A coupled core-mantle evolution

Insight from numerical and theoretical geodynamics modeling

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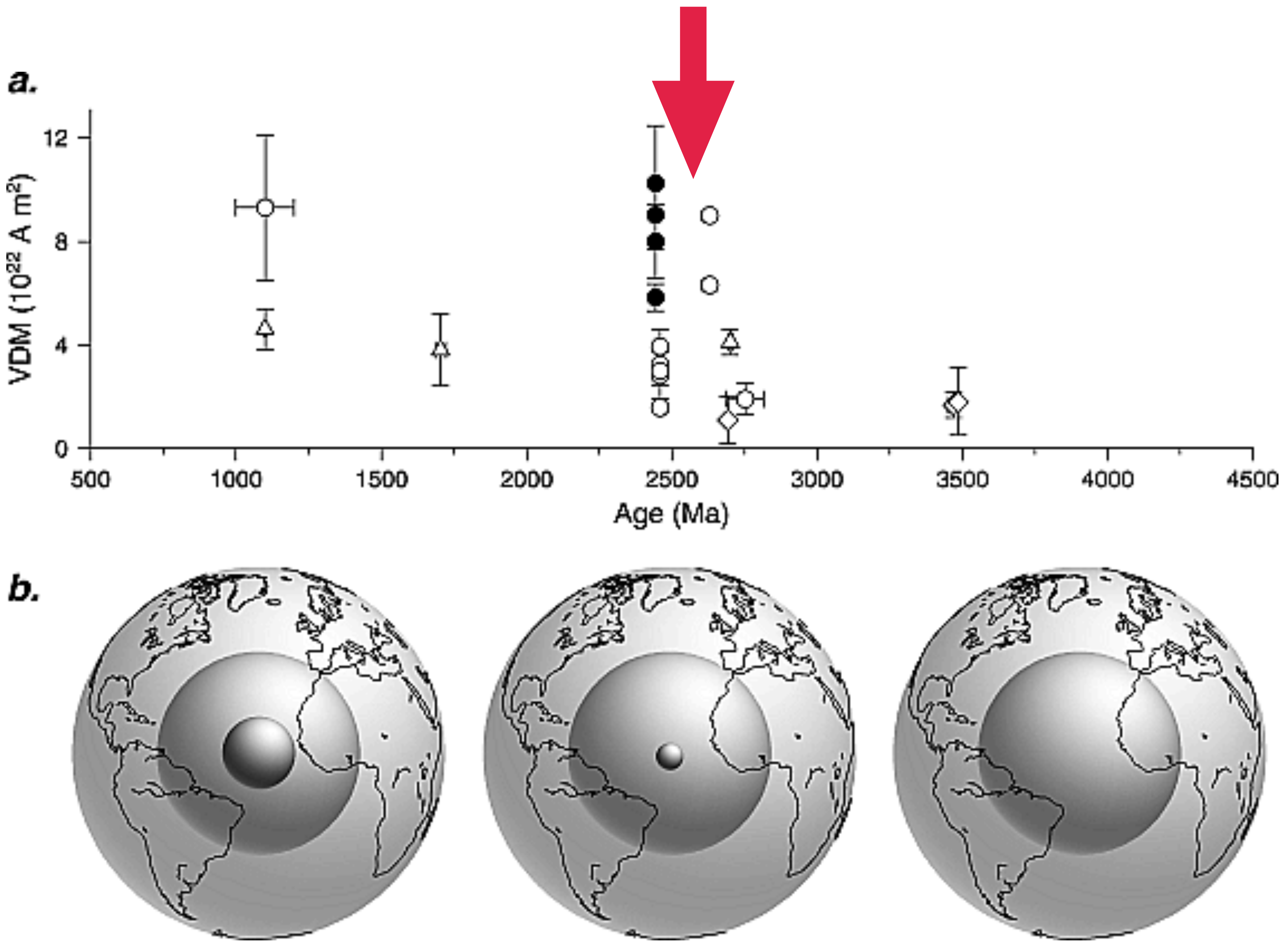
Contents

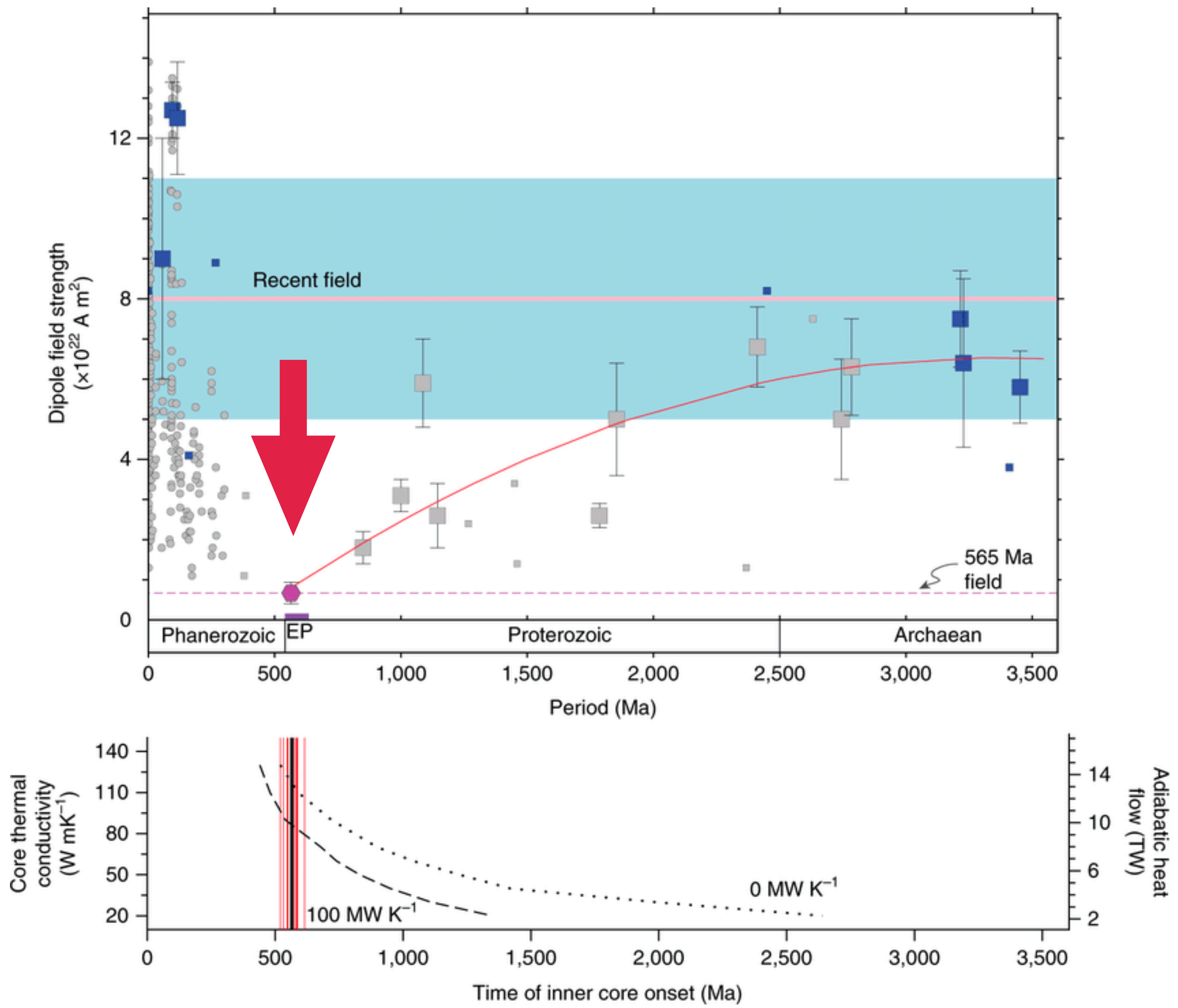
- Motivation and Development of coupled core-mantle evolution model
- Radioactive heat productions: How they affect the long-term evolution of Earth's deep interior
- Structure of Earth's outer core: Emergence on the stable region or not.
- Consulting to the neutrino community from geodynamics community if possible?

Primary motivation: Paleomagnetic experiments - Age of the inner core

Controversial: Younger or older?



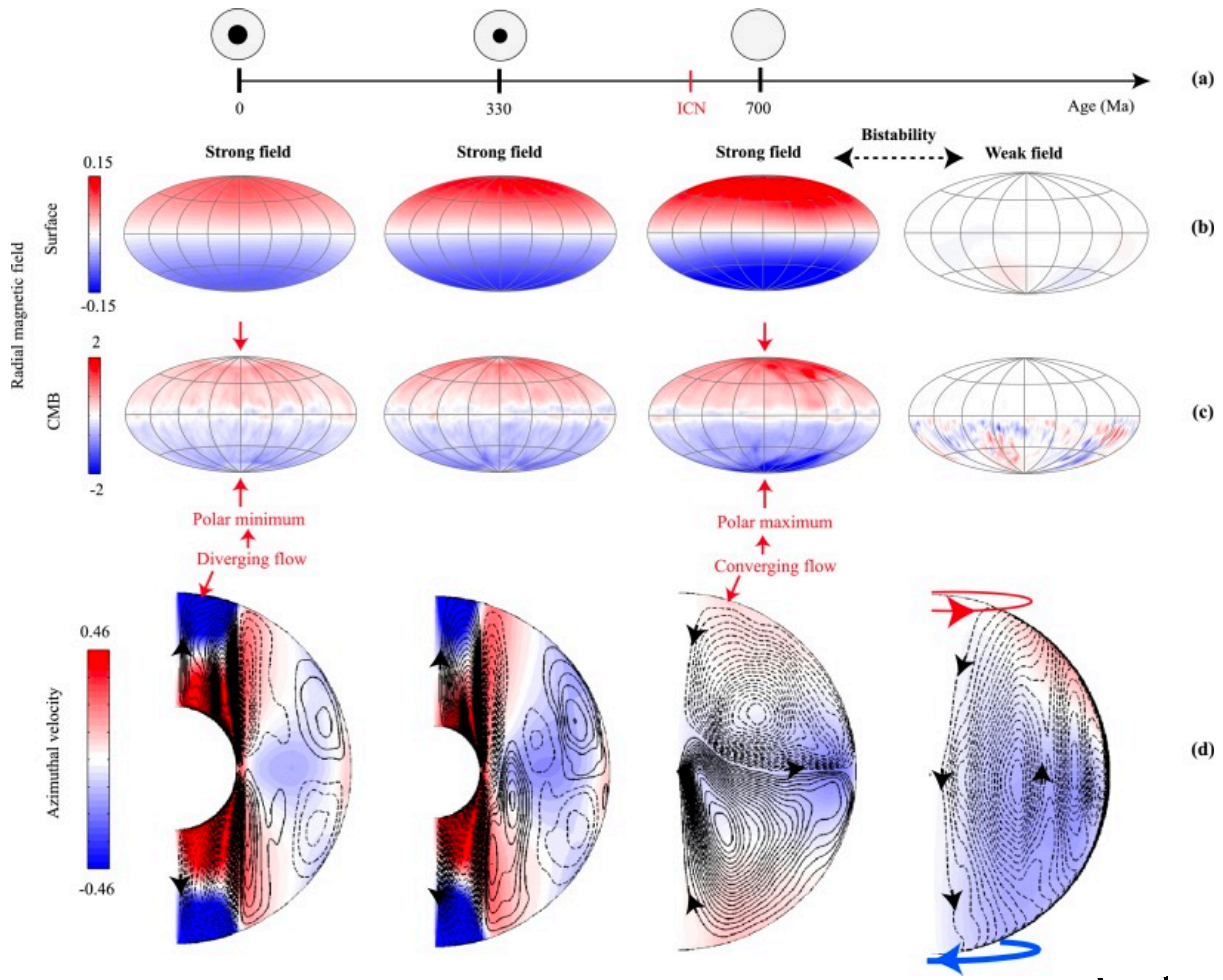
Tarduno et al. (2006)



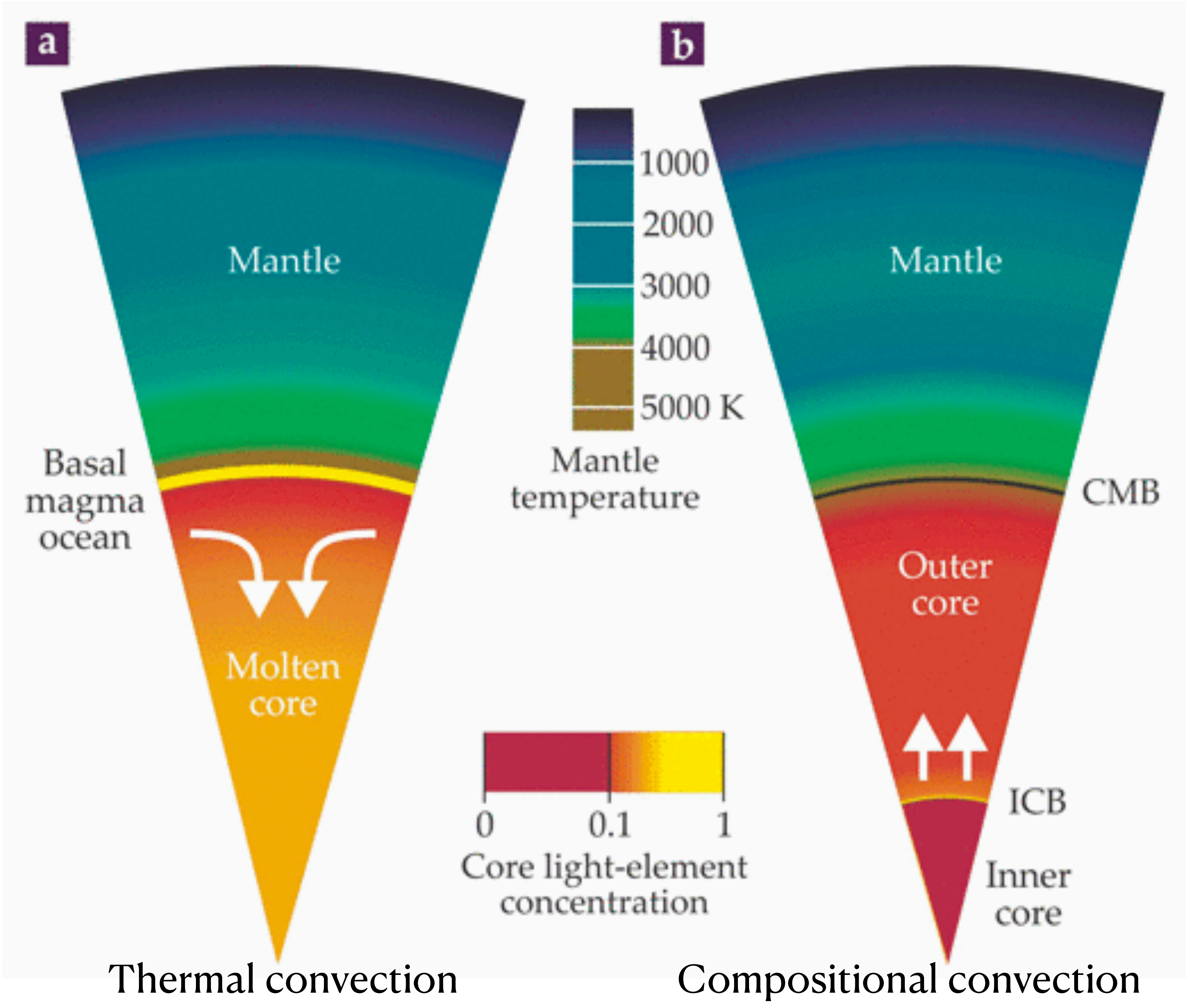
Bono et al. (2019)

Why could the magnetic field suddenly increase with the inner core growth?

Switching of major source of geodynamo action



Landeau et al. (2017)



Olson (2013)

How can we understand the core evolution?

Geodynamo simulations or simplified approach? - Time-scale of dynamics and evolution matters

Typical parameters in geodynamo simulations: still far away for approaching the Earth's values and impossible to perform time integration over 4 billion years - Needed to use the simplified approach.

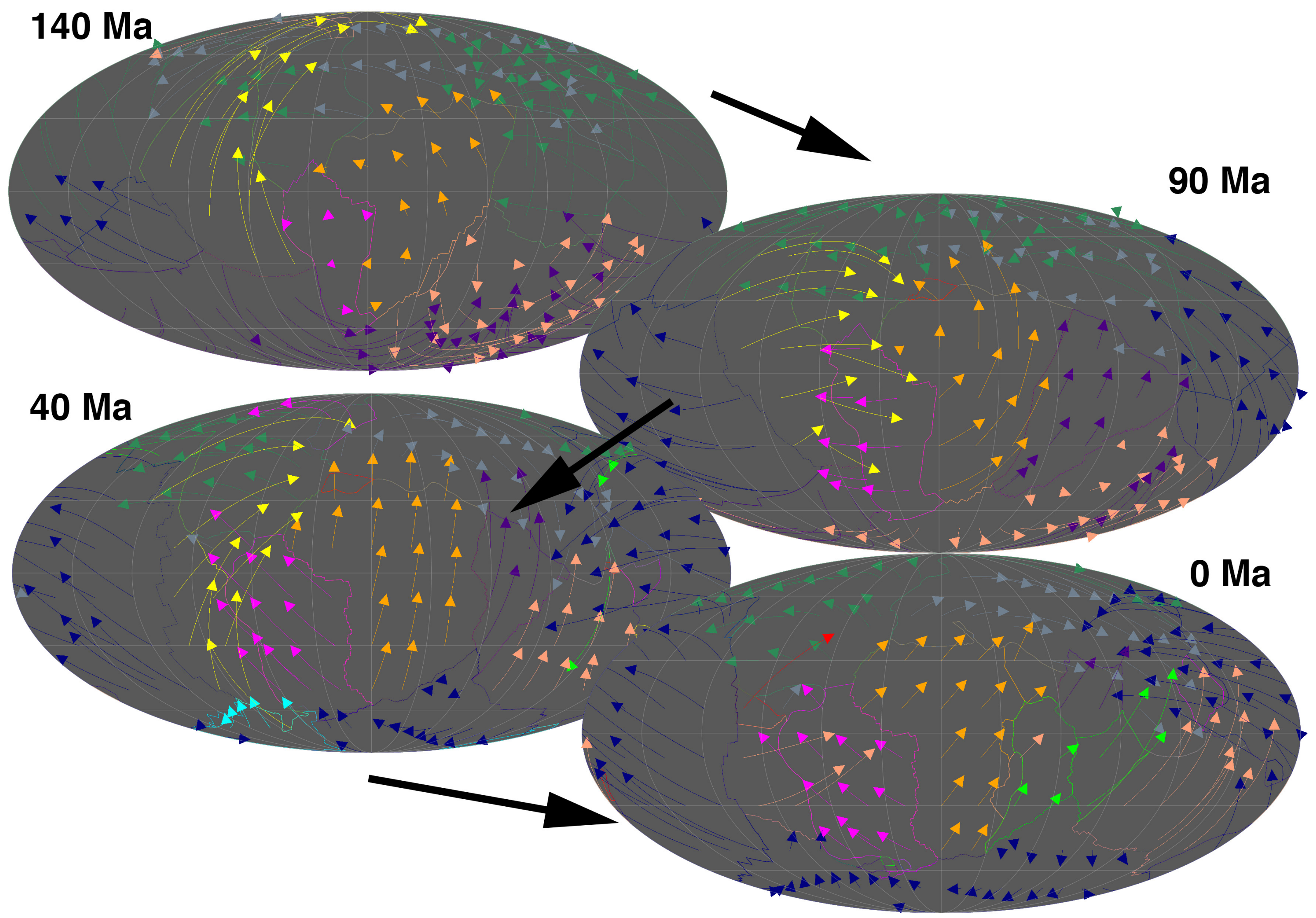
Name	Symbol	Definition	Meaning	Range in this work	Earth
Ekman	E	$\nu/\Omega D^2$	$\frac{\text{planetary rotation period}}{\text{viscous diffusion time}}$	$10^{-8} - 3 \times 10^{-5}$	$O(10^{-15})$
Magnetic Prandtl	Pm	ν/η	$\frac{\text{magnetic diffusion time}}{\text{viscous diffusion time}}$	0.045–2.5	$O(10^{-6})$
Flux Rayleigh	Ra_F^*	$\frac{g_o F}{4\pi\rho\Omega^3 D^4}$	$\left(\frac{\text{power input rate}}{\text{planetary rotation rate}}\right)^3$	$9 \times 10^{-9} - 2.9 \times 10^{-5}$	$O(10^{-12})$
Lehnert	λ	$\frac{B}{(\rho\mu)^{1/2}\Omega D}$	$\frac{\text{planetary rotation period}}{\text{Alfvén time}}$	2×10^{-3}–2×10^{-2}	$O(10^{-4})$
Elsasser	Λ	$B^2/\rho\mu\eta\Omega$	$\frac{\text{Lorentz force}}{\text{Coriolis force}}$	18.4–31.7	$O(10)$
Rossby	Ro	$U/\Omega D$	$\frac{\text{planetary rotation period}}{\text{overturn time}}$	2.4×10^{-4}–1.1×10^{-2}	$O(10^{-6})$
Reynolds	Re	UD/ν	$\frac{\text{viscous diffusion time}}{\text{overturn time}}$	372–2.4×10^4	$O(10^9)$
Magnetic Reynolds	Rm	UD/η	$\frac{\text{magnetic diffusion time}}{\text{overturn time}}$	930–1099	$O(10^3)$
Squared Alfvén	A^2	$\rho\mu U^2/B^2$	$\frac{\text{kinetic energy}}{\text{magnetic energy}}$	1.4×10^{-2}–0.48	$O(10^{-4})$

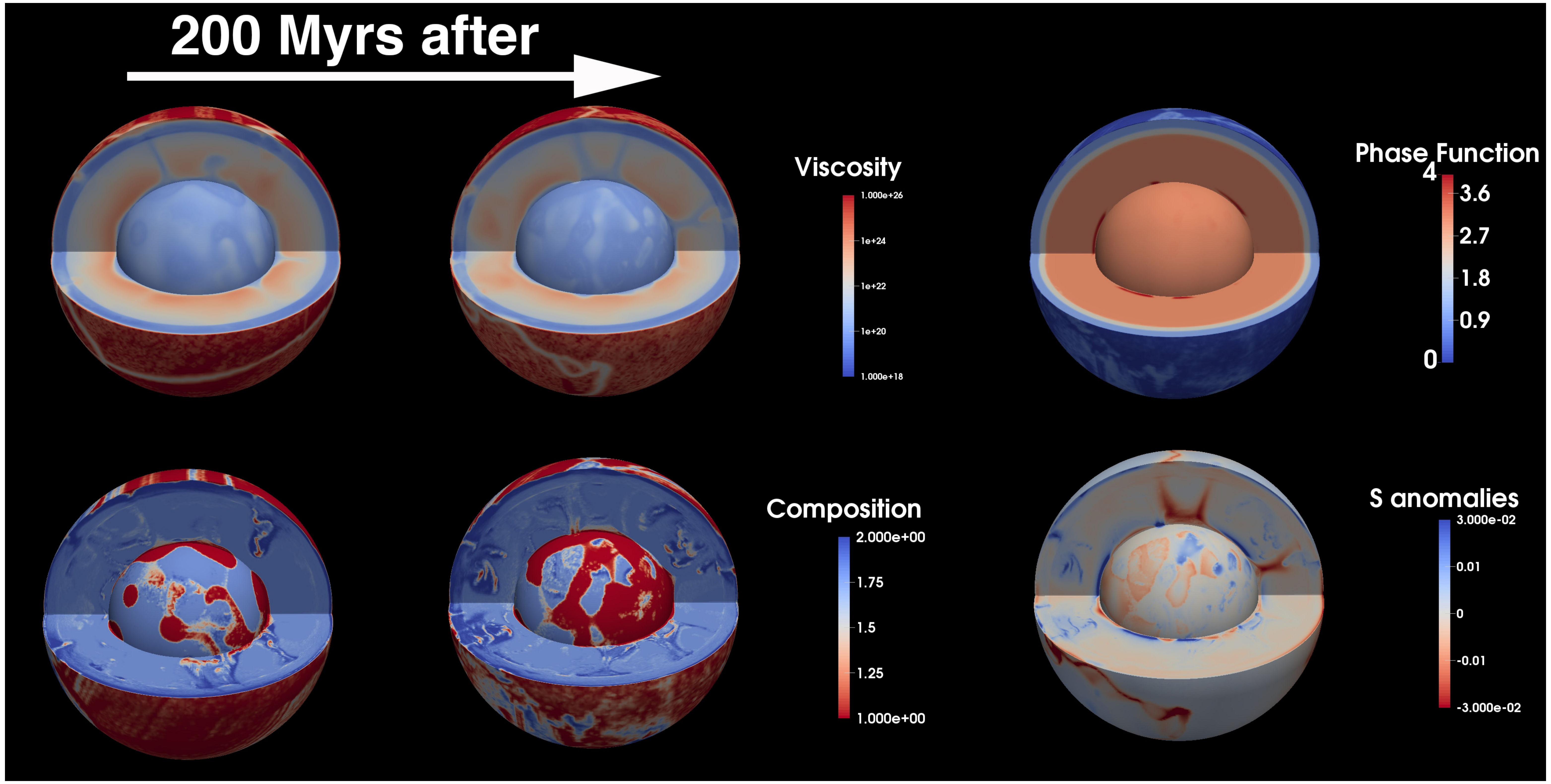
TABLE 1. Summary of the main input and output parameters, together with their values in this work and in the Earth's core. See § 2 for definitions and § 3 for a discussion of geophysical estimates.

Aubert et al. (2017)

Earth's mantle as the heat and mass engine

Long-term dynamics



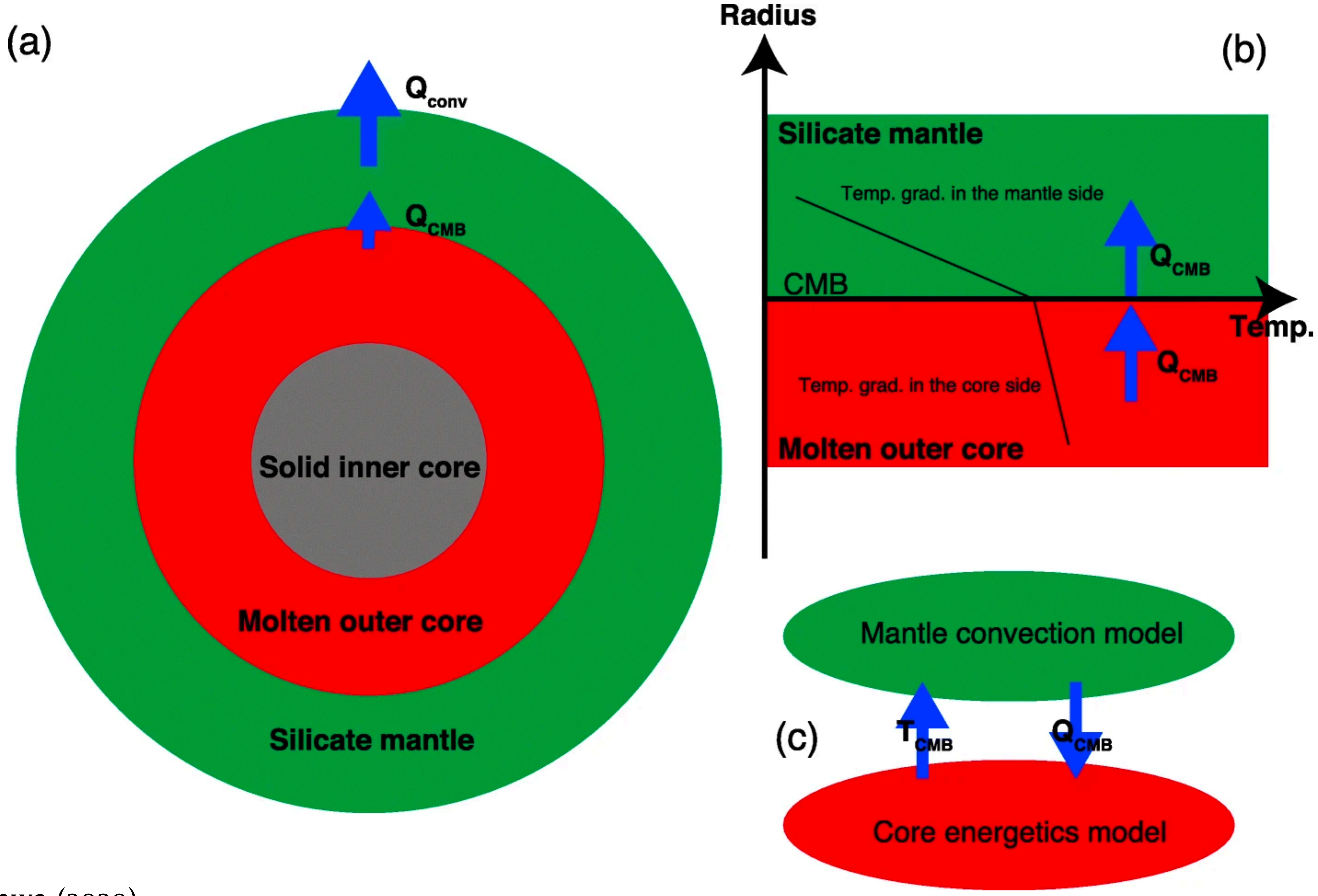


Nakagawa in IASPEI (2016)

Time-scale of plate tectonics~200 Myrs - Possible to resolve the long-term evolution of Solid Earth.

Potential solutions: A coupled core-mantle evolution

Can find the long-term evolution in both plate tectonics and geodynamo



Mantle dynamics - fully solved by using the large-scale computer simulation. Core dynamics - simplified energy and mass balances by using semi-analytical approach.

A continuous condition at the core-mantle boundary is required - Heat flow across the CMB has to be the same at both sides

Nakagawa (2020)

Heat budget across the Earth's deep interior

How radioactive heat production works out in the system?

Table 1 Heat budget across the Earth's deep interior. Model estimates are taken from Nakagawa and Tackley (2012); Observational constraints are taken from Jaupart et al. (2007). The heat production rate is indicated after excluding the heat production of the continental crust which is typically ~7 TW (see Jaupart et al. 2007). The cooling rate at the core-mantle boundary is represented as the convective cooling rate in the whole mantle

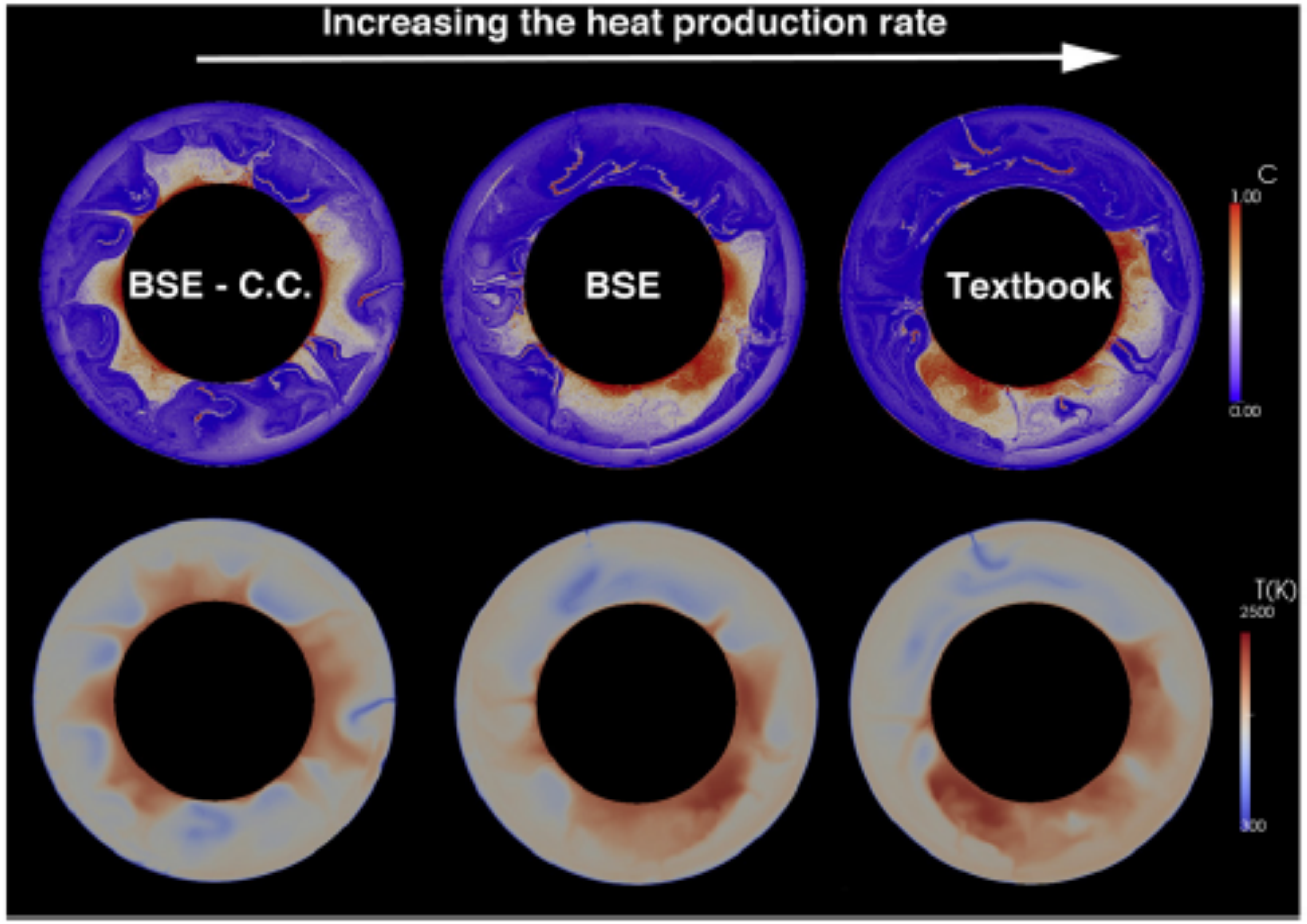
	Model	Observational constraints
Surface heat flow across the oceanic lithosphere	~35 TW	32 TW
Heat flow across the CMB	12 TW	8 TW 8 to 15 TW or more (Lay et al., 2008)
Heat production in the silicate mantle (excl. the continental crust)	12.5–28.5 TW	13 TW
Cooling rate at the core-mantle boundary	~70 K/Gyrs	118 K/Gyrs

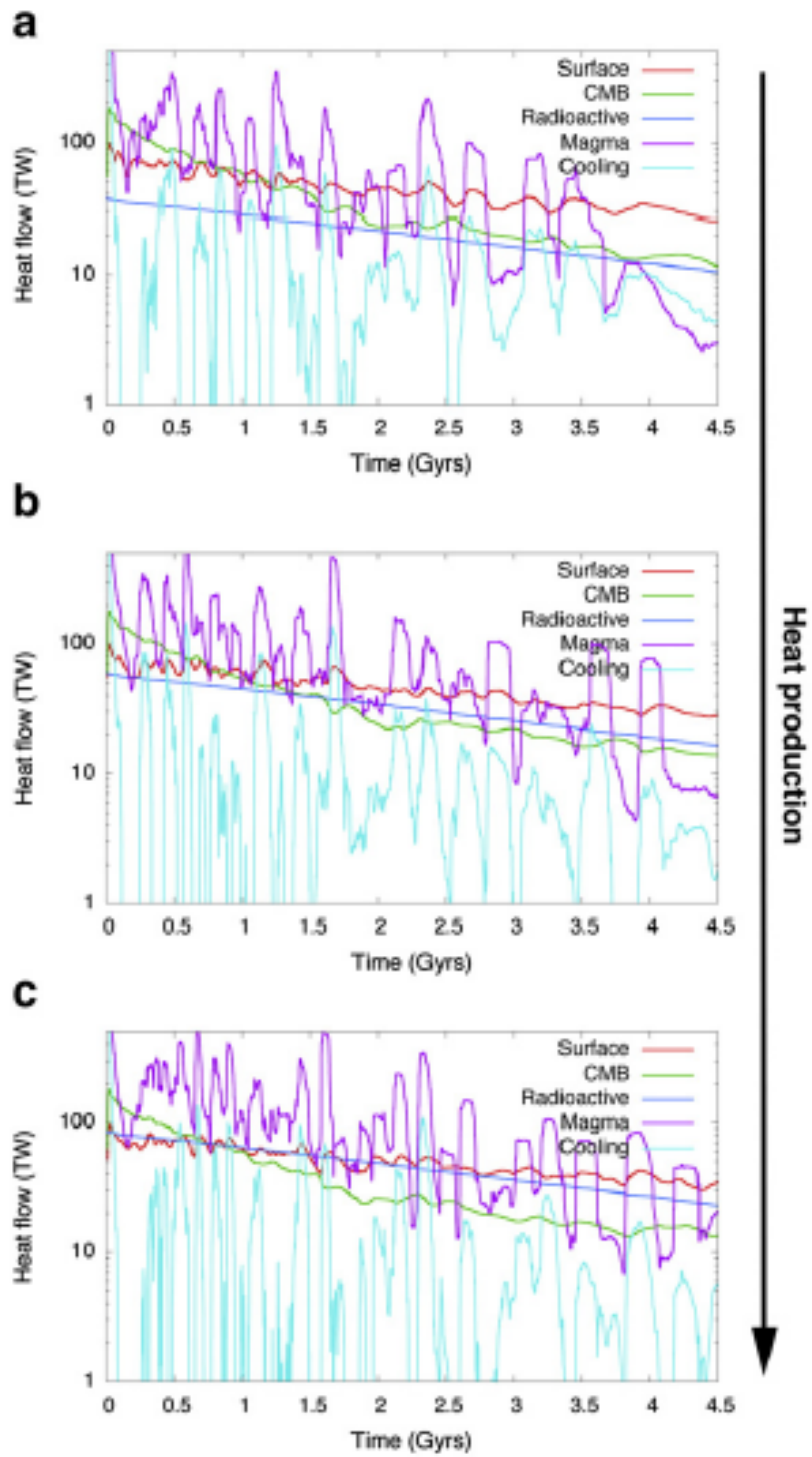
Mantle convection drives plate tectonics and heat engine of the Earth.

Sensitivity to the radioactive heat source in silicate mantle

Might not be very sensitive
Magnetic heat transfer could control the system

BSE-CC=12.5TW; BSE=20TW; Textbook=28.5TW of radioactive heat production.

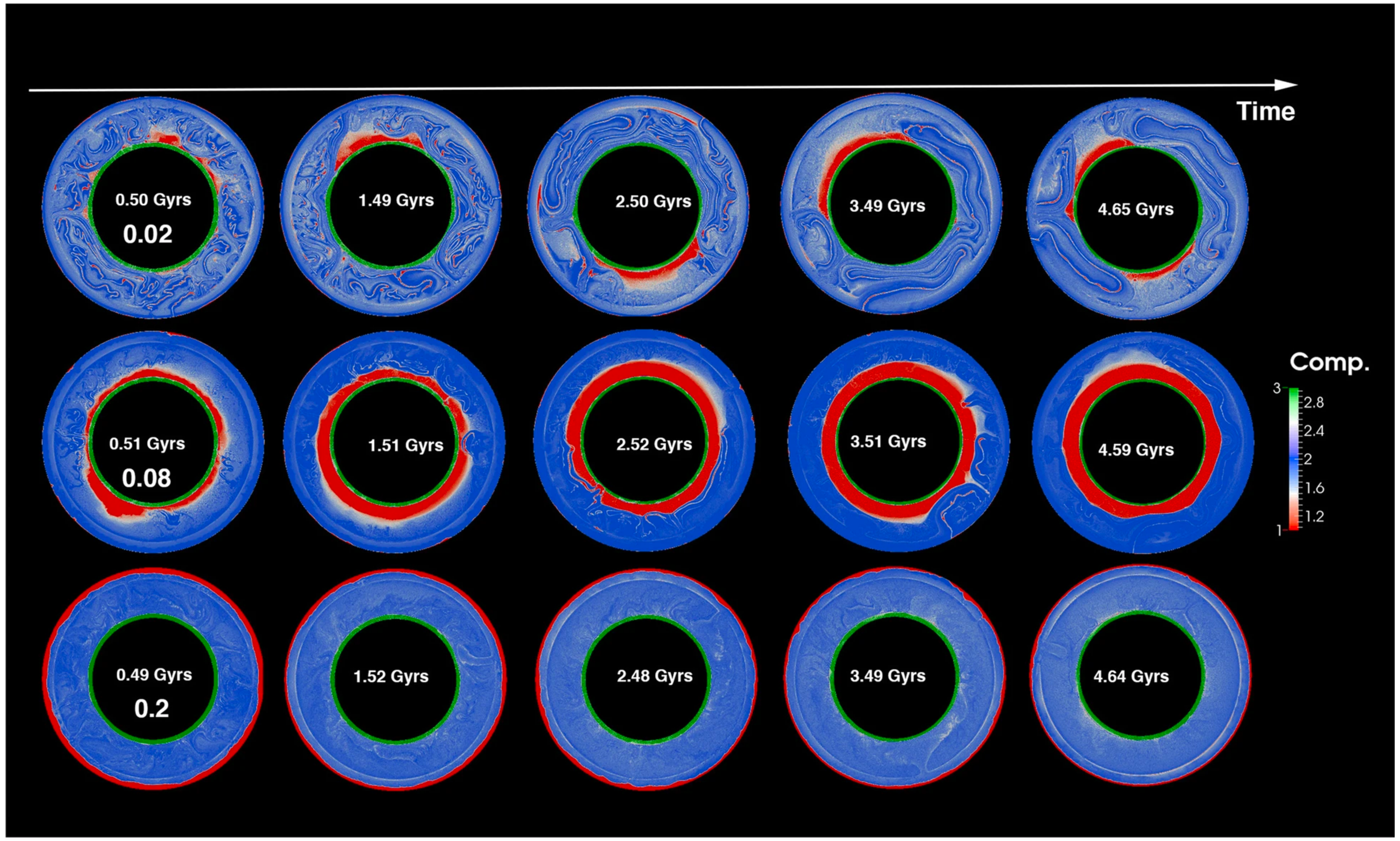


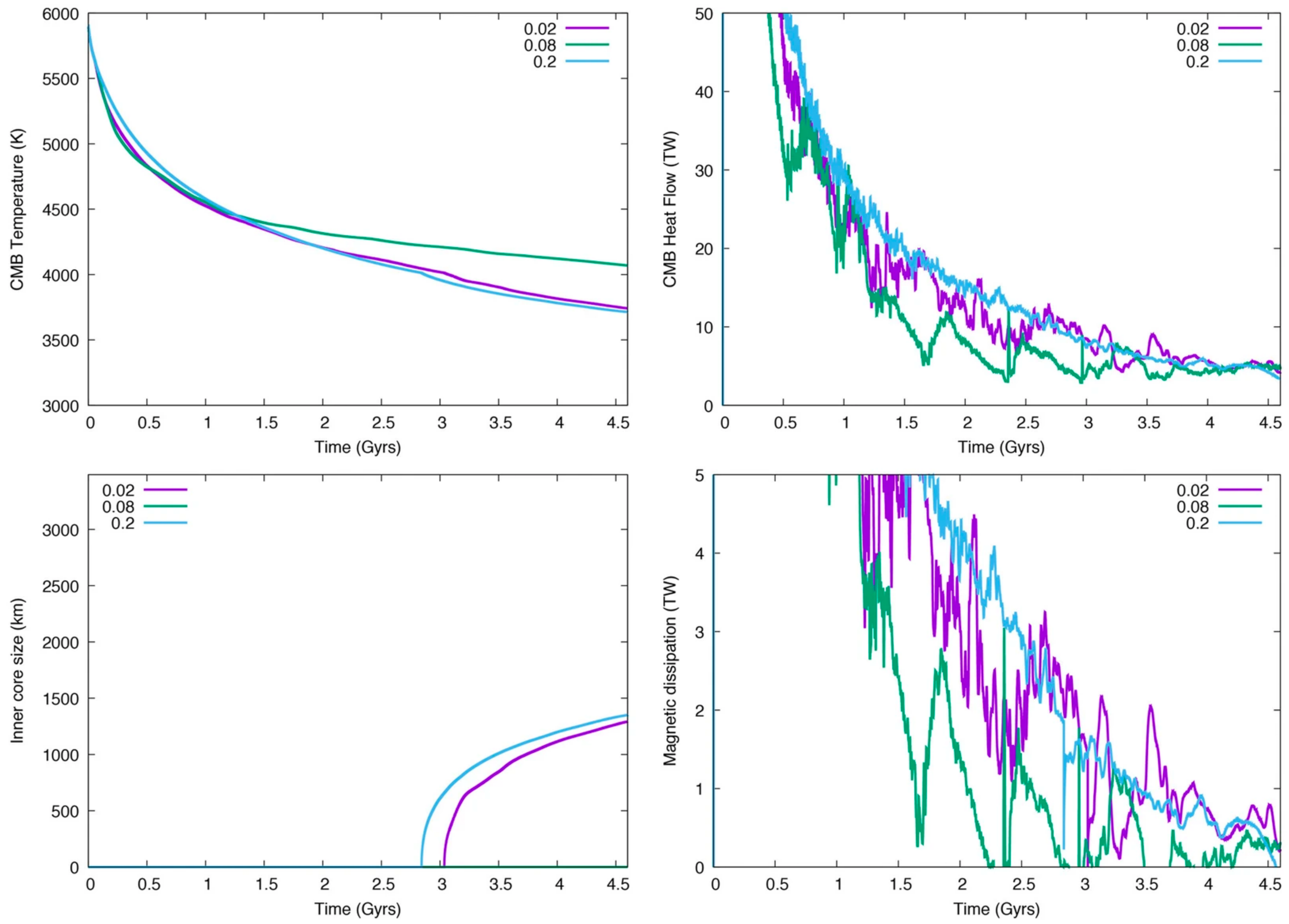


Nakagawa and Tackley (2012)

Mantle dynamics coupled with the core energetic

Plate tectonics-heat engine-magnetic field generation





Strength of plate: Sufficiently weak due to the earthquakes- Plate tectonics is driven by mantle convection (Nakagawa and Karato, 2021)

After Nakagawa and Tackley (2015)

Energy budget of Earth's core

Potentially, the radioactive heat production is needed?

Energy balance across the Earth's core

$$Q_{CMB} = Q_C + Q_L + E_G + Q_R$$

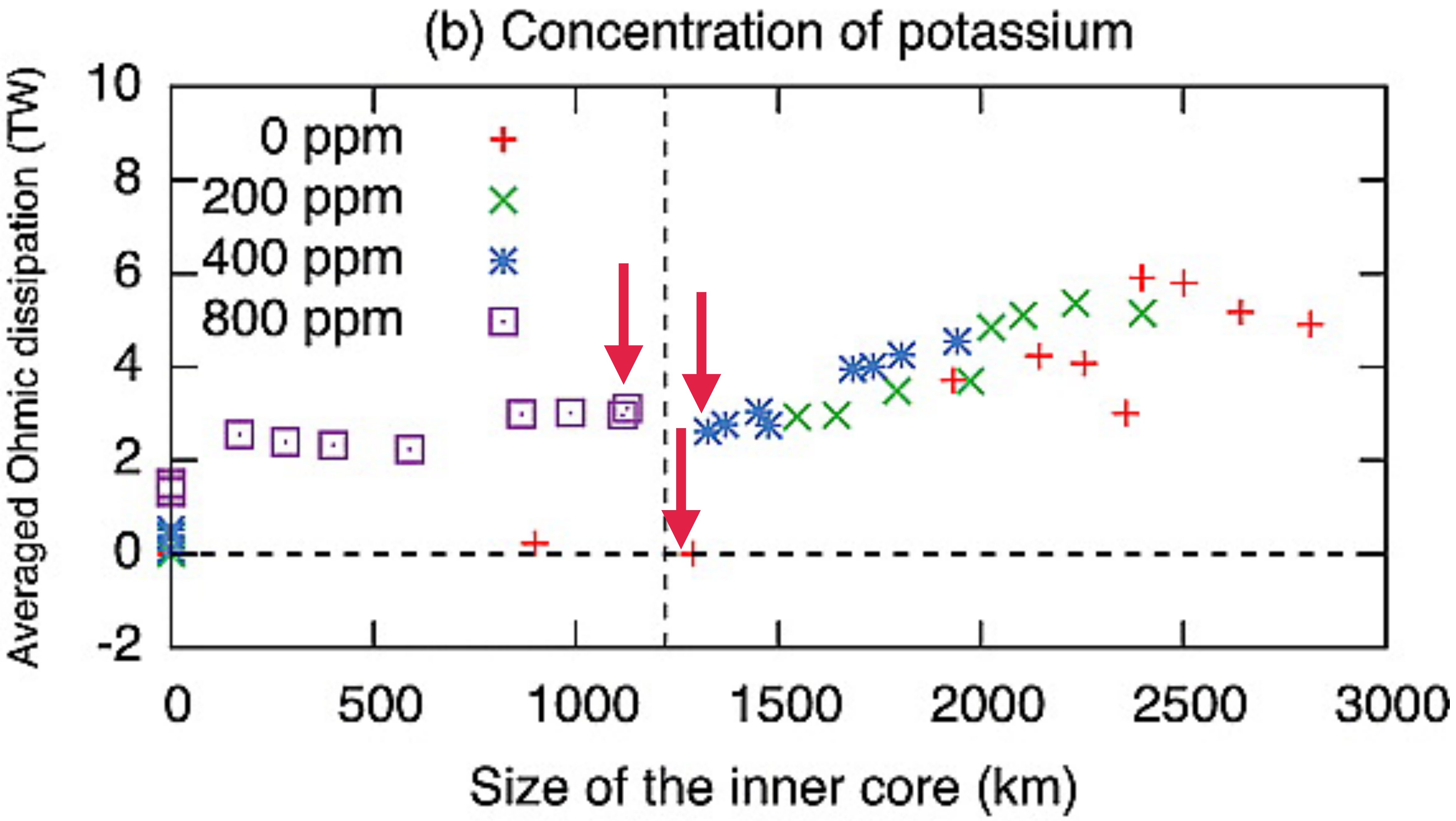
$$Q_{CMB} = 15\mathrm{TW}$$

Secular cooling Q_C	9.14 TW
Latent heat release Q_L	3.49 TW
Gravitational energy E_G	2.37 TW
Radioactive heat production Q_R	0 TW

Is the radioactive heat production of Earth's core really zero?

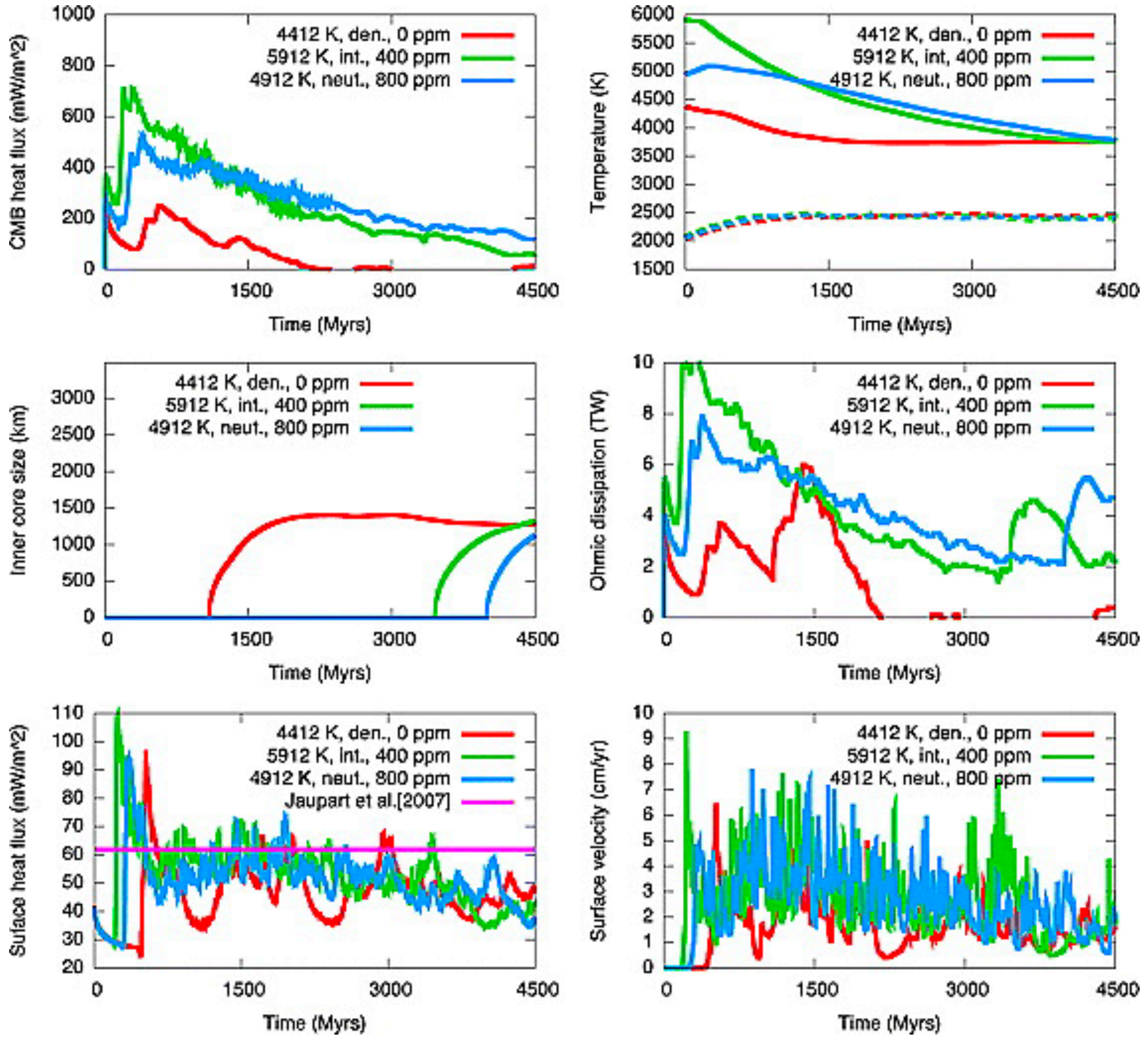
Possibility of the radioactive elements in Earth's core

Maybe or unlikely?



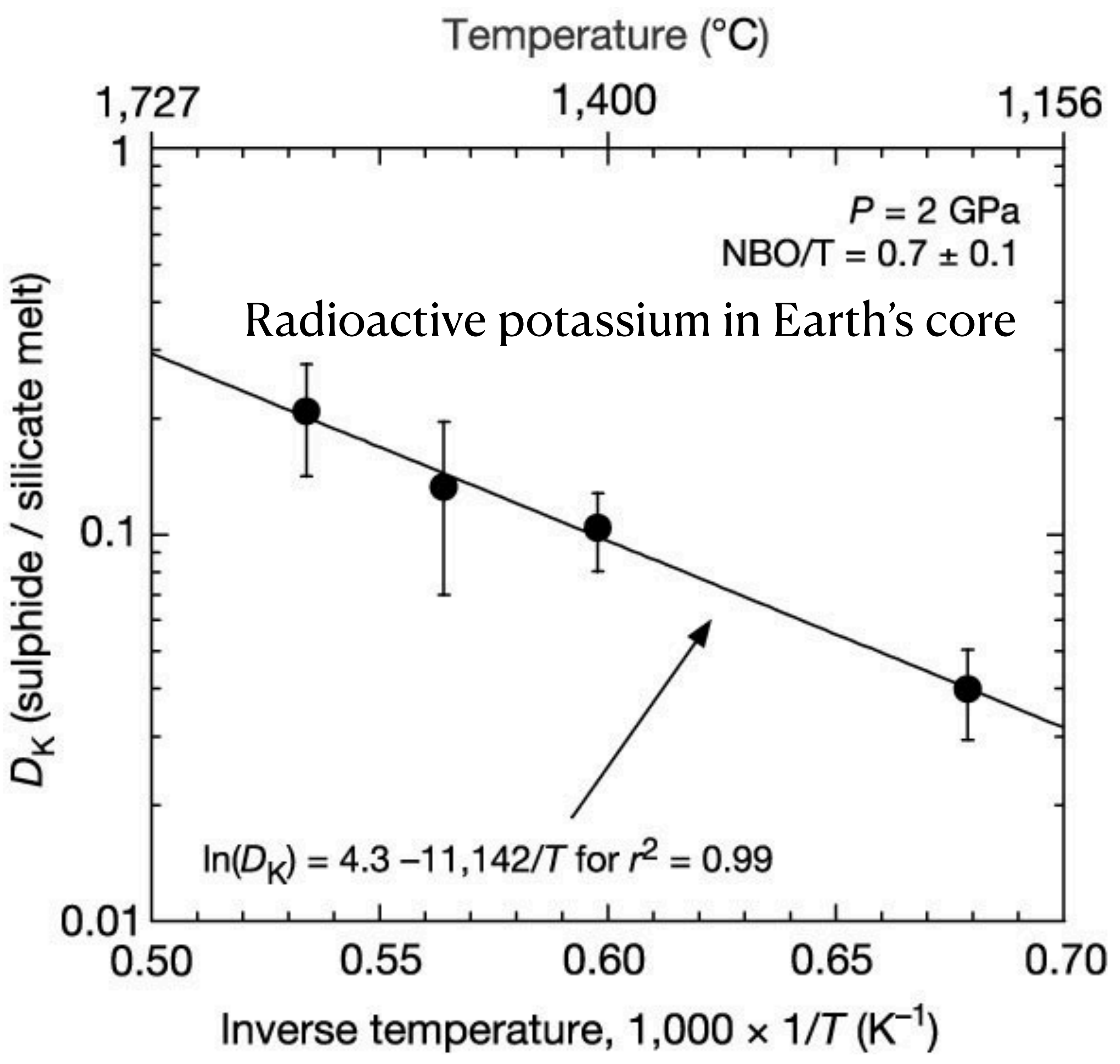
Nakagawa and Tackley (2010)

Potentially, the initial thermal structure of Earth's deep interior might be unrealistically hot!



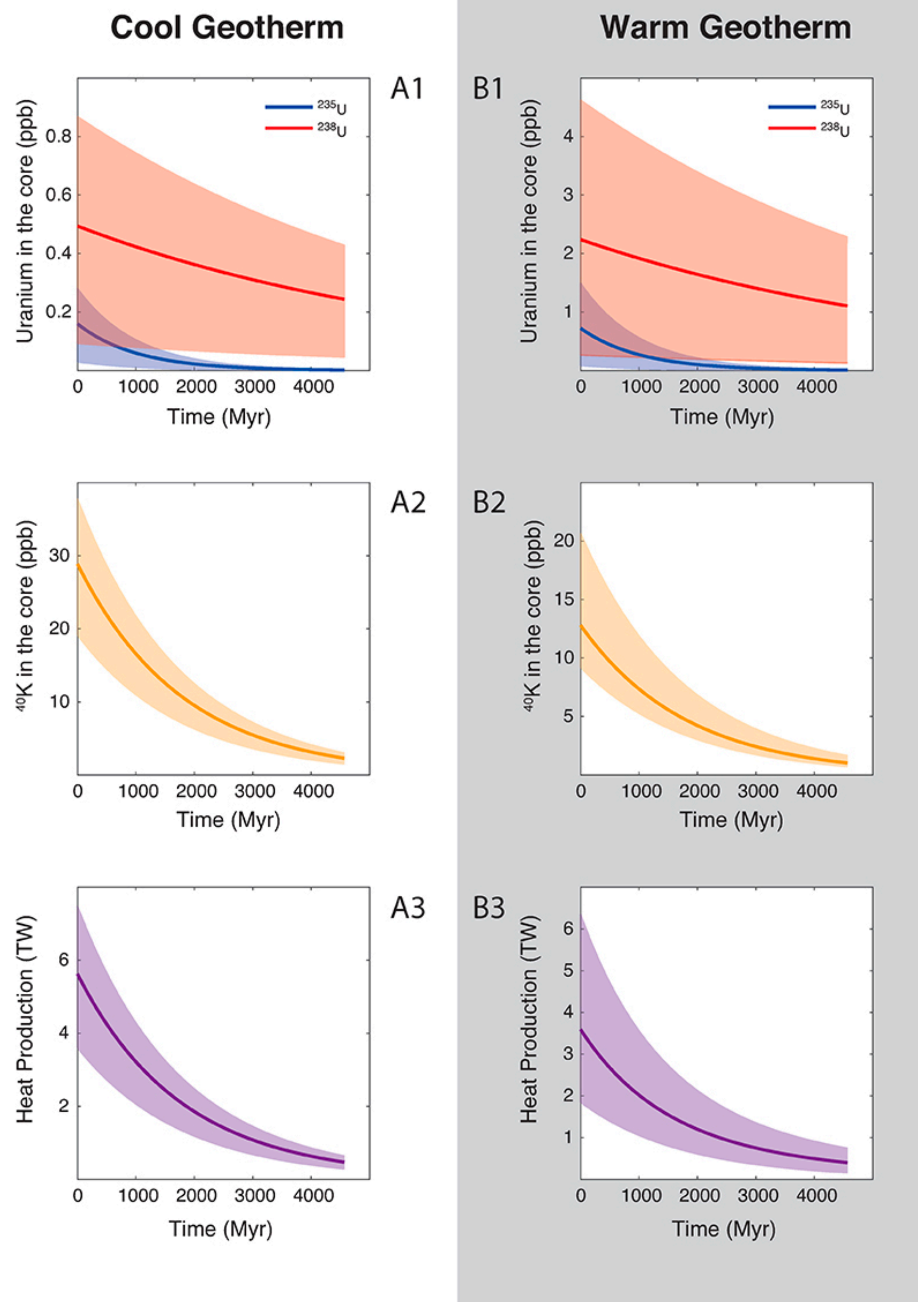
Radioactive heat production in Earth's core

High P-T experiments: Likely to unlikely



Rama Murthy et al. (2003): O(100) ppm could be contained in Earth's core

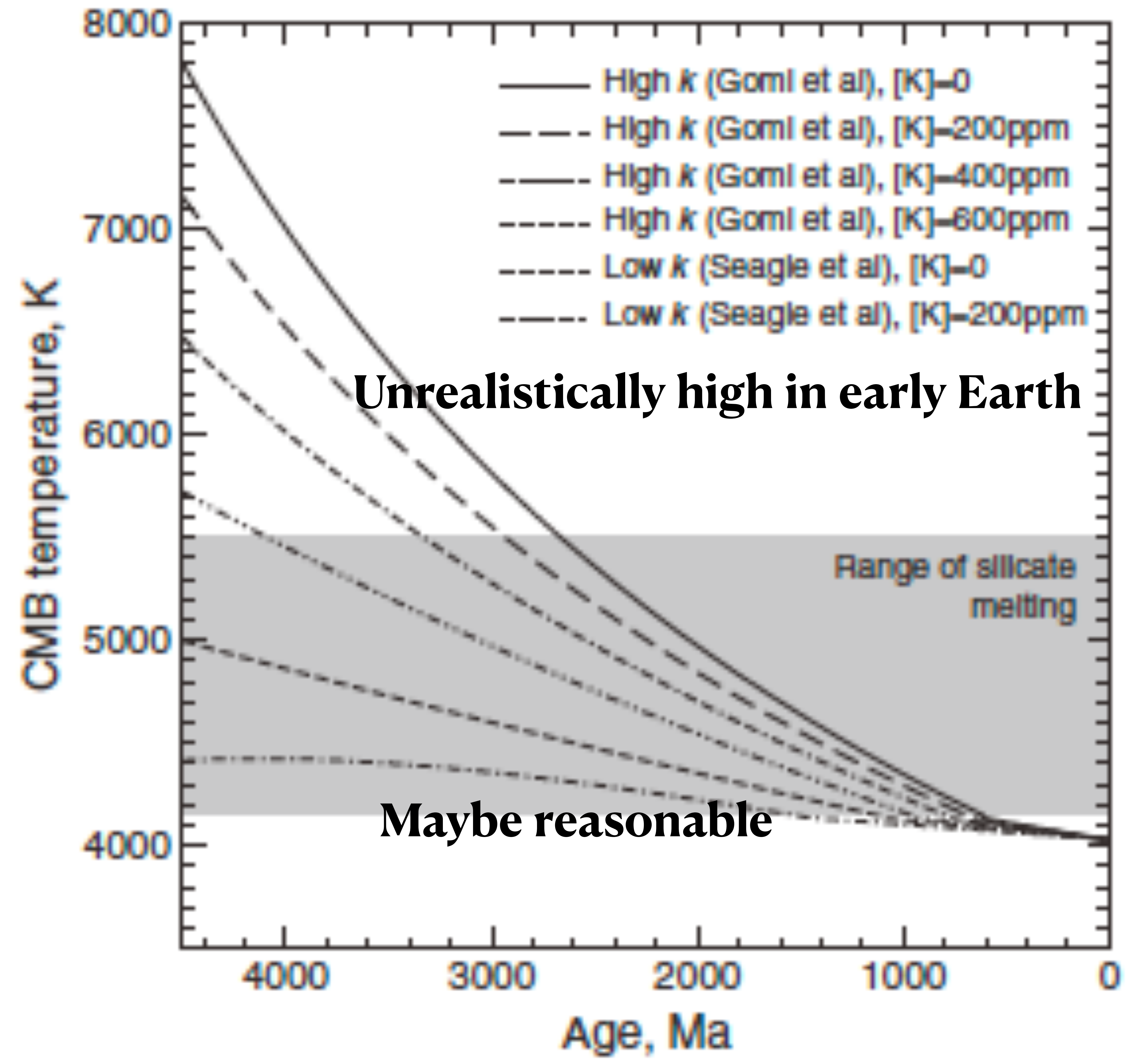
Unlikely in Earth's core



Blanchard et al. (2019): Unlikely

Possibility of radioactive heat production in Earth's core

Based on simplified analysis



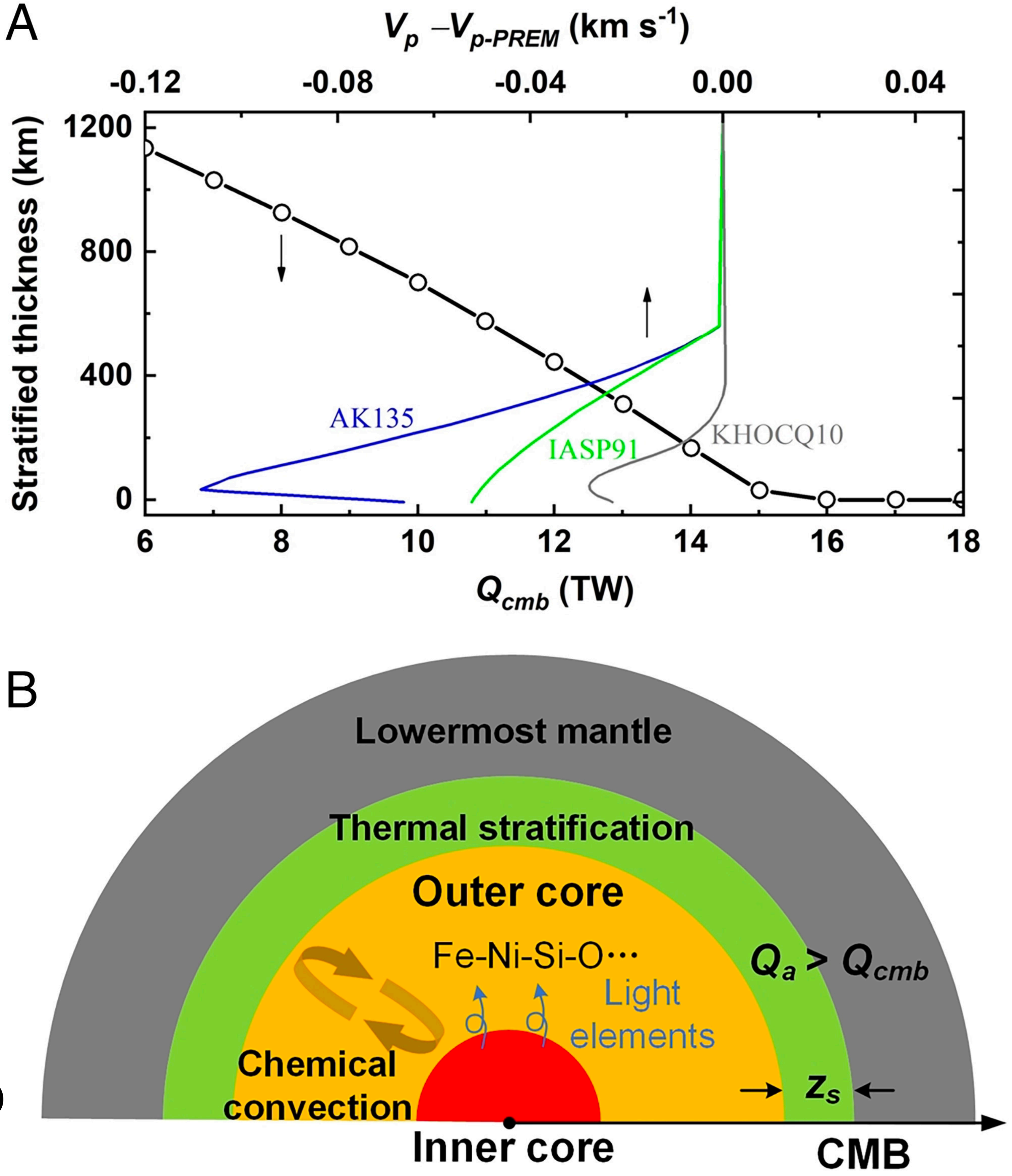
Possibly, a few 100 ppm of radioactive potassium might be acceptable.

This is a big gap between theoretical/ numerical modeling and high P-T experiments - Needed to resolve this issue in geoscience side.

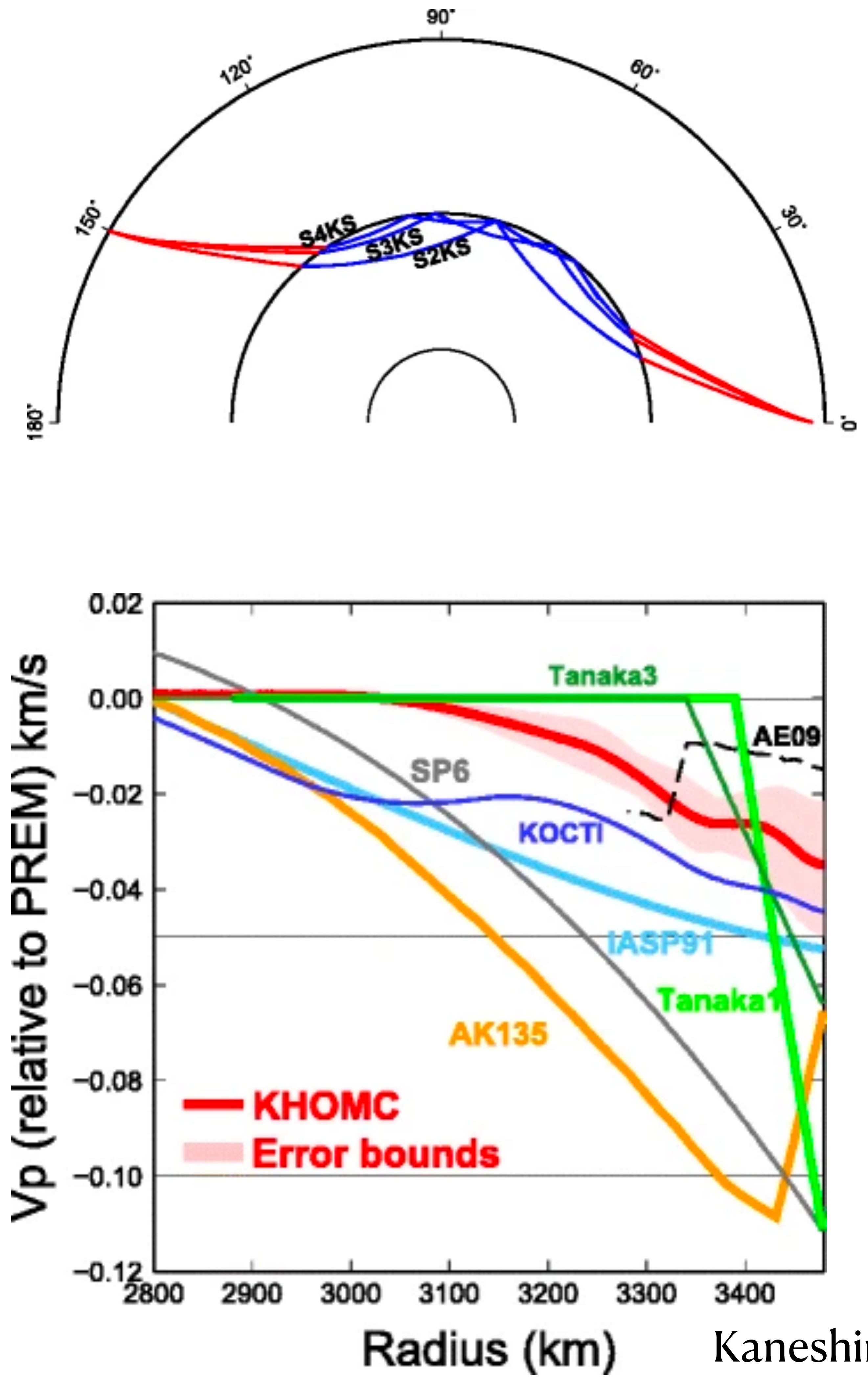
Labrosse (2015)

Structure of Earth's outer core

Observation - Emergence of stably stratified region at the uppermost outer core



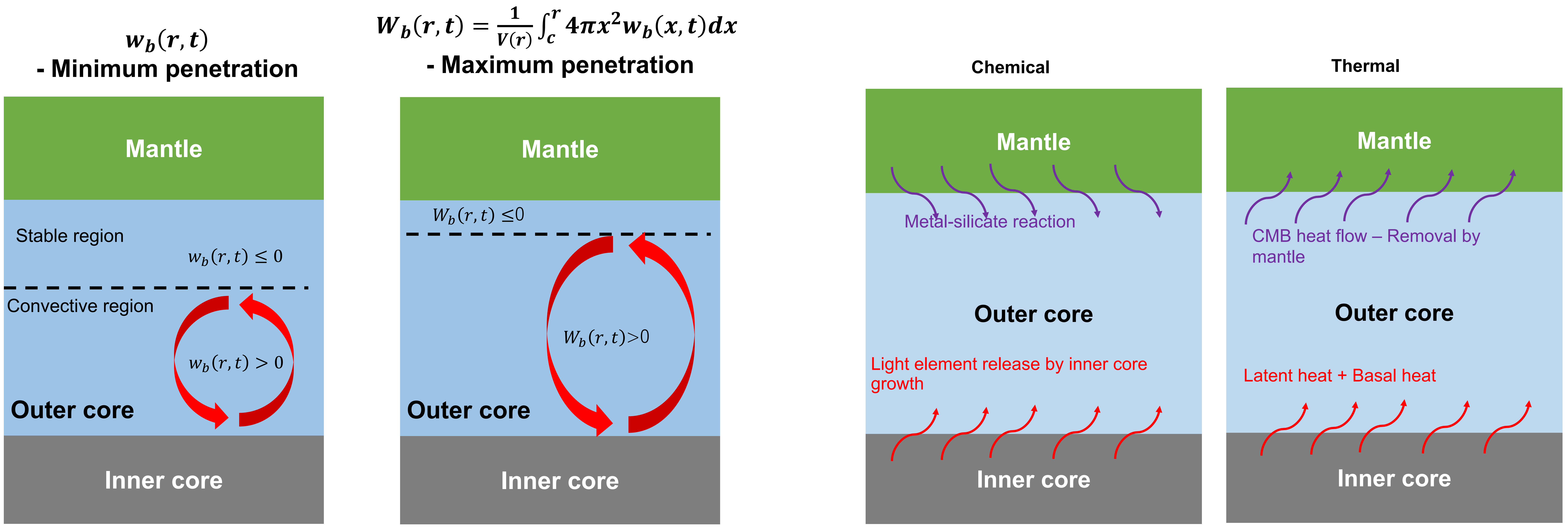
Zhang et al. (2022)



Kaneshima and Matsuzawa (2015)

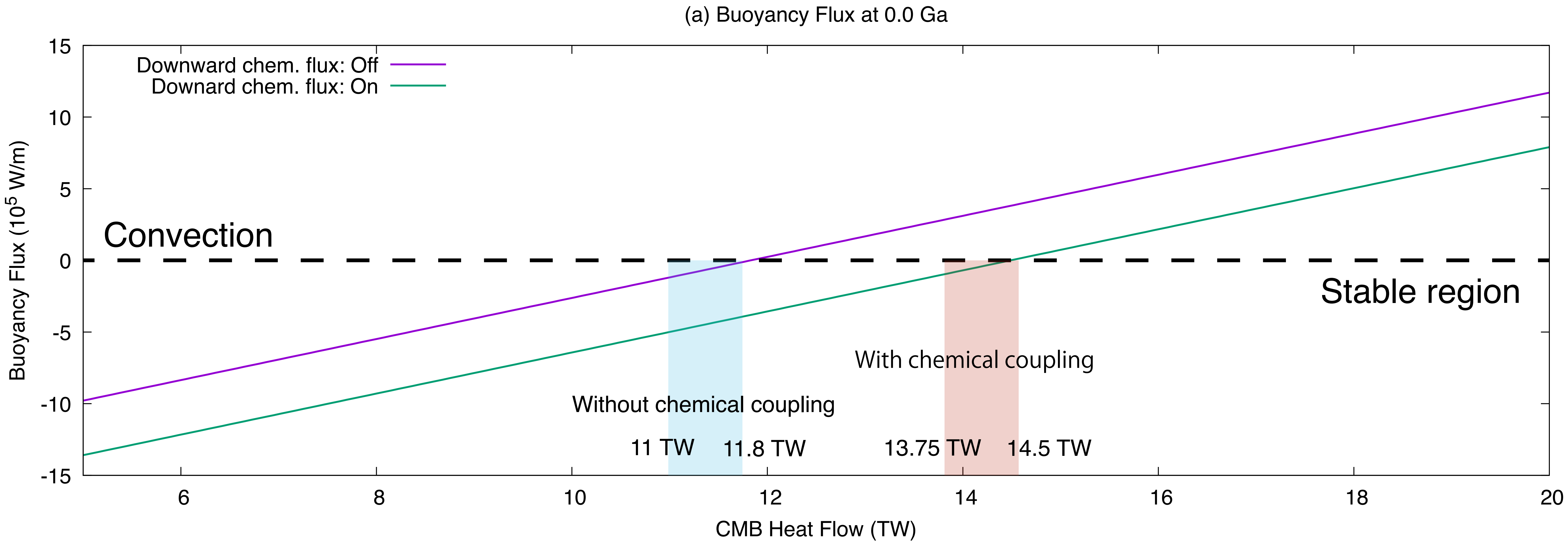
Simplified approach: Heat and mass balance across the Earth's core

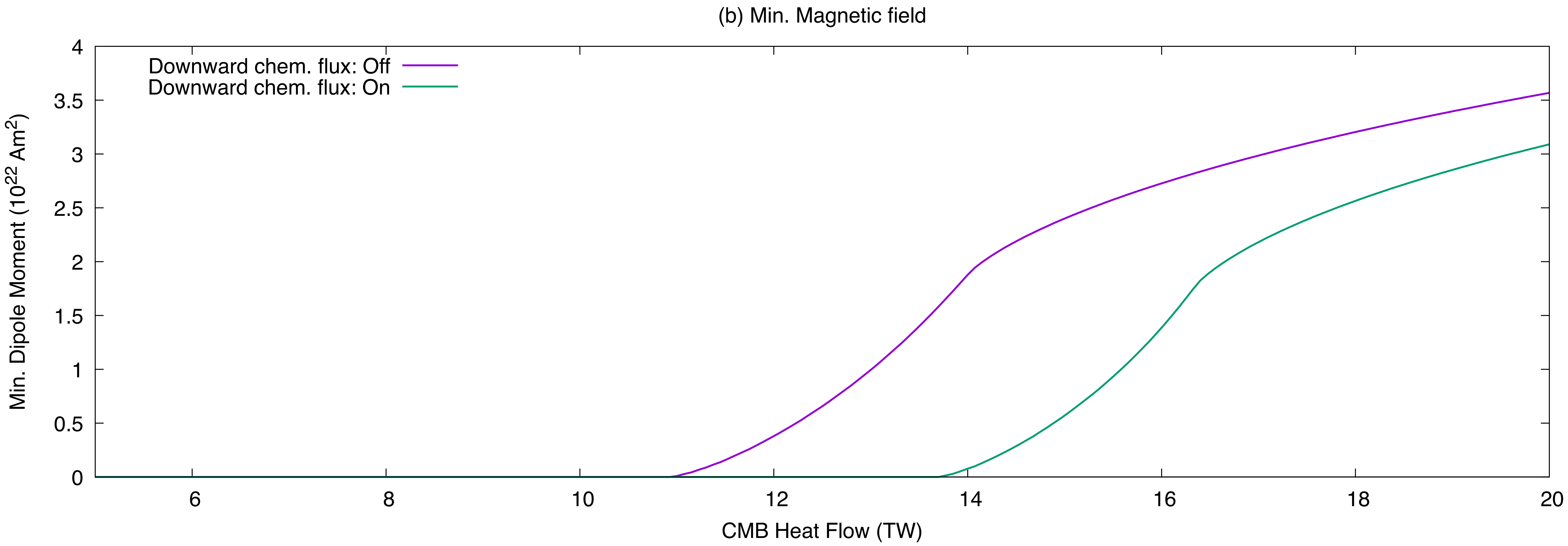
Convective flux evaluation (Nakagawa et al., in press and Takehiro and Sasaki, 2018)



Evaluate the work rate by convection computed by mass and heat balances

Heat transfer across the CMB matters with emerging the stable region

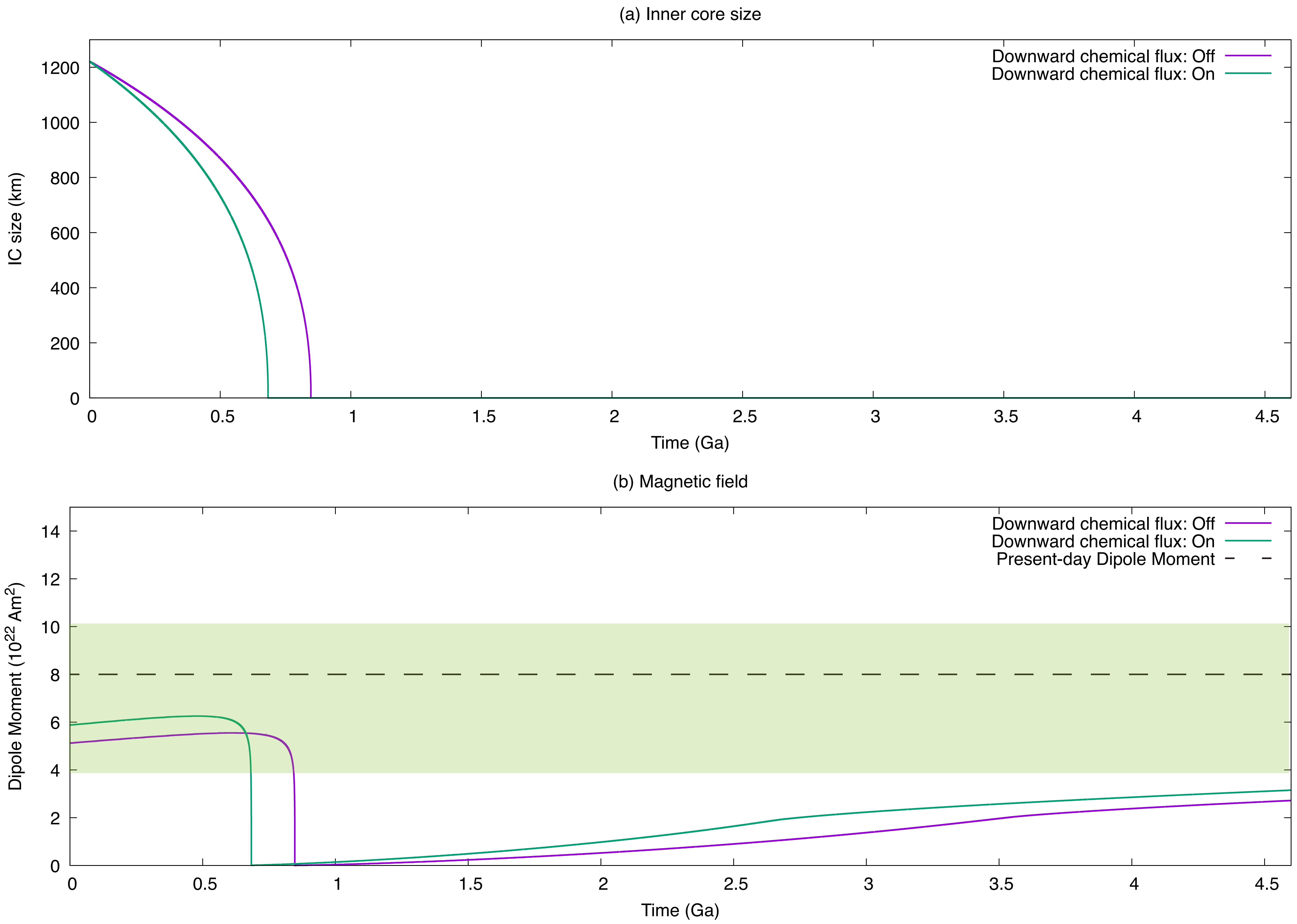




Expected to find the stable region below 13 TW of CMB heat flow at present-day.

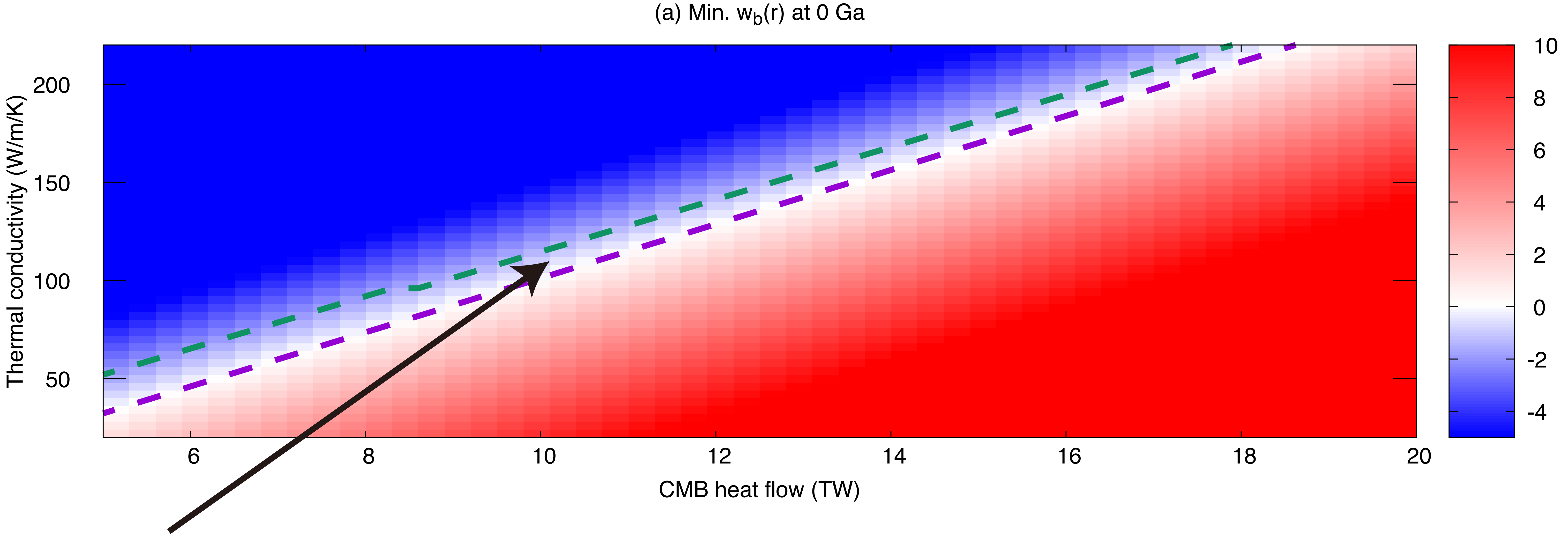
Nakagawa et al. (in press)

Core evolution

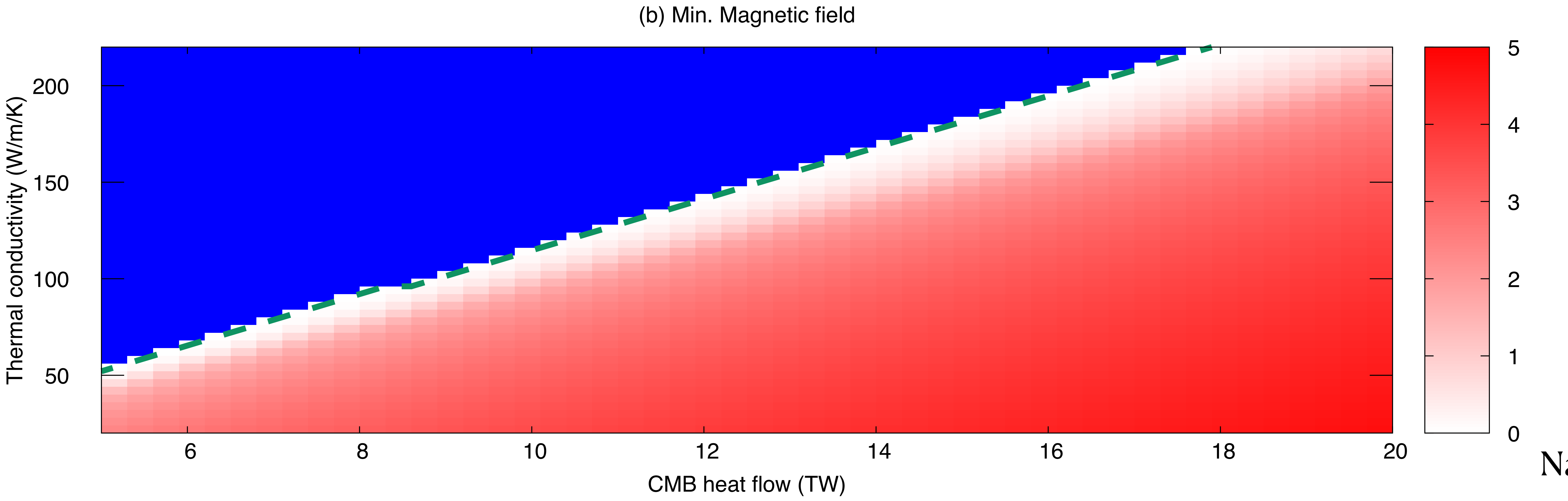


Sensitivity to the thermal conductivity of Earth's core

Requesting from high P-T experiment community



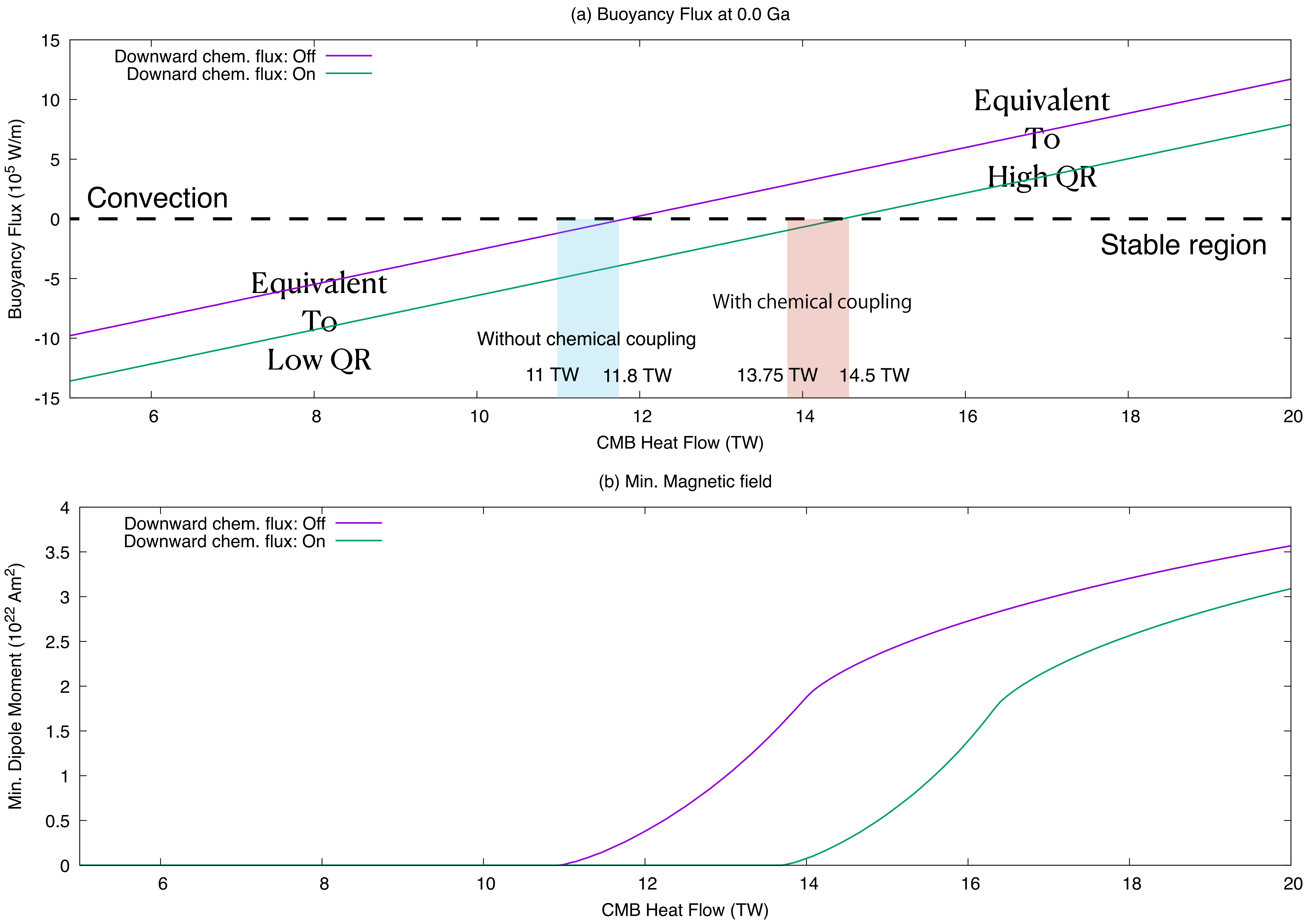
Possible solutions for both magnetic field and stable region



Nakagawa et al. (in preparation)

Implication: What happens if the radioactive element in Earth's core might be found?

Enhance thermal convection - unlikely to emerge the stable region?



Stable region:
Not likely to find when the radioactive heat production is included.

Nakagawa et al. (in press)

Consulting to the neutrino community

Based on geodynamics simulations

- On the expectation from mantle dynamics community, the spatial distribution of radioactive heat production is more preferable because of less sensitive to thermal history.
- Radioactive heat production in Earth's core: Expected to be around ~1 TW. Still uncertain but unlikely from the partitioning of such elements to molten iron.
- A coupled core-mantle evolution: Small amount of radioactive heat production in Earth's core might be acceptable (~O(100) ppm).
- Radioactive heat production might enhance the thermal convection in Earth's core - Not likely to emerge the stable region at outermost Earth's core. Would be required to find the other implication on slow velocity region found there.