Water & mantle evolution in Mars: a comparison with the Moon

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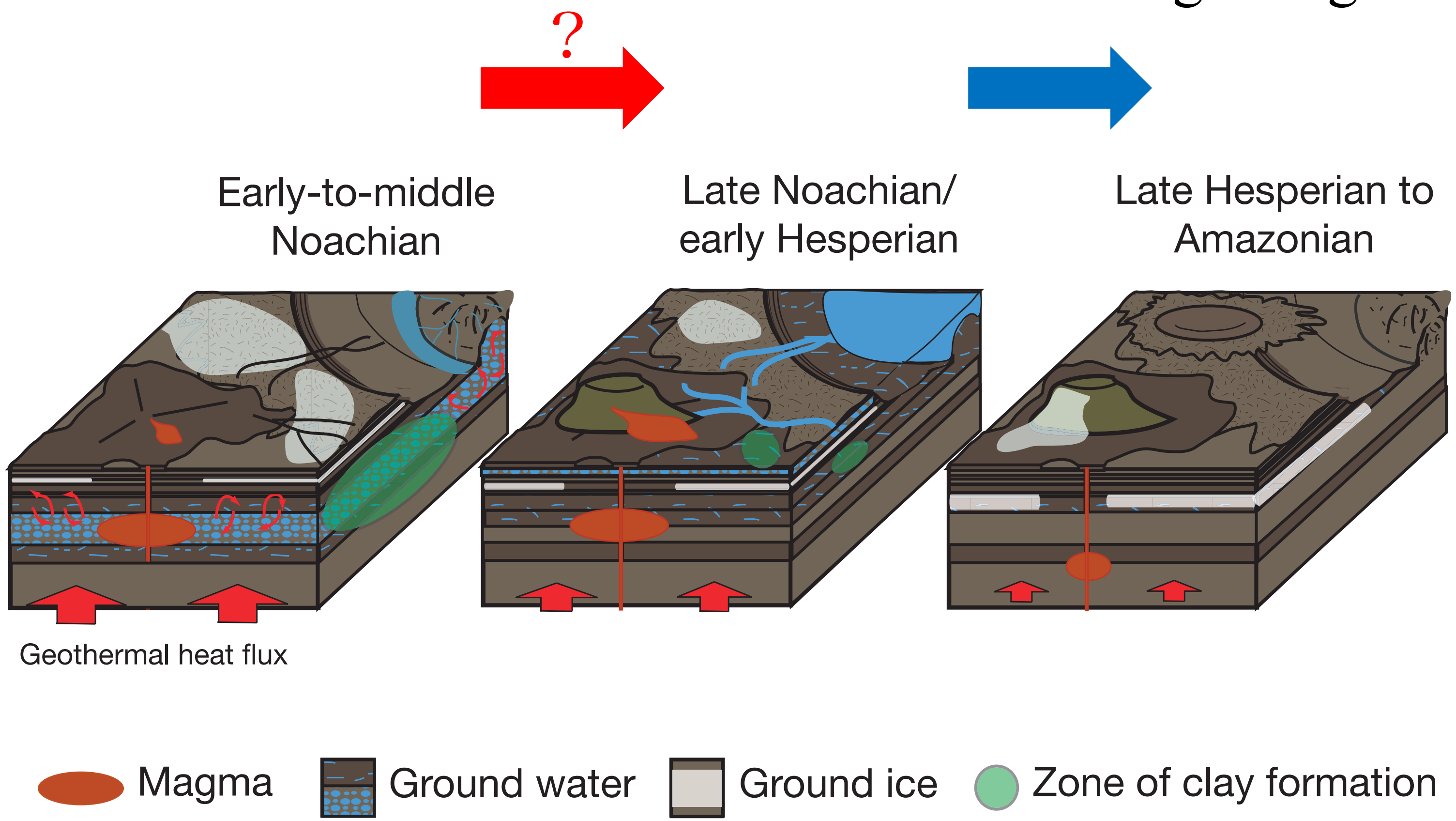
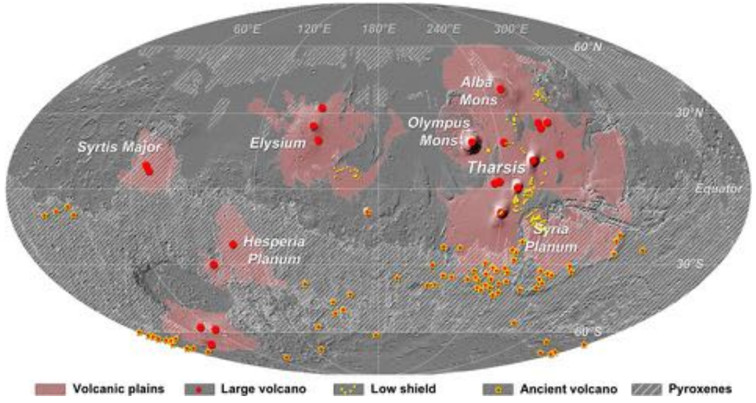
Recent exploration by landers has revealed the overall history of the Martian climate for the past 4 Gyrs: (1) Before the middle Noachian, the surface was rather arid, although there were hydrothermal activities within the crust. (2) Then the surface became more temperate and an ocean developed in the late Noachian to early Hesperian, about 3.7 Ga, but (3) became again colder and more arid since the middle Hesperian. Water-supply to Mars by the Late Heavy Bombardment (LHB) has been invoked to explain the temperate climate at around 3.7 Ga in the literature. Crater-chronology on the Moon, however, suggests that the flux of meteorite was only moderately elevated at most during an extended period of 3.8 to 4.2 Ga. Here, I suggest that the climate of Mars has closely followed its history of outgassing by magmatism, based on a numerical model of a coupled magmatism-mantle convection system. The model suggests that the mantle of Mars that is assumed to have started hot and wet has evolved in four stages: (a) An extensive magmatism caused by vigorous mantle convection formed the crust and made the mantle compositionally stratified in the first few tens of million years. The magmatism extracted about 80 % of the water that the mantle initially contained, although the deep mantle retained some initial water. (b) The compositional stratification suppressed mantle convection, and magmatism ceased for the next several hundred million years. (c) Then partially molten plumes episodically ascended from the deep mantle to the surface to cause magmatism and outgassing of the water retained in the deep mantle. (d) However, the magmatism waned, as the magmatism itself extracts heat producing elements in the deep mantle. The dormant period of Stage (b) may correspond to the rather arid period before the middle Noachian, while the temperate climate at around 3.7 Ga may be a consequence of episodic outgassing of water caused by plume magmatism in Stage (c). The model also predicts that the crust of Mars was formed by an extensive magmatism caused by mantle convection and is different from the lunar crust that was formed by crystal fractionation in the magma ocean.

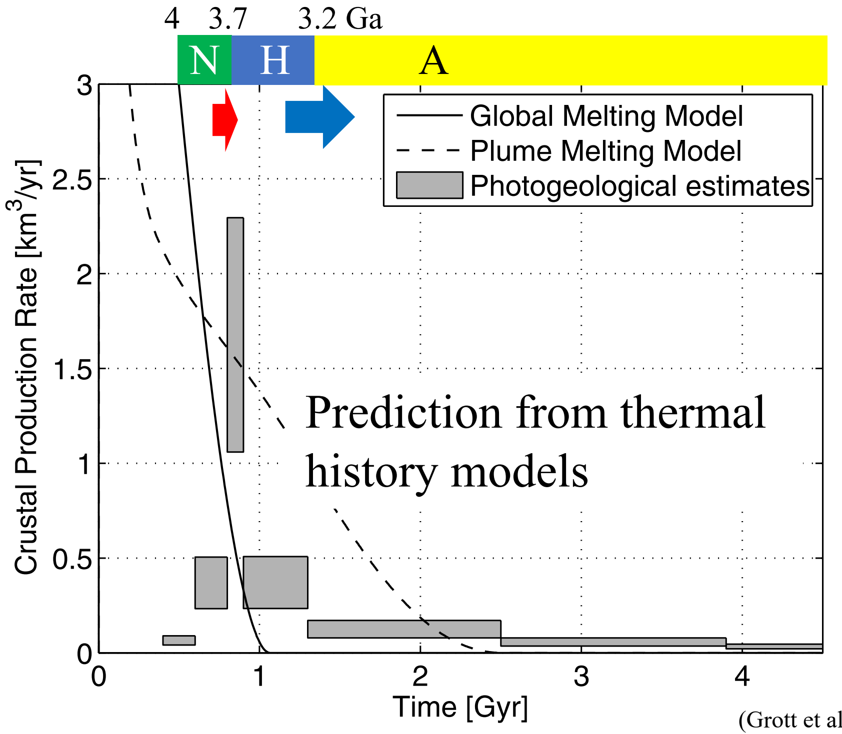
The history of surface environment on Mars

decline in outgassing & atmospheric escape ?



(Ehlmann et al., 2011)

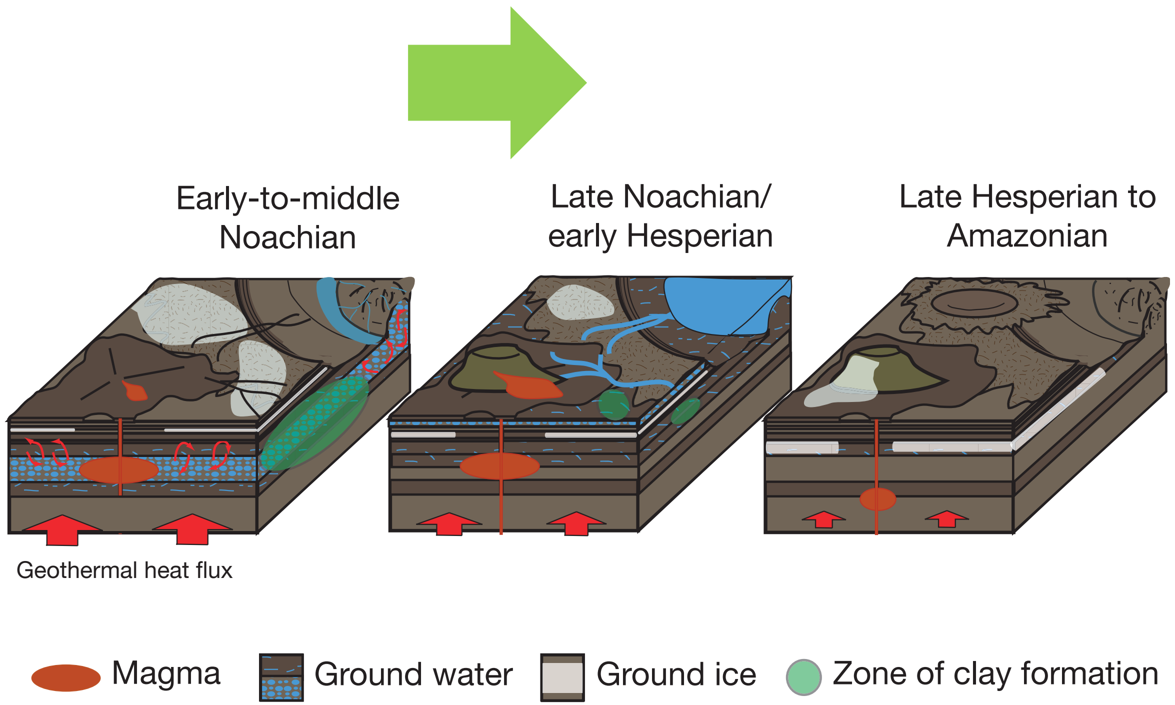




(Grott et al., 2013)

Water-supply by late heavy bombardment?

Figure 1 of Bottke, W.F., Norman, M.D. (2017) The late heavy bombardent, *Ann. Rev. Earth Planet. Sci.*, **45**, 619-647



(Ehlmann et al., 2011)

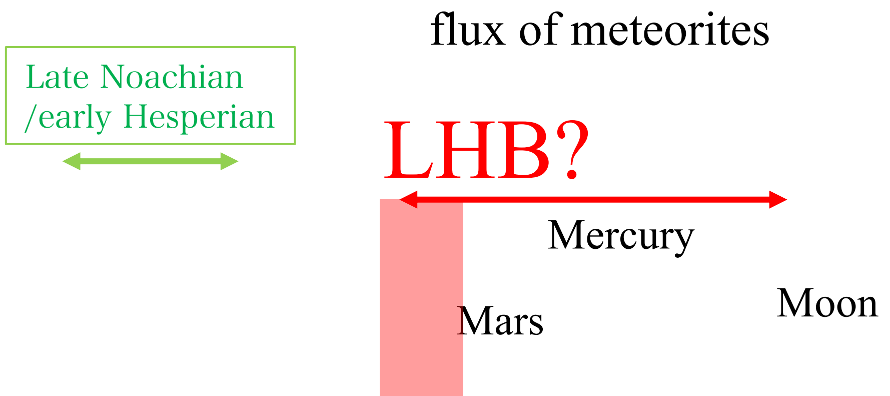


Figure 9 of "Werner, S.C. (2014)Moon, Mars, Mercury: Basin formation ages and implications For the maximum surface age and the migration of gaseous planets, *Earth Planet. Sci. Lett.*, **400**, 54-65"

late veneer prior to Borealis formation (> 4.4 Ga)?

A critical issue for future lunar exploration

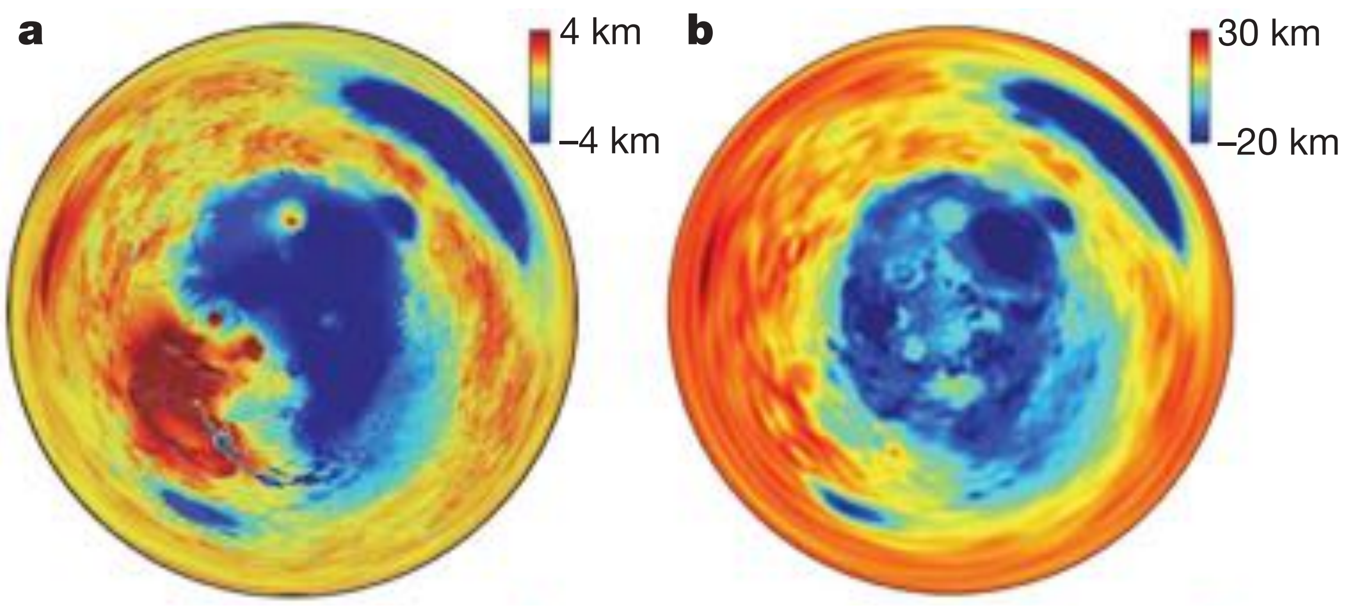
Highly siderophile elements in Mars by late veneer

Figure 8 of Walker, R.J. (2009) Highly siderophile elements in the Earth, Moon and Mars: Update and implications for planetary accretion and differentiation *Chemie der Erde,* ***69, 101-125***

No crustal recycling after Borealis

topography

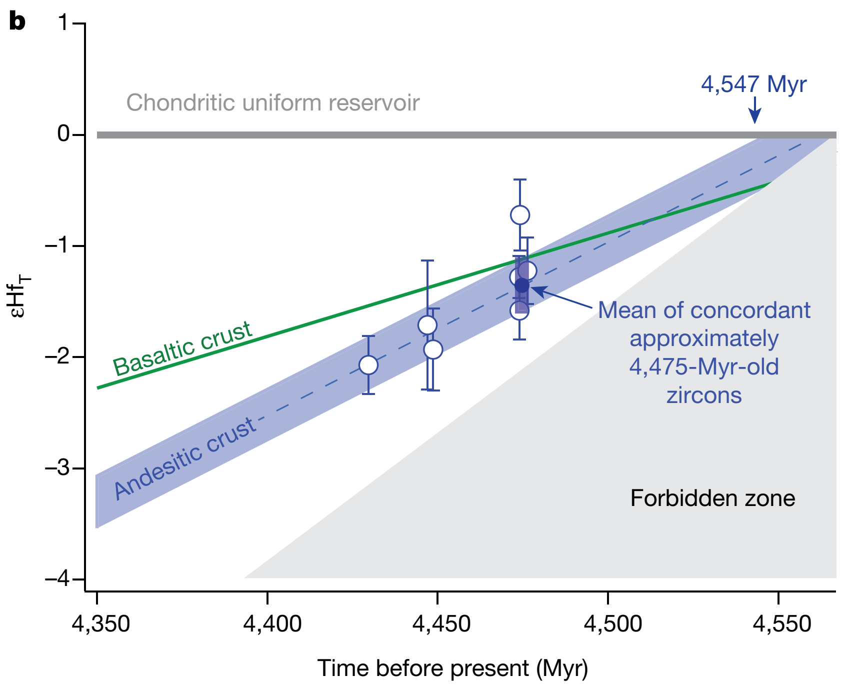
Moho-depth



(Andrew-Hanna et al., 2009)

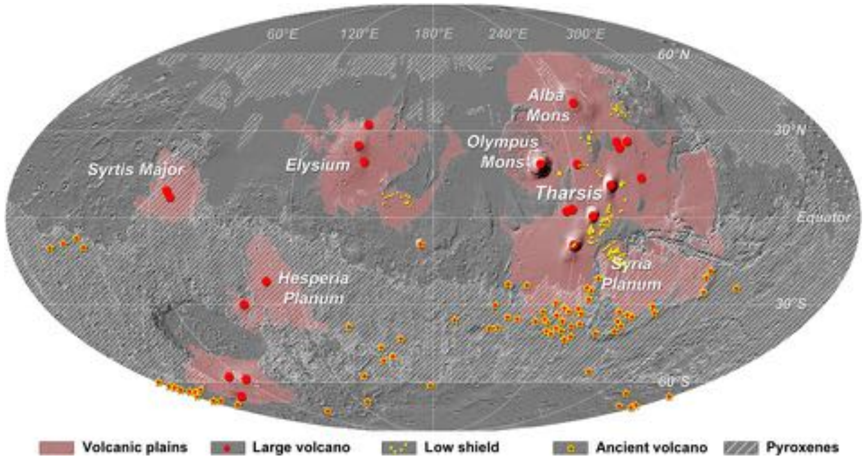
A direct consequence of the history of magmatism?

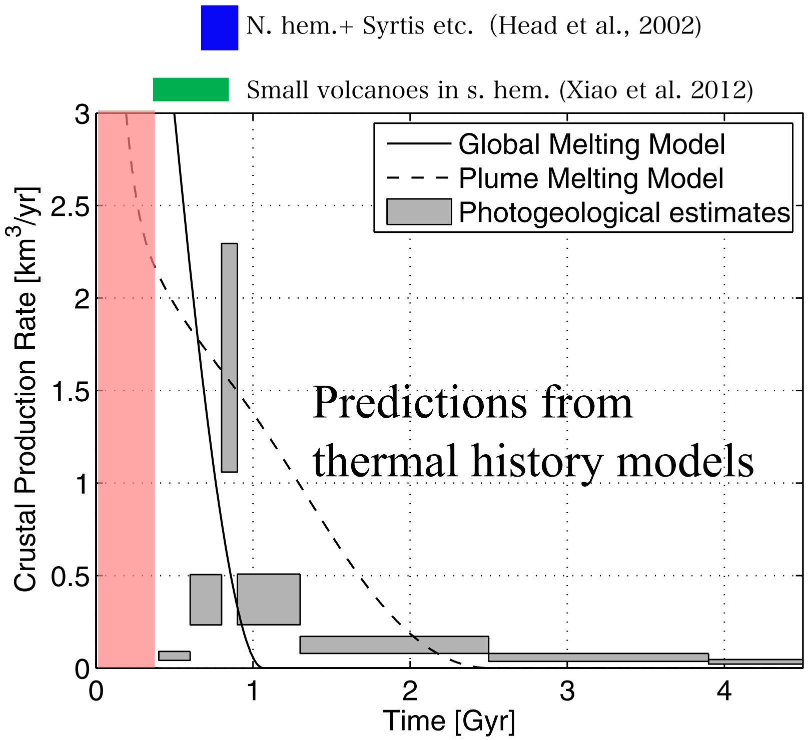
The crustal formation within 20 Myr



(Bouvier et al., 2018)

Resurfacing by subsequent early magmatism?



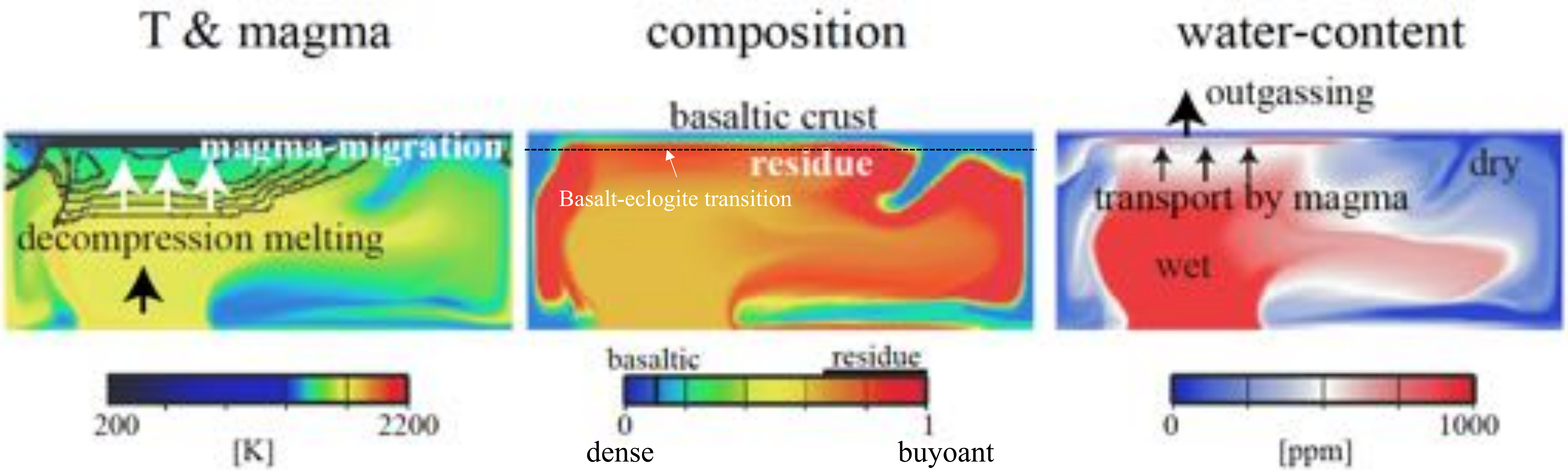


(Grott et al., 2013)

A numerical model of magmatism & mantle-convection with water-circulation

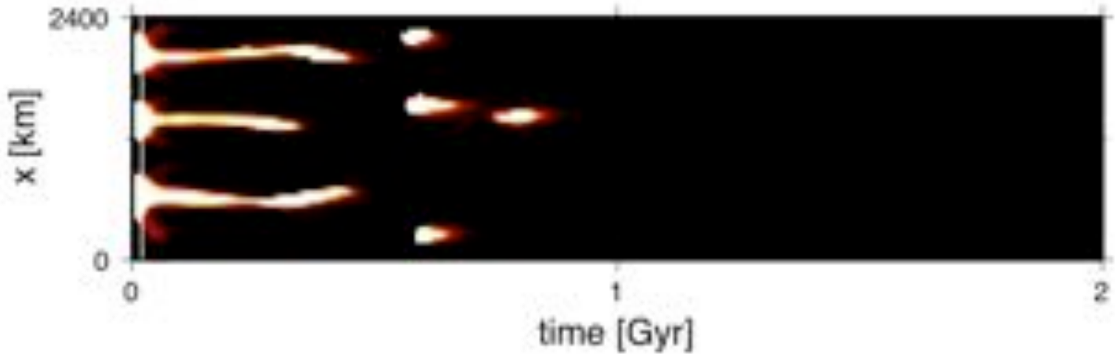
	Density in the mantle	melting temperature
basalt	high	low
residue	low	high

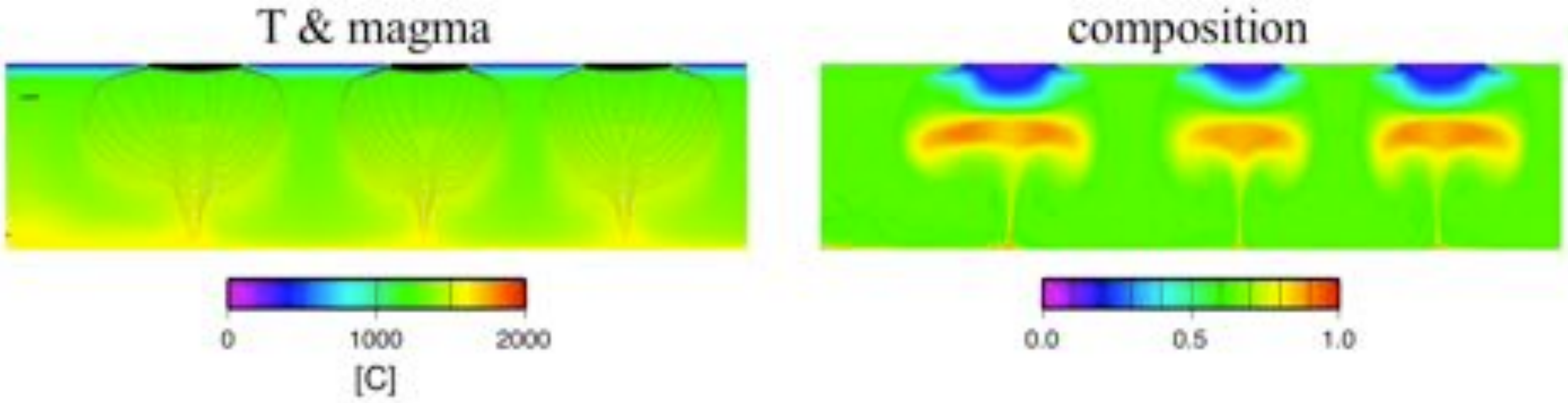
Reduction of the solidus-temperature & viscosity by water



Mantle-differentiation by magmatism in small planets (e.g. the Moon)

Figure 1 of "Morota, T. et al. (2011) Timing and characteristics of the latest mare eruption on the Moon, *Earth Planet. Sci. Lett.*, **302**, 255-266



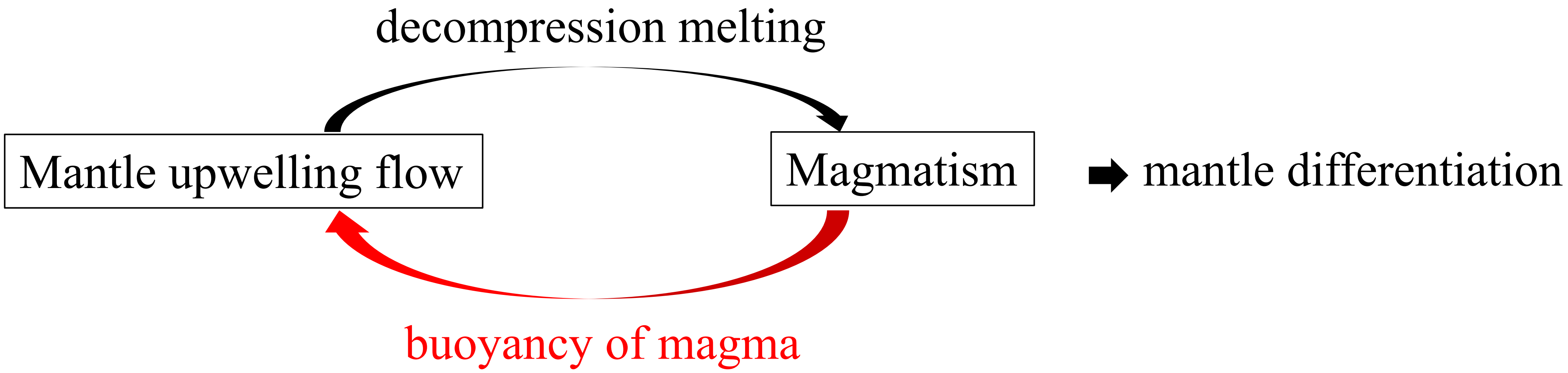


Extrapolation to Mars

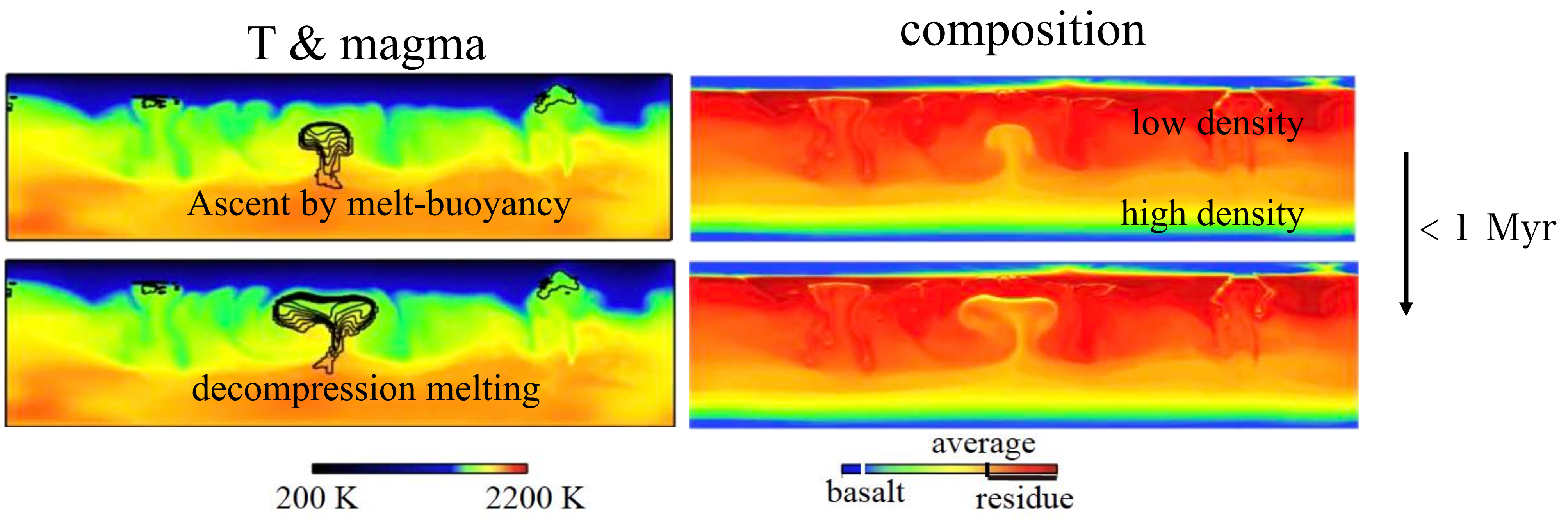
deeper & wetter mantle: larger d^3/η ($\propto$ Rayleigh number)

↓

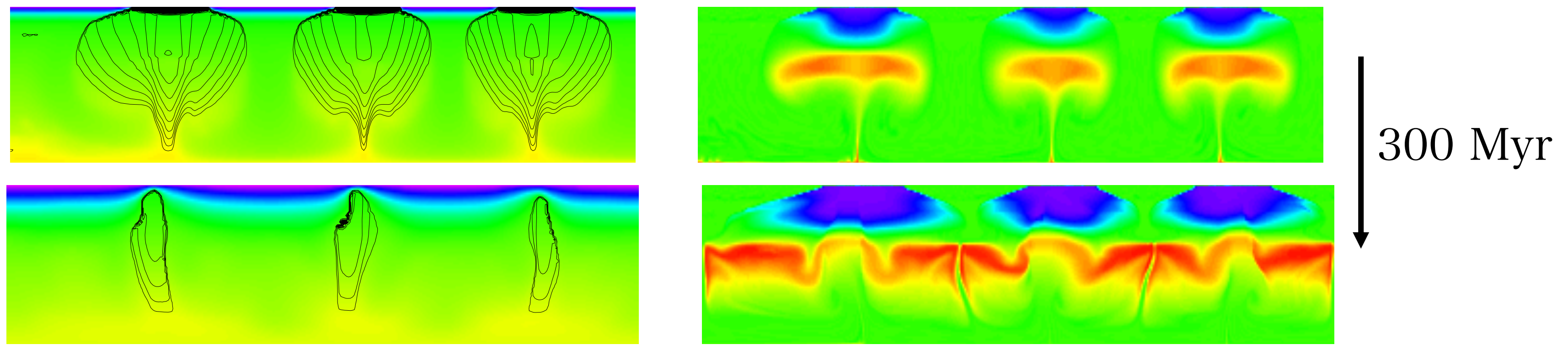
the magmatism-mantle upwelling (MMU) feedback



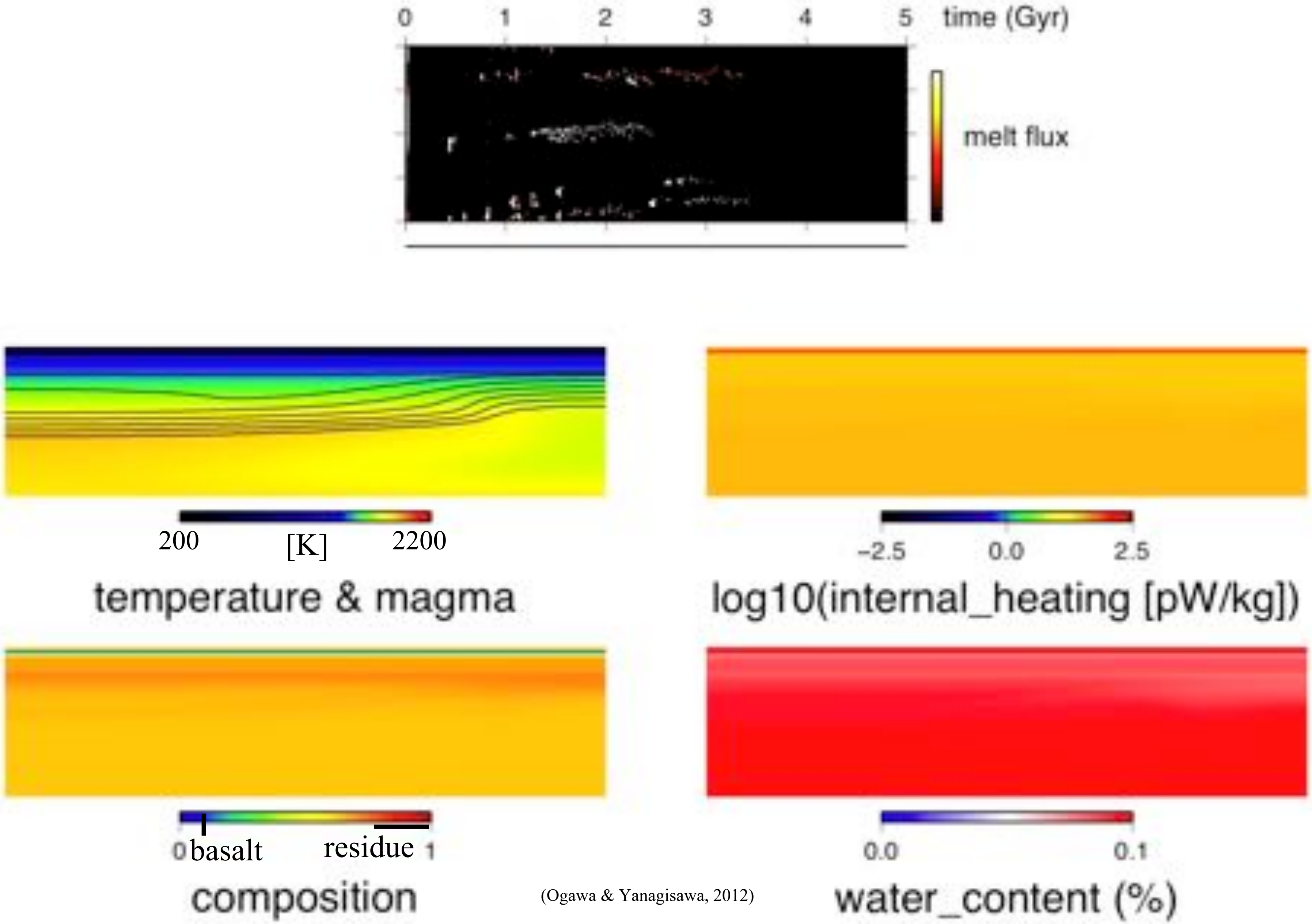
With the MMU feedback: Mars



Without the MMU feedback: the Moon



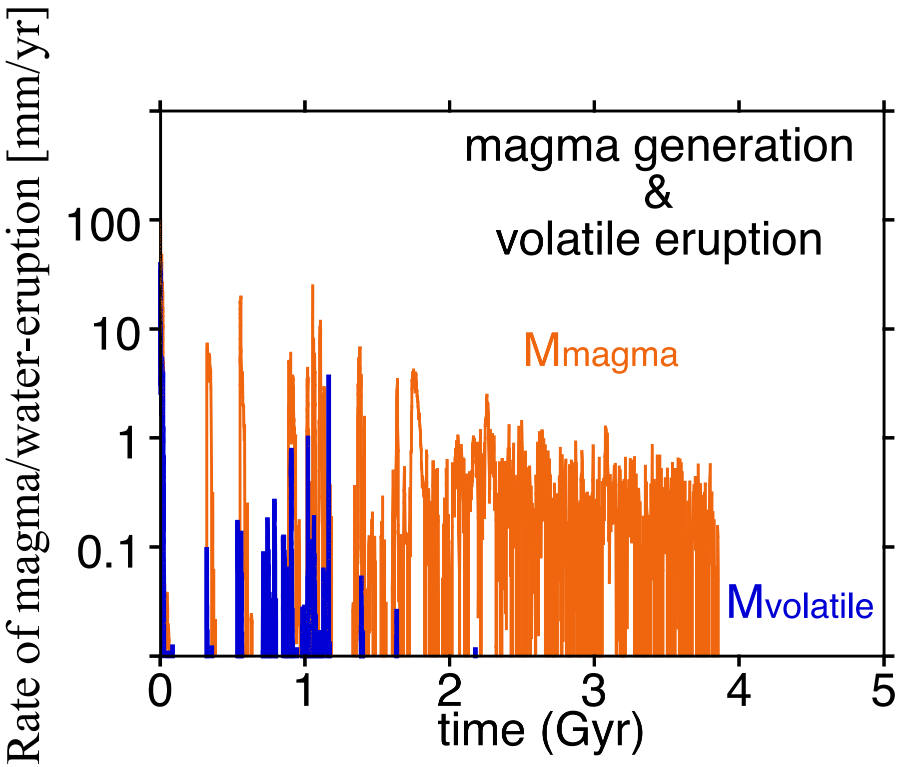
wetmars S7−18−1 (0.18 My)

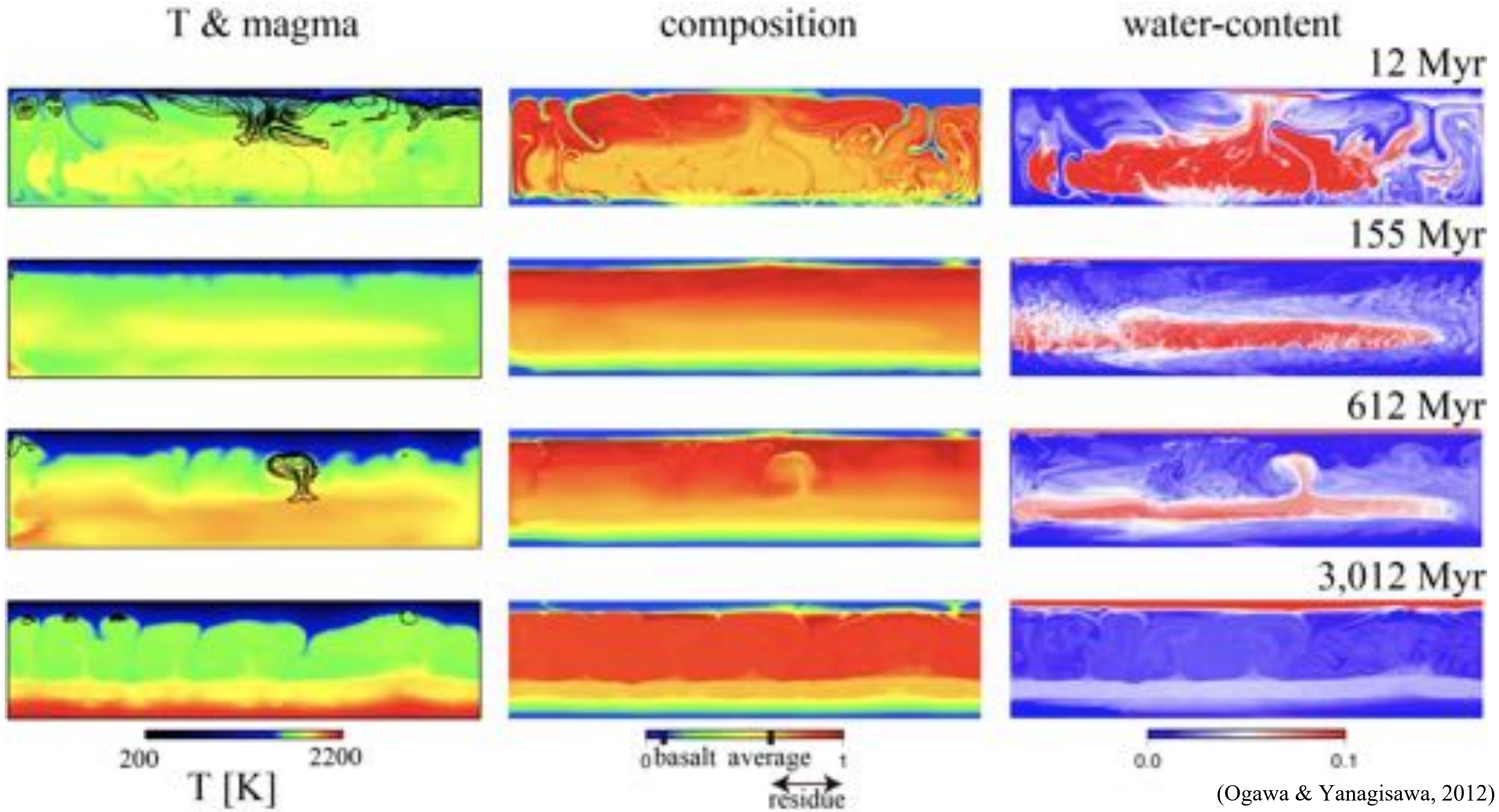


(Ogawa & Yanagisawa, 2012)

The four stages of the mantle evolution

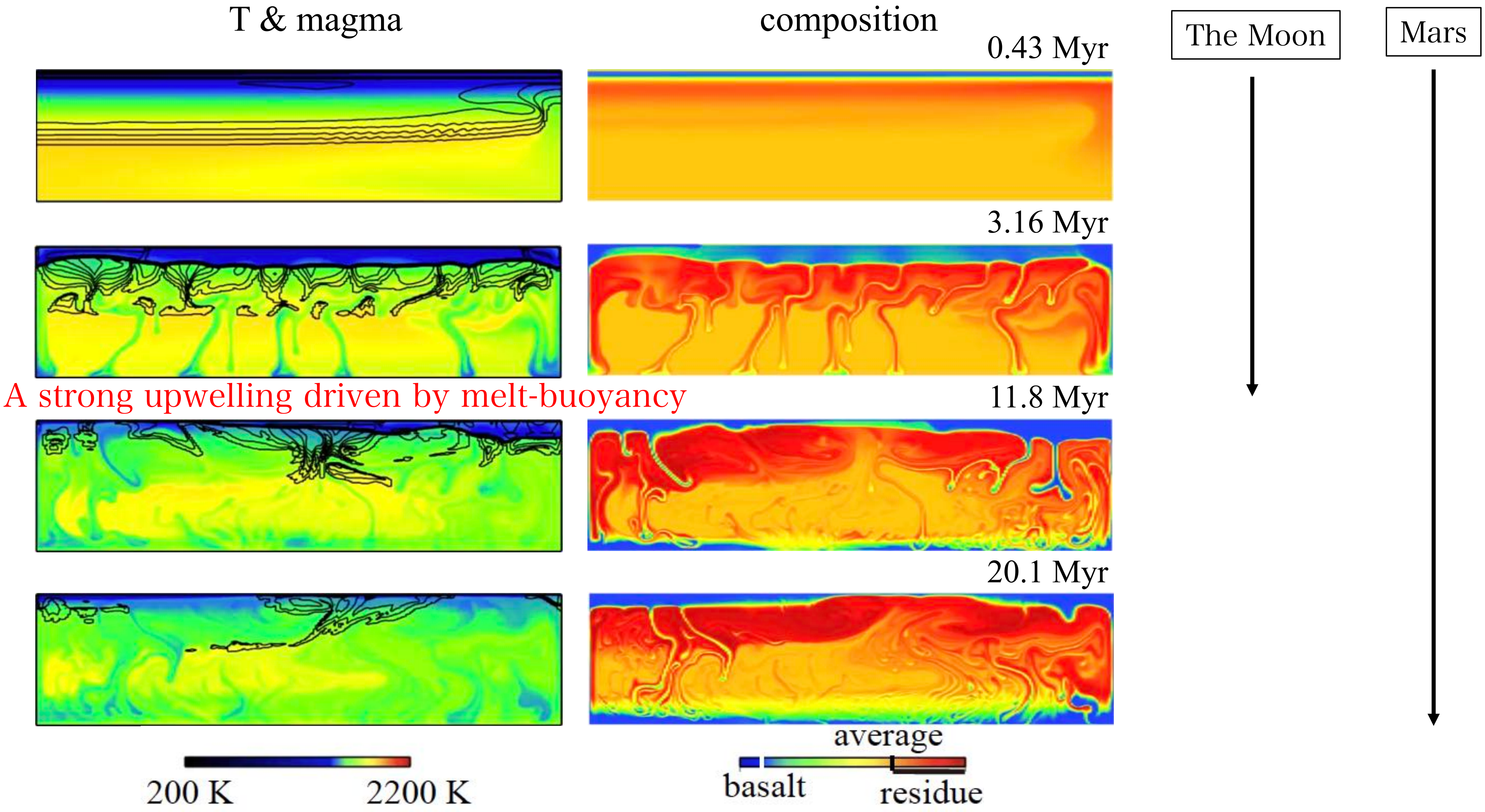
(1) crustal formation & mantle layering within 20 Myr
(2) the dormant era
(3) episodic plume magmatism & degassing
(4) decline of magmatism & degassing





(Ogawa & Yanagisawa, 2012)

crustal formation: the MO-crust → resurfacing by the MMU feedback



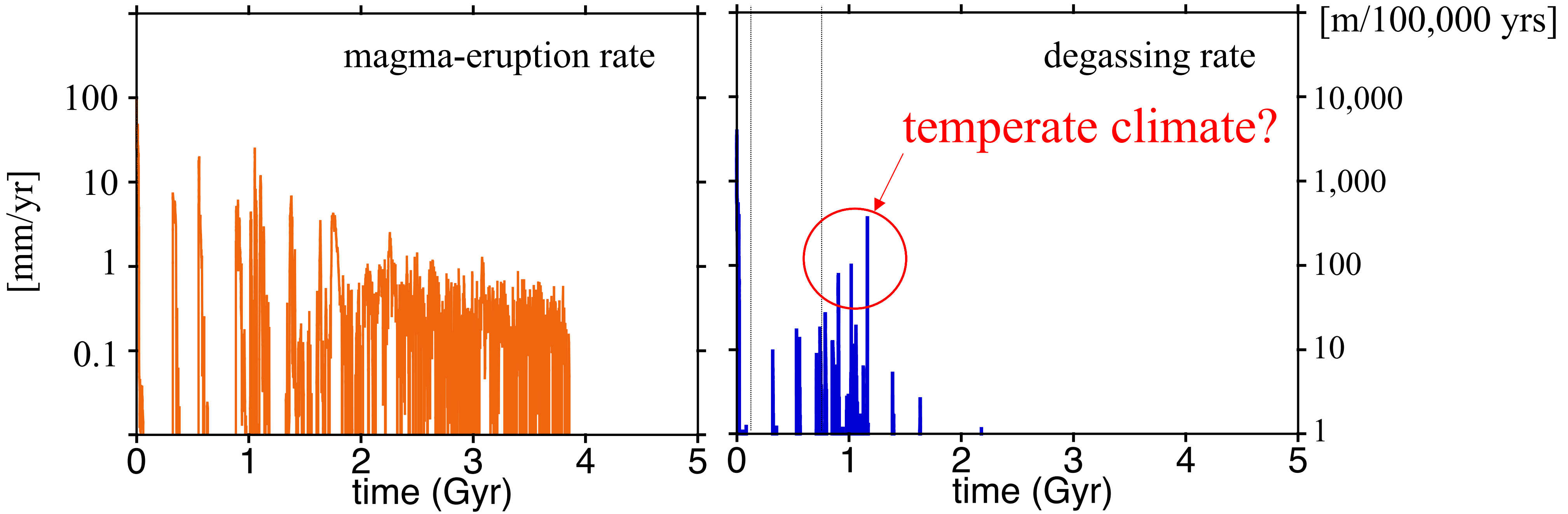
Extrapolation from the Moon to the Earth

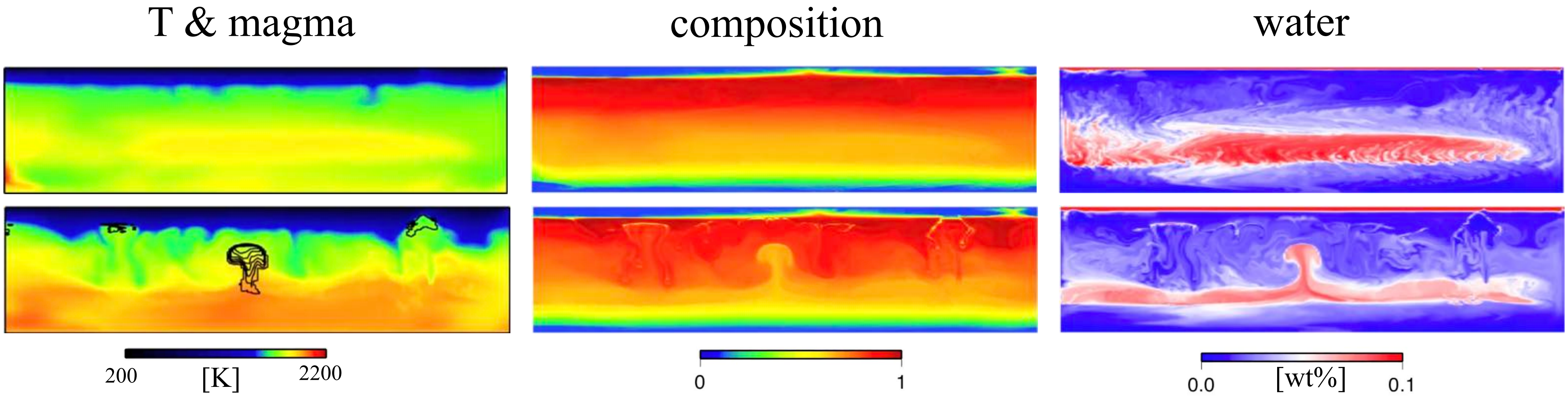
Why are vestiges of the MO so scarce in the Earth?

The Moon: by the MO-curst?

Mars: by flood basalt?

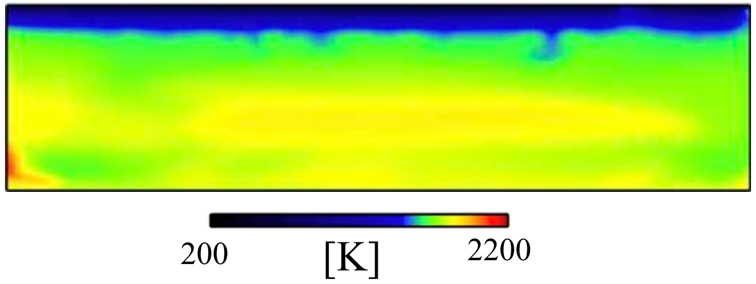
The dormant era & the episodic degassing by plume magmatism



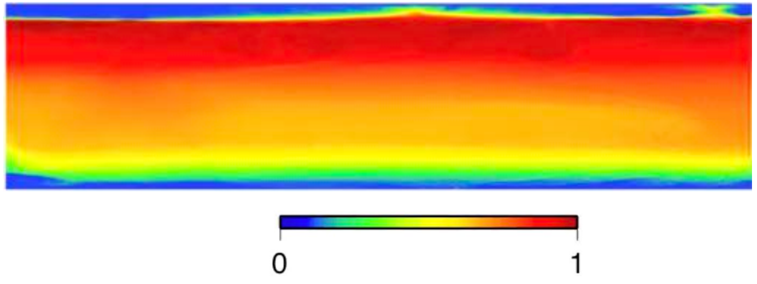


The dormant era?

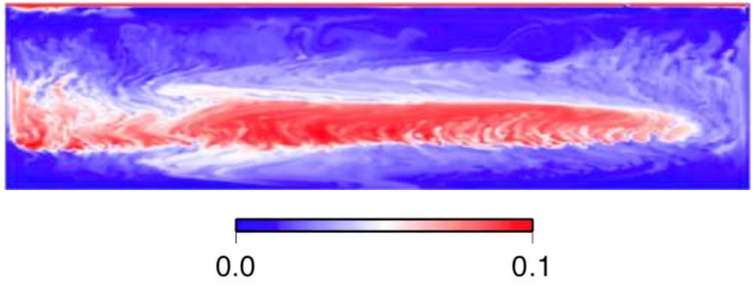
T & magma

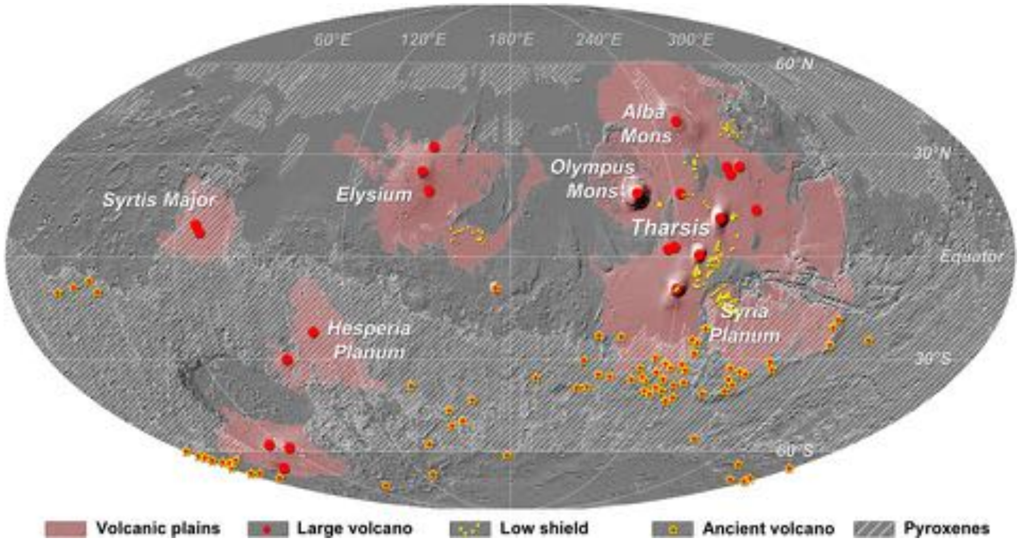


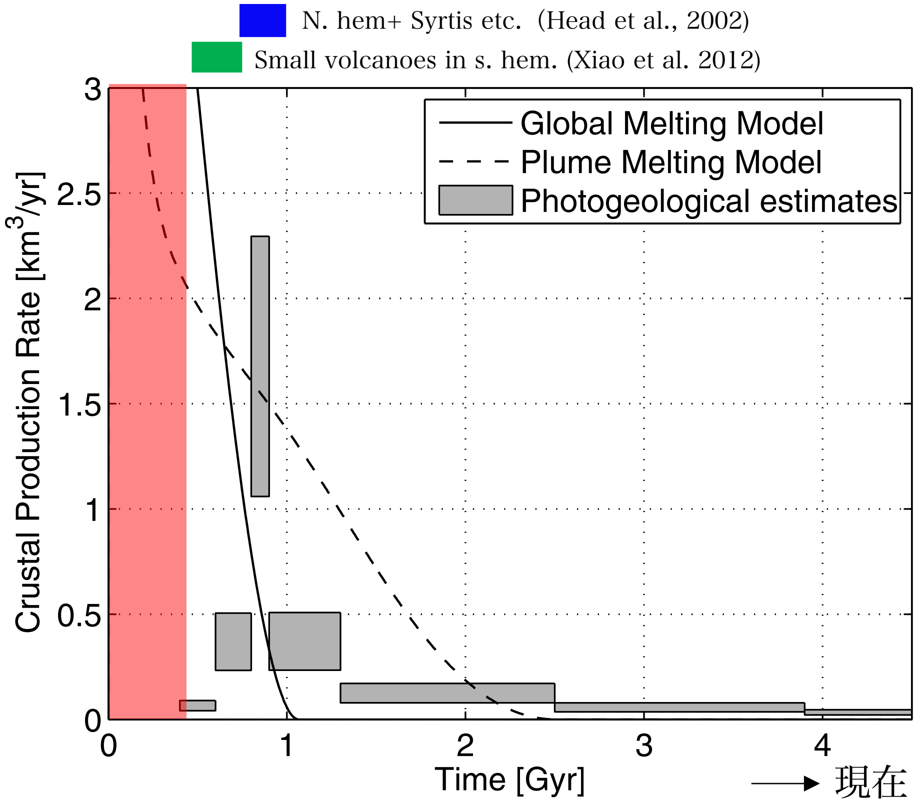
composition



water



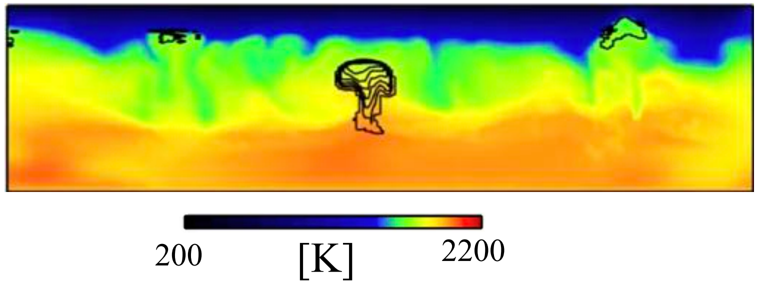




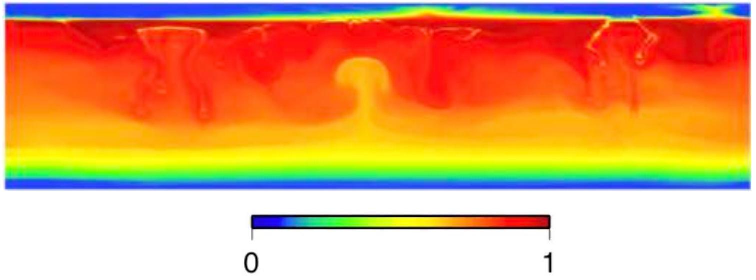
(Grott et al., 2013)

episodic magmatism ⇒ episodic temperate environment?

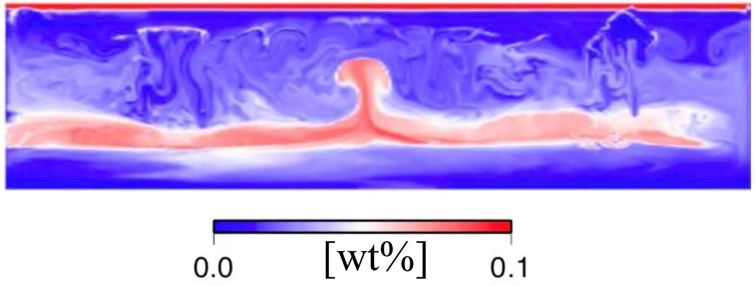
T & magma



composition

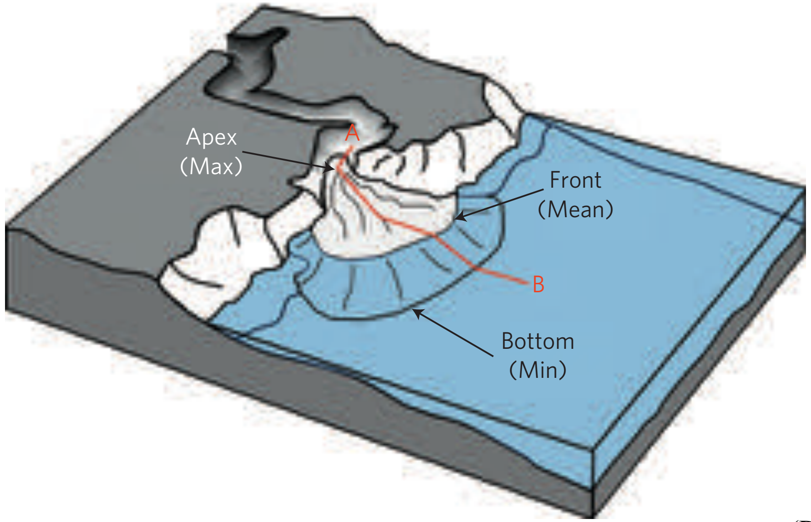


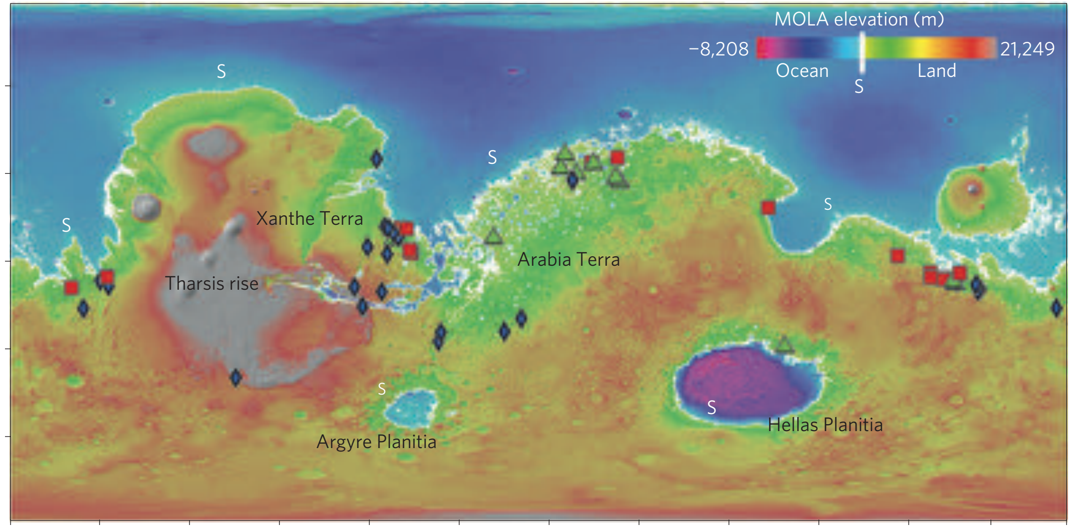
water



delta ⇒ more than 0.1 Myr

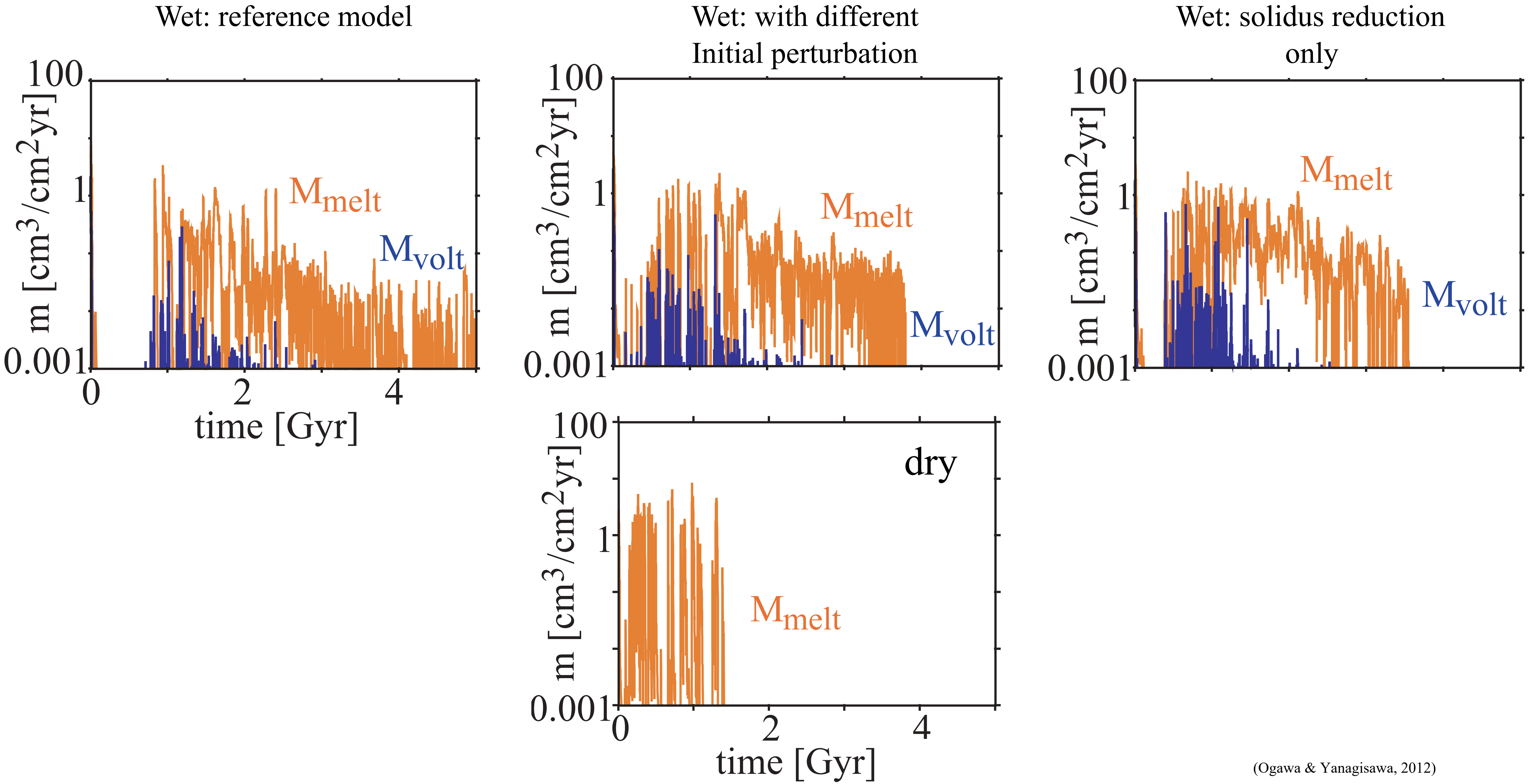
analyses of clay minerals ⇒ less than 1 Myr





(Di Achille & Hynek, 2010)

The effects of water on mantle evolution



(Ogawa & Yanagisawa, 2012)

Mantle evolution ⇒ surface environment

water supply by episodic plume magmatism?

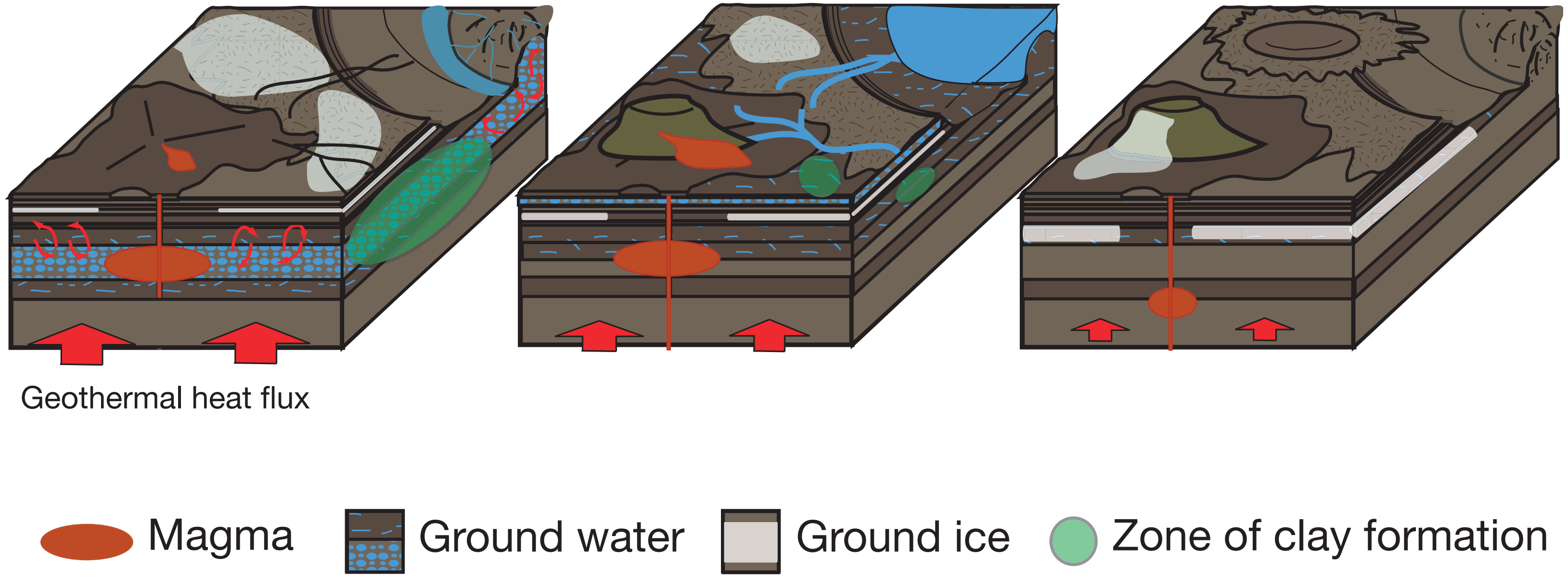
the dormant era?

decline of magmatism?

Early-to-middle Noachian

Late Noachian/ early Hesperian

Late Hesperian to Amazonian



(Ehlmann et al., 2011)