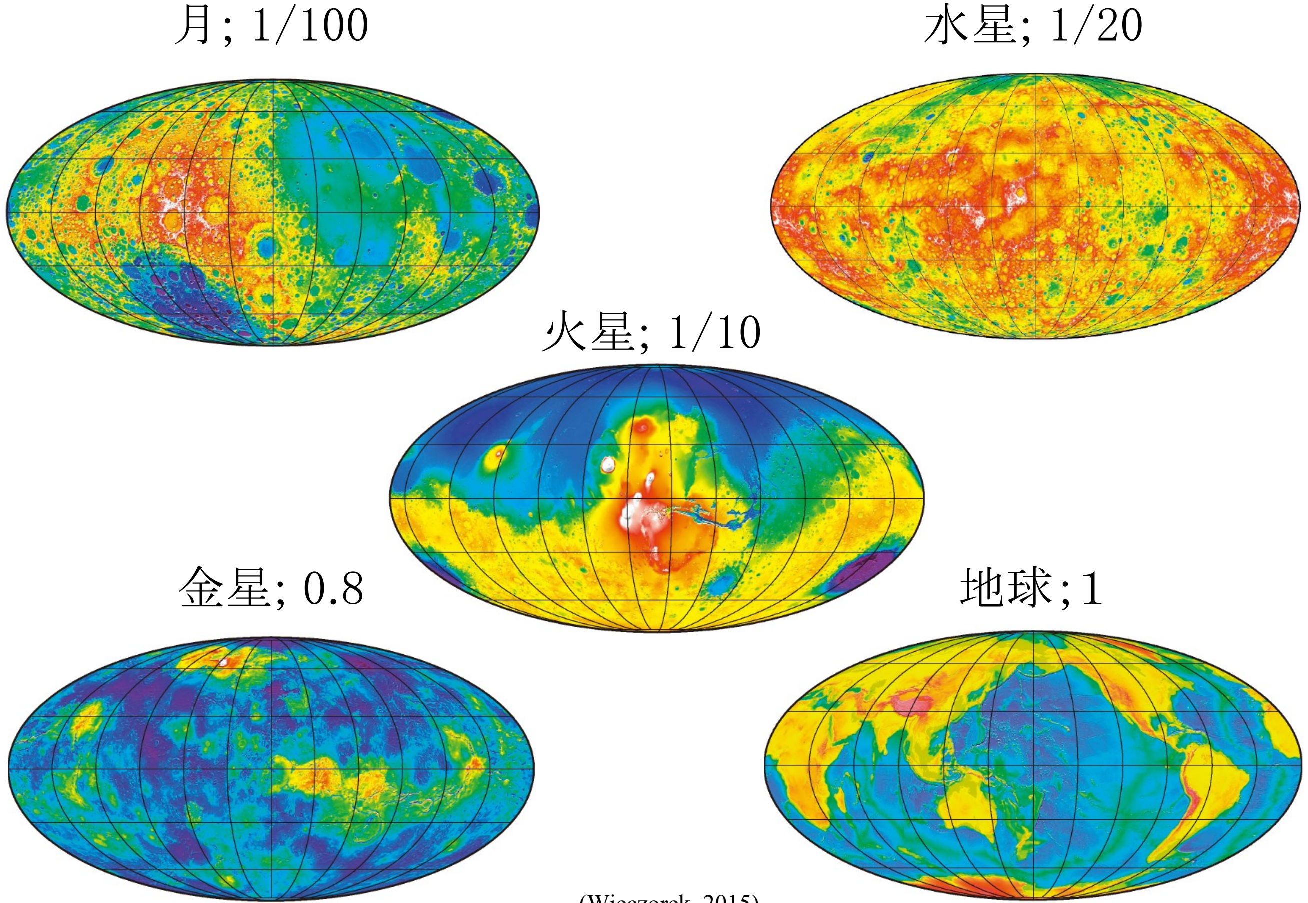
第二部　地球型惑星の内部進化

地球を理解するための比較惑星学



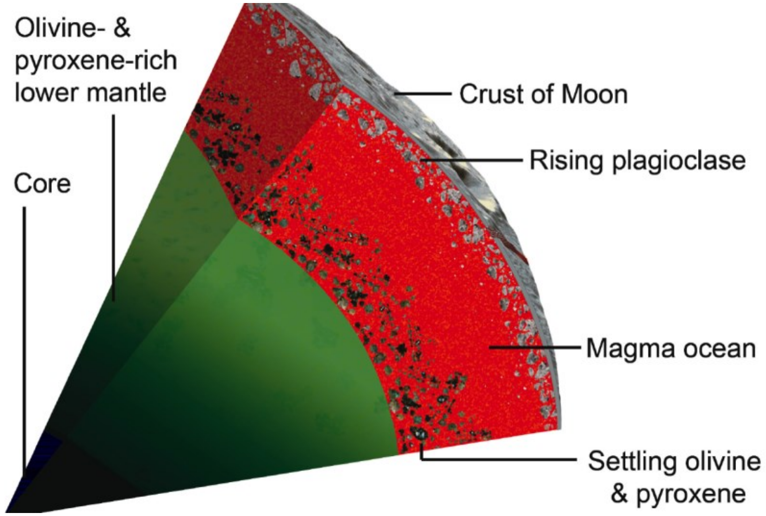
(Wieczorek, 2015)

第4章　月：惑星内部進化の雛形？

巨大衝突による形成
高温起源

NASA作成：wikipediaより引用

マグマ・オーシャン
地殻形成・マントルの分化

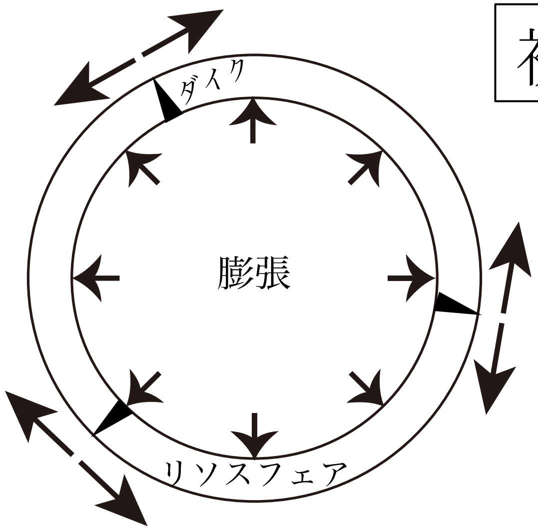


http://www.lpi.usra.edu/exploration/training/illustrations/planetaryInteriors/

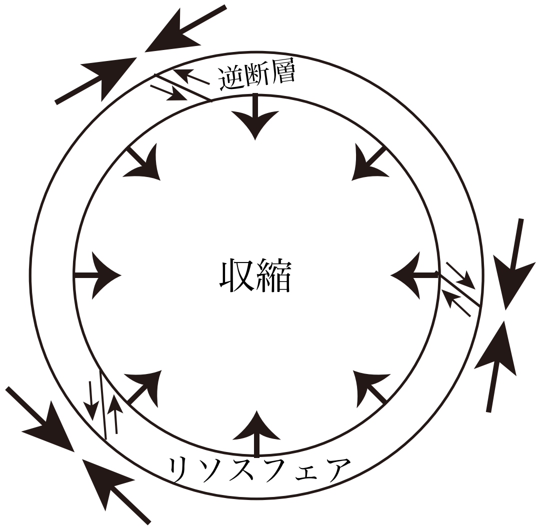
冷却による進化
海の火山活動の減衰

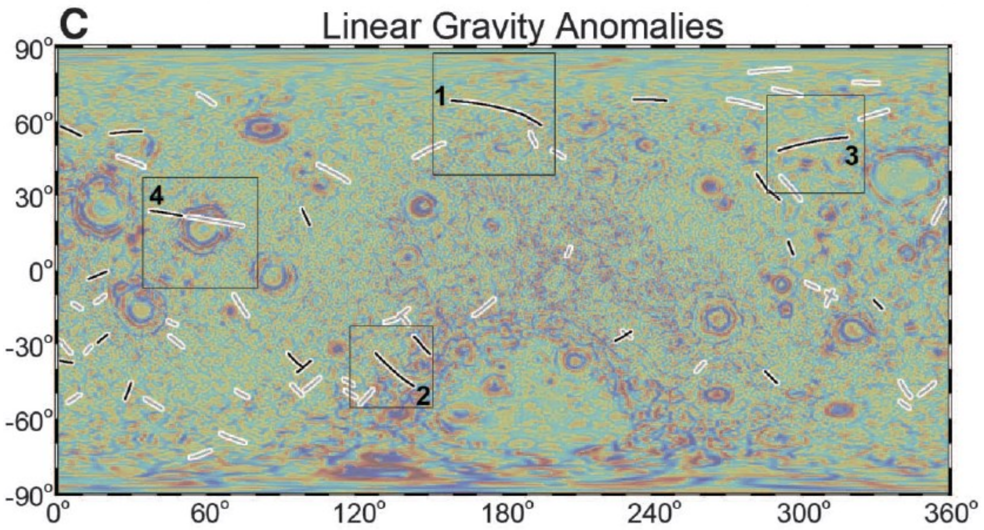
4-1. 熱史・火山活動史・磁場の歴史

月形成
(45億年前)

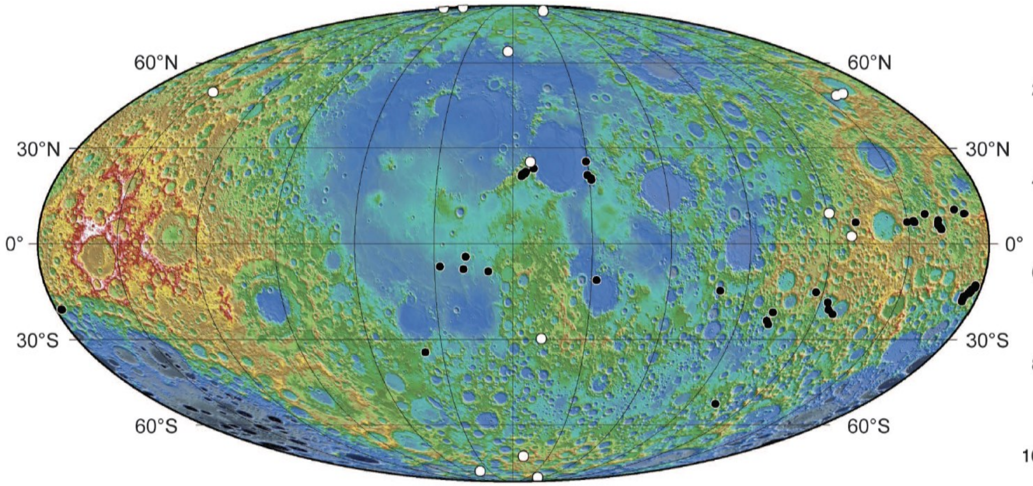


初期膨張とその後の収縮

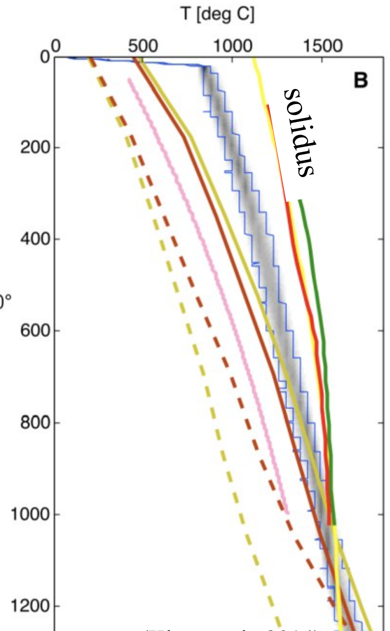




(Andrews-Hanna et al., 2013)

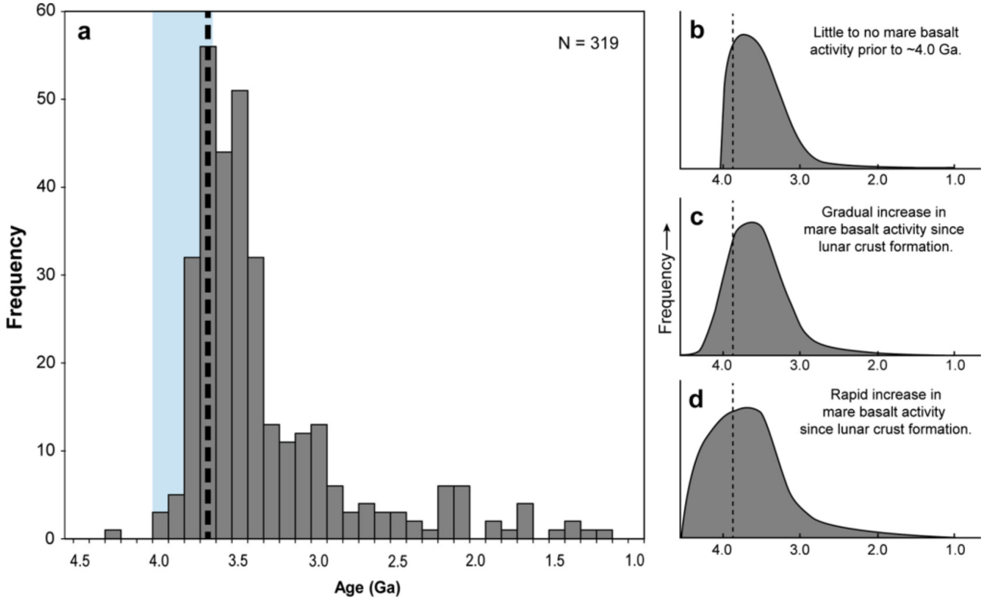


(Watters et al., 2010)

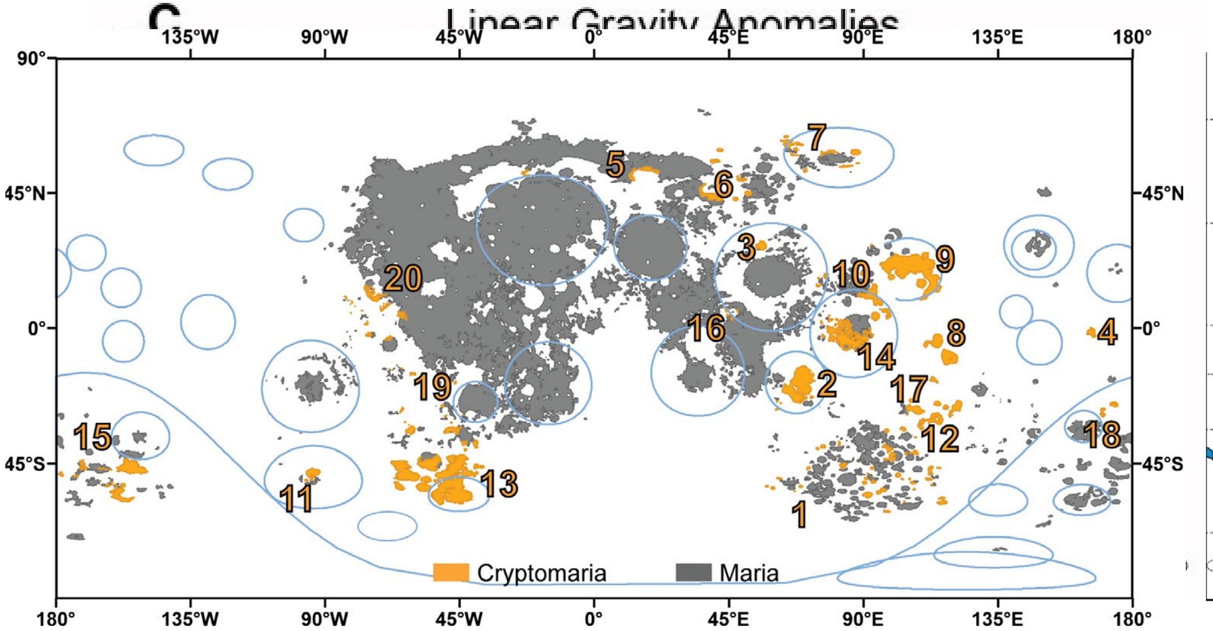


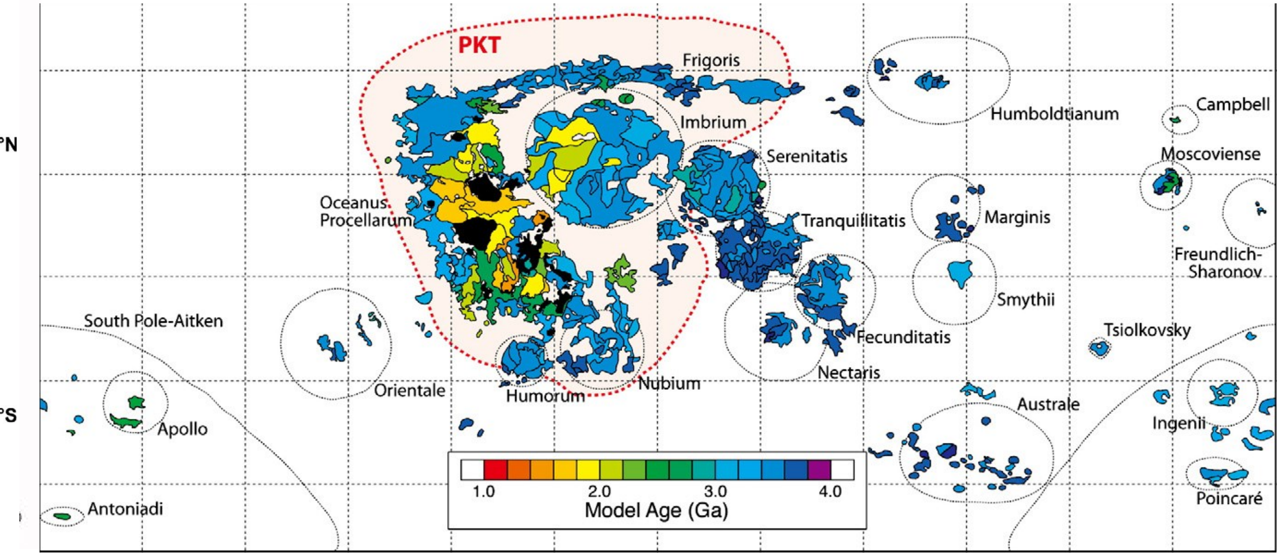
(Khan et al., 2014)

海の火山活動史：40-30億年前のピーク→10-20億年前まで持続



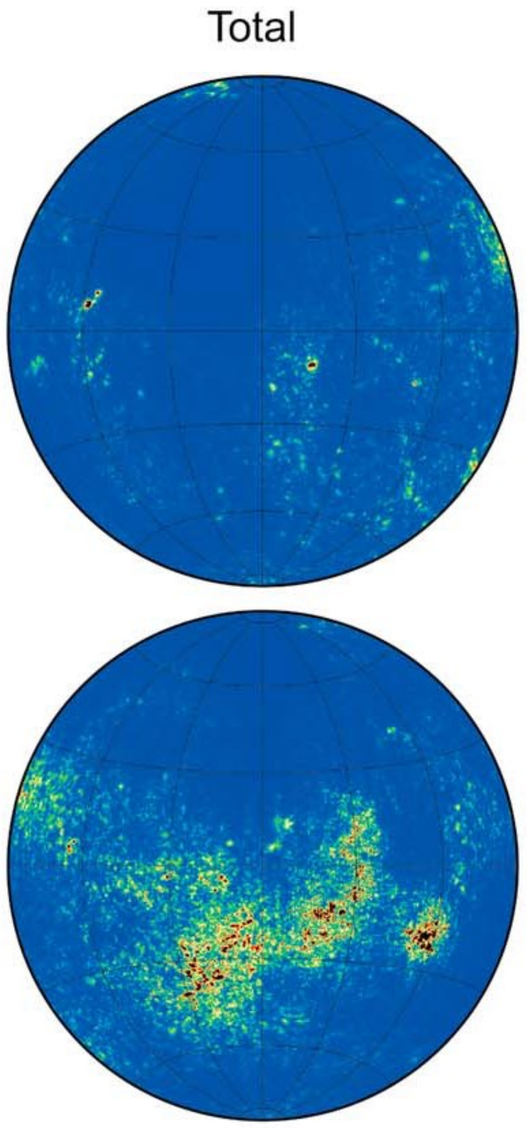
(Hiesinger et al., 2003; Witten & Head, 2015)



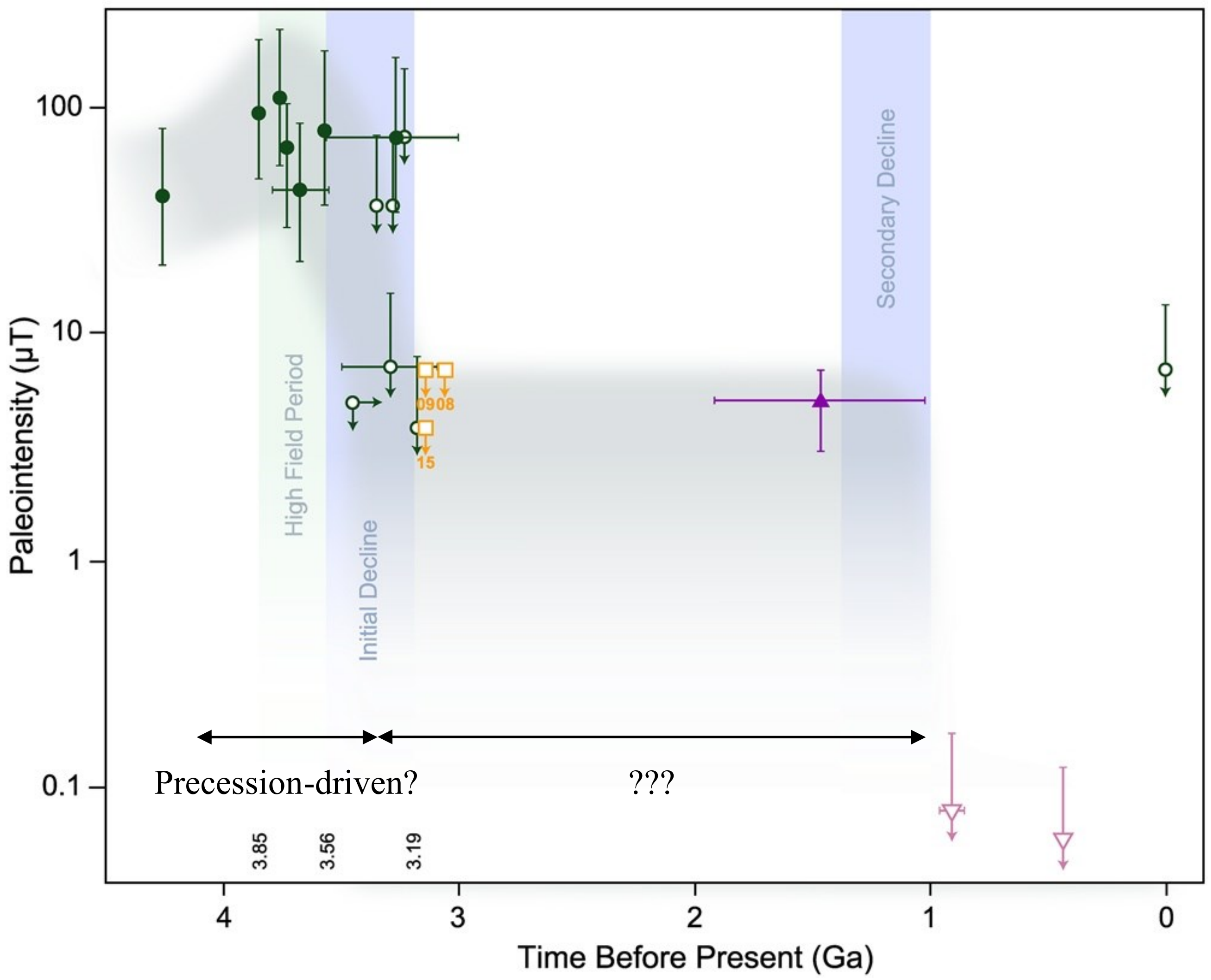


(Morota et al., 2011)

磁場の歴史 → 熱史への制約？:第11章で議論



(Tsunakawa et al., 2015)

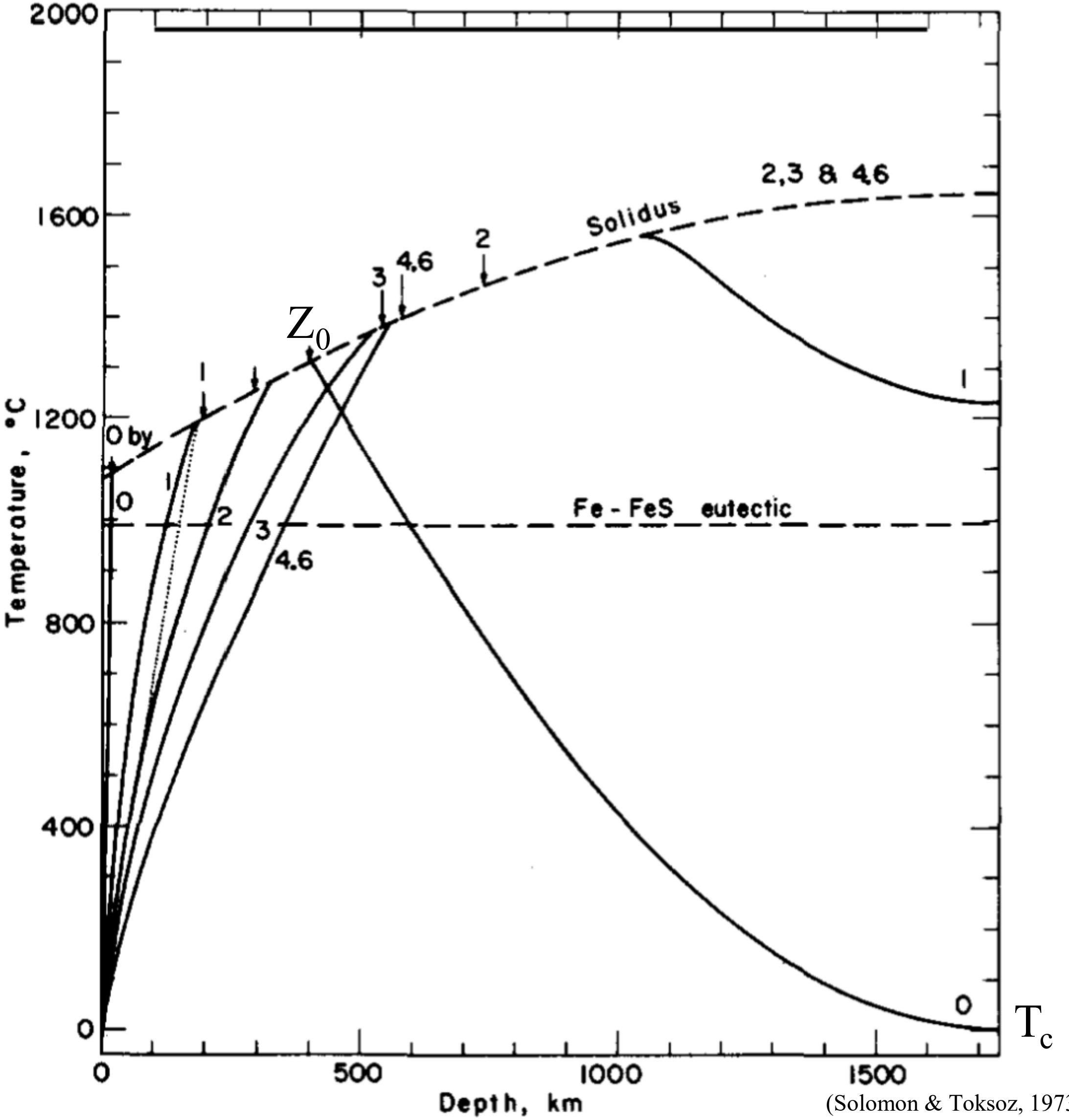


(Strauss et al., 2021)

4-2. マントル進化の低温起源モデル

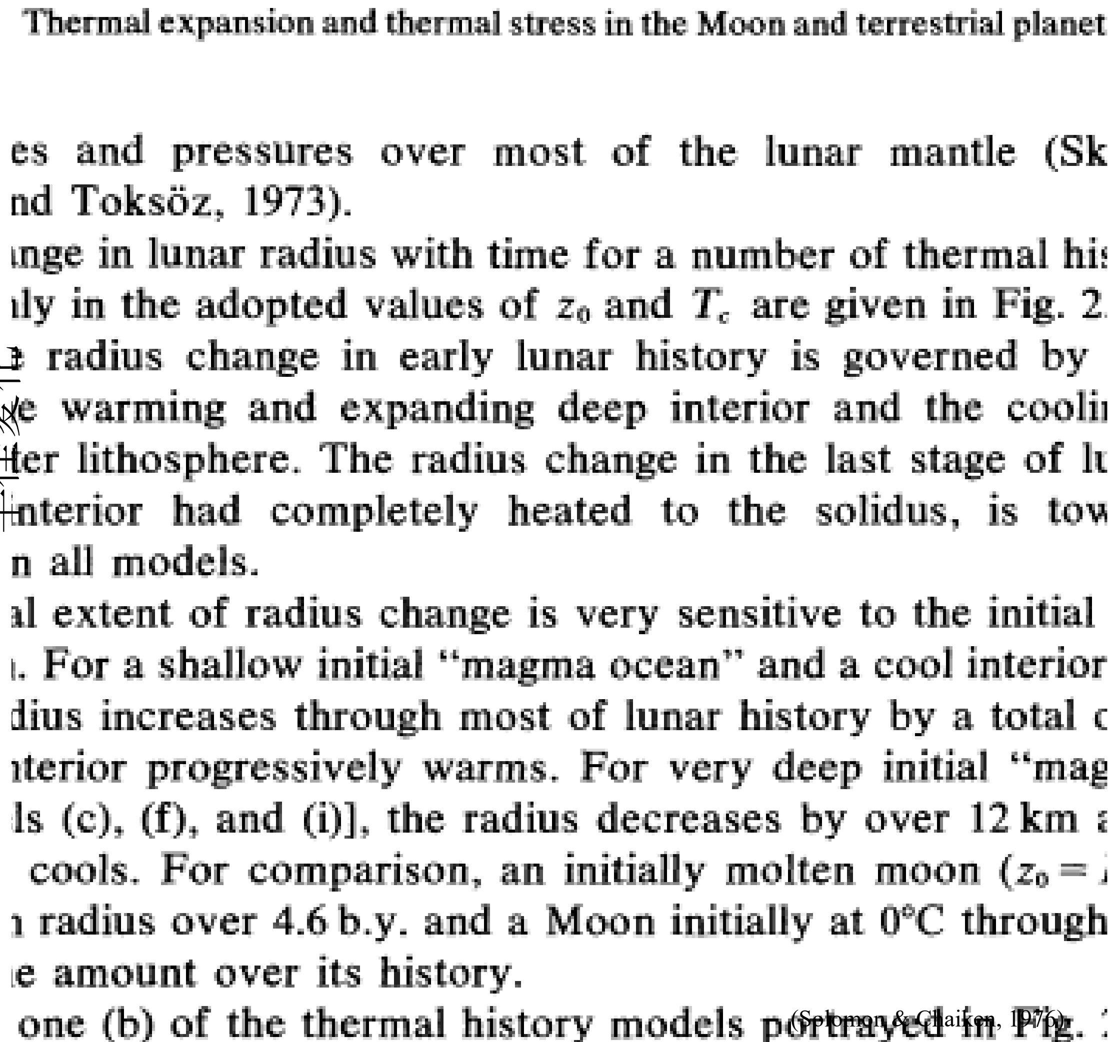
初期の膨張は熱膨張？ $\Rightarrow T_c < 1210\ K, Z_0 = 200 \sim 400\ km$ (Kirk & Stevenson, 1989)

内部温度変化



(Solomon & Toksoz, 1973)

半径変化



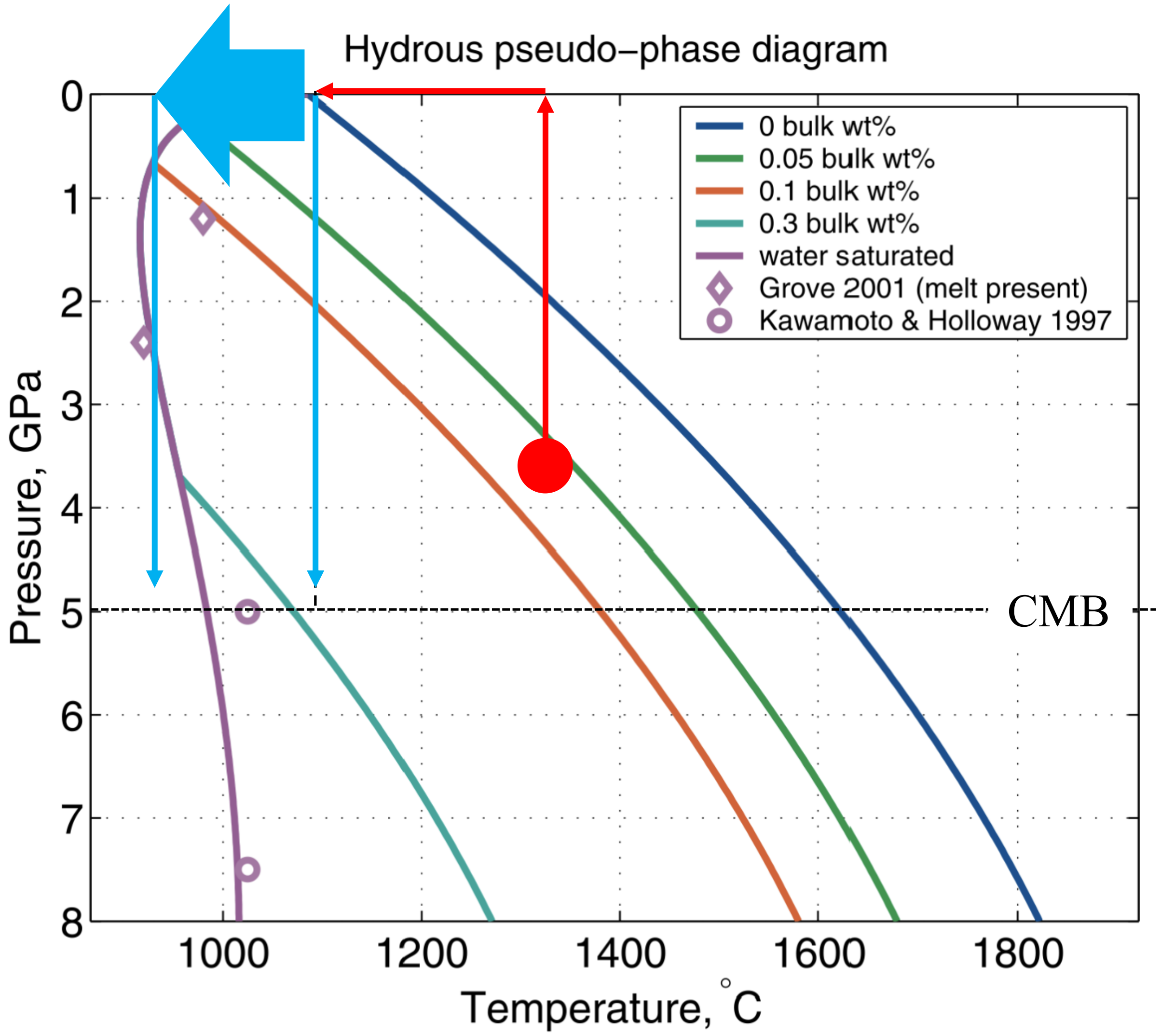
Thermal expansion and thermal stress in the Moon and terrestrial planet

es and pressures over most of the lunar mantle (Sk
nd Toksöz, 1973).
ınge in lunar radius with time for a number of thermal his
ıly in the adopted values of z_0 and T_c are given in Fig. 2.
e radius change in early lunar history is governed by
e warming and expanding deep interior and the cooli
ter lithosphere. The radius change in the last stage of lu
nterior had completely heated to the solidus, is tow
n all models.
al extent of radius change is very sensitive to the initial
ı. For a shallow initial "magma ocean" and a cool interior
dius increases through most of lunar history by a total c
ıterior progressively warms. For very deep initial "mag
ls (c), (f), and (i)], the radius decreases by over 12 km a
cools. For comparison, an initially molten moon (z_0 =
ı radius over 4.6 b.y. and a Moon initially at 0°C through
e amount over its history.
one (b) of the thermal history models portrayed in Fig.

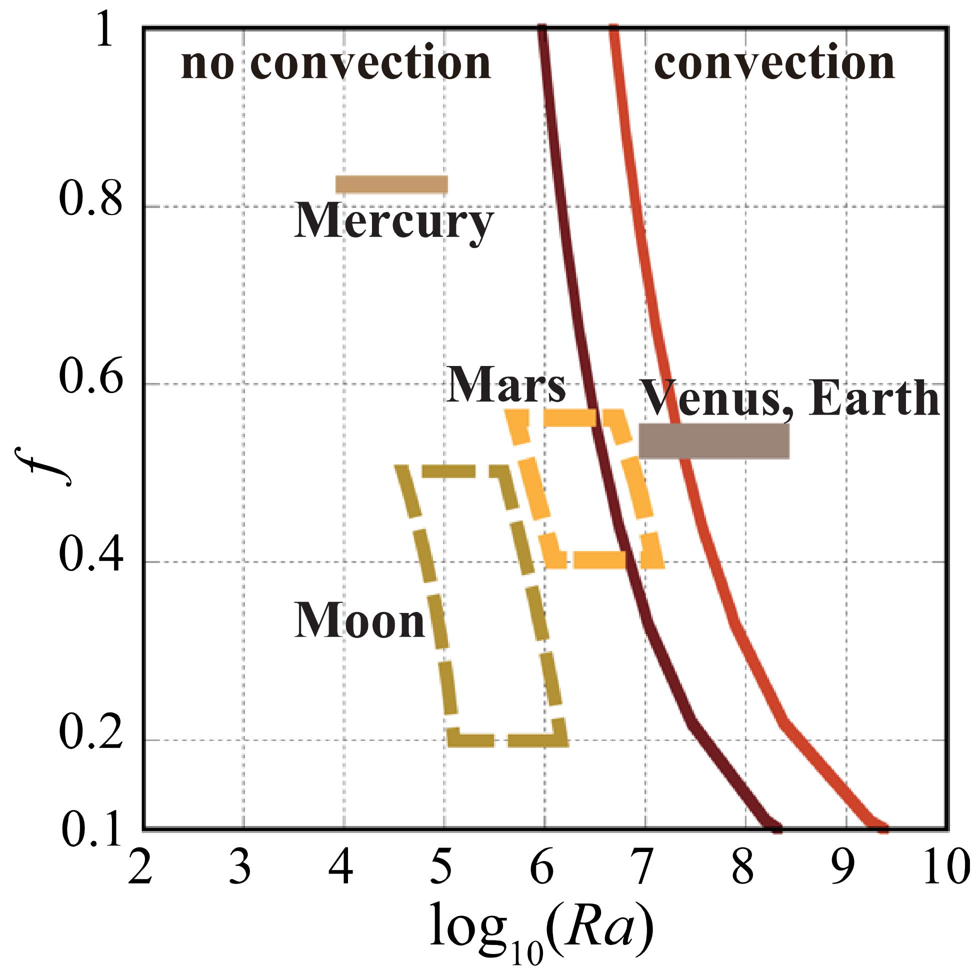
(Solomon & Chaiken, 1976)

$T_c < 1210$ K ↔ 月の巨大衝突起源？

マグマ・オーシャン期に温度を地表面におけるソリダス以下に下げるメカニズム？



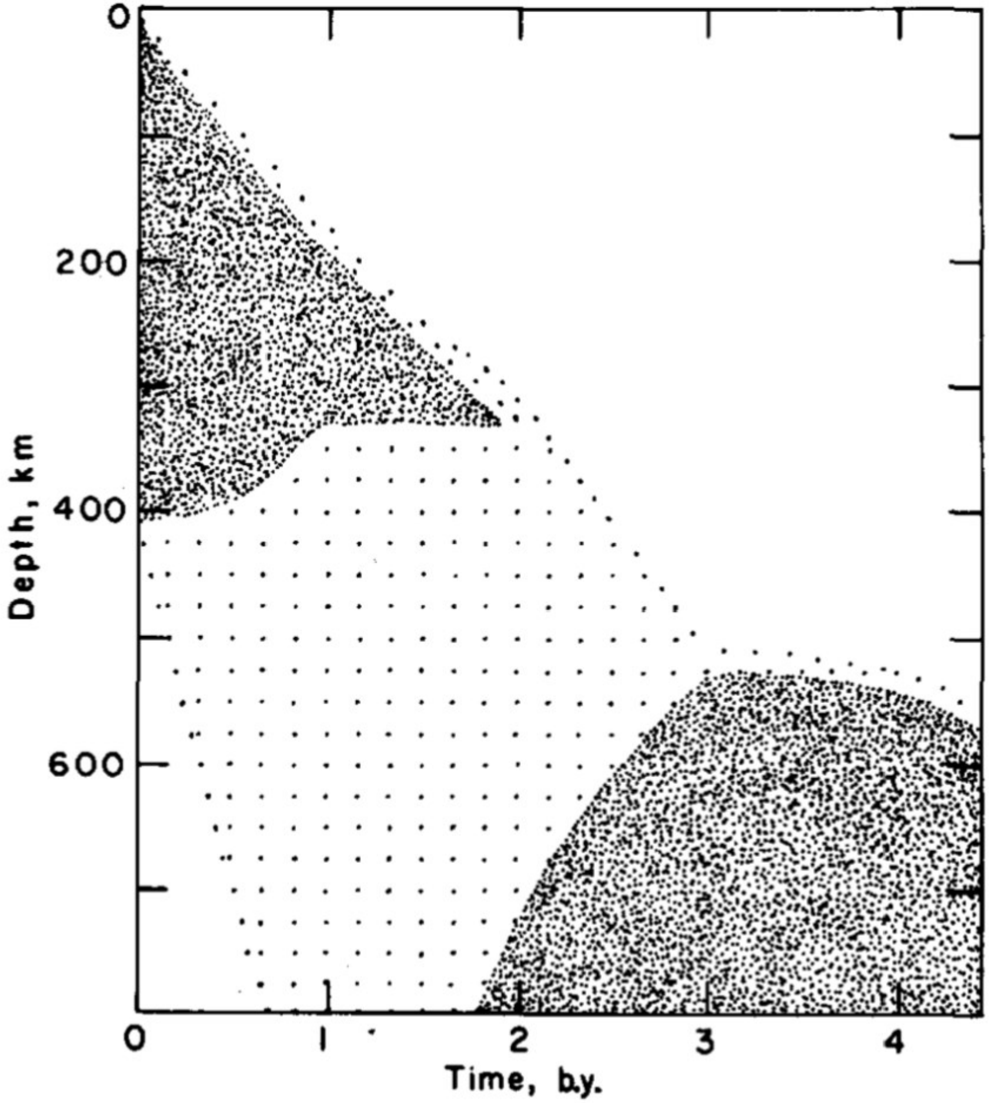
(Katz et al., 2003)



(Yanagisawa et al., 2016)

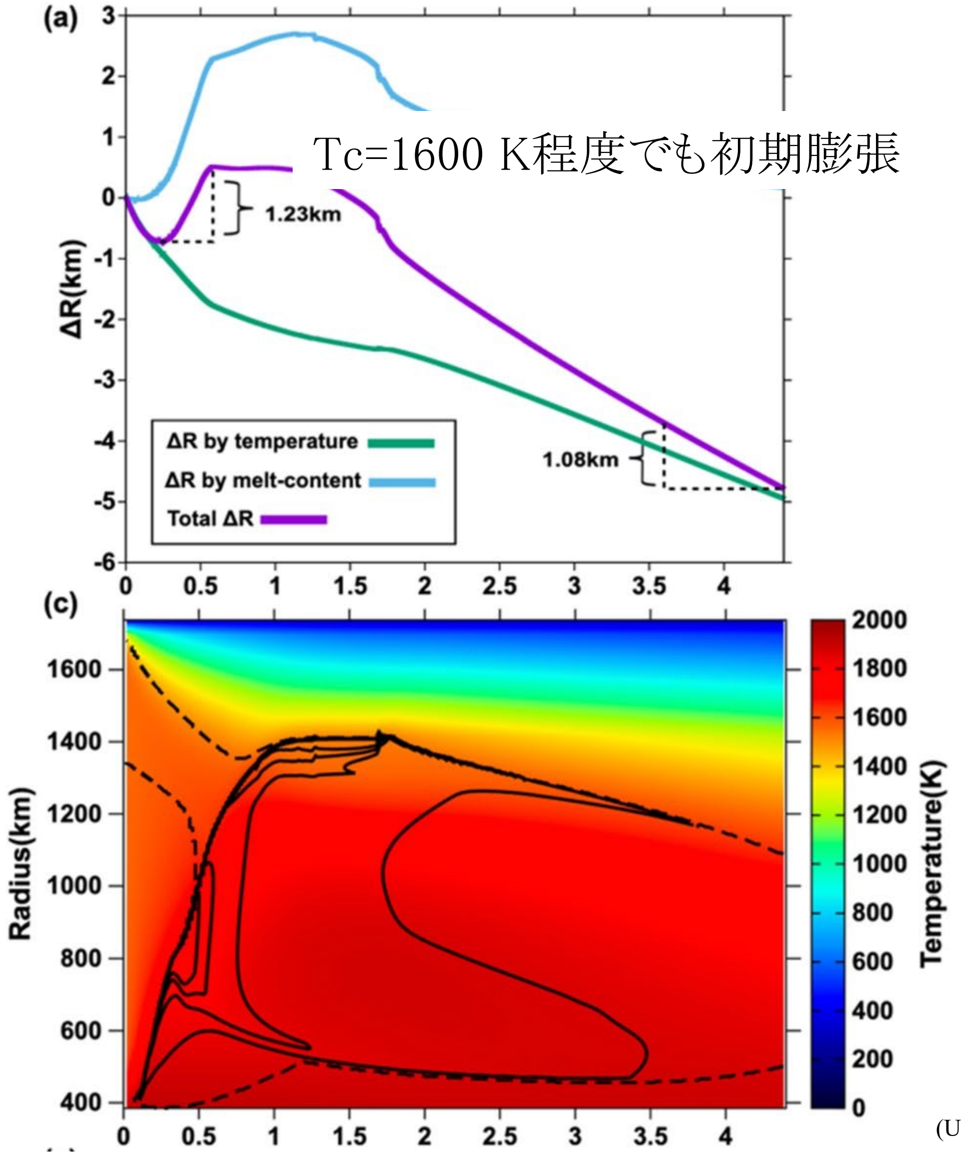
熱膨張以外の初期膨張のメカニズム？ → マントルの融解

マグマ生成域の分布



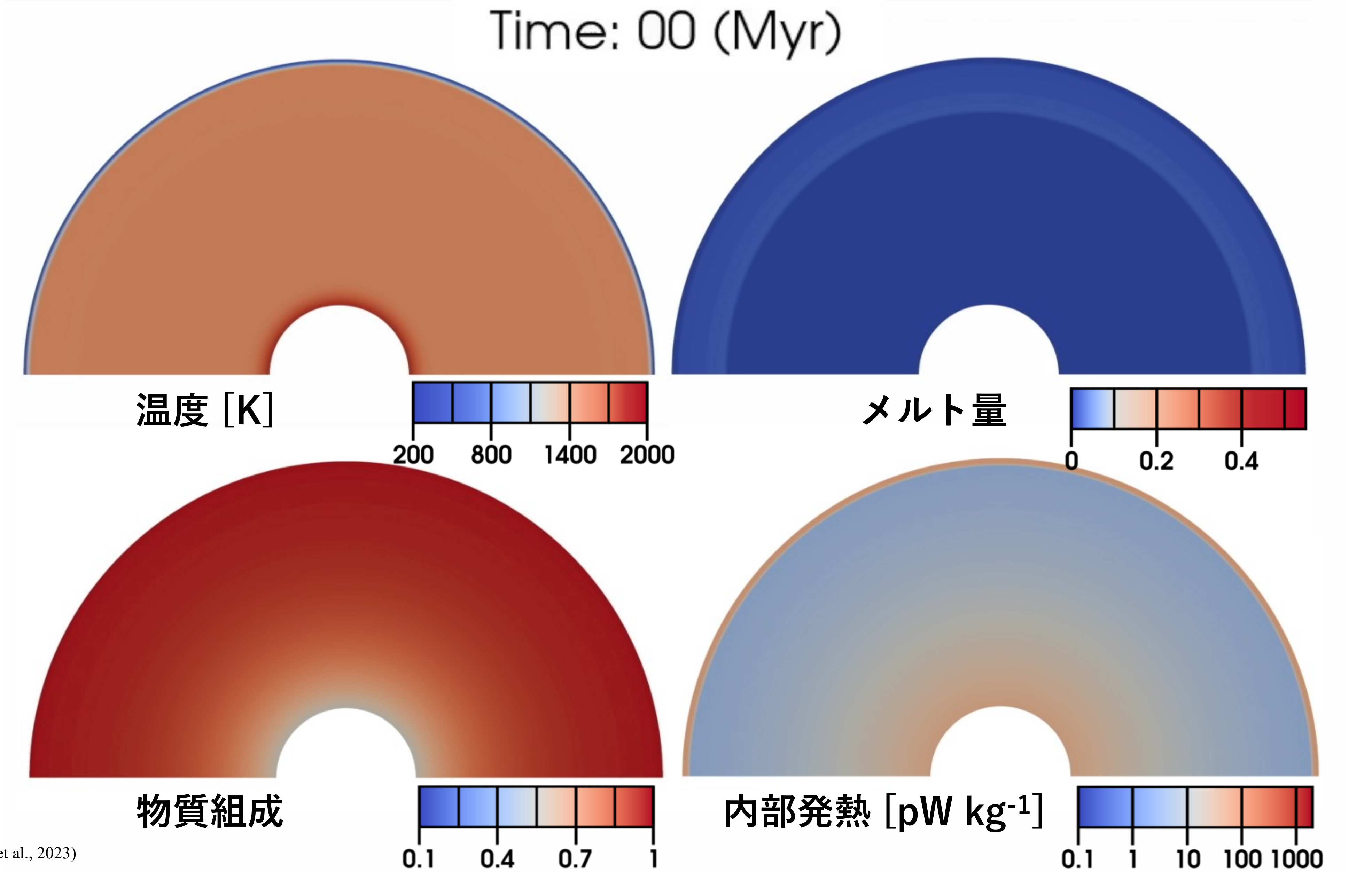
(Solomon & Toksoz, 1973)

内部発熱によるマグマの生成と移動を考慮した
膨張・収縮の球対称モデル

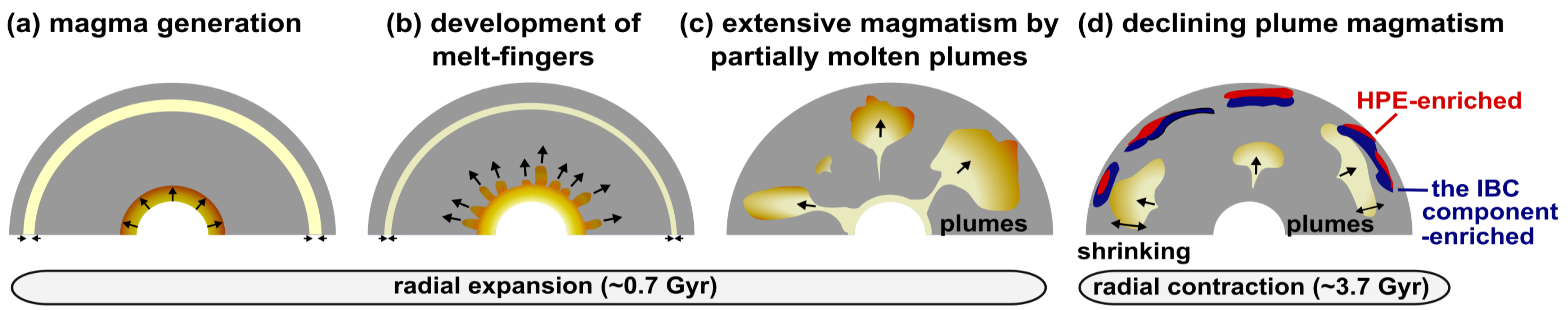


(U et al., 2022)

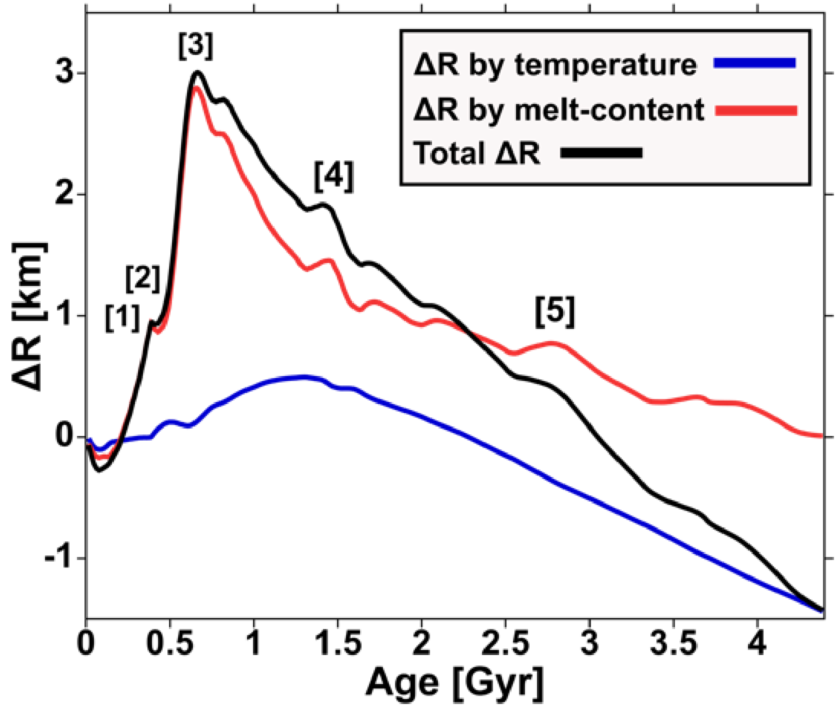
惑星内部でのマグマ生成の主要メカニズム ＝ 対流によるdecompression melting



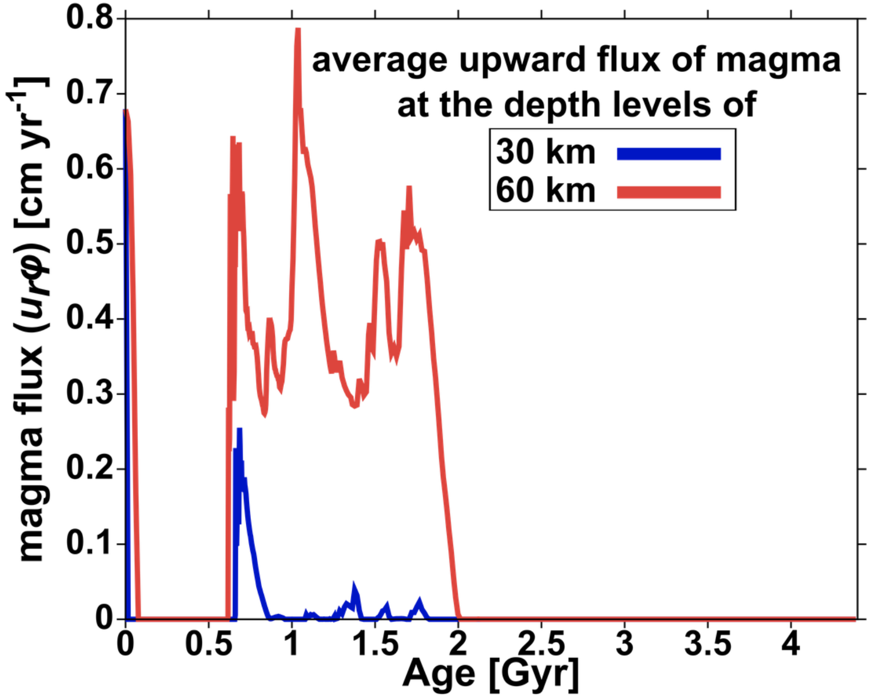
(U et al., 2023)



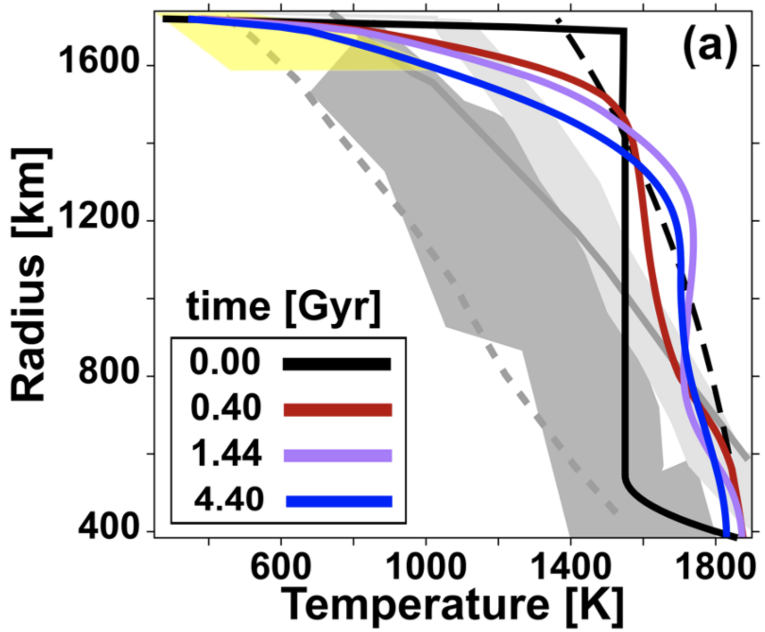
(a) magma generation
(b) development of melt-fingers
(c) extensive magmatism by partially molten plumes
(d) declining plume magmatism
HPE-enriched
the IBC component -enriched
plumes
plumes
shrinking
radial expansion (~0.7 Gyr)
radial contraction (~3.7 Gyr)



ΔR by temperature
ΔR by melt-content
Total ΔR
[1]
[2]
[3]
[4]
[5]
ΔR [km]
Age [Gyr]



average upward flux of magma at the depth levels of
30 km
60 km
magma flux ($u_r\varphi$) [cm yr^{-1}]
Age [Gyr]



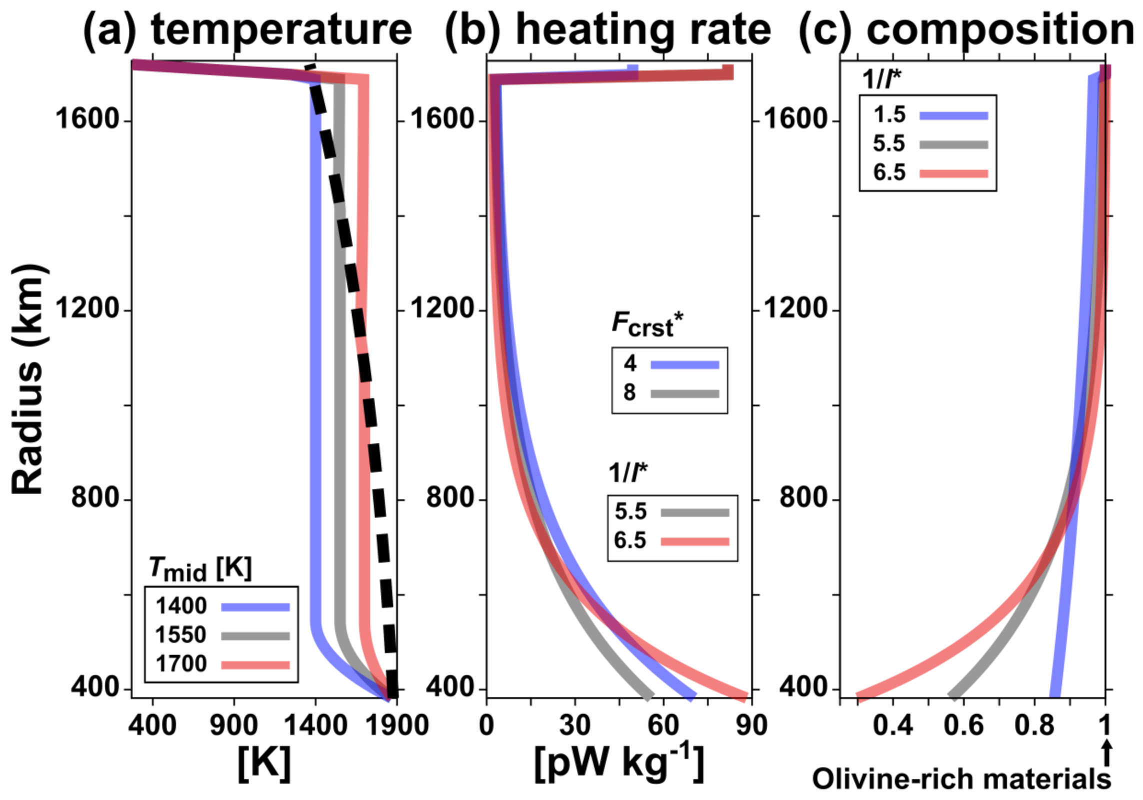
(a)
time [Gyr]
0.00
0.40
1.44
4.40
Radius [km]
Temperature [K]

(U et al., 2023)

4-3. 進化の初期条件 （頭出し→第9章）

初期マントルは大部分固体

初期温度 ≈ $1600\ K$



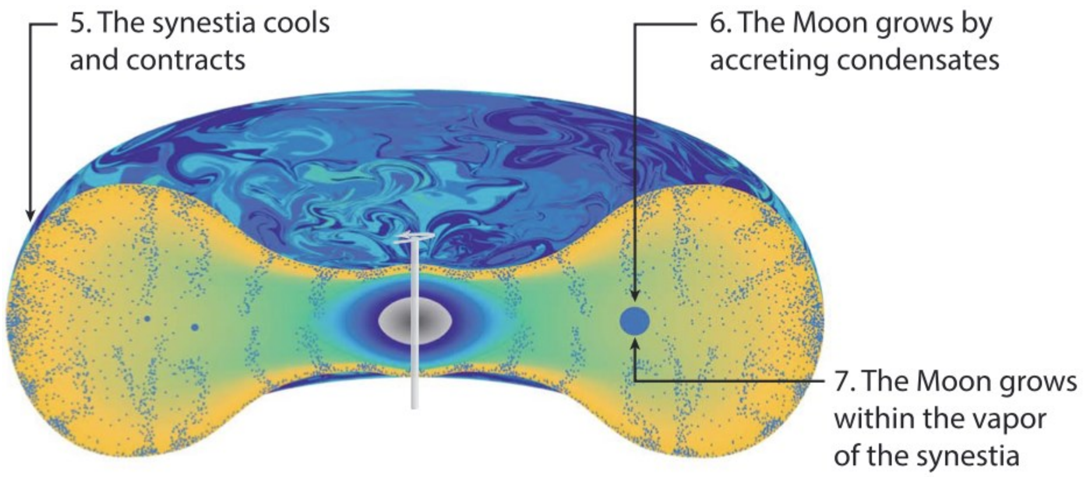
矛盾？

GI model：高エネルギー衝突

（cf. O-同位体）

↓

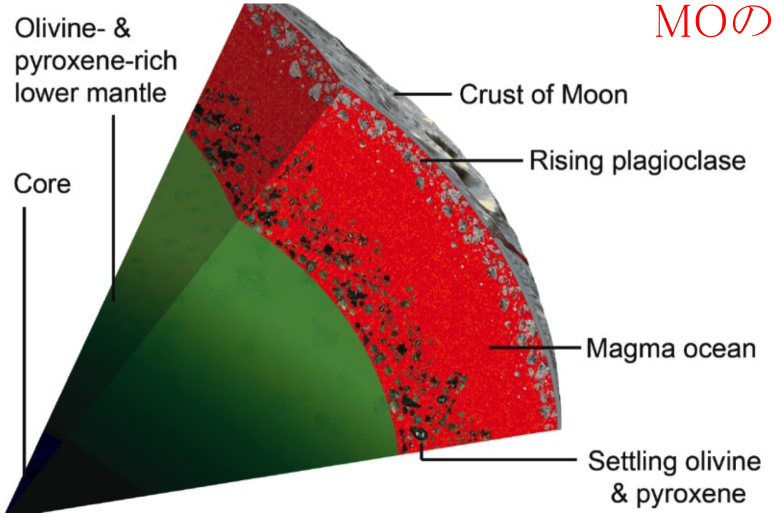
高温起源



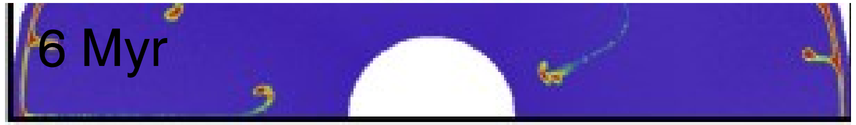
(Lock et al., 2018)

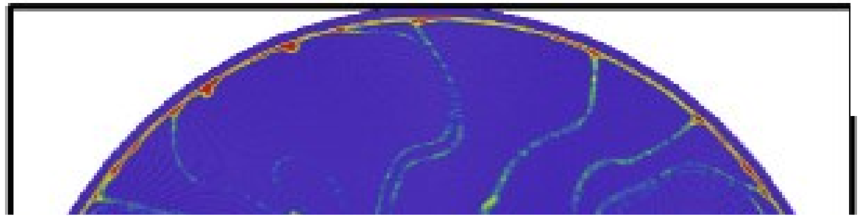
MO期に冷却＋化学成層？

MOの冷却効率？しょぼいオーバーターン？ → 第9章

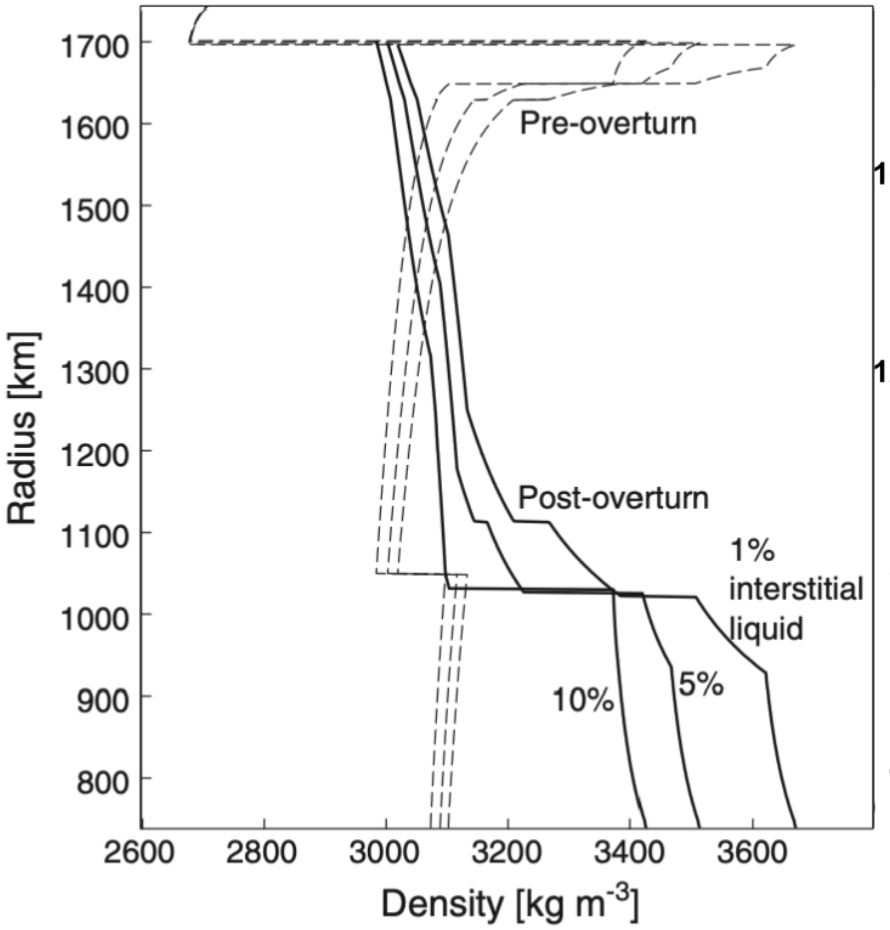


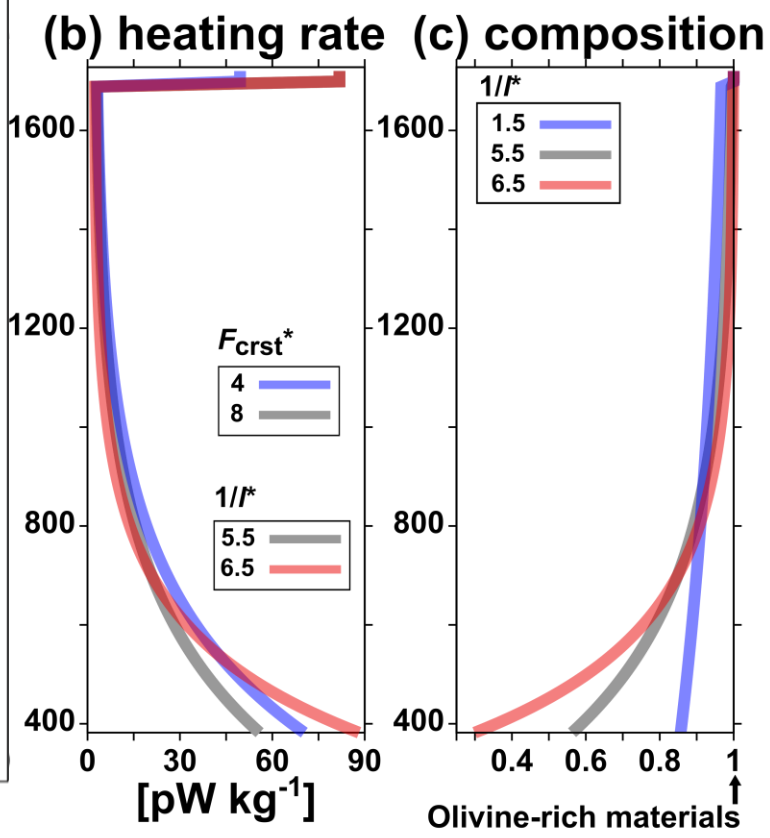
http://www.lpi.usra.edu/exploration/training/illustrations/planetaryInteriors/





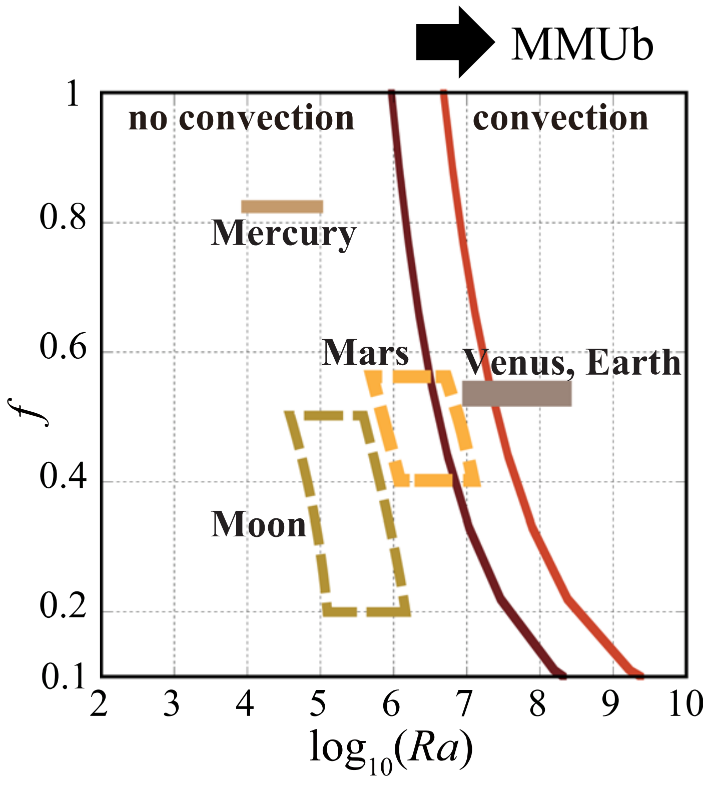
(Parmentier et al., 2002) (Zhang et al., 2012)





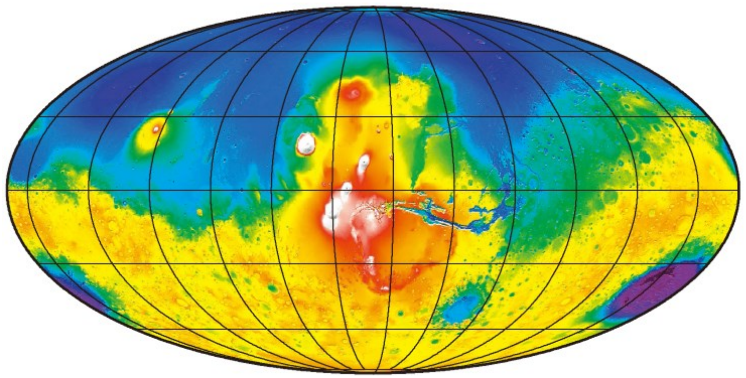
(Elkins-Tanton et al., 2011)

第5章　火星：月＋MMUフィードバック



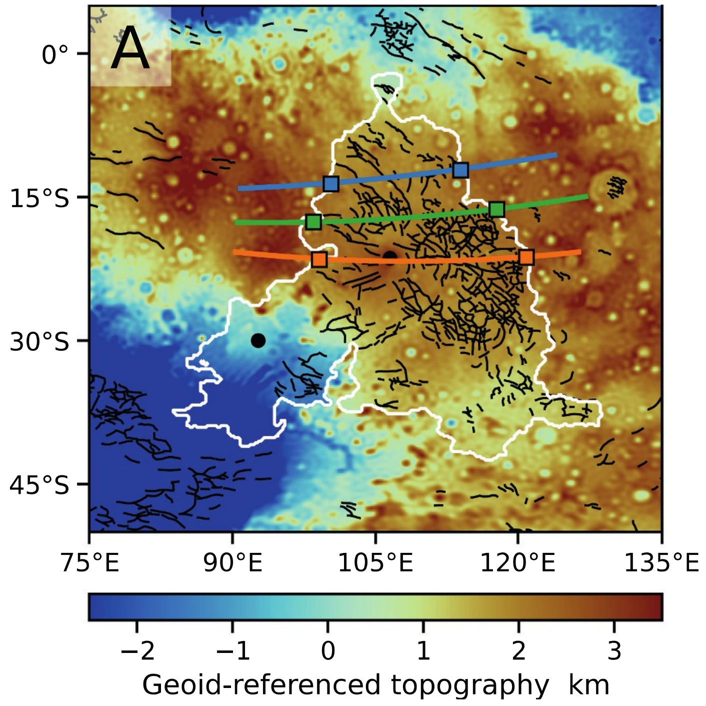
(Yanagisawa et al., 2016)

ホットスポット



(Wieczorek, 2015)

LIP活動

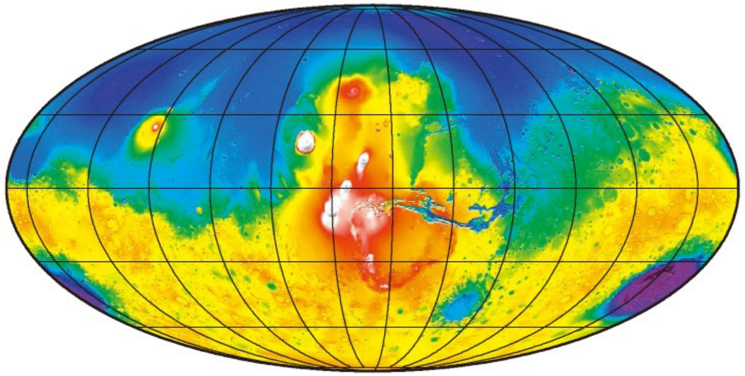


(Broquet & Andrews-Hanna, 2023)

南北ディコトミーは衝突起源 (Andrews-Hanna et al., 2008)、省略；磁場は後回し(第11章)

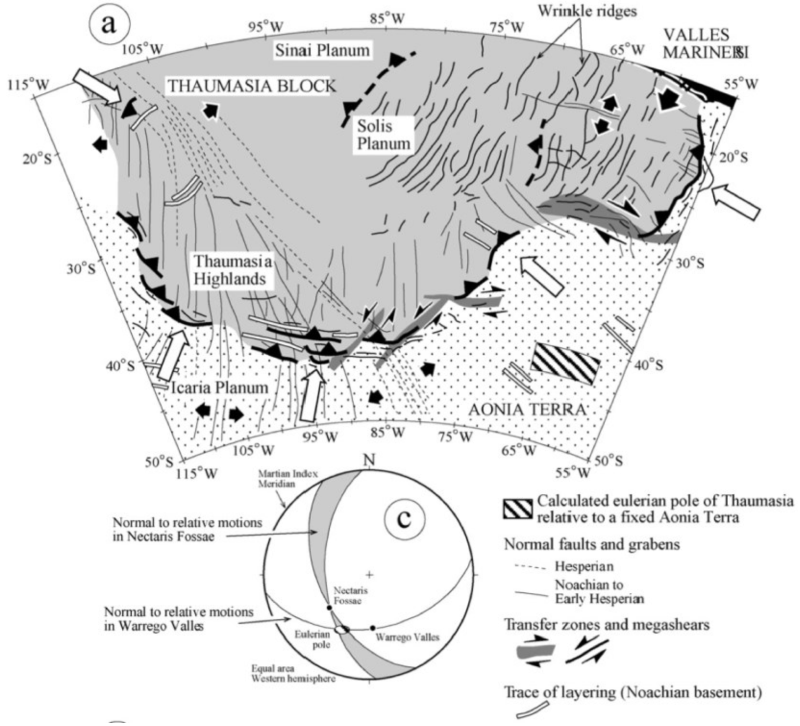
5-1　火星史概観

プレートテクトニクスなし:リソスフェアが厚すぎる?



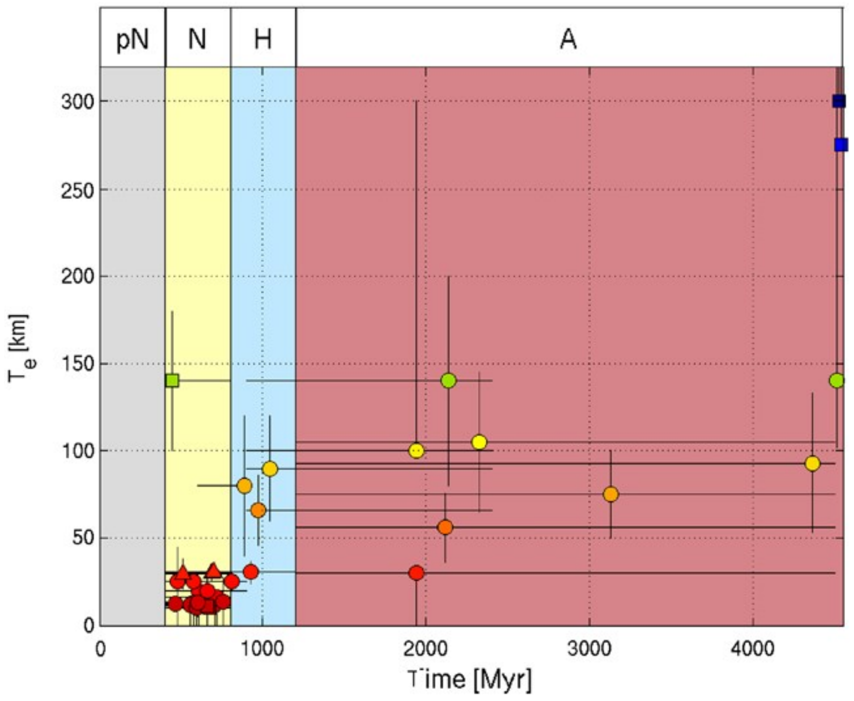
(Wieczorek, 2015)

Noachian-early Hesperianの造山帯?



(Anguita et al., 2006)

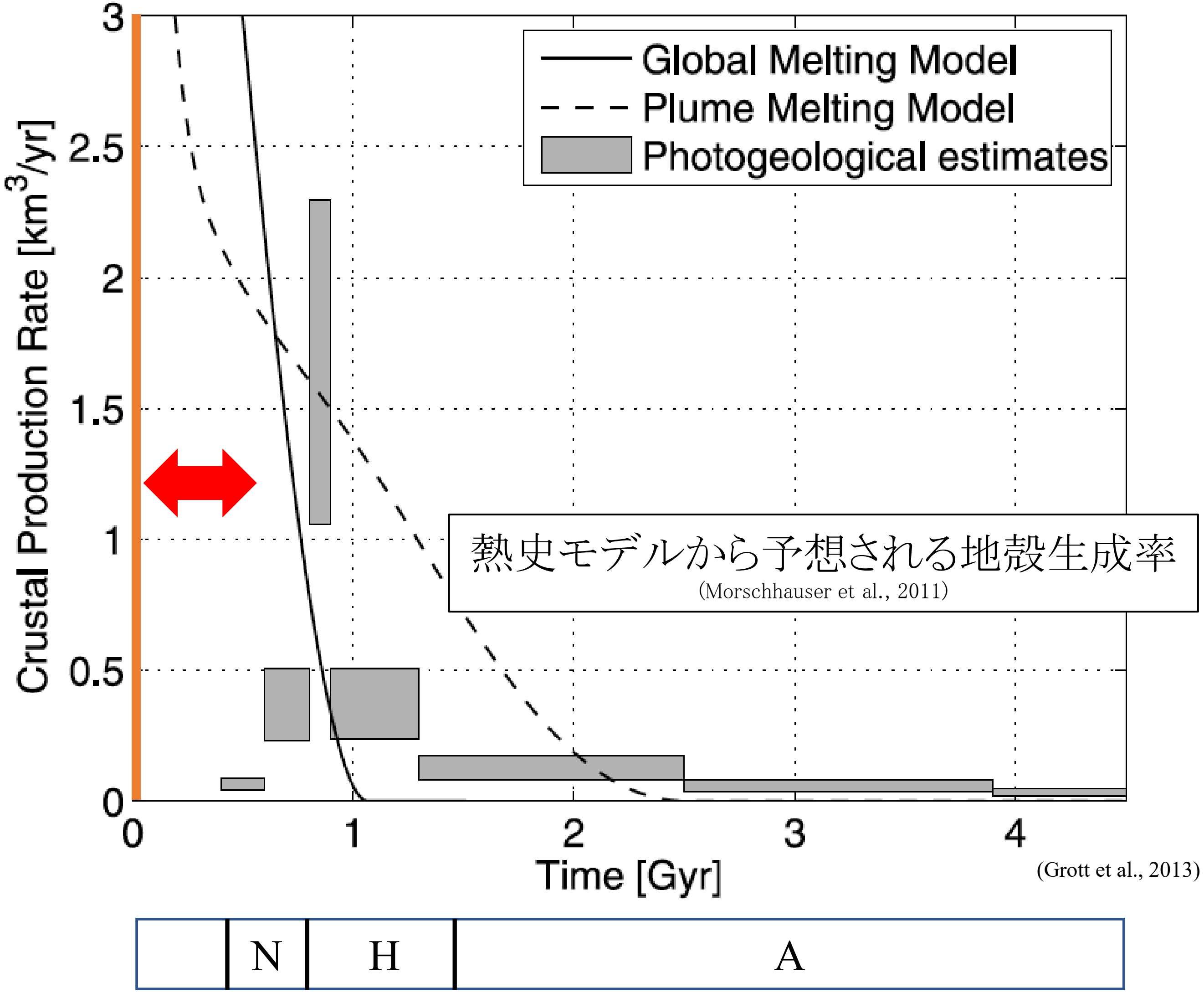
リソスフェアの弾性的厚さ



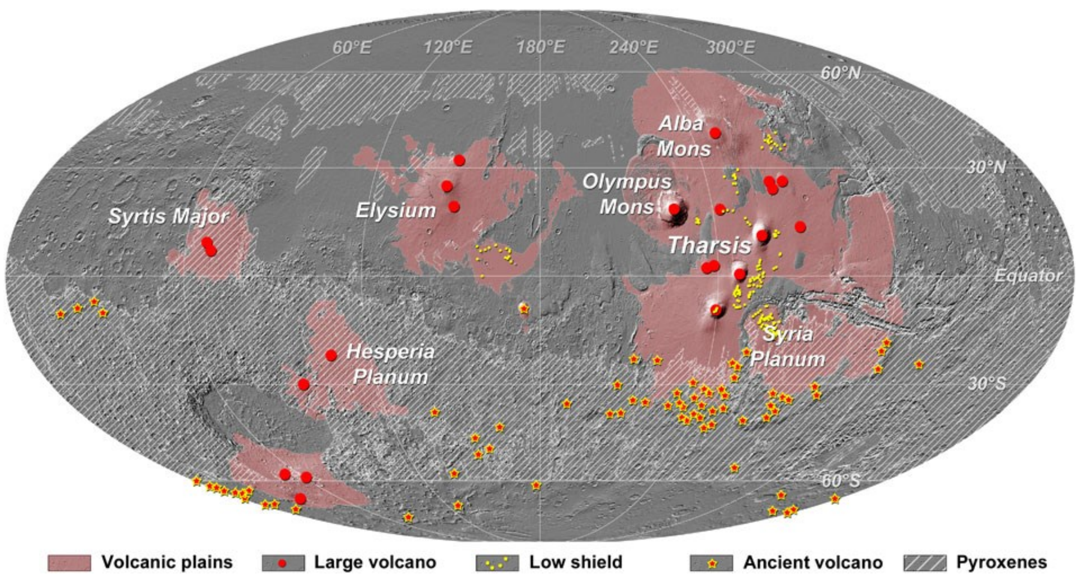
(Grott et al., 2013)

火山活動史:3.5 Ga頃にピーク？

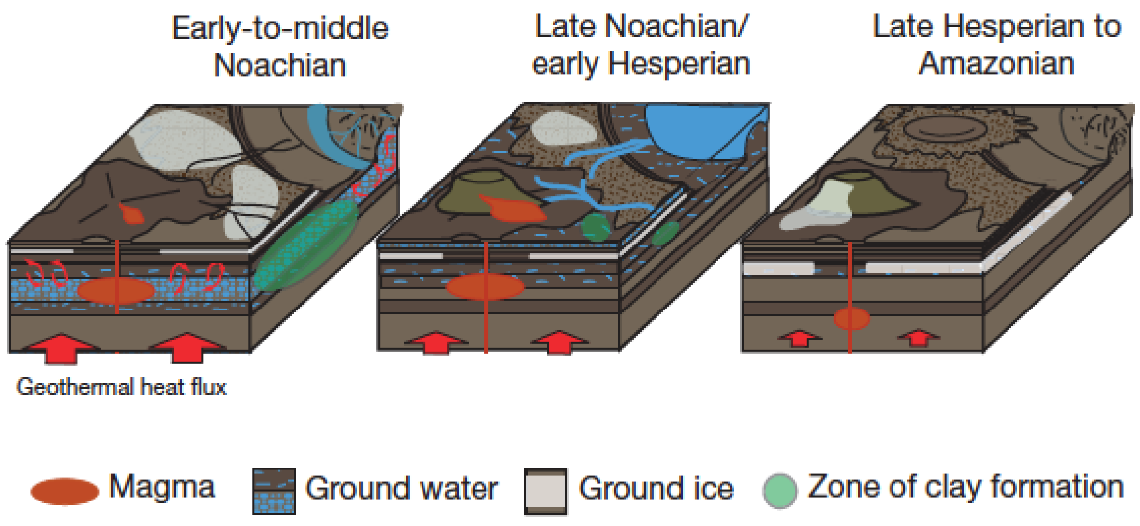
crust-formation (basalt)



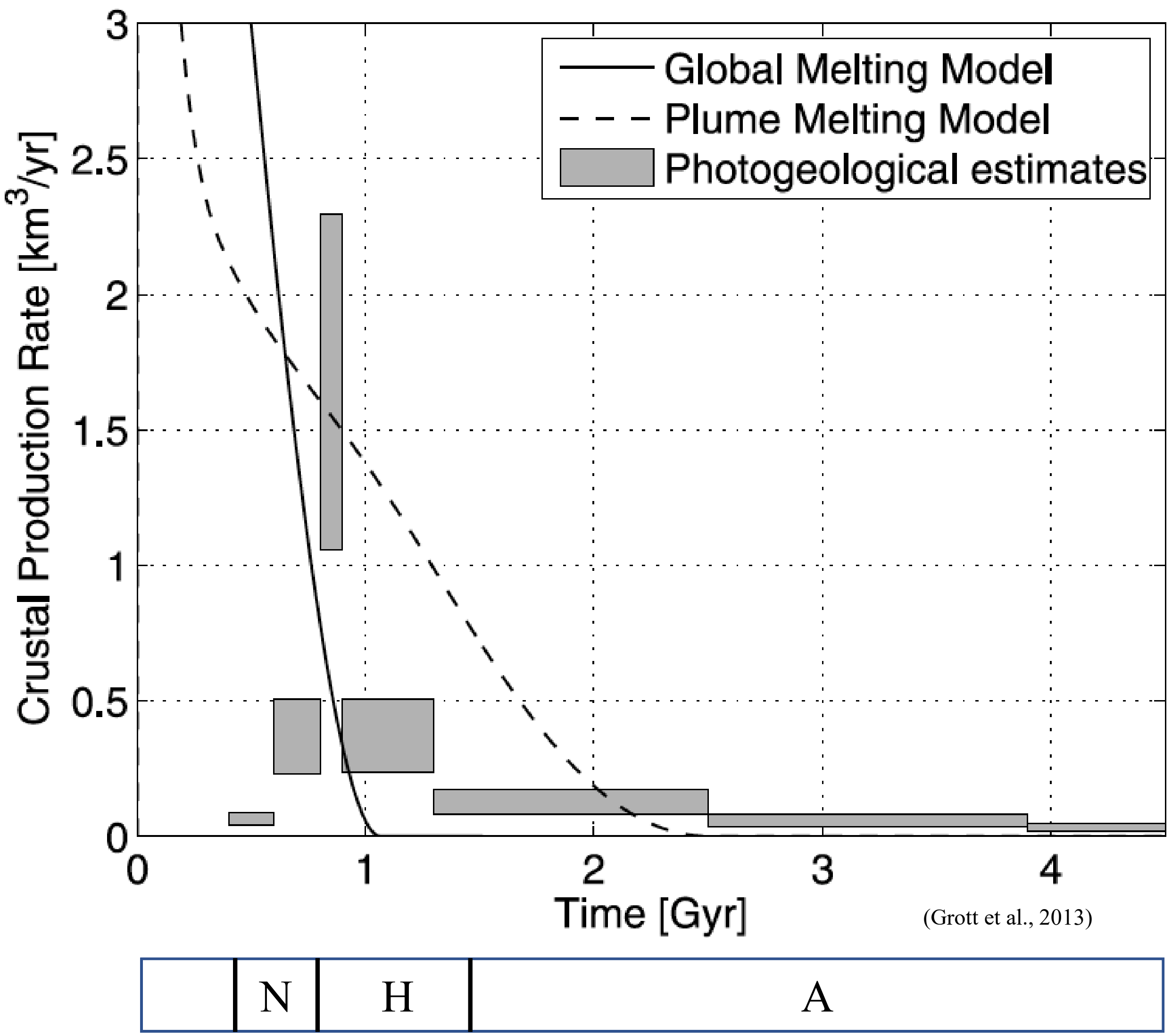
Volcanism in the early Hesperian



表層環境史: 3.5 Ga頃に温暖・湿潤な環境？（→ 第10章）



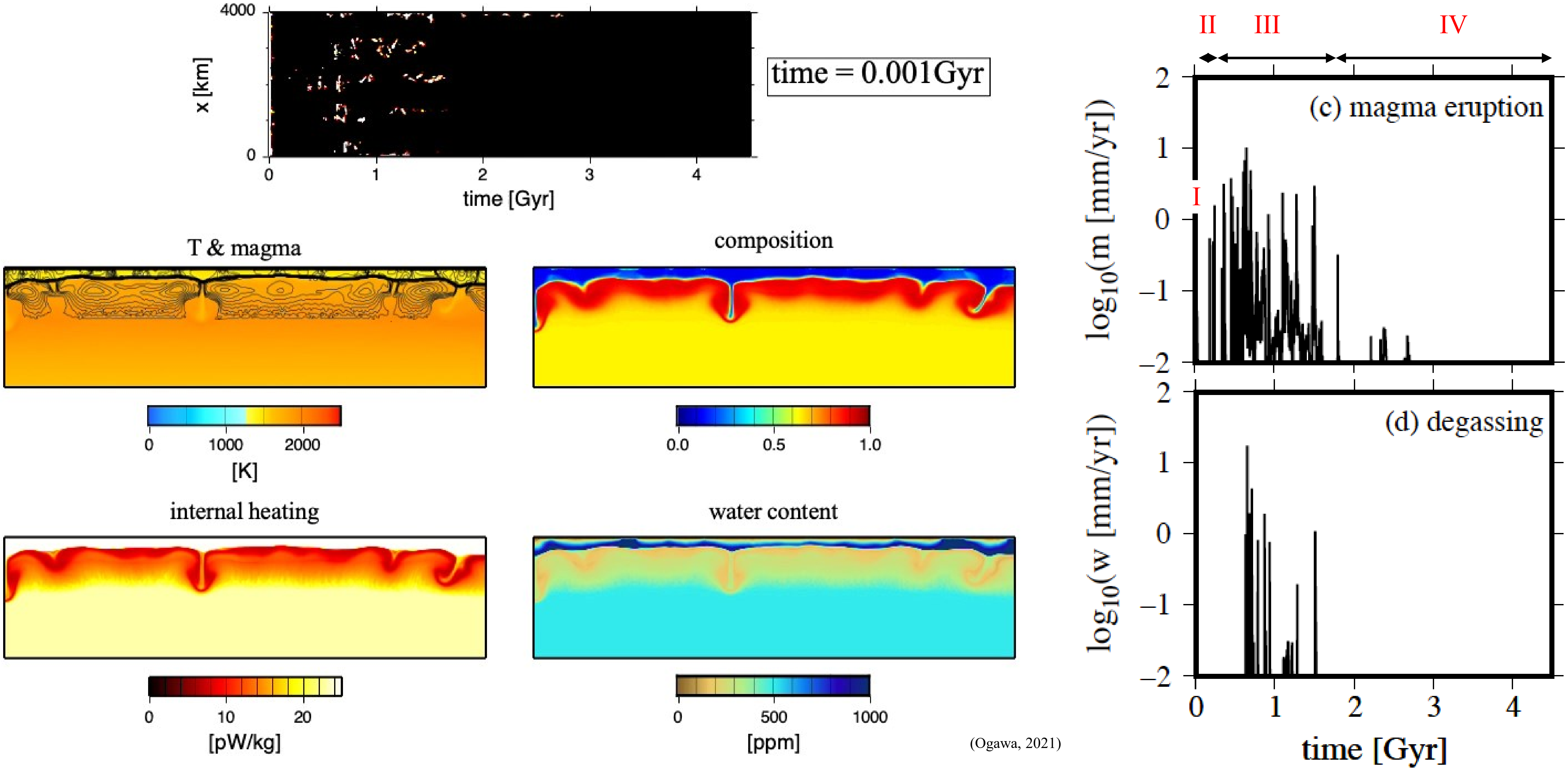
(Ehlmann et al. 2011)



(Grott et al., 2013)

原因
(1)火山の脱ガス?
(2)隕石が持ち込むvolatile?　時期的に合わない

5-2　MMUフィードバックとマントルの4段階進化



(Ogawa, 2021)

火成活動と対流によるマントルの構造変化が進化の本質

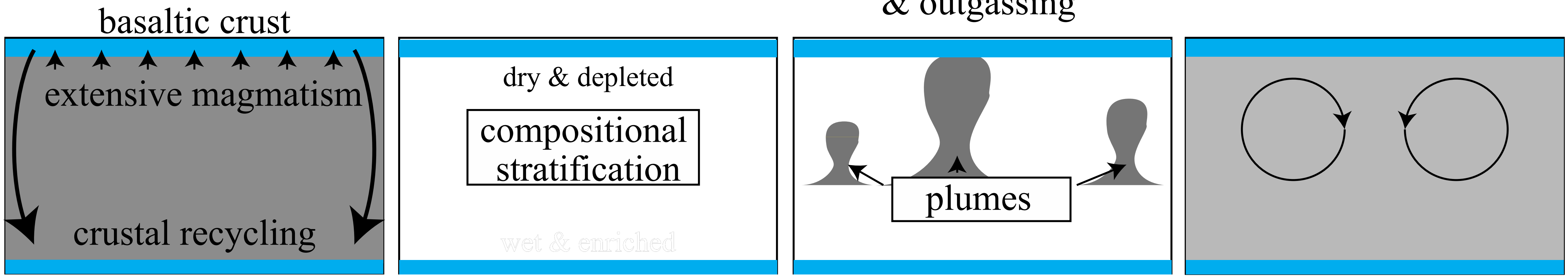
The four-stage evolution (FSE) model of Mars

Stage I:
crustal formation

Stage II:
the dormant mantle

Stage III:
plume magmatism
& outgassing

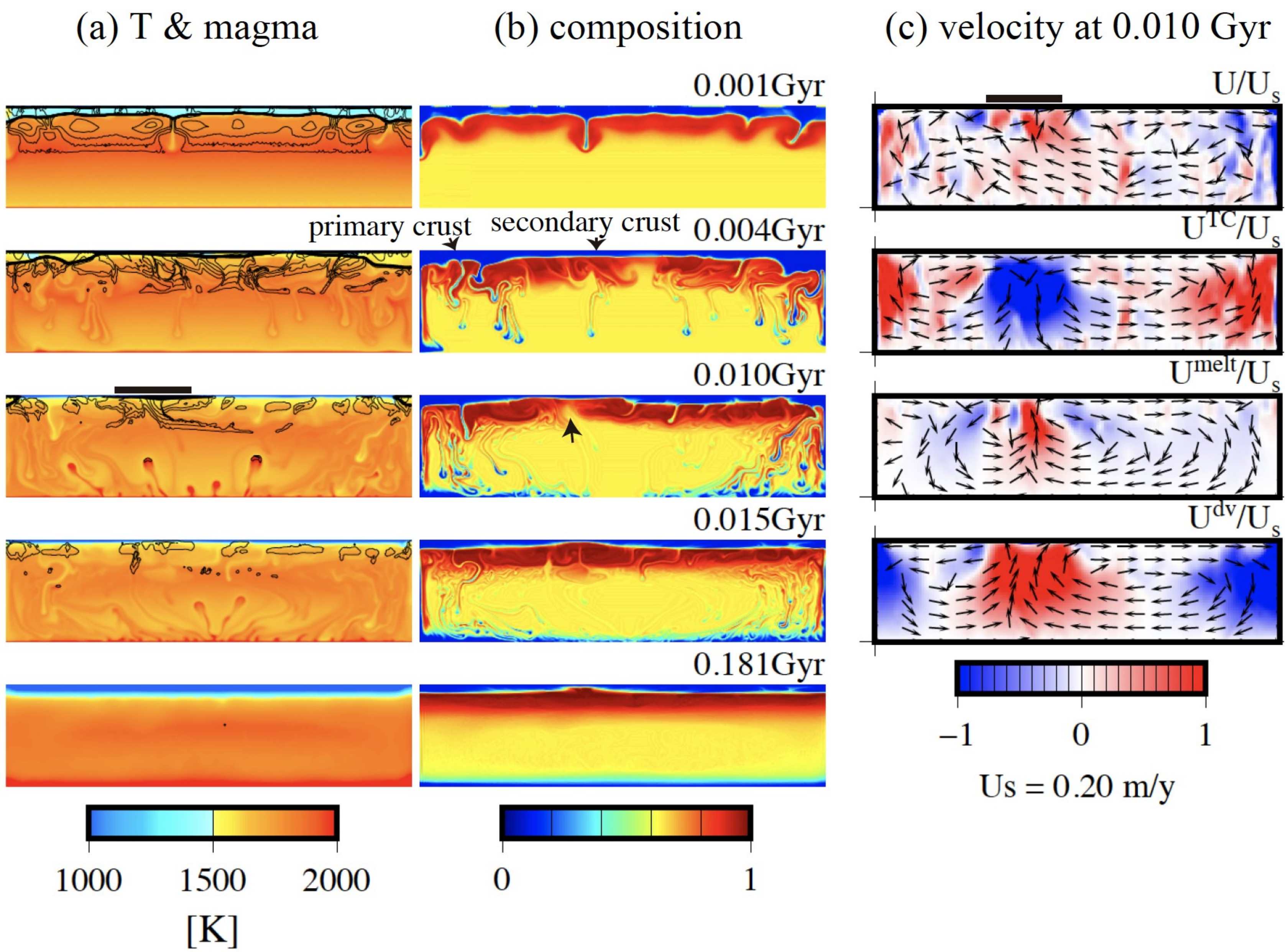
Stage IV:
thermally driven convection



MMUb,c feedbackの強い影響

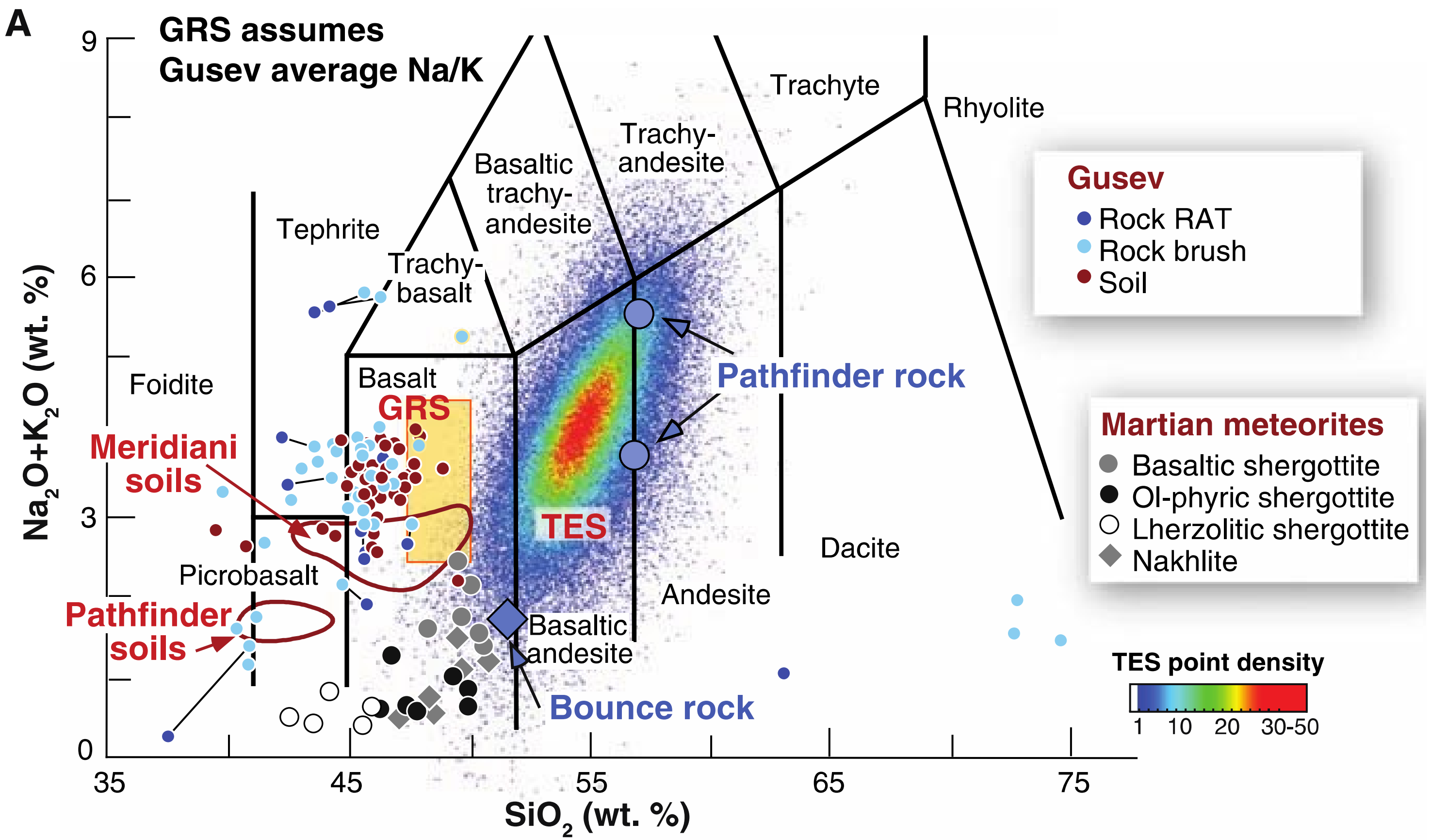
MMUb feedbackが駆動するプルーム火山活動

Stage I: 地殻形成とMMU feedback：一次地殻と二次地殻

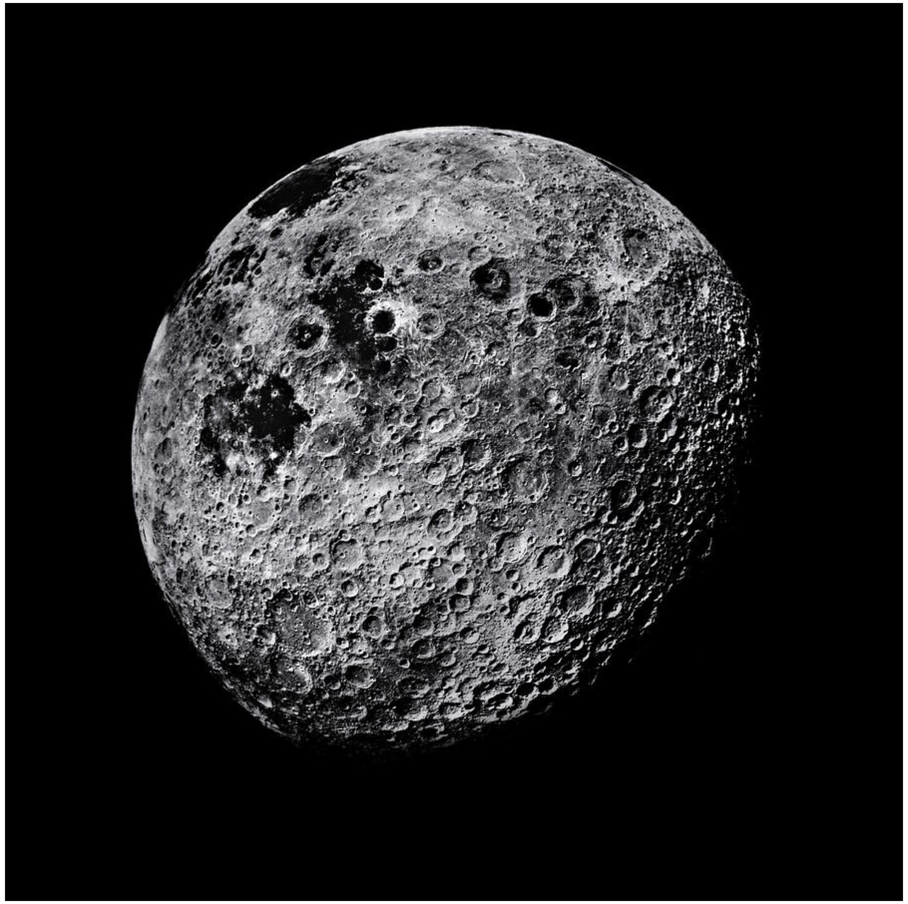


Mars (MMU) : secondary crust

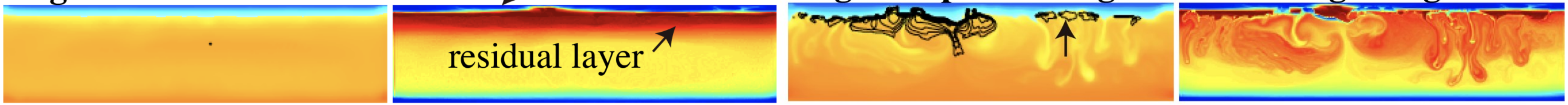
The Moon (no MMU) : primary crust



(McSween et al., 2009)

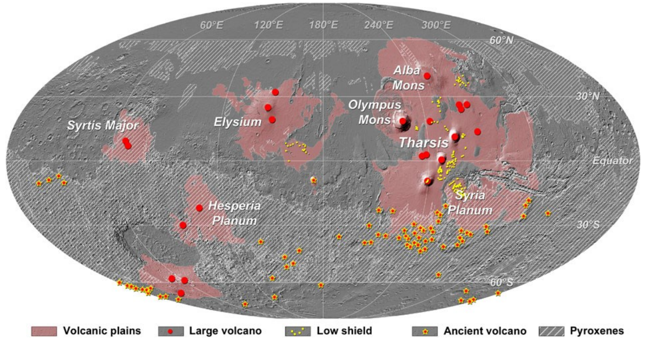


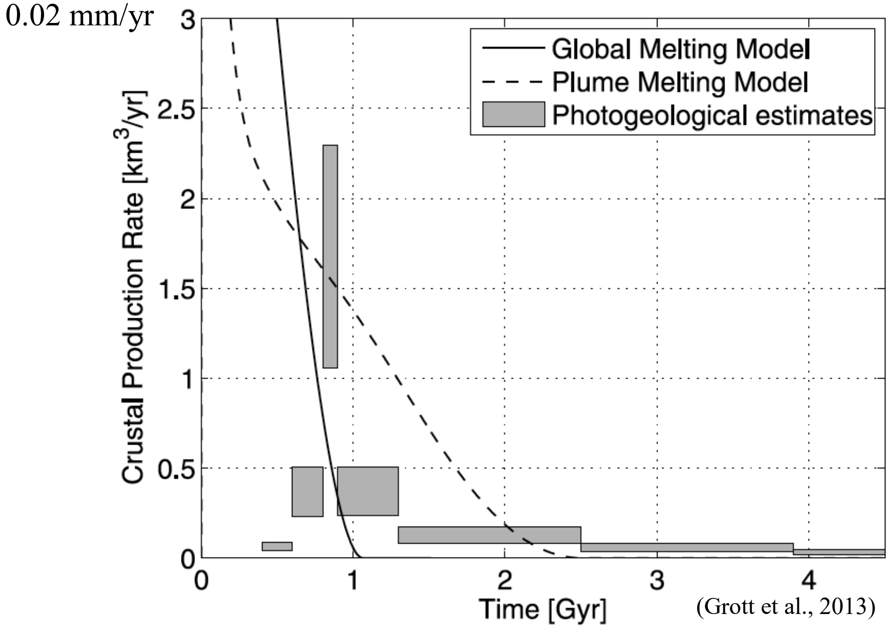
Stage II: the dormant mantle **Stage III: plume-magmatism & outgassing**



MOによるマントル化学成層構造→静穏期

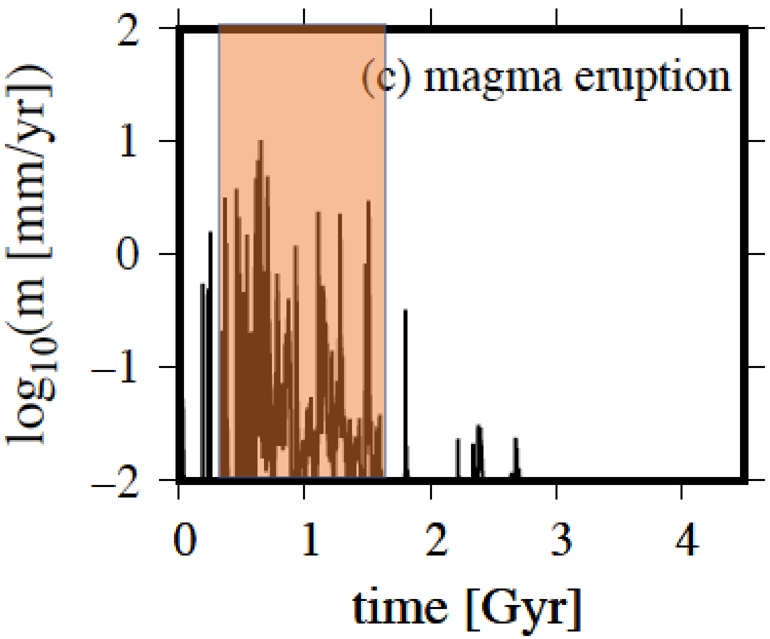
MMU feedbackによるプルーム火山と
化学成層マントルの攪拌・均質化



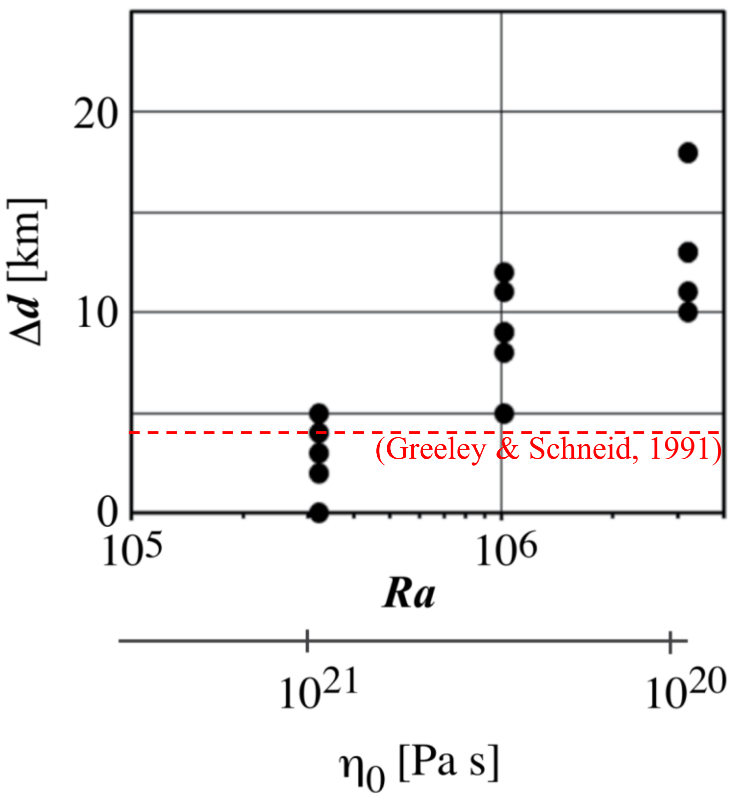


(Grott et al., 2013)

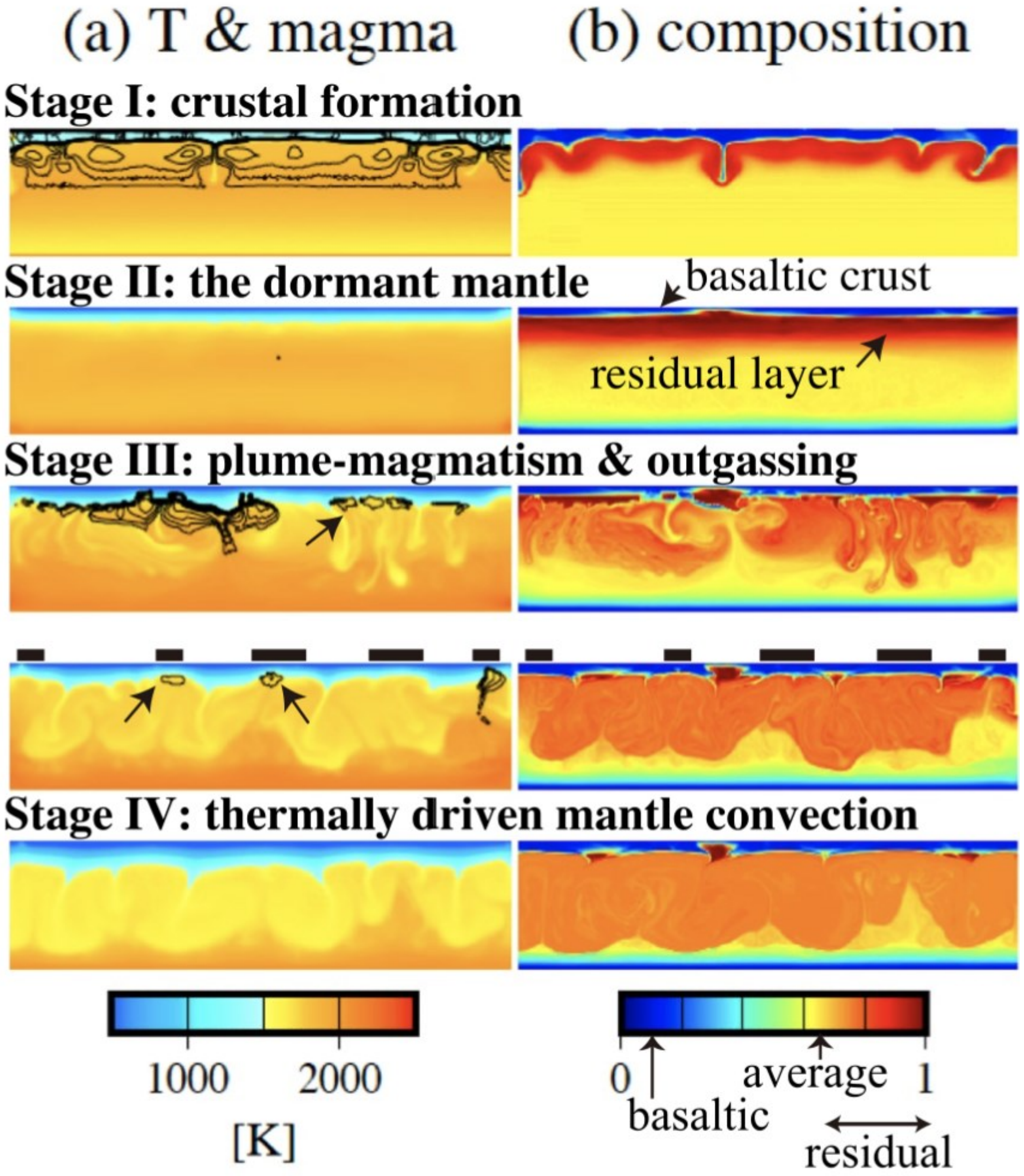
melt-flux crossing BE-boundary at 110 km

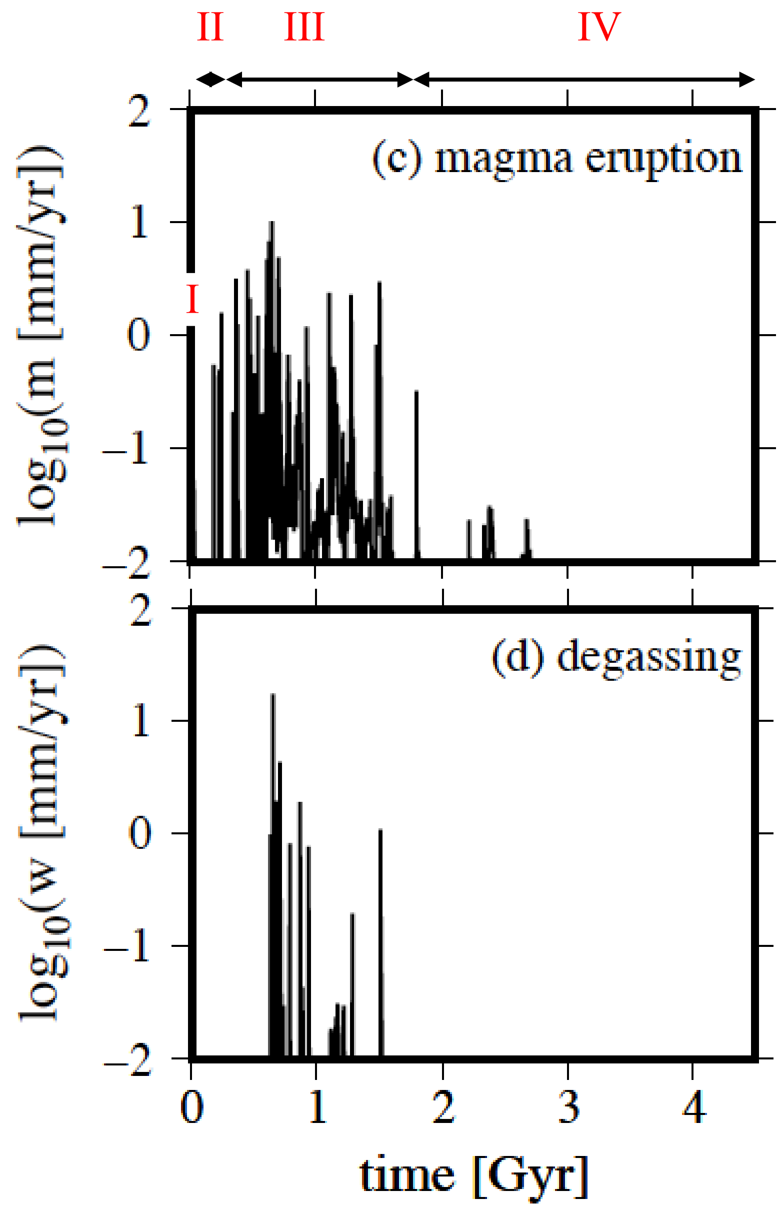


(a) total crustal growth

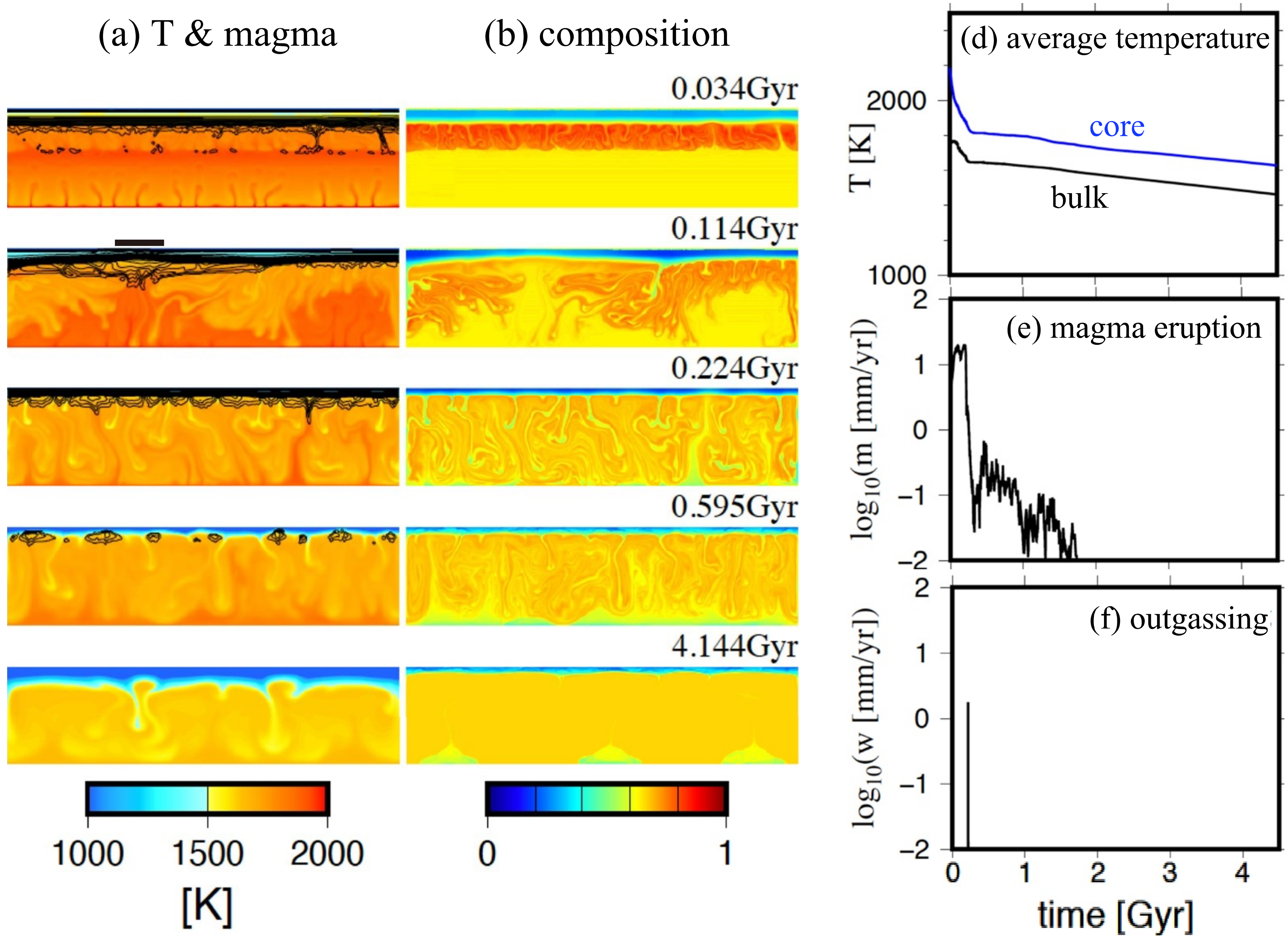


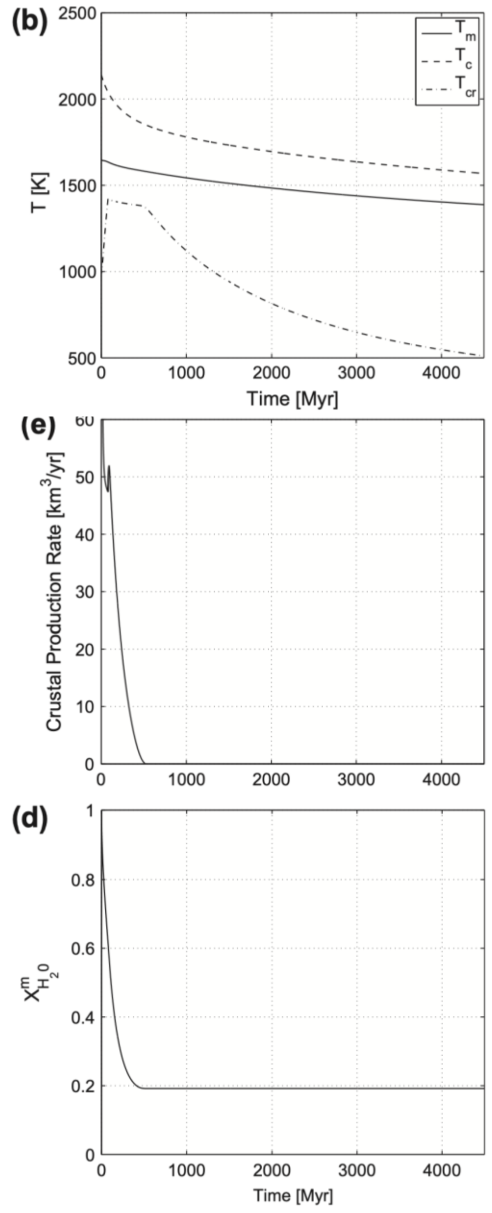
マントル進化の本質＝MMUcが起こす初期の成層とMMUbによる均質化





小さいPm → 強いMMUb、弱いMMUc → 均質なマントル：parameterized modelに類似

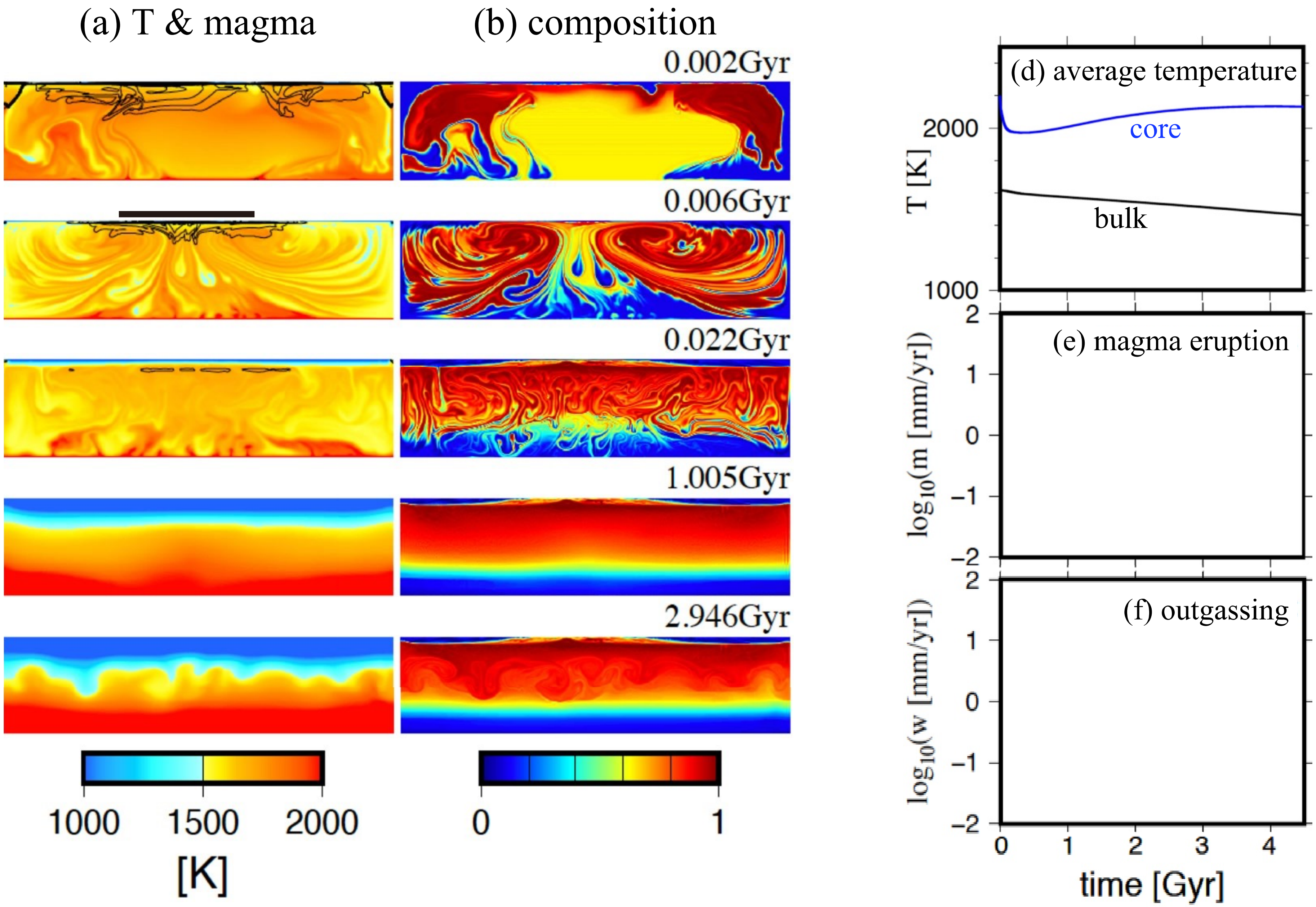




(Morschhauser et al., 2011)

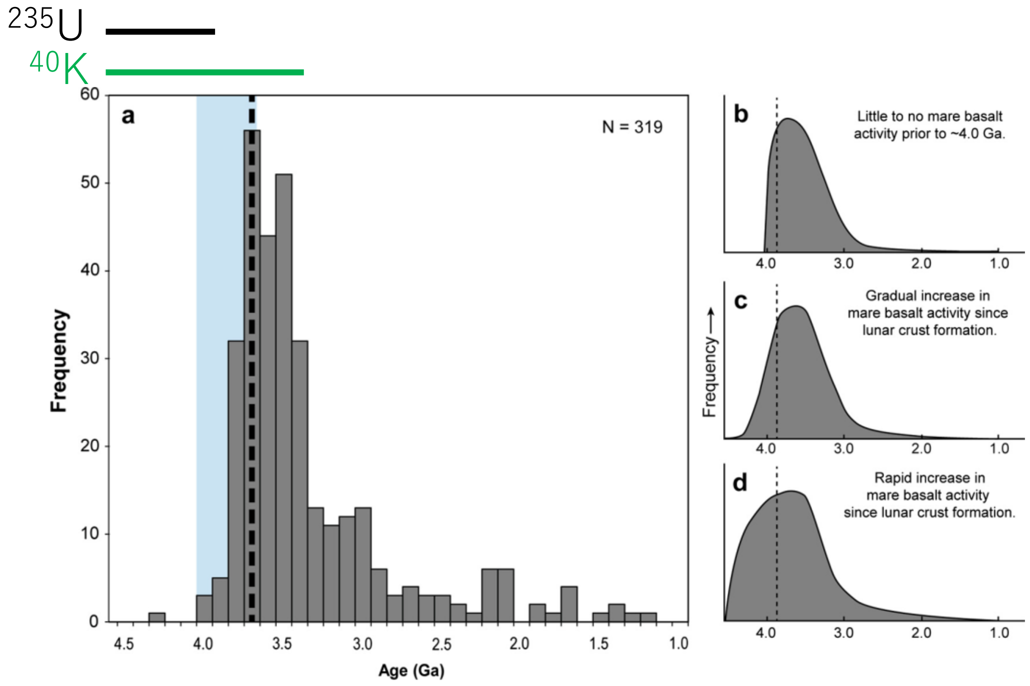
大きいPm → 強いMMUcと弱いMMUb → マントルの化学成層

昔からの火星のマントル進化の問題 (Plesa et al., 2014)

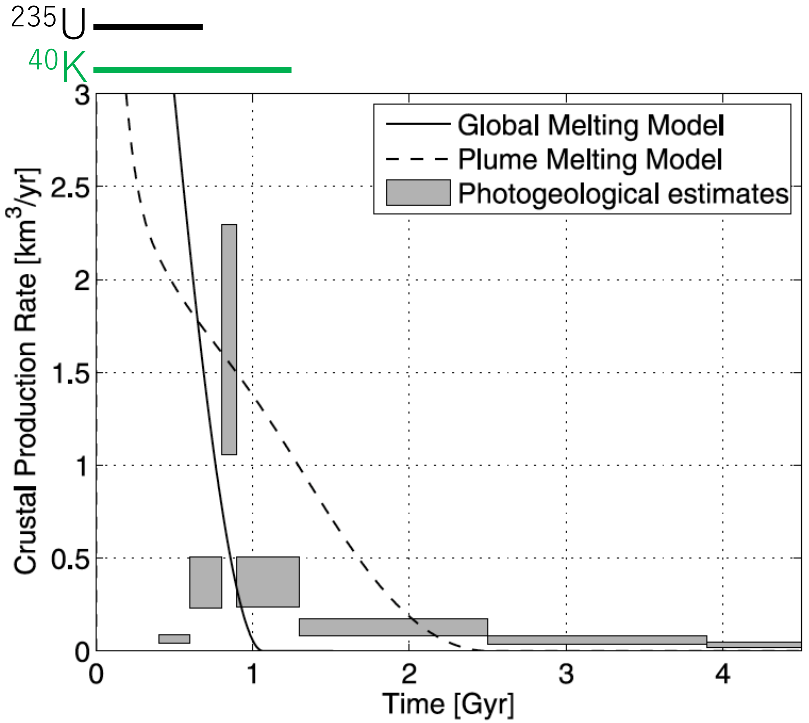


5-3　月と火星

月　　　熱容量の違い一桁　　　火星



(Hiesinger et al., 2003; Witten & Head, 2015)



(Grott et al., 2013)

（低温起源を仮定）
マントルの構造はMOが決定
マントル進化の本質＝熱史

MMU
フィードバック

マントル進化の本質＝構造発達史
MMUcによる初期分化＋MOでの結晶分化？
⇓
MMUbによるマントルの均質化

マントル進化の初期条件（第9章へ）

月の進化:形成期→マグマ・オーシャン期(100～1000万年？)→進化

初期条件はMOが決定？

火星では三つのステージは同時進行？

	惑星形成時間	マントル対流開始の時間	地殻
月	数時間～200年	数億年	斜長岩:マグマ・オーシャンの結晶分化
火星	200～300万年 太陽周りの長い惑星形成時間	200～300万年 MMUフィードバックによるマントル対流の早い立ち上がり	玄武岩:火山活動による二次地殻