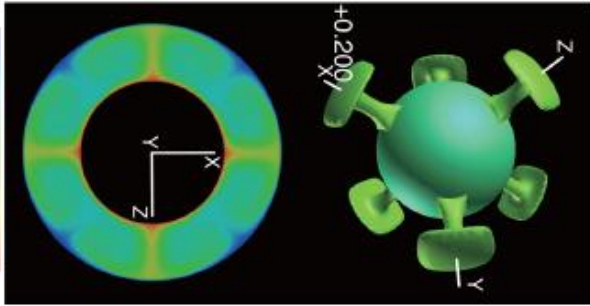
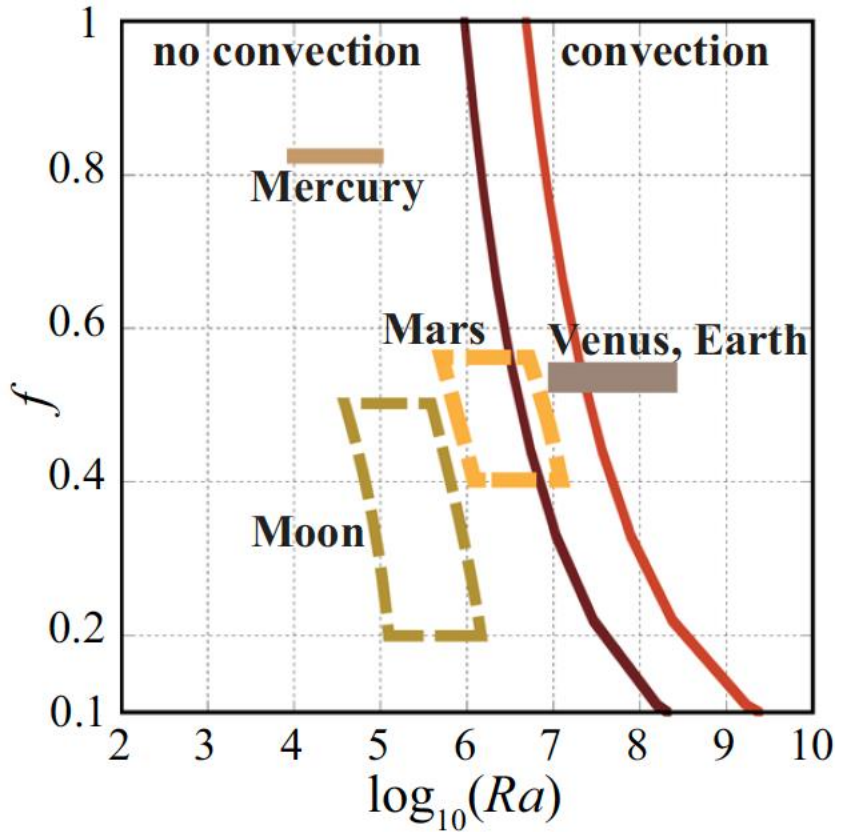


(1) マントルの対流不安定

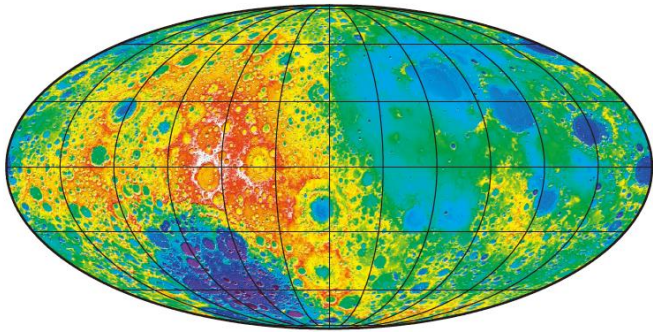


(Yanagisawa et al., 2016)

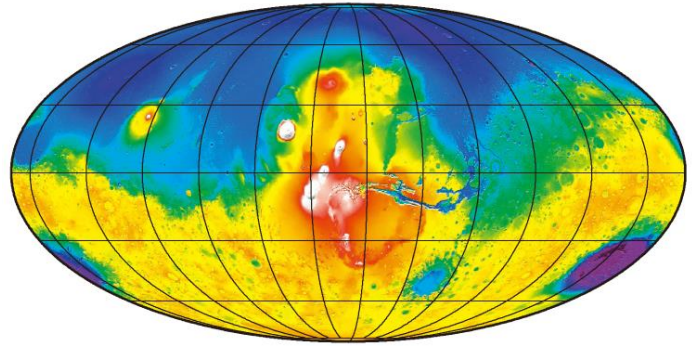
内径 (例: コアサイズ) / 外径比



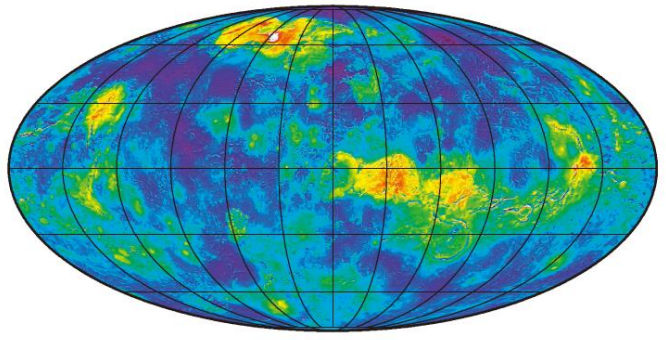
$\log[(\text{マンツルの深さ})^3 / \text{マンツルの粘性率}]$



-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7



-8 -6 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8

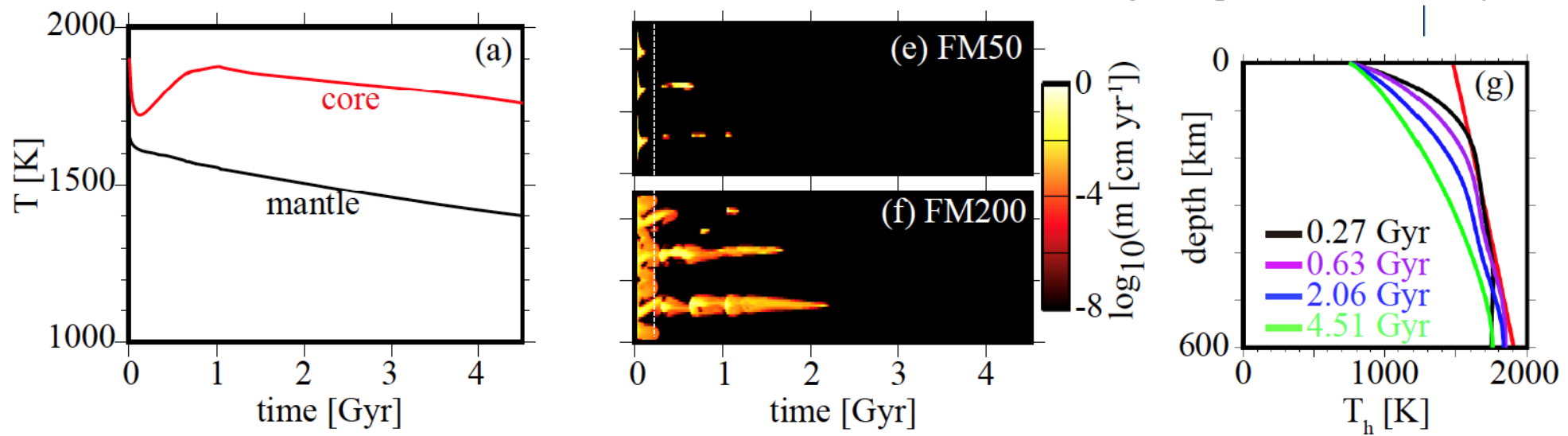


-2 -1 0 1 2 3 4 5 6 7

Topography (km)

(Wieczorek, 2015)

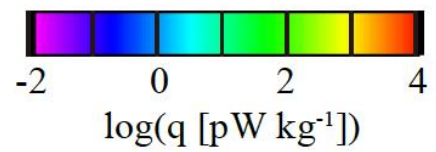
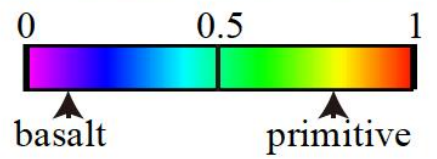
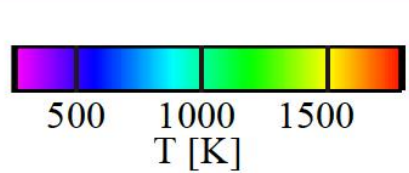
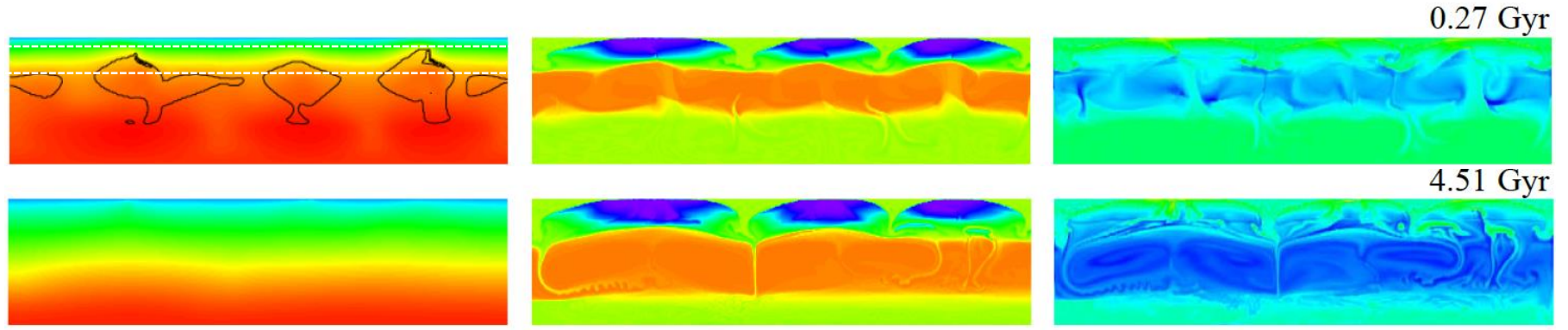
(2) 放射性元素の地殻への濃集と火成活動の減衰
 持続する火成活動 = 地殻のリサイクル



(h) T & magma

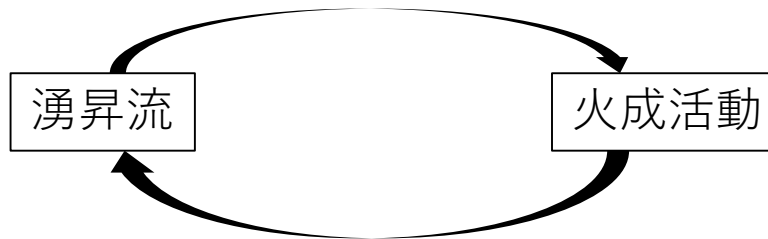
(i) composition

(j) internal heating rate

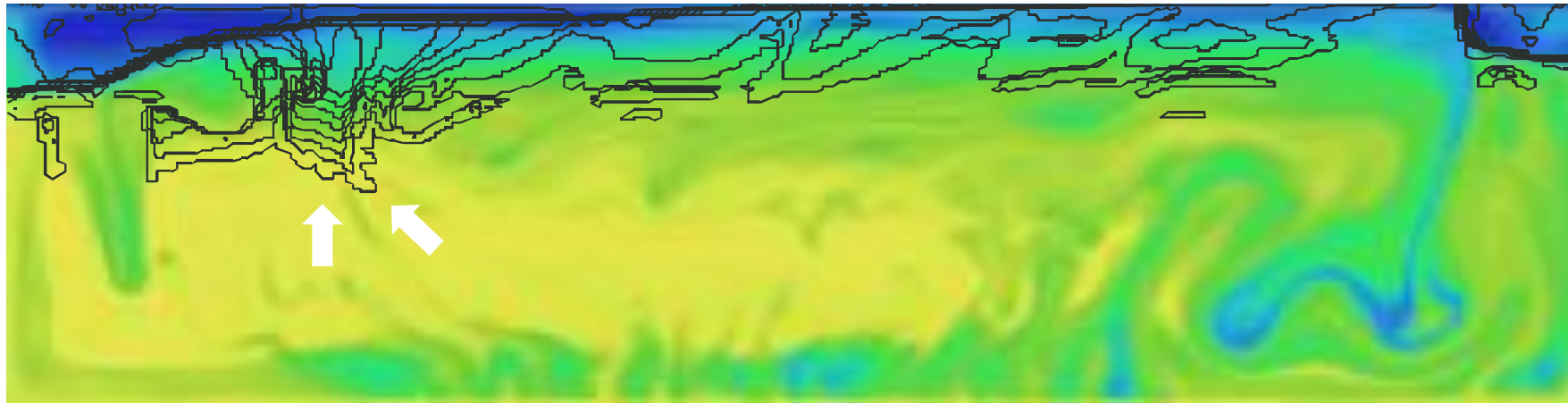


(3) 火成活動マントル湧昇流フィードバック

圧力解放によるマグマ生成

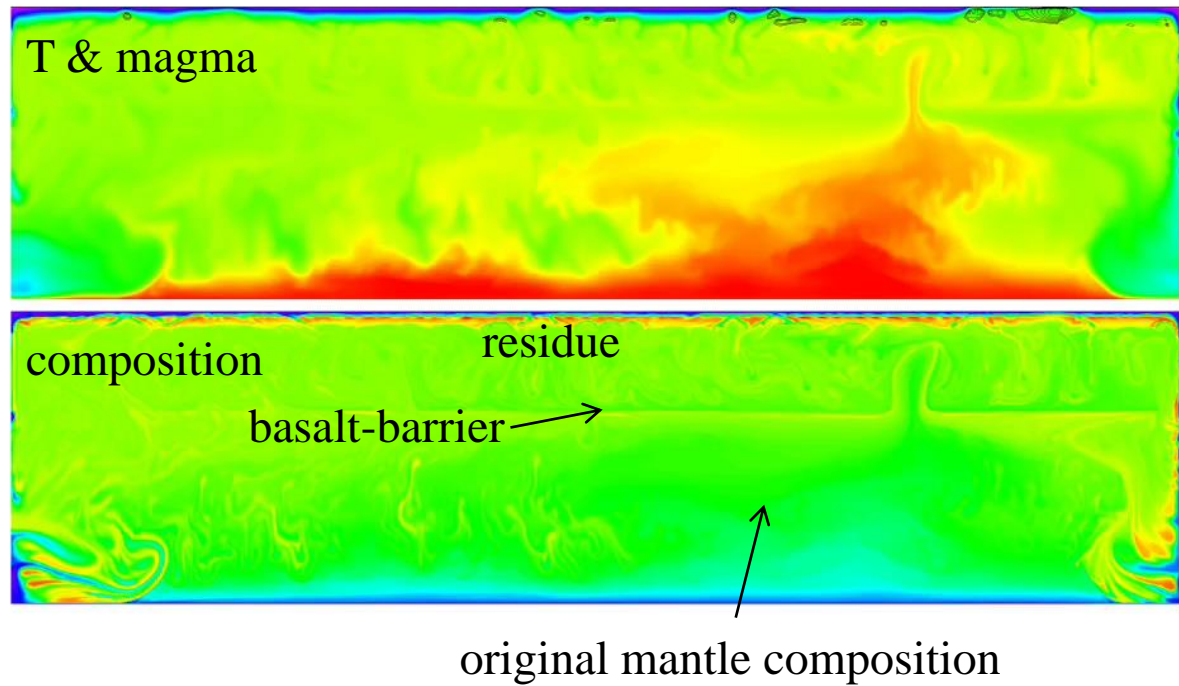
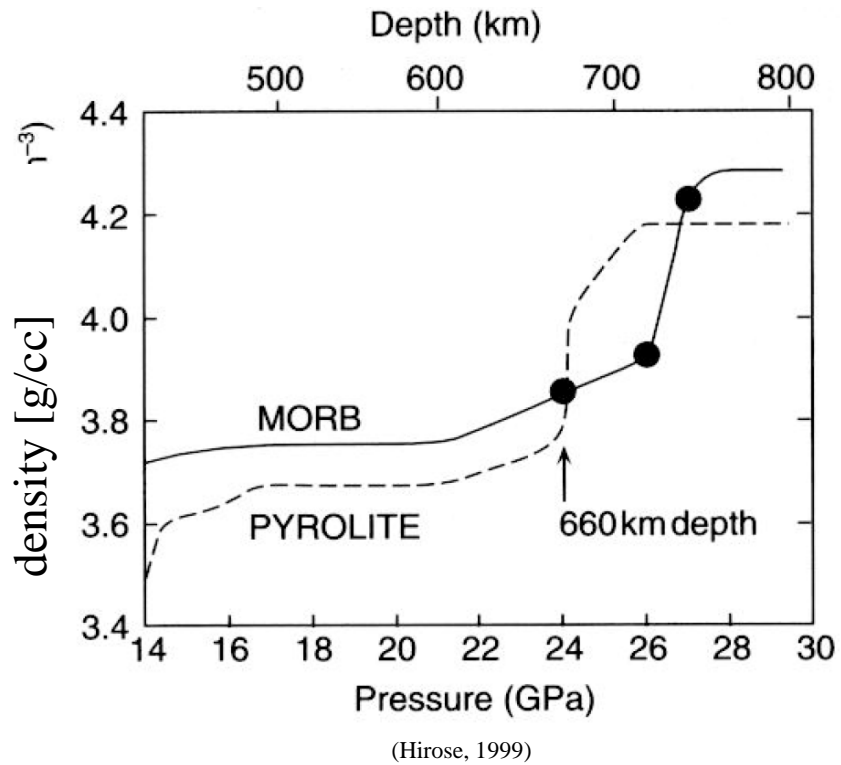


マグマの浮力+マグマ移動による母岩の体積変化



$R > R_{\text{MMU}b}$ の時のみ働く: 惑星サイズの効果

(4) バースト

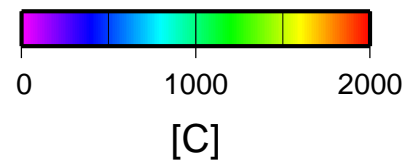
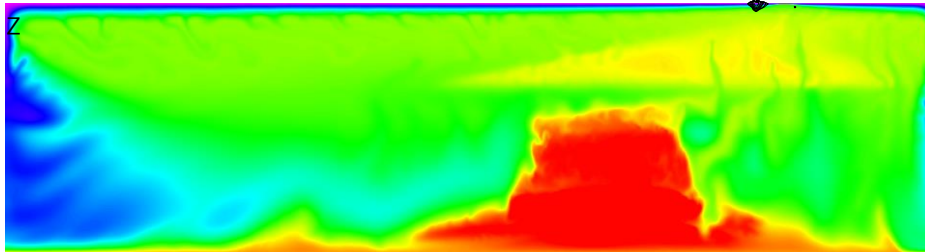


$H > H_c$ の時にマントル・ダイナミクスを支配。下部マントルの存在が前提

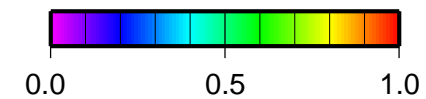
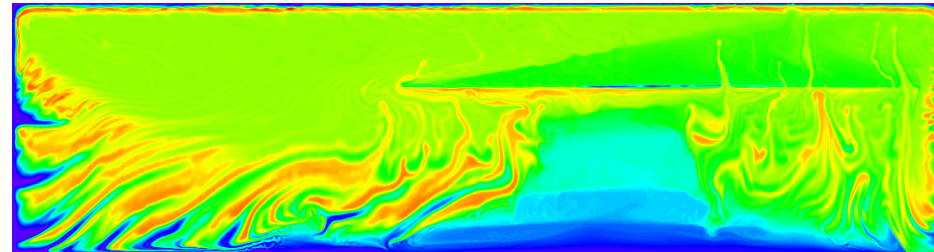
地殻のリサイクリング

(5) プレート・テクトニクスと海嶺火山活動

温度とマグマの分布

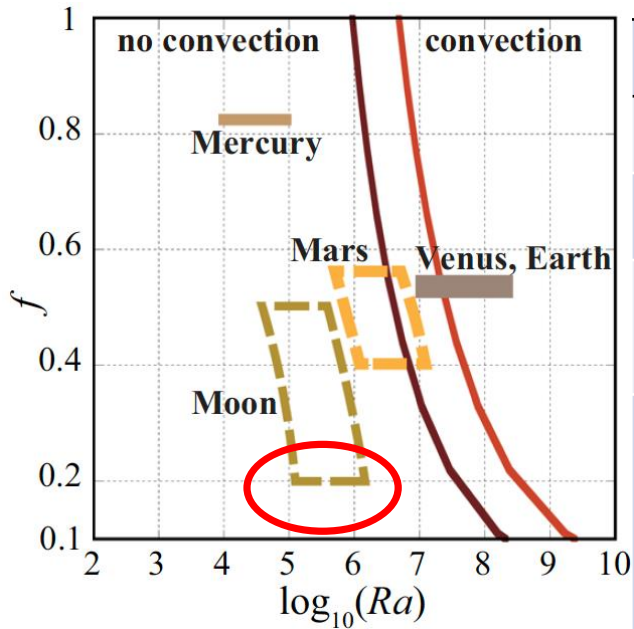


組成分布



連続的火成活動と地殻のリサイクリング

月

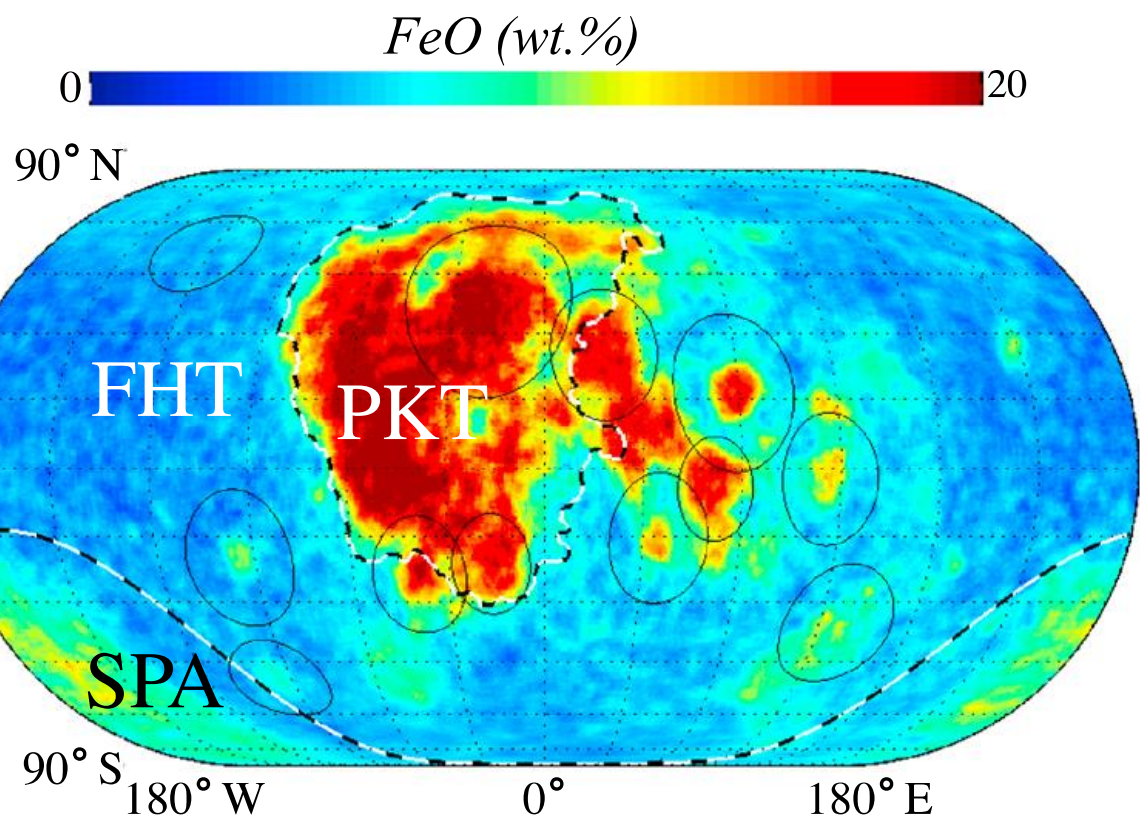


(Yanagisawa et al., 2016)

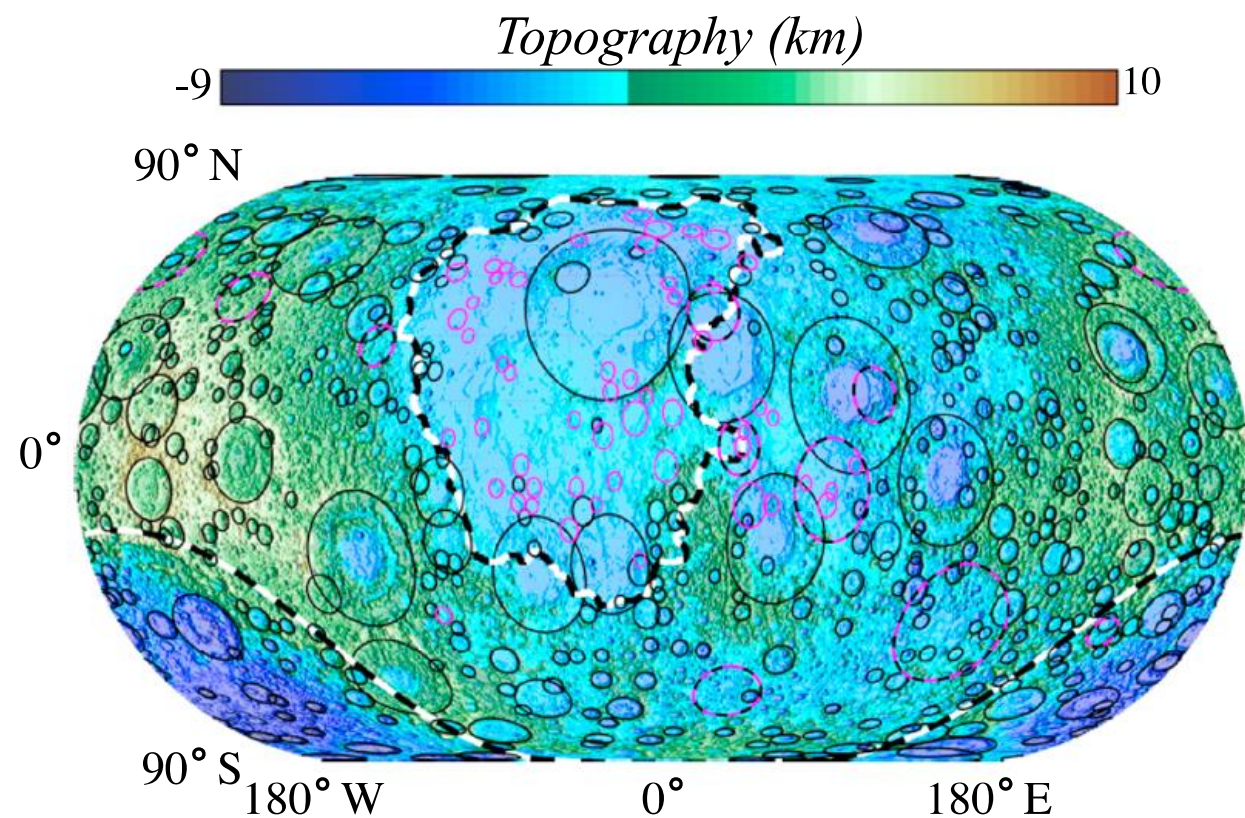
素過程	効果	月	水星	火星	金星	地球
放射性元素の地殻への濃集	火成活動の減衰	○	○	○	○	○
対流不安定・プルーム	ホットスポット火山	×	×	○	○	○
火成活動・マンテル湧昇流 フィードバック	パルスの火成活動 マンテルの均質化	×	○?	○	○	○
バースト	惑星の二段階進化 パルスの火成活動 地殻のリサイクリング	×	×	×	○	○
プレート・テクトニクス	連続的の火成活動 マンテルの不均質化 地殻のリサイクリング	×	×	×	×	○

マグマ・オーシャンによる地殻形成 弱いマンテル対流起源の火成活動 Dichotomy

(a)

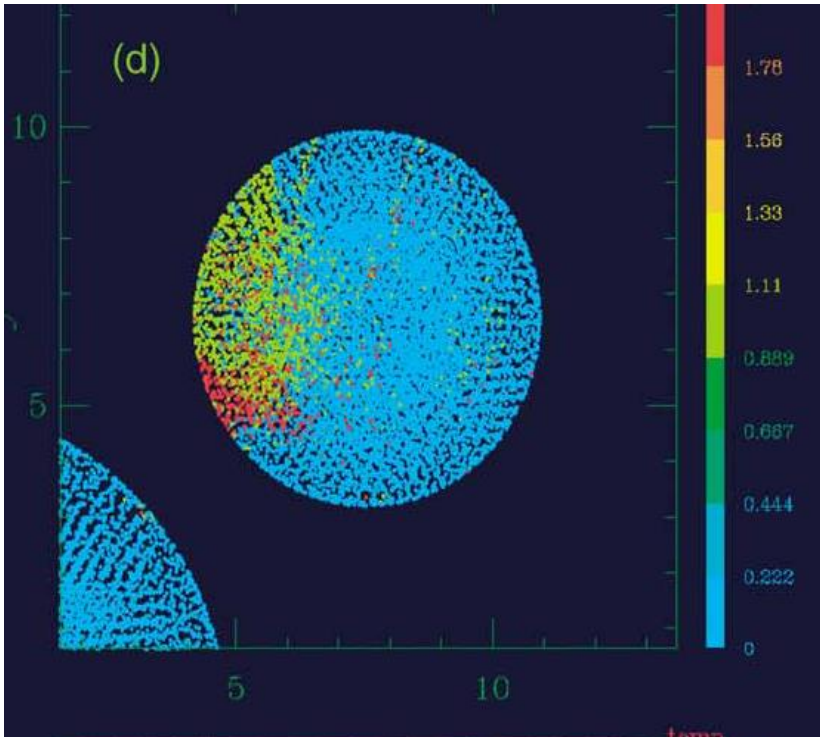


(c)

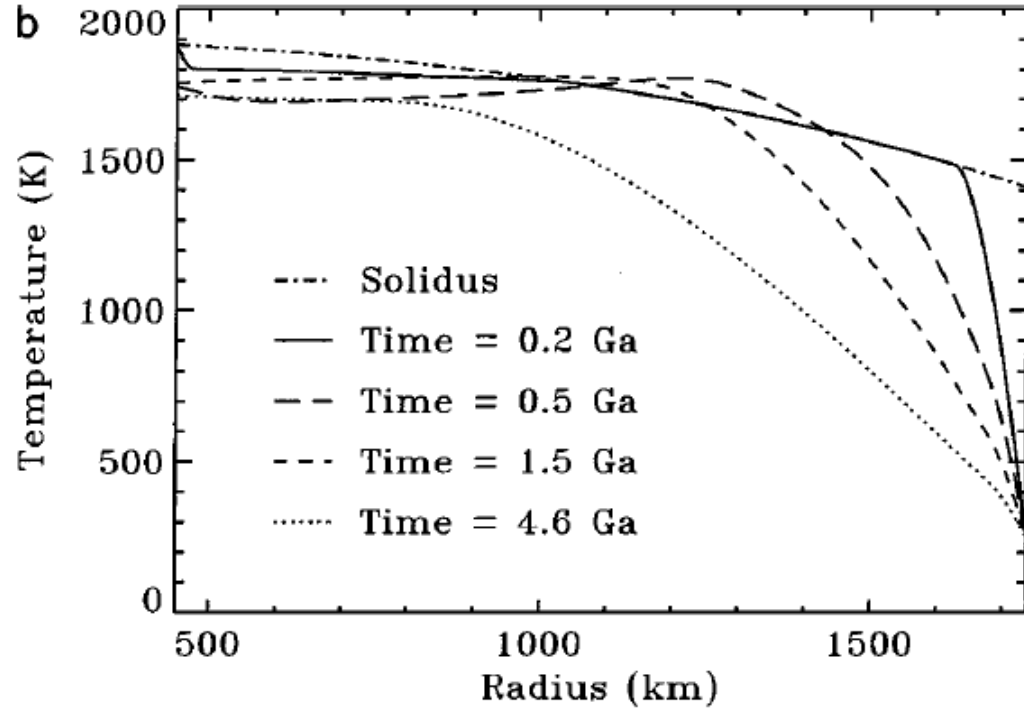
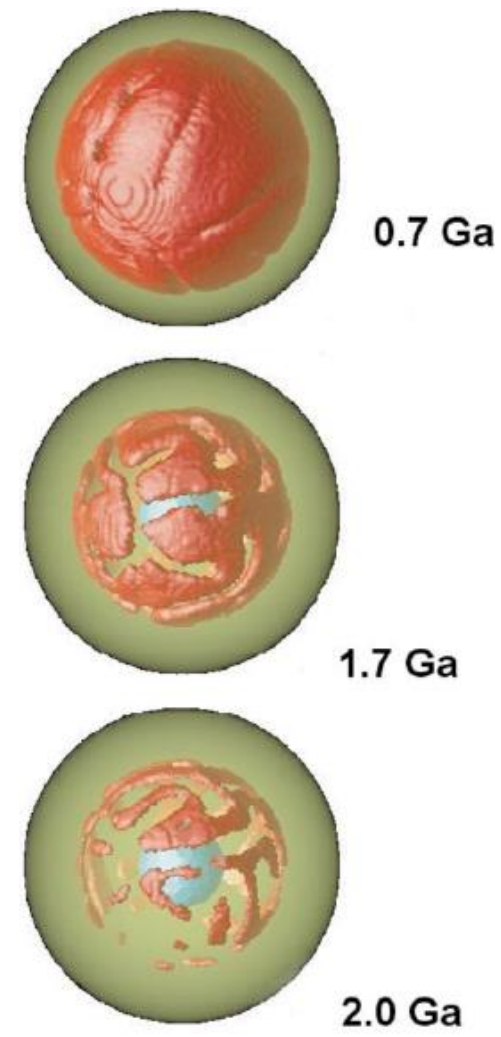


月は高温起源？

古典的巨大衝突モデルによる月の初期温度
(各粒子が経験した最高温度)

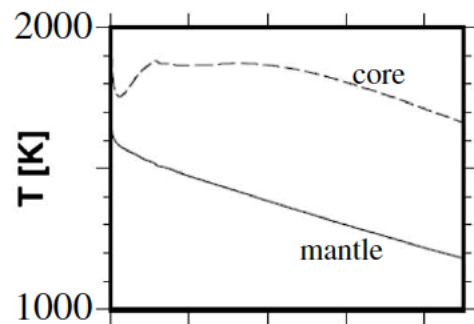


(Canup, 2004)

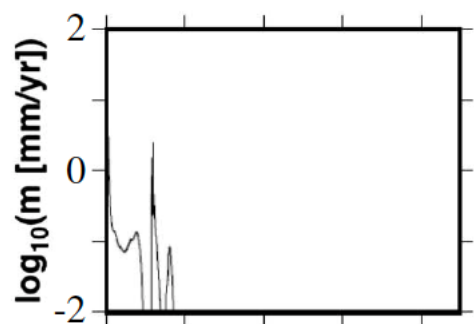


(Spohn et al., 2001)

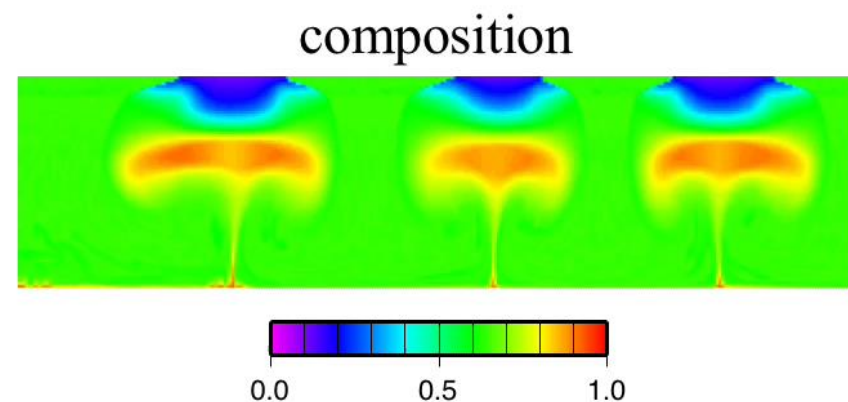
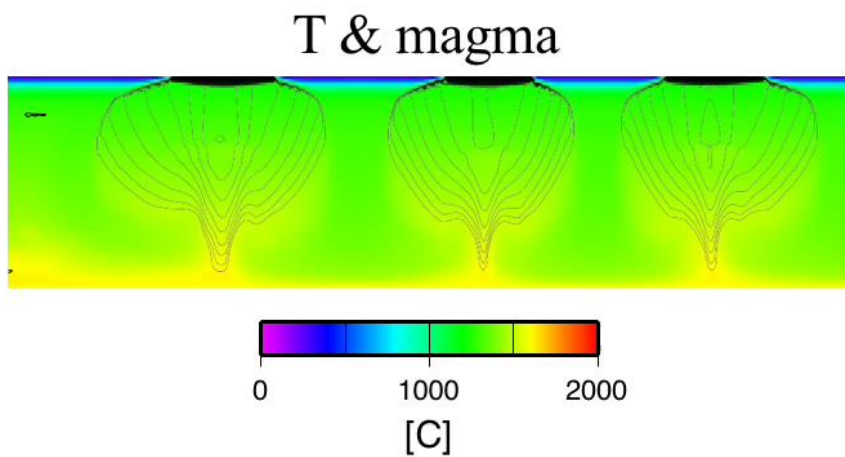
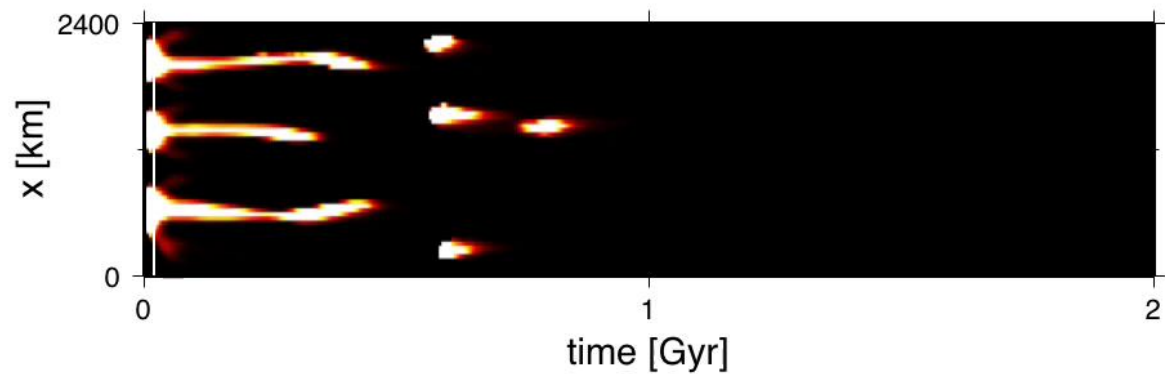
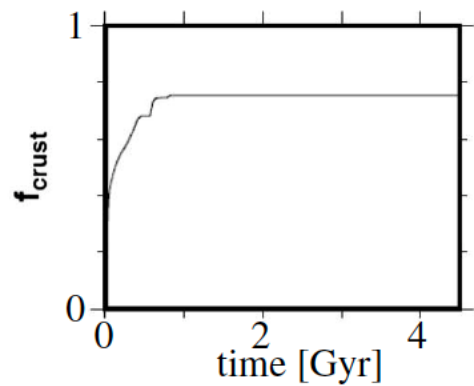
(a) average temperature



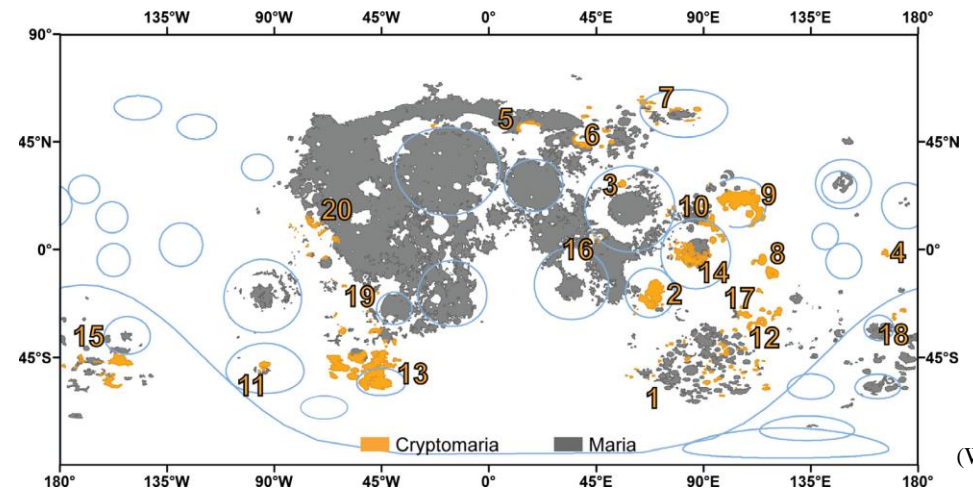
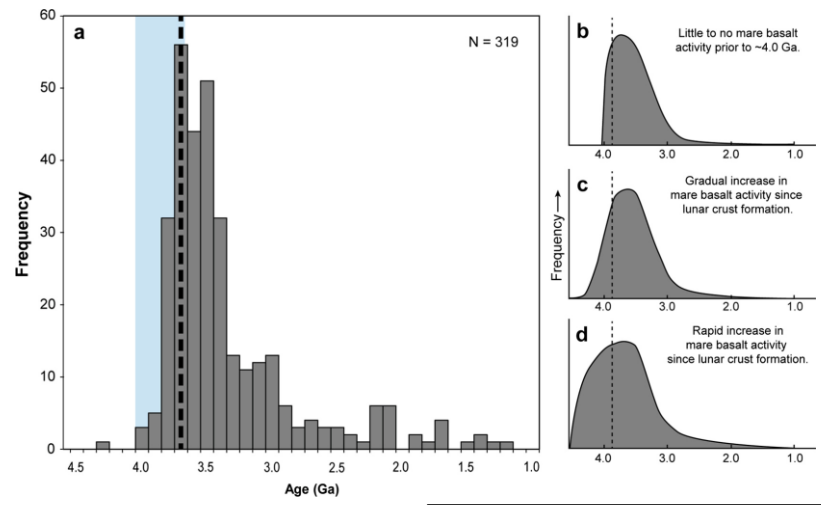
(c) flux of magma



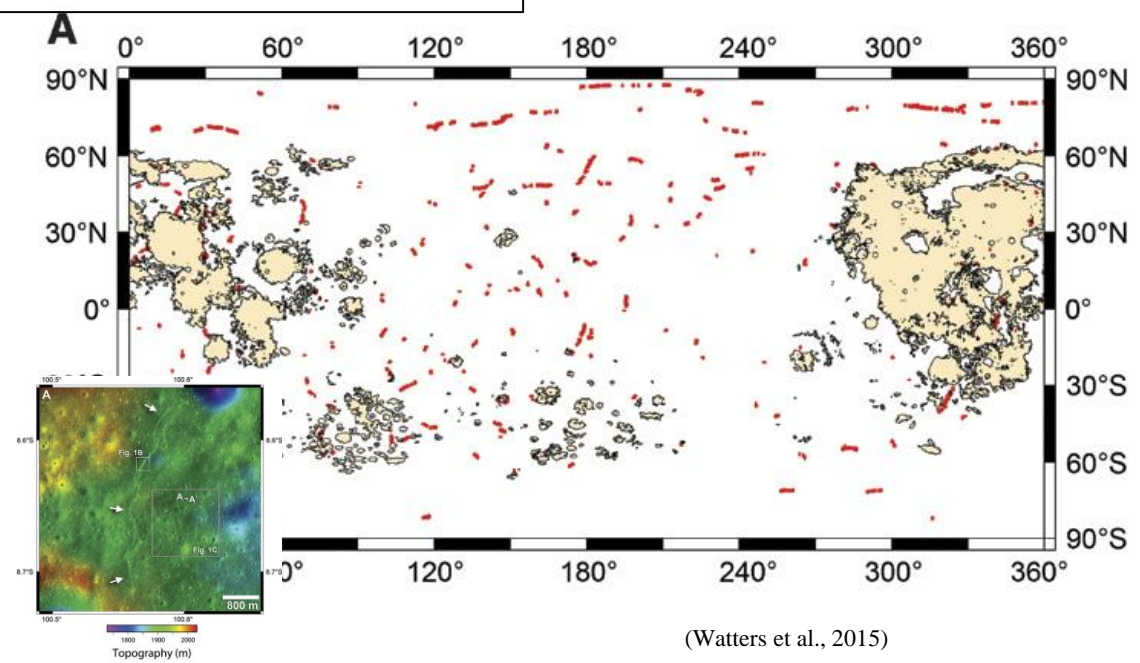
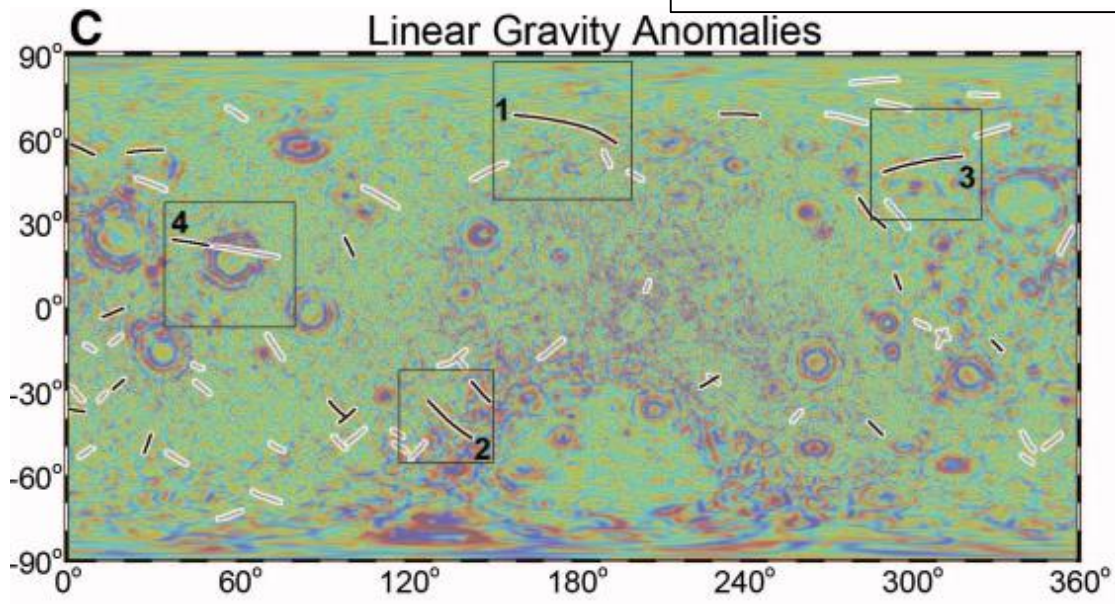
(e) fraction of crustal HPEs



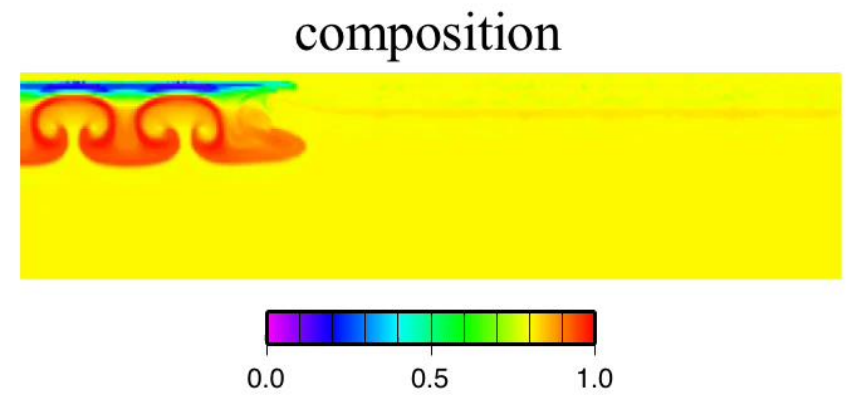
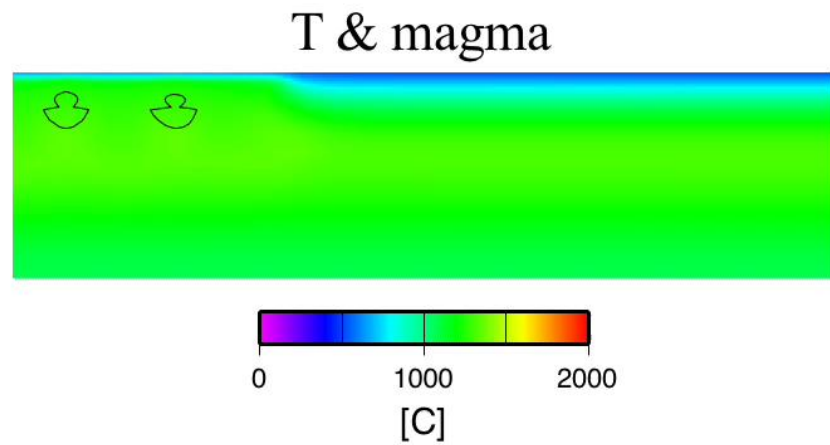
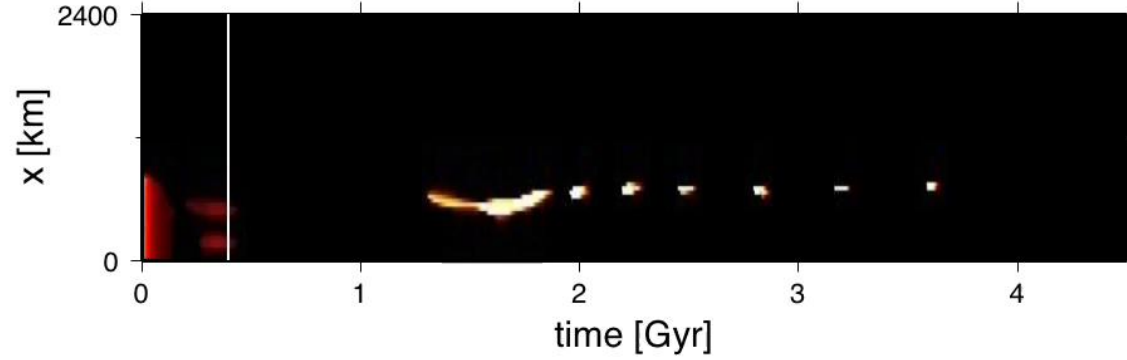
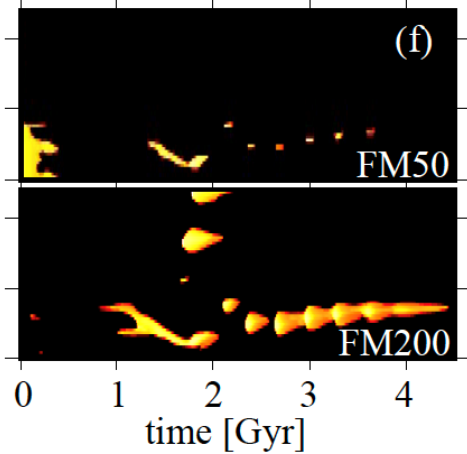
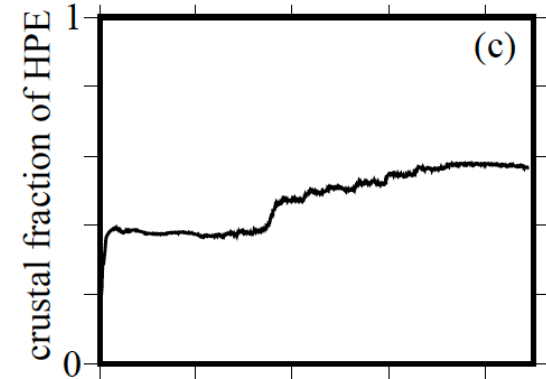
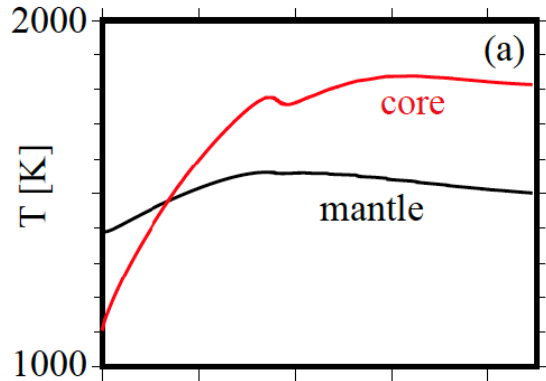
海の火成活動史：40億年前頃→10-20億年前まで持続



熱史：熱膨張 → わずかに熱収縮



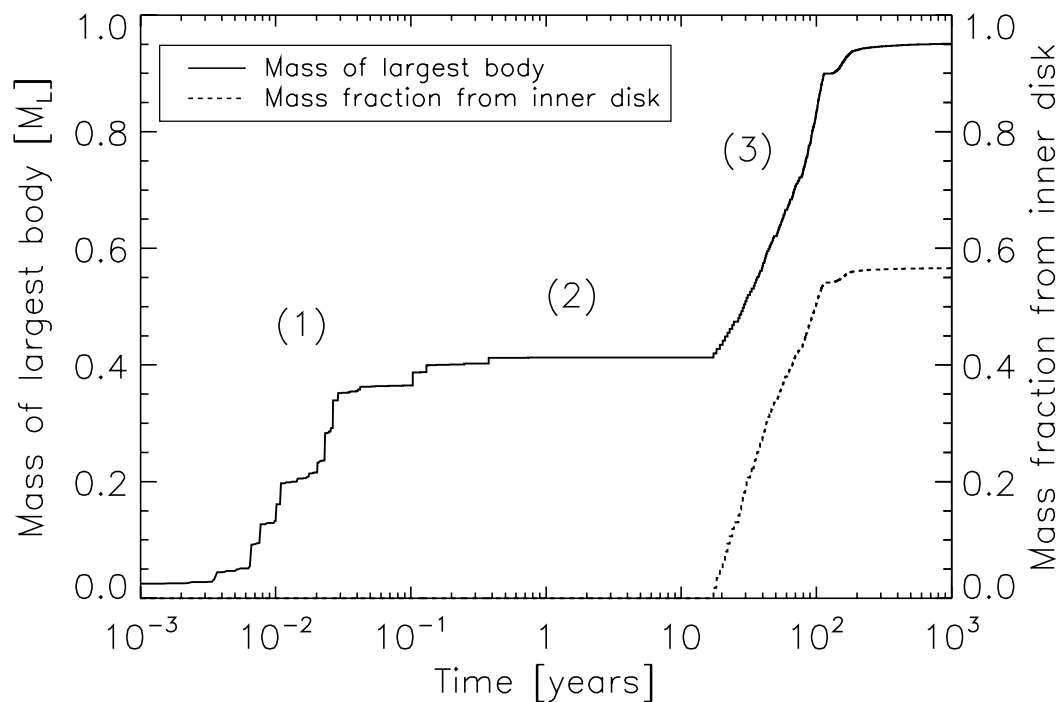
低温起源モデル（水平不均質なHPE-分布）



月の作り方？

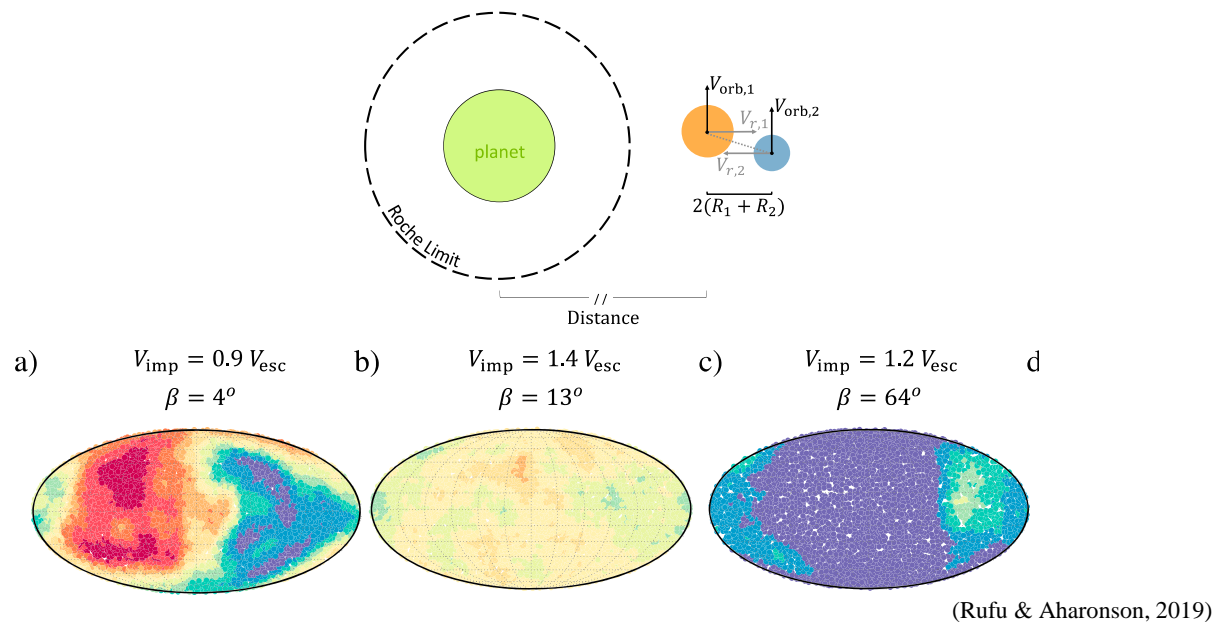
(1) マグマ・オーシャン、 (2) 内部は低温、 (3) dichotomy

形成時間 >> 数ヶ月？

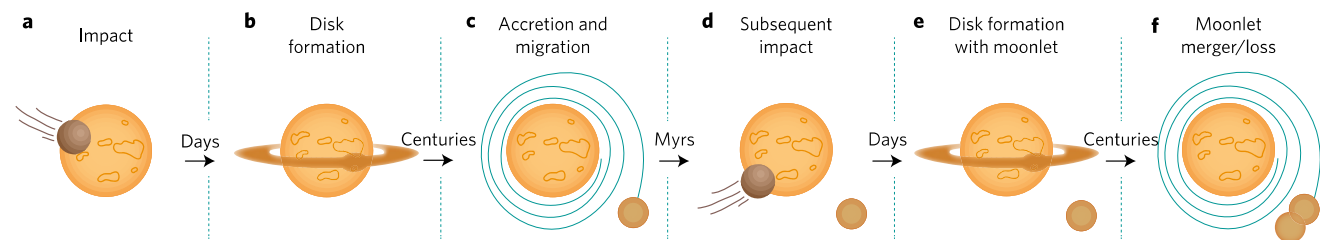


(Salmon & Canup, 2012)

単発衝突による複数の原始月形成と衝突？

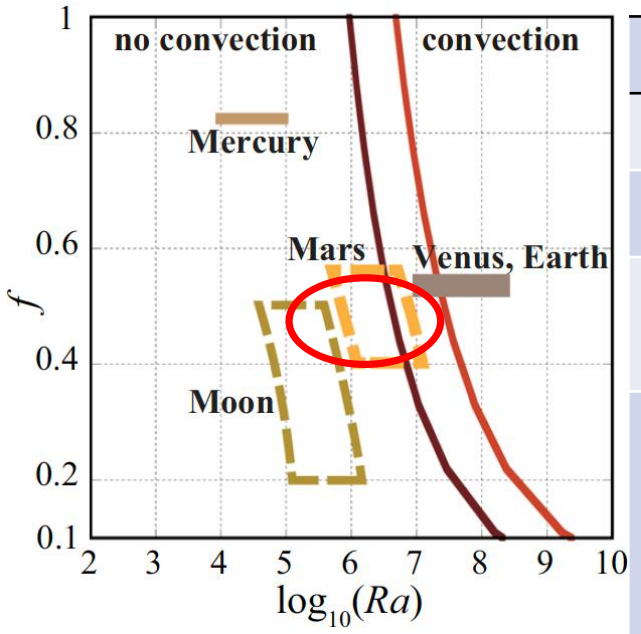


多重衝突モデル(数百万年)？



(Rufu et al., 2017))

火星



(Yanagisawa et al., 2016)

素過程	効果	月	水星	火星	金星	地球
放射性元素の地殻への濃集	火成活動の減衰	○	○	○	○	○
対流不安定・プルーム	ホットスポット火山	×	×	○	○	○
火成活動・マンテル湧昇流 フィードバック	パルスの火成活動 マンテルの均質化	×	○?	○	○	○
バースト	惑星の二段階進化 パルスの火成活動 地殻のリサイクリング	×	×	×	○	○
プレート・テクトニクス	連続的の火成活動 マンテルの不均質化 地殻のリサイクリング	×	×	×	×	○

火星 = 月 + MMUb フィードバック + プルーム

MO地殻 + 海

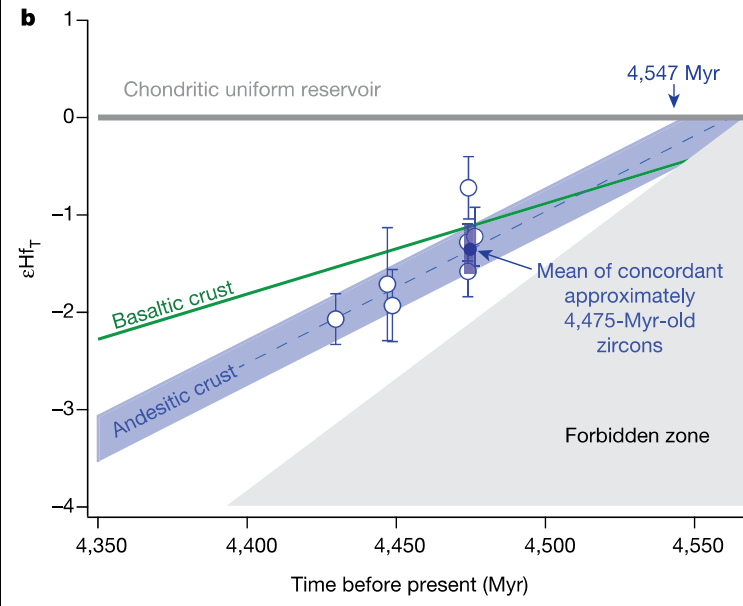


二次的火山による地殻？



地殻形成：20Myr以内

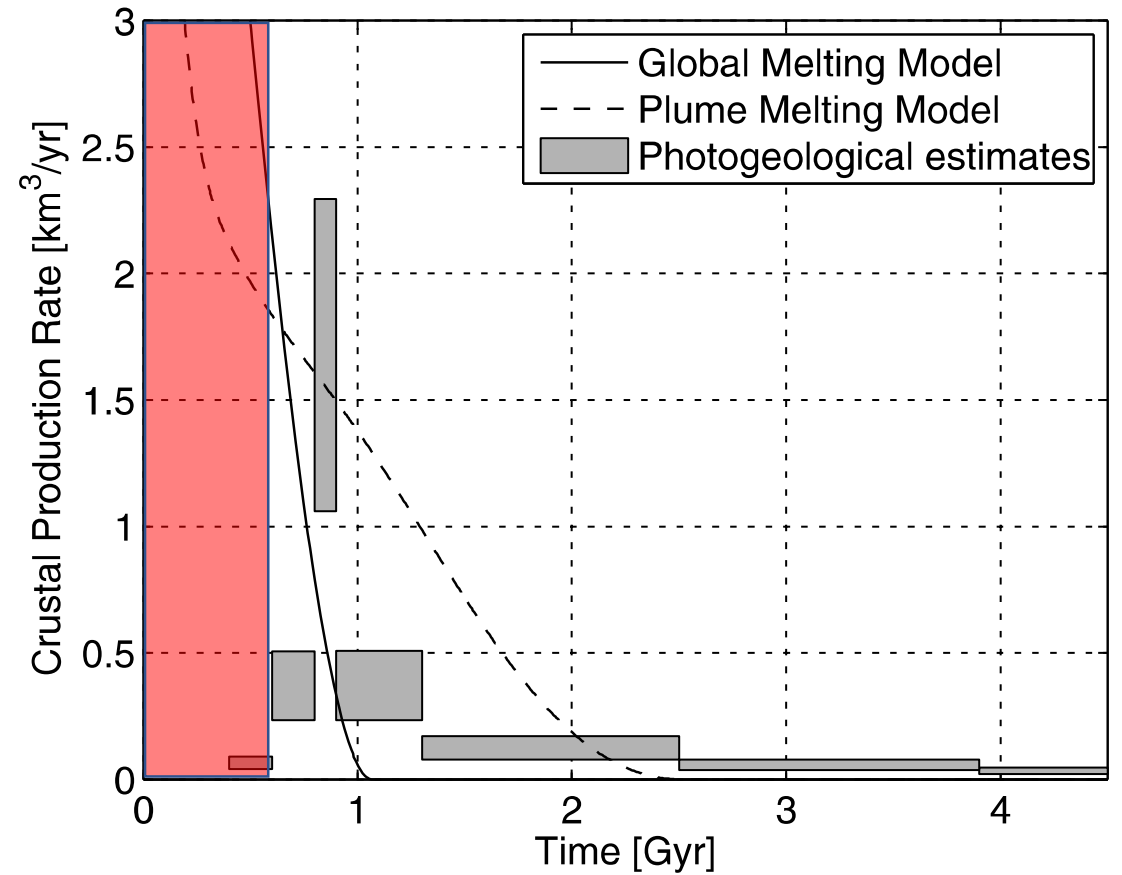
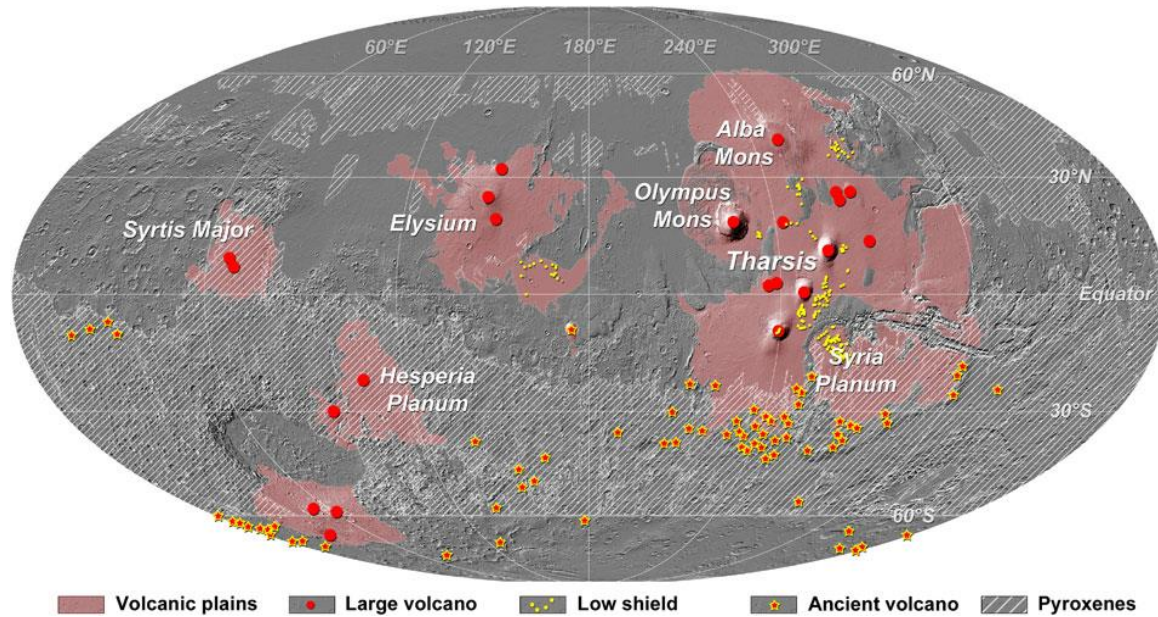
～マントル対流の時間スケール



(Bouvier et al., 2018)

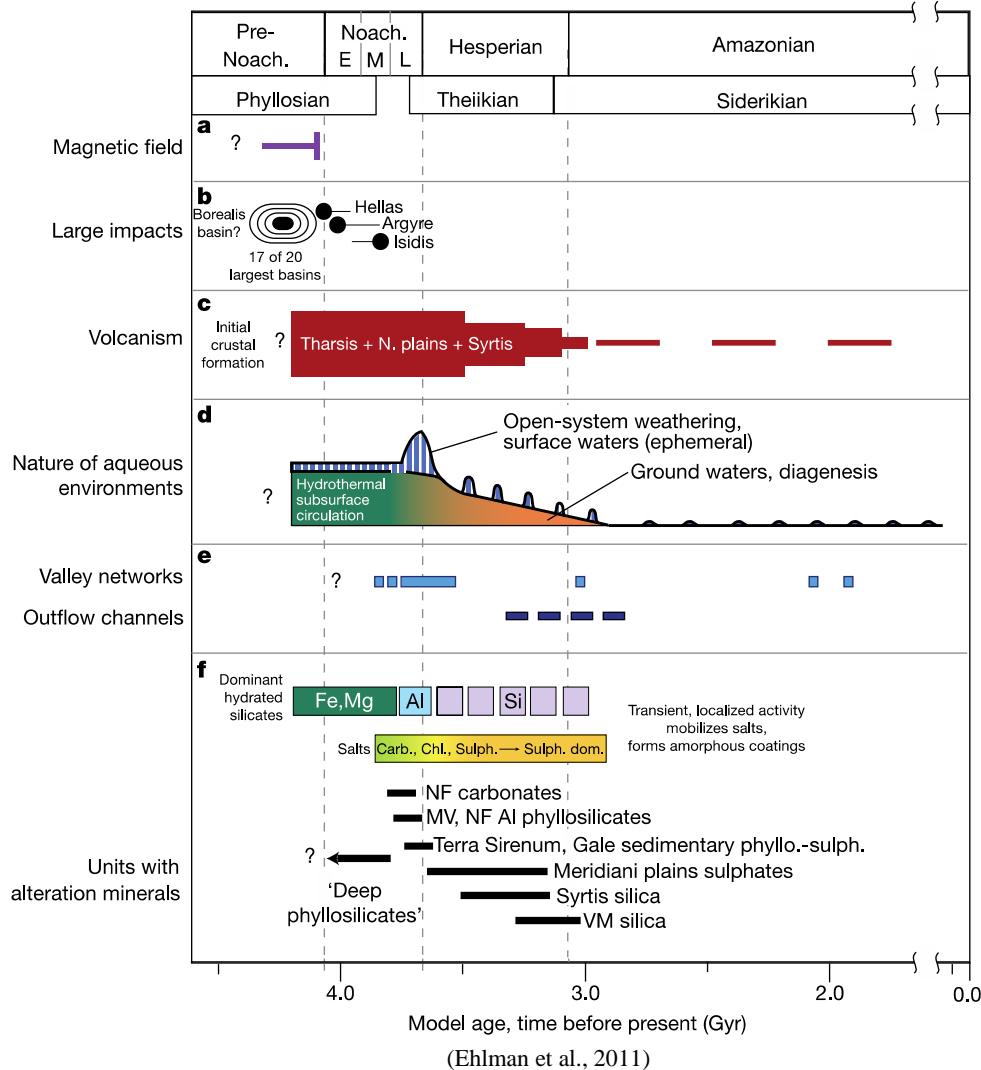
火星の火山活動史

地殻形成(MO)・成長？

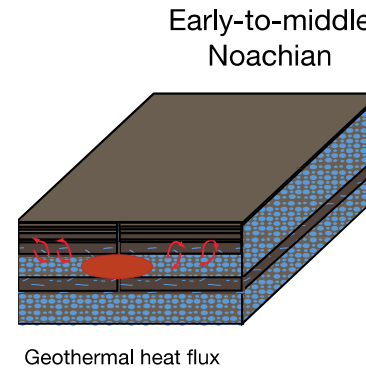


(Grott et al., 2013)

火成活動史と表層環境史の相関

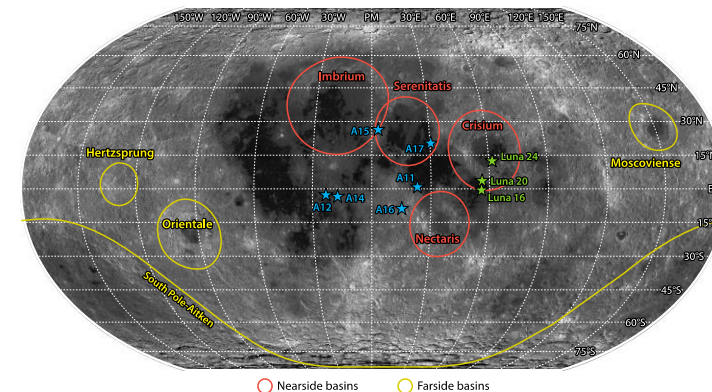


後期重爆撃による水の供給？



(Ehlman et al., 2011)

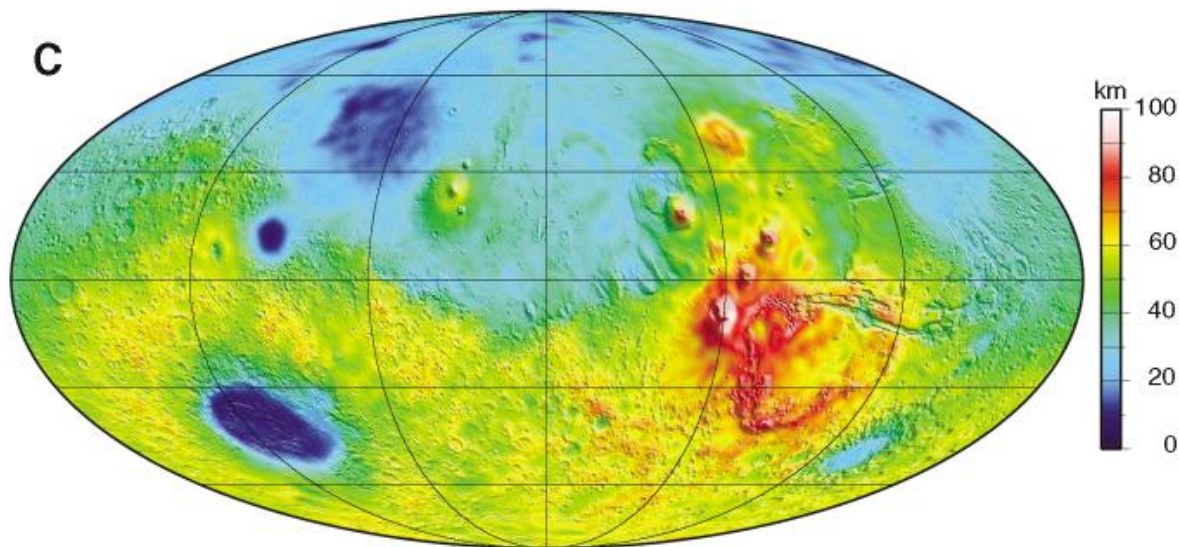
後期重爆撃？



(Bottke & Norman., 2017)

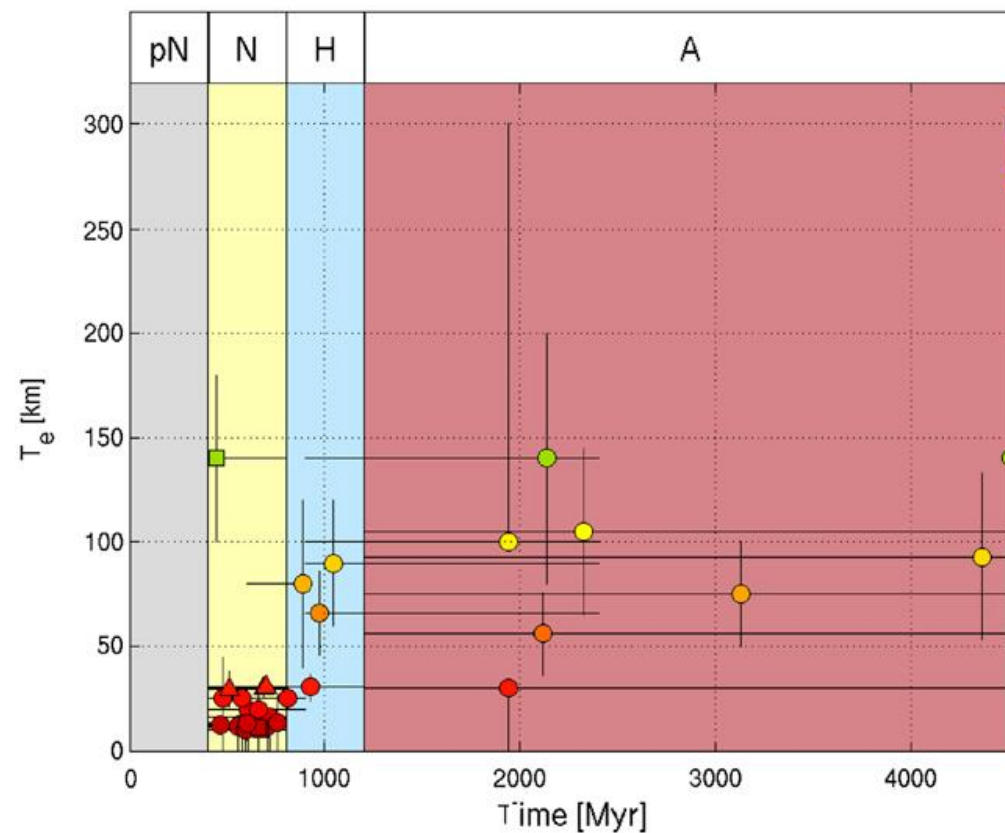
初期条件：高温起源？

磁場(>4 Ga)



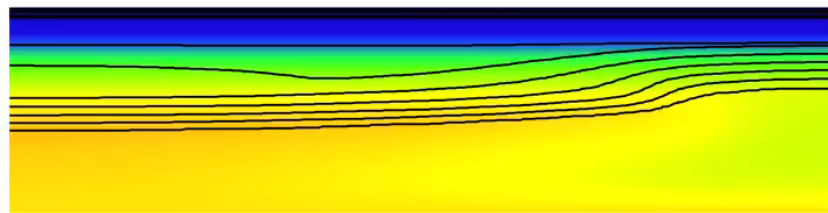
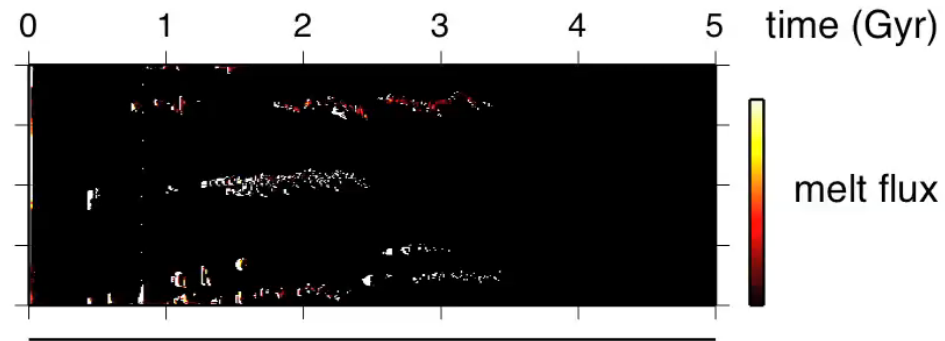
(Solomon et al, 2005)

リソスフェアの弾性的厚さ



(Grott et al., 2013)

wetmars S7-18-1 (0.18 My)



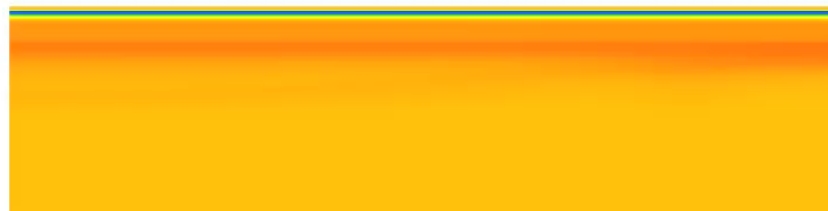
200 [K] 2200

temperature & magma



-2.5 0.0 2.5

log10(internal_heating [pW/kg])



0 1

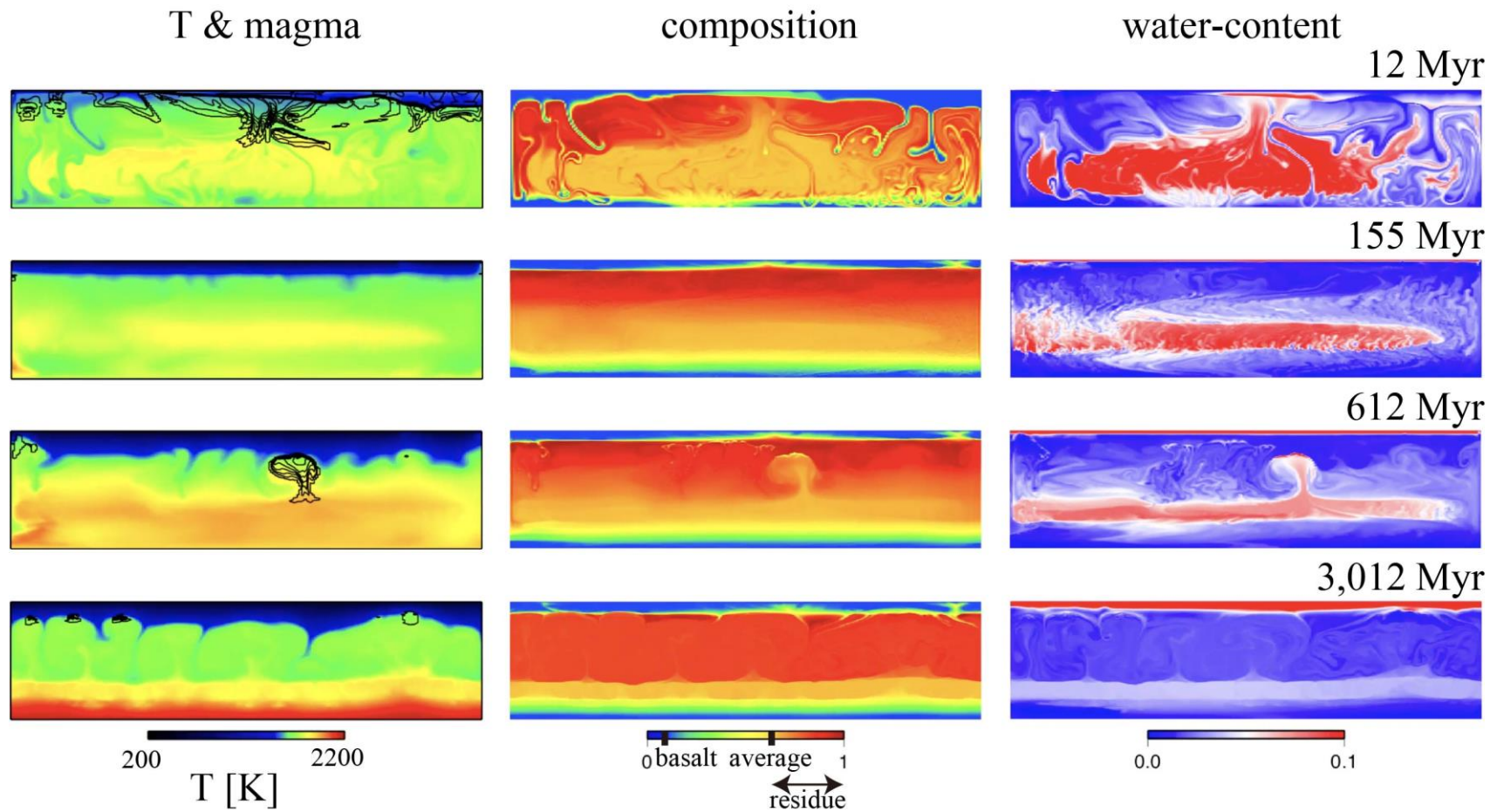
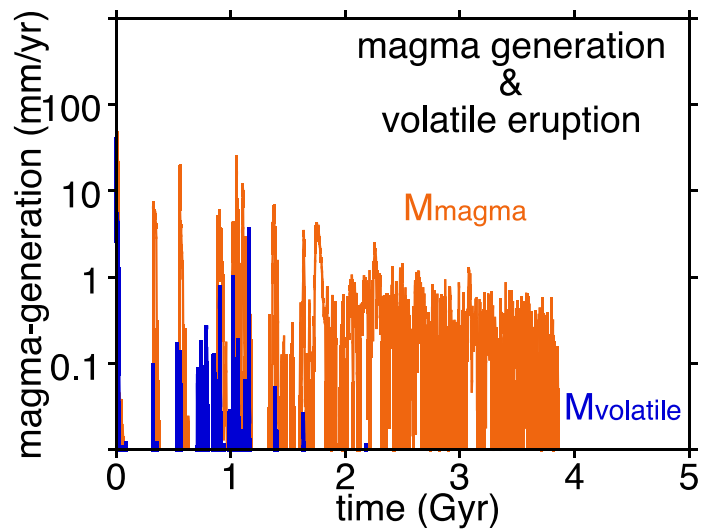
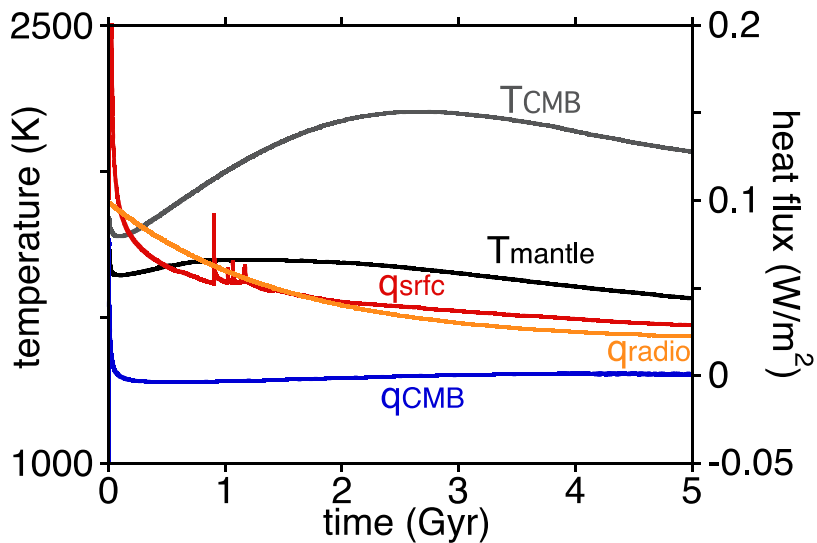
composition



0.0 0.1

water_content (%)

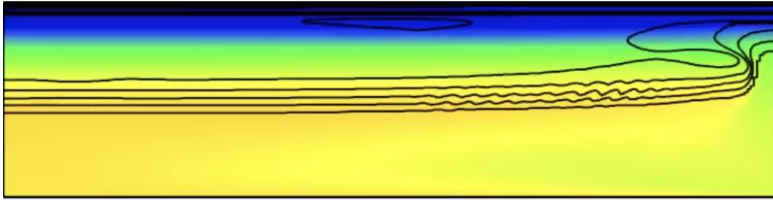
MOとMMUフィードバックによる地殻形成→静穏期→プルーム火山による脱ガス



(Ogawa & Yanagisawa, 2012)

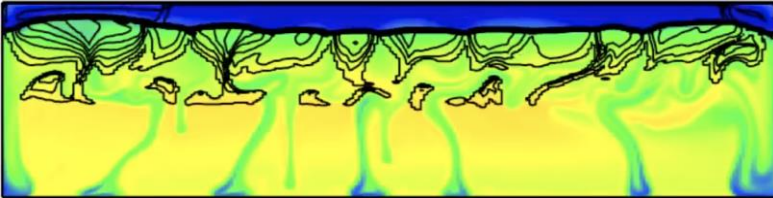
Crustal formation: MO \rightarrow flood basalt

T & magma

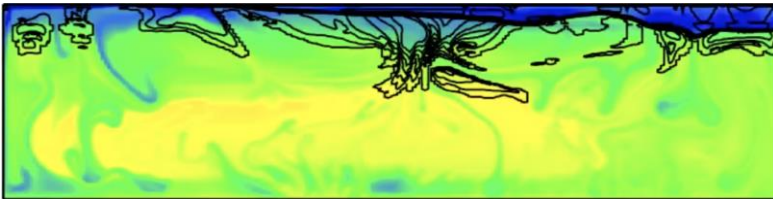
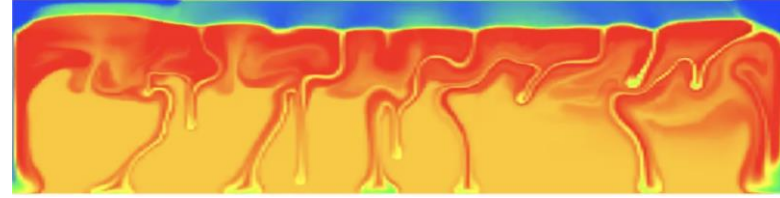


composition

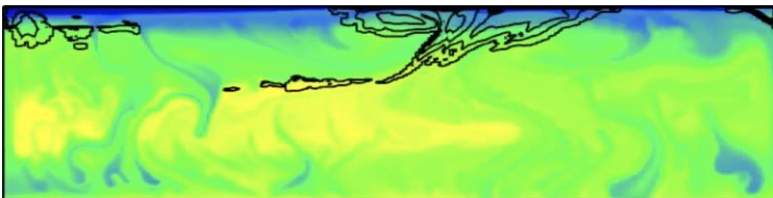
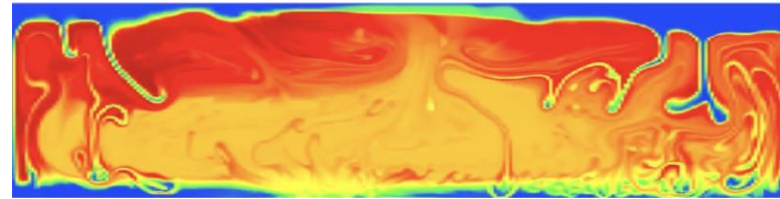
0.43 Myr



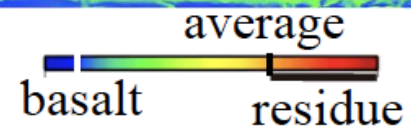
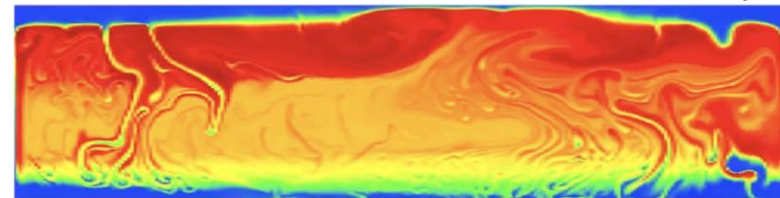
3.16 Myr



11.8 Myr

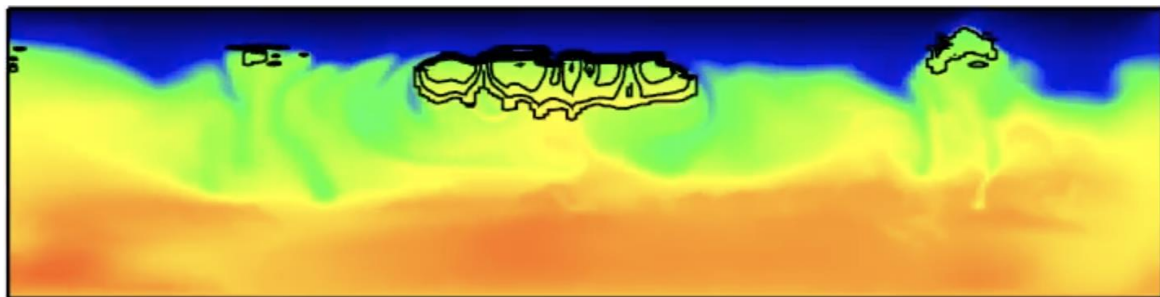
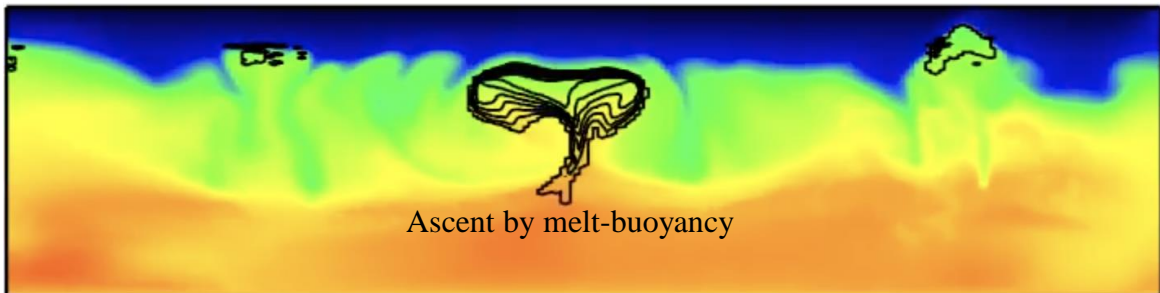
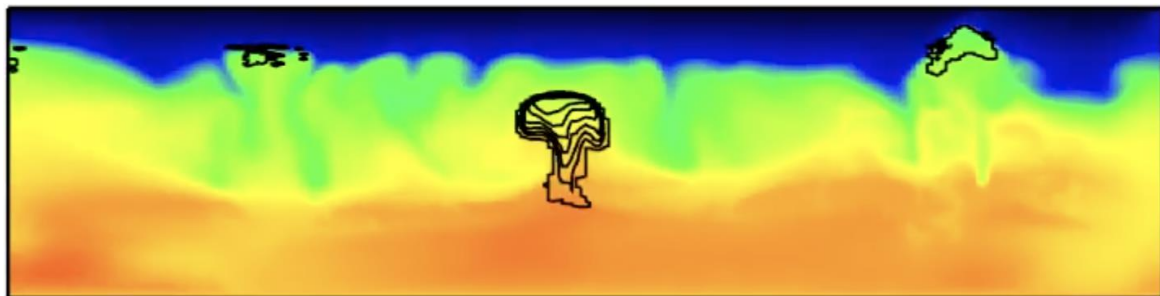


20.1 Myr

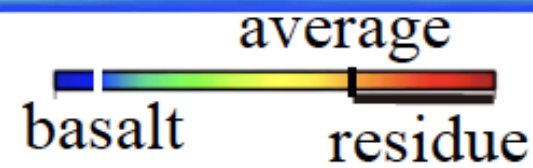
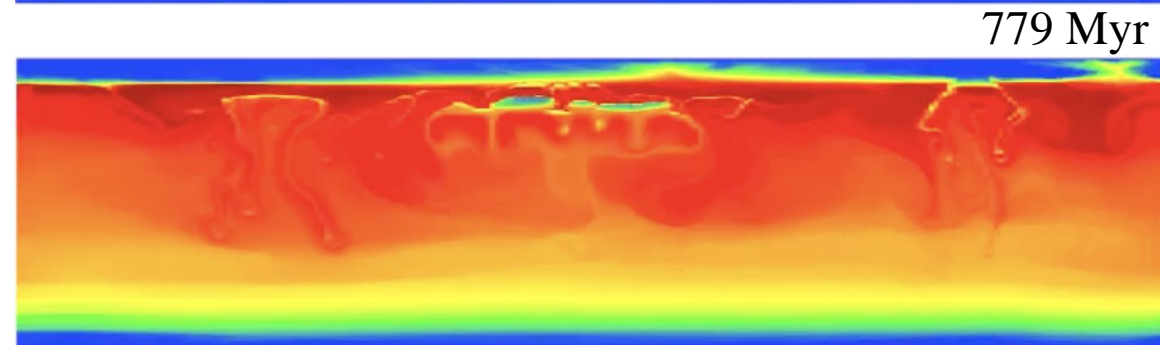
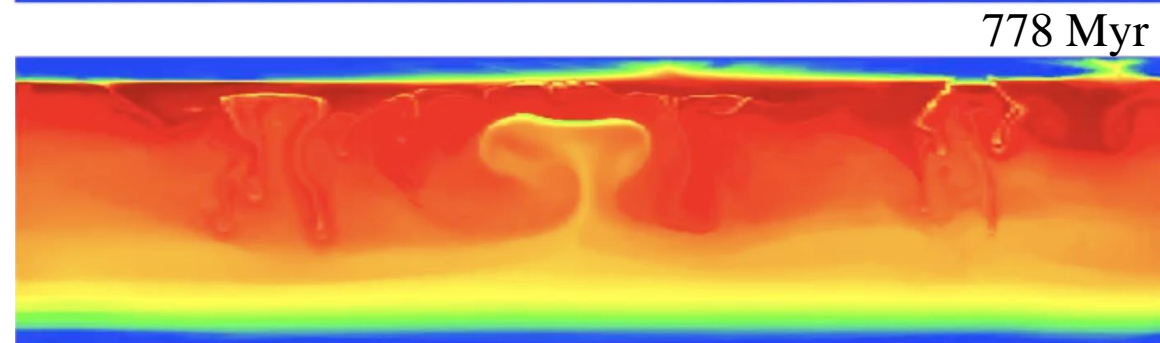
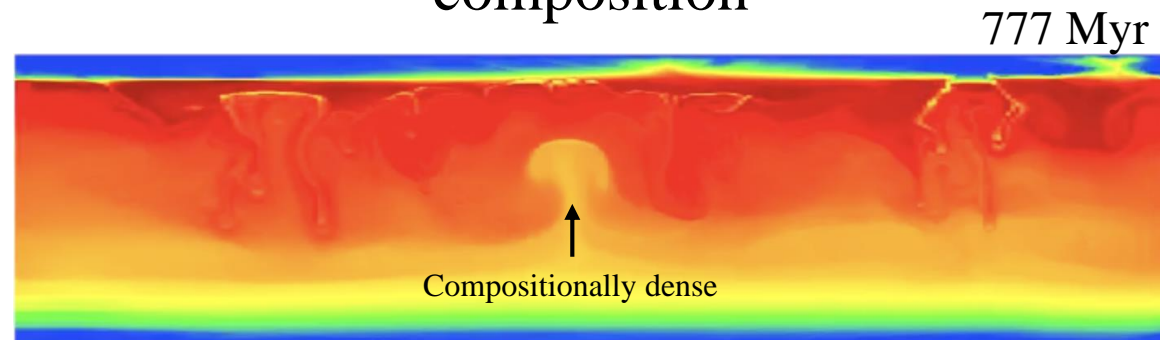


Plume magmatism caused by the MMU-feedback

T & magma



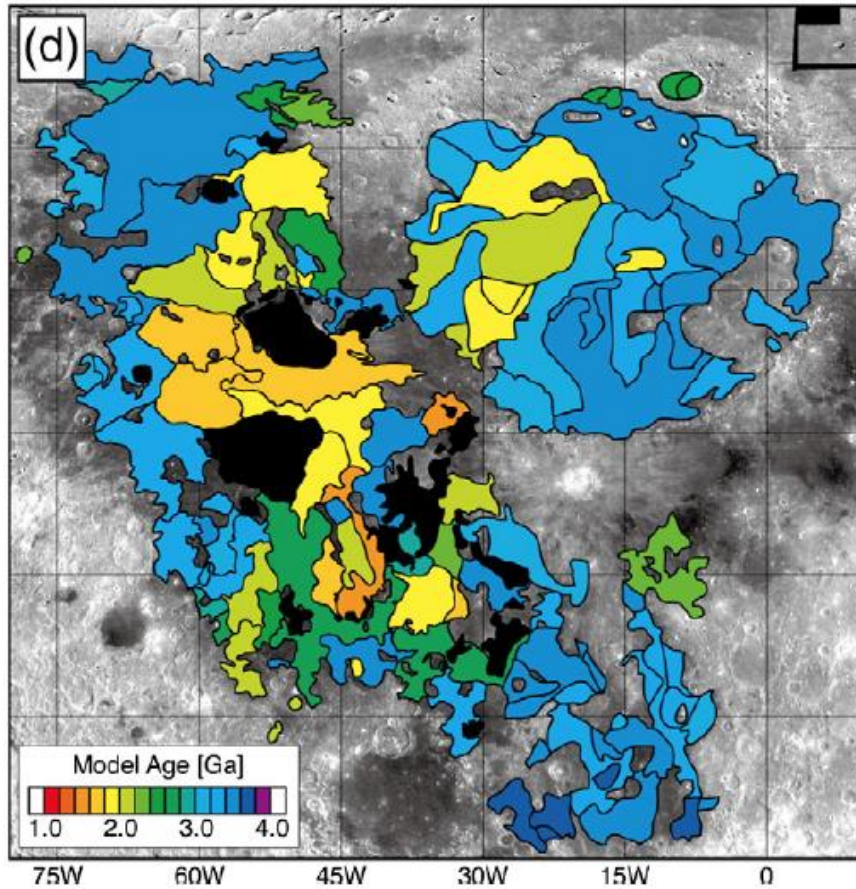
composition



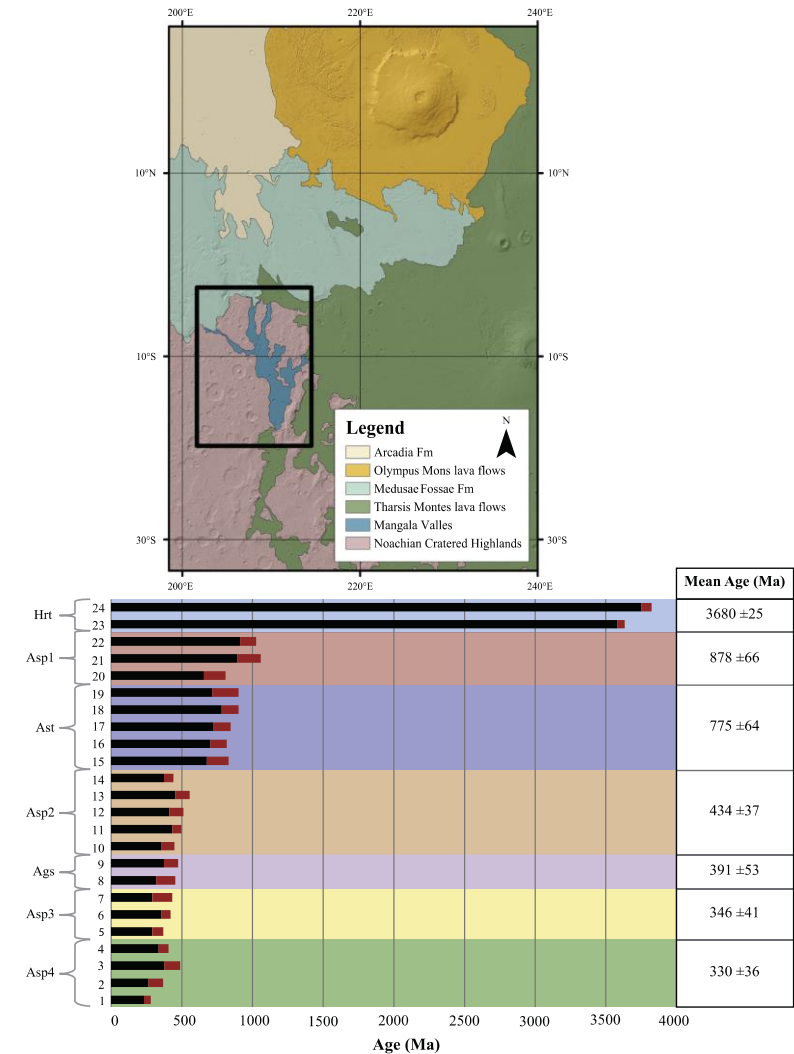
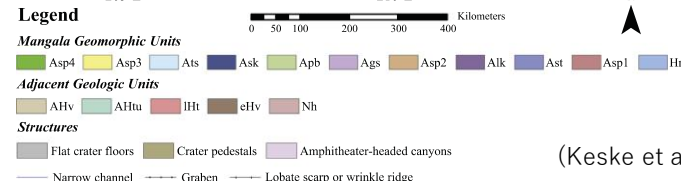
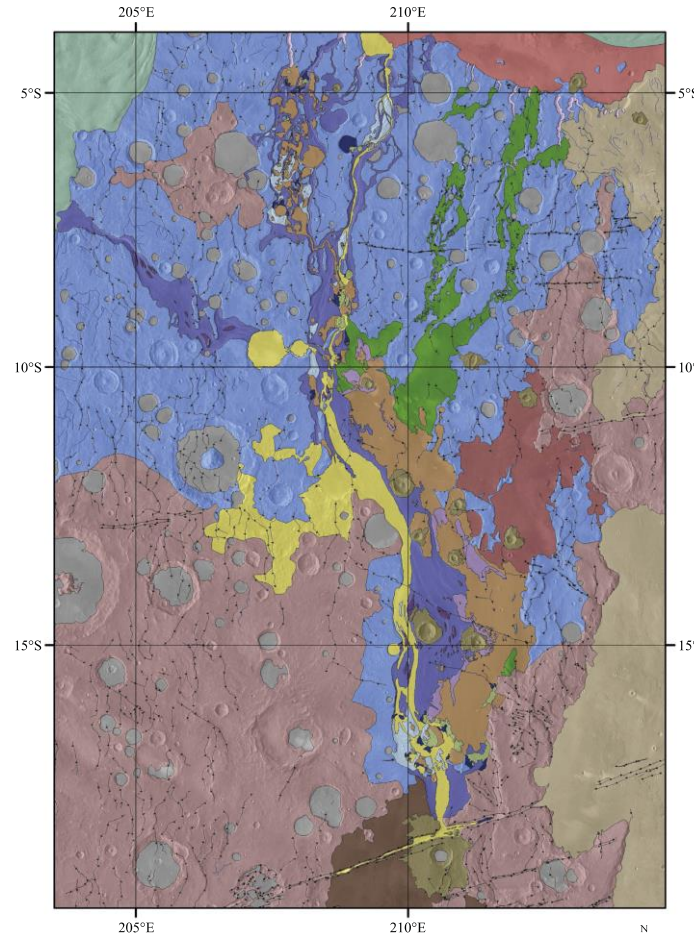
MMUbフィードバックと火山活動

月

火星

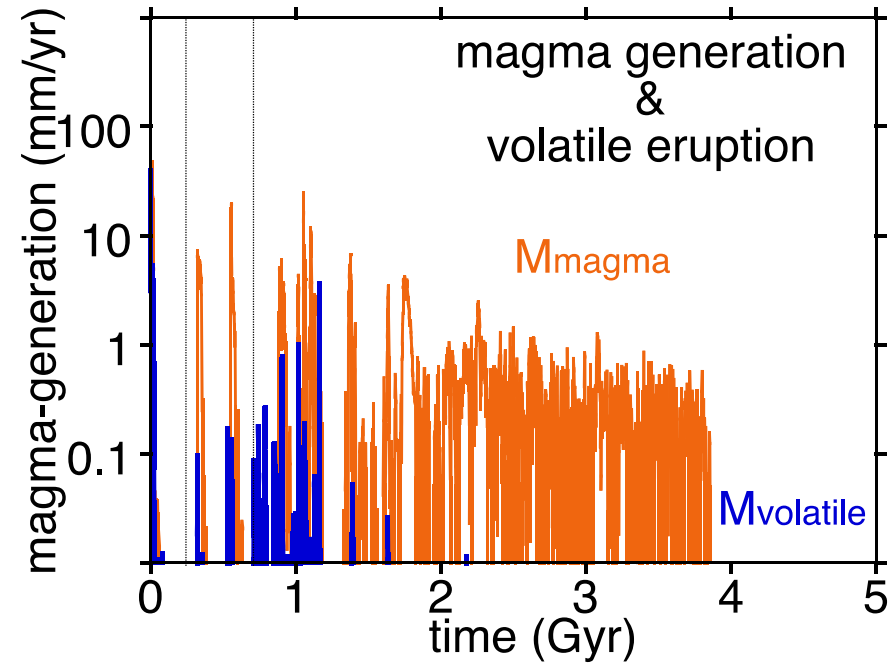


(Morota et al., 2011)

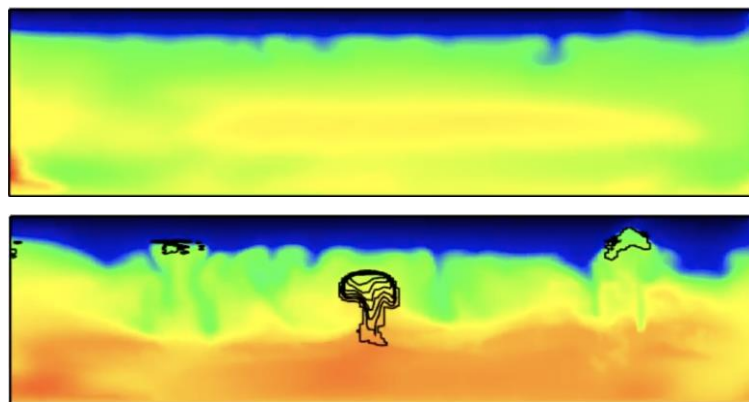


(Keske et al., 2015)

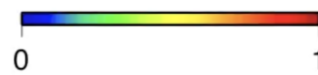
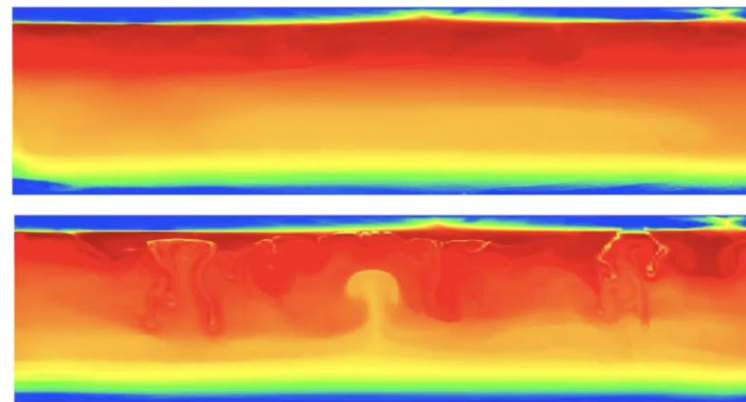
The dormant era & the later degassing by plume magmatism



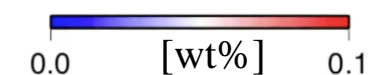
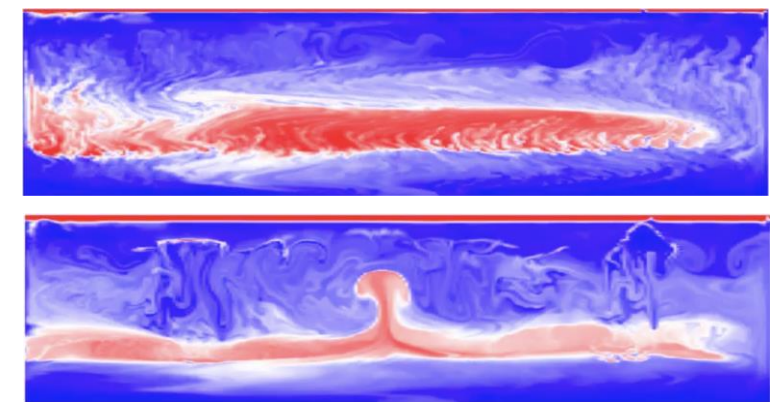
T & magma



composition



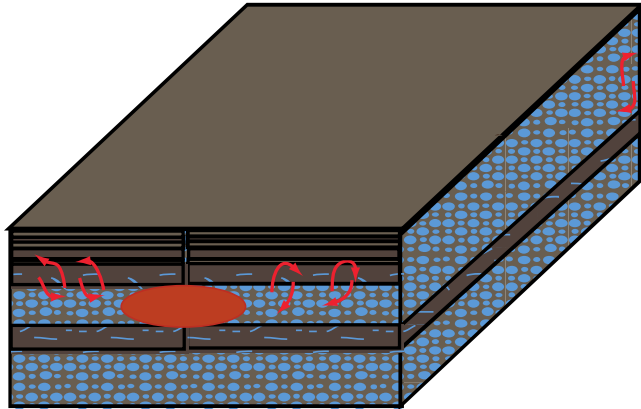
water



Not so wet in the dormant era?



Early-to-middle
Noachian



Geothermal heat flux

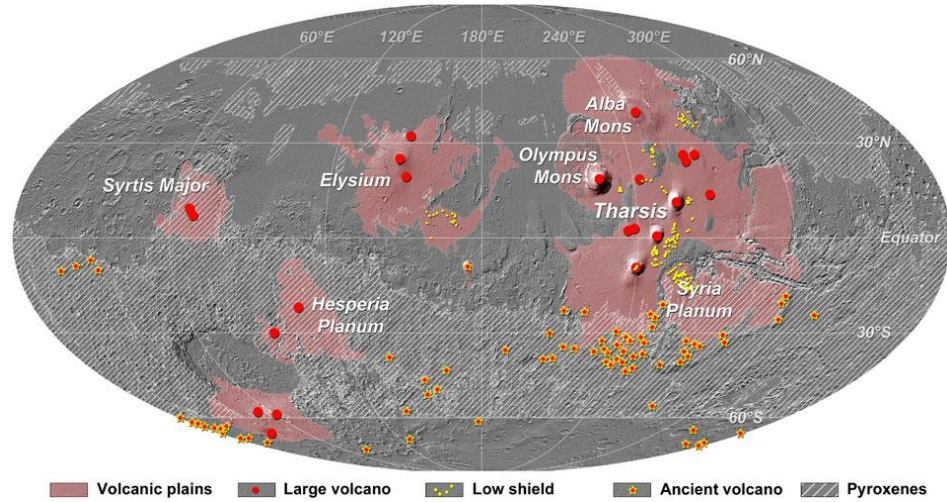
Water supply by plume magmatism?



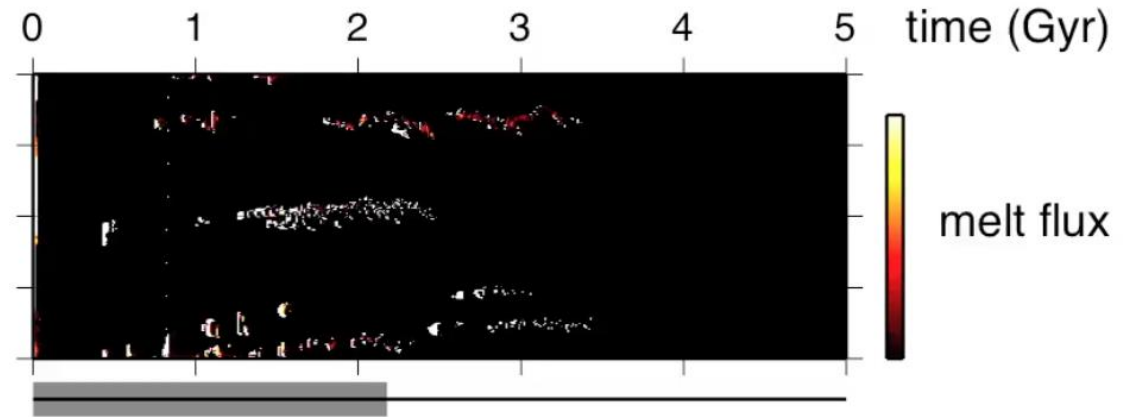
By decline of plume magmatism?



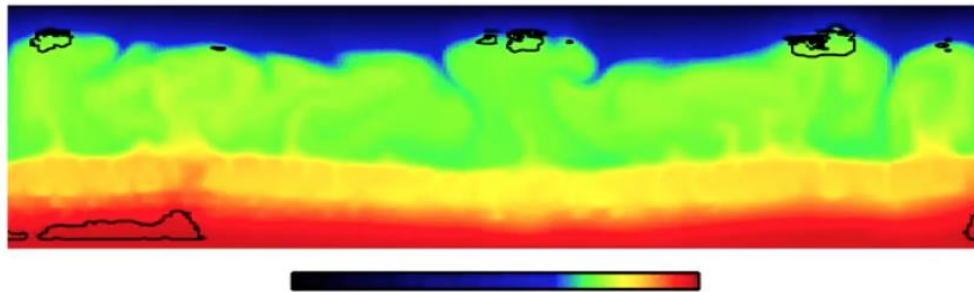
火山活動の局在化



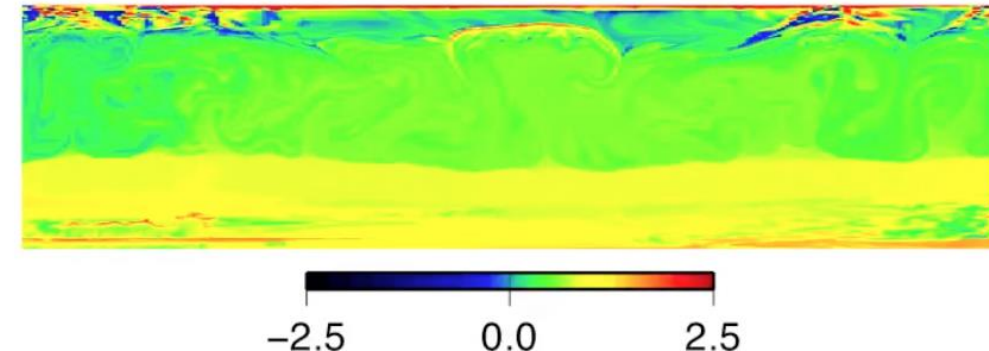
(Grott et al., 2013)



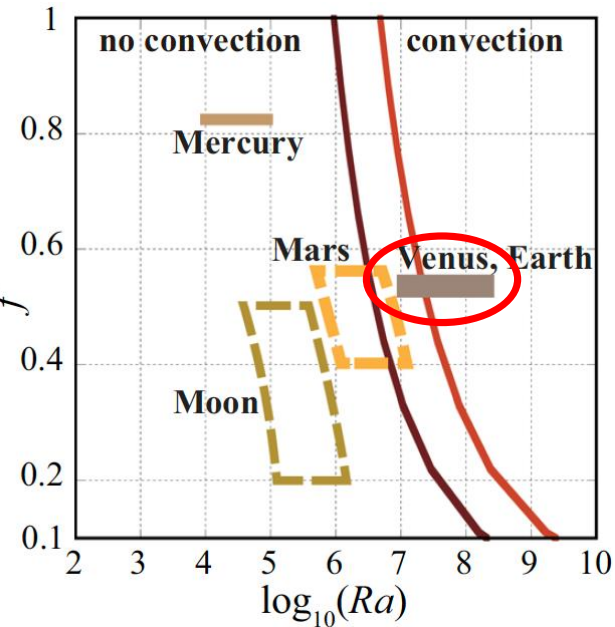
温度とマグマ分布



熱源分布



金星



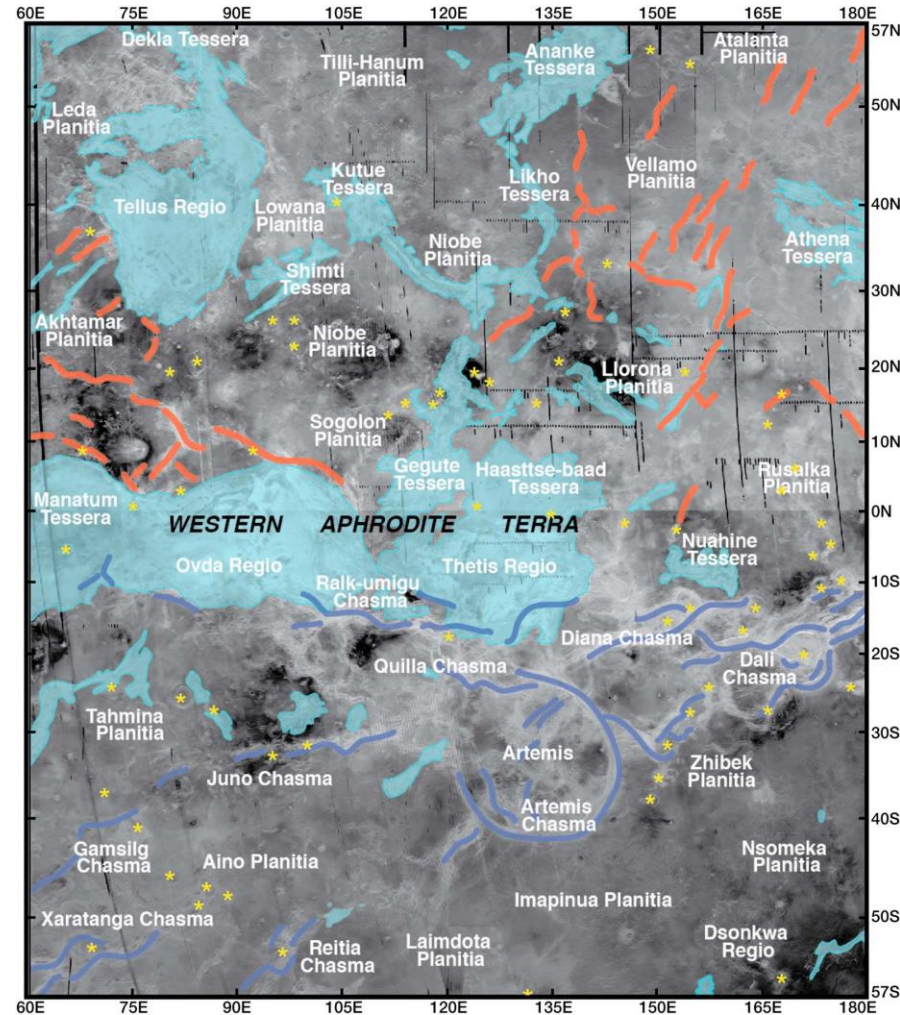
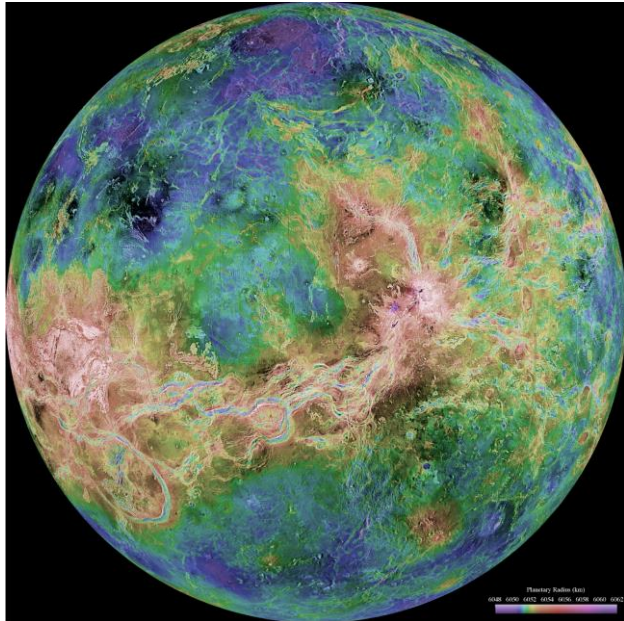
(Yanagisawa et al., 2016)

素過程	効果	月	水星	火星	金星	地球
放射性元素の地殻への濃集	火成活動の減衰	○	○	○	○	○
対流不安定・プルーム	ホットスポット火山	×	×	○	○	○
火成活動・マンテル湧昇流 フィードバック	パルスの火成活動 マンテルの均質化	×	○?	○	○	○
バースト	惑星の二段階進化 パルスの火成活動 地殻のリサイクリング	×	×	×	○	○
プレート・テクトニクス	連続的の火成活動 マンテルの不均質化 地殻のリサイクリング	×	×	×	×	○

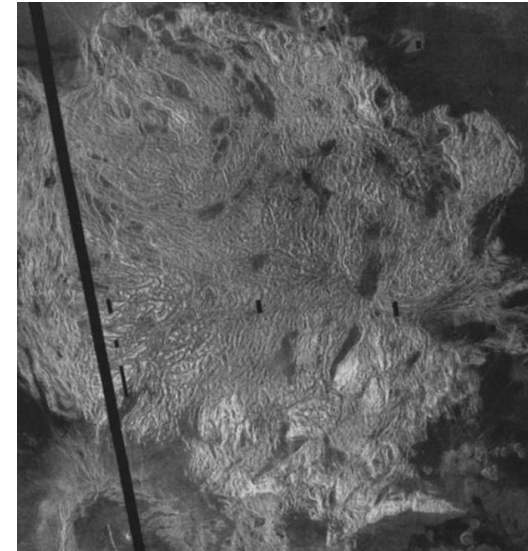
火星 + バースト = 金星

7億? (年前)

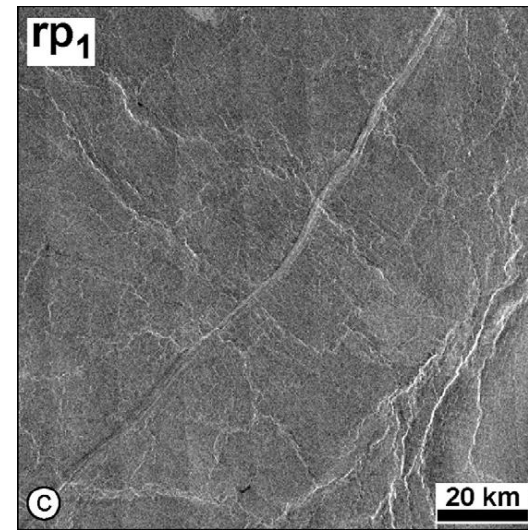
? テセラテレン 火山平原



(Hansen & Lopez, 2018)



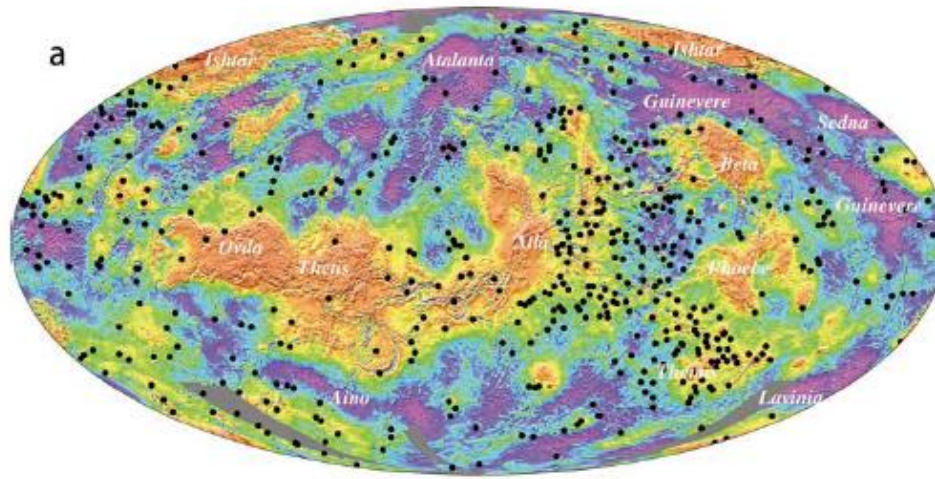
(Ivanov & Head., 2011)



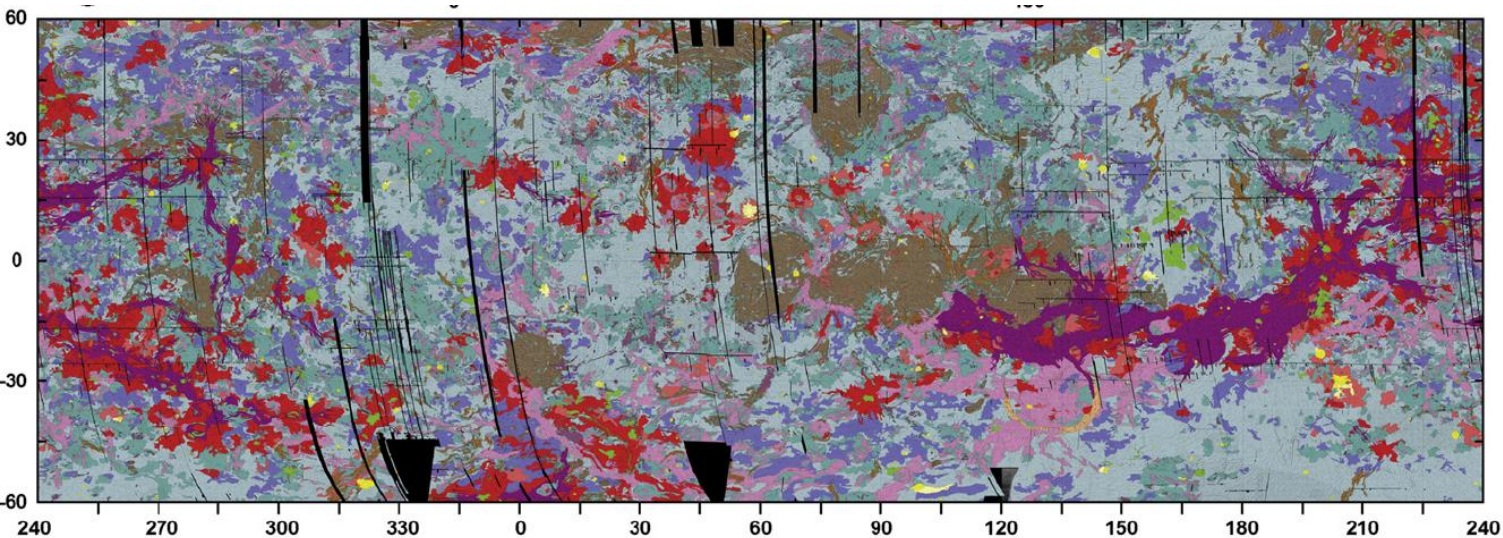
(Bindschadler et al., 1992)

Continuous resurfacing による火山平原の形成

コロナの分布



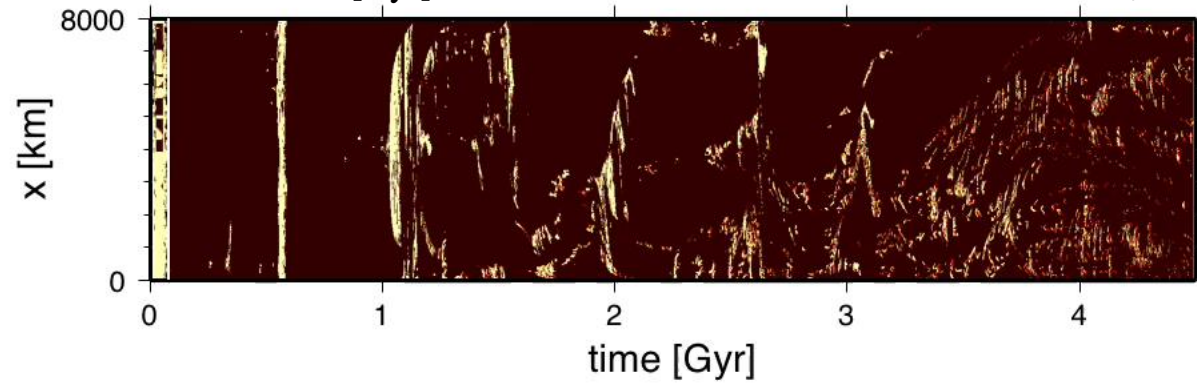
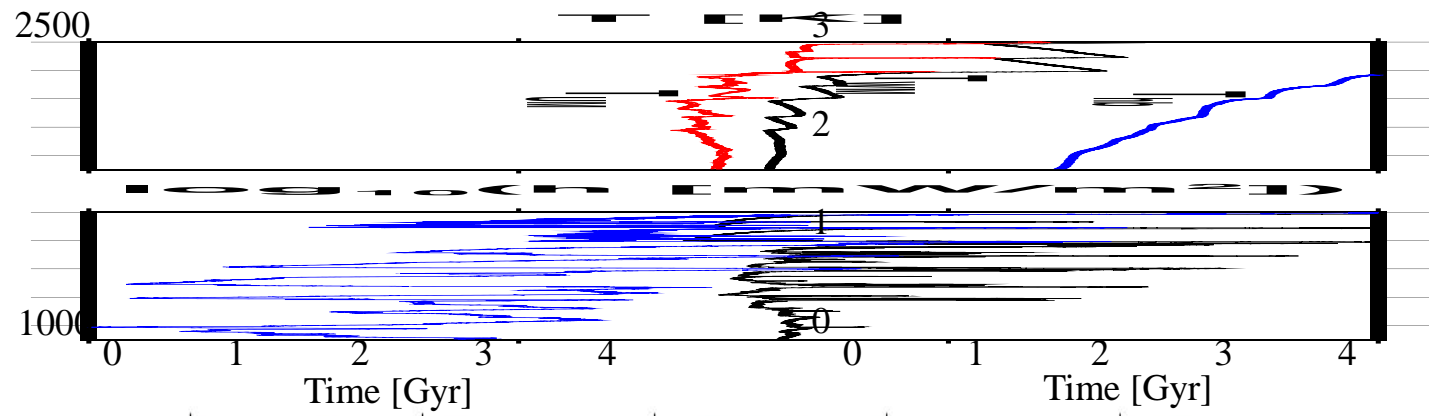
(Johnson & Richards., 2003)



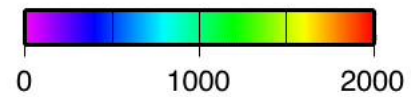
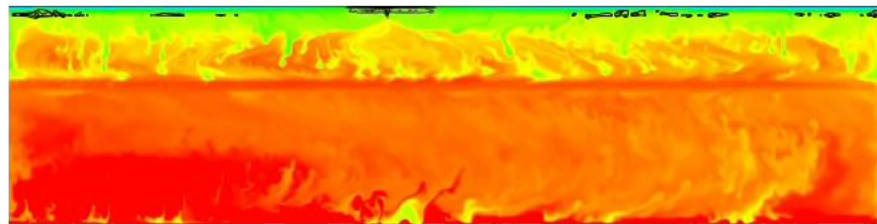
Impact craters (c) and outflows (cf)	
■ rz	■ psh
■ pl	■ gb
■ ps	■ mb
■ sc	■ pr
■ rp2	■ pdl
■ rp1	■ t

(Ivanov & Head., 2011)

Geologic time units	Time-stratigraphic units	Rock-Stratigraphic units and structures
Atlian Period	Atlian System	Aurelia Formation (dark parabola)
		Devana Formation (rz)
		Bell Formation (pl)
		Gunda Formation (ps)
		Boala Formation (sc)
Guineverian Period	Guineverian System	Ituana Formation (rp2)
		Rusalka Formation (rp1)
		Accruva Formation (psh)
		Agrona Formation (gb)
		Akna Formation (mb)
		Lavinia Formation (pr)
		Atropos Formation (pdl)
Fortunian Period	Fortunian System	Fortuna Formation (t)
Pre-Fortunian Period	Pre-Fortunian System	?

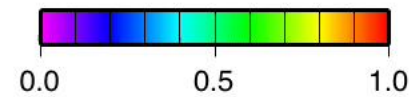
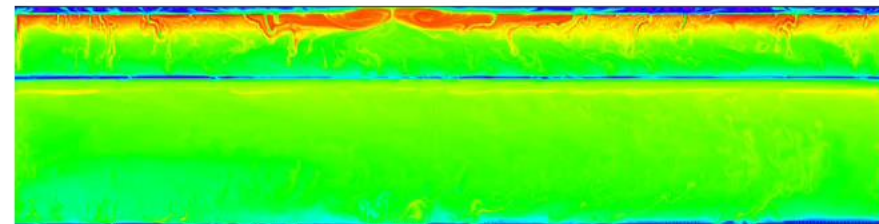


T & magma

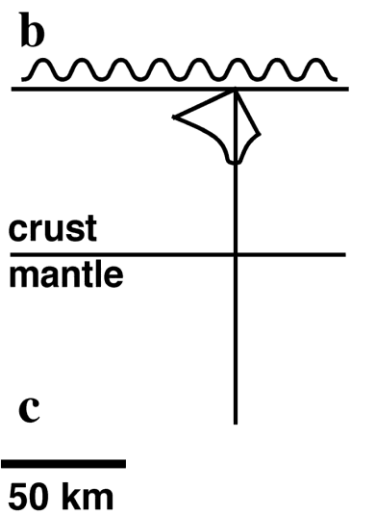
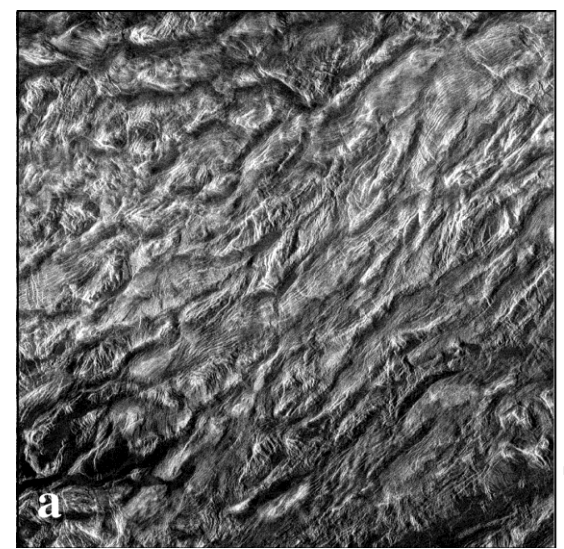
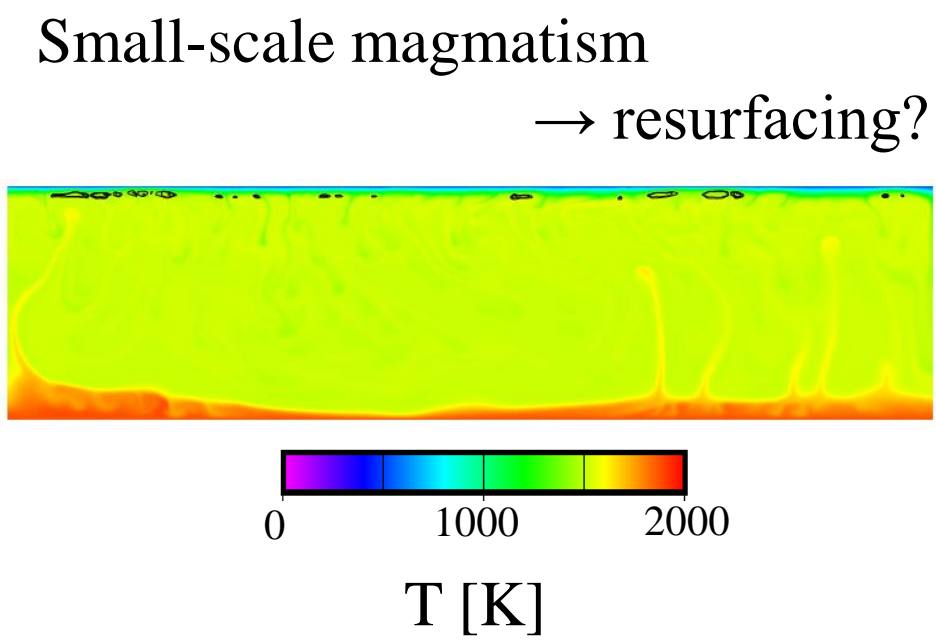
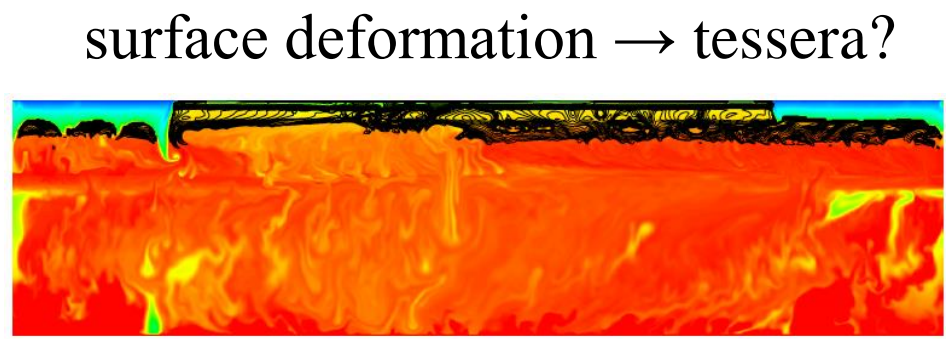
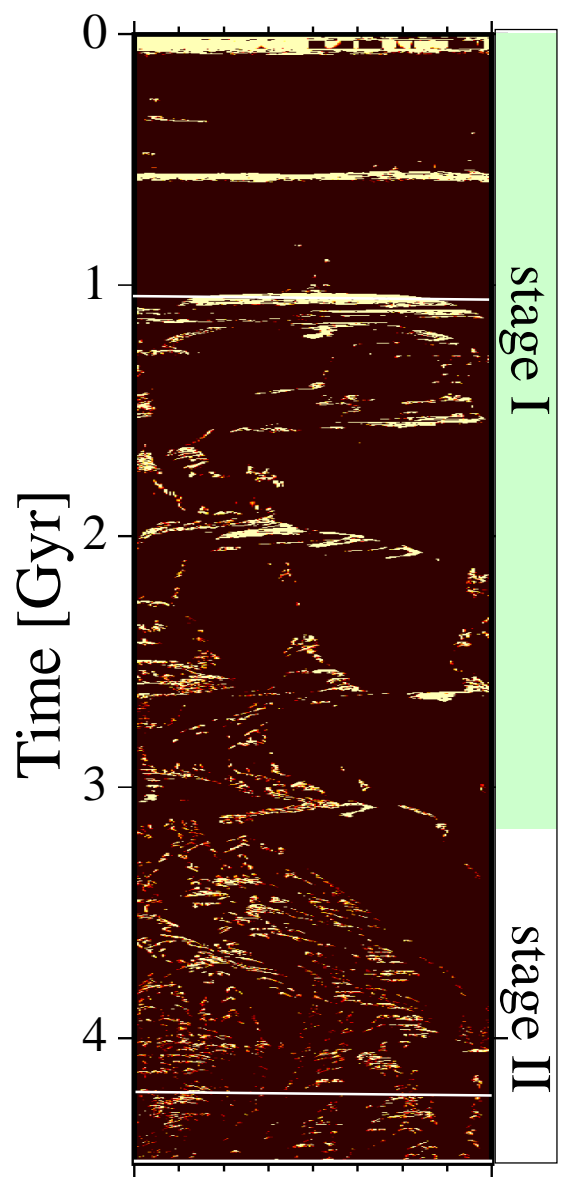


[C]

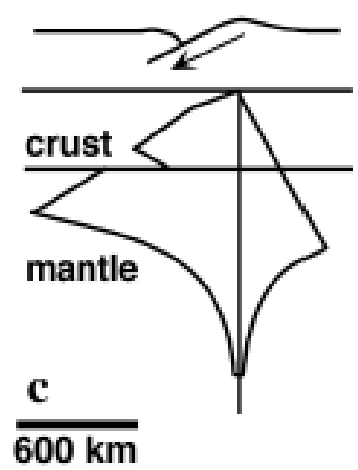
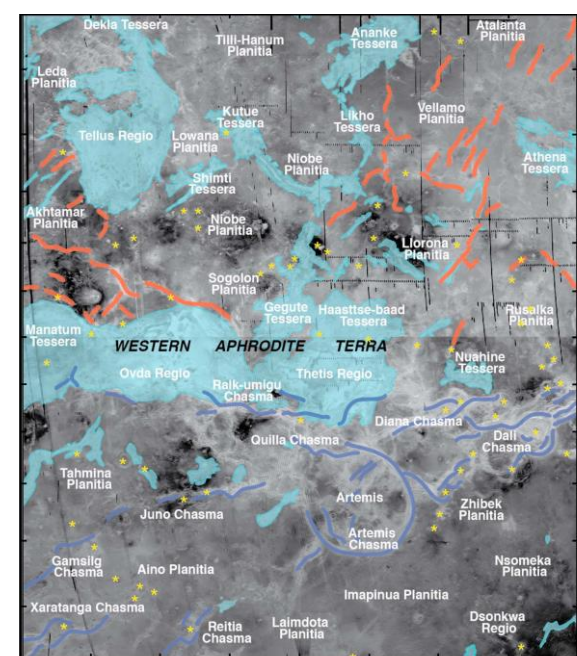
composition



力学系の相転移による二段階進化:バーストの時代→熱対流の時代

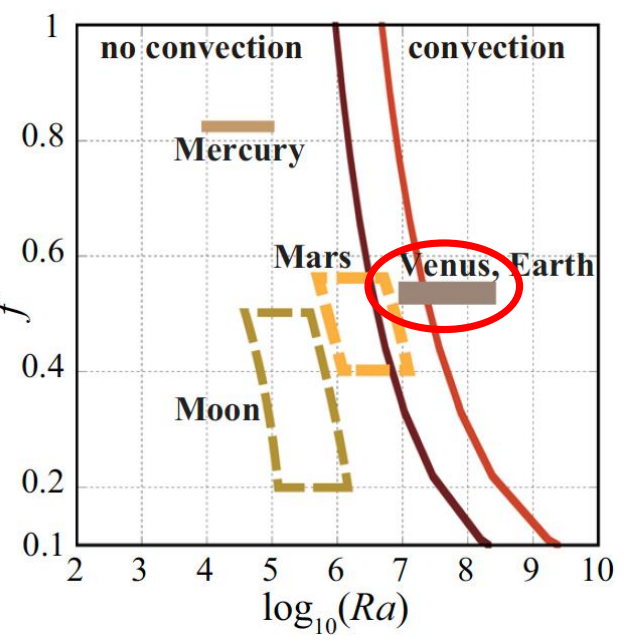


(Brown & Grimm, 1999)



(Hansen & Lopez., 2018)

地球

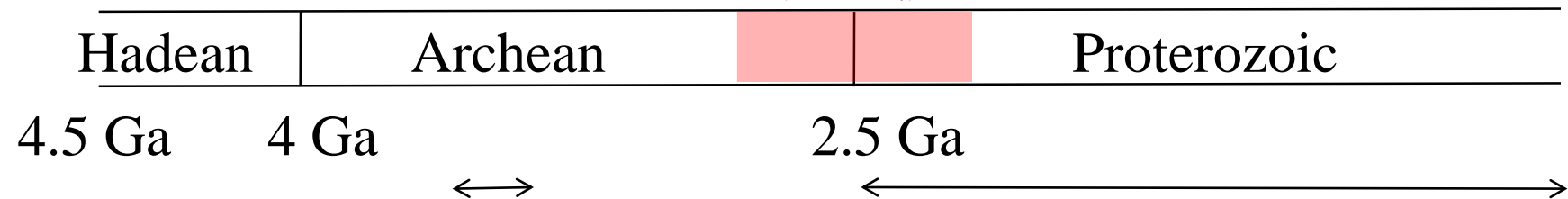


(Yanagisawa et al., 2016)

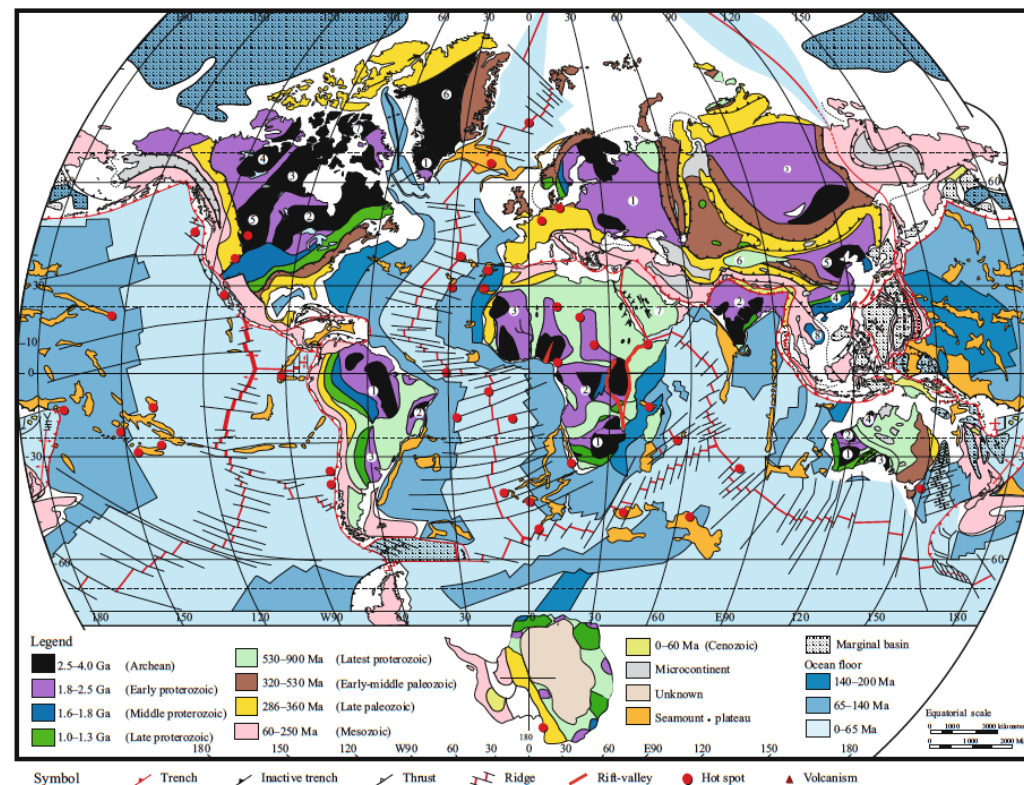
素過程	効果	月	水星	火星	金星	地球
放射性元素の地殻への濃集	火成活動の減衰	○	○	○	○	○
対流不安定・プルーム	ホットスポット火山	×	×	○	○	○
火成活動・マンテル湧昇流 フィードバック	パルスの火成活動 マンテルの均質化	×	○?	○	○	○
バースト	惑星の二段階進化 パルスの火成活動 地殻のリサイクリング	×	×	×	○	○
プレート・テクトニクス	連続的の火成活動 マンテルの不均質化 地殻のリサイクリング	×	×	×	×	○

金星 + プレート・テクトニクス = 地球の二段階進化

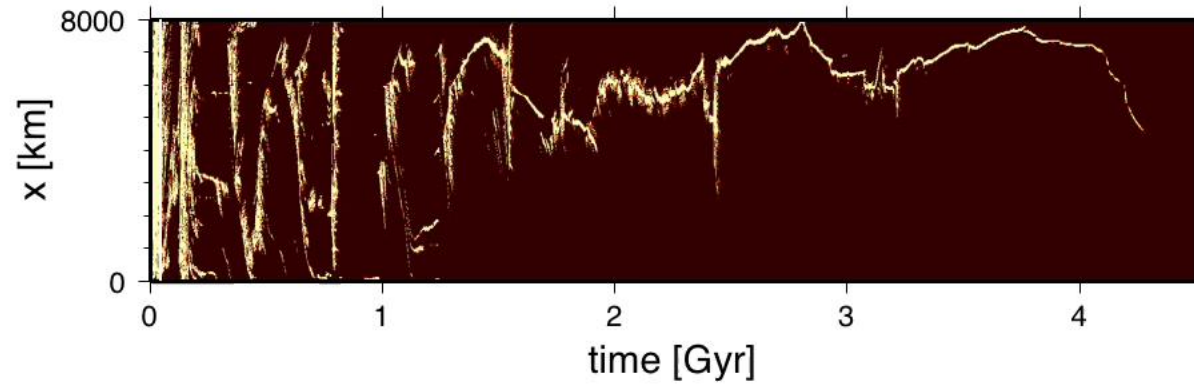
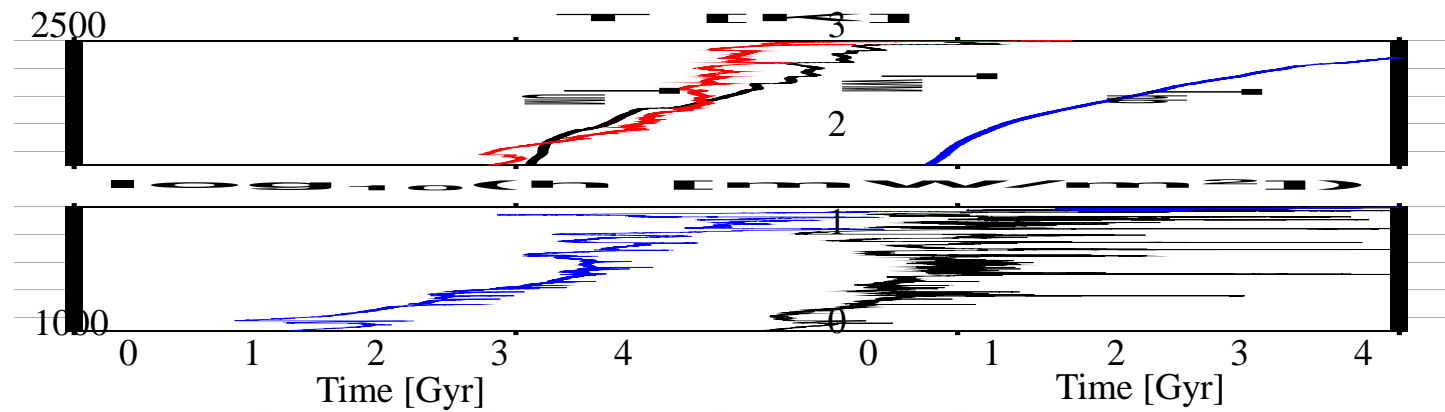
相転移



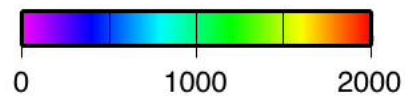
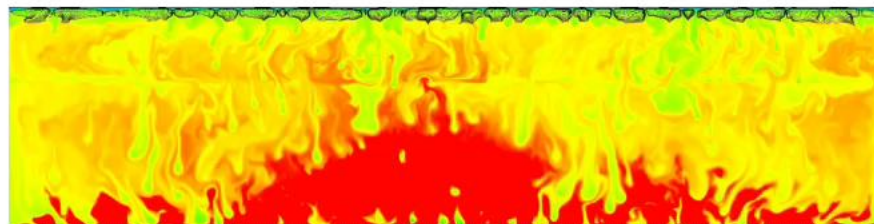
Google earth マイル 100 200 km



(Utsunomiya et al., 2007)

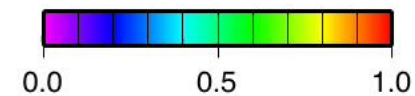
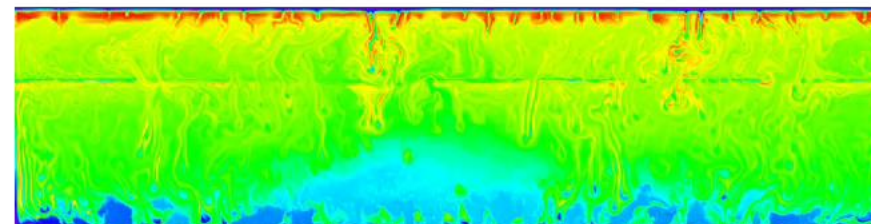


T & magma



[C]

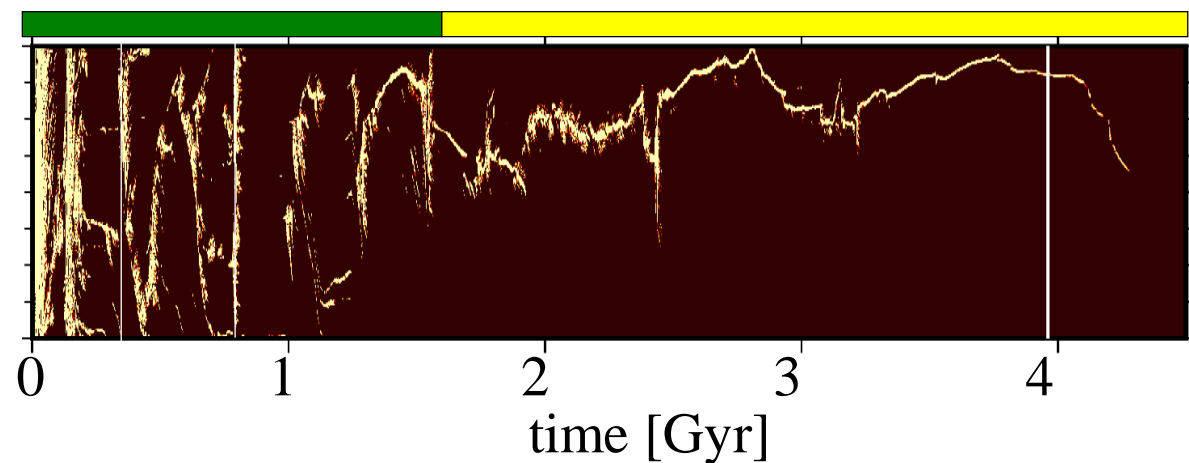
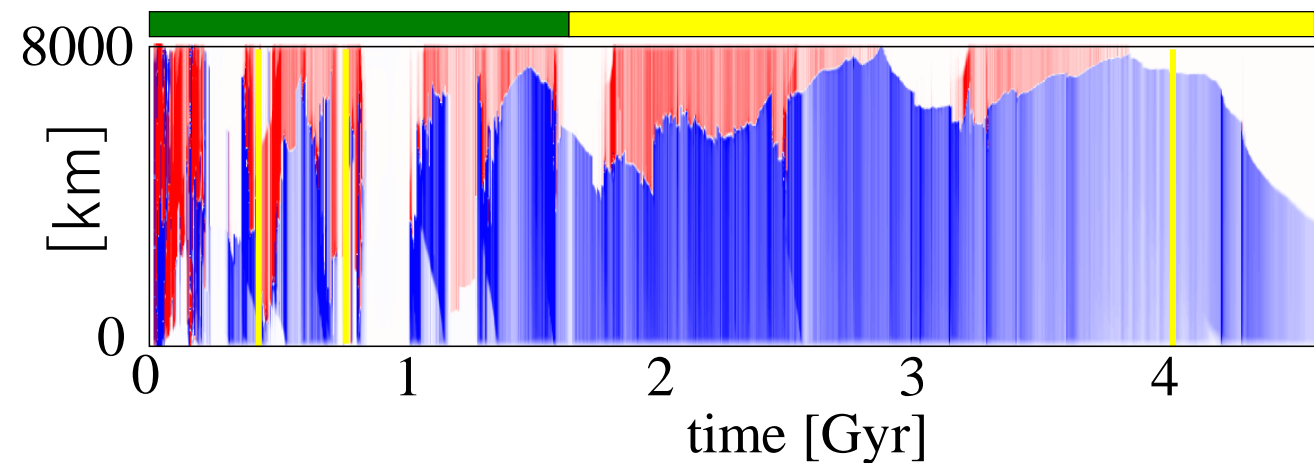
composition



Two stages of plate tectonics and magmatism

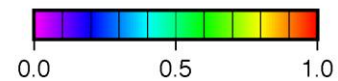
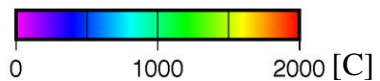
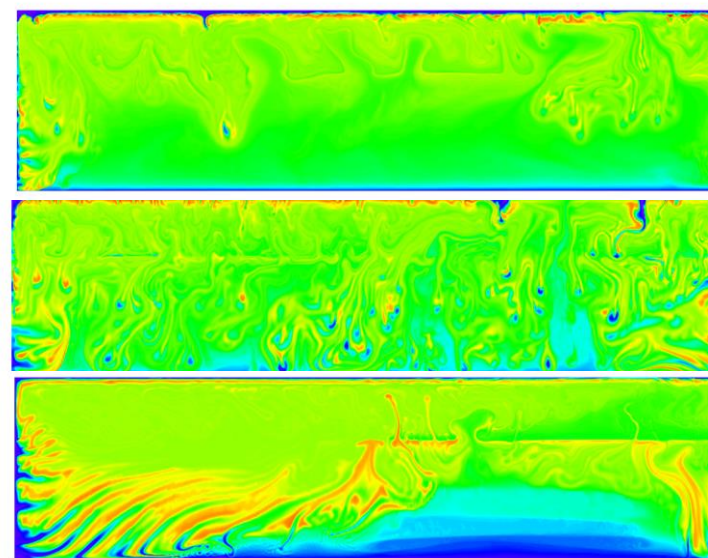
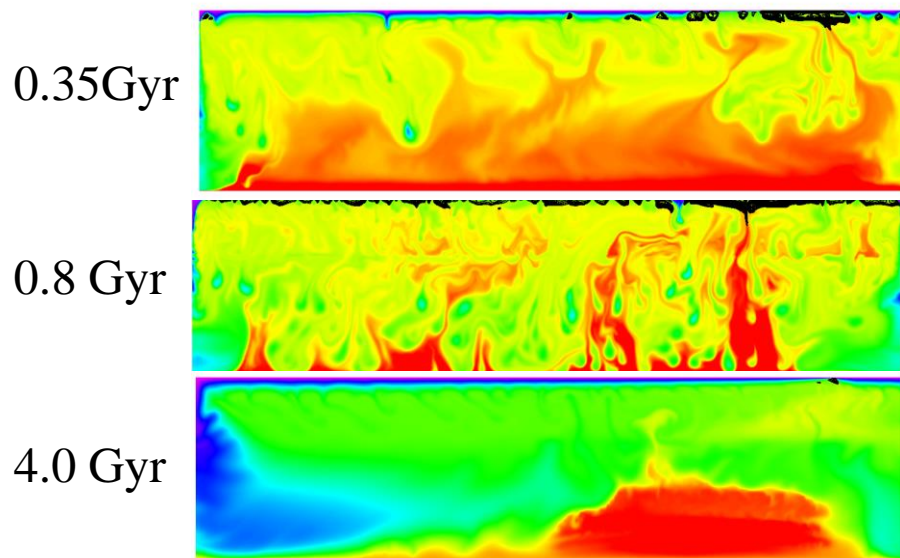
plate velocity (± 5 cm/yr)

magma eruption



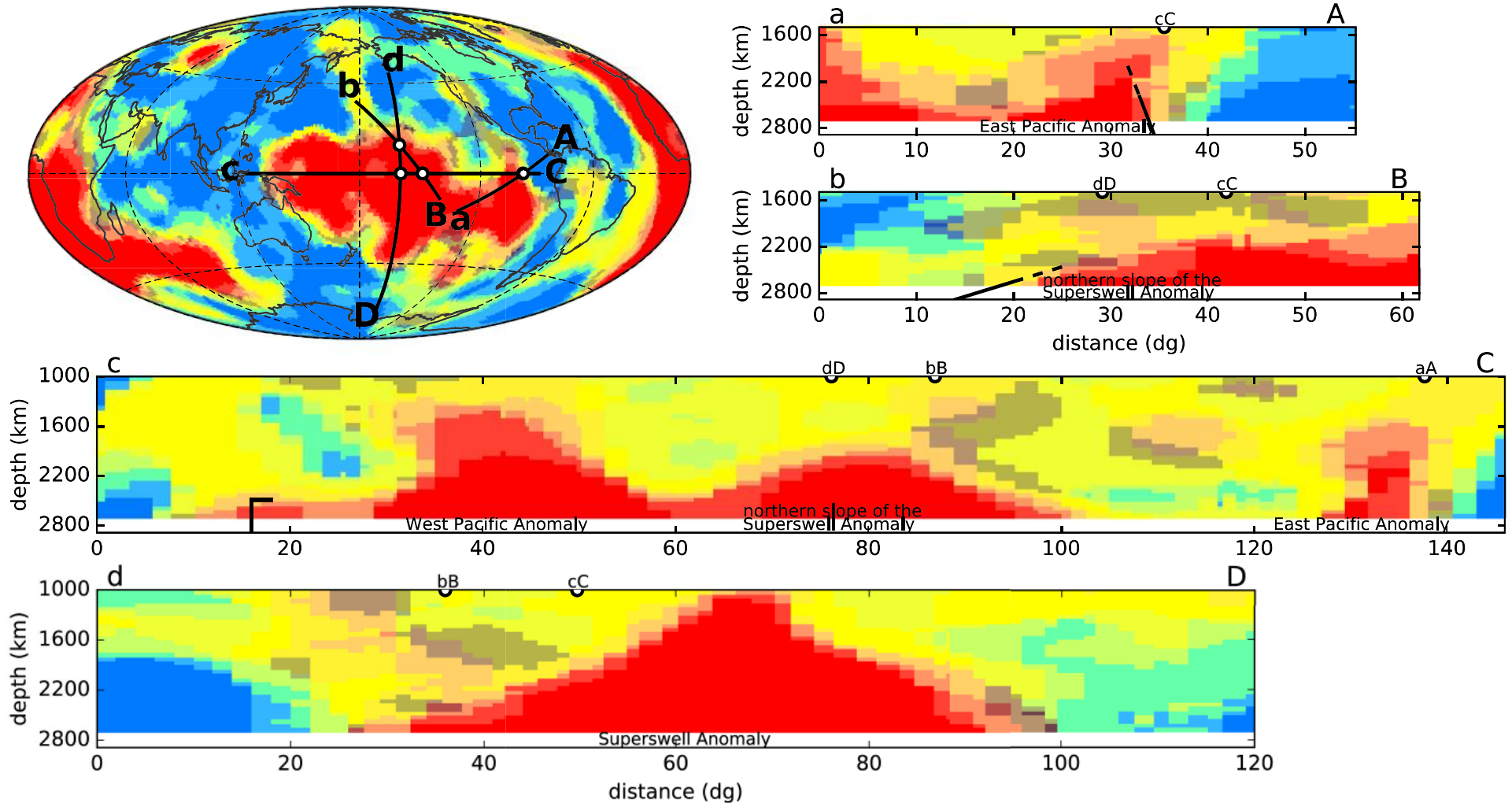
T & magma

composition



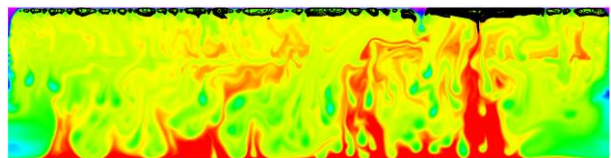
Large Low Shear Velocity Provinces = thermo-chemical pile

1128 *S. Cottaar and V. Lekic (2016)*



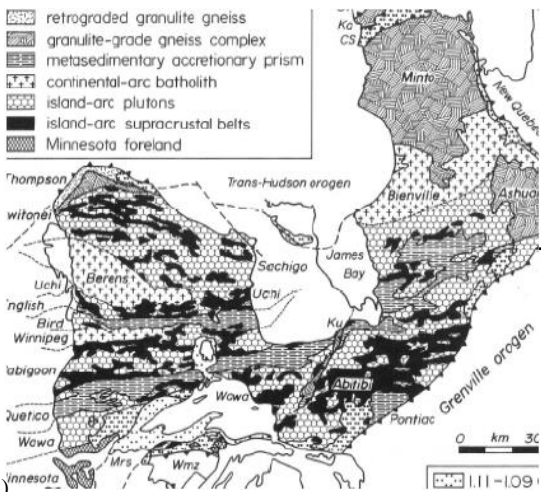
Formation of the Earth

Heavy bombardment



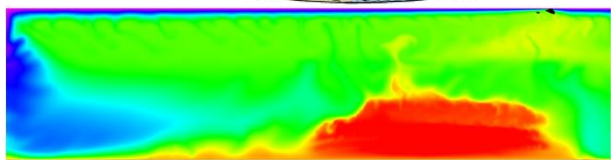
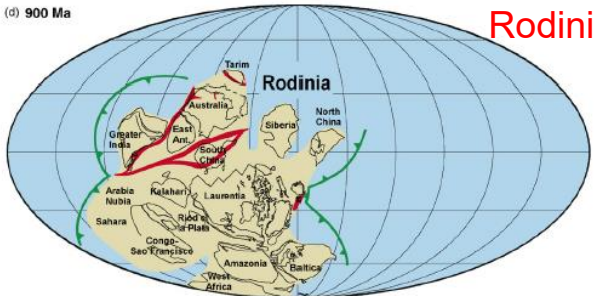
4 Ga

Superior



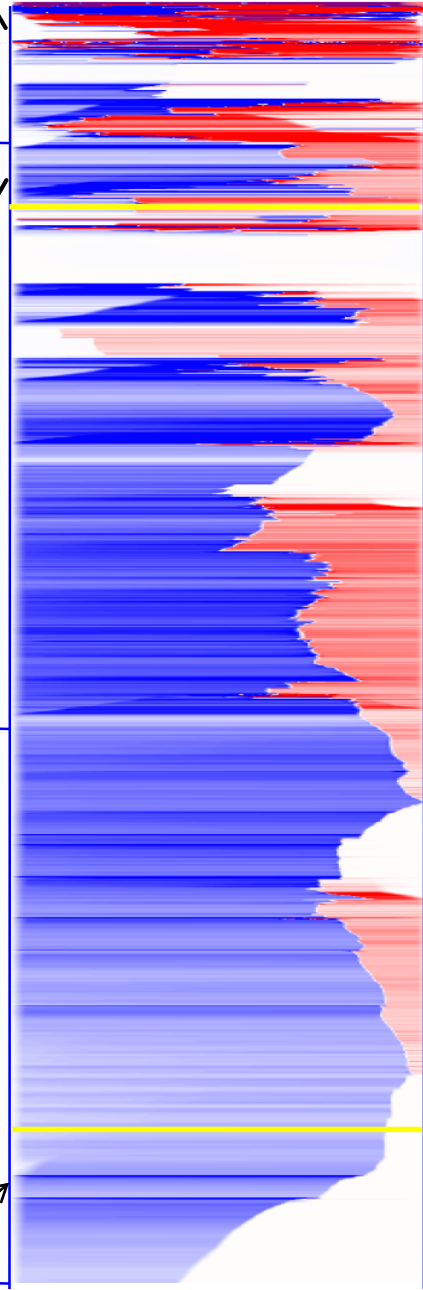
2 Ga

Rodinia



Pangea

0 Ga



Hadean

Archean

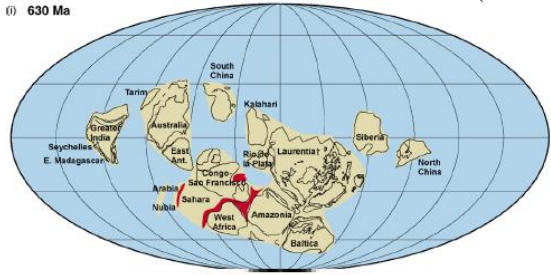
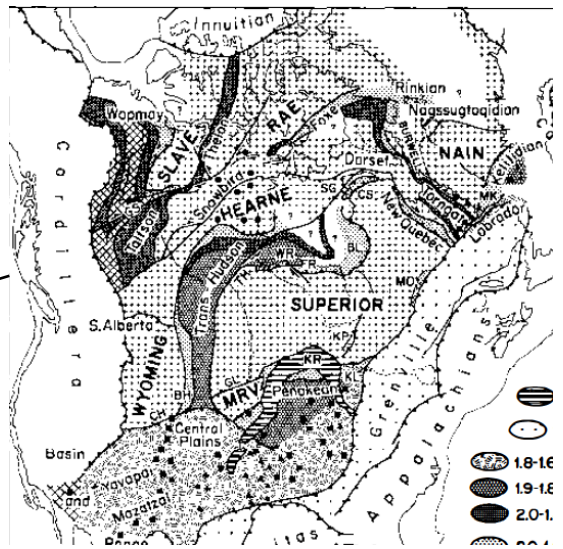
Proterozoic

Phanerozoic

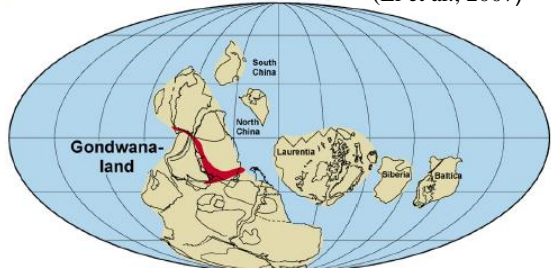


Pilbara

United Plates of America



Gondwana

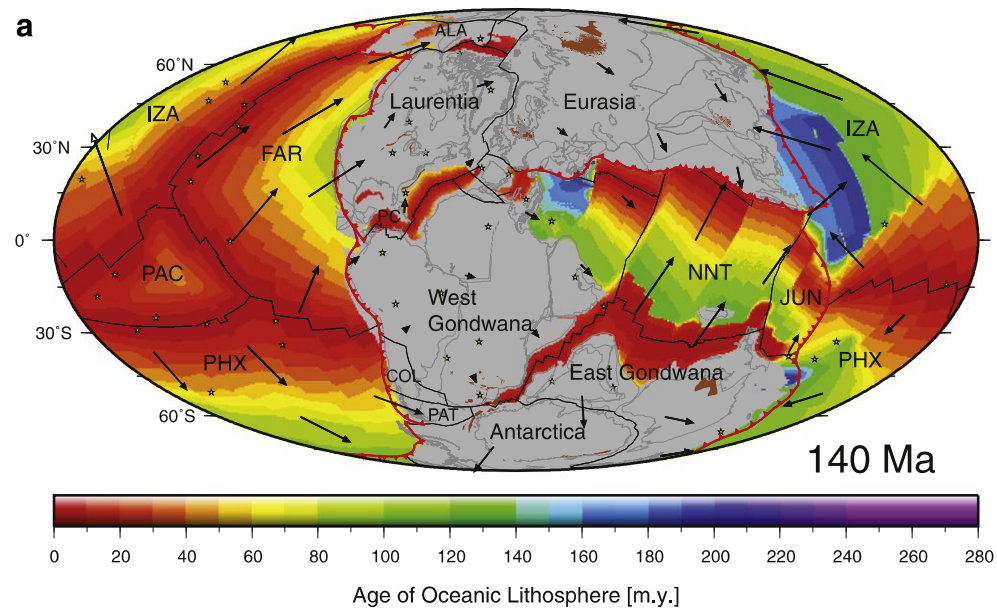


Large Igneous Provinces とプレート・テクトニクス

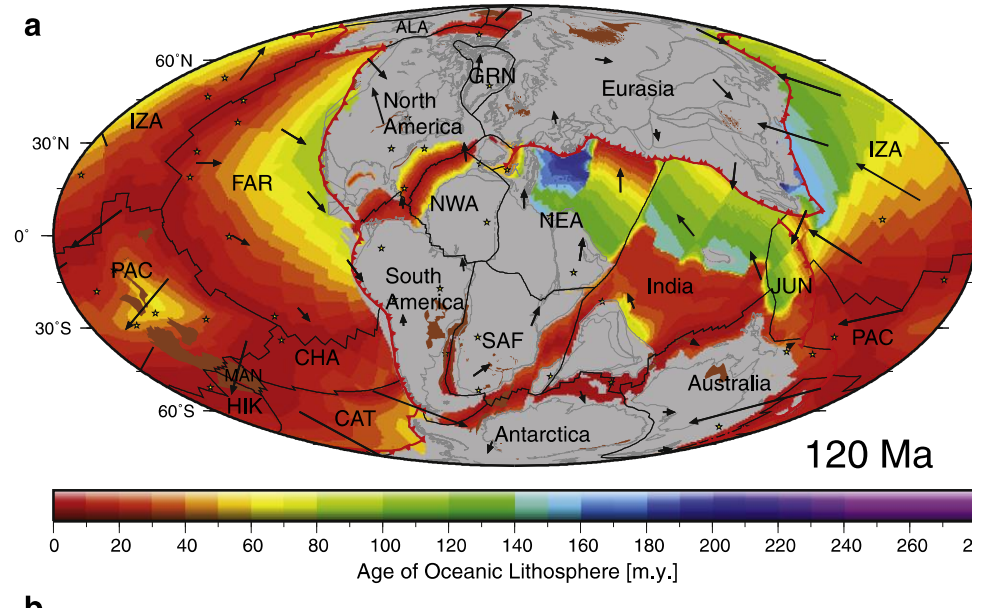


初期地球のテクトニクス？

M. Seton et al. / Earth-Science Reviews 113 (2012) 212–270

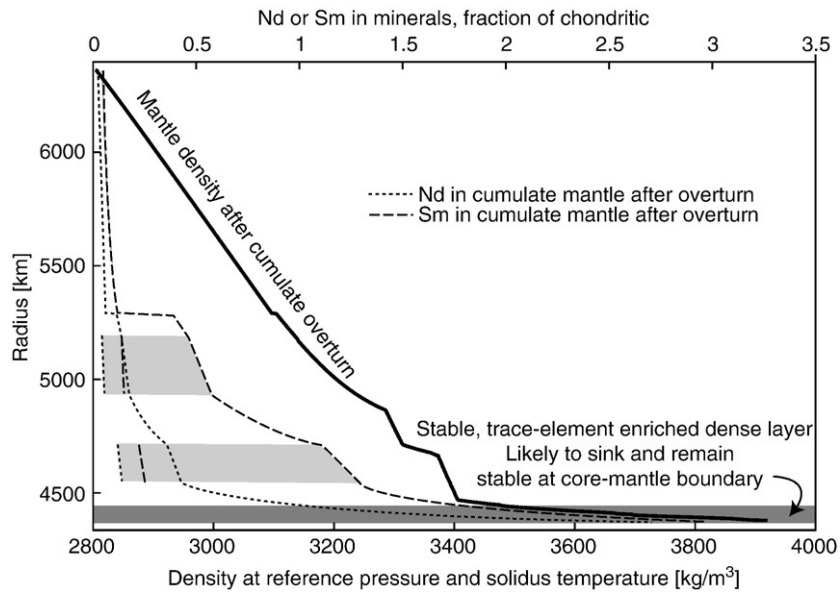


M. Seton et al. / Earth-Science Reviews 113 (2012) 212–270

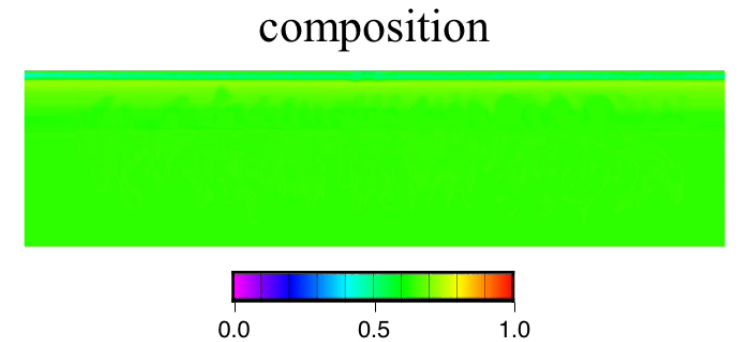
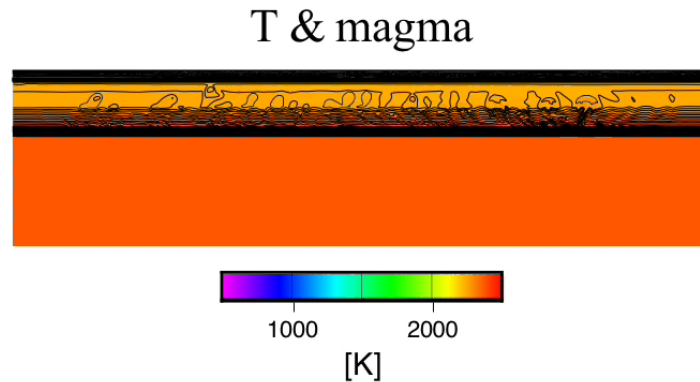


なぜマグマ・オーシャンの痕跡が見つからない？

マグマ・オーシャンからMMU-feedbackへ

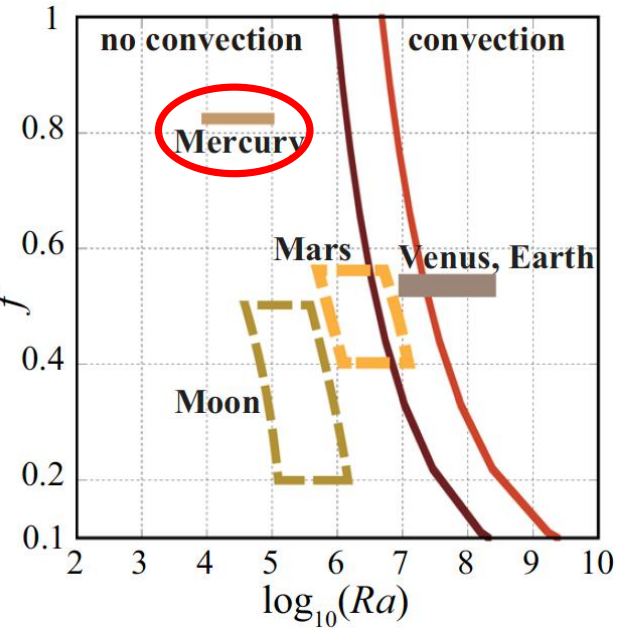


(Elkins-Tanton, 2008)



0 Myr

水星

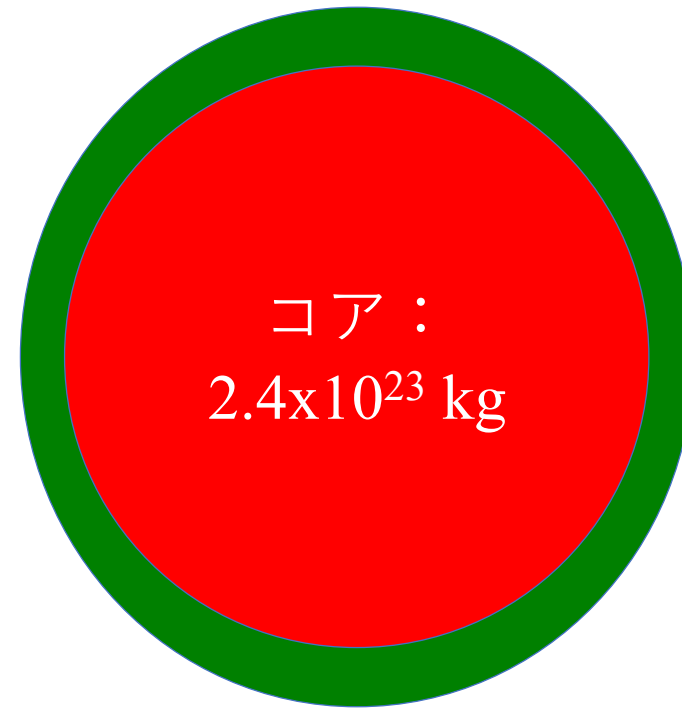
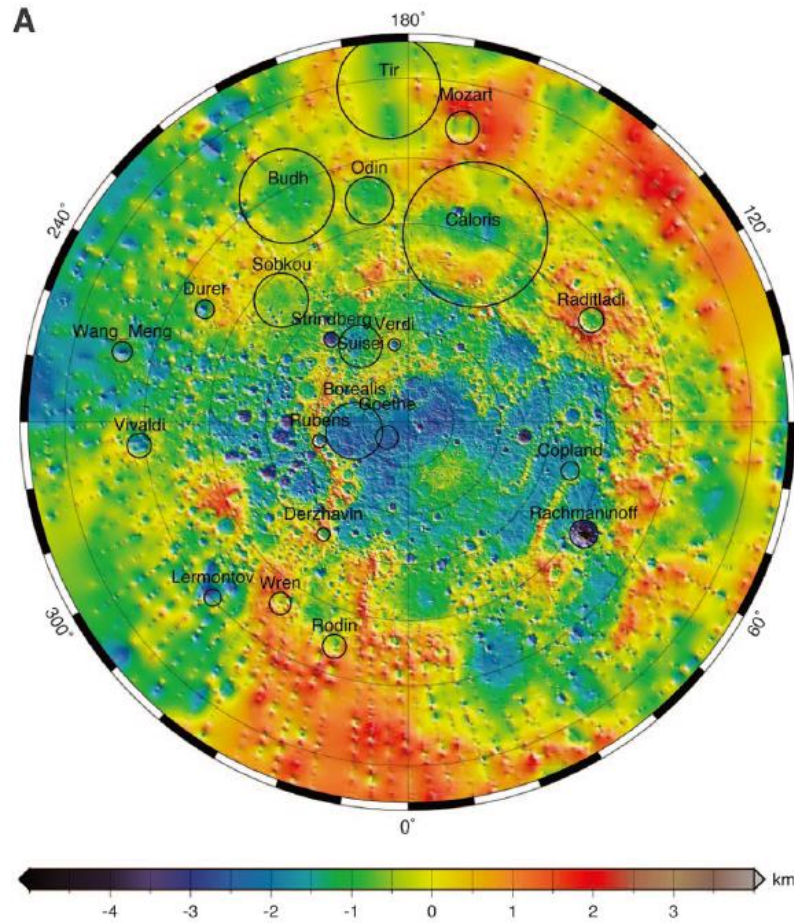


(Yanagisawa et al., 2016)

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火成活動・マンテル湧昇流 フィードバック	パルスの火成活動 マンテルの均質化	×	○?	○	○	○
バースト	惑星の二段階進化 パルスの火成活動 地殻のリサイクリング	×	×	×	○	○
プレート・テクトニクス	連続的の火成活動 マンテルの不均質化 地殻のリサイクリング	×	×	×	×	○

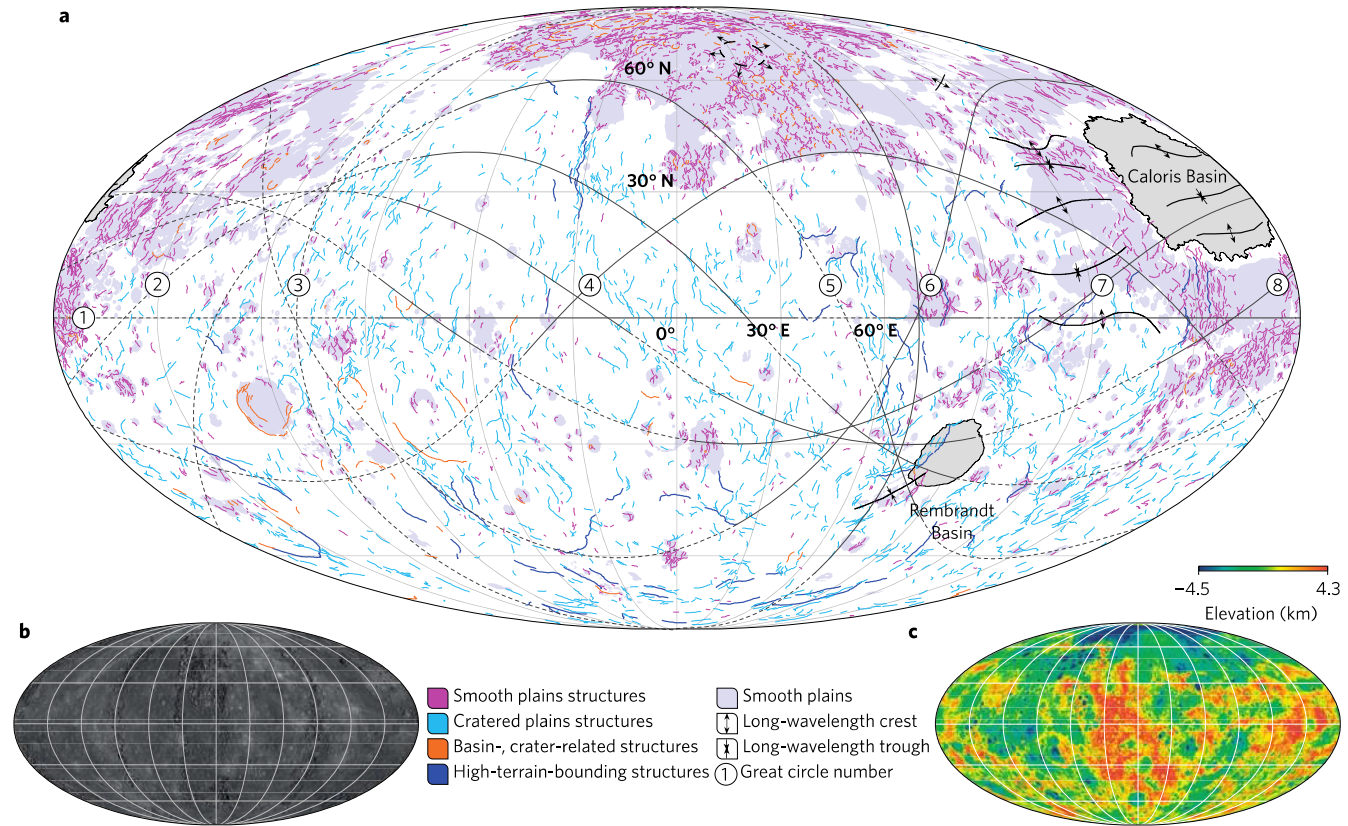
コアからの加熱が重要な惑星

マントル： 0.8×10^{23} kg



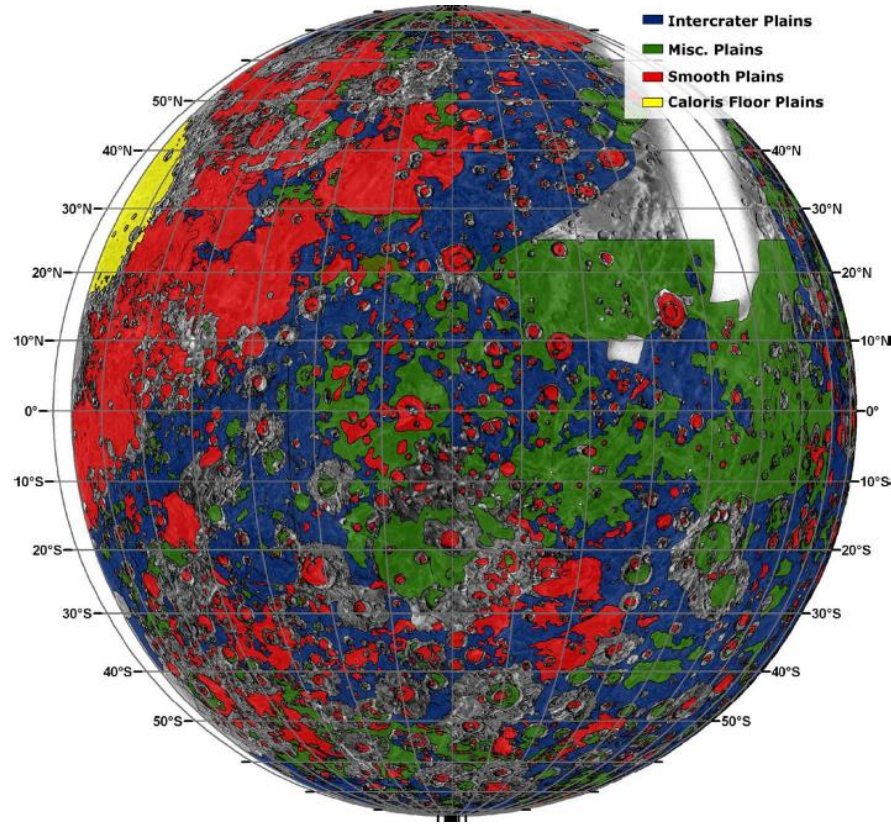
(Zuber et al., 2009)

熱收縮 (5km程度) → 冷却 (-250K程度)

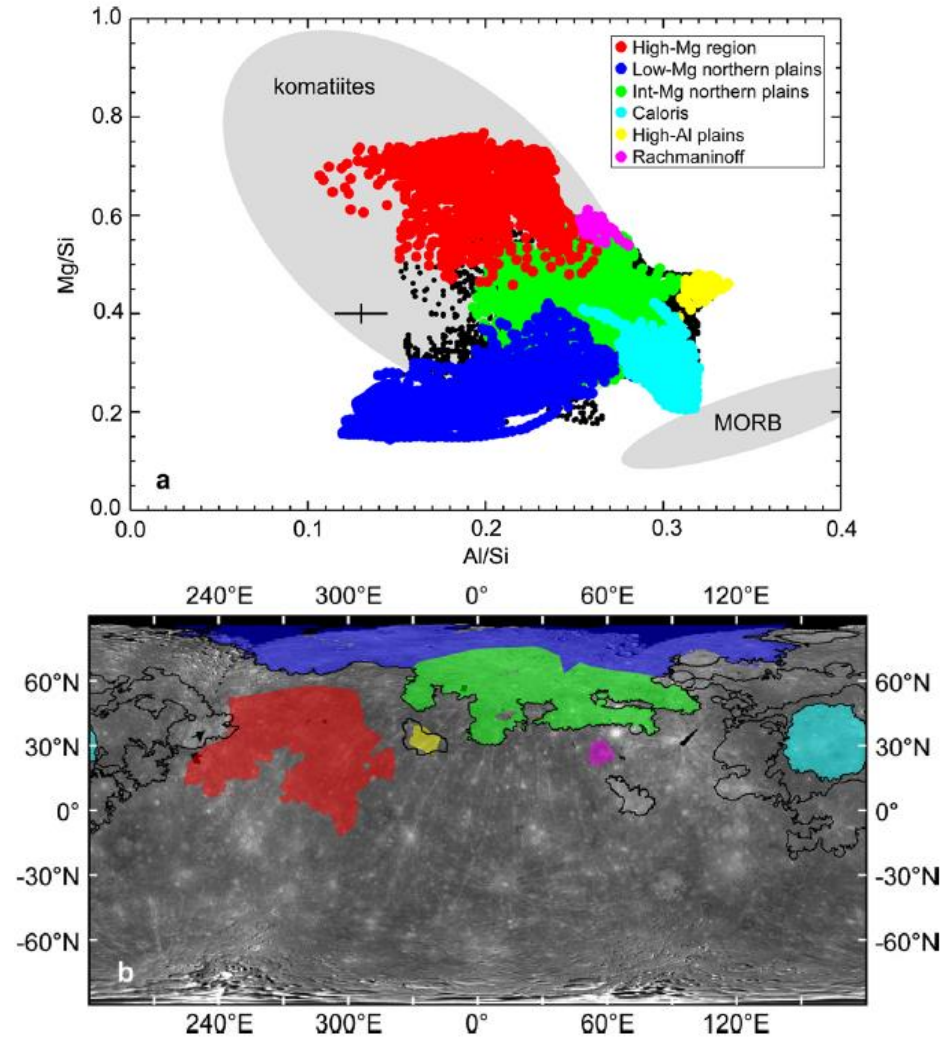


(Byrne et al., 2014)

火山活動による二次的地殻: 4-4.1Ga



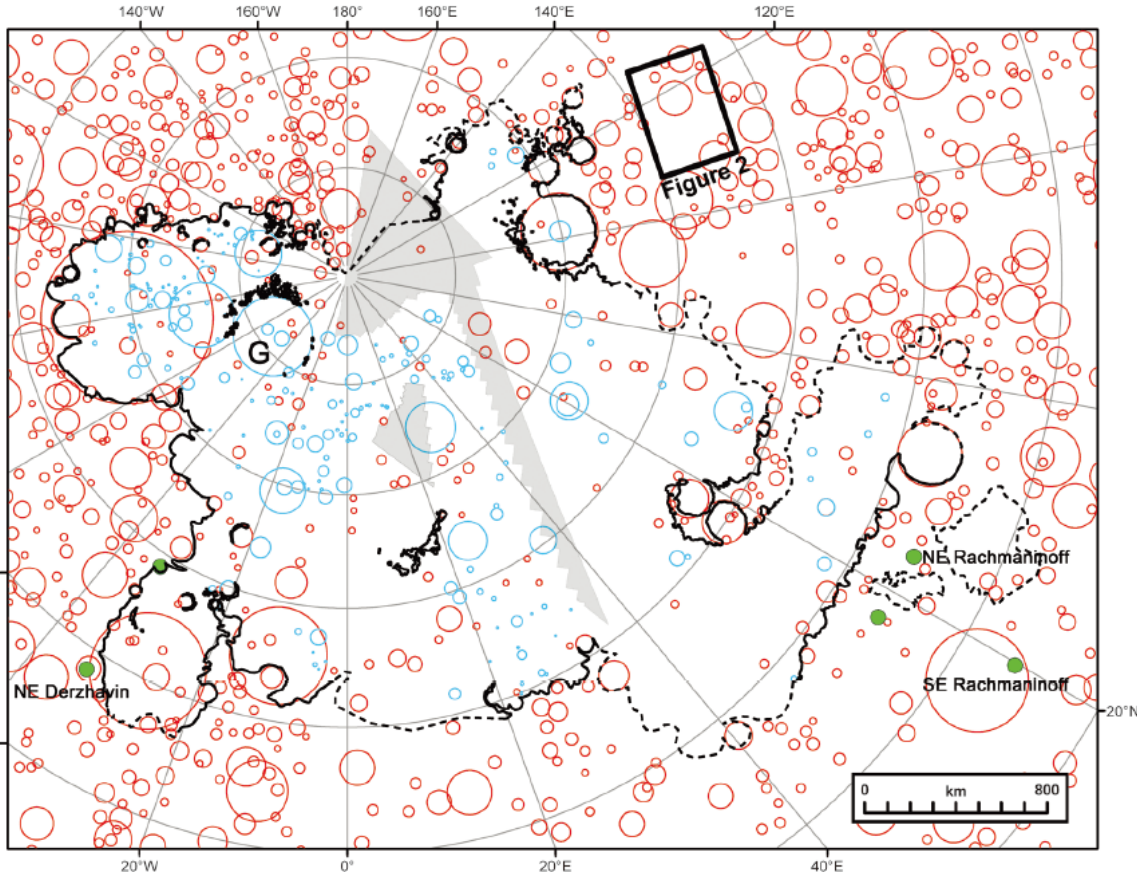
(Head et al., 2009)



(Weider et al., 2015)

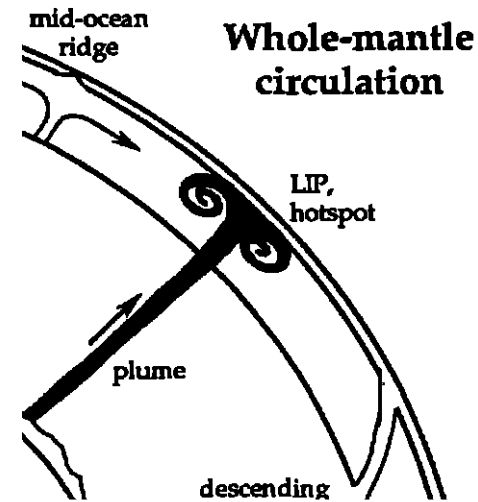
洪水玄武岩→MMUb feedback

玄武岩量：デカン高原→母岩の差し渡し300-700km？
マントルオーバーターン→低い粘性率



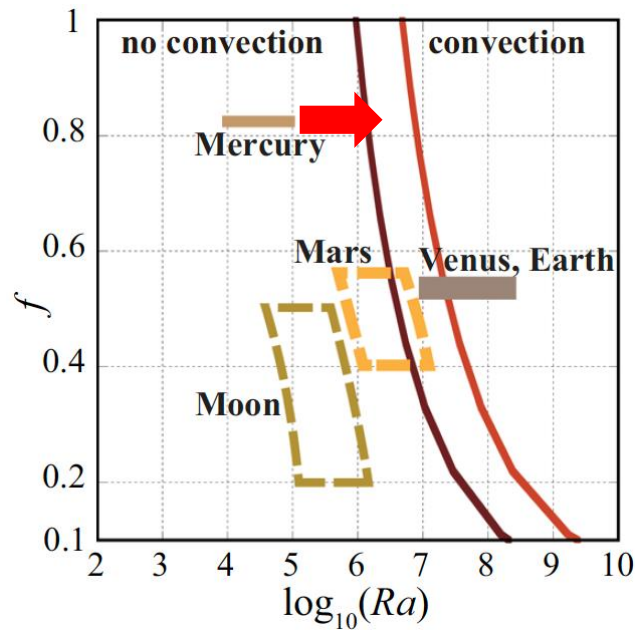
(Head et al., 2011)

Coffin and Eldholm: LARGE IGNEOUS PROVINCES •

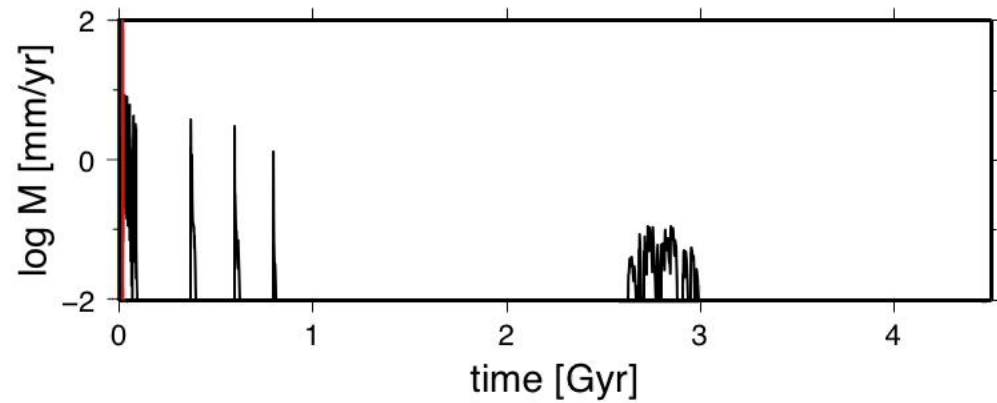


(Coffin & Eldholm., 1994)

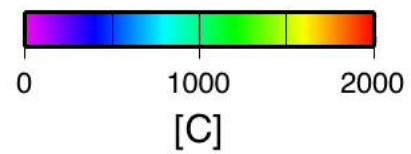
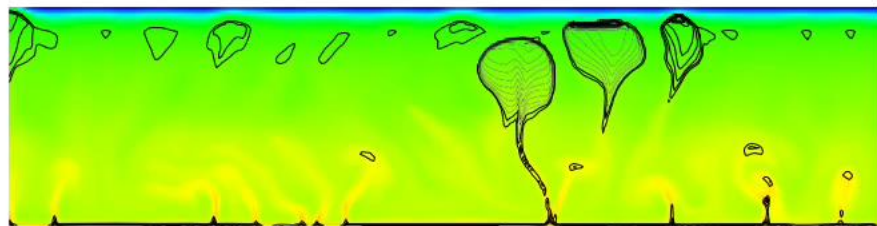
Figure 9. Cartoons of (left) layered [e.g., *Anderson et al.*, 1992a, b] and (right) whole [e.g., *Davies and Richards*, 1992] mantle circulation.



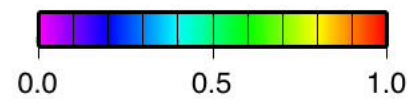
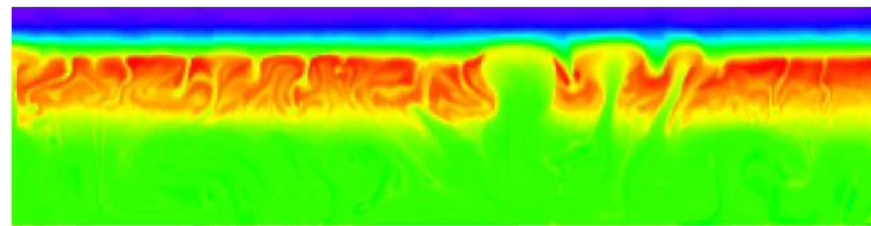
(Yanagisawa et al., 2016)



T & magma

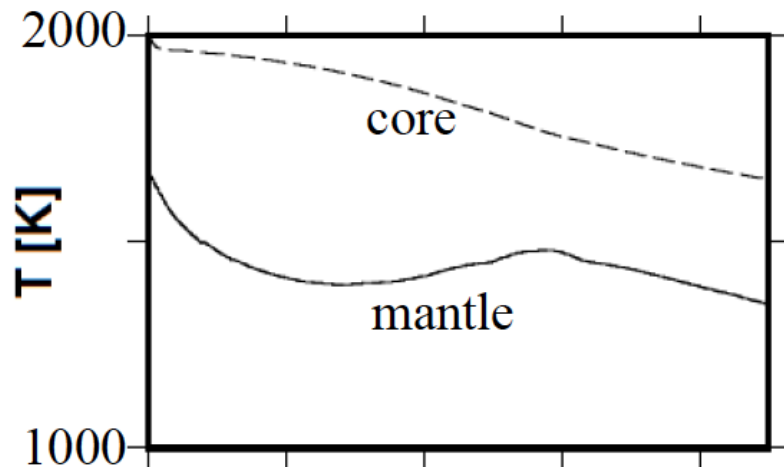


composition

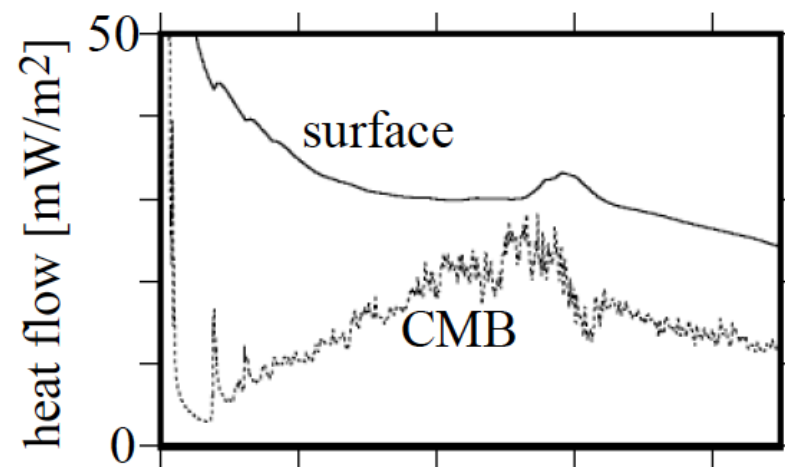


コアの熱容量 = 4xマンツルの熱容量、 $Ra = 6 \times 10^5$

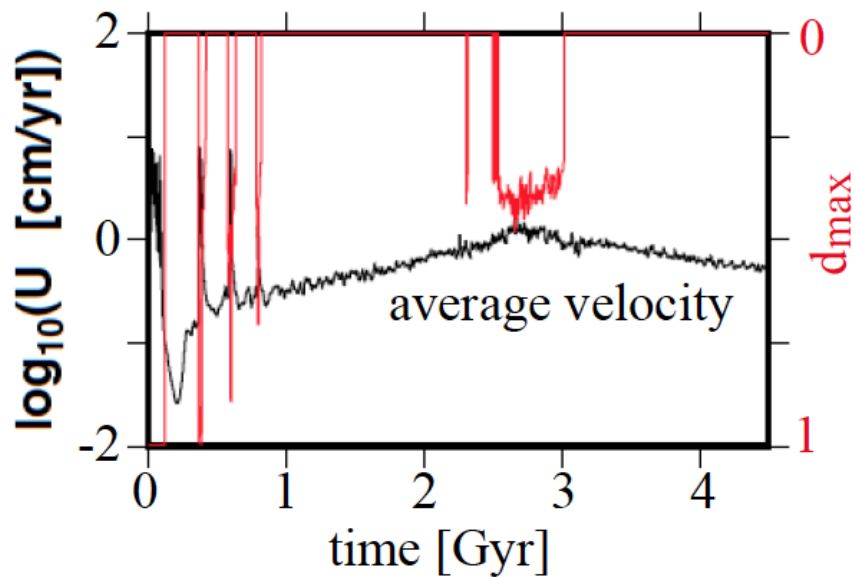
(a) 平均温度



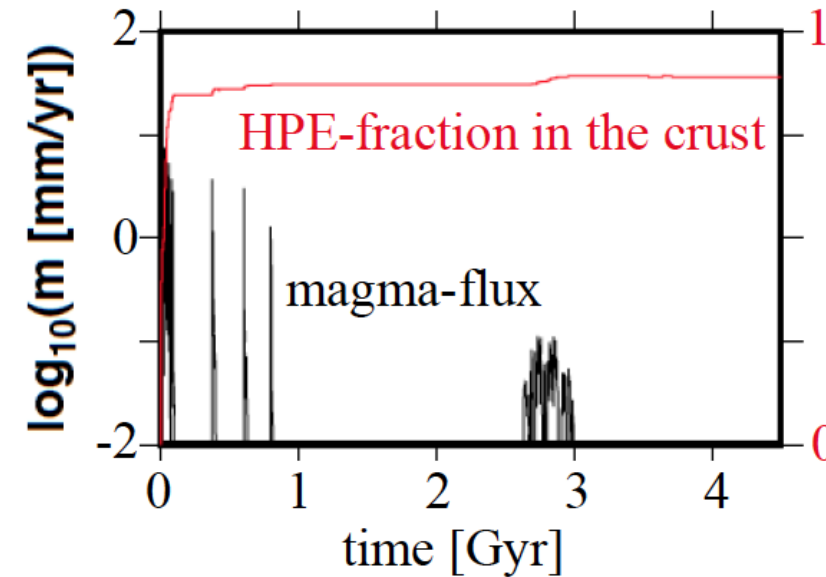
(b) 熱流量



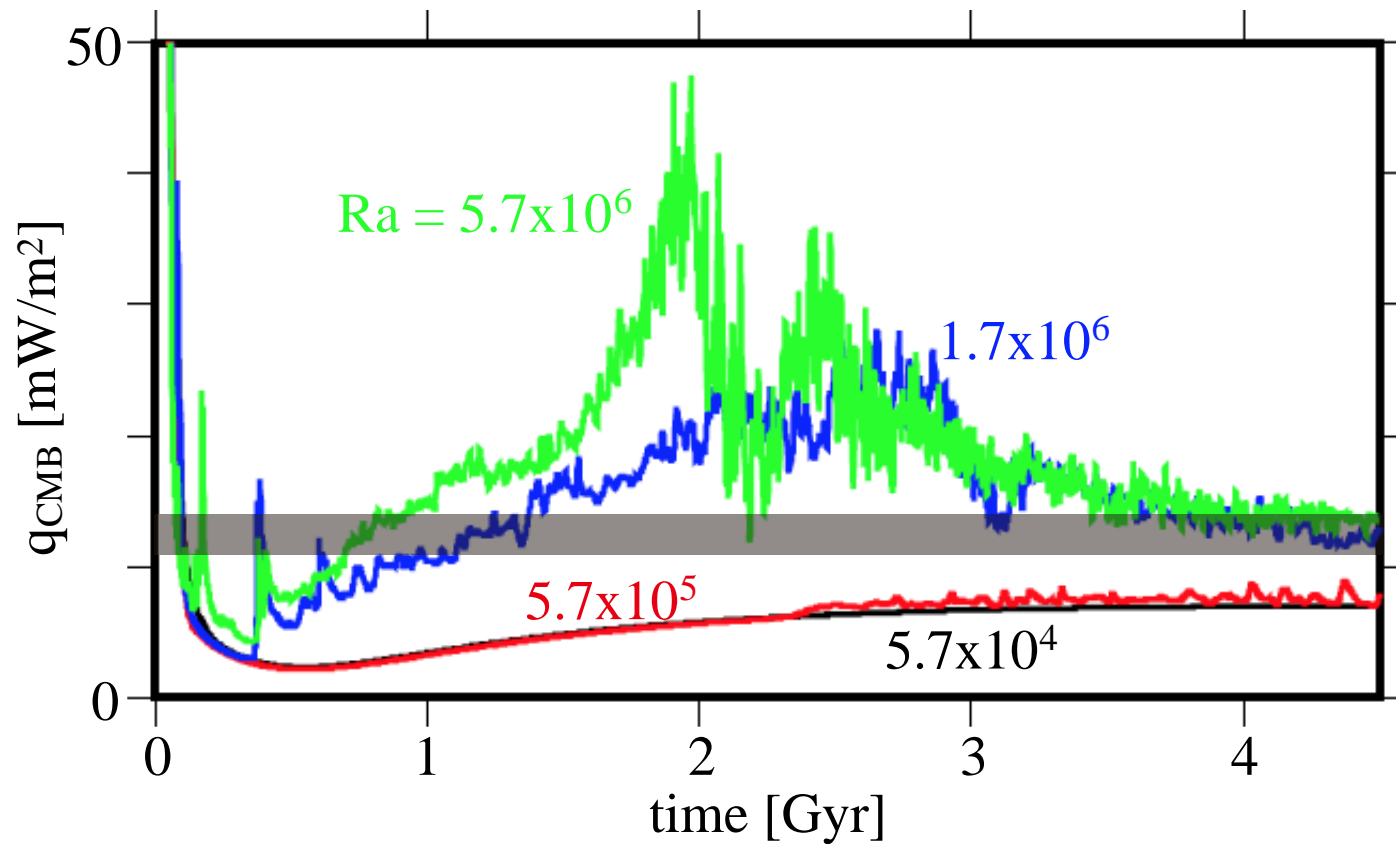
(c) 流速とマグマ生成の最大深度



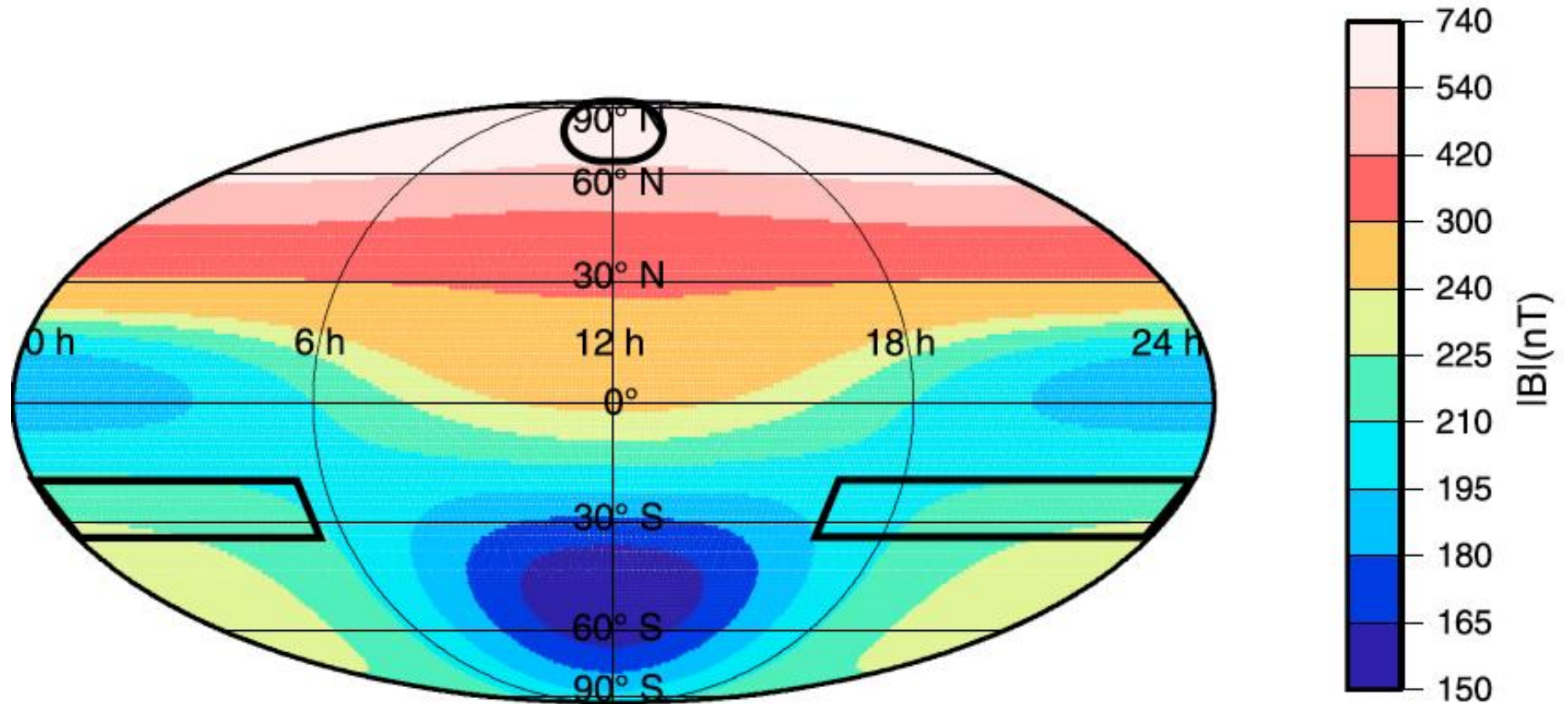
(d) マグマの噴出率と地殻の放射性元素量



MMU_bフィードバックとコア・マントル境界の熱流量



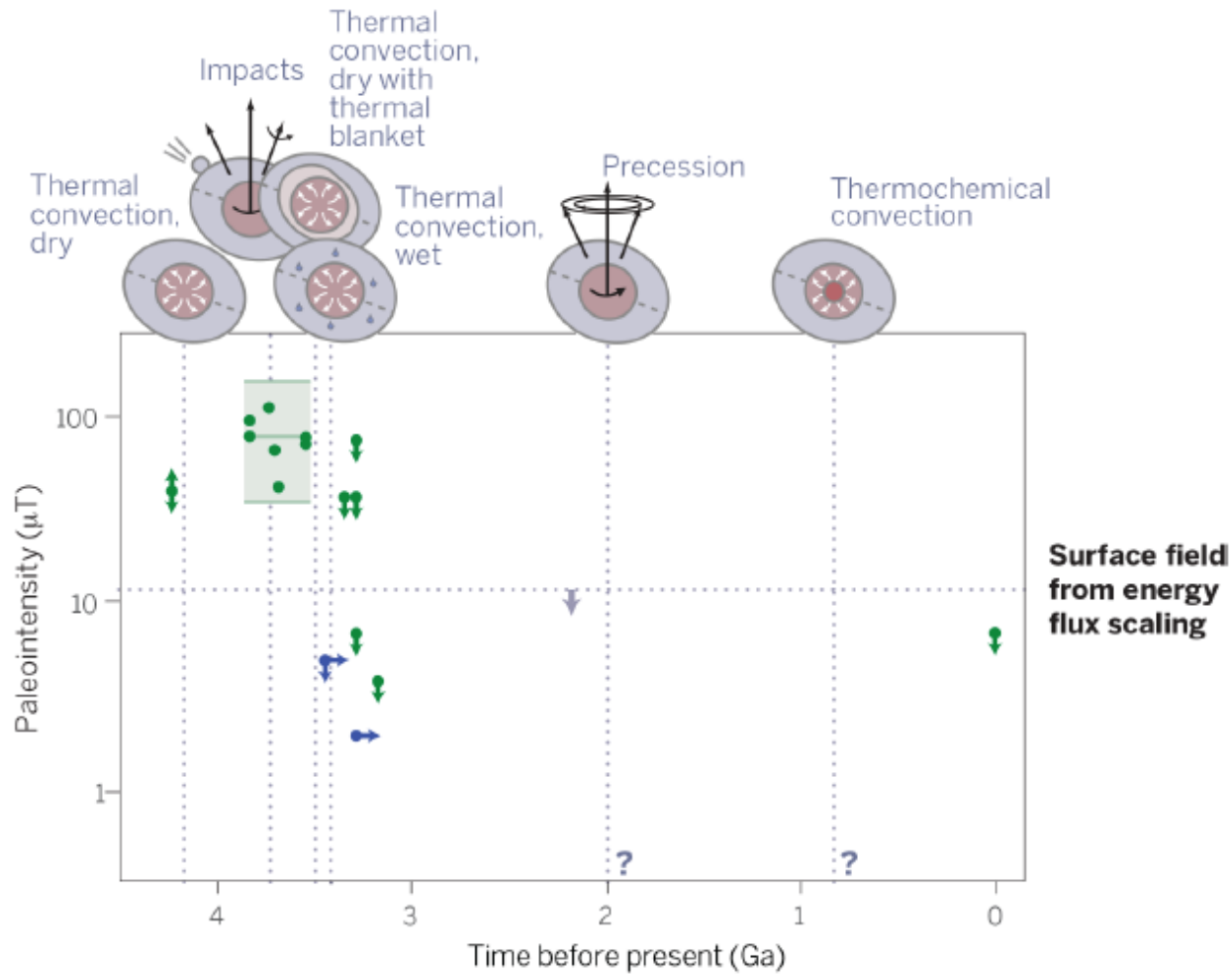
磁場;地球の1/100程度



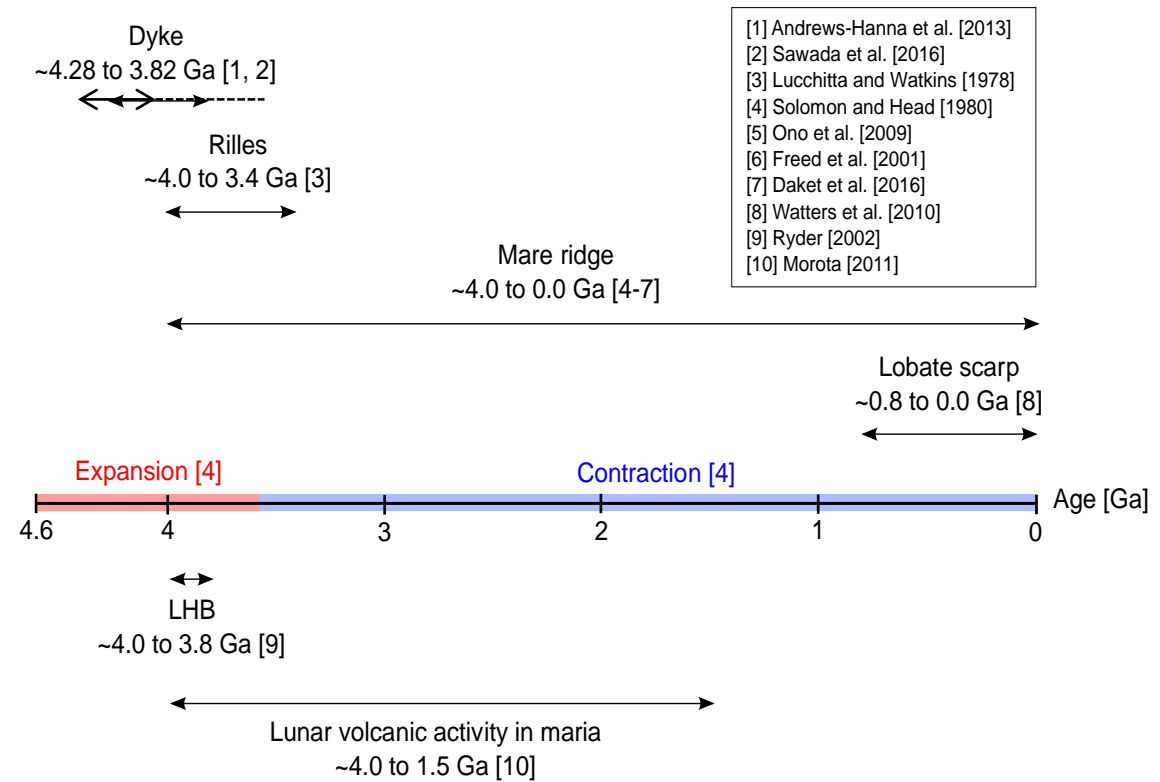
(Winslow et al., 2014)

問題提起(1): コア・ダイナモ

月の磁場：原因はコア冷却ではない？



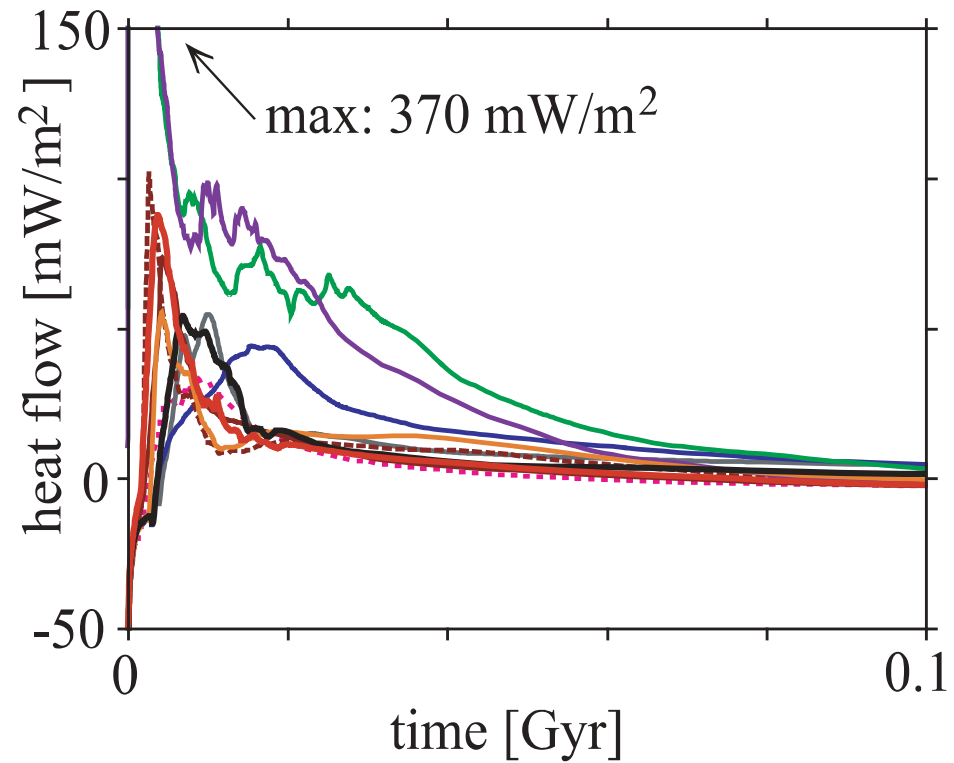
(Weiss & Tikoo, 2014)



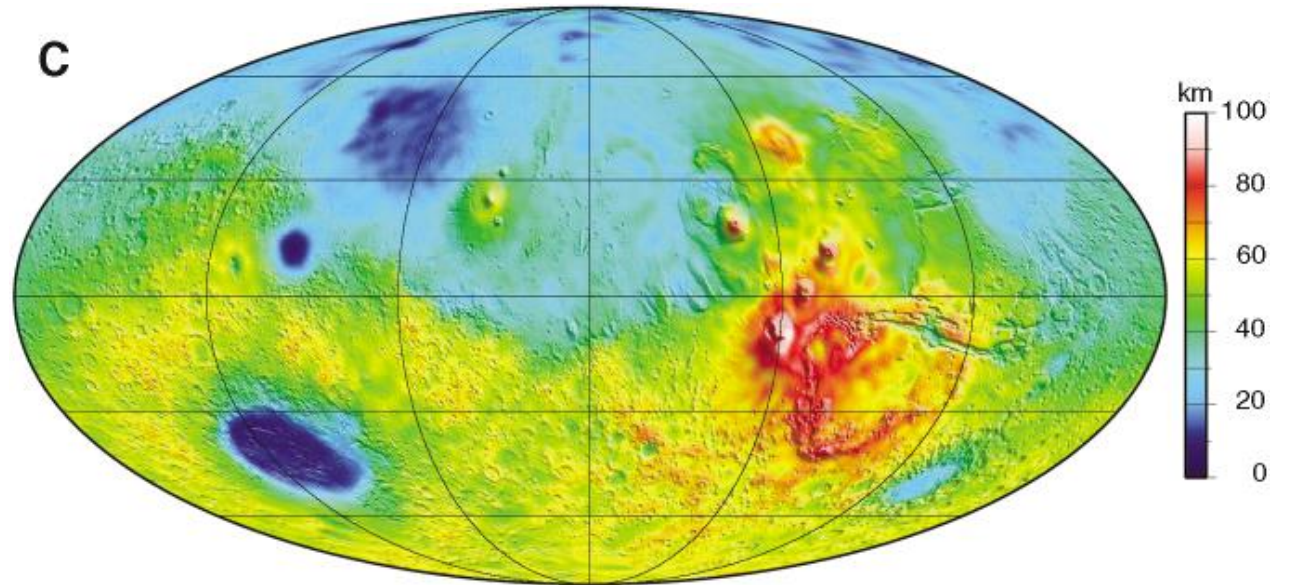
月サイエンスブック4.2.3節(石山他)

火星の固有磁場 (> 4Ga)

(d) CMB heat flow

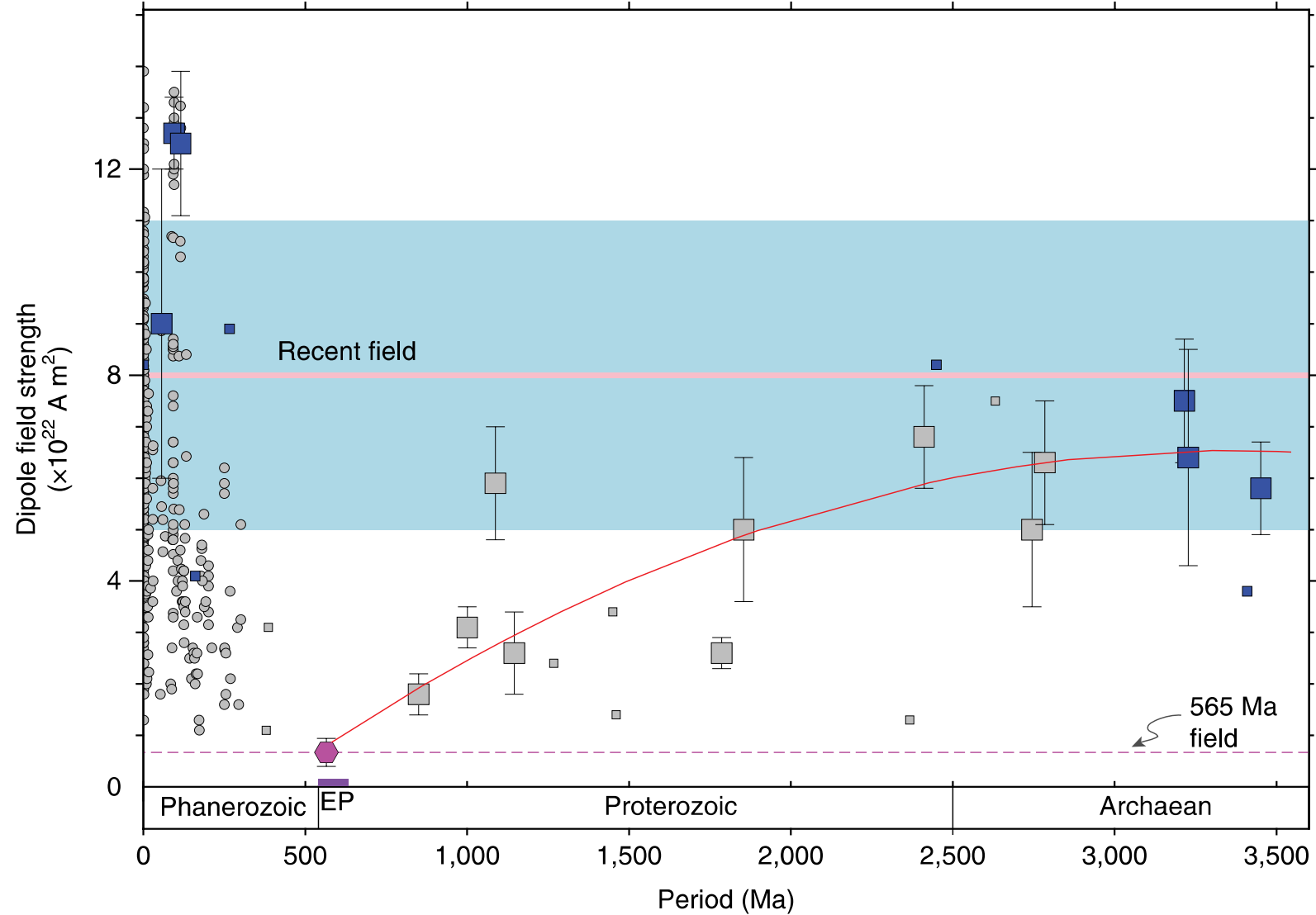


(Ogawa & Yanagisawa., 2012)



(Solomon et al., 2005)

地球の磁場：エネルギー不足



ダイナモ？→乱流問題

(1) マグネティック・プラントル数

$P_m > 1$ がダイナモの条件 \Leftrightarrow 鉄の $P_m = 0 \Rightarrow$ 乱流？
乱流を維持するエネルギー？

(2) 乱流対流による熱輸送？

$Q_{CMB} > k_{eddy} \Delta T/d$; k_{eddy} ; 乱流による熱伝導率 \gg 物性値

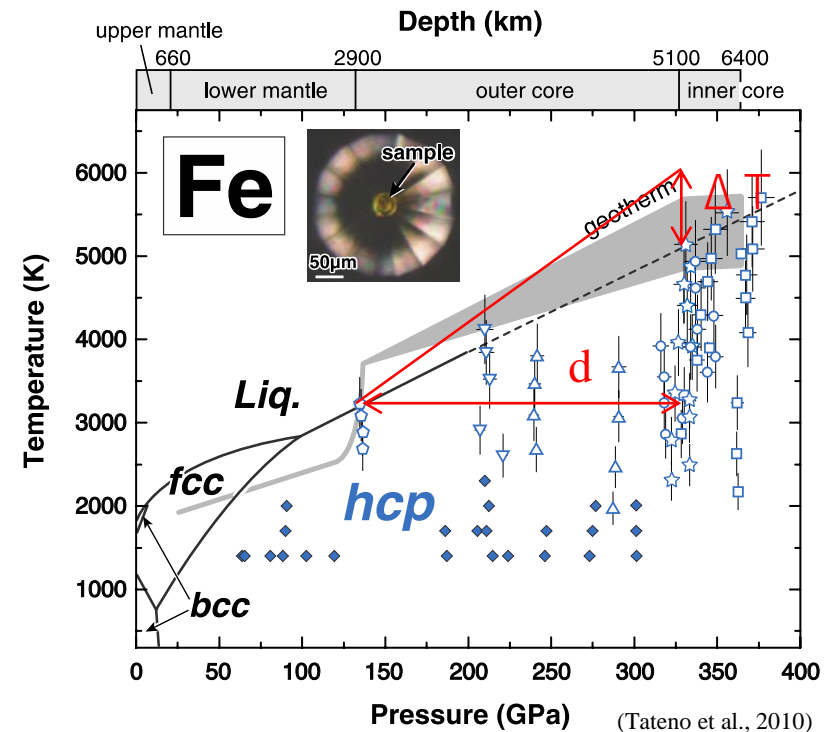
$\Delta T \approx 0$ が必要

\updownarrow

CMB直上の水平温度コントラスト
= 500-1000 °C

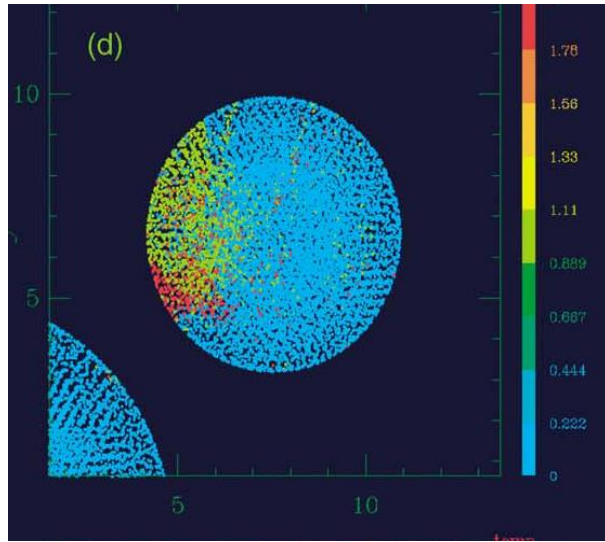
(3) 内核の成長による熱組成対流

$Q_{CMB} < Q_{adiabatic}$?

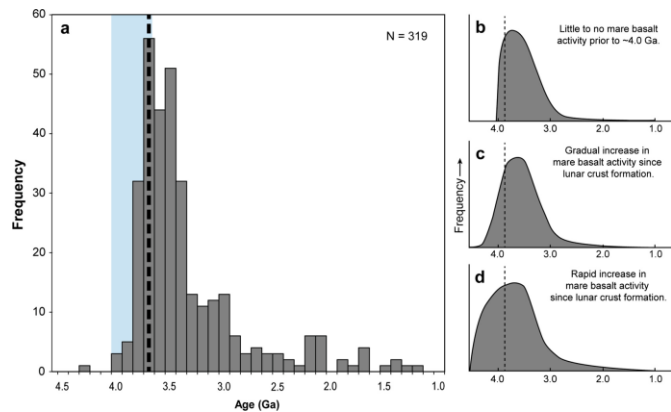


問題提起（2）：惑星の形成過程とMOと進化の整合性

月：高温起源？

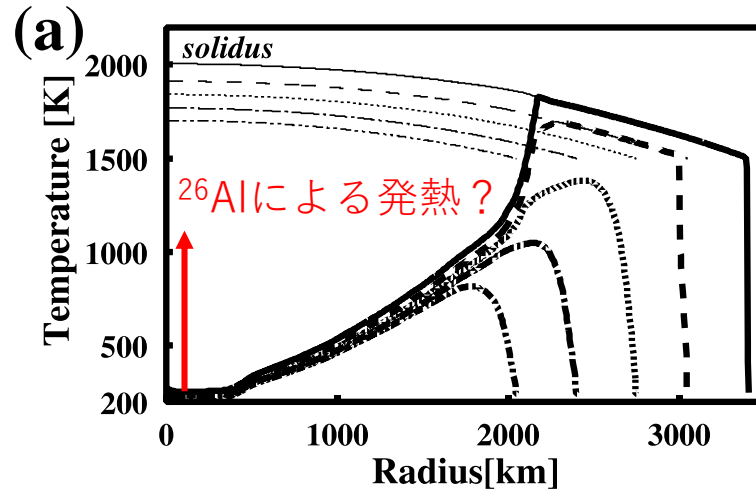


(Canup, 2004)

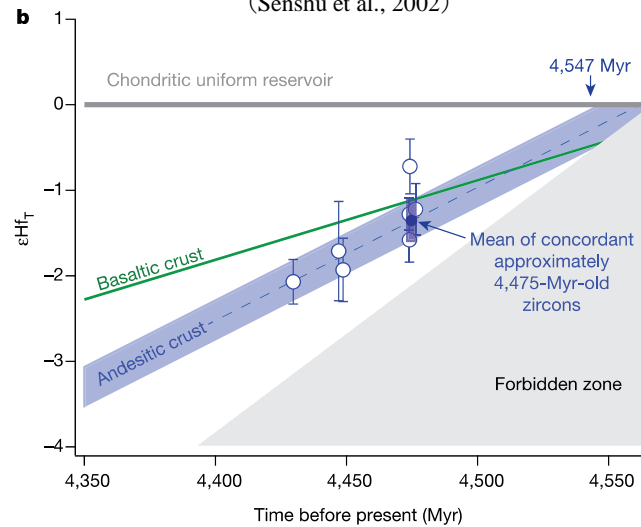


(Whitten et al., 2015)

火星：低温起源？

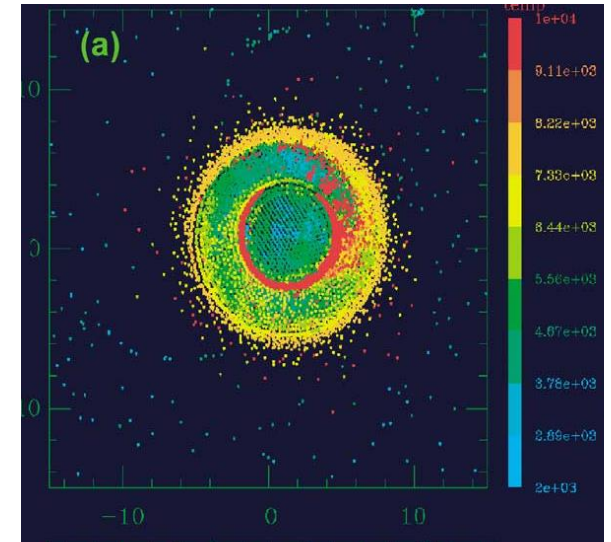


(Senshu et al., 2002)



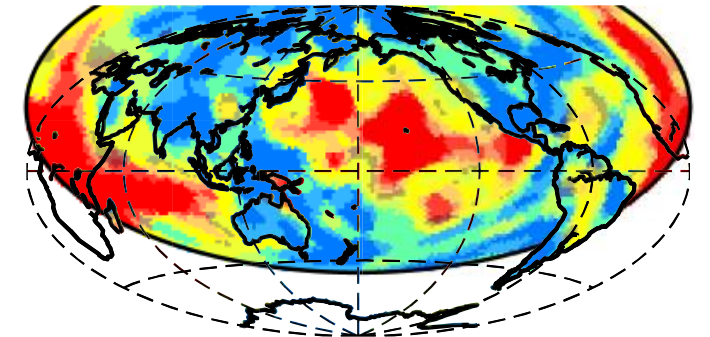
(Bouvier et al., 2018)

地球：高温起源？



(Canup, 2004)

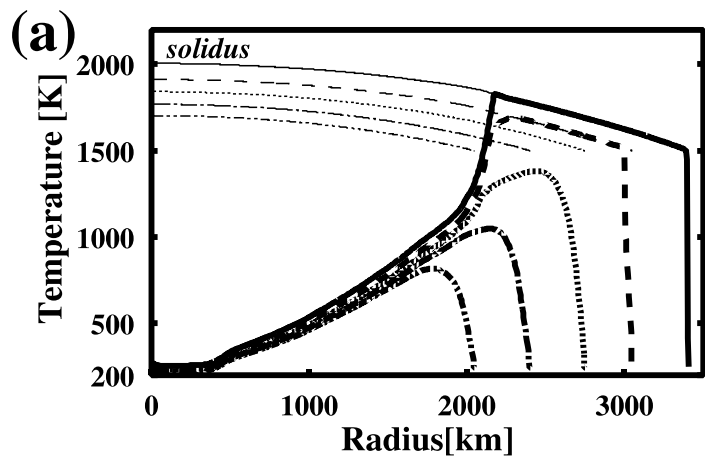
MMU-feedbackによる攪拌・混合



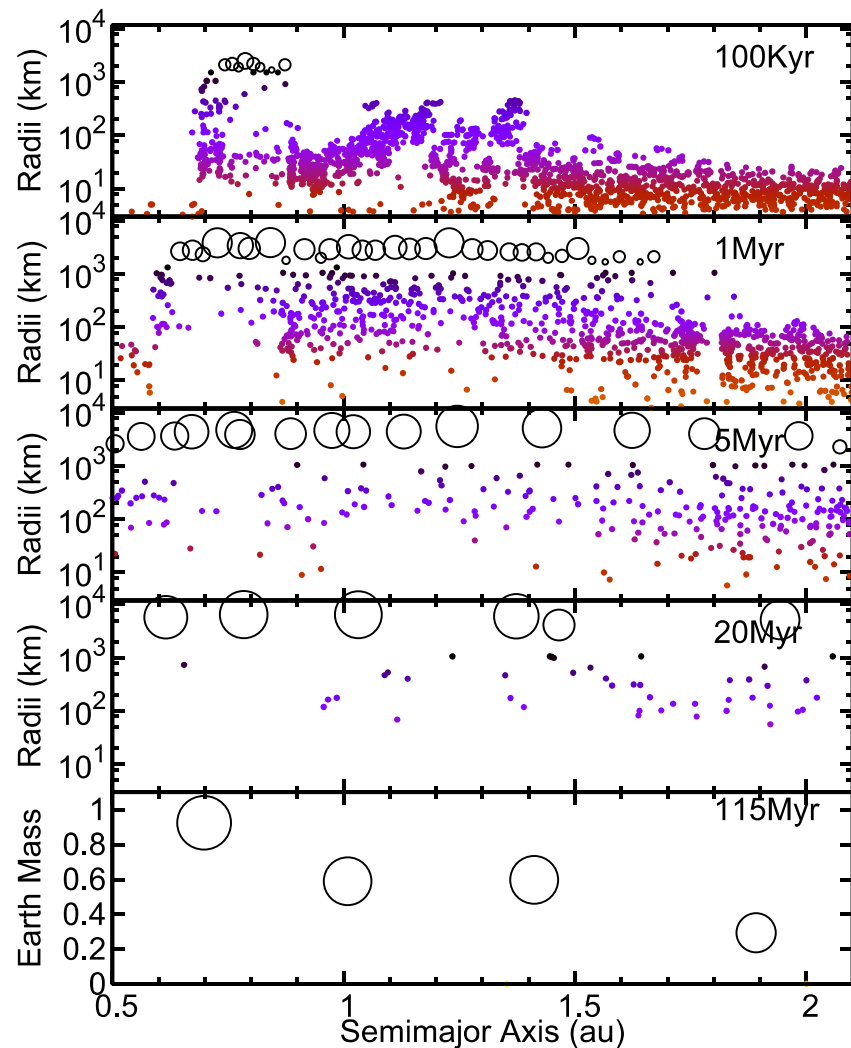
(Cottaar & Lekic, 2016)

火星：Cold primordialの問題

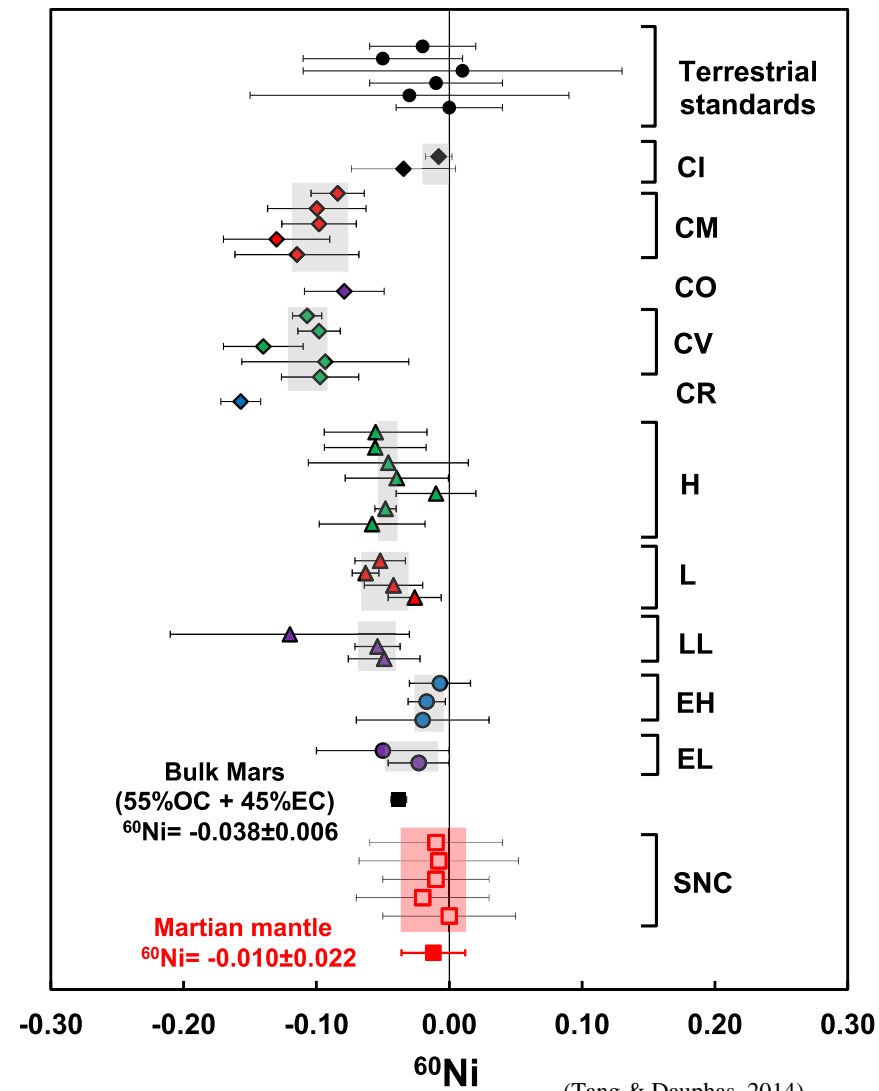
2Myr程度で惑星形成→ ^{26}Al による加熱？



(Senshu et al., 2002)



(Walsh & Levinson, 2019)



(Tang & Dauphas, 2014)

月の巨大衝突モデル:月は原始地球起源?

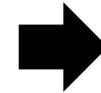
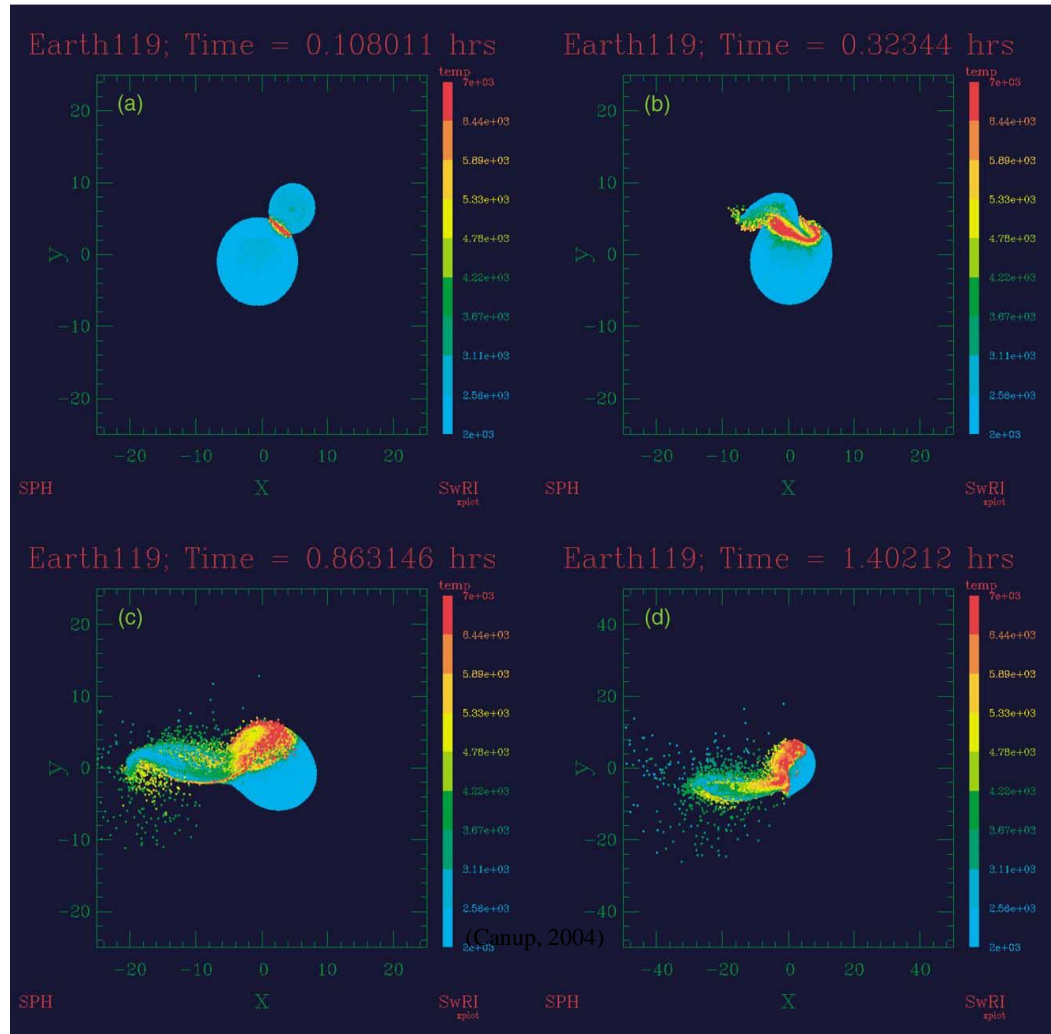
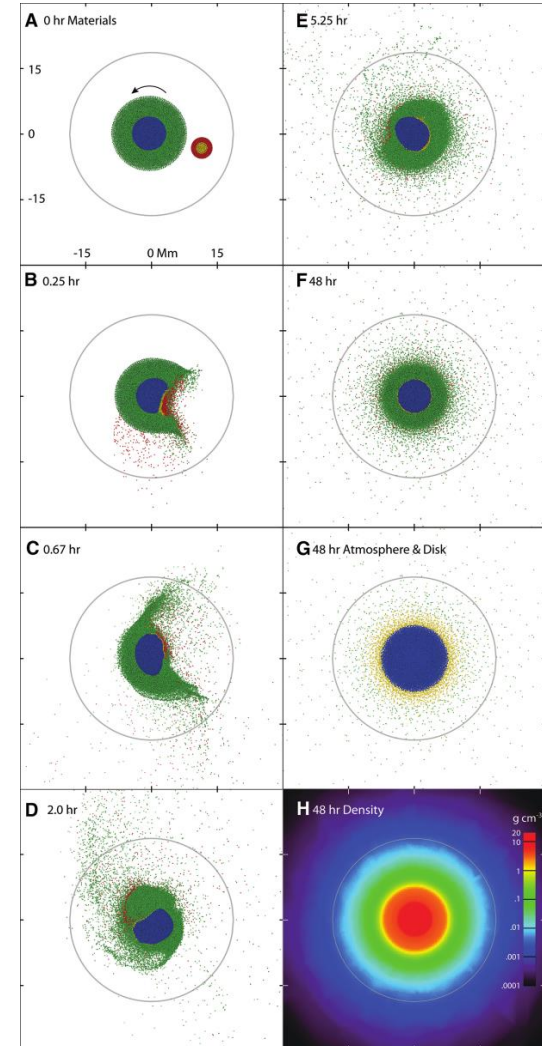


Fig. 1. Formation of the lunar disk from Earth's mantle. Example impact of a $0.05M_E$ impactor at 20 km s^{-1} and $b = -0.3$ onto a $1.05M_E$ Earth spinning with a period of 2.3 hours (\dagger in Table 1). Gray circles denote the Roche radius. (A to F) View of SPH particles in the lower hemisphere looking down the counterclockwise spin axis, where colors denote the silicate mantles and iron cores of the Earth and the impactor. The disk is dominated by material originating from Earth's mantle near the impact site (fig. S1 and movie S1). (G) Lower hemisphere view with particle colors denoting the planet (blue), atmosphere (yellow), and disk (green). (H) Density in the equatorial plane of the disk and planet, which is stably stratified.



月と地球の物質的類似性

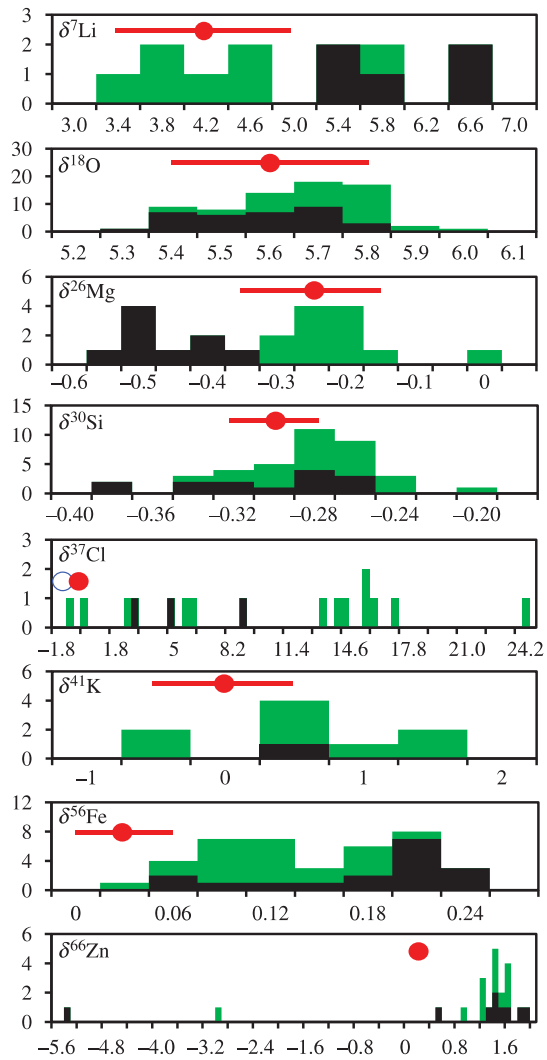
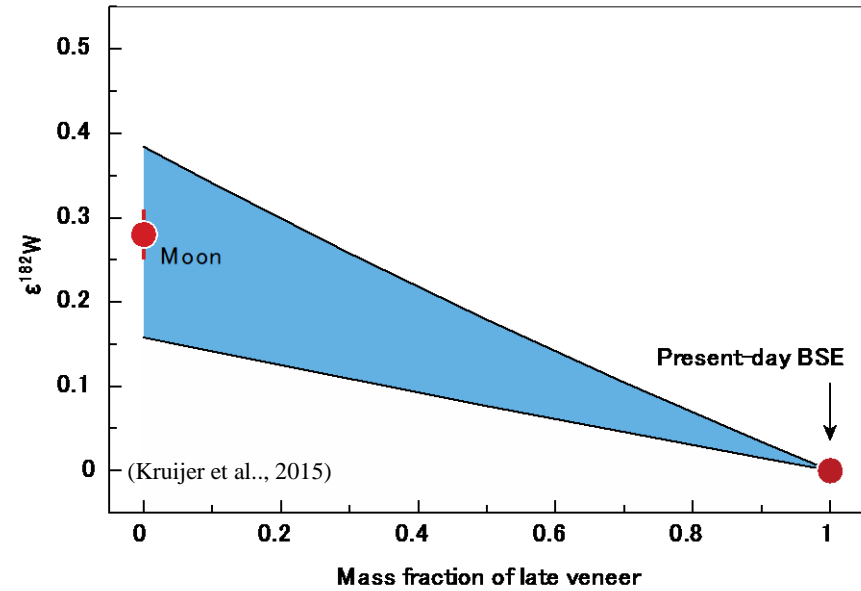
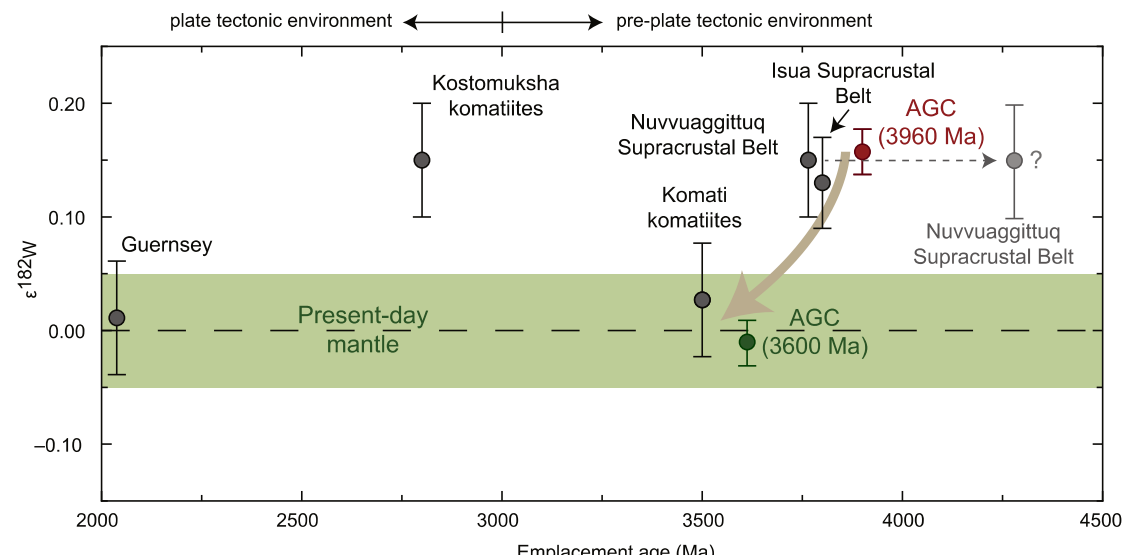


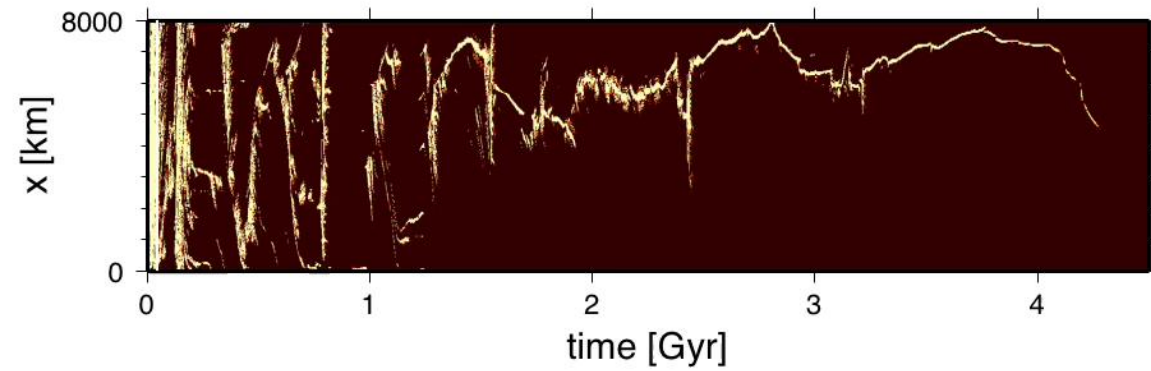
Figure 3. Histograms of Li [71,72], O [11–13,73], Mg [74], Si [21–23], Cl [75], K [76], Fe [73,77–79] and Zn [80] isotopic compositions of the Moon, as represented by lunar basalts (black, high-Ti basalts; green, low-Ti basalts) except for Cl, where samples include basalt, soil, regolith and apatite from basalts. The average isotopic compositions of the Earth (red dots) and typical uncertainties (horizontal red lines) for Li [81,82], O [83], Mg [84], Si [22,23,85–88], Cl [89,90], K [91], Fe [92,93] and Zn [80] are plotted for comparison. (Online version in colour.) (Dauphas et al., 2014)



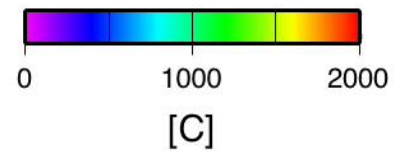
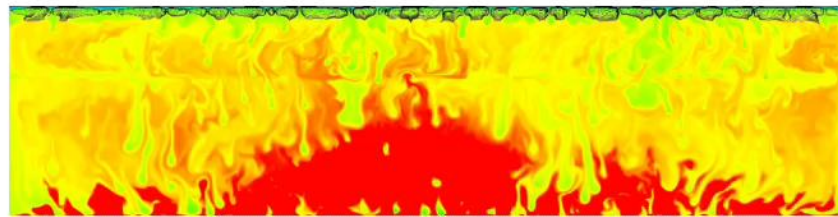
M. Willbold et al. / Earth and Planetary Science Letters 419 (2015) 168–177



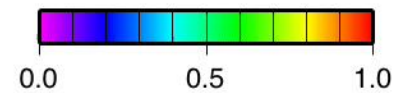
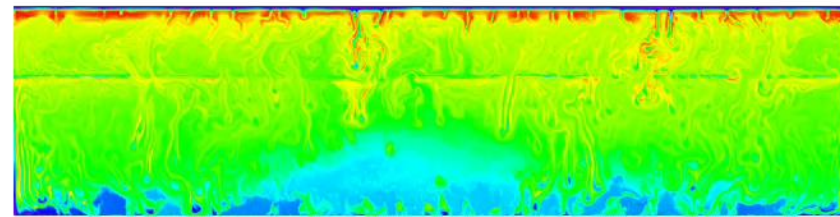
Late veneer による地球のW-同位体比変化？



T & magma



composition



月も初期地球の地殻もTheia 起源？ (Cf. Dauphas et al., 2014)

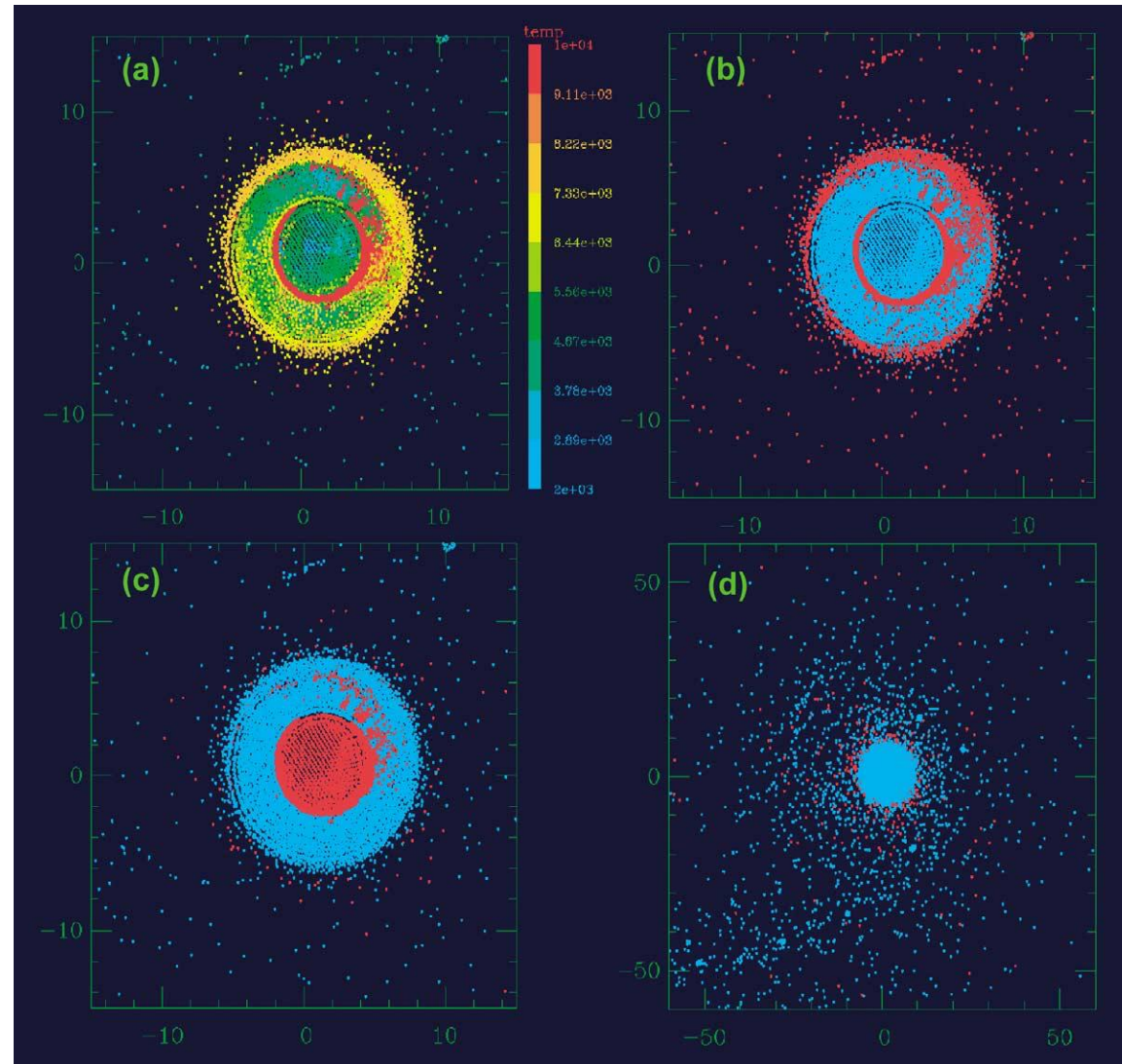


Fig. 4. Post-impact state of protoearth and disk from simulation shown in Fig. 2. (a) Temperatures within a 2000-km thick slice through the protoearth, parallel with and centered on the equatorial plane of the planet; (b) same slice as shown in (a), but here color scales with the source object of the material, with red particles originating from the impactor and blue from the target; (c) same slice as in (a), but color scales with material type, with iron particles in red and dunite particles in blue; (d) the entire protoearth and disk, with color scaling with material type (iron vs. dunite) as in (c).

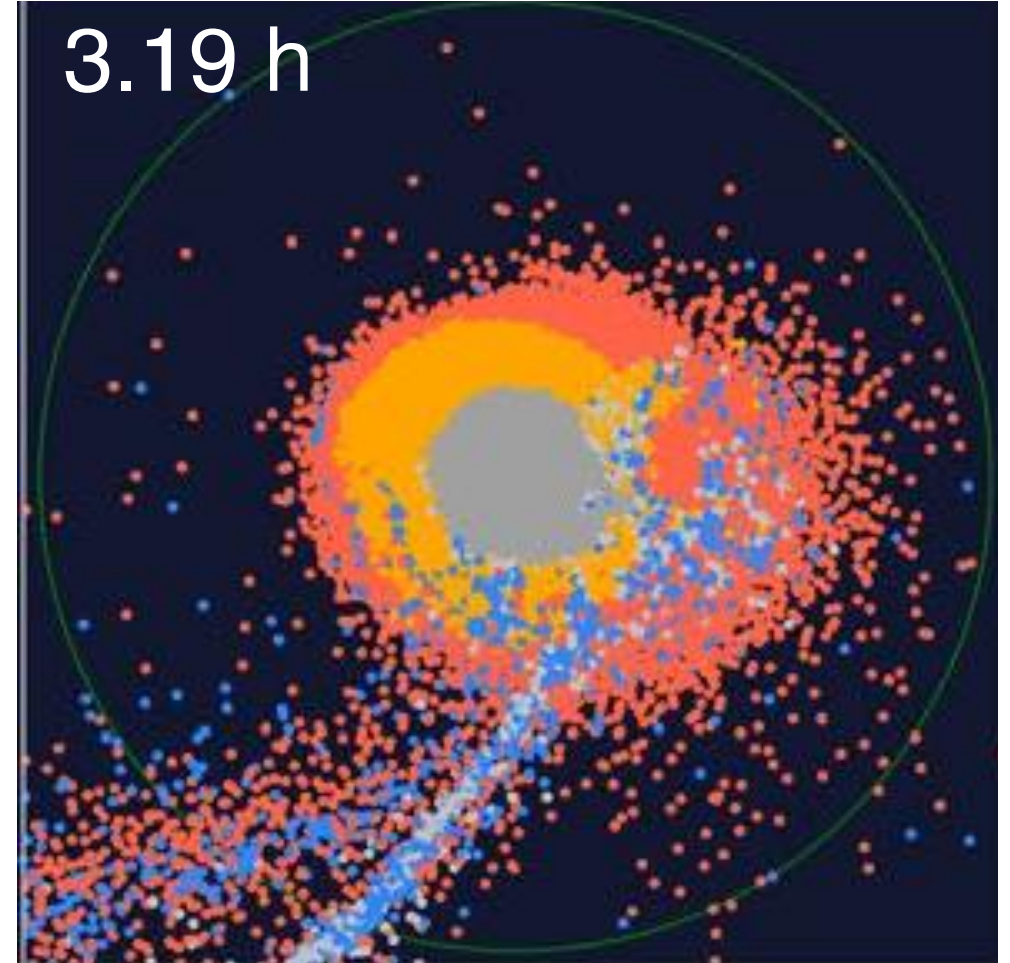
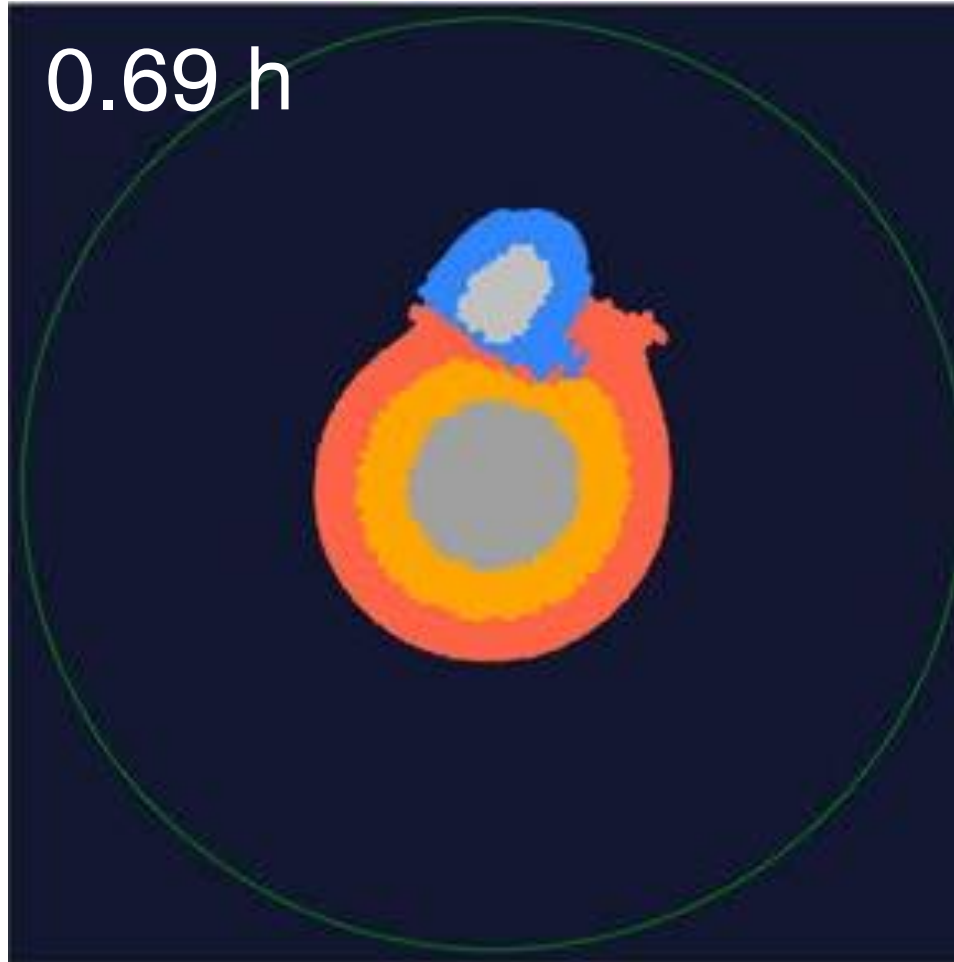
月の形成年代（巨大衝突の年代） = CAI形成以降 >60 Myr?



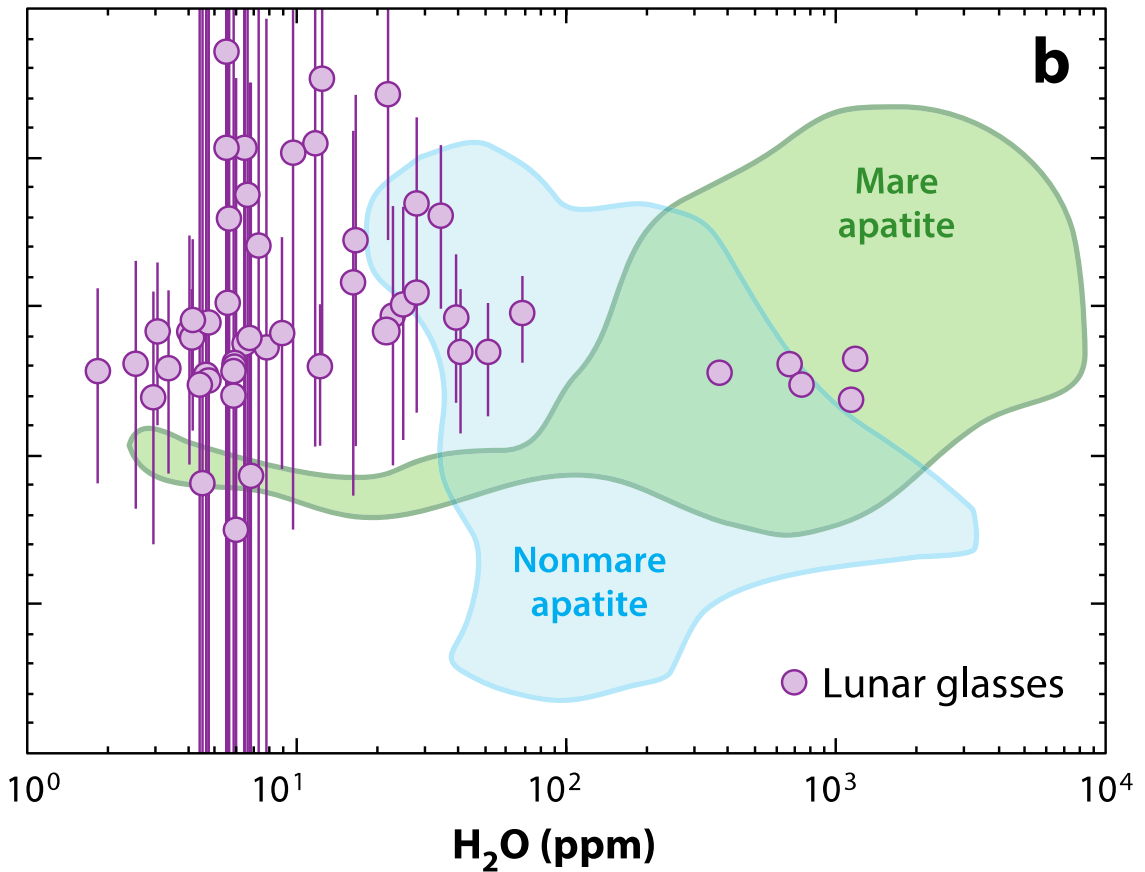
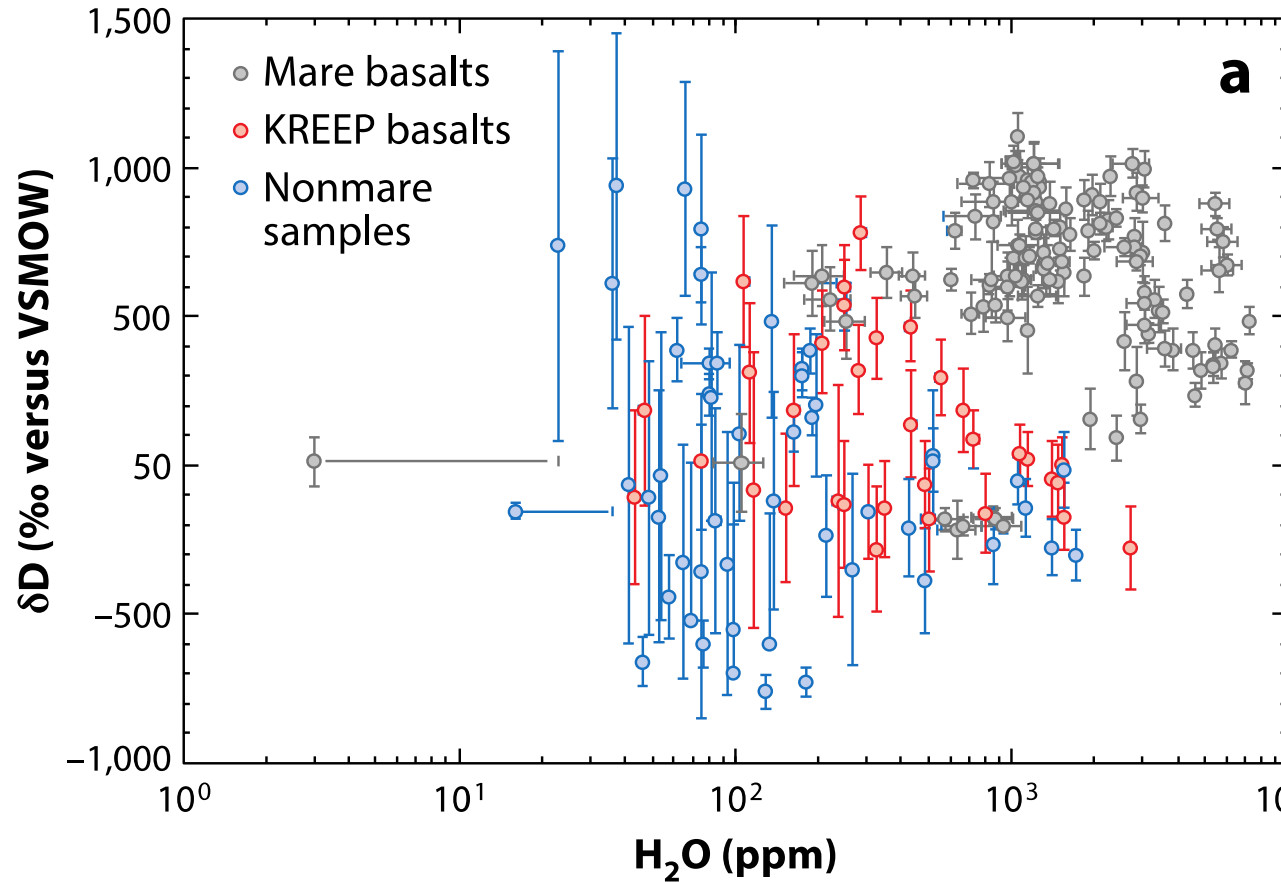
マグマ・オーシャンによる原始地球・Theia内部の分化？



月と地球の組成は異なるはず？



高温起源にしては水がある：K/Th比との関係？

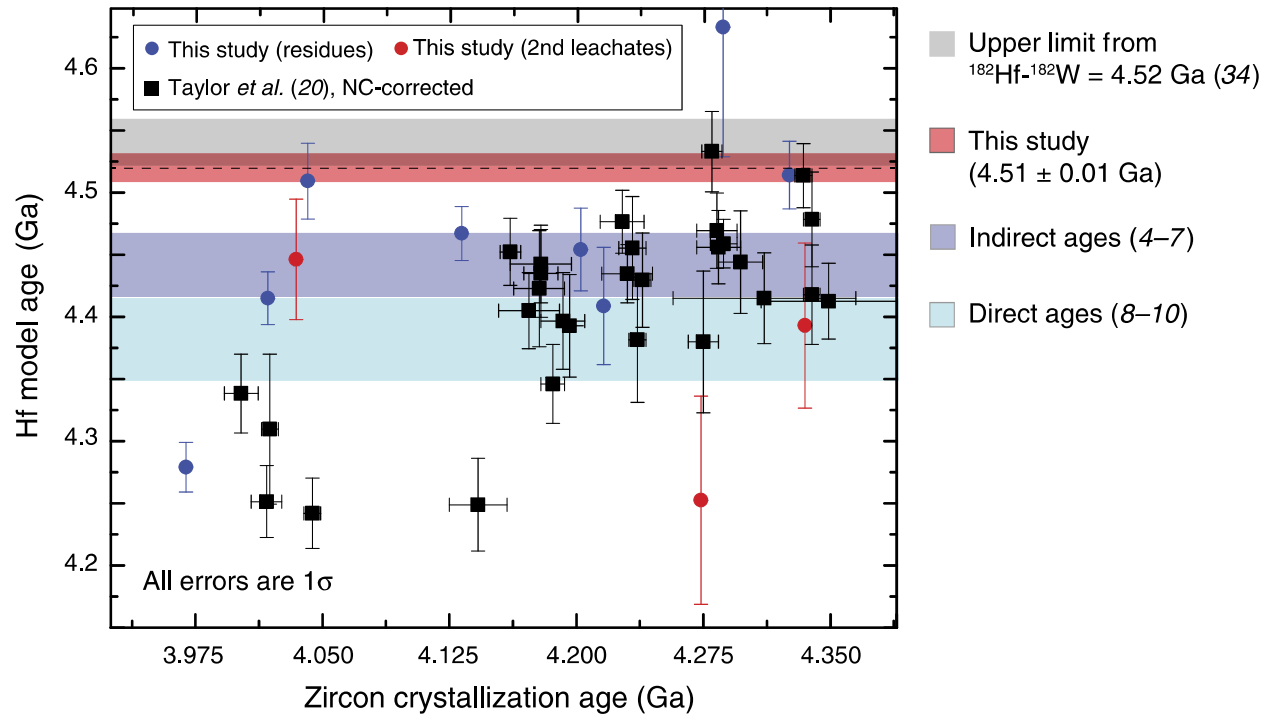


(Hauri et al., 2017)

月のマグマ・オーシャンの寿命

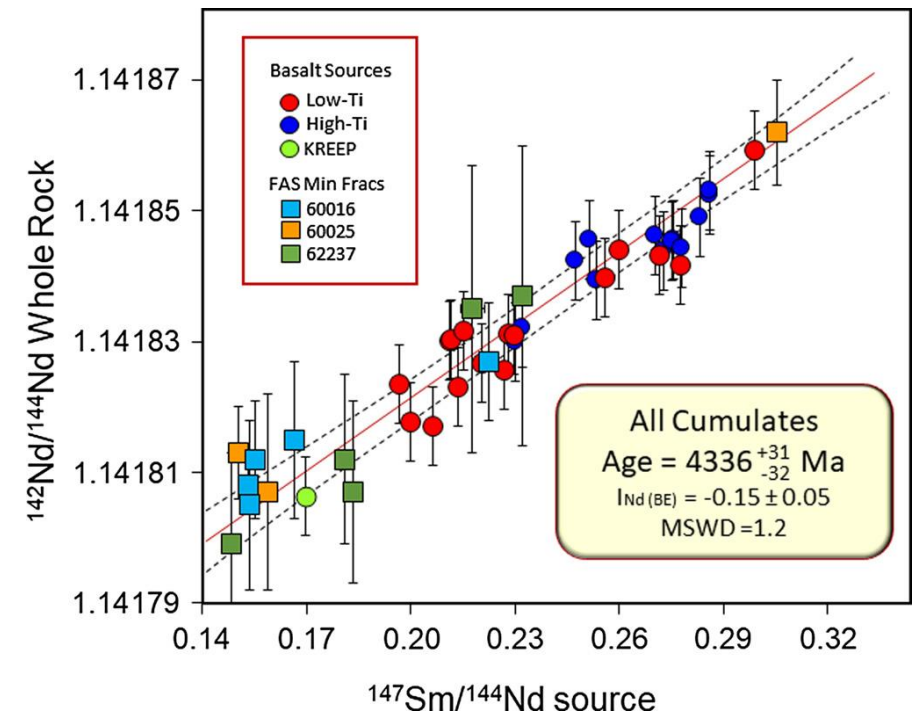
億年スケール？ ⇔ 火星ではおよそ20 Myr?

高地地殻の年齢
Apollo14 sample



(Barboni et al., 2017)

マグマ・オーシャンの年齢



(Borg et al., 2019)

月探
月マ
火星
マ内

行こう。
月と火星
そうだ



ク)