Cooling of Earth's core and mantle - With or Without a mysterious structure below the core-mantle boundary

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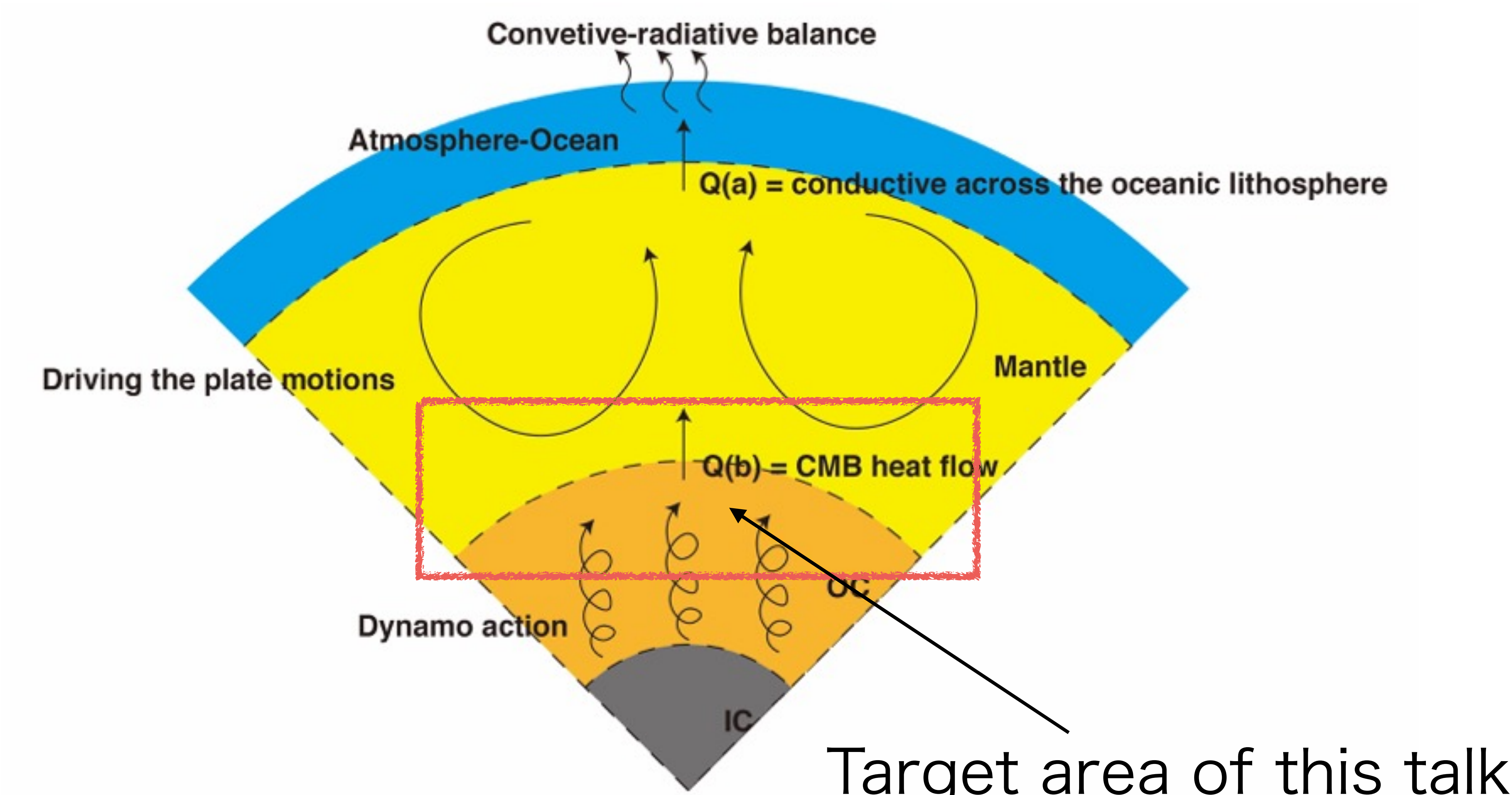
CoreMantle Coevolution
MEXT Grant-in-Aid for Scientific Research on Innovative Areas
Interaction and Coevolution of the Core and Mantle
Toward Integrated Deep Earth Science

Earth system dynamics modeling and target of this talk…

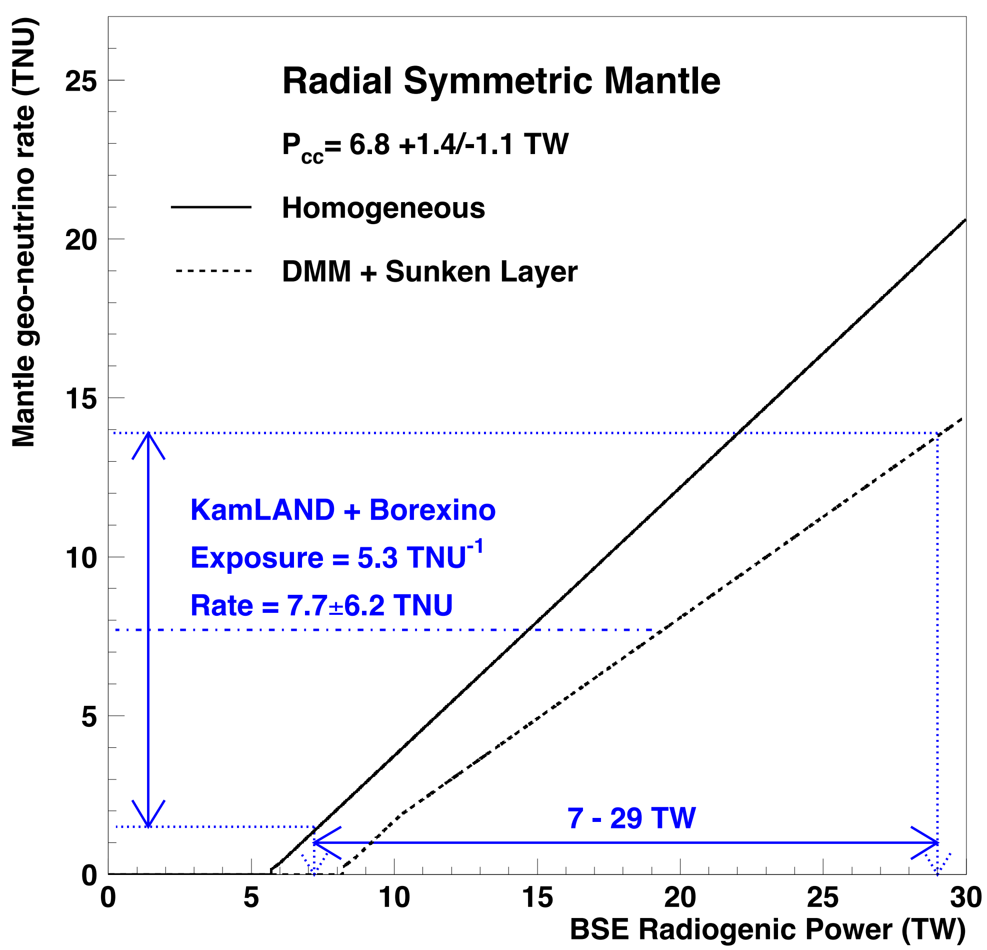


The long-term thermal and chemical evolution of Earth could be described as core-mantle-plate-environmental system connected in terms of heat transfer caused by mantle dynamics (the slowest dynamics)

Earth as a cooling system

Radiogenic heat producing element (HPE)

Geochemical analysis as well as 'geoneutrino' observations



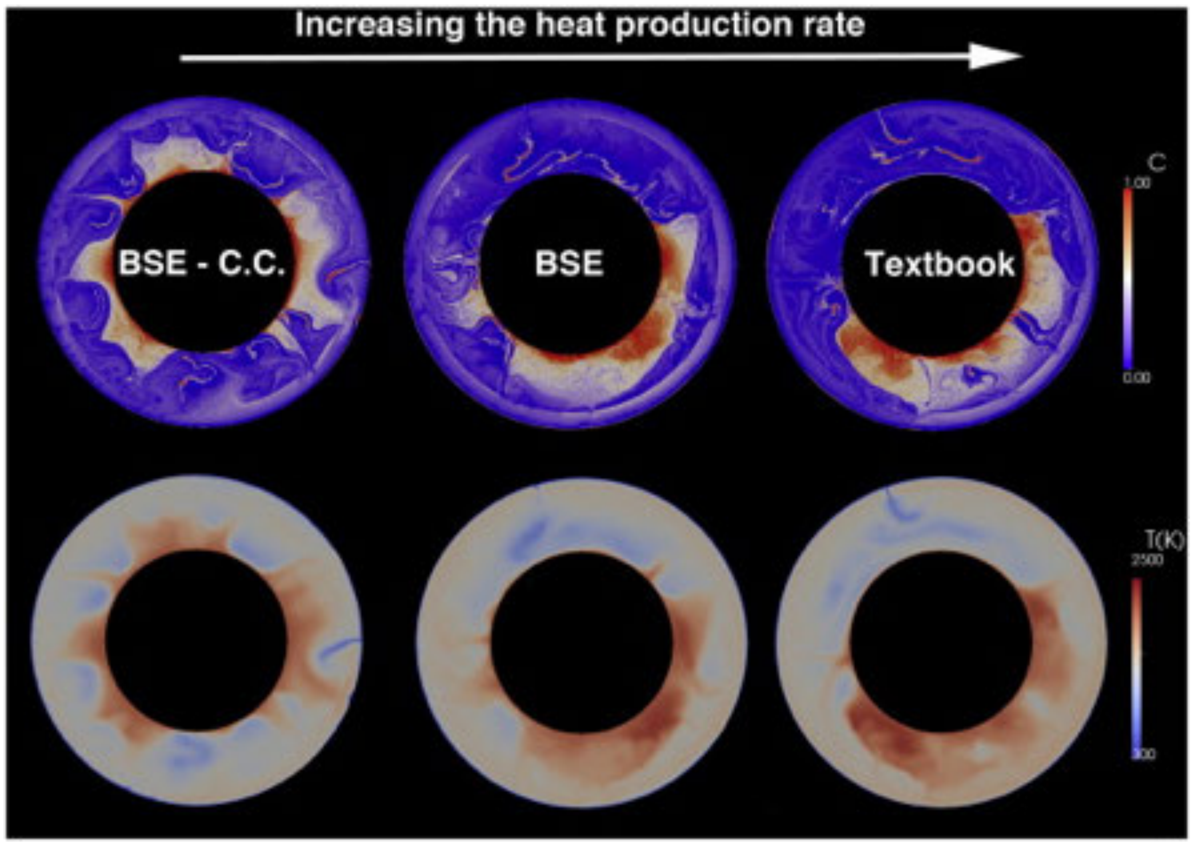
Dye et al. [2015]

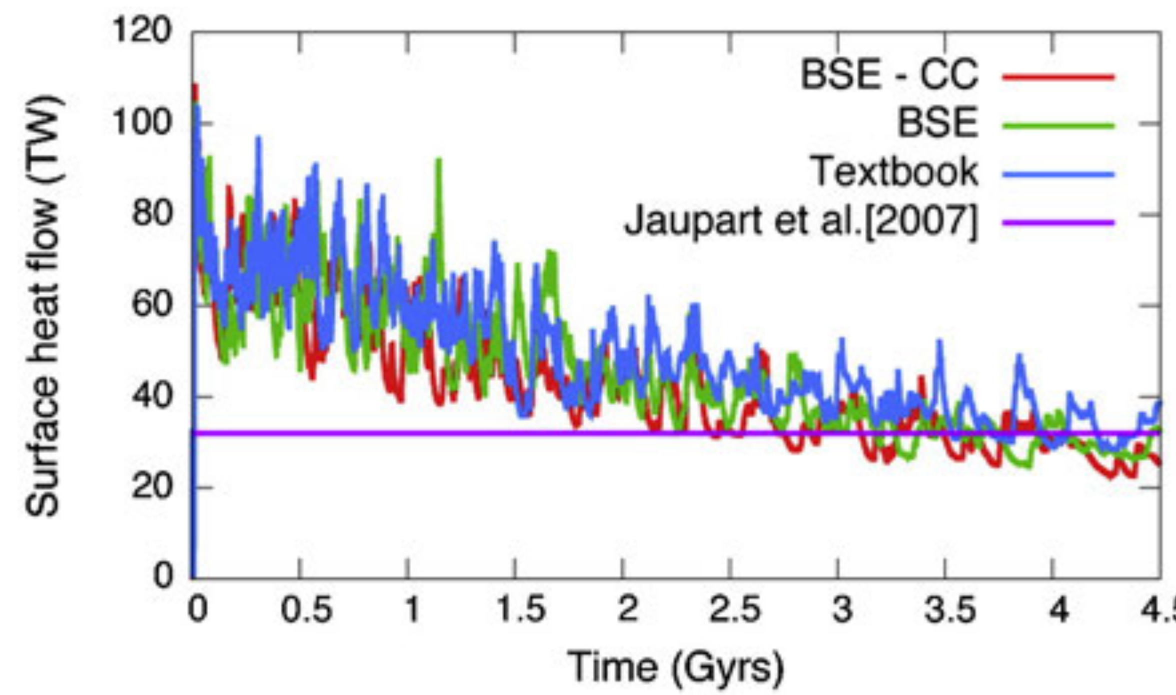
$$M c_p \frac{dT_m}{dt} = F_{CMB} - F_S + Q_R$$

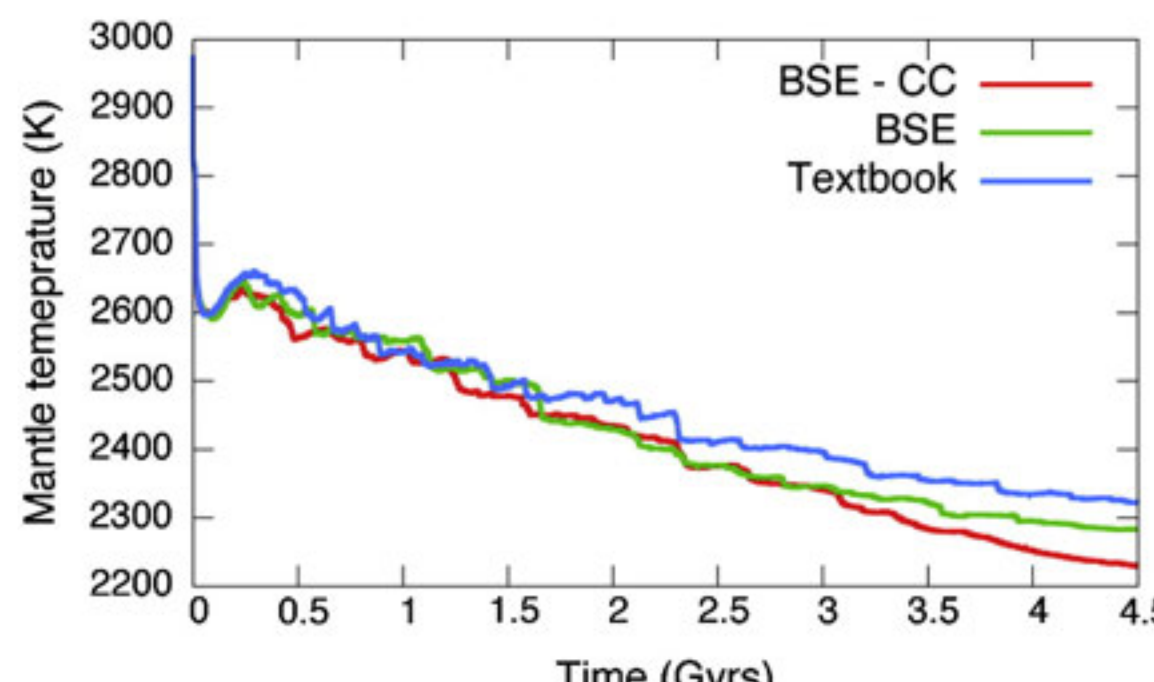
F_{CMB}~10 TW; F_S~40 TW; Q_R~10 to 30 TW - Cooling rate ~ 125 to 200 K/Gyrs

Melting Model in the upper mantle - Cooling rate ~ 75 K/Gyrs [Abbott et al., 1994]

However, the amount of HPE would not matter with thermal evolution



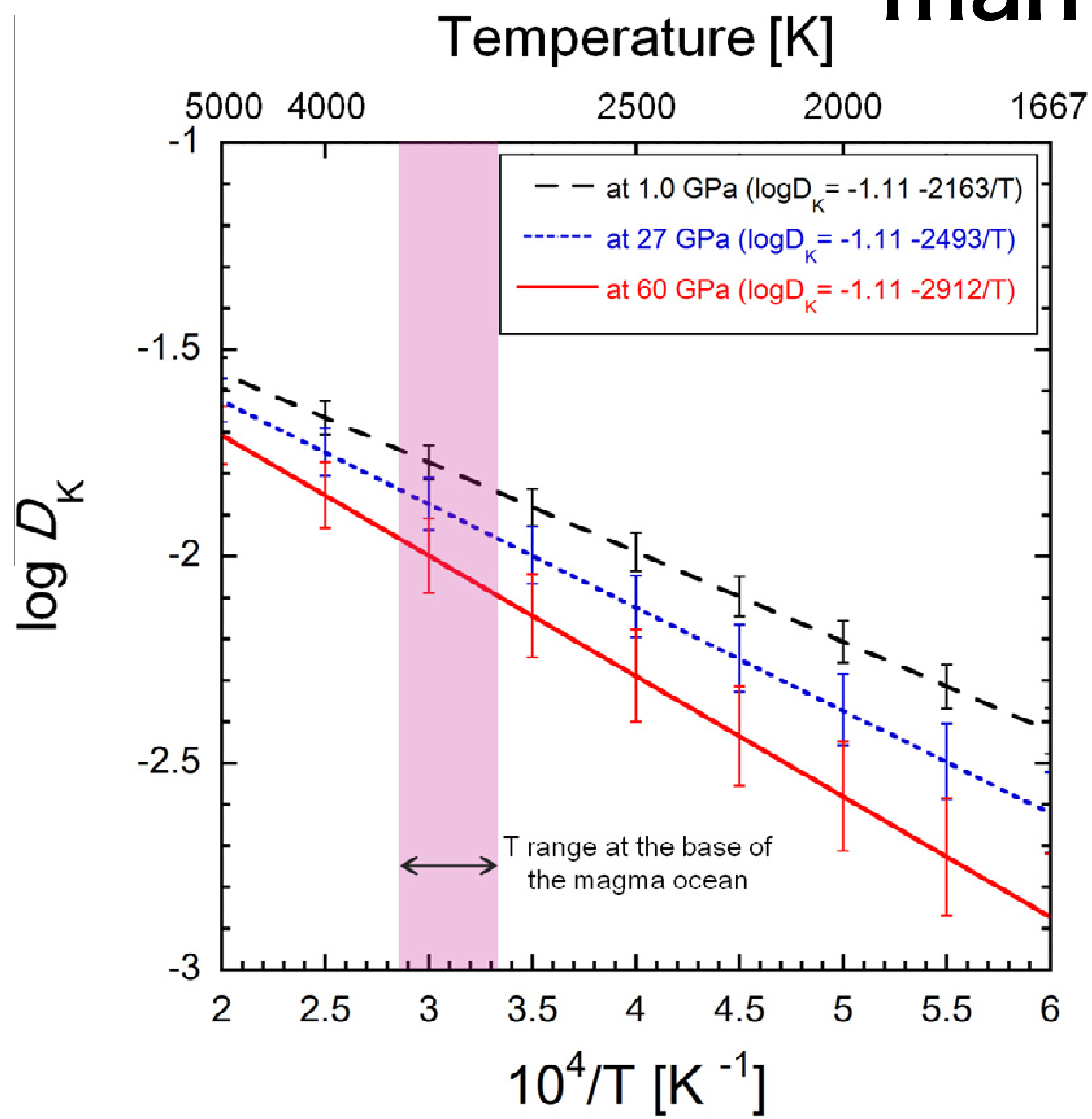




Not very different for the amount of HPE in the mantle
- Cooling rate ~ 70 to 80 K /Gyrs

Nakagawa and Tackley [2012]

HPE in the metallic core - Tiny partition coefficient: Mainly partitioning into the mantle



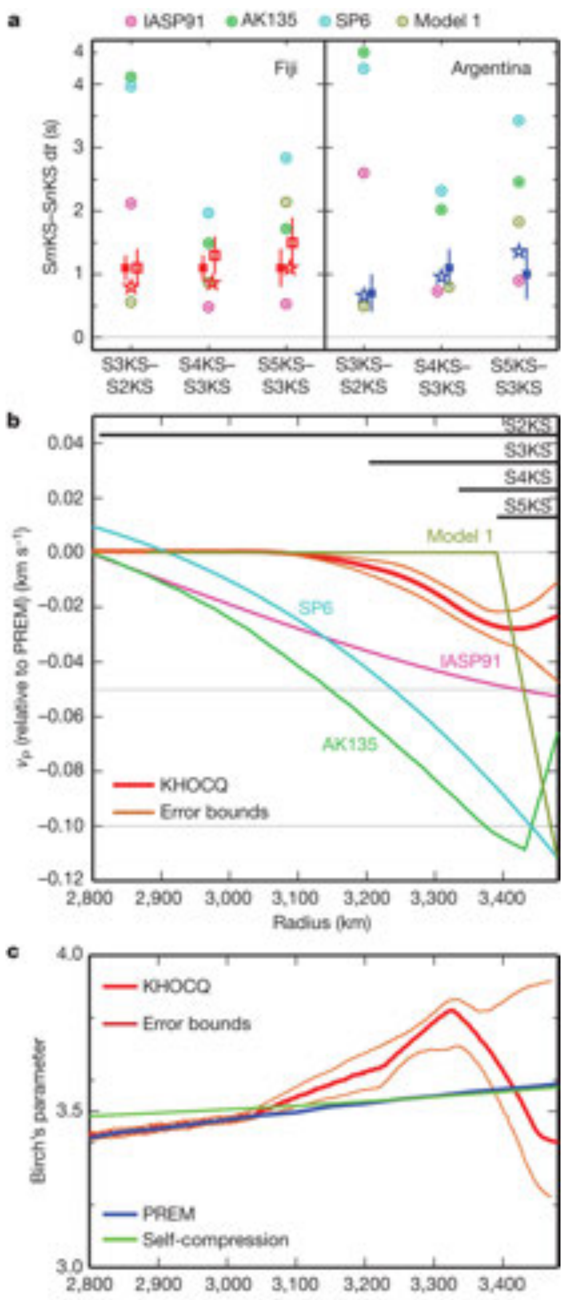
Watanabe et al. [2014]

Major HPE source in the core - Potassium

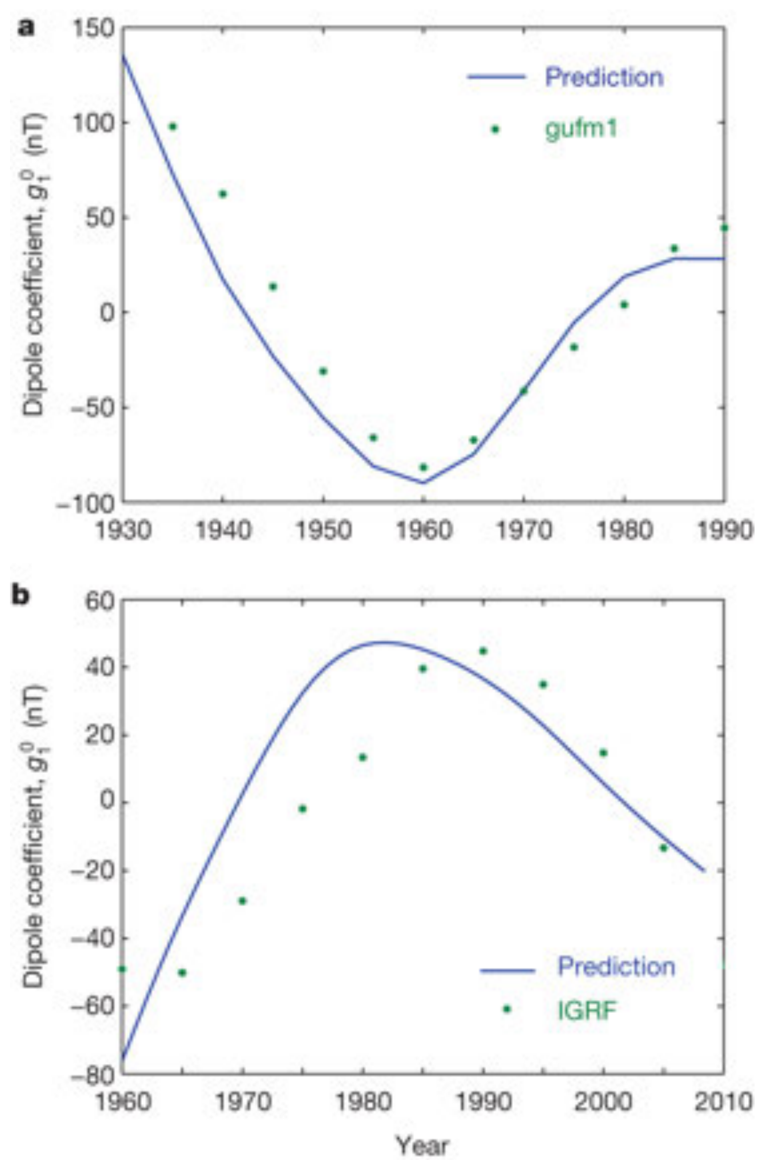
D_K~O(0.01) - only few 10s ppm could be partitioned into the molten iron: Very small contribution of core heat budget - HPE would not be likely to be found in the mantle rather than metallic core.

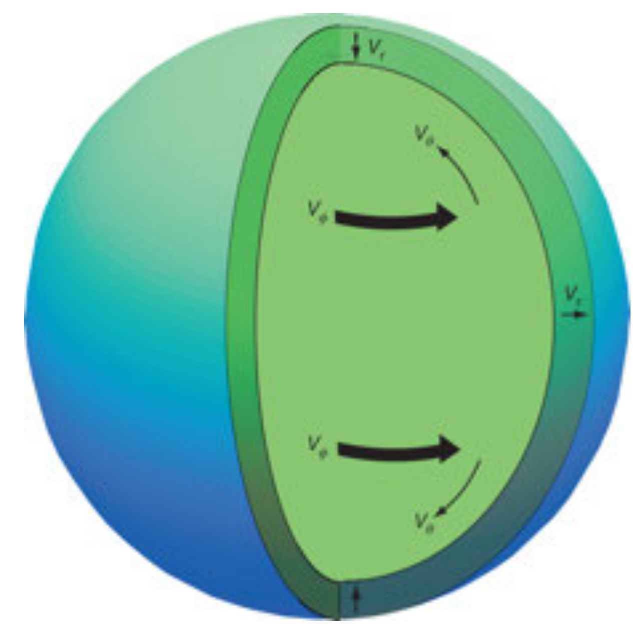
Also suggested from partitioning of light elements in the metallic core [Hirose et al., 2013].

Recent hot topic on structure in the core-mantle boundary region - A weird (mysterious) feature found in seismological and geomagnetic secular variation analyses



Helffrich and Kaneshima [2010] - Seismology



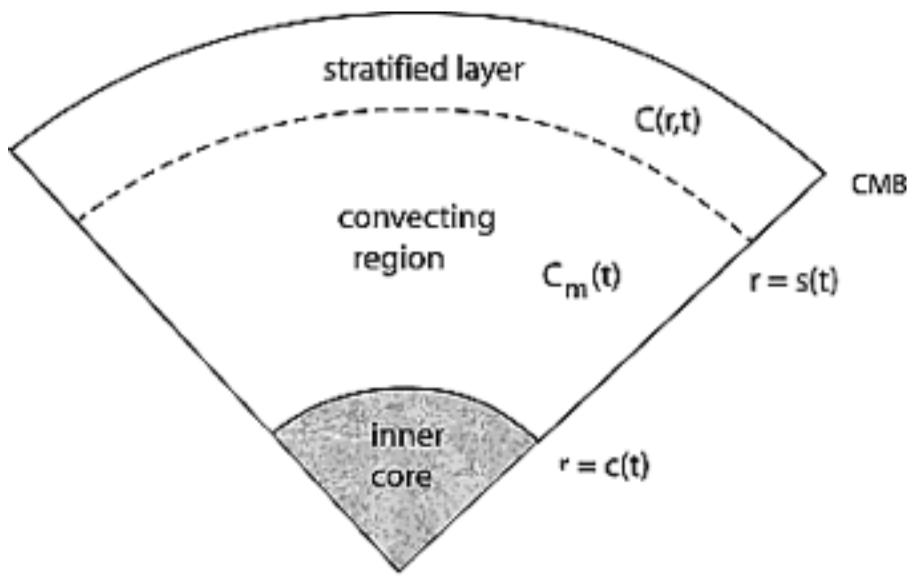


Buffett [2014] - Geomagnetic secular variations MAC wave in the stable region could be explained.

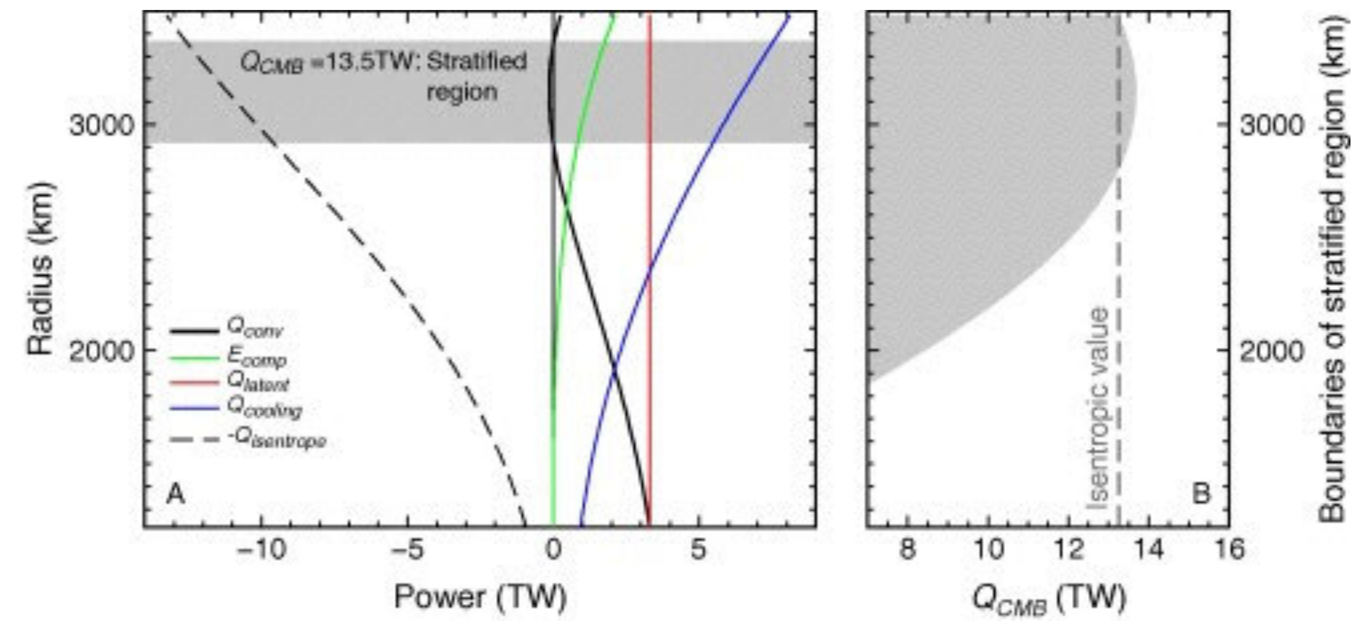
Goal of this talk

- Formulate thermo-chemical evolution of Earth’s core
- Implement it into numerical mantle convection simulations
- How does it work in core-mantle evolution system.
- Implications and conclusions.

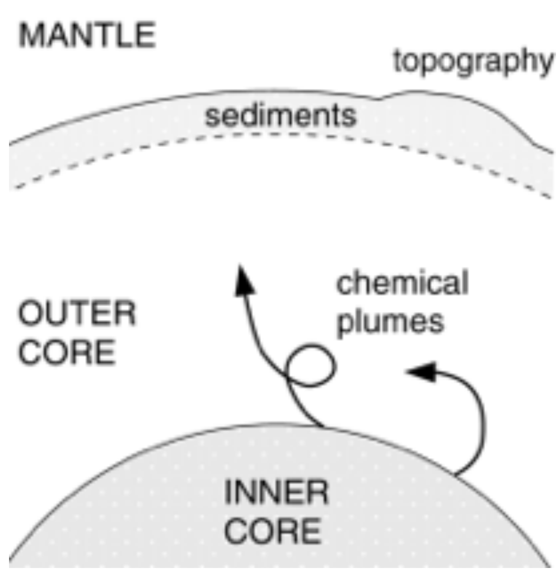
The origin of stable region below the CMB - Thermal or chemical or both?



Buffett and Seagle [2010]
- Core-mantle chemical coupling



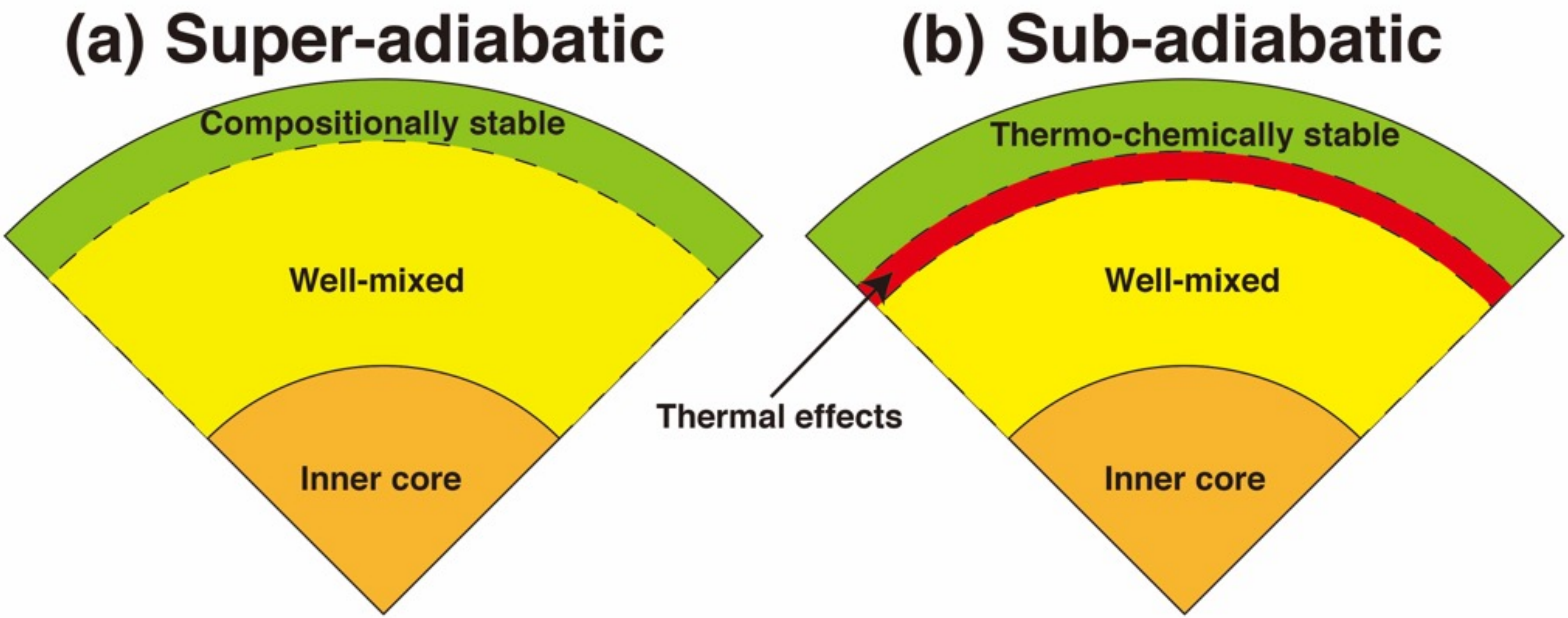
Labrosse [2015] - sub-adiabatic region occurred by high core thermal conductivity



Buffett et al. [2001]
- Sediment caused by inner core growth?

Core-mantle thermo-chemical coupling?

Two types of stable region beneath the CMB



Sub-adiabatic shell allows growing beneath the compositionally-stable region only if the heat flow across the CMB is sub-adiabatic - Assume that the heat flow in the stable region would be equivalent to the CMB heat flow.

First - Compositional evolution

Based on Buffett and Seagle [2010 in JGR]

Assumptions

1. Two diffusion processes are assumed in the stable region - Simple chemical diffusion and baro-diffusion.
2. Fe(mw)→Fe(m)+O(m): Oxygen is the light element of Earth's core; This oxygen is supplied from core-mantle equilibrium chemical reaction (Frost et al., 2010); Chemical boundary condition at CMB is as a function of CMB temperature.
3. At the interface, the neutral buoyancy state is assumed.

$$\rho_{CMB}\frac{\partial C_s}{\partial t} = -\nabla \cdot \mathbf{I}$$

$$\mathbf{I} = -\rho_{CMB} D_c \left(\nabla C_s + \frac{\alpha_c}{\rho_{CMB} H_c}\nabla P\right)$$

$$H_c \sim \frac{RT_{CMB}}{M_o C_s \left(1 - C_s \frac{\bar{M}}{M_o}\right)}$$

$$M_m \frac{dC_m}{dt} = -4\pi s^2 I_r(s^-, t) + 4\pi c^2 \frac{dc}{dt} C_m$$

$$\alpha_T \frac{\partial T}{\partial r} + \alpha_c \frac{\partial C_s}{\partial r} = 0$$

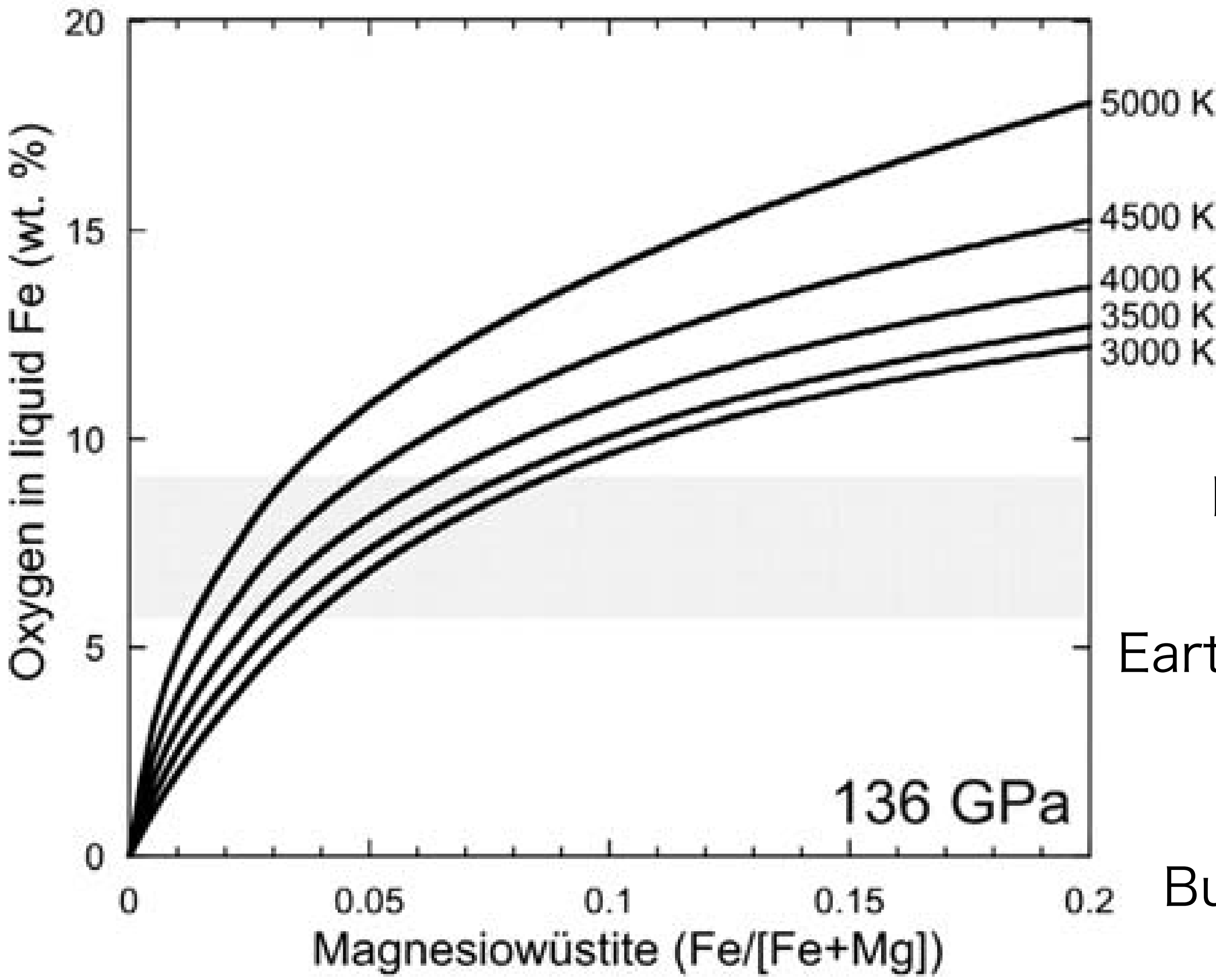
$$\frac{\partial T}{\partial r} = \max\left(\frac{q_{CMB}}{k_c}, \frac{q_s}{k_c}\right)$$

$$I_r(s^+, t) = I_r(s^-, t)$$

From the mass balance at the interface,

$$\left(\frac{ds}{dt}\right)_c = \left(\frac{\partial C_s}{\partial t} - \frac{dC_m}{dt}\right)\left(\frac{\partial C_s}{\partial r}\right)^{-1}$$

Core-mantle chemical coupling - Thermodynamics model developed from high P-T experiments



Frost et al. [2010]

$FeO^{mw} \rightarrow Fe^{m} + O^{m}$

Equilibrium partitioning reaction

Earth's core - Under-saturated for light elements

But not assumed for partitioning of HPE in the metallic core here.

Next, thermal evolution

Modified from Lister and Buffett [1998]

If the stable region can be found in the system, two temperatures can be also computed as following global heat balance equations.

$$M_s c_p \frac{dT_s}{dt} = -4\pi b^2 q_{CMB} + 4\pi s^2 q_s + 4\pi s^2 \left\{ -\frac{ds_t}{dt}, 0 \right\} \rho_{CMB} c_p (T_m - T_s)$$

$$M_m c_p \frac{dT_m}{dt} = -4\pi s^2 q_s + 4\pi c^2 \frac{dc}{dt}(L + E_g) + 4\pi s^2 \rho_{CMB} c_p \left\{ \frac{ds_t}{dt}, 0 \right\} (T_m - T_s)$$

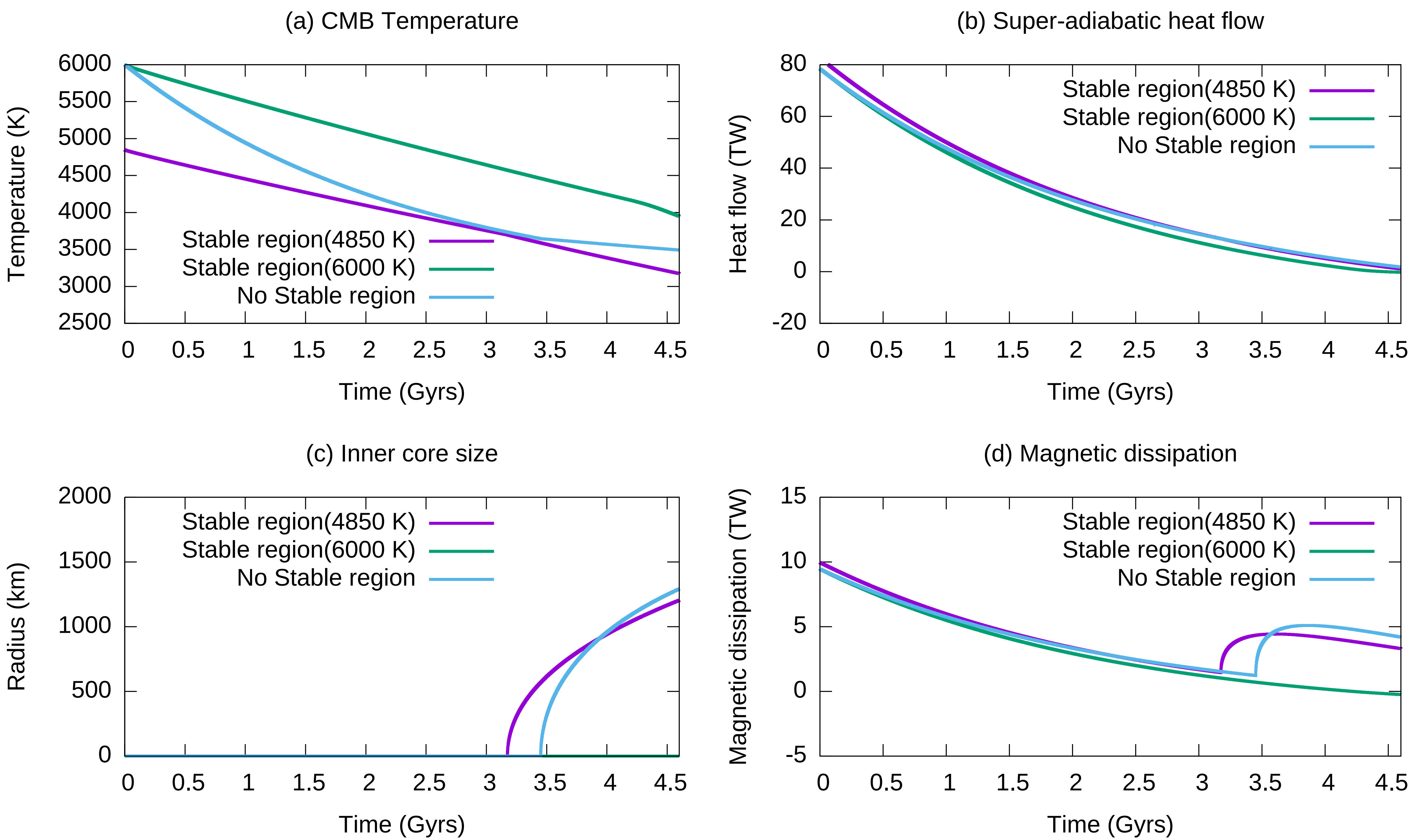
Again, using the heat balance at the interface, we also find the thermal effects of displacement rate of stable region -

$$\left(\frac{ds}{dt}\right)_t = \left(\frac{\partial T_s}{\partial t} - \frac{dT_m}{dt}\right)\left(\frac{\partial T}{\partial r}\right)^{-1}$$

Finally, the position of interface between stable and well-mixed regions can be computed as

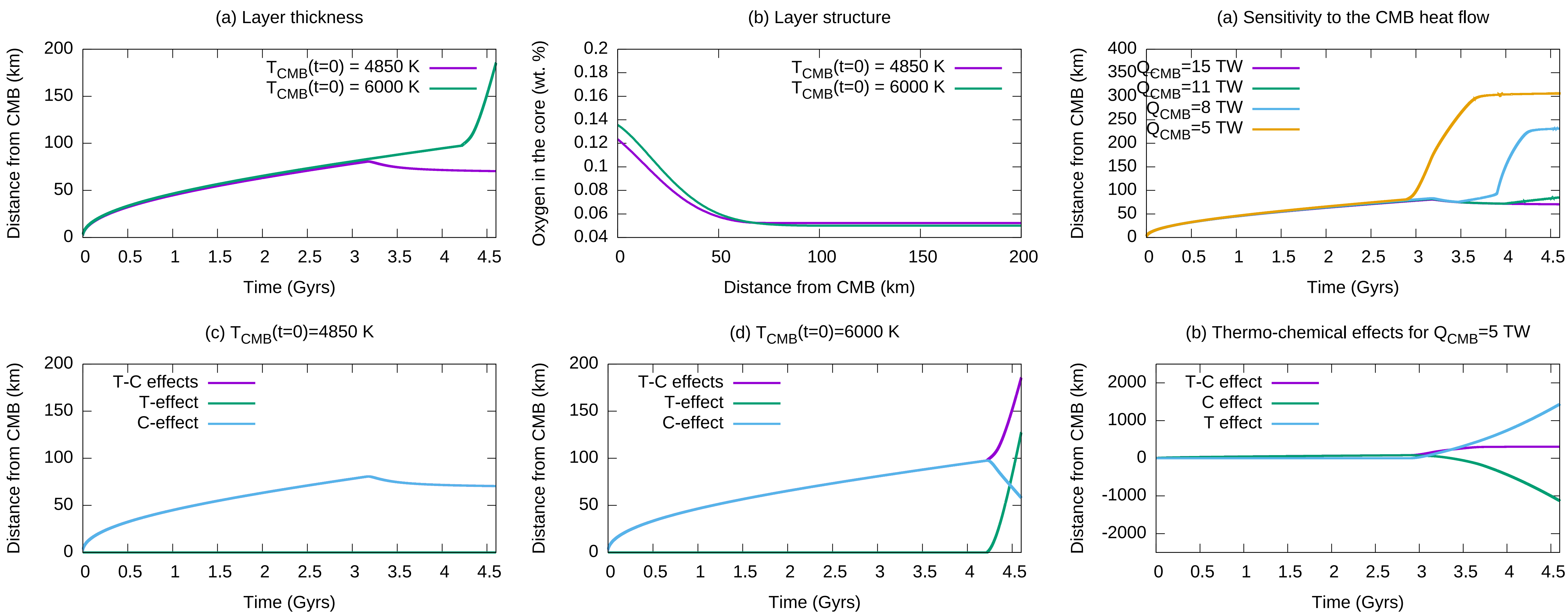
$$s = s_c + s_t$$

Simple case - Heat flow across the CMB given as a function of time



$$q_{CMB} = q_{CMB,p} \exp(a(t_a - t))$$

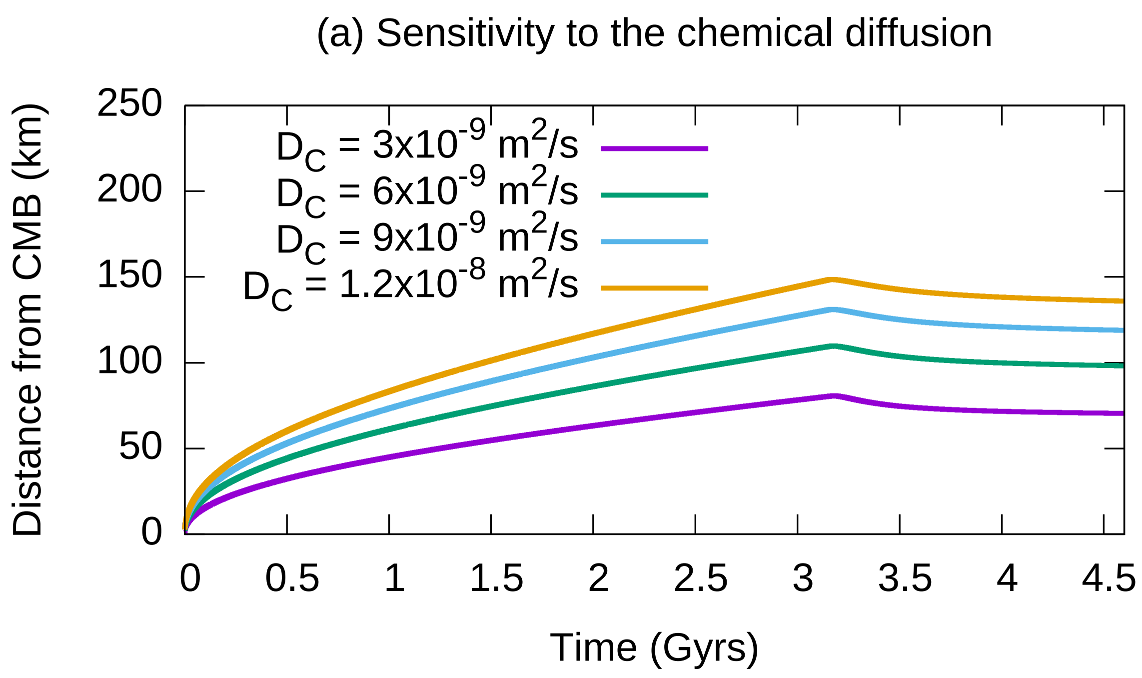
What happens with the stable region - Preferable origin

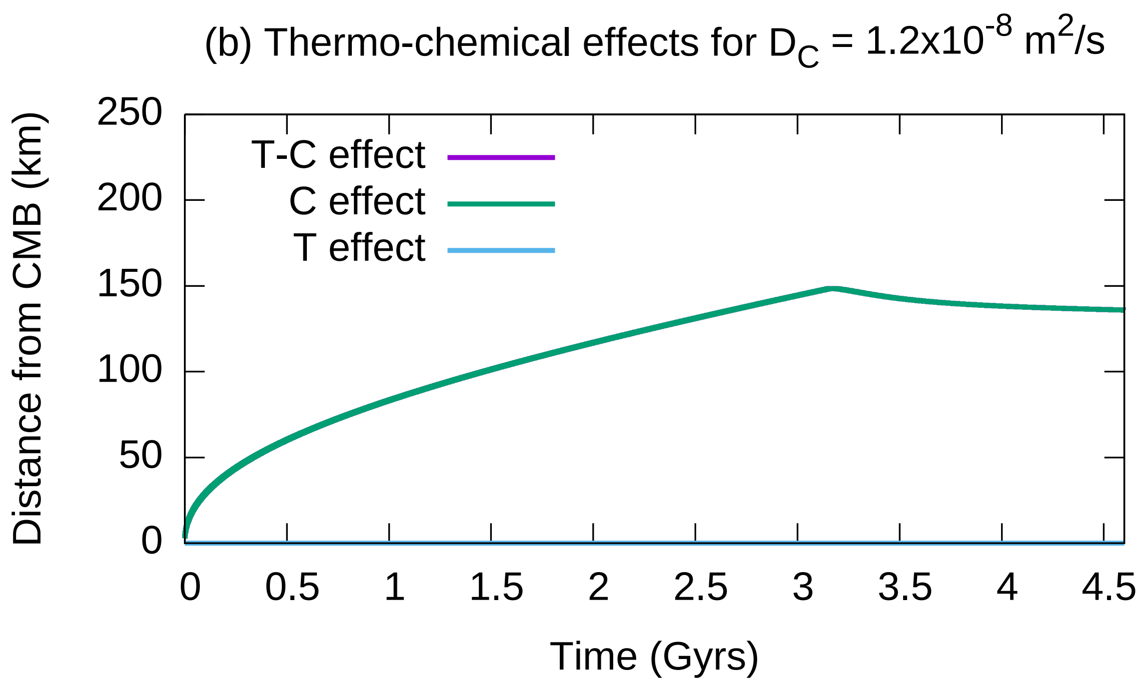


Growth rate caused by sub-adiabatic effects - 1500 km for 1.0 billion years: Compositional effects are required for consistent thickness of stable region.

From some constraint on CMB heat flow (~11 TW), the preferable origin would be purely compositional effects

Effects on chemical diffusivity of Earth's core



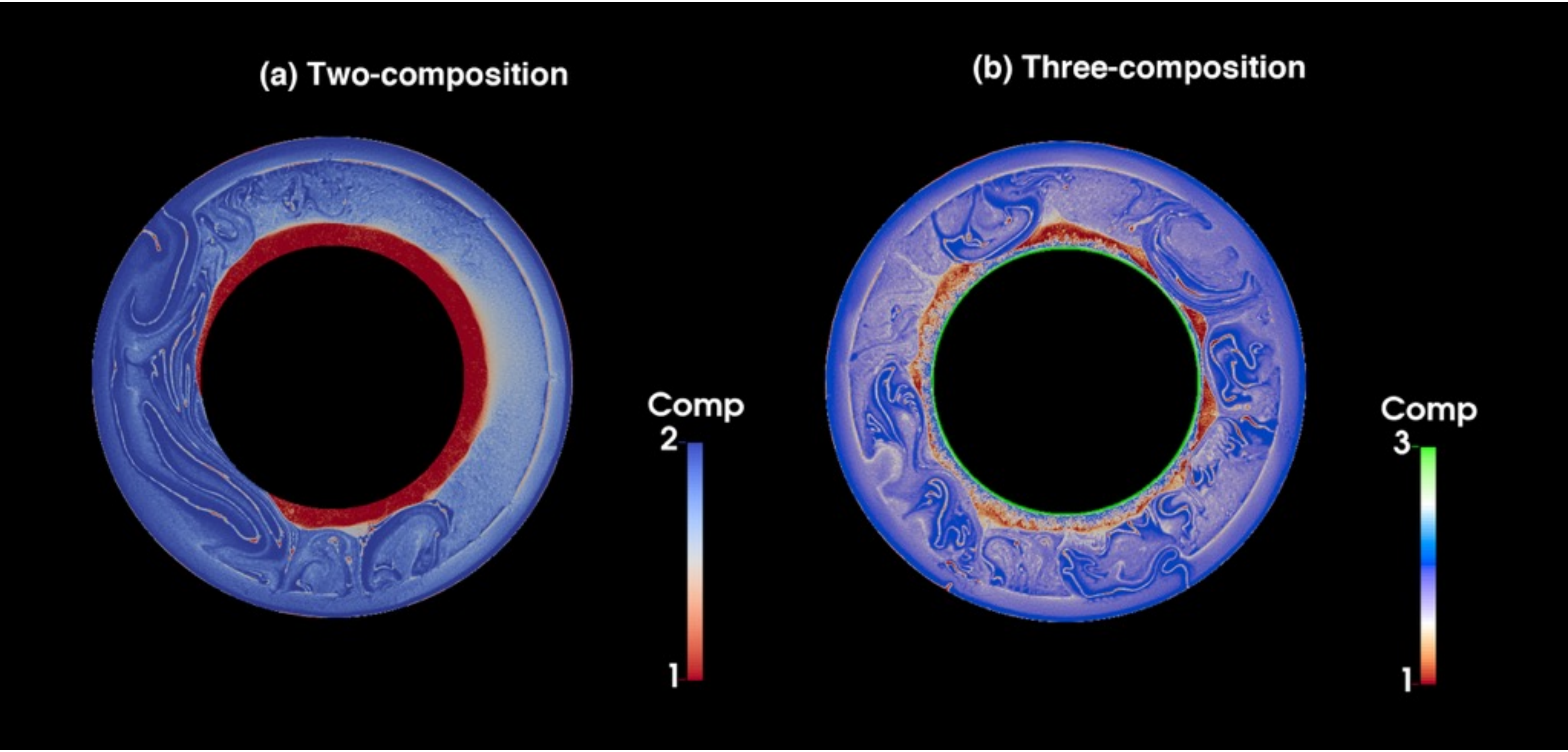


CMB heat flow at the present time = 15 TW

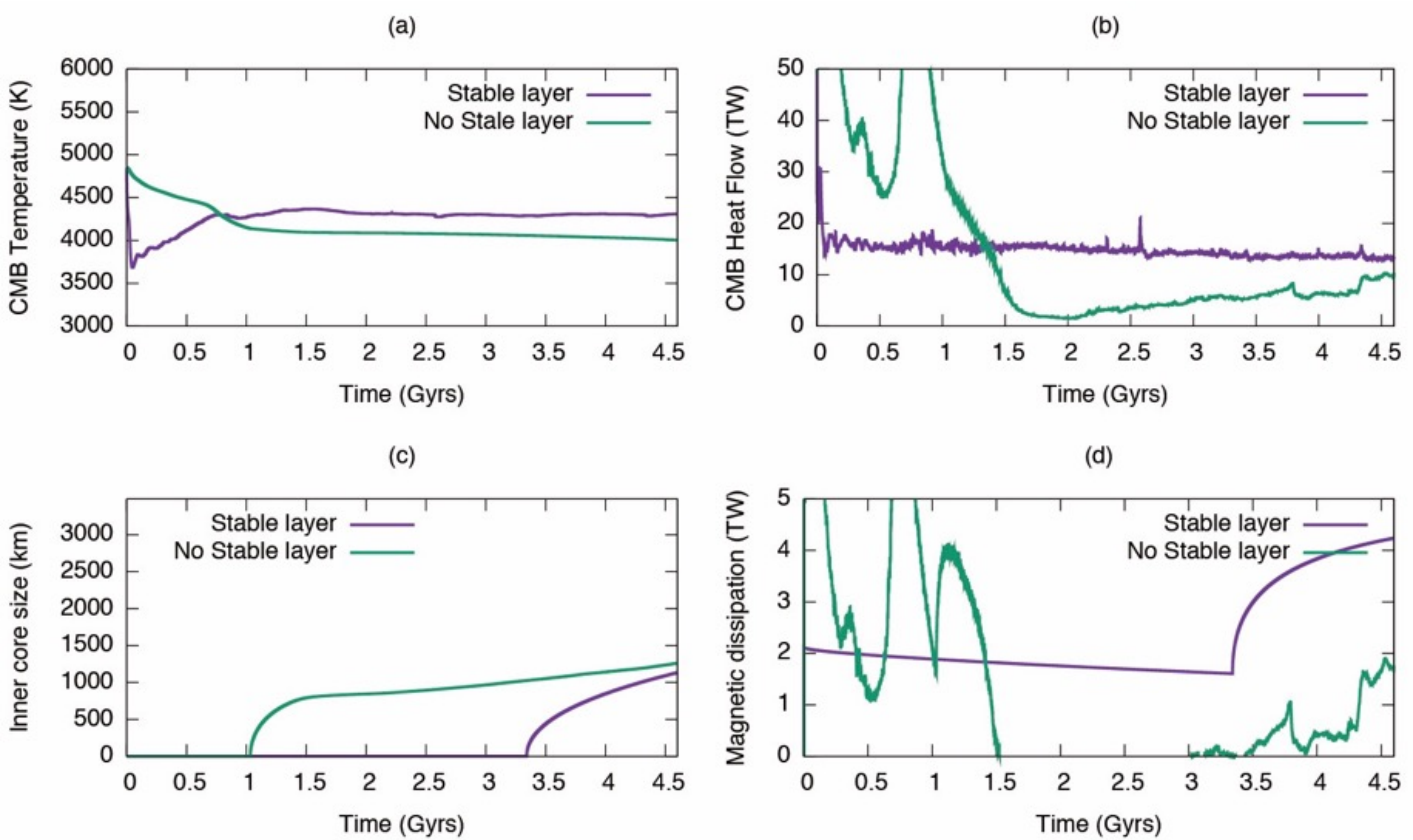
Initial CMB T = 4850 K

To be consistent with a constraint on stable layer thickness estimated from geomagnetic secular variation (~140 km) [Buffett, 2014], the chemical diffusivity would be O(10^{-8}) m^2/s - Somewhat consistent with with theoretical estimates [Pozzo et al., 2013; Ichikawa and Tsuchiya, 2015].

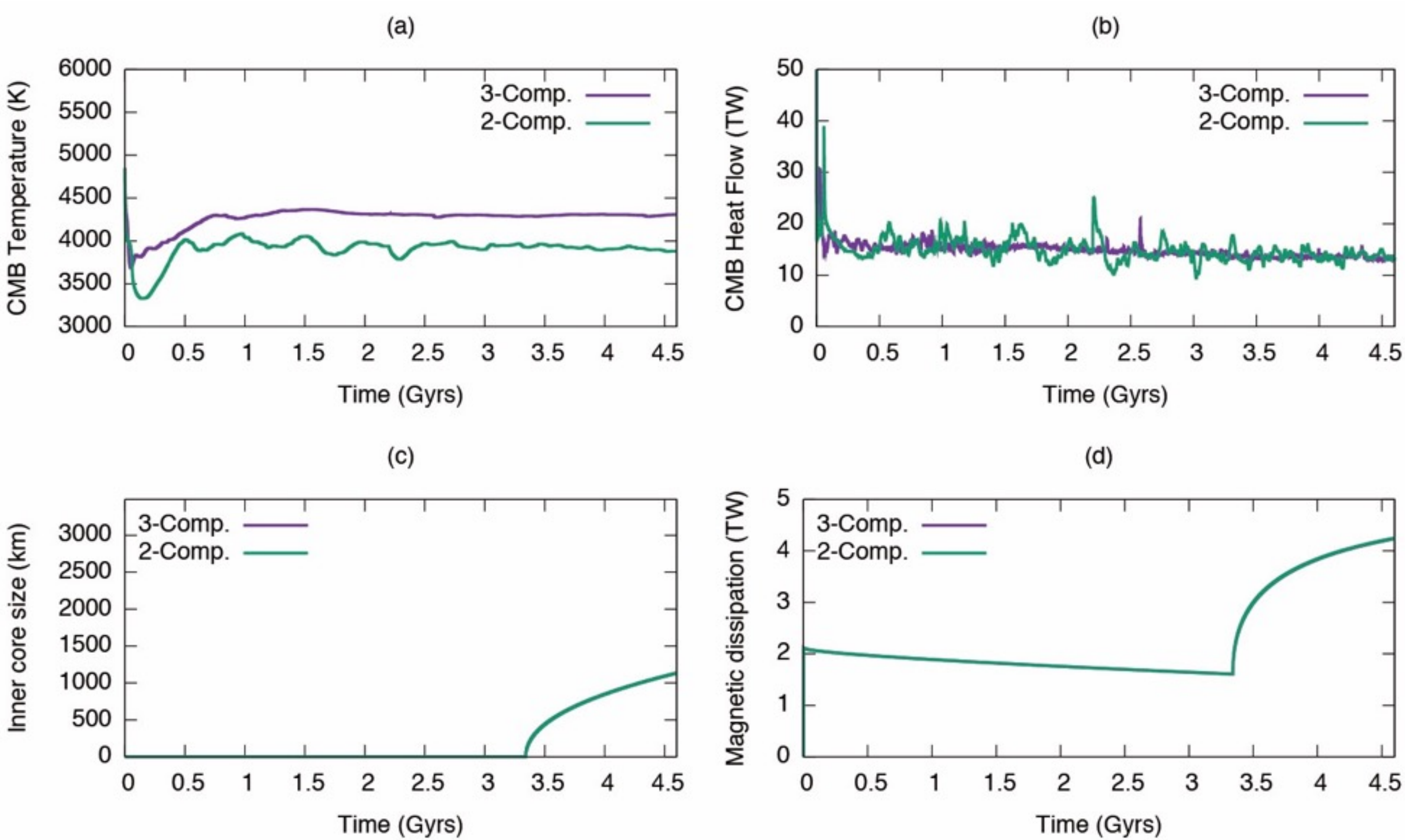
CMB heat flow given from numerical mantle dynamics model



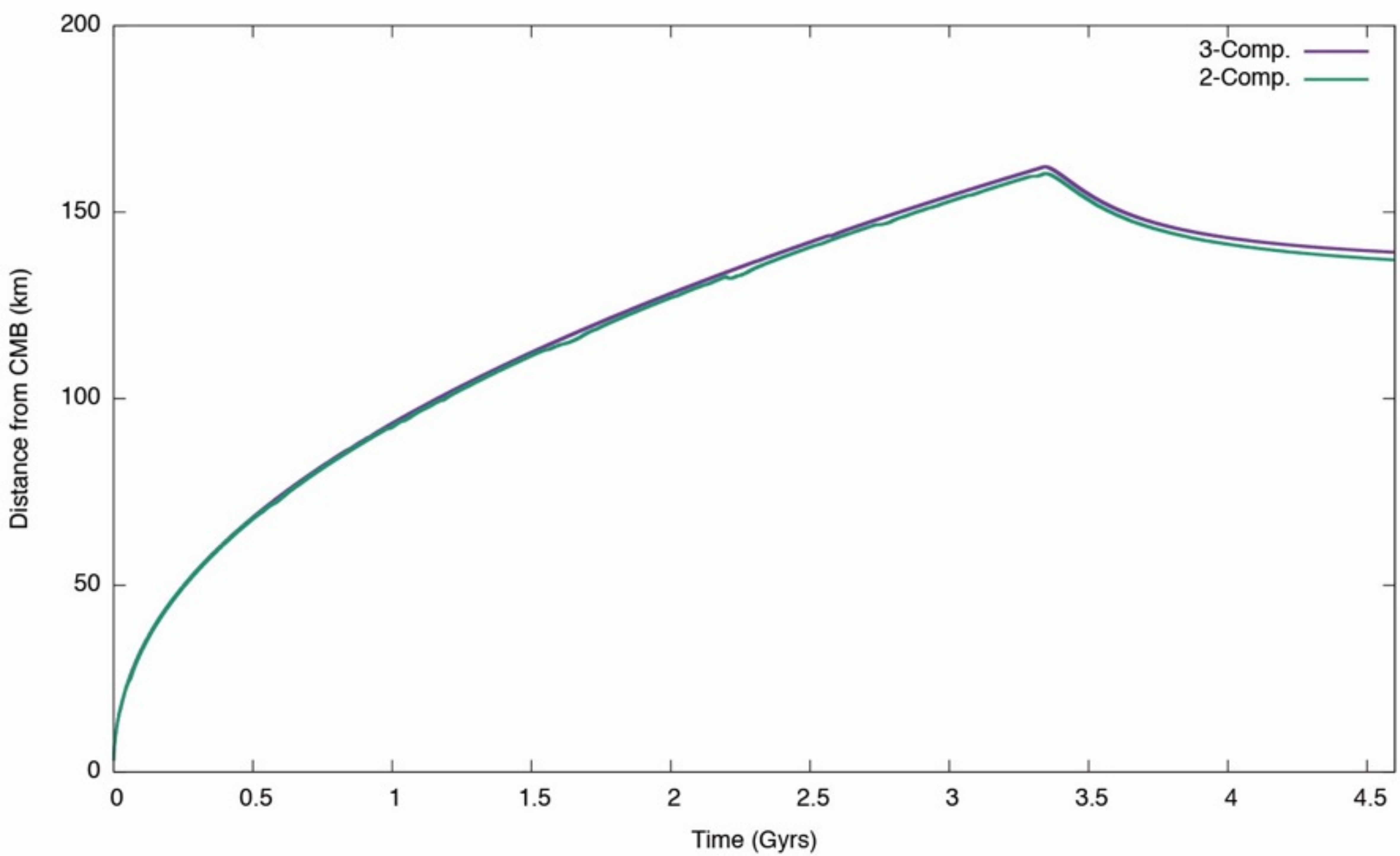
Stable region - The strongest heat buffer



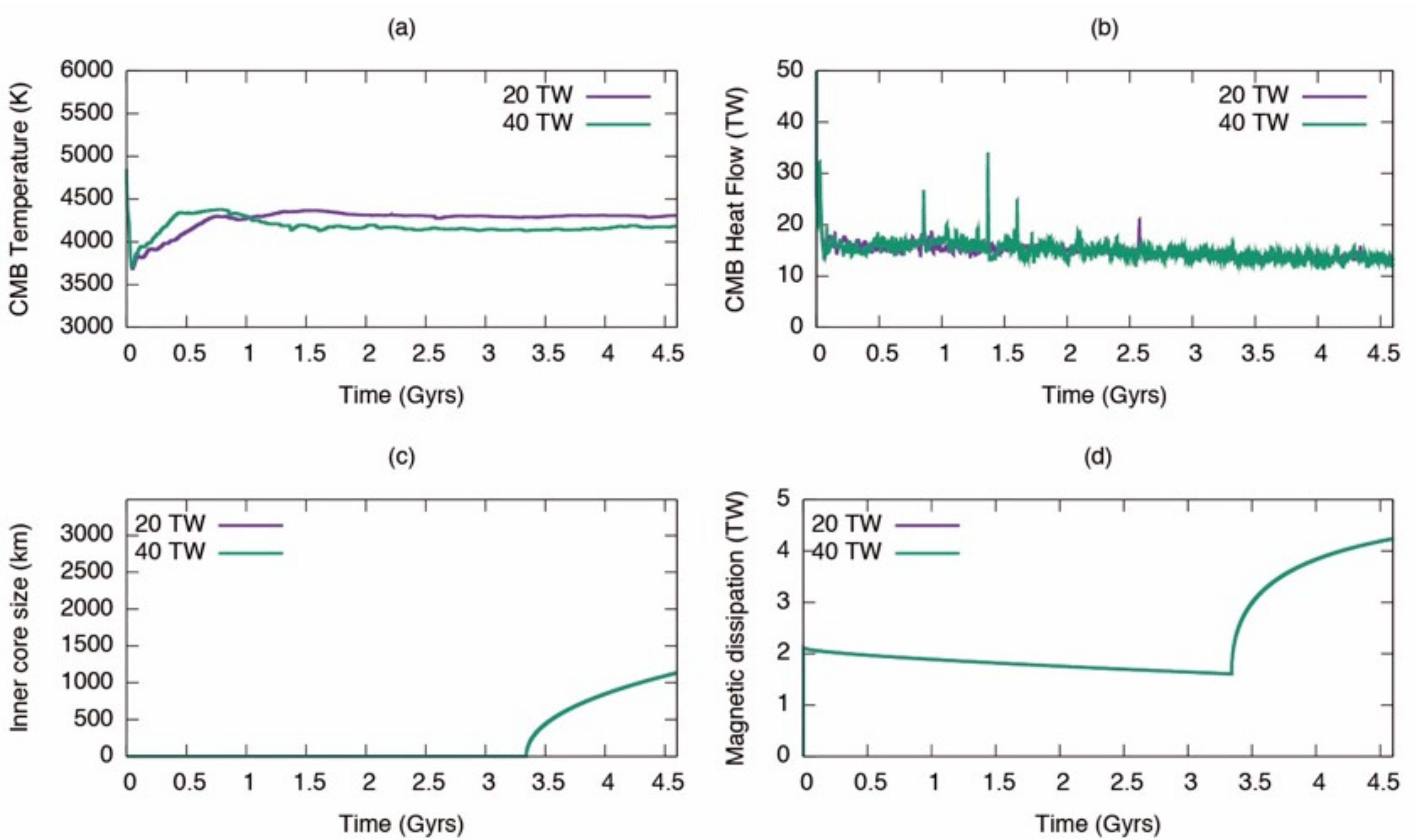
Core evolution diagnostics



Quick view on evolution of stable region

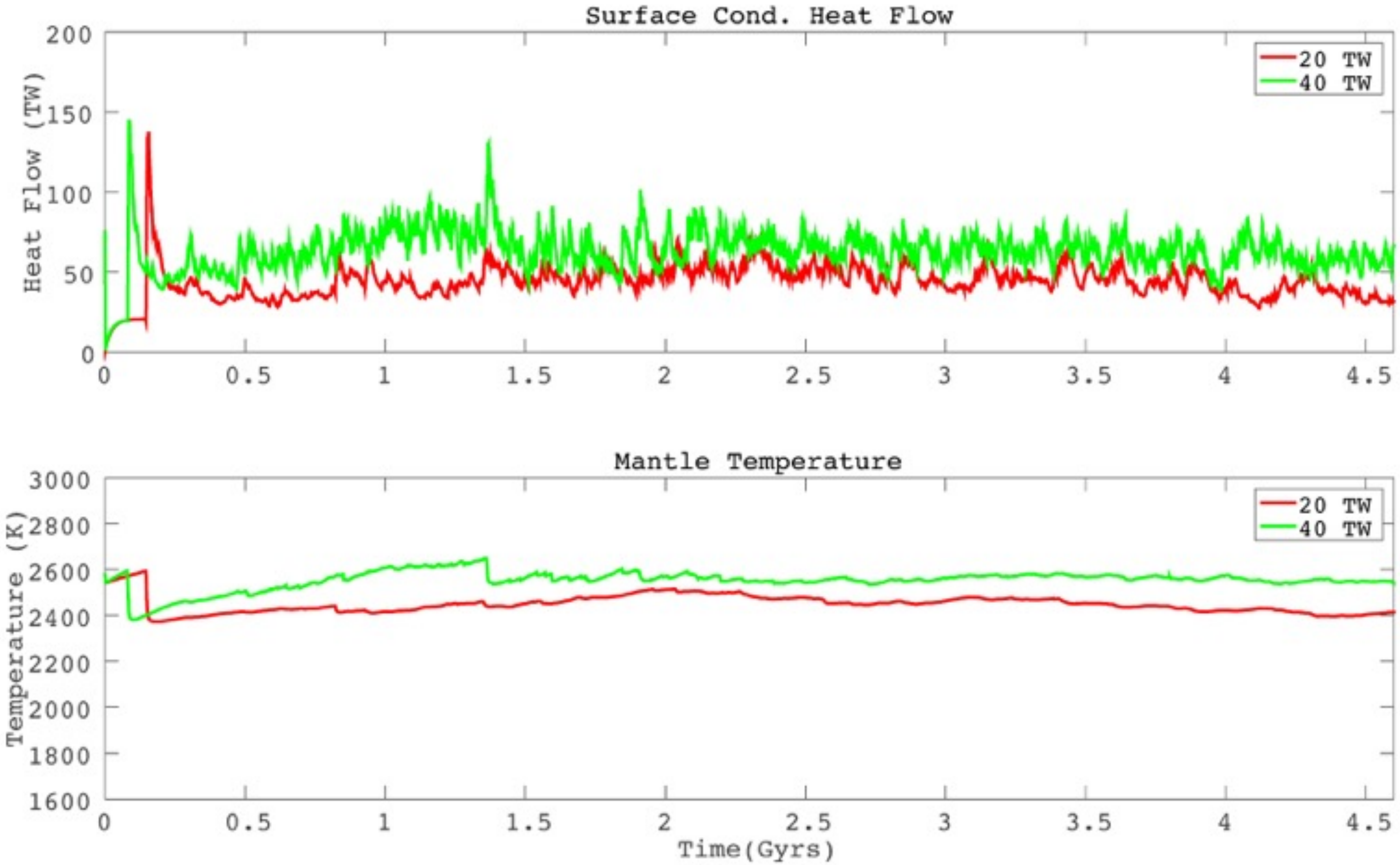


Influences of HPE in the mantle



Nothing happened with HPE in the mantle.

HPE effects in the mantle



High HPE - very slow cooling down but rapid cooling down in early Earth corresponding to the spike of surface heat flow (~initiate the plate-like behavior).

Summary and implications

- Incorporating 'core-mantle chemical coupling' into numerical mantle convection simulations to check how the stable region works for core-mantle evolution system
- Reducing the initial CMB temperature from unrealistically high temperature - 4900 K with the stable region.
- Low CMB heat flow may not explain the possible thickness of stable region - Compositional origin would be preferable and purely thermal origin may not be allowed (ceasing the geodynamo actions and so on).
- High chemical diffusivity would be rather explained for the current constraint on thickness of stable region inferred from geomagnetic secular variations.
- With realistic mantle dynamics (?), the core-mantle boundary would not be rapidly cooled down because the stable region works for the much stronger heat buffer of heat transport across the core but keeping high CMB heat flow (~13 TW).
- HPE in the mantle may not affect the core evolution but small effects for mantle evolution. - If HPE in the mantle would be upper-limit value inferred from 'geoneutrino flux', the mantle would not be rapidly cooled down over the age of the Earth. Most amount of cooling might be happened in around the 'early Earth' = 50 K/Gyr. The heat transport system in a convecting mantle would be almost balanced after the early Earth stage has been finished, that is, CMB heat flow + HPE + magmatic heat flow-Surface heat flow ~ 0 TW. This would be consistent with the recent melting experiments under high P-T condition and its implications [Andrault et al., 2016].

The END!

Thanks!