The long-term climate evolution and planetary habitability - Onset timing of the plate tectonics in early Earth

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Key points of this presentation

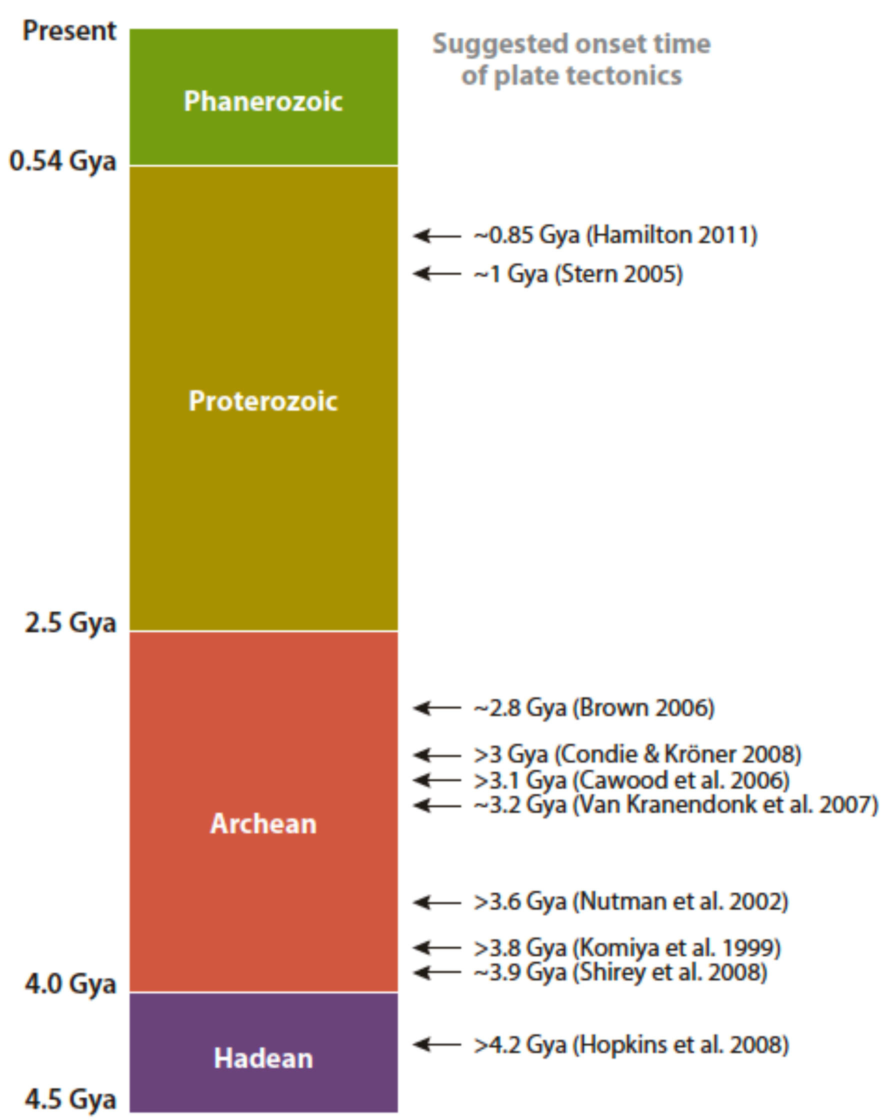
1. Find the best-fit evolution scenario that is consistent with both the present-day ocean volume and inner core size as a function of the onset timing of the plate subduction in the coupled core-mantle evolution approach: The best-fit scenario may be controlled by the total amount of water and viscosity increasing across the mantle.

2. The onset timing of the plate subduction may control the long-term climate change: With the plate tectonics, the climate could be the mild as in the present-day Earth but, without the plate tectonics, the climate solution could indicate 'Snowball' limit cycle. The climate evolution is mainly controlled by both outgassing flux of the carbon across the deep interior and incoming solar flux.

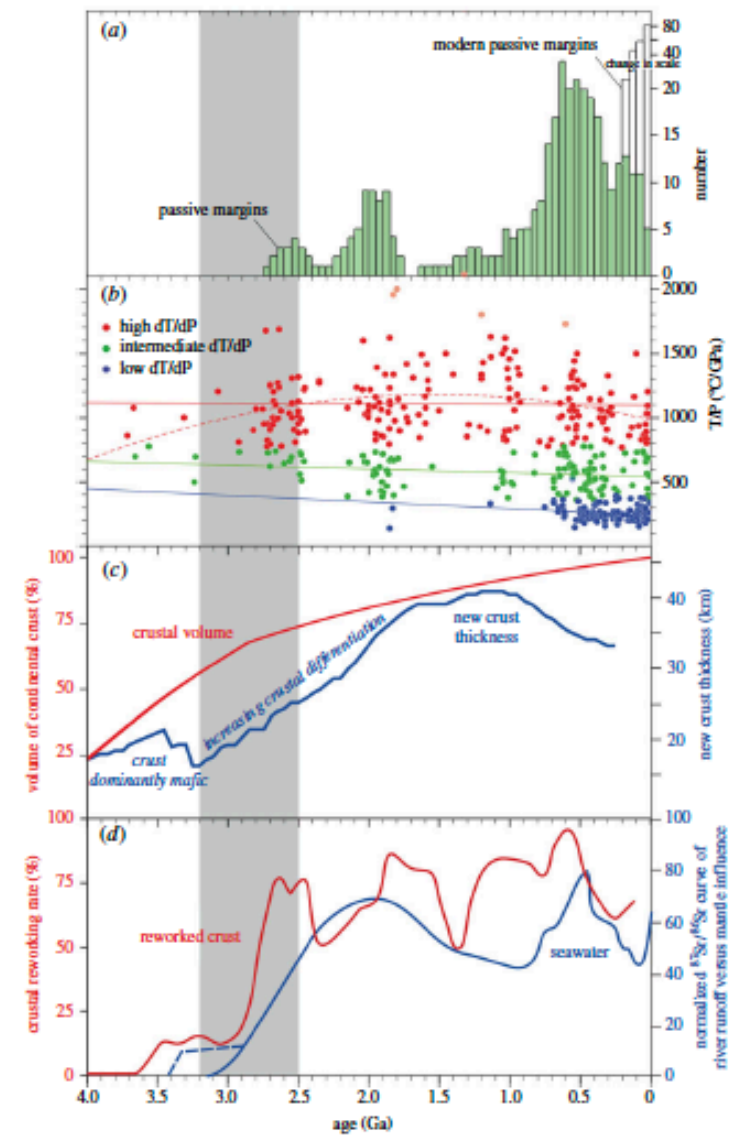
3. The plate tectonics may play a significant role in finding the habitable condition on the rocky planet such as the Earth.

4. Note: Most of results have not published yet: Now working hard to write up the manuscript. Any suggestions and advice on further improvements are definitely welcome.

Motivation: Onset timing of the plate subduction: Great uncertain?



Korenaga (2013)



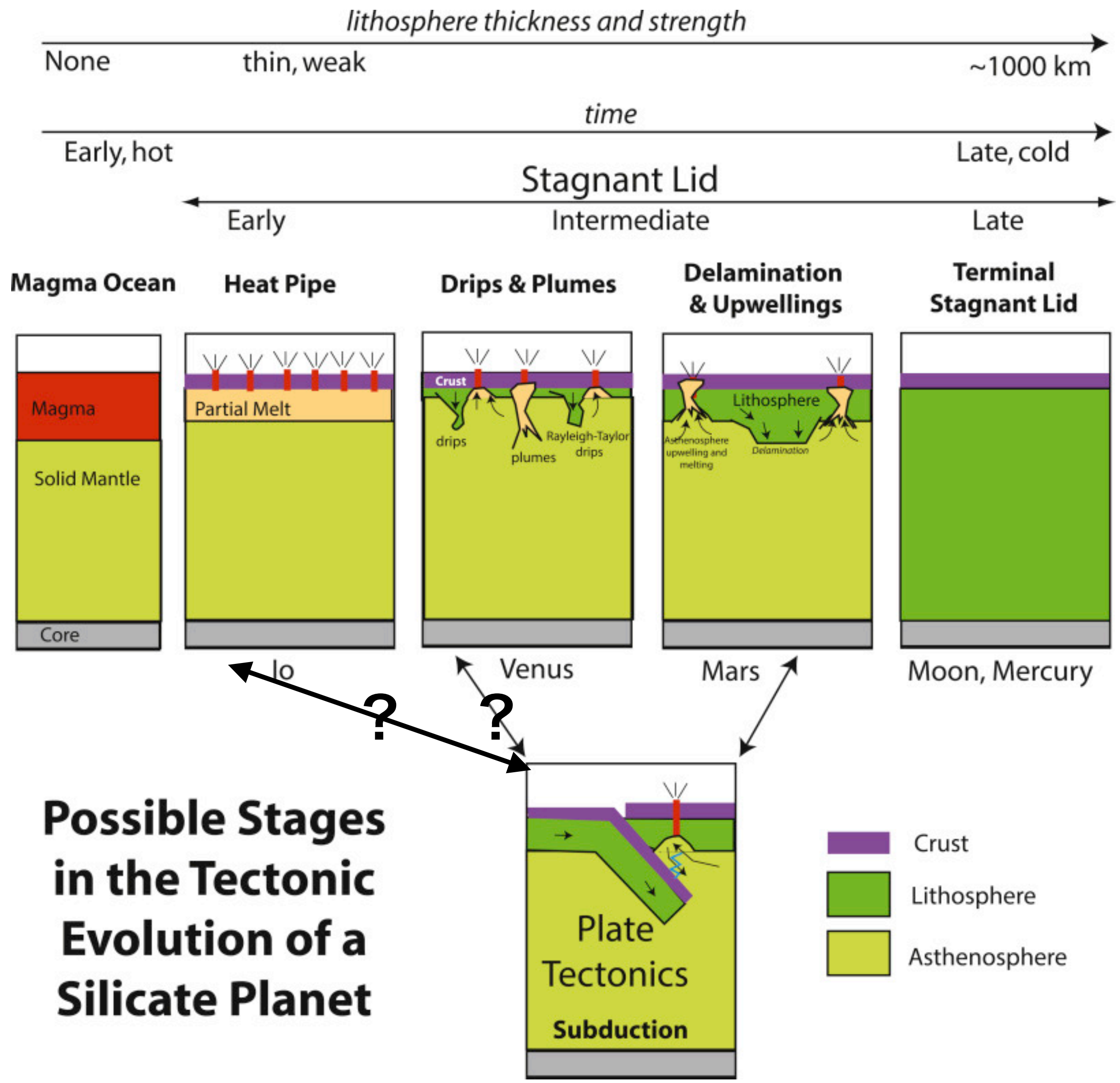
Cawood et al. (2018)

Explanation: As indicated in the compilation from the geologic data, the onset timing of the plate subduction may have a great uncertain ranging from 4.3 Ga to 0.8 Ga. This onset timing may affect the evolution of the planetary interior

Onset of the plate tectonics: How can the subduction be initiated?

Stagnant lid

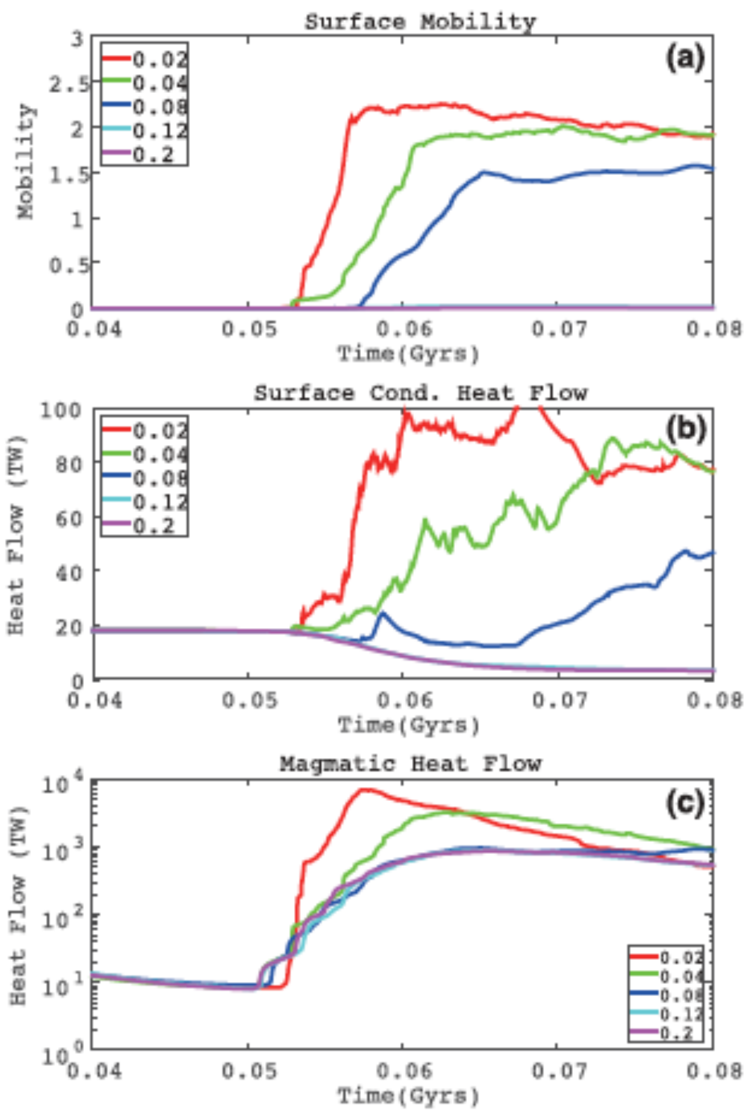
Plate tectonics



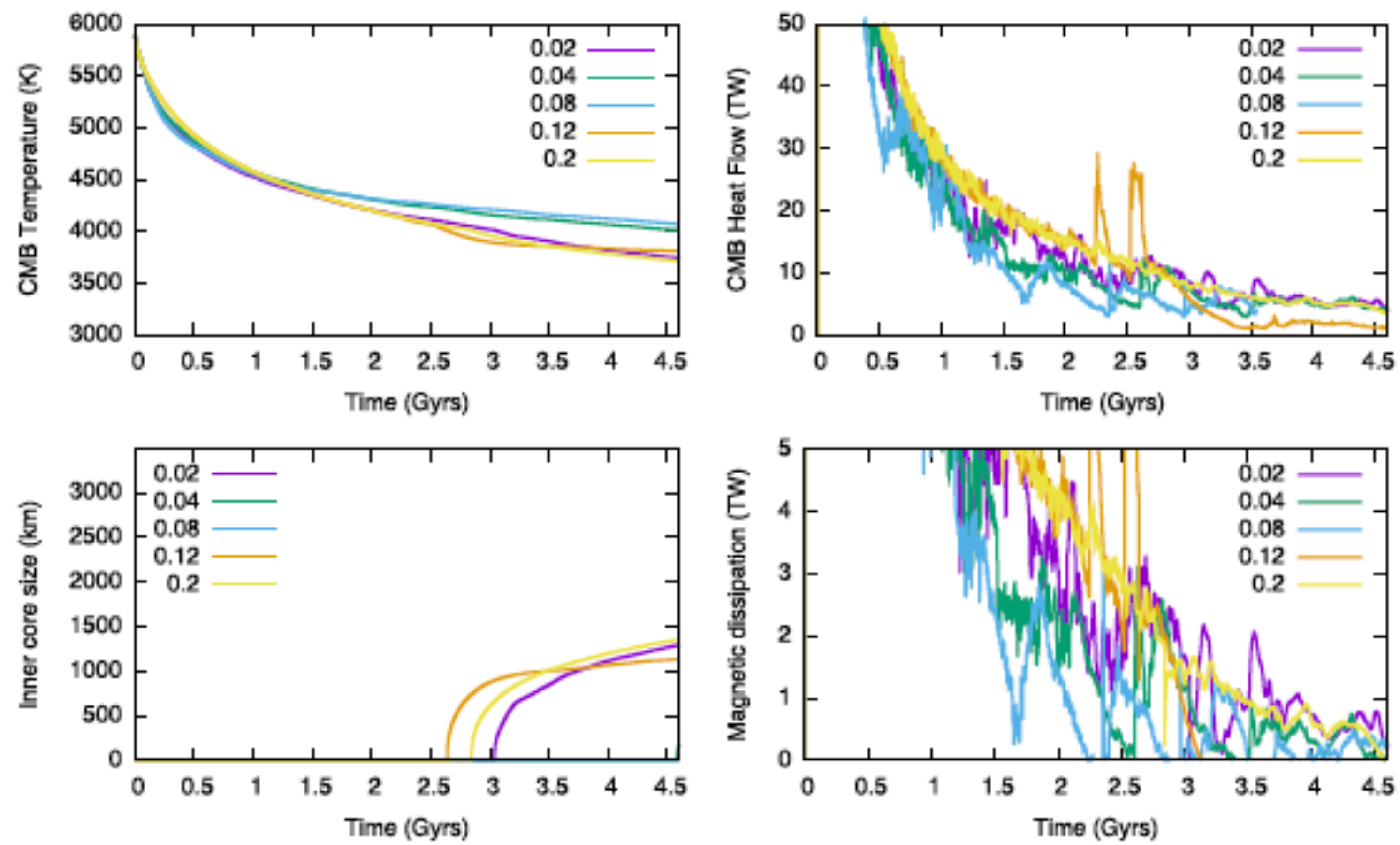
Stern (2018)

Explanation: Two possibilities are proposed for the mechanism on the initiation of the plate subduction - Plume-Lithosphere interaction (Gerya et al., 2015) and Melt extraction caused by the Heat-pipe volcanism (Moore and Webb, 2013).

Earlier investigation on the long-term evolution of the deep planetary interior



Nakagawa and Tackley (2015)

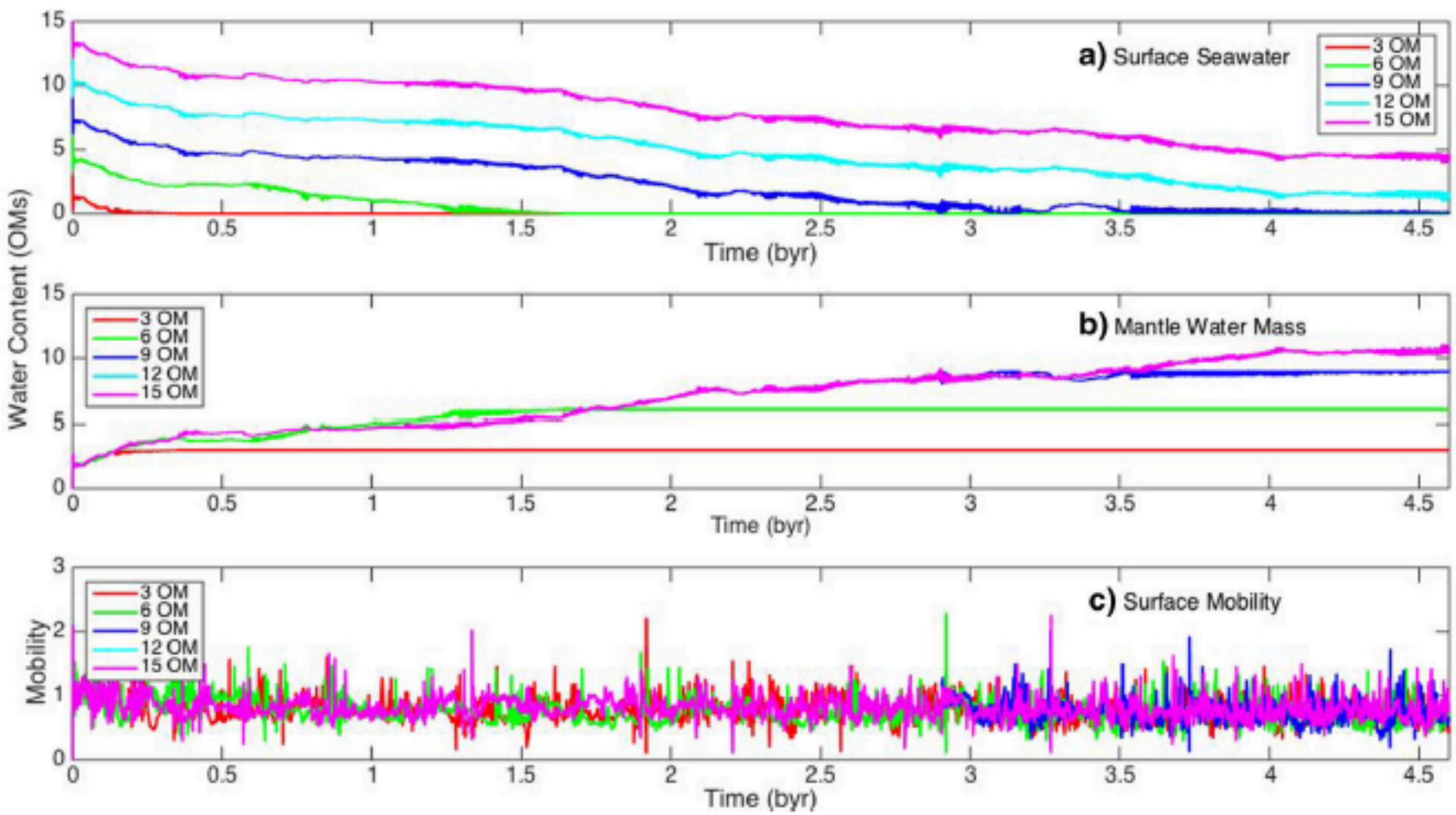


Explanation: Both plume-lithosphere interaction and heat-pipe volcanism may be worked for the onset of the plate motion. Plate tectonics planet gives a better understanding of the long-term evolution in terms of the magnetic evolution rather than the stagnant lid planet.

Question: How can the evolution of the deep interior could affect the surface environment?

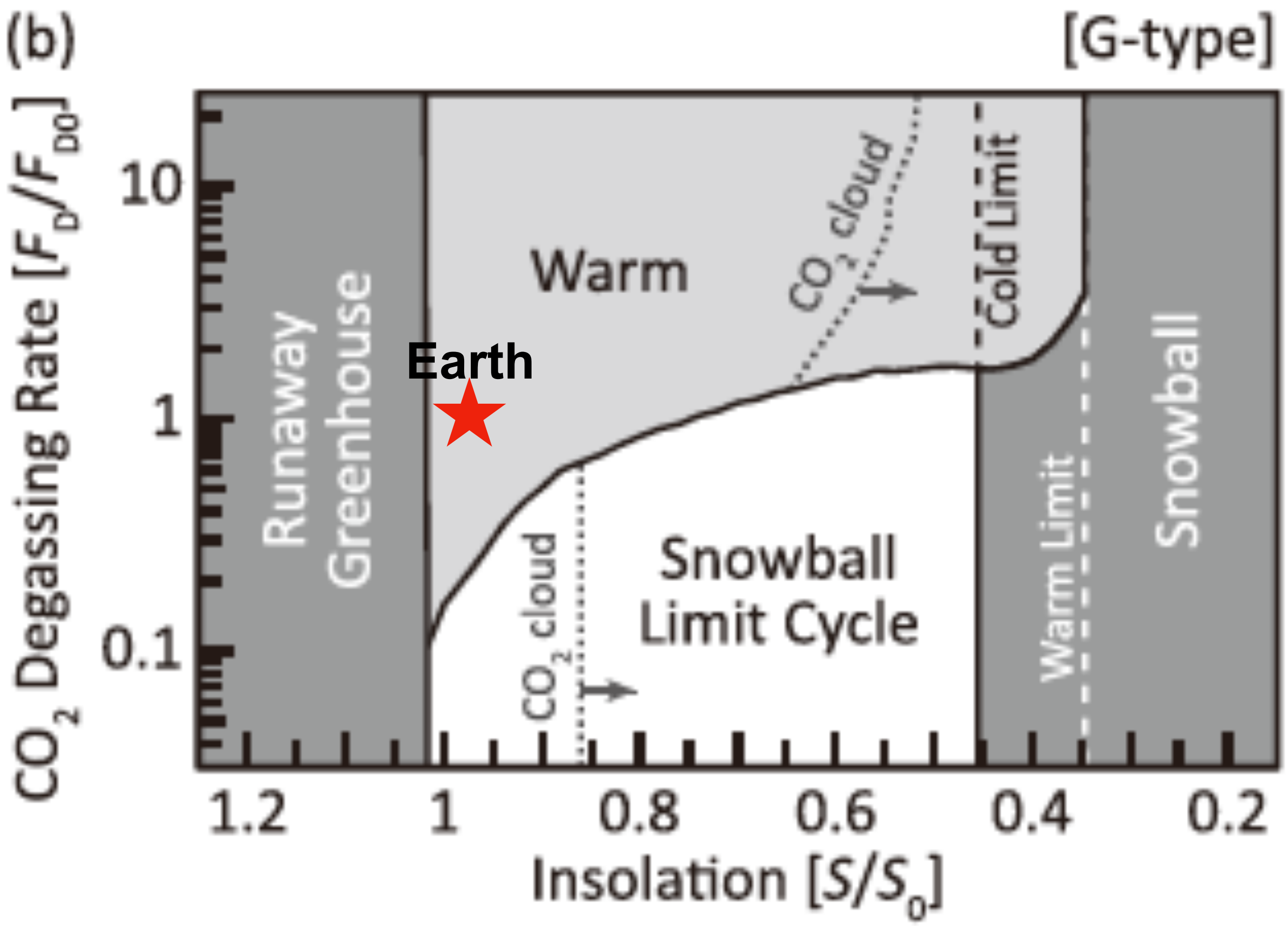
Earlier investigation: Can the plate tectonics control the surface environment? - Ocean Evolution

Nakagawa et al. (2018)

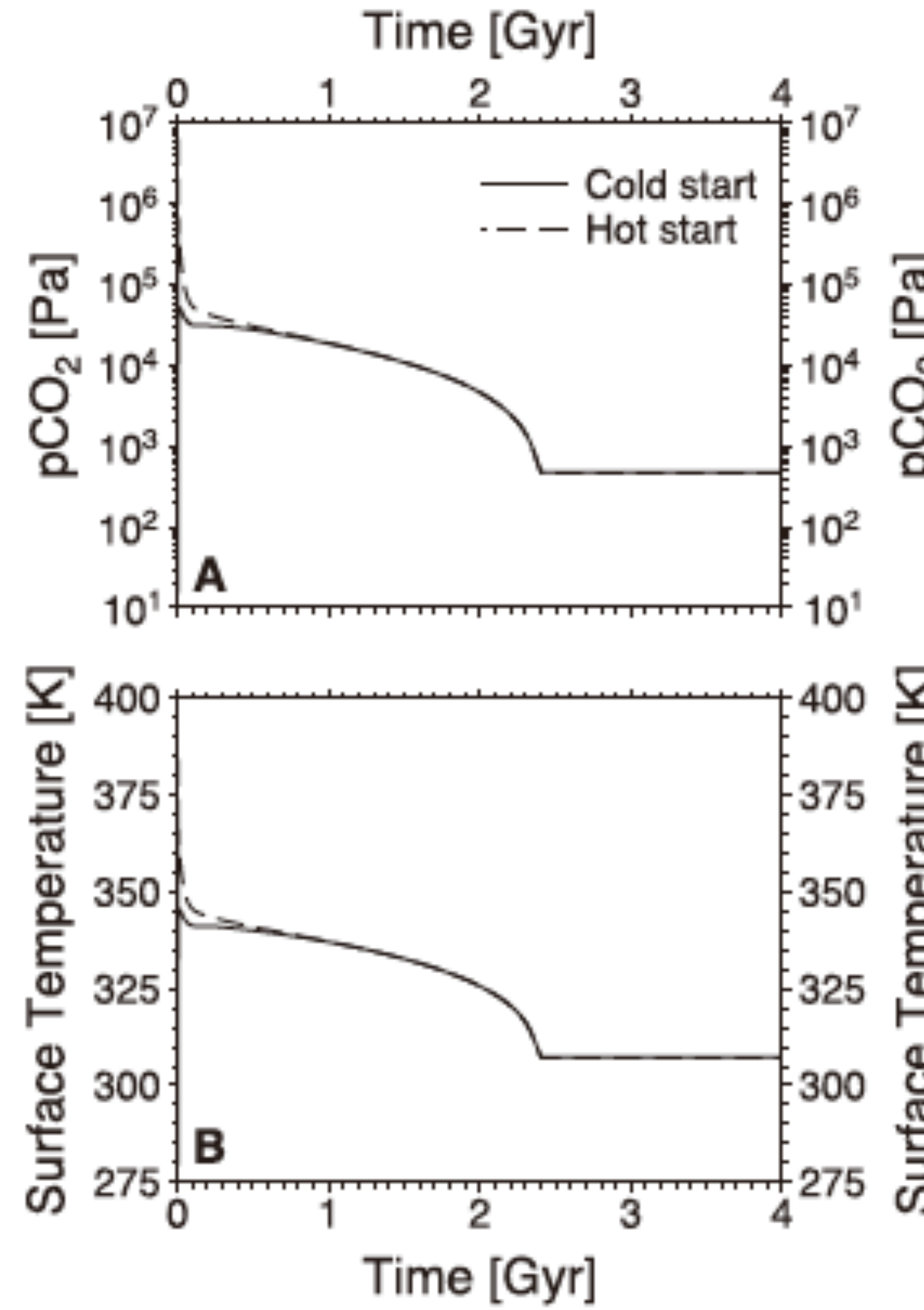


Explanation: An example of the surface environment - Ocean. The plate motion driven by the mantle convection could control the volume of the surface ocean and the huge amount of water may be absorbed into the deep interior (~10 times as large as the present-day ocean volume). Question: How can the evolution of the ocean be sensitive to the onset timing of the plate subduction?

Climate evolution in two different planets: Planet tectonics vs Stagnant lid



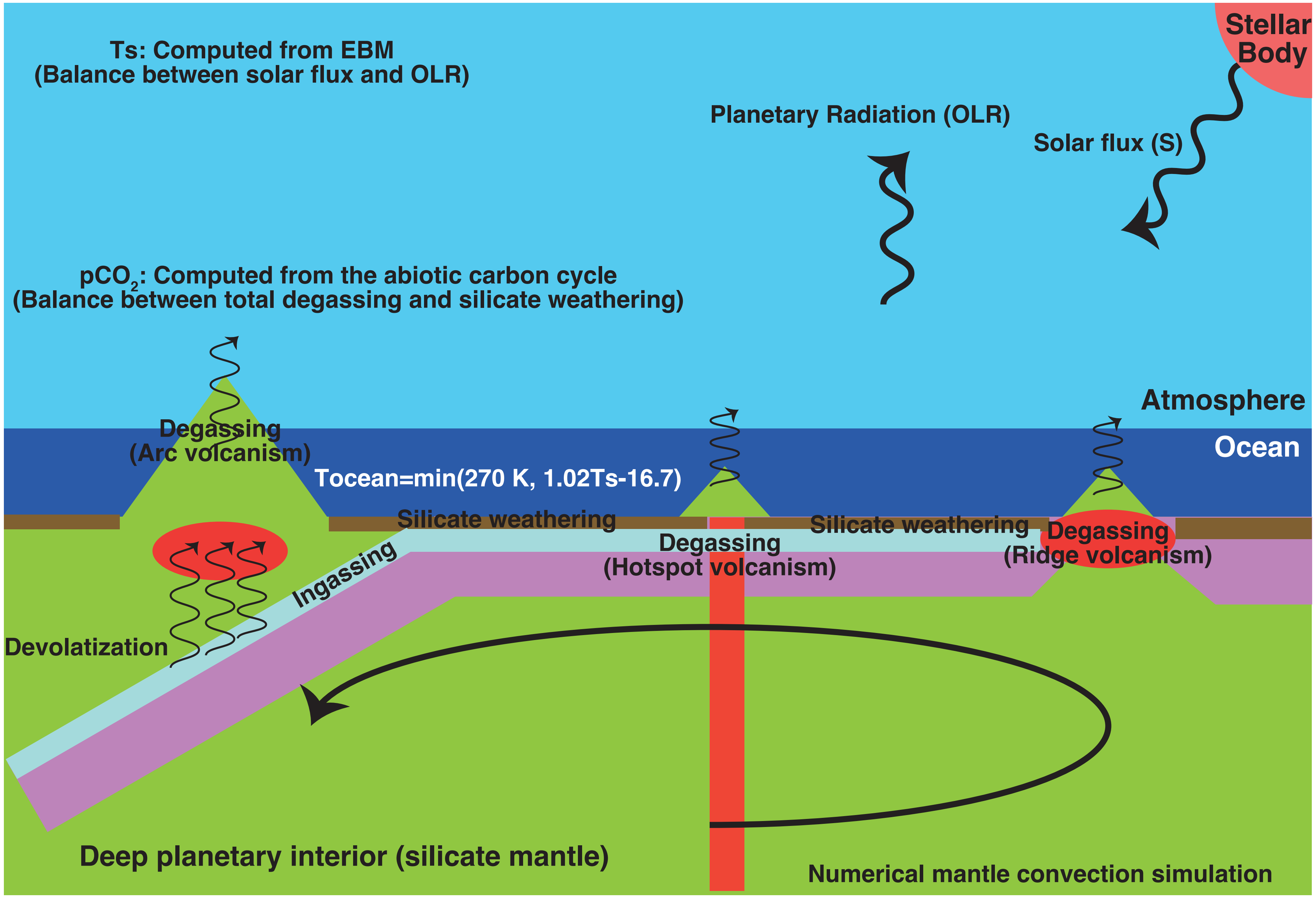
Kadoya and Tajika (2019): Plate tectonics planet
- Complicate climate



Foley (2019): Stagnant lid planet

Question: Can the plate tectonics be needed for the habitable climate?

What do we expect the image of the interaction between exosphere-interior evolution of the plate tectonic planet?

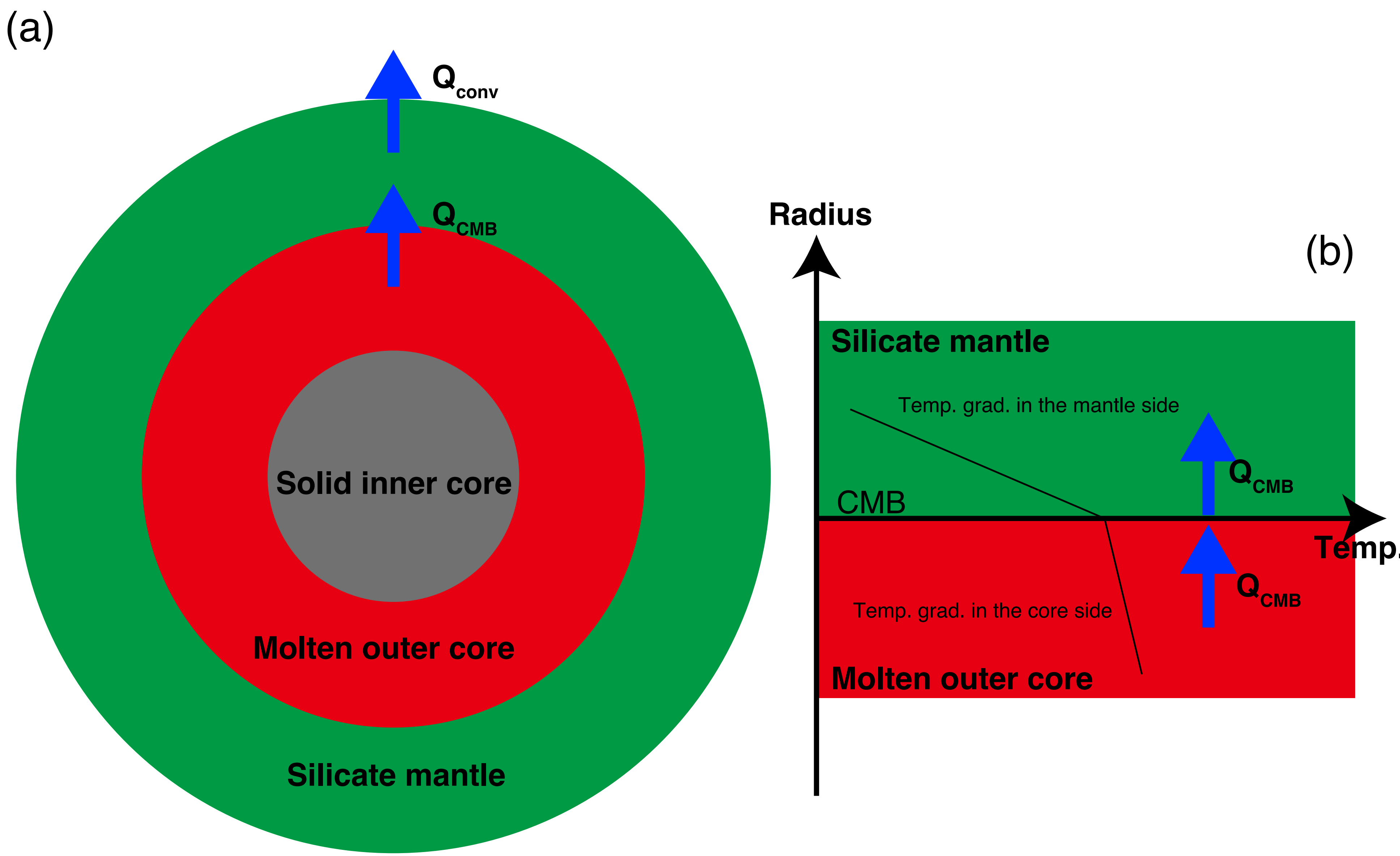


Explanation: This is an expected image on the exterior-interior evolution including what is the modeling approach in this investigation.

Questions addressed in this investigation

1. How can the evolution of the deep interior affect the surface environment?
2. How can the onset timing of the plate subduction change the long-term evolution of deep interior and exterior?

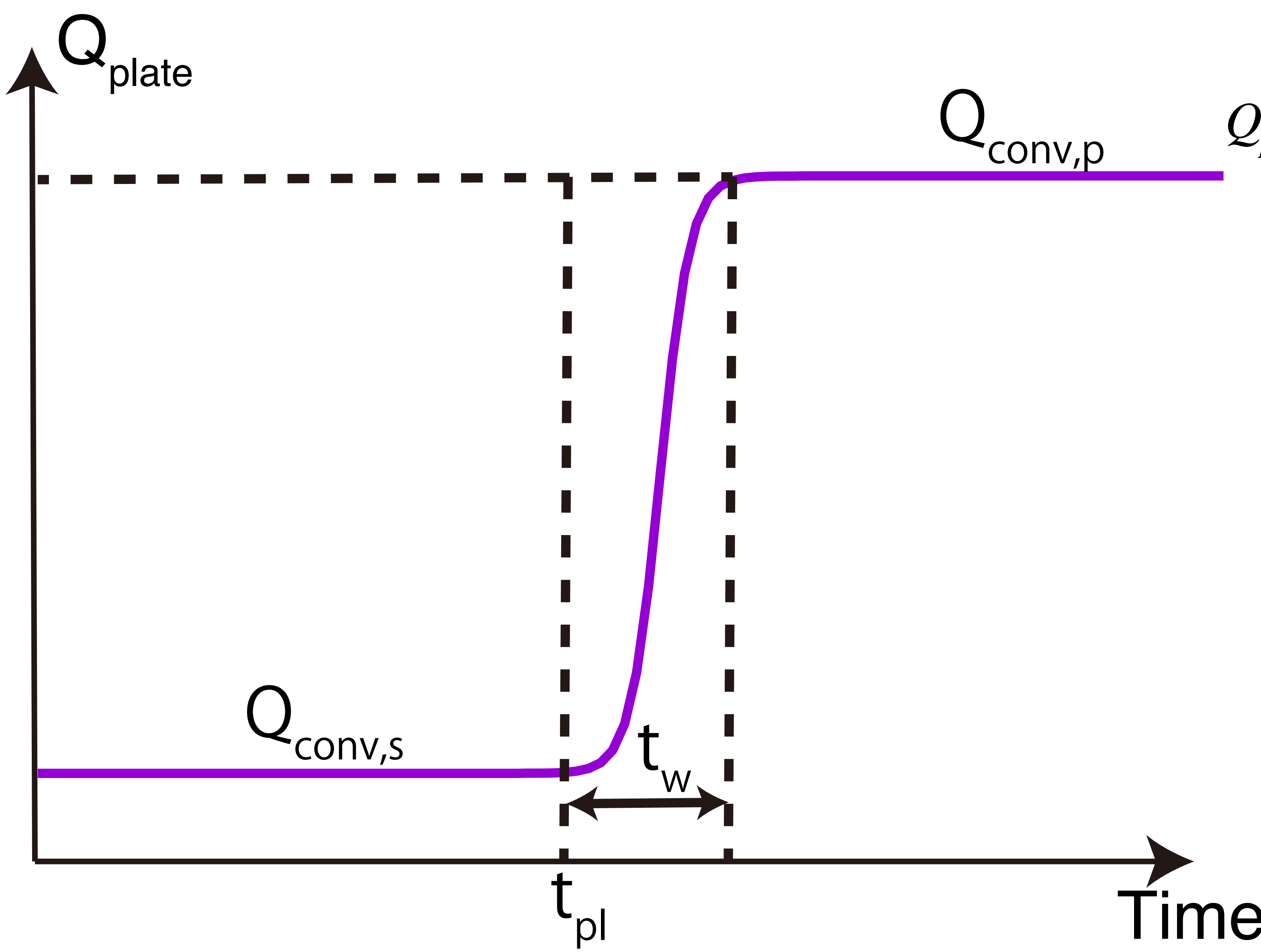
Modeling approach on the evolution of the deep interior: Parameterized mantle convection coupled with the global energetics of the Earth's core



$$M_m c_m \frac{dT_m}{dt} = Q_{CMB} + H_m - (Q_{conv} + Q_{melt})$$ Heat budget across the mantle

$$Q_{CMB} = Q_c + Q_L + E_G$$ Heat budget across the core

Point of the modeling: How can the onset of the plate subduction be expressed in the heat budget?



$$Q_{plate} = Q_{conv,s} + \frac{1}{2} Q_{conv,p} \tanh\left(\frac{t - t_{pl}}{t_w}\right)$$

$$Q_{conv,s} = \frac{2}{p(1 + p^{\frac{1}{3}})} Q_{conv,p}$$

$$Q_{conv,p} = A_s k_{um} \left(\frac{\alpha_{um} g}{Ra_c \kappa_u m}\right)^{\frac{1}{3}} \Delta T_s^{\frac{4}{3}} \nu_{um}^{-\frac{1}{3}}$$

$$p = \frac{E_a}{RT_0}$$

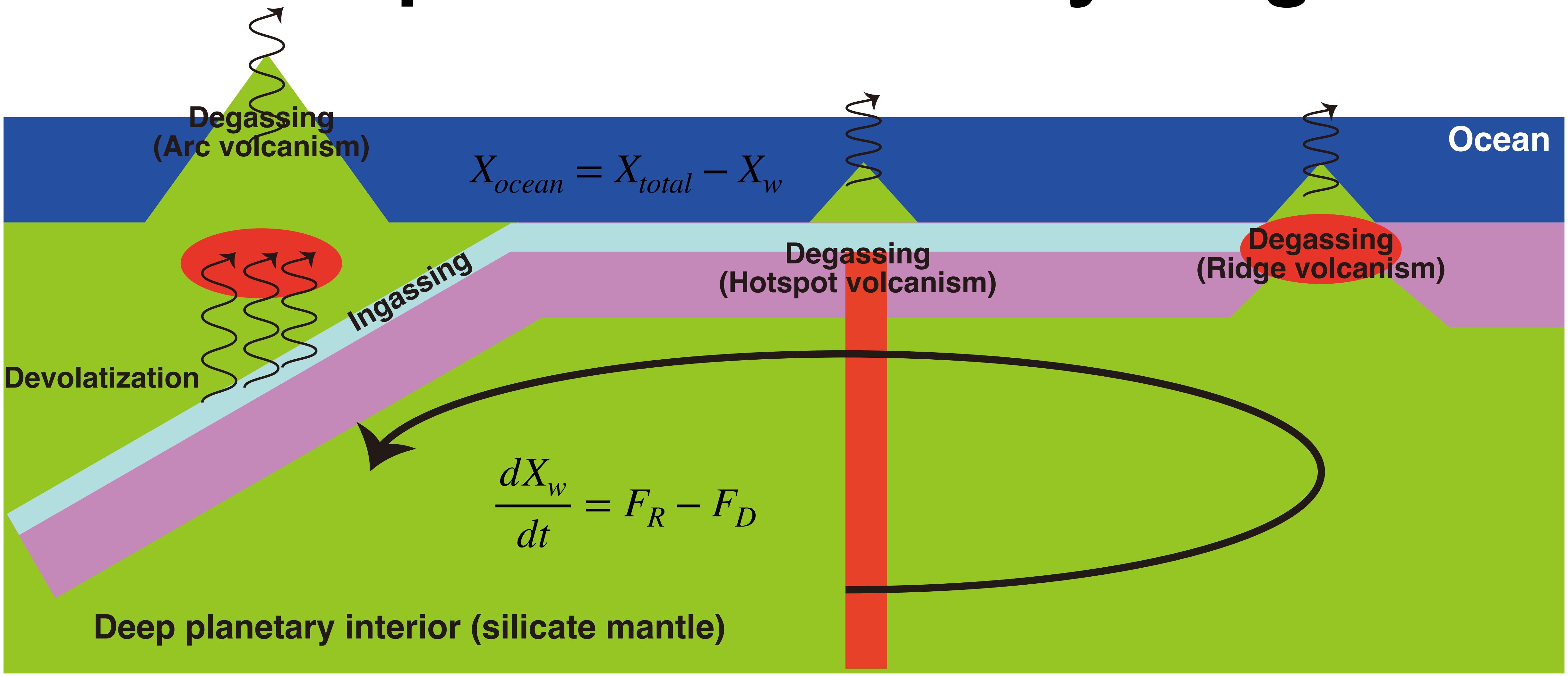
$$\nu_m = \nu_0 \exp\left(\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right)$$

$$\nu_{um} = 0.1 \nu_m$$

$$\nu_{lm} = f_{visc} \nu_{um}$$

Explanation: This figure indicates how to incorporate the onset timing of the plate subduction in the parameterized mantle convection model.

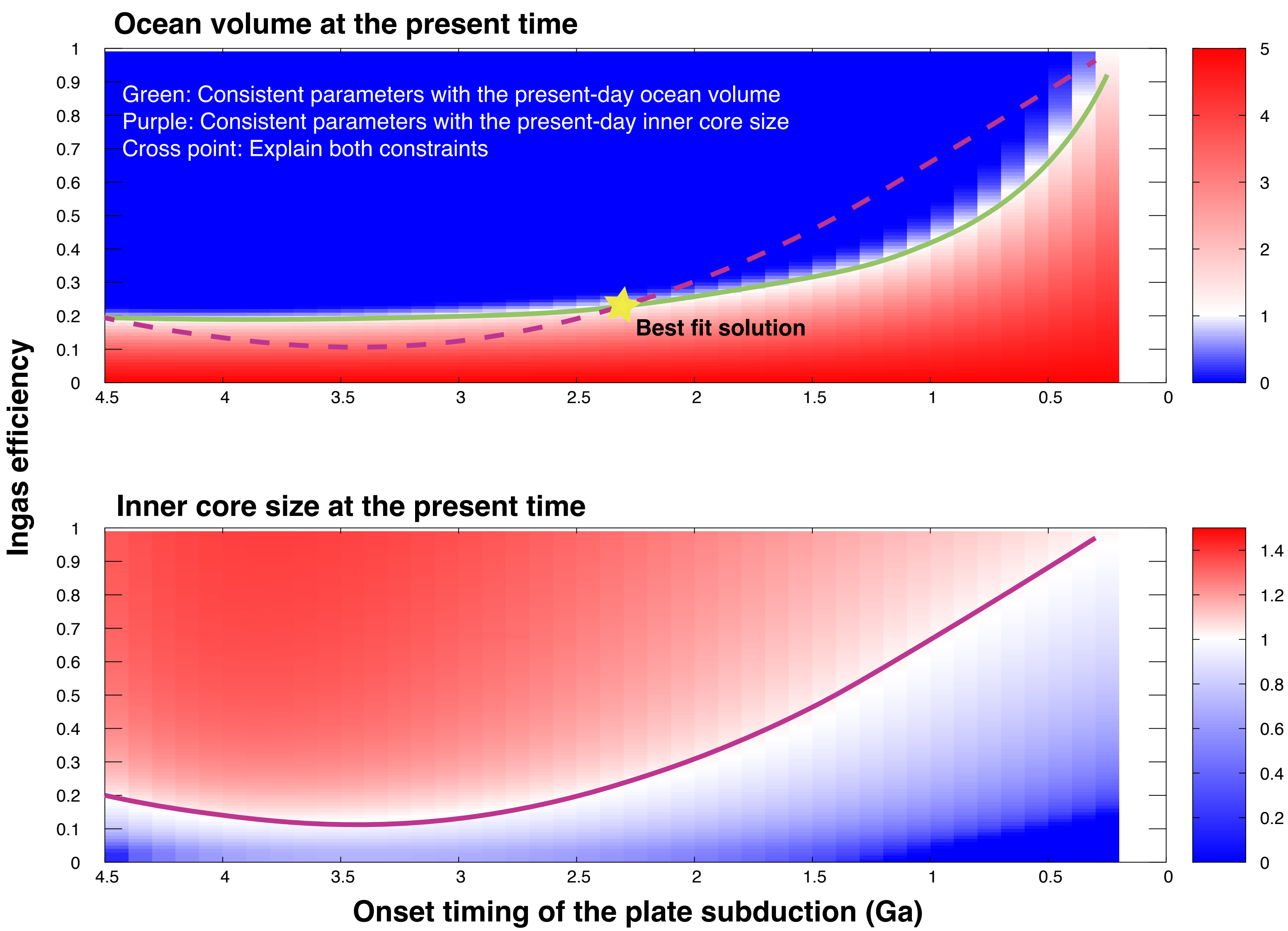
Deep mantle water cycling



Assumption:

1. Ingassing: Regulation of the water entrance due to the choke-point (dissolving point of the serpentine) is included (Schaeffer and Sasselov, 2015).
2. Outgassing: Include the effects of the devolatization plus all volcanic activities are included (Fraeman and Korenana, 2010).

Result: Ocean-Interior evolution



Explanation: These figures indicate the solution regime diagrams for the ocean volume (Top) and the size of the inner core (bottom) at t = 0Ga.

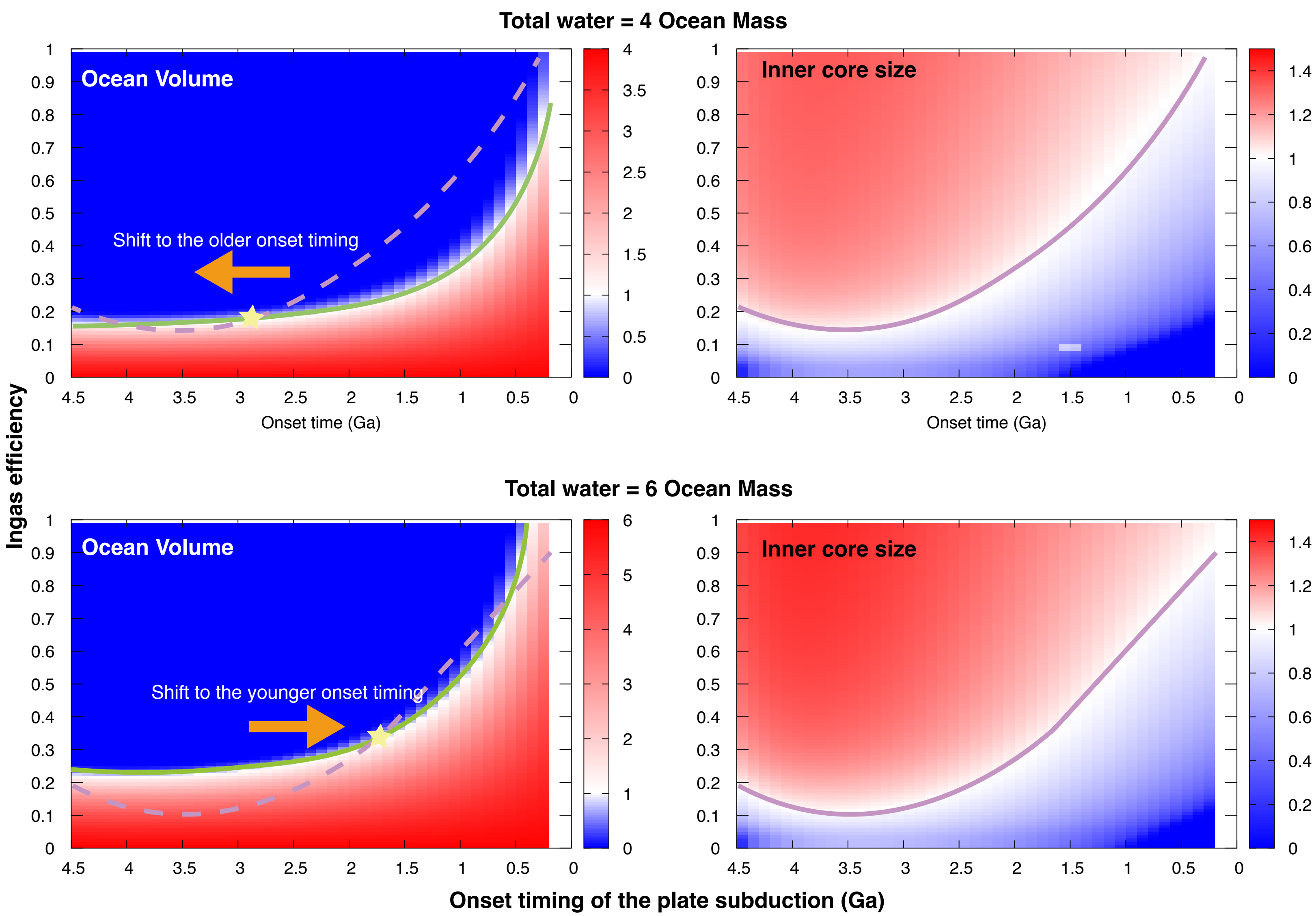
Initial partitioning of the water between ocean and mantle: 1 Ocean Mass in the ocean. The rest of the water should be partitioned into the mantle side at the initial point.

On the solution regime diagram for the ocean at t = 0 Ga, the green line indicates the same value of the surface water as the present-day ocean volume.

The purple line indicates the size of the inner core that is consistent with the present-day size of the inner core. The yellow star indicates the cross-point between two lines being consistent with both constraints.

Total water in the system = 5 Ocean Mass

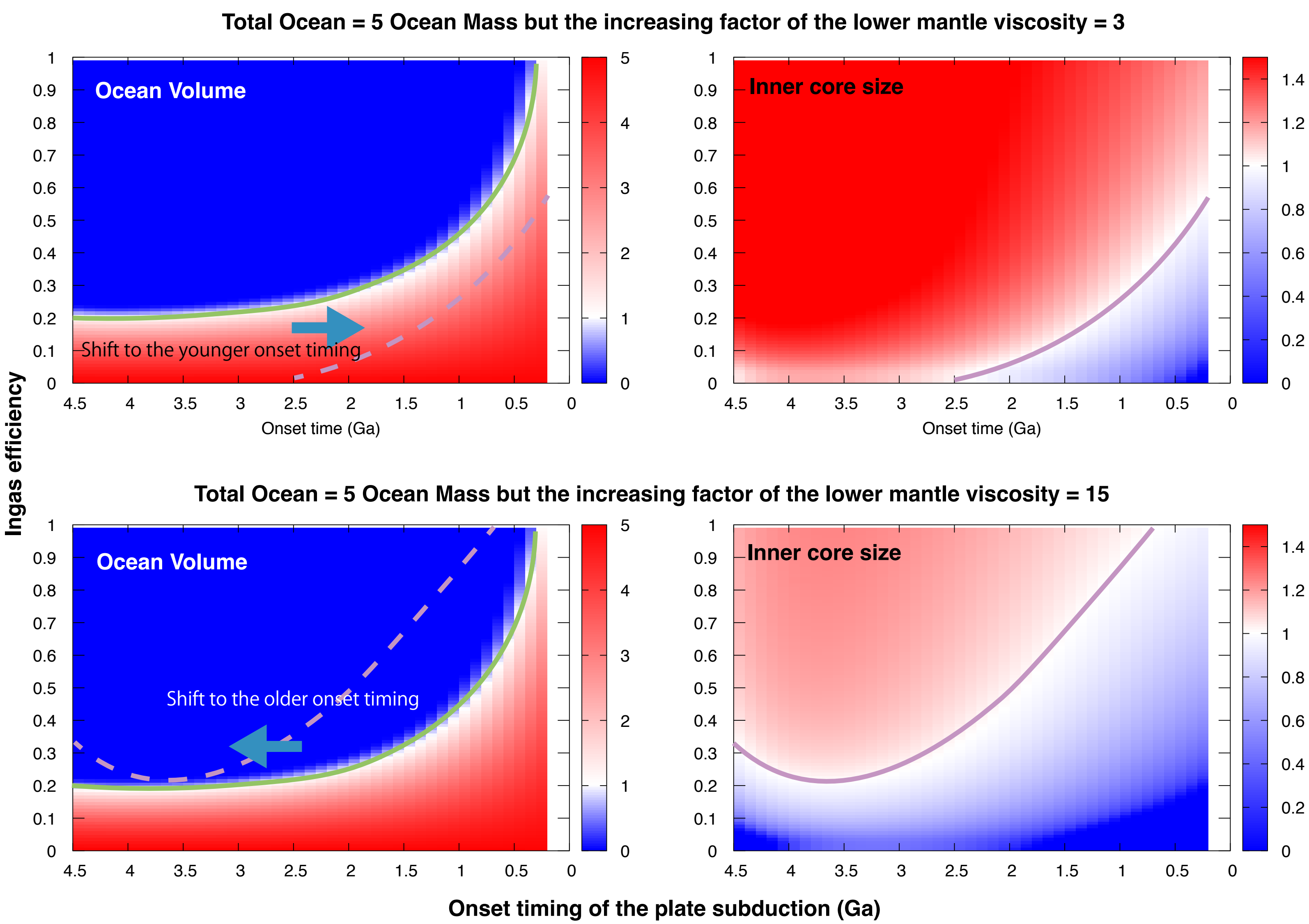
Sensitivity of the total water in the system



Explanation: Model sensitivity of the total water in the system to the solution regime diagram.

1. Less amount of the total water - Shift to the older age of the onset timing of the plate subduction (Less ingassing efficiency of the water transport).
2. Larger amount of the total water - Shirt to the younger age of the onset of the plate subduction (More ingassing efficiency of the water transport).

Sensitivity of the viscosity increasing across the deep interior

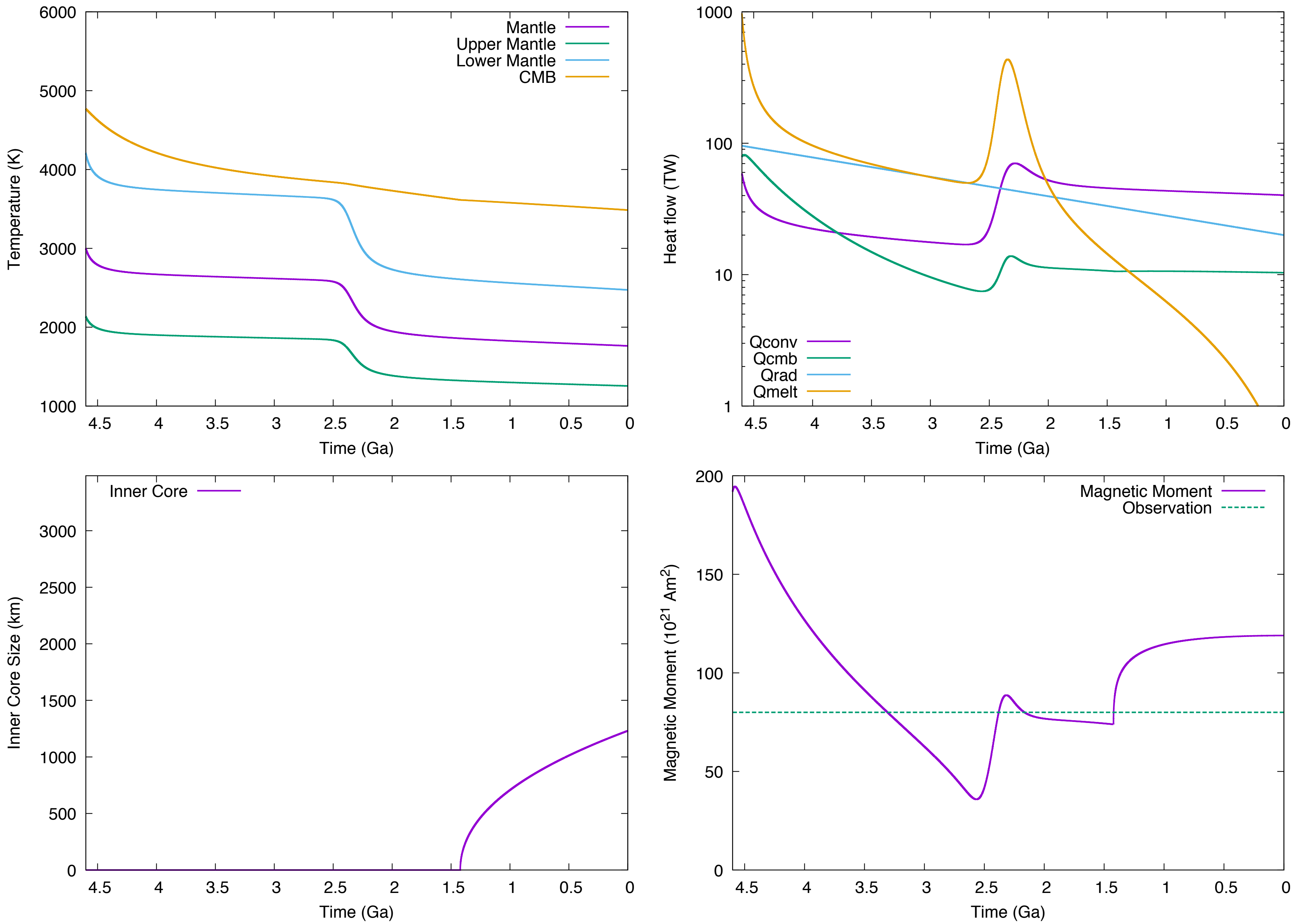


Explanation: Model sensitivity of the viscosity increasing across the deep interior.

1. Less viscosity increasing - Shift to the younger age of the plate subduction (more heat transport across the CMB requires the much younger age of the inner core).
2. More viscosity increasing - Shift to the older age of the plate subduction (less heat transport across the CMB indicates the much older age of the inner core).

Successful evolution of the deep interior

Case: Yellow star shown in Slide 11

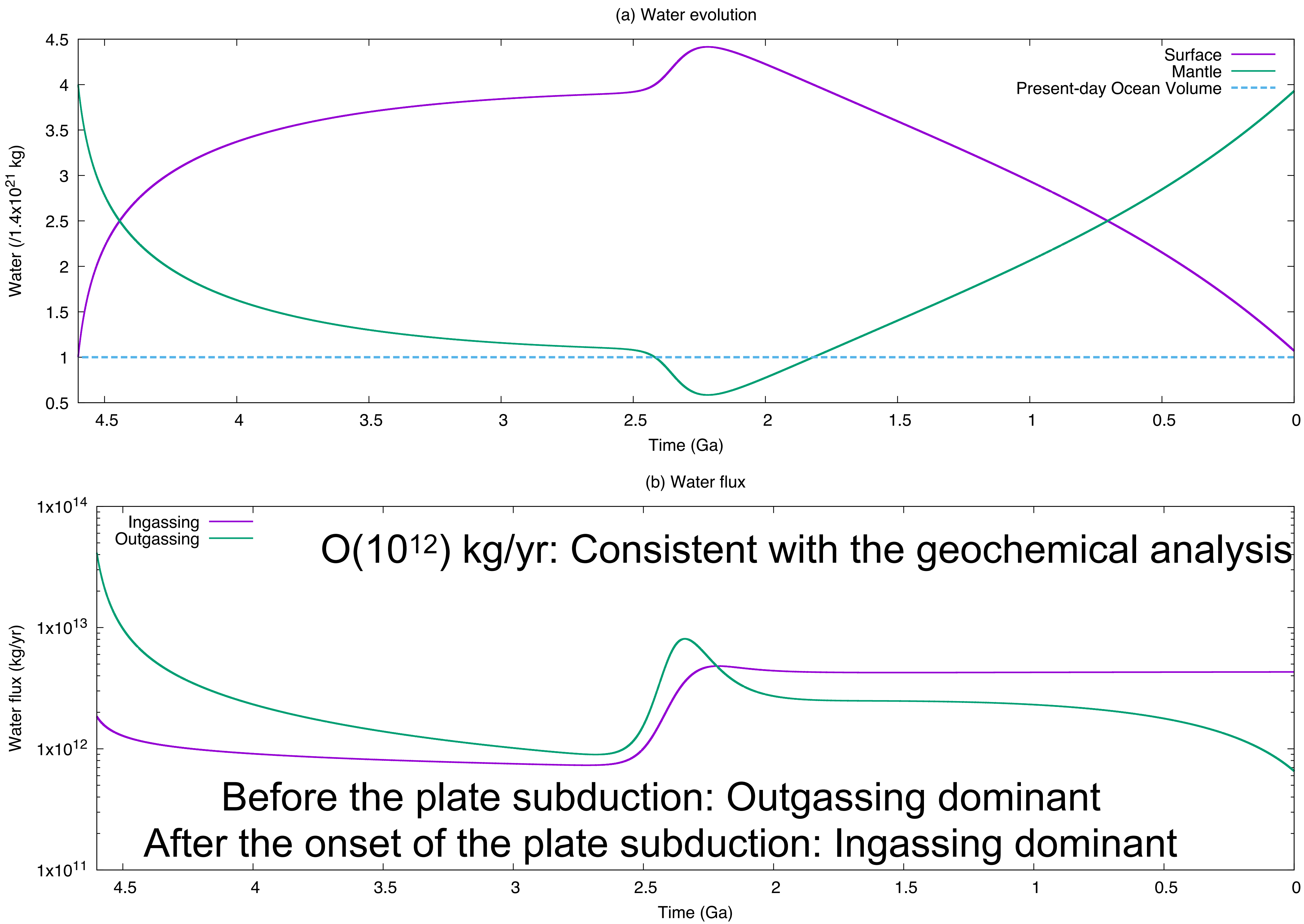


~40 TW at surface
~10 TW at the CMB

Two-step jump of the magnetic intensity

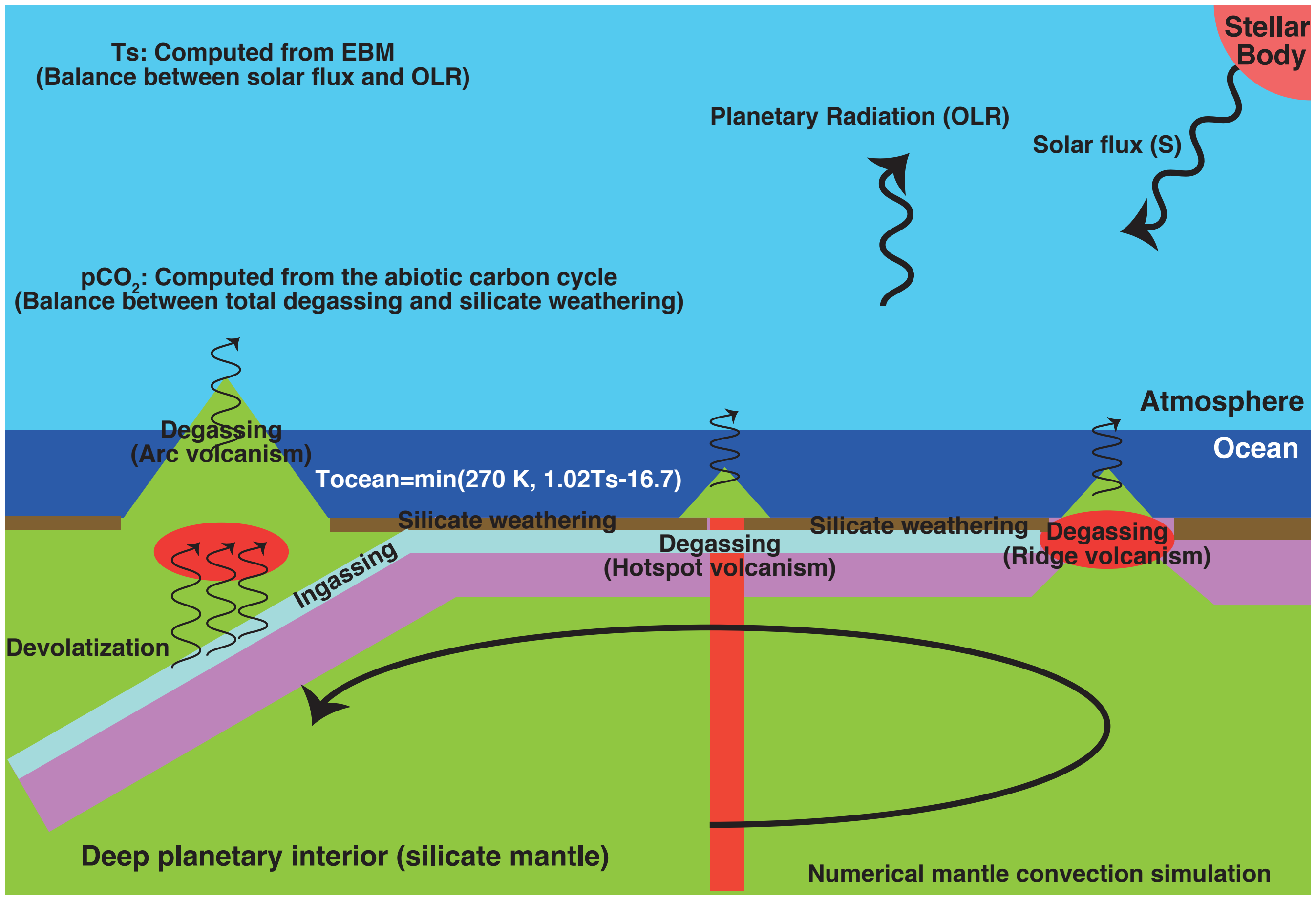
- Onset timing of the plate subduction
- Inner core growth
- One potential interpretation on the intensity of the geomagnetic field measured by paleomagnetism.

Deep mantle water cycling



Assessment of the climate evolution

Assumption: Carbon is only contributed for the climate evolution



Required to couple the carbon cycle

- Outgassing provides the greenhouse gas to the atmosphere-ocean
- Weathering: Uptake the carbon from the atmosphere-ocean system
- Deep mantle carbon cycling: Same as the water cycling except for the partition to the molten material.

Atmosphere-ocean temperature: Give the feedback to the deep interior system

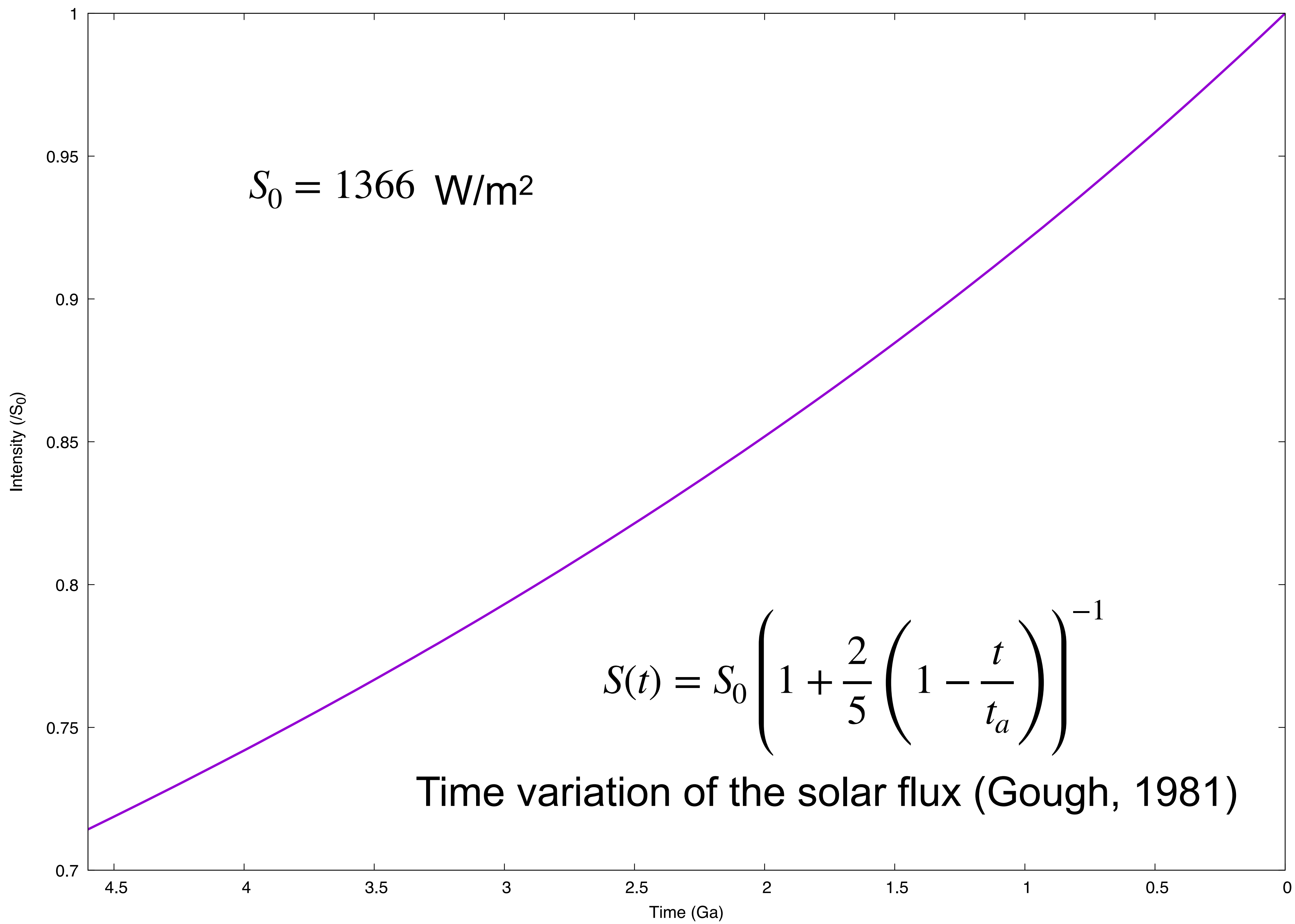
Computed by Energy Balance Model (EBM) - Balance between incoming solar flux and outgoing infrared radiation. See Kadoya and Tajika (2019) for the detailed formulation.

Equations for computing the evolution of the atmosphere-ocean system

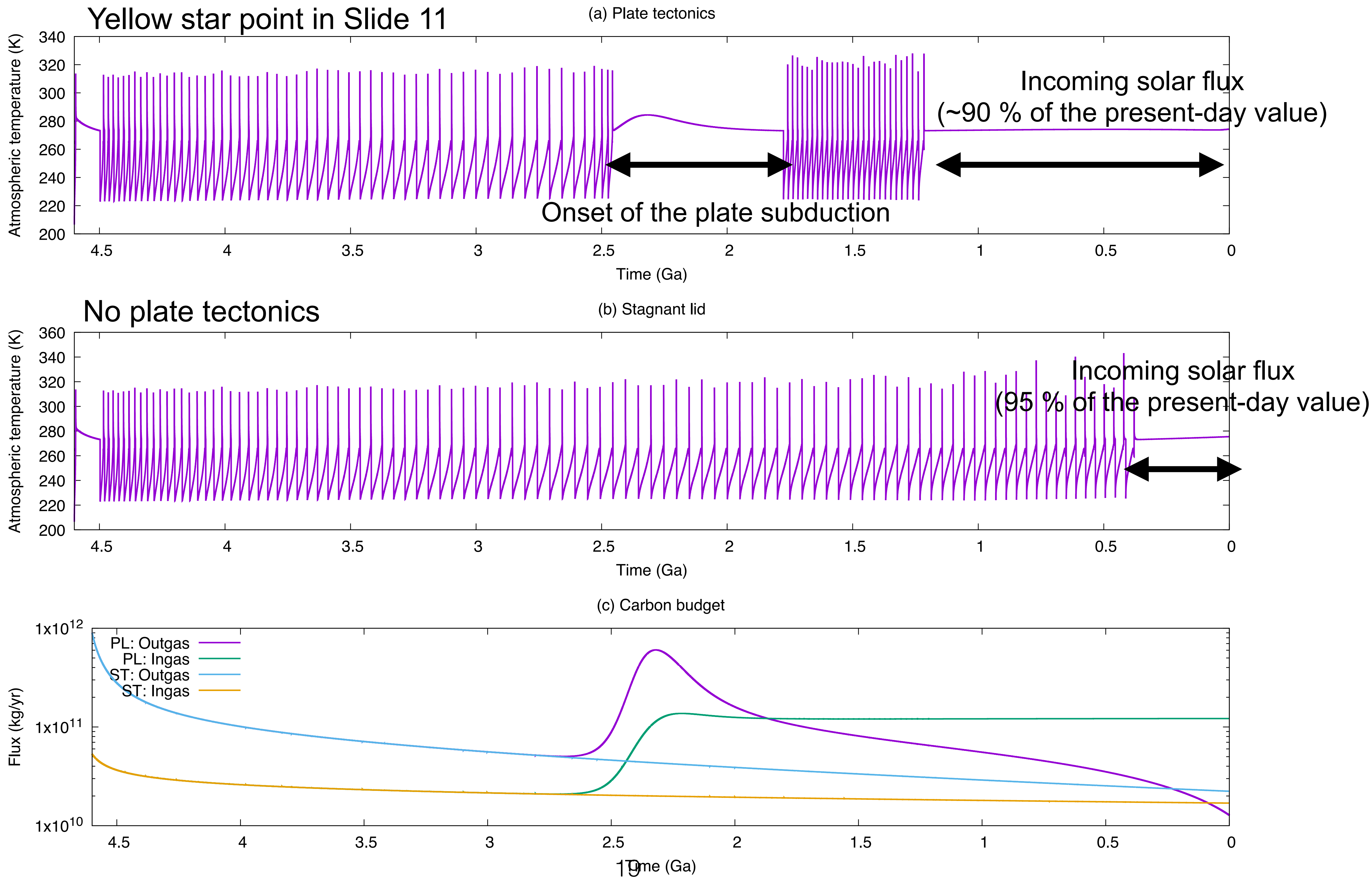
$$C_{a+o}\frac{dT_a}{dt} = \frac{1}{4}(1 - \alpha(T_a, P_{CO_2})S(t) - OLR(T_a, P_{CO_2})$$

$$\frac{dP_{CO_2}}{dt} = F_D - W(T_a, P_{CO_2})$$

Key point - Increasing the luminosity of the central star



Climate evolution: Plate tectonic (best successful model) vs Stagnant lid



Summary and discussion point

1. Simplified assessment model for the deep interior-exterior evolution is developed in the coupled core-mantle evolution model plus the deep volatile cycling and climate evolution model.

2. Plate tectonics: Onset timing may play an essential role in the planetary habitability constrained from dynamics and evolution of the deep interior?: Onset timing ~ 2.3 Ga in this investigation to find the best-fit model for constraints on ocean volumes, inner core size and magnetic field intensity.

3. Two-step jump of the magnetic field intensity: Might give an additional interpretation on the paleomagnetic intensity profile?

4. Feedback to the climate: The plate tectonic plate would be more promising for finding the habitable state. Transit from Snowball limit cycle to Mild climate. For determining the climate state on the rocky planet, the incoming solar flux might be more significant than the outgassing of the carbon?

5. To further improve: Replace the full dynamic simulation of mantle convection?; Assume that the water is an additional greenhouse gas?

6. Any questions, suggestions, and comments: Please send email inquiries to me (ntakashi@hku.hk or takashi.geodynamics@gmail.com).