Comparative magmatism-mantle convection systems: Implication for outgassing history

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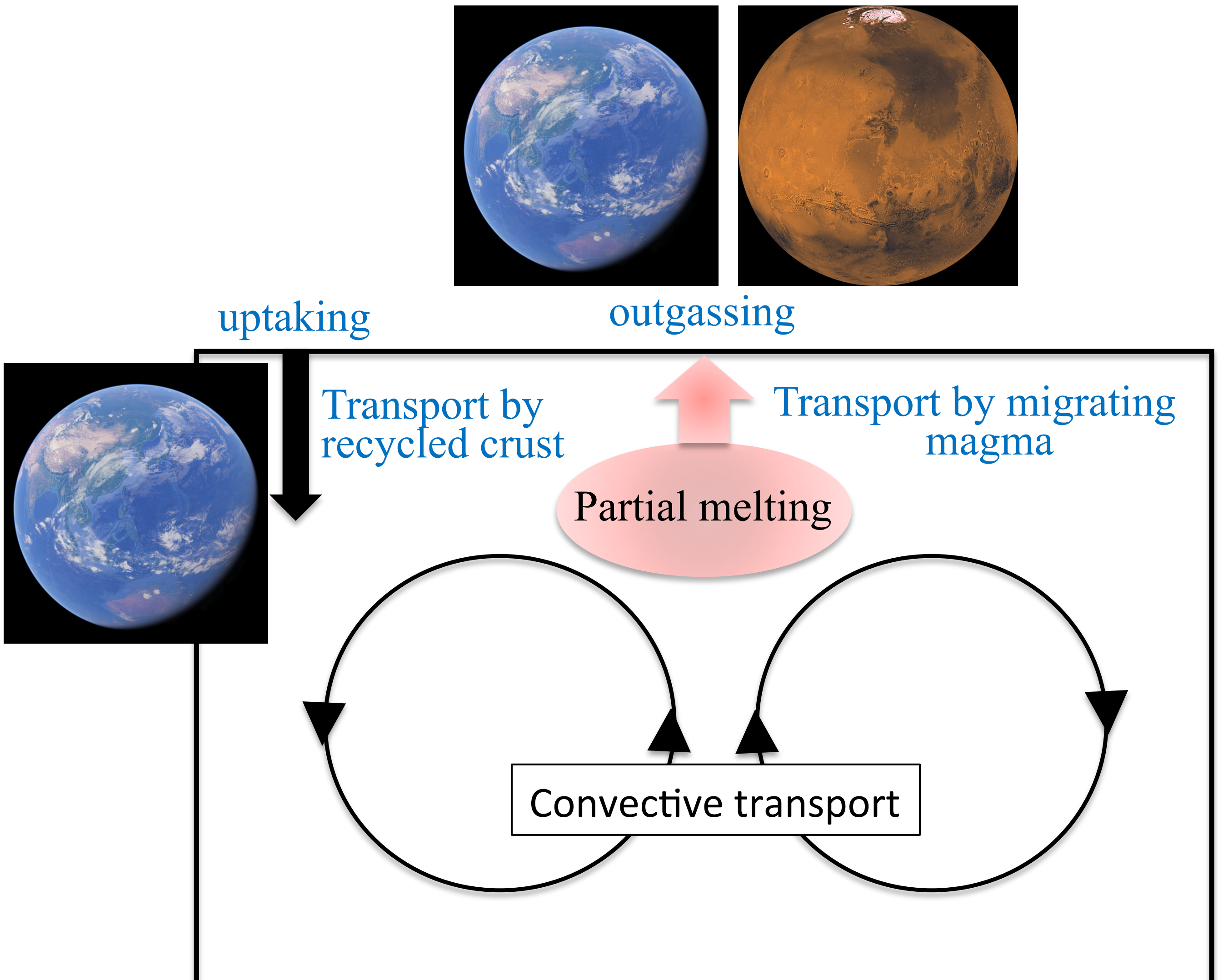
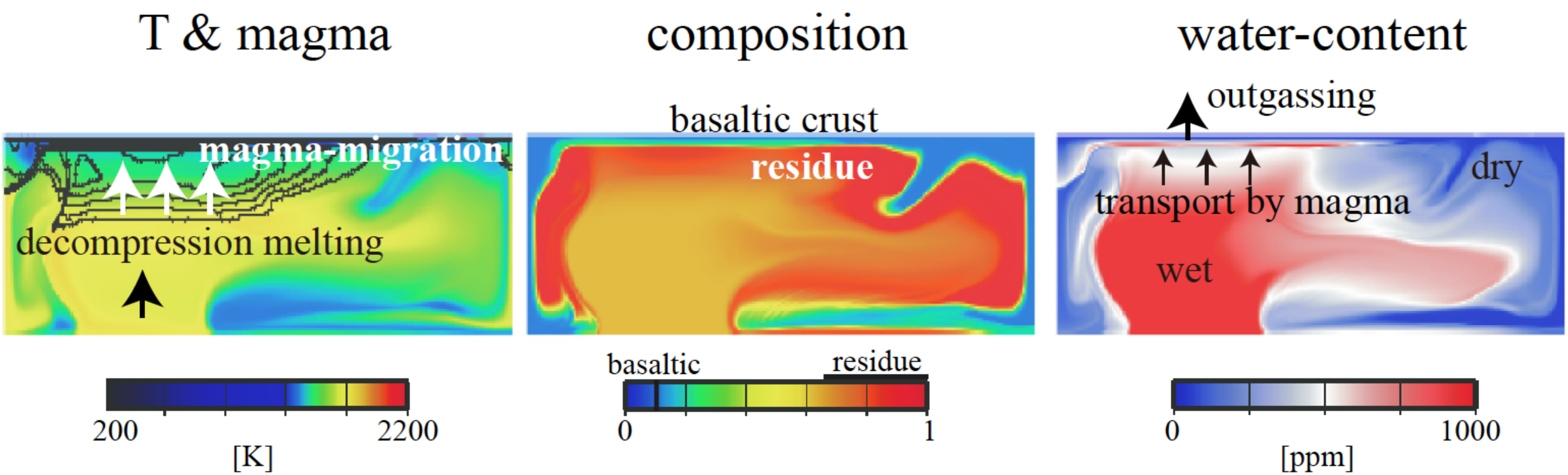
Abstract:

I present a numerical model of a coupled magmatism-mantle convection system to discuss how magmatism and mantle convection exert control over water-circulation in the mantle of Mars and the Earth. In Mars and larger planets, the buoyancy of magma generated by a mantle upwelling flow enhances the upwelling flow itself. This magmatism-mantle upwelling (MMU) feedback makes magmatism vigorous and episodic, and also boosts mantle convection to efficiently stir the mantle. In Mars, an extensive magmatism caused by the assumed high initial temperature in the deep mantle extracts most of the water that the mantle initially contained, since the MMU-feedback enhances the magmatism. The magmatism also generates the basaltic crust, a layer of residue of the crust in the shallow mantle, and a layer of recycled basaltic crust along the core-mantle boundary (CMB); the water that still remains in the mantle mostly resides in the basal basaltic layer. After this initial extensive magmatism, plume magmatism further extracts the remaining water to exhaust it within 2 Gyr. The magmatism ceases by 4 Gyr, because the magmatism also extracts heat-producing elements (HPEs) from the mantle and concentrates them to the crust. In the Earth, two more elementary processes operate to dominate water-circulation in the mantle: plate tectonics and mantle burst, i.e. an episodic and massive flow of hot materials in the lower mantle into the upper mantle caused by the solid-solid phase transitions that occur at the top of the lower mantle. These two elementary processes let the Earth's mantle evolve in two stages: On the earlier stage where the mantle is strongly heated by HPEs, mantle bursts repeatedly takes place to cause a vigorous and episodic magmatism. The mantle is strongly stirred, and water is efficiently extracted from the mantle, if it is initially wet. As the HPEs decay, the mantle evolves into the later stage. Mantle bursts subside, and plate tectonics stably operates to cause ridge magmatism that induces large piles of recycled hot basaltic materials and so called slab graveyards on the CMB. The subducting slabs transport water to the basaltic piles, and the water-content in the lower mantle steadily increases with time.

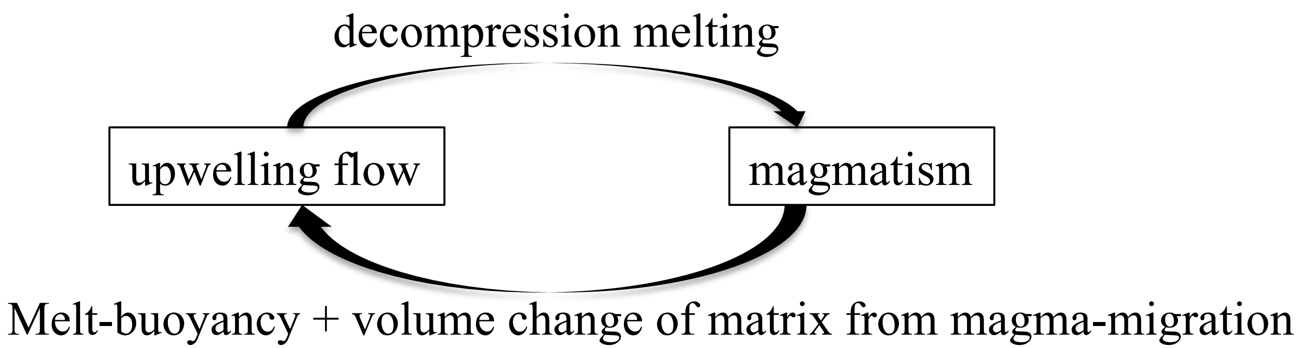
How do magmatism & mantle convection exert control over the water-circulation in Mars & Earth?

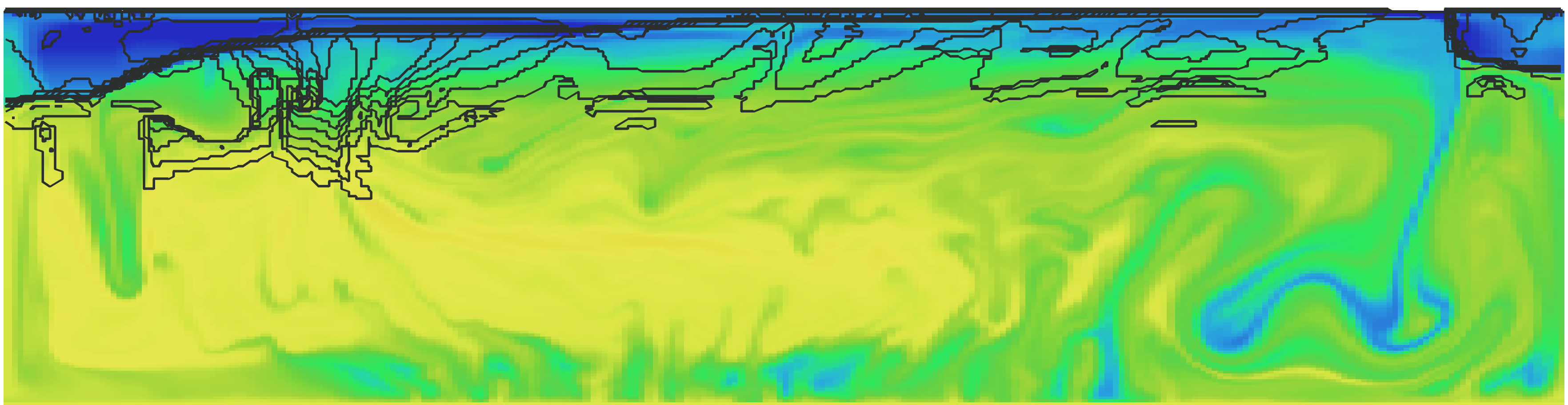


The adopted numerical model of water-circulation by magmatism & mantle convection



The Magmatism-Mantle Upwelling feedback



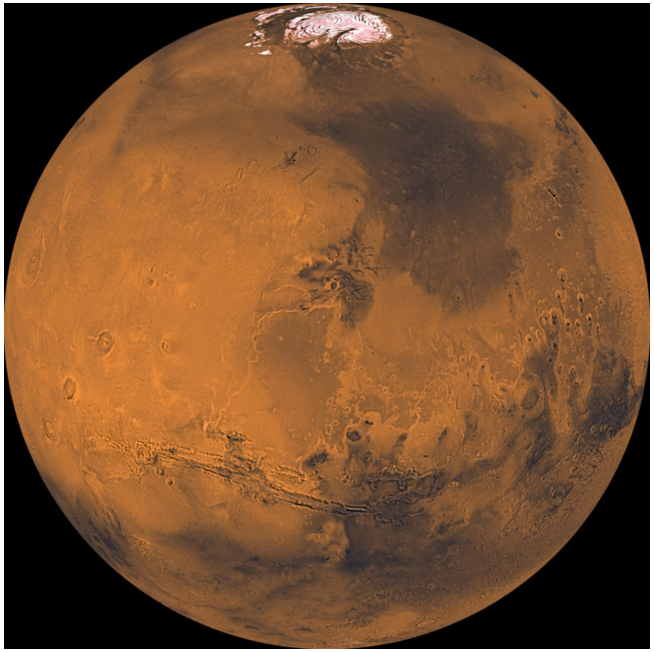


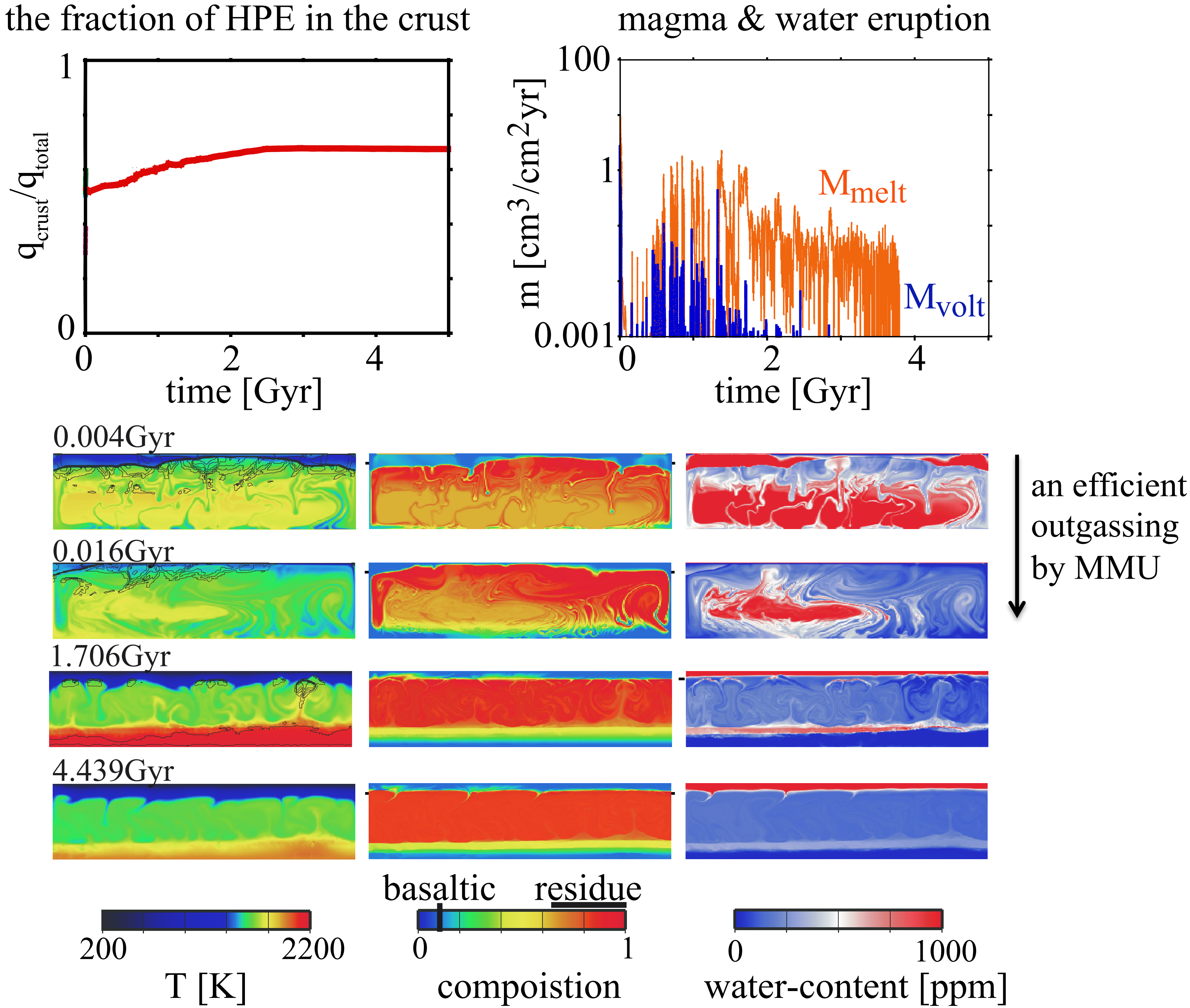
Strong and episodic upwelling flow with magmatism in Mars and larger planets.

Mars

The mantle is initially wet with the initial water-content = 1000 ppm.

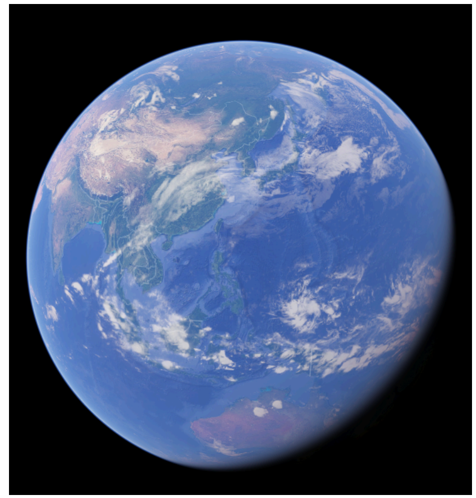
Degassing by magmatism & mantle convection





(Ogawa & Yanagisawa, 2012)

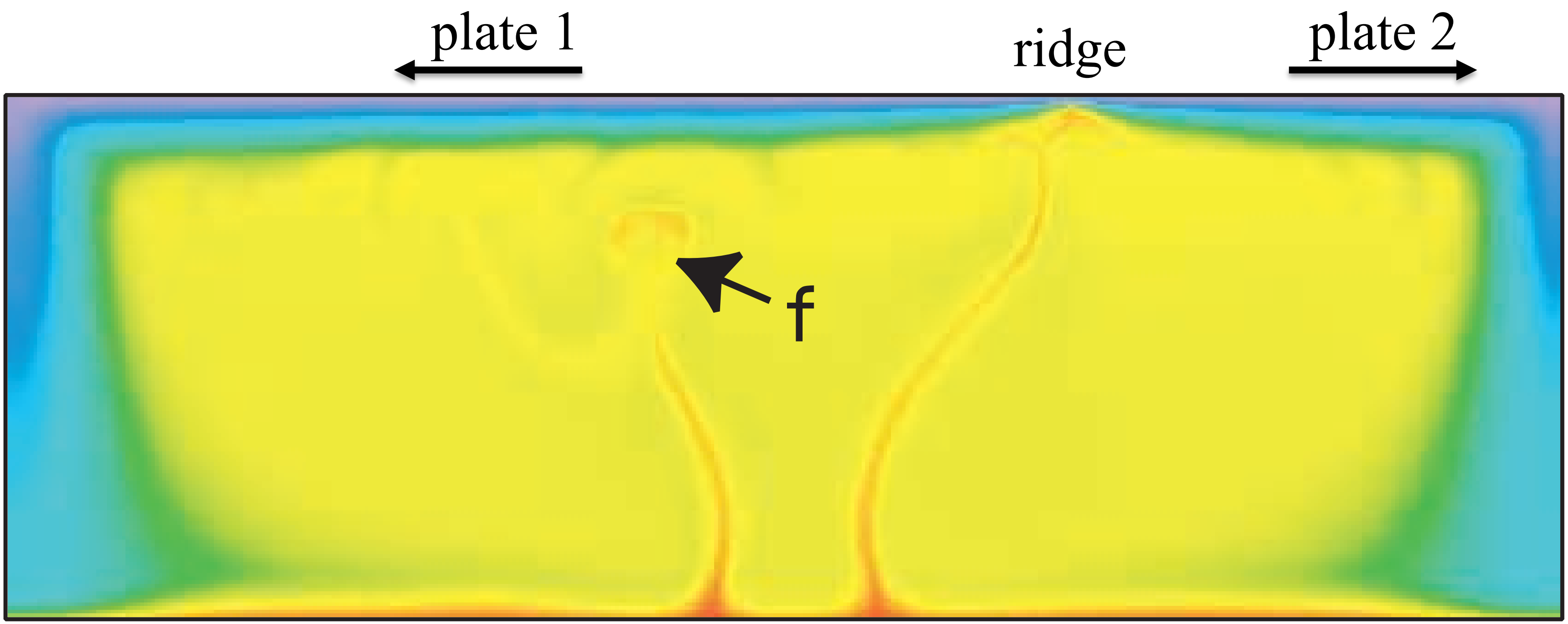
Extension to the Earth



In addition to the MMU feedback,
(1) plate tectonics
(2) the solid-solid phase transitions at the top of the lower mantle
the "660 km" phase transition
the garnet vs. perovskite transition
are taken into account.

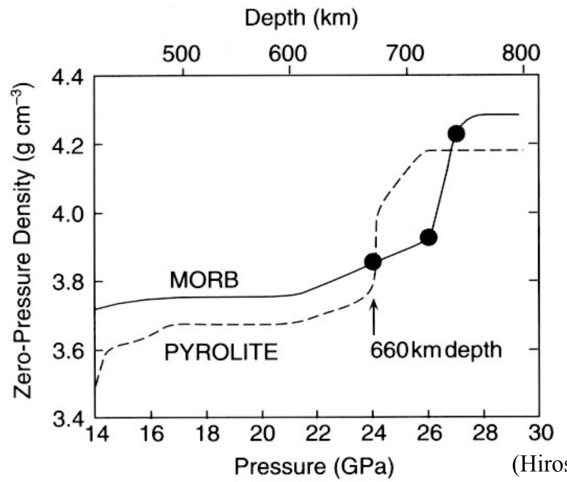
(1) The adopted model of plate tectonics

Plate margins self-consistently develop.

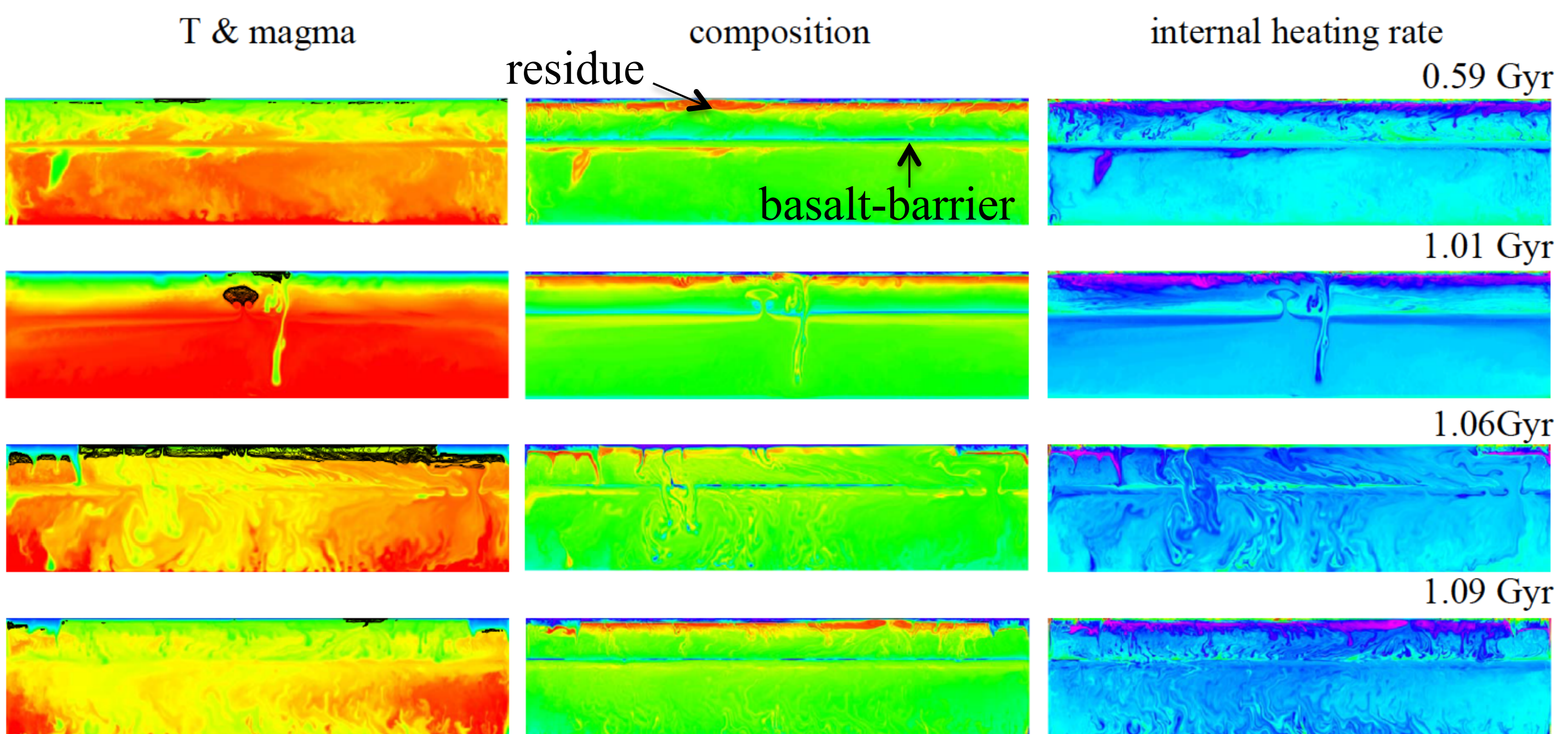


(Ogawa, 2002)

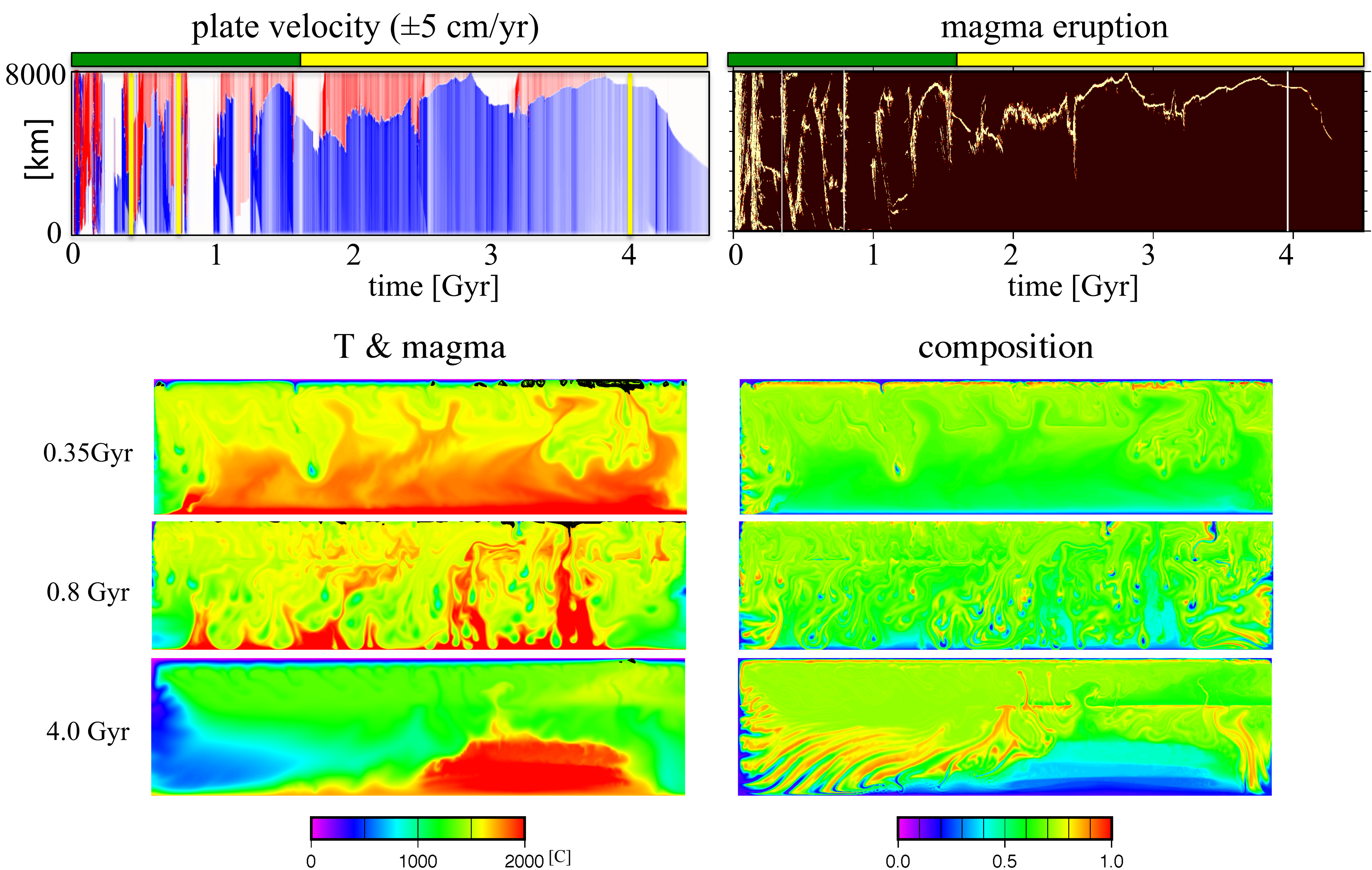
(2) the solid-solid phase transitions & mantle burst



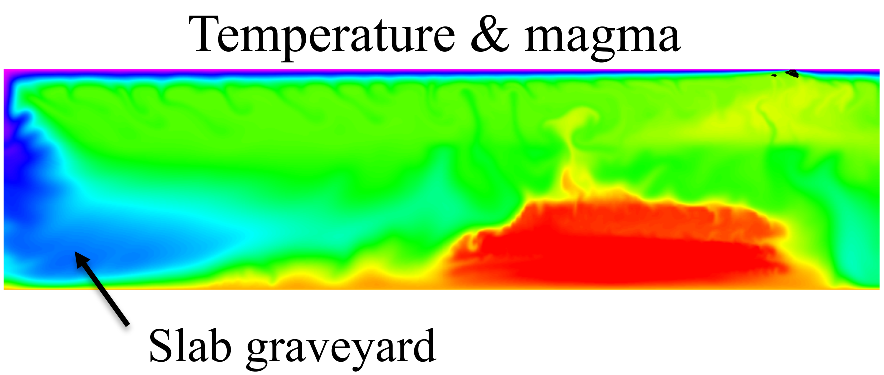
(Hirose, 1999)

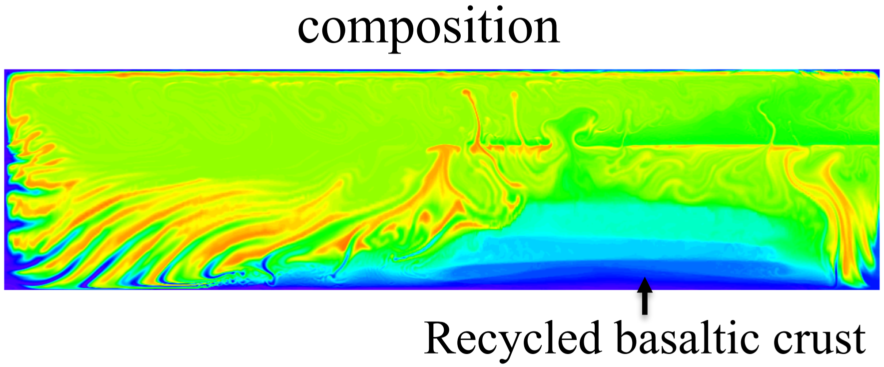


Two-stage evolution model of the Earth: a dry model

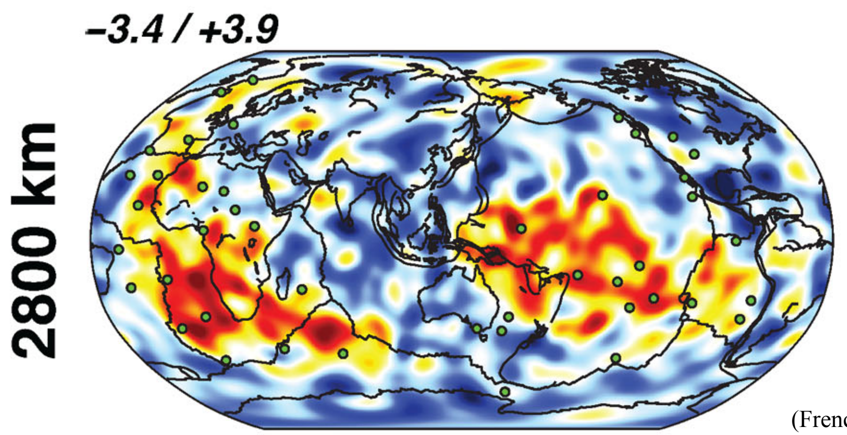


A thermo-chemical pile in the deep mantle ↔ LLSVP



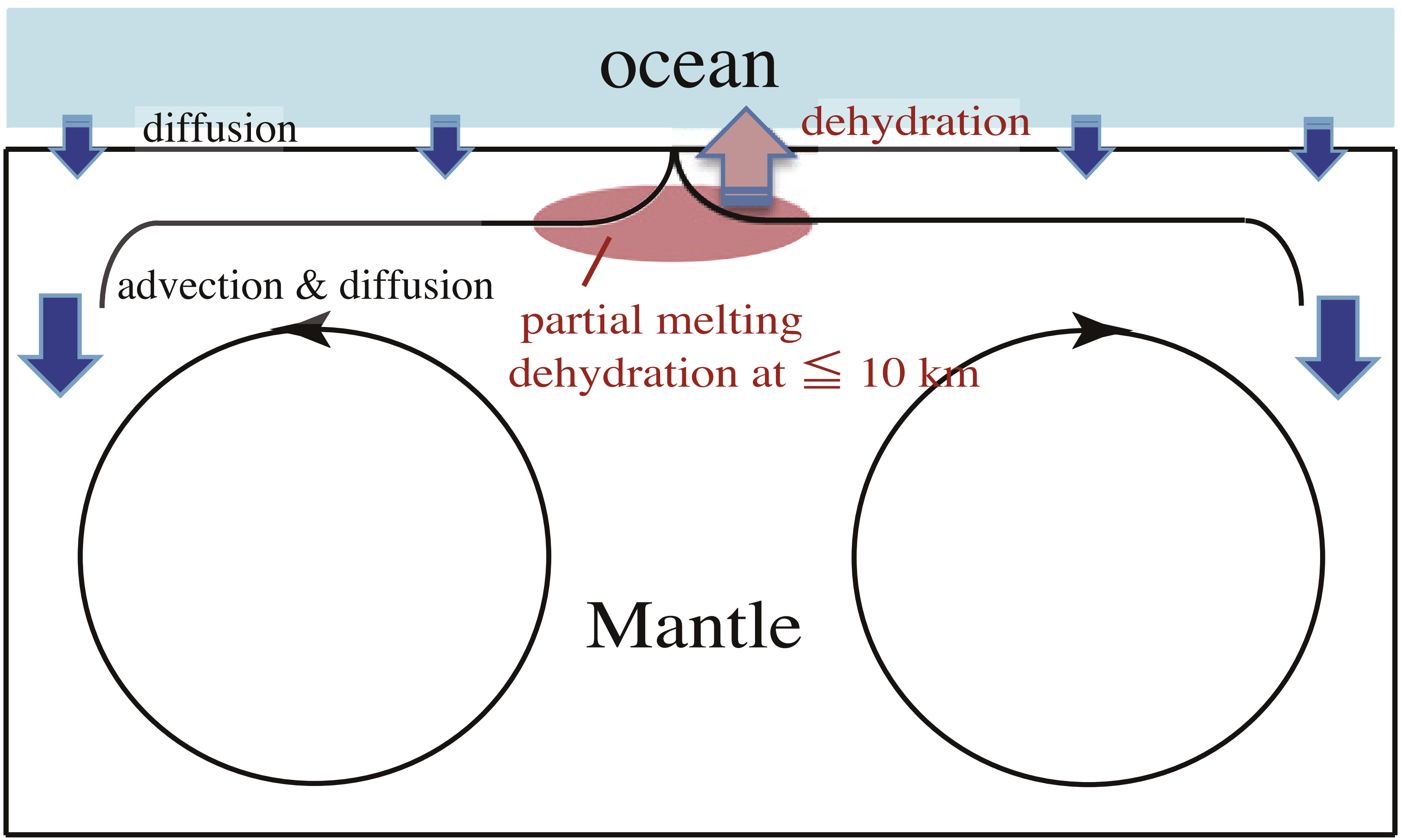


Mantle heterogeneity just above the core-mantle boundary

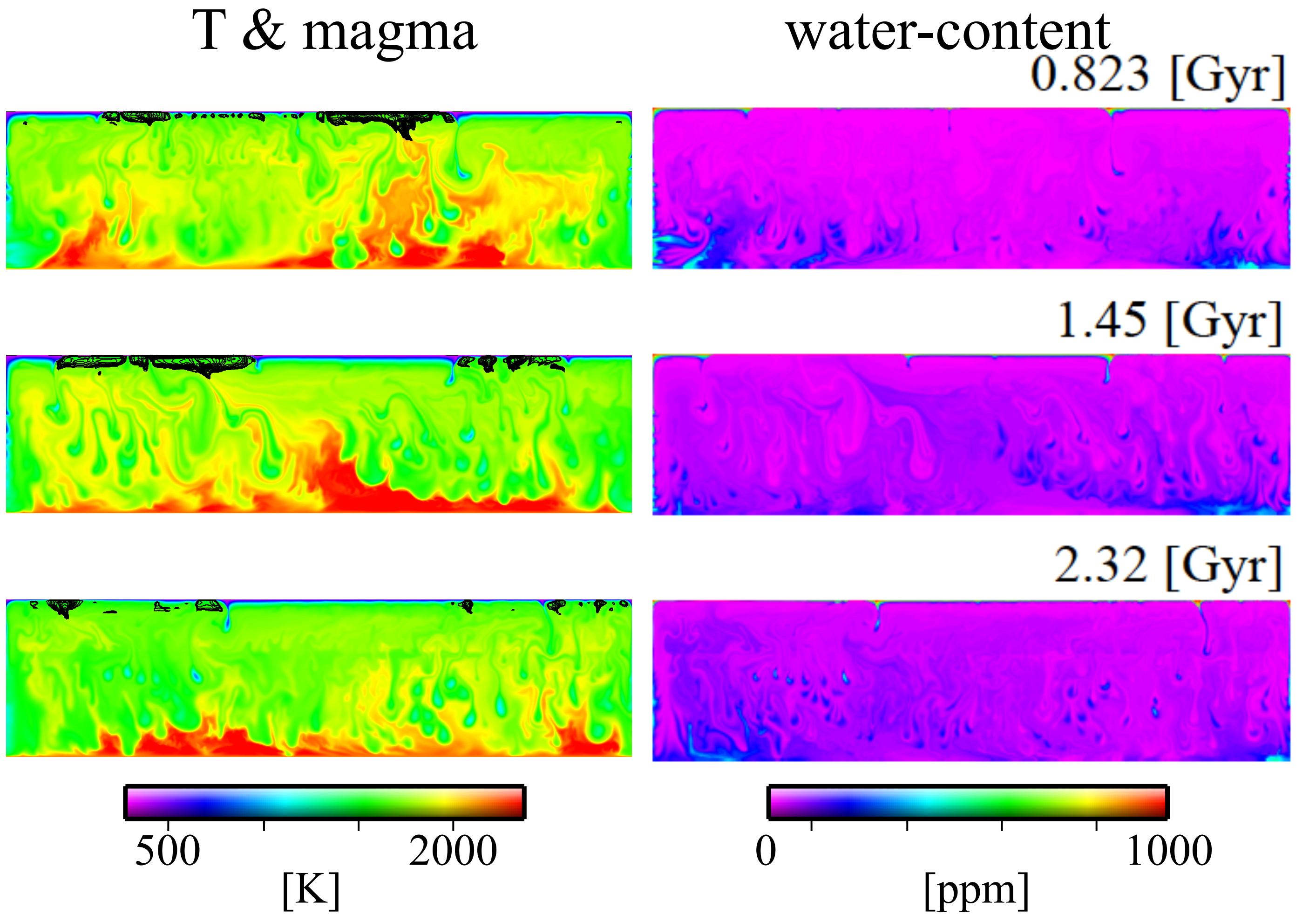


(French & Romanowicz, 2014)

A model of water-circulation in the Earth

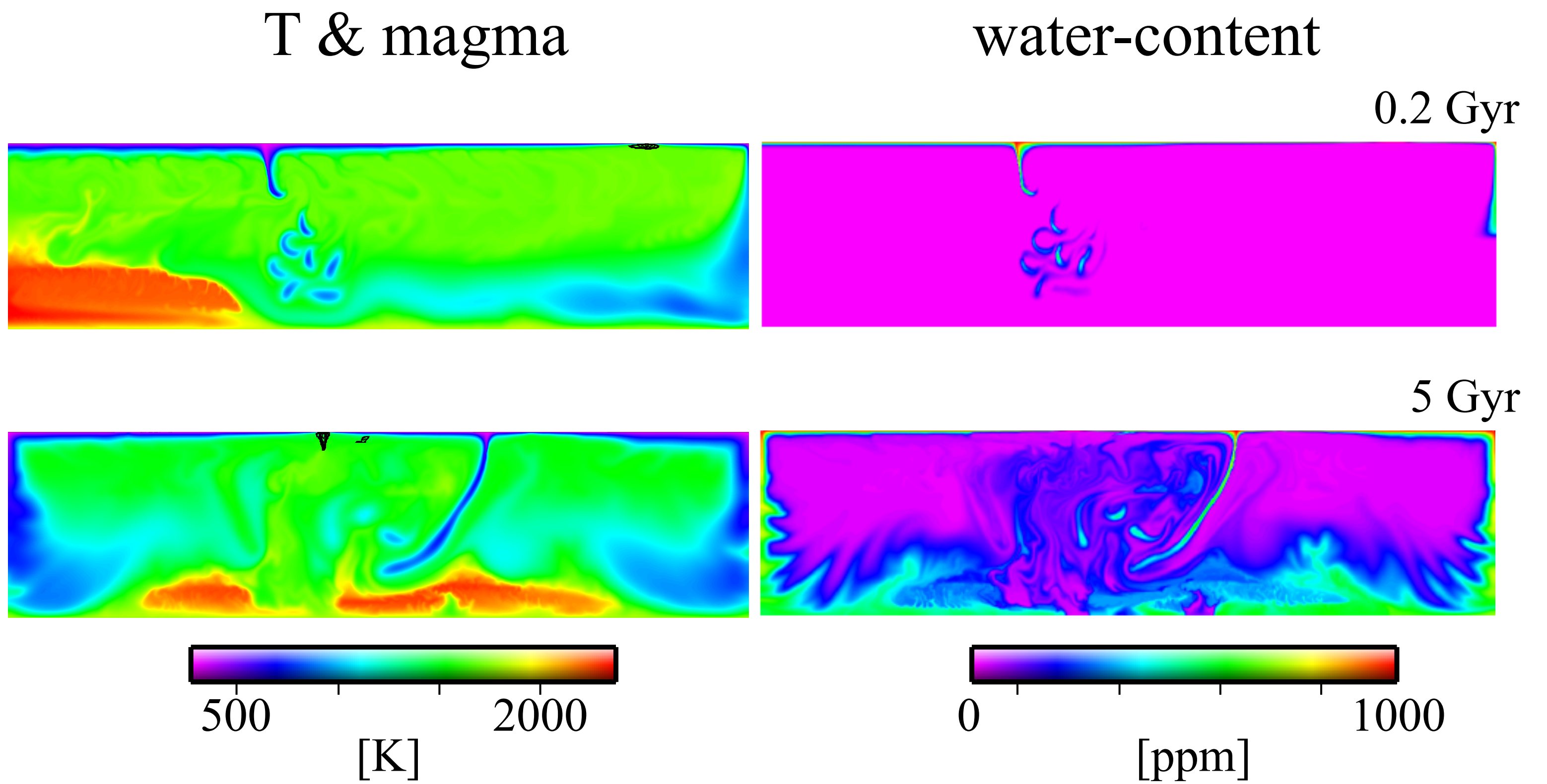


When internal heating is strong, magmatism by mantle bursts efficiently extracts water from the mantle.



(Fujita & Ogawa, 2013)

When internal heating is weak, slabs inject water into the LM.



(Fujita & Ogawa, 2013)

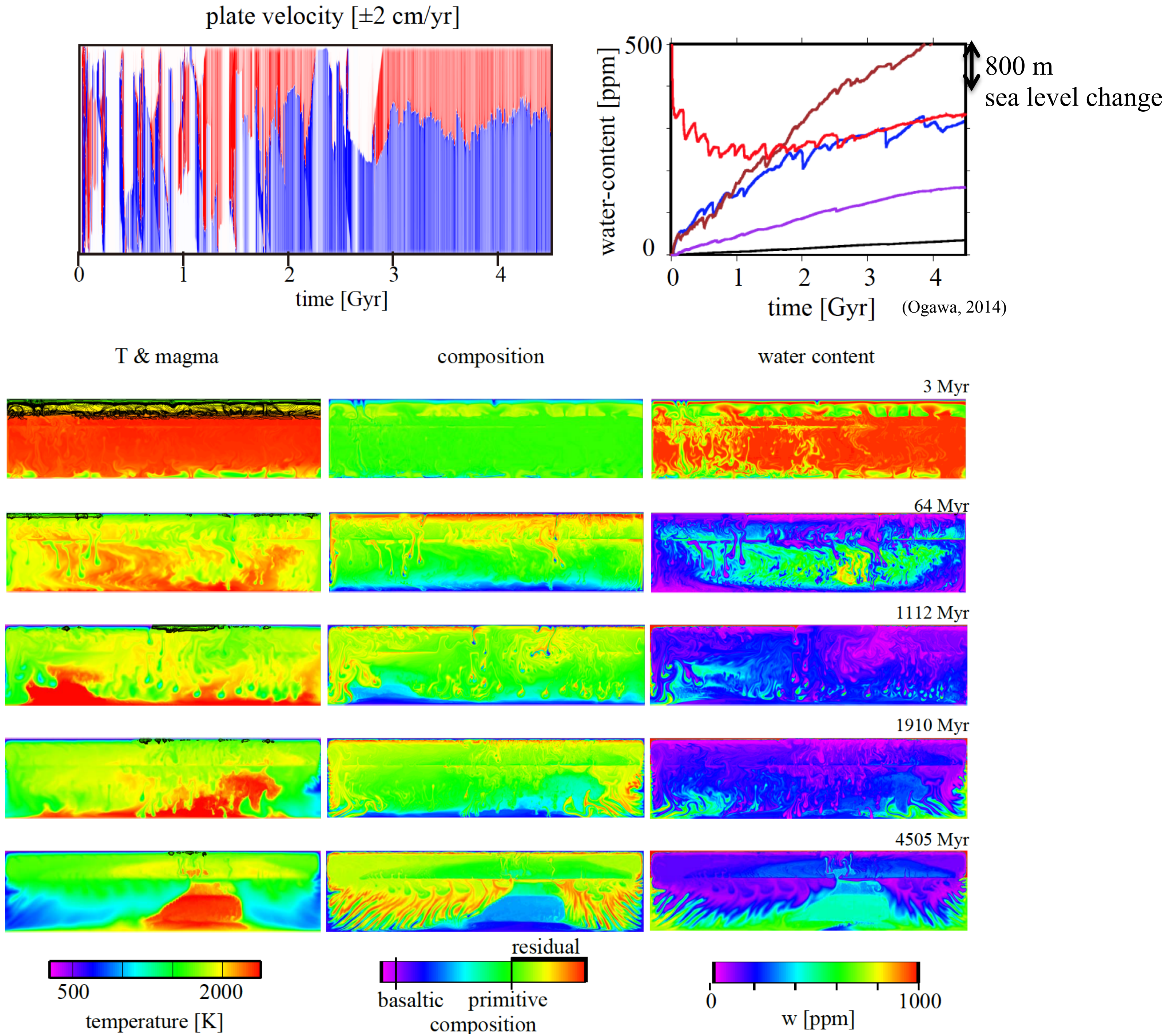


plate velocity [±2 cm/yr]
0
1
2
3
4
time [Gyr]
500
0
water-content [ppm]
800 m
sea level change
time [Gyr]
(Ogawa, 2014)
T & magma
composition
water content
3 Myr
64 Myr
1112 Myr
1910 Myr
4505 Myr
500
2000
temperature [K]
residual
basaltic
primitive
composition
0
1000
w [ppm]

Summary

(A)Magmatism enhanced by the MMU feedback efficiently extract water from the mantle with a characteristic time of ca. 1 Gyr.

(B) In the Earth, the mantle evolves in two stages:
(the earlier stage) frequent mantle bursts
(the later stage) stable plate motion.

(C) Subducting slabs transport water into the deep mantle on the later stage of the Earth.