Elementary processes of mantle evolution in terrestrial planets and lunar mission

(月探査による地球型惑星内部進化の素過程の検証)

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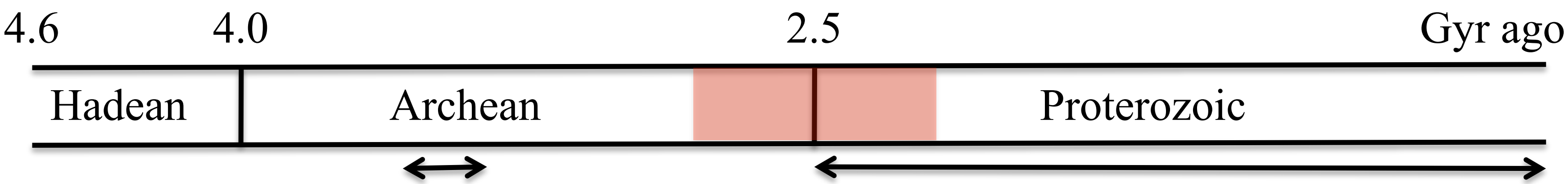
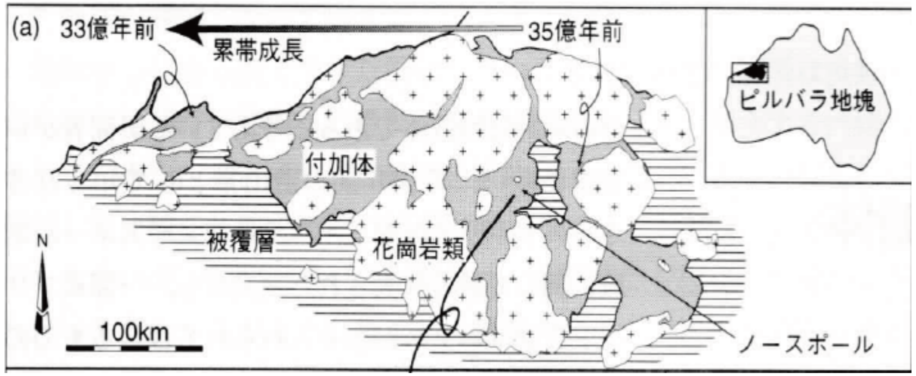
ABSTRACT

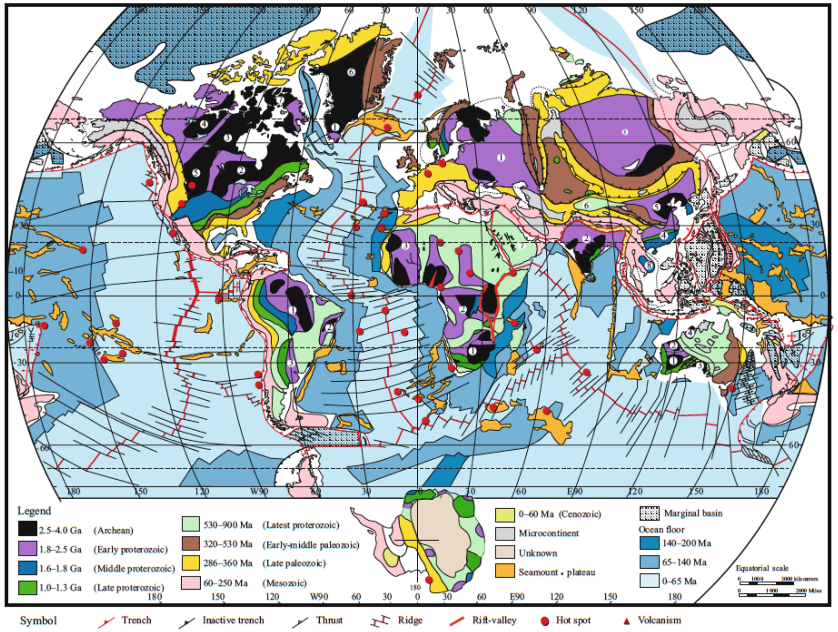
Numerical models of mantle evolution are systematically presented to show that studies of the internal structure and the history of magmatism of the Moon are crucial to understand the mantle evolution in terrestrial planets in general including the Earth. When upwelling mantle materials generate magma by decompression melting in large planets like the Earth and Venus, the volume change of the coexisting matrix caused by migration of the magma enhances the upwelling flow itself. This positive feedback boosts magmatism and mantle convection in the early stage of mantle evolution to efficiently cool the mantle, to make magmatism occur episodically, and to strongly stir the mantle to make it homogeneous in spite of the chemical differentiation by the vigorous magmatism. In small planetary bodies like the Moon, however, this feedback does not operate. Because of the resulting weak convective stirring, a compositionally stratified structure well develops in the mantle, and magmatism occurs continuously with a characteristic time of several hundred million years. Confirming the predicted striking contrast between the Moon and the larger planets like the Earth and Venus by lunar mission is a critical test of the proposed models of mantle evolution in planets.

the Earth's history
An irreversible transition of tectonics at 2.5 Gyr ago



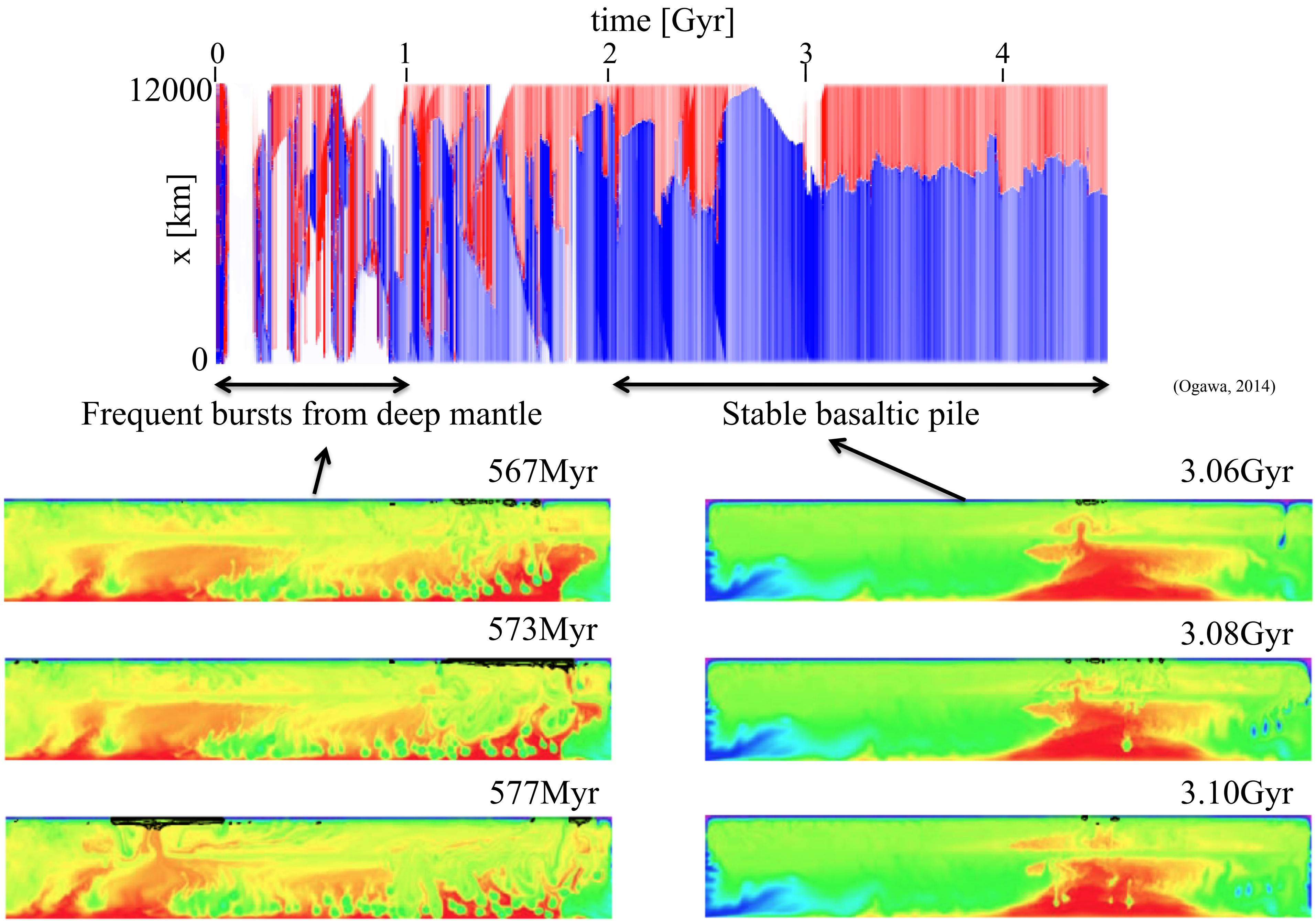


(Kabashima & Terabayashi, 2002)



(Utsunomiya et al., 2007)

the two-stage evolution model of the Earth



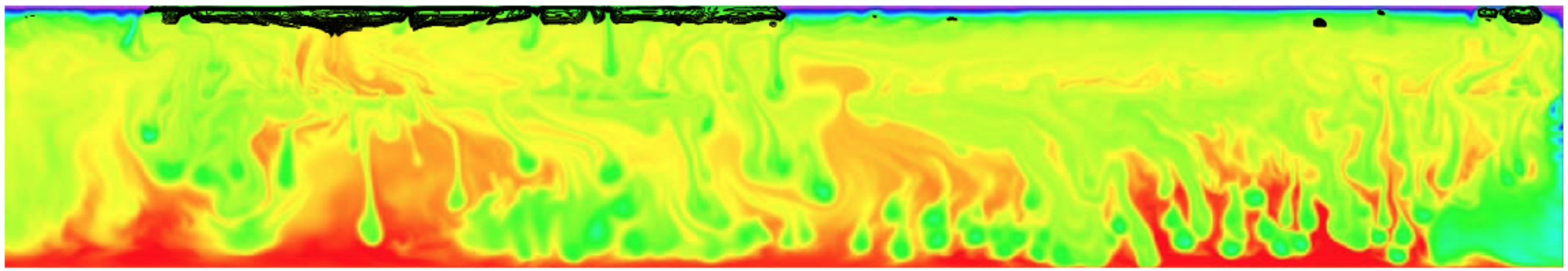
(Ogawa, 2014)

Mantle bursts in the early Earth

the abundant heat producing elements ➡ frequent bursts

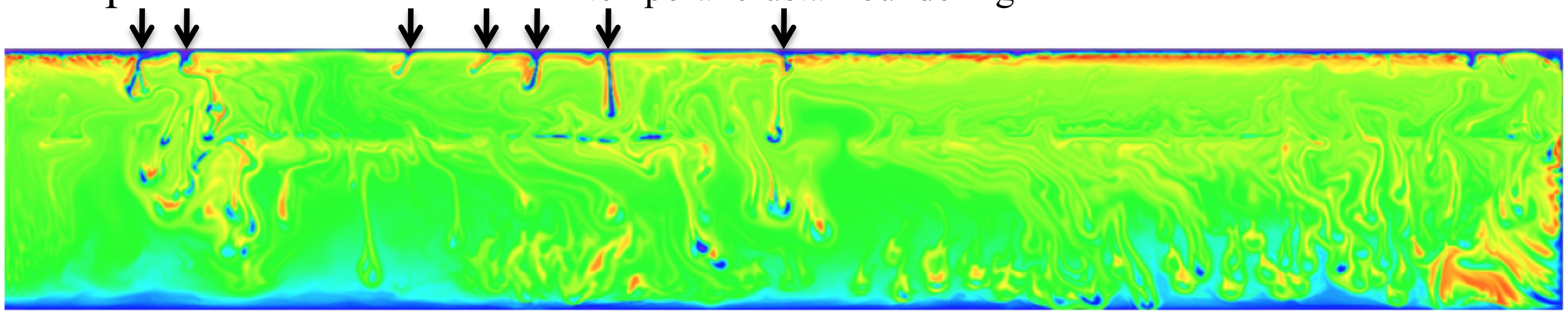
the homogeneous mantle + chaotic plate motion

temperature and magma-distribution



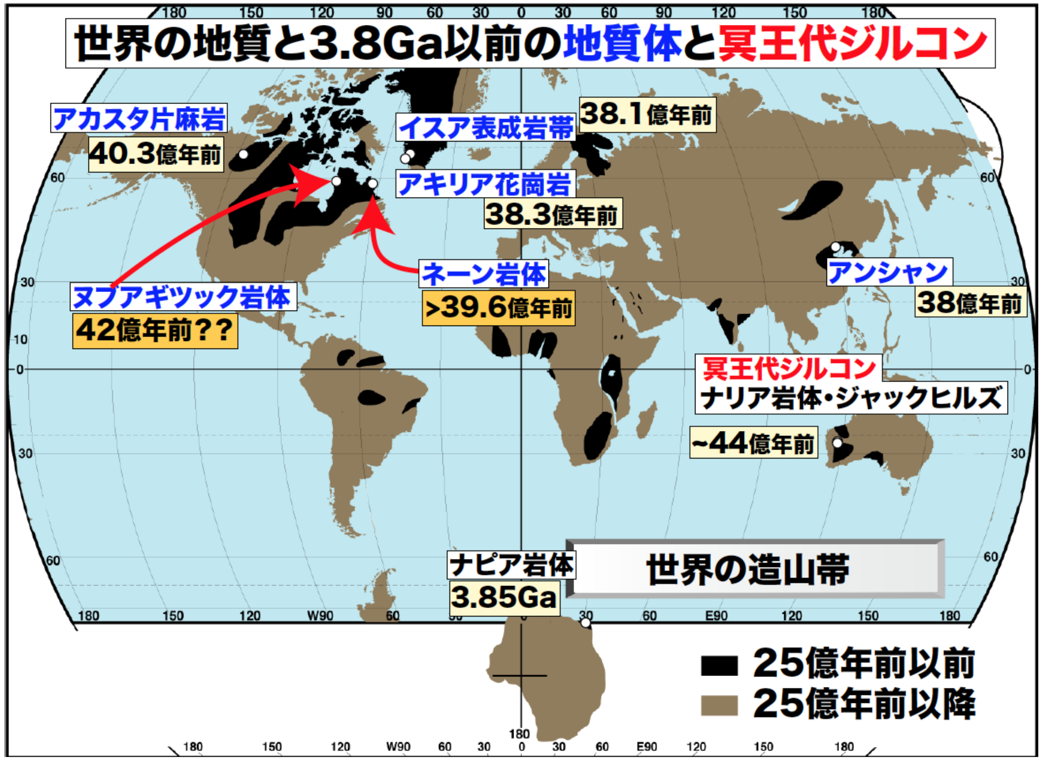
compositional distribution

temporal crustal foundering



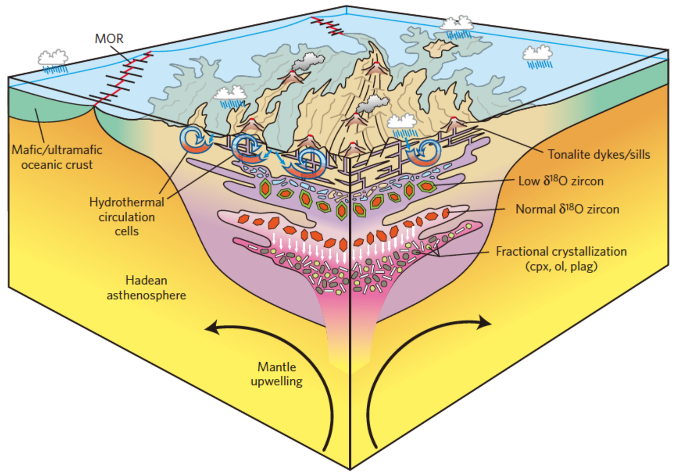
It is crucial to confirm the predicted mantle bursts by observation.

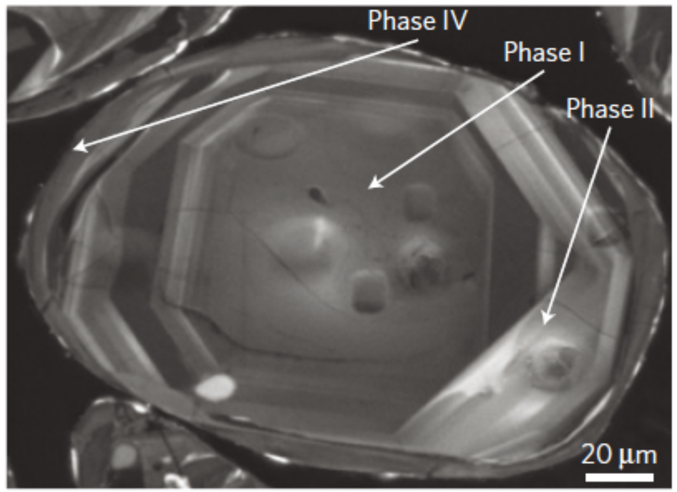
Confirmation by geologic studies?➡difficult



(Komiya, 2014)

A model of
Acusta continental crust formation





(Reimink et al., 2014)

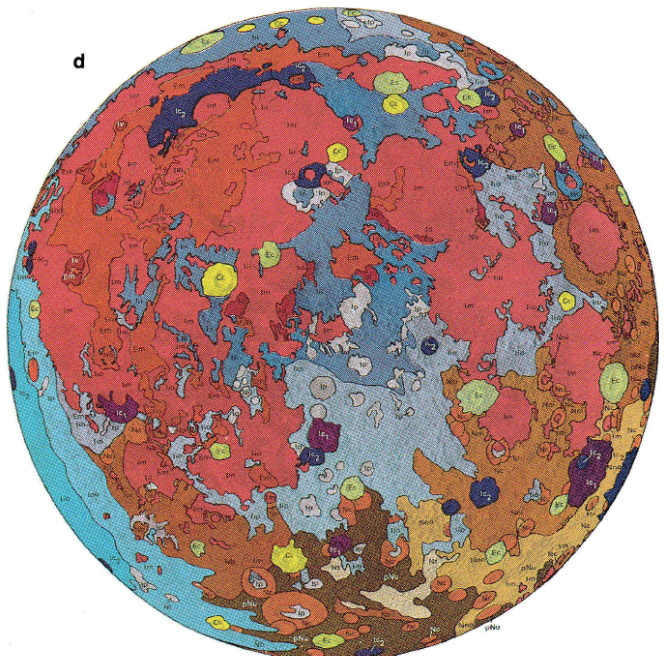
Ancient surface is well preserved on the Moon.

However, the Moon is so different from the Earth.

⬇

Numerical modeling is necessary

to clarify the effects of planetary size on mantle dynamics.

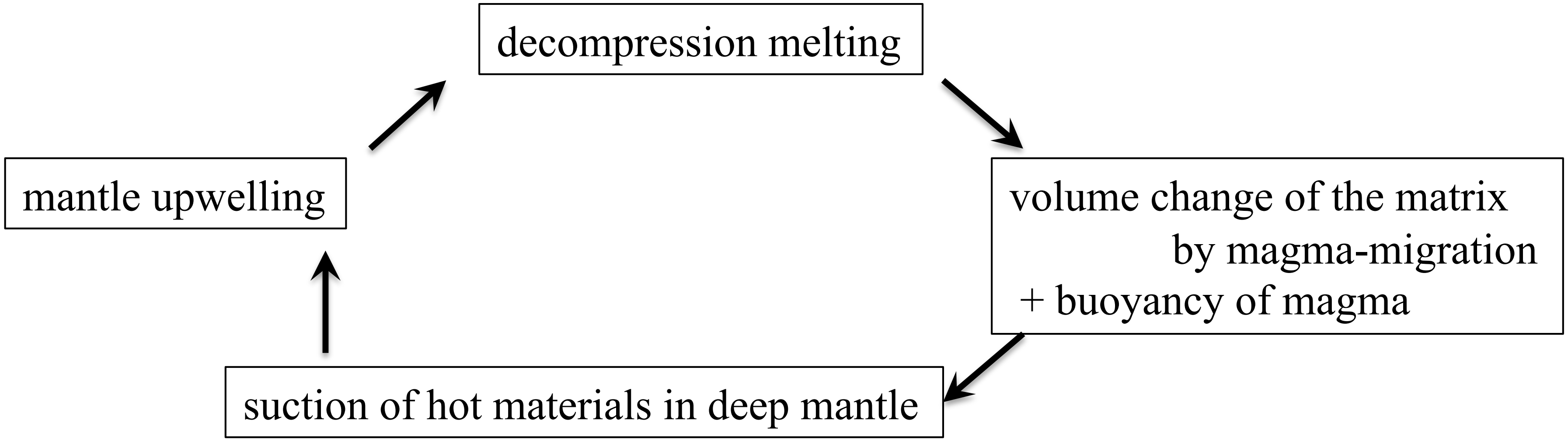


(Spudis, 1990)

Various imprints of the magma ocean

http://www.nikon.co.jp/channel/stars/0809/index.htm

The Magmatism-Mantle Upwelling (MMU) feedback



The feedback works, when the Rayleigh number $\gtrsim$ the critical value for thermal convection

➡ episodic magmatism with characteristic time on the order of 10 Myr
& efficient cooling and convective stirring of the mantle

➡ compositionally homogeneous mantle

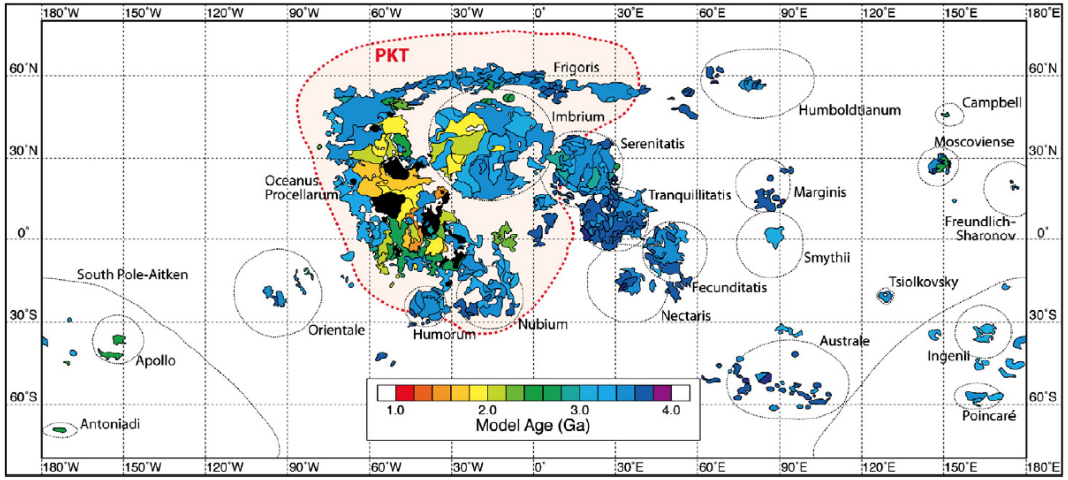
The Rayleigh number of the Moon is below the threshold.

➡ continuous magmatism + compositionally stratified mantle

(Ogawa, "A positive feedback between magmatism and mantle upwelling in terrestrial planets: Implications for the Moon", a manuscript submitted to JGR)

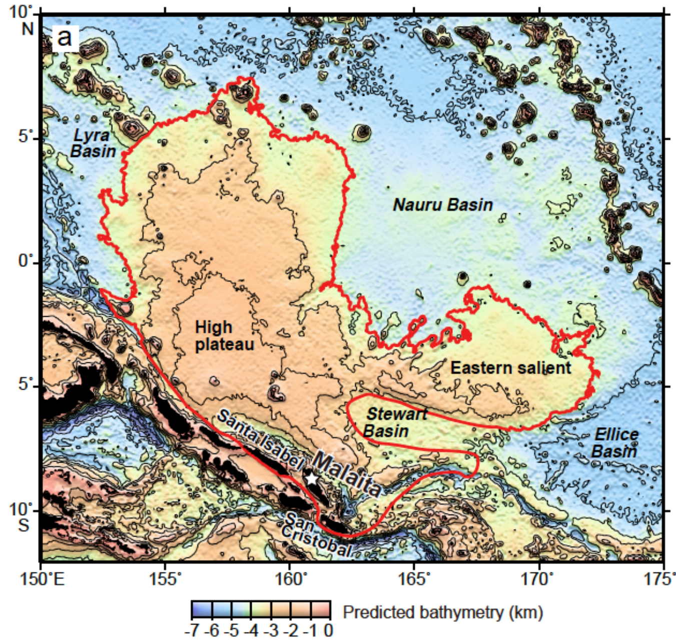
Lunar magmatism; NOT boosted by the MMU feedback
(1) long characteristic time

Mare volcanism of the Moon
several humdred Myr



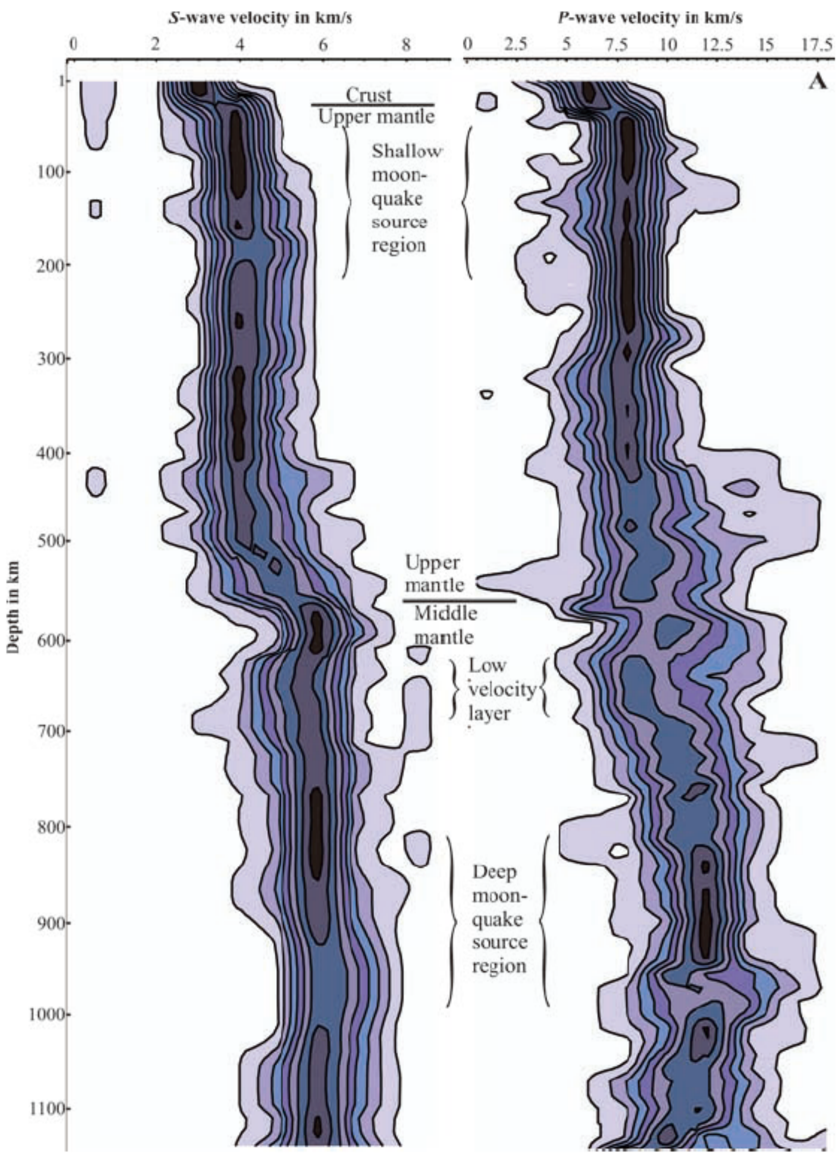
(Morota et al, 2011)

Large Igenous Provinces of the Earth
a few Myr



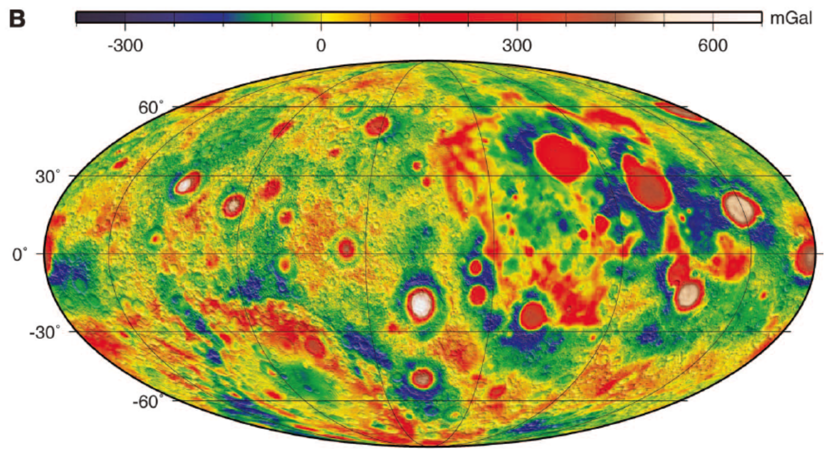
(Smith and Sandwell, 1997)

(2) the compositionally heterogeneous crust and mantle

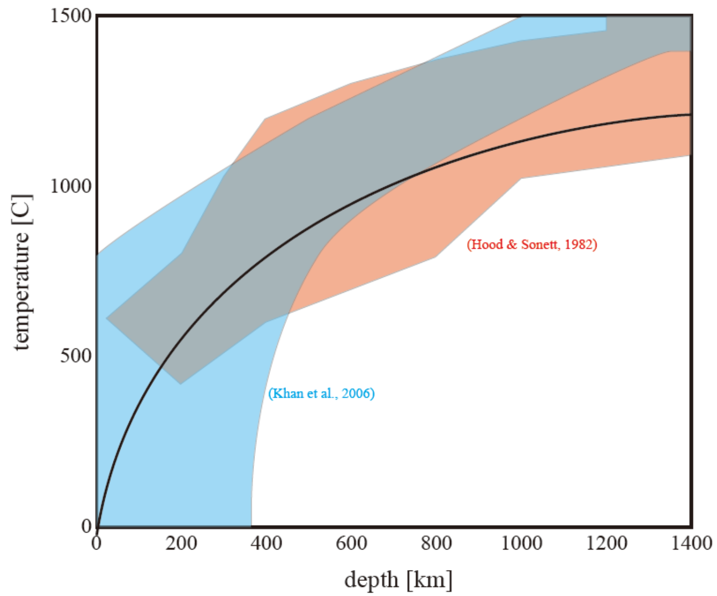


(Kahn and Mosegaard., 2002)

Bouguer anomaly



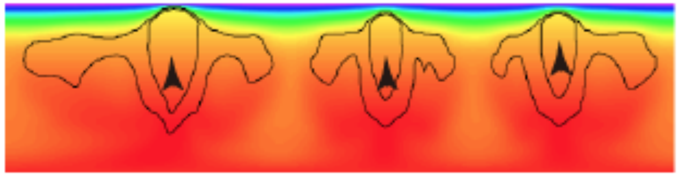
(Zuber et al., 2013)



too large contrast in the Rayleigh number between the Earth & the Moon

the Rayleigh number

10^5 the Moon



No MMU-feedback

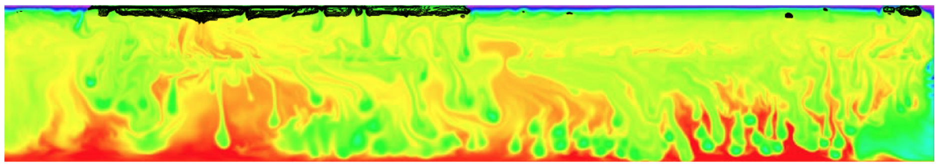
10^6

the MMU-feedback operates

Mars as a planet of intermediate size

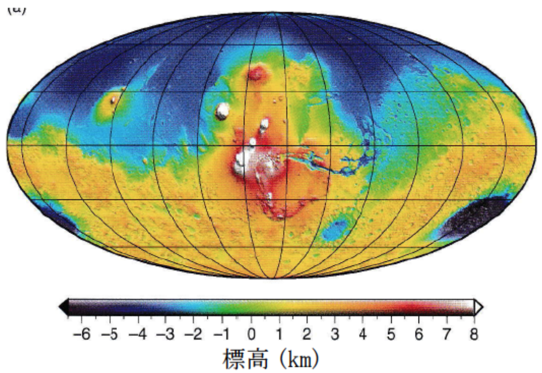
10^7

10^8 the Earth

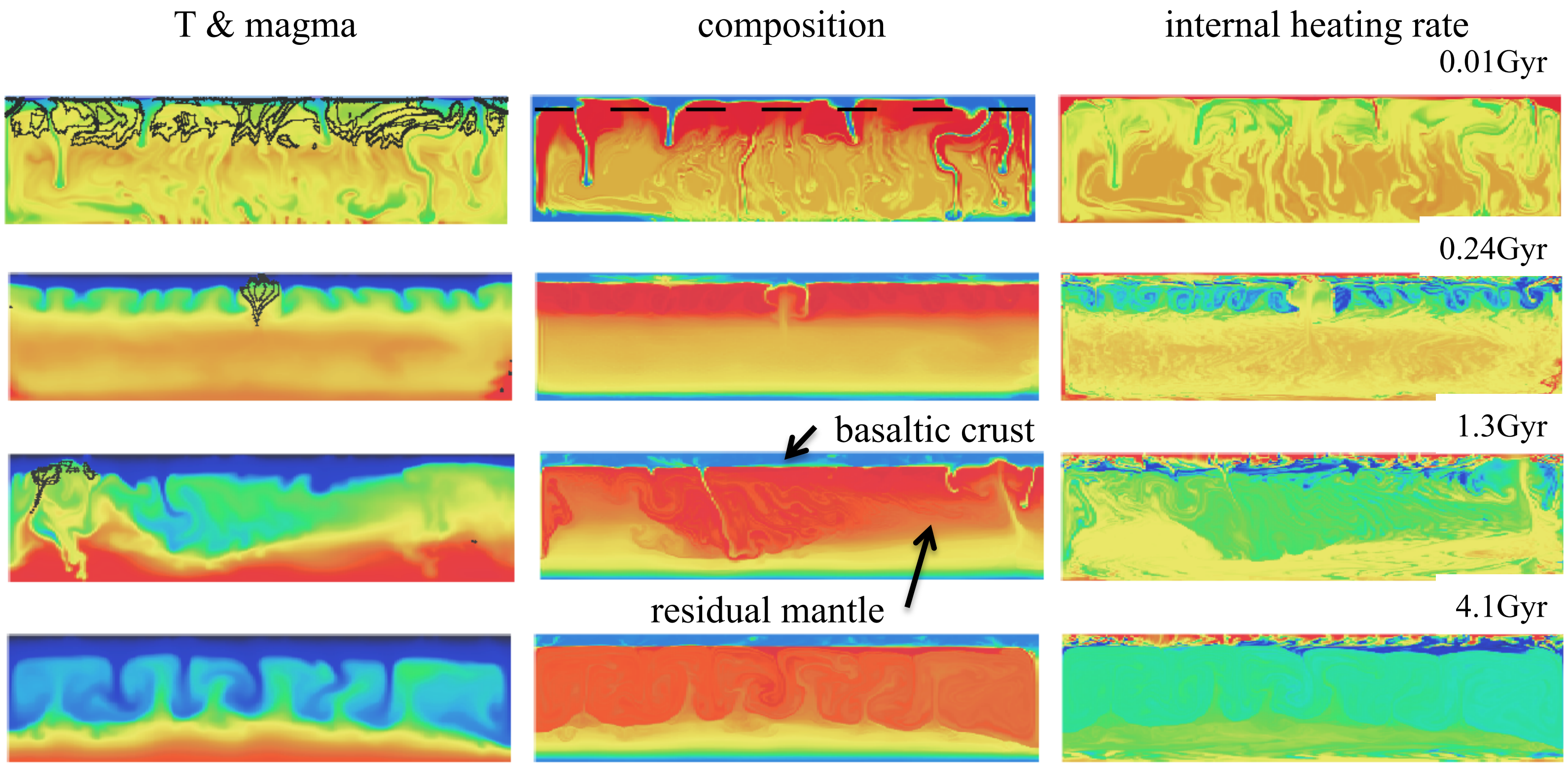


the Mantle evolution in Mars;
the weak MMU feedback + plume magmatism

火星の地形

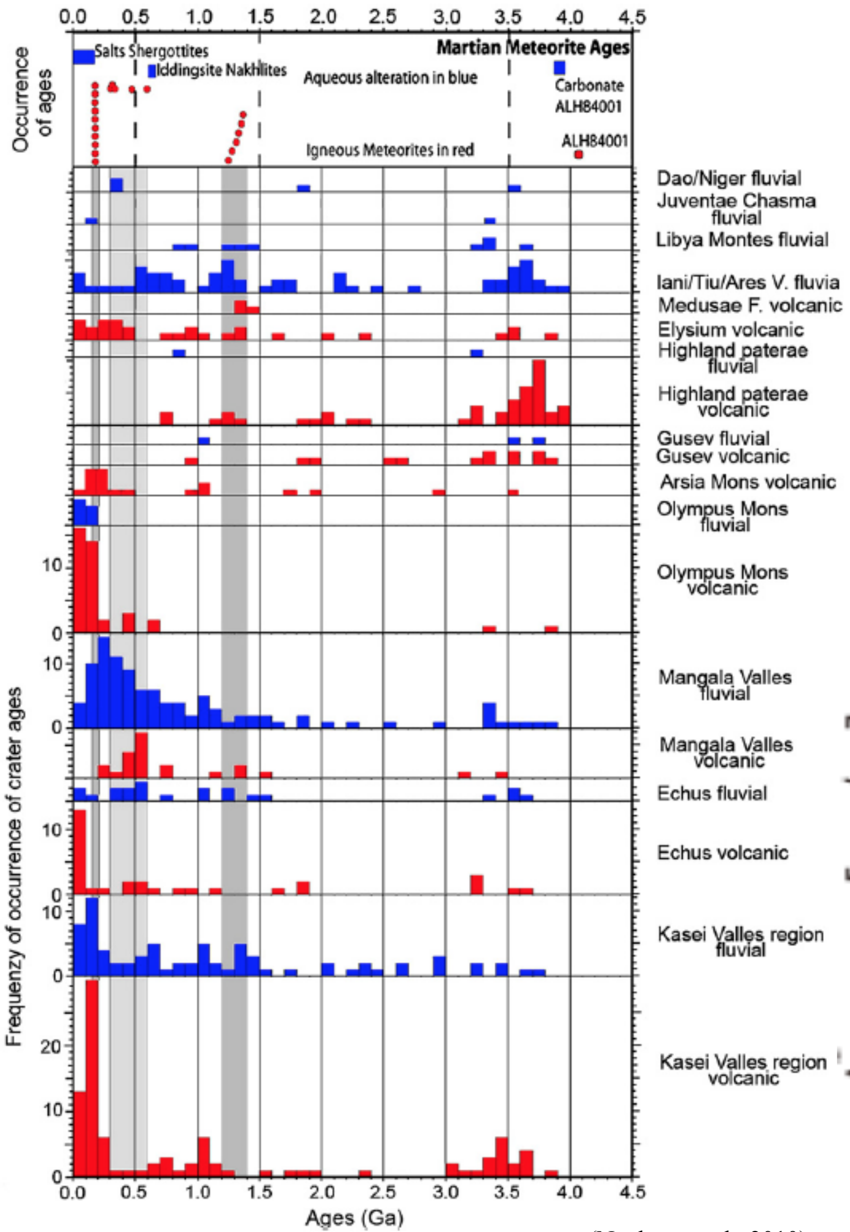


(Wiekzorek, 2007)

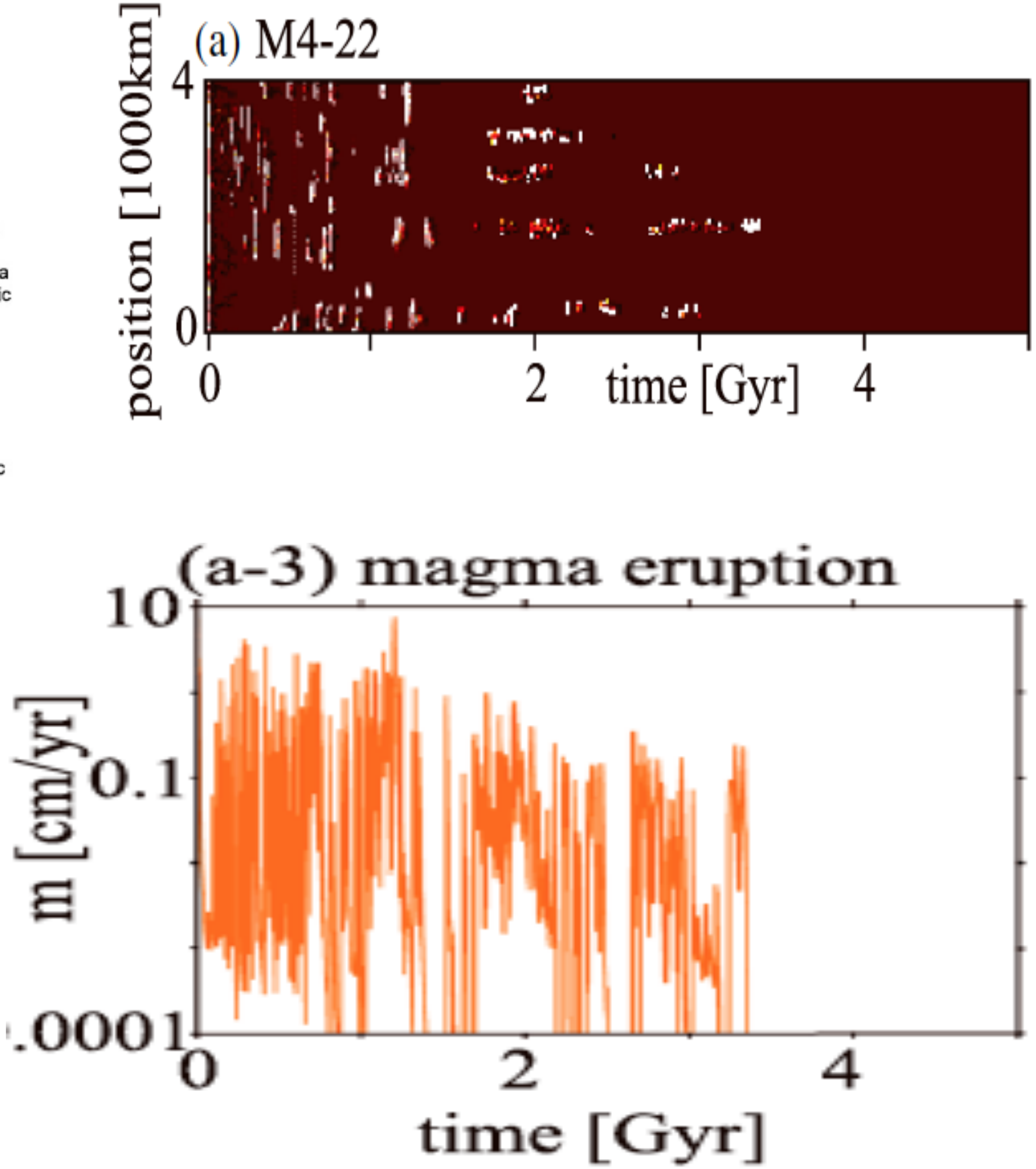


(Ogawa & Yanagisawa, 2011)

time series of magmatism



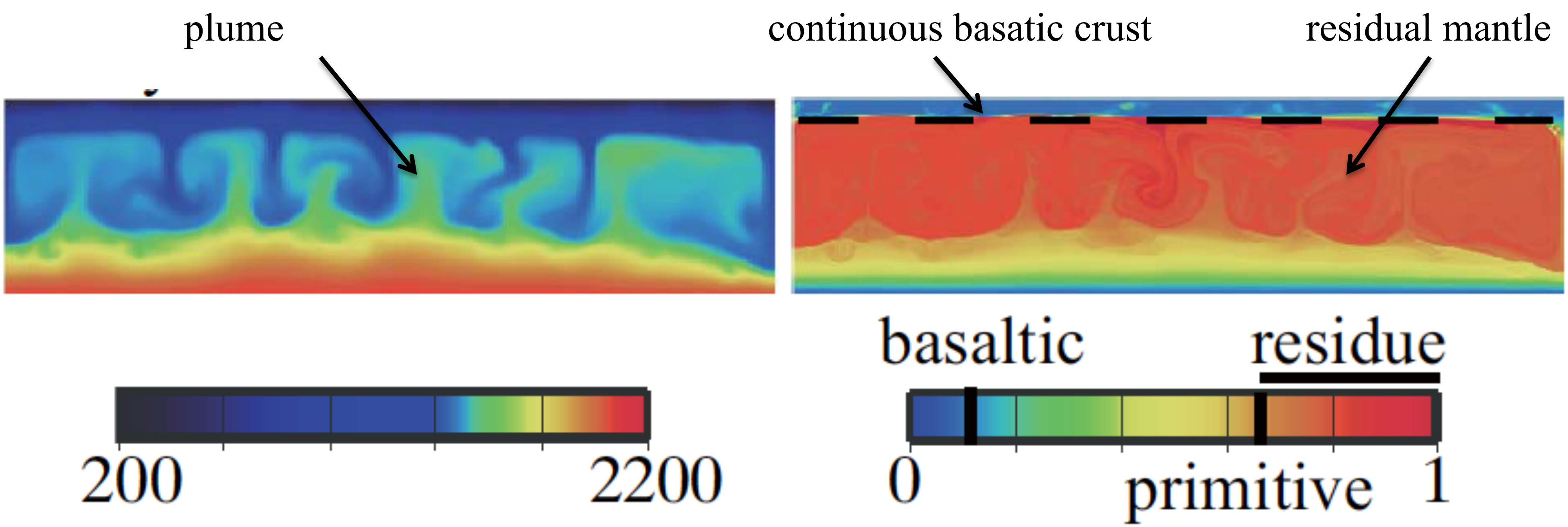
(Neukum et al., 2010)



(Ogawa & Yanagisawa, 2014)

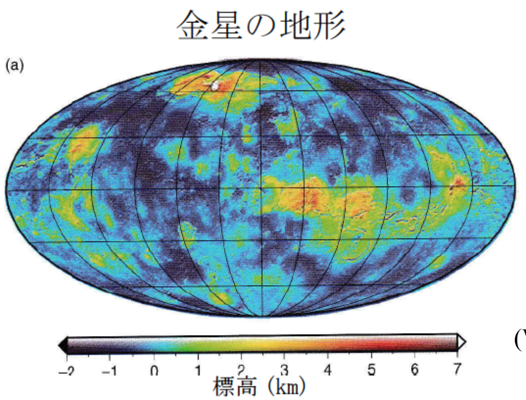
predicted structure of the Martian mantle & the crust more homogeneous compared with the Moon

T-distribution compositional distribution

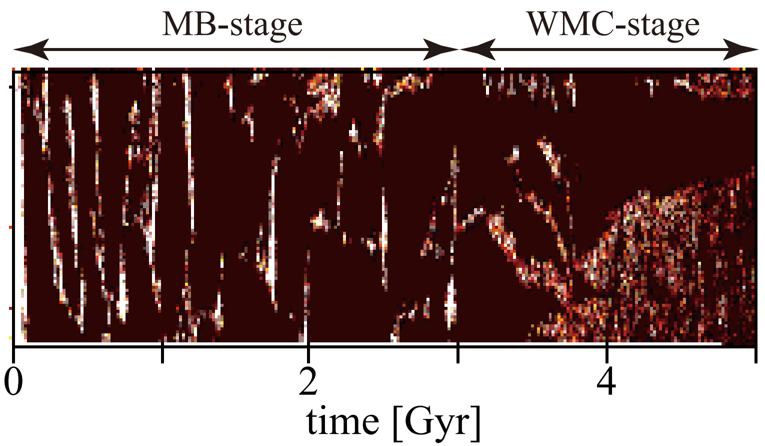


(Ogawa & Yanagisawa, 2011)

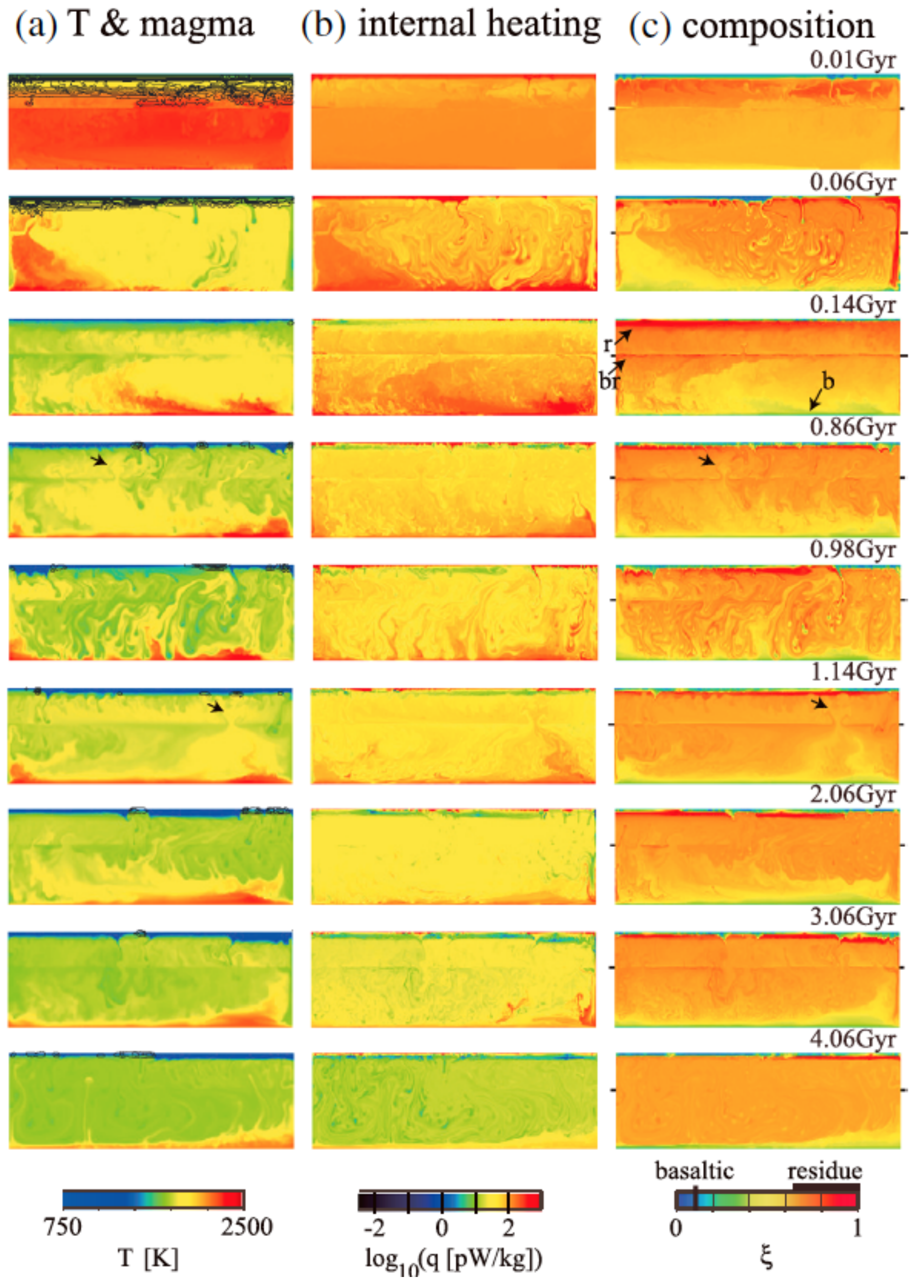
Two-stage mantle evolution in Venus
strong MMU feedback ➡strong mantle cooling+efficient stirring



(Wiekzorek, 2007)



(Ogawa & Yanagisawa, 2014)



three elementary processes of mantle evolution

(1)the MMU feedback;
  operates in Mars and larger planets,
  but does not in the Moon

(2) mantle busts due to the post spinel & garnet transitions;
  two-stage mantle evolution in Venus and the Earth.

(3) plate tectonics; peculiar to the Earth