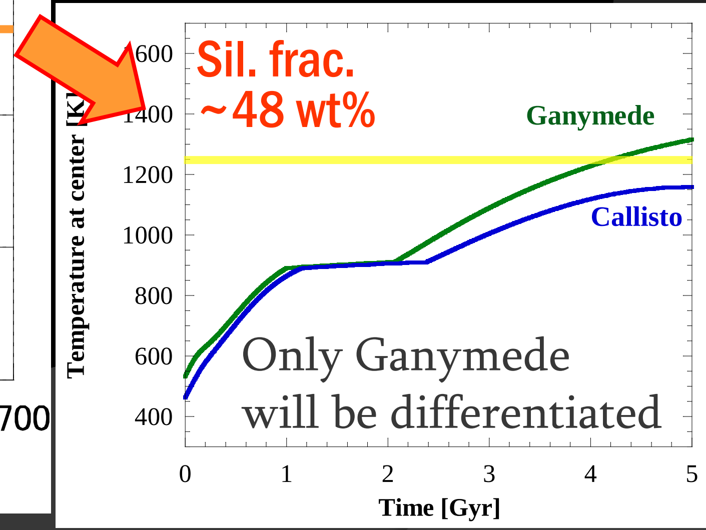
Systematic simulations with various silicate fractions



Systematic simulations with various silicate fractions

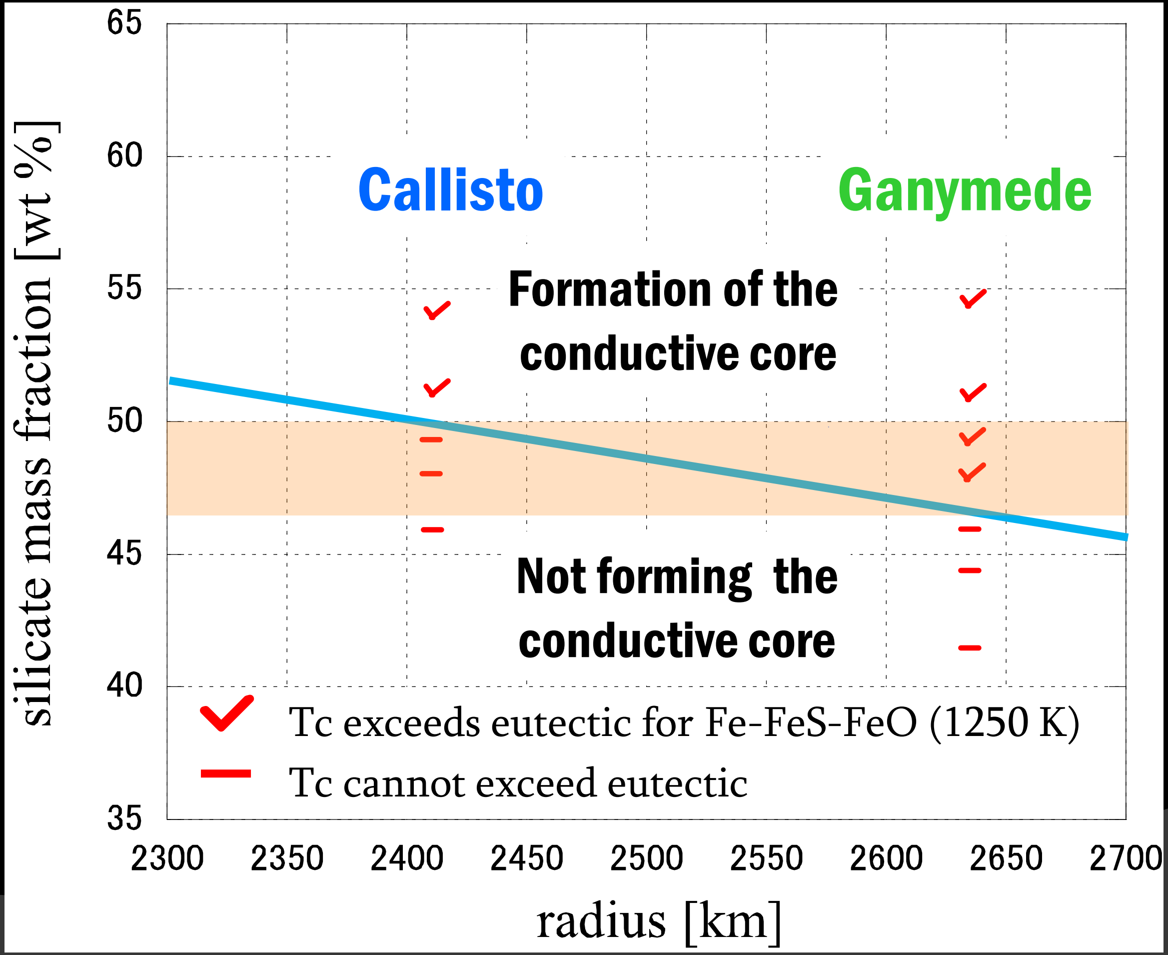






Contrasting interior from Callisto
- Structural regime that is capable of differentiation -

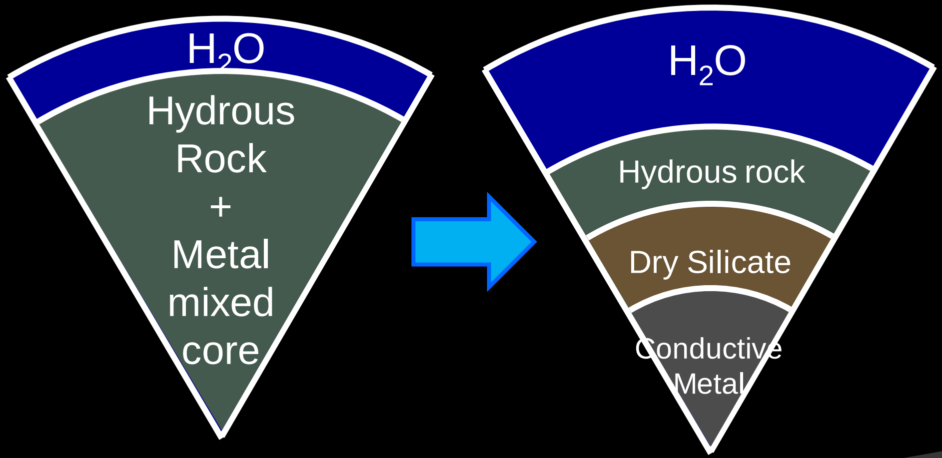
Specific range for the silicate fractions, that is capable of conductive core differentiating



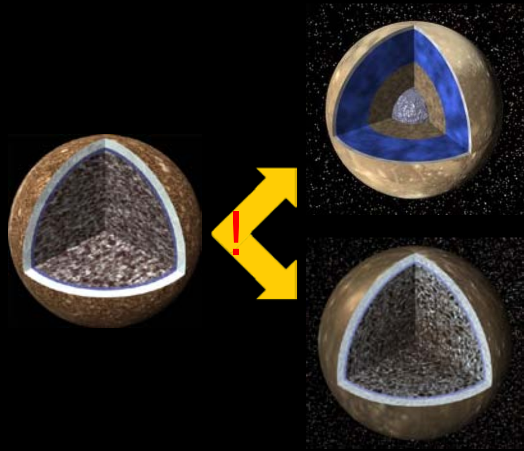
- Smaller moon needs larger silicate fraction to make it possible to form the conductive metallic core.
- For intermediate value of the silicate fraction (47-50 wt%), Ganymede can differentiate, while Callisto cannot.

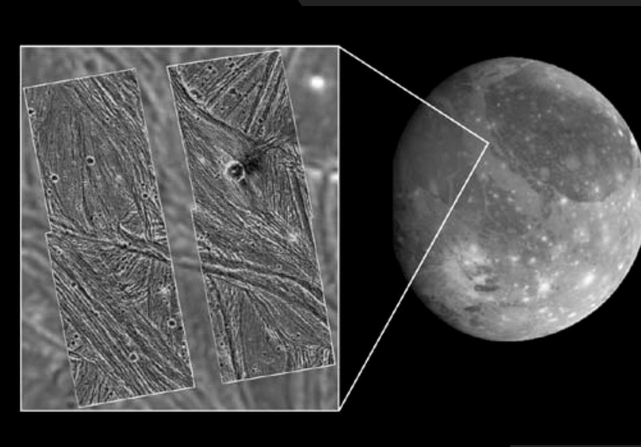
Ongoing works

- Advection heat transport due to a released water associated with dehydration
- Structural evolution associated with dehydration, thickening the outer water layer while shrinking the inner region.
- Comparing final state for the interior structure in these simulations with the current moment of inertia.



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.

宇宙惑星科学(P) / 惑星科学(PS) / **国際セッション

P-PS02 Toward future explorations of Jupiter and Saturn system

プログラム掲載短縮名	Jovian and Saturnian explorations		
口頭発表 発表日時／会場／座長	5月24日 PM1 (13:45 - 15:15)	301A	木村 淳 谷川 享行
	5月24日 PM2 (15:30 - 17:00)	301A	圷 千尋 笠羽 康正
ポスター発表 発表日時／会場	5月24日 (コアタイム 17:00 - 18:30)		
連絡先	木村 淳		
メールアドレス	junkim@ep.sci.hokudai.ac.jp		
コンビーナ	木村 淳 藤本 正樹 笠羽 康正 佐々木 晶		
スコープ	Giant planets are the most prominent representative bodies not only in the solar system but also in the extrasolar systems. In this session, origin, interior, atmosphere, composition, surface feature, and electro- magnetic field etc. of the Jovian planets and the icy moons will be comprehensively discussed. Toward future exploration missions, we'd like to promote the study of giant planetary systems, and also progress in developing a solar sail mission to observe Jovian system and Trojan asteroids will be discussed.		
発表者への注意事項	国際セッションですので，講演は英語でお願いします．		

Session Title	**Icy Satellites and Rings**
Session Description	This session will be devoted to outer planet satellites, rings and icy dwarf planets. The session will include solicited, contributed, and poster presentations addressing observational, laboratory, and theoretical studies relevant to past, ongoing, and future missions. Relevant topics include: (1) interior structure, composition and thermal evolution, (2) surface geology and composition, (3) orbital dynamics and satellite interactions, (4) structure and dynamics of planetary rings, (5) physical properties of ring particles and small satellites of outer planet satellites.
Expected Duration of Session	1 day
Preliminary List - Invited Speakers	Frank Spahn (Univ of Potsdam) Christophe Sotin (JPL) Ozgur Karatekin (Royal Observatory of Belgium)
Main Convener	Dr. Jun Kimura (Hokkaido University, Japan), junkim@ep.sci.hokudai.ac.jp
Co-convener(s)	Dr. Hauke Hussmann (German Aerospace Center, Germany), hauke.hussmann@dlr.de Dr. Frank Postberg (Universitaet Heidelberg, Germany), Frank.Postberg@mpi-hd.mpg.de Dr. Frank Sohl (DLR, Germany), frank.sohl@dlr.de Dr. Mathieu Choukroun (Jet Propulsion Laboratory, California Institute of Technology, United States), mathieu.choukroun@jpl.nasa.gov