The role of mineralogical-dependent thermal properties on the evolution of Mercury's interior

Manon Lécaille[1], Nicola Tosi[2], Olivier Namur[3], Attilio Rivoldini[4] and Bernard Charlier[1]

[1]Department of Geology, University of Liège, Belgium (manon.lecaille@uliege.be)
[2]DLR Institute of Planetary Research, Planetary Physics, Berlin, Germany
[3]Department of Earth and Environmental Sciences, KU Leuven, Belgium
[4]Royal Observatory of Belgium, Brussels, Belgium

abstract

The crystallization of Mercury's magma ocean likely resulted in a compositionally stratified mantle comprising olivine, pyroxene, plagioclase, quartz, and sulfur phases (Namur & Charlier, 2017). These minerals possess distinct thermal properties that are expected to influence the planet's long-term thermal evolution. However, previous thermal evolution models (e.g. Hauck et al., 2004; Grott et al., 2011; Tosi et al., 2013; Hauck et al., 2018) have not accounted for this variability, instead assuming constant thermal parameters (thermal conductivity, heat capacity, density, and thermal diffusivity) typically derived from measurements of terrestrial volcanic and plutonic rocks under ambient conditions (Clauser & Huenges, 1995).

In this study, we used a 1D parametrized model of mantle convection (Baumeister et al., 2023), accounting for mantle melting, melt extraction, and crust formation. We simulated the thermal evolution of Mercury, incorporating variable mantle properties representative of key mineral endmembers, specifically from forsterite (Mg-rich olivine) to enstatite (Mg-rich orthopyroxene), in agreement with the Fe-poor nature of Mercury's mantle. Crustal thermal conductivity values were adopted from experimental data for basaltic compositions (Seipold, 1998), and simulations were conducted both with and without the effects of crustal porosity. Mineral thermal conductivities were sourced from recent experimental studies (Guo et al., 2024; Zhang et al., 2019), while heat capacities and densities were computed using thermodynamic equations of state (Stixrude & Lithgow-Bertelloni, 2005, 2024).

Thermal conductivity: / **Heat capacity and density:**

Constant parameters used in previous studies:

$k_{mantle} = 4$ W m^{-1} K^{-1}
$k_{crust} = 1.5$ W m^{-1} K^{-1}

$C_{p,\,mantle} = 1212$ J K^{-1} kg^{-1}
$C_{p,\,crust} = 1000$ J K^{-1} kg^{-1}

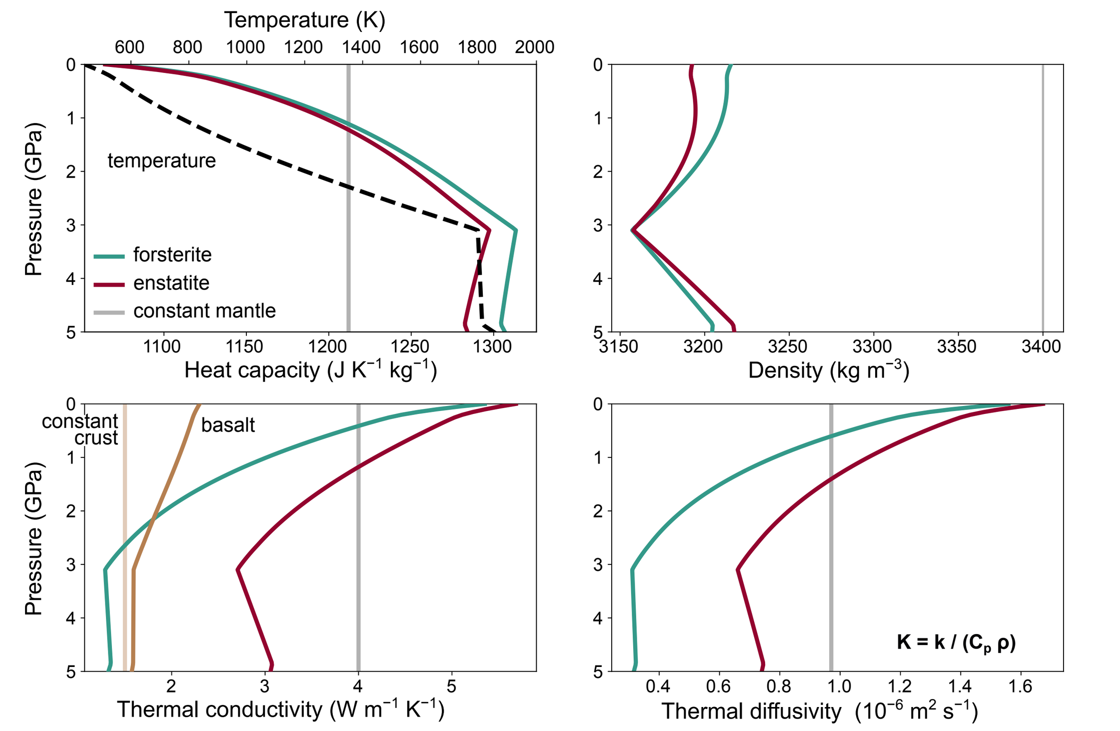
$\rho_{mantle} = 3400$ kg m^{-3}
$\rho_{crust} = 2800$ kg m^{-3}

New parameters:

$k_{forsterite} = 8.114\,(300\,T^{-1})^{1.087}\,(1 + 0.036\,P)$
$k_{enstatite} = 7.667\,(293\,T^{-1})^{0.736}\,(1 + 0.11\,P)$
$k_{basalt} = (1.42 \times 10^{-4}\,(T - 532) + 0.448)^{-1}$

where T is the temperature in K, P is the pressure in GPa and k is in W m^{-1} K^{-1}.

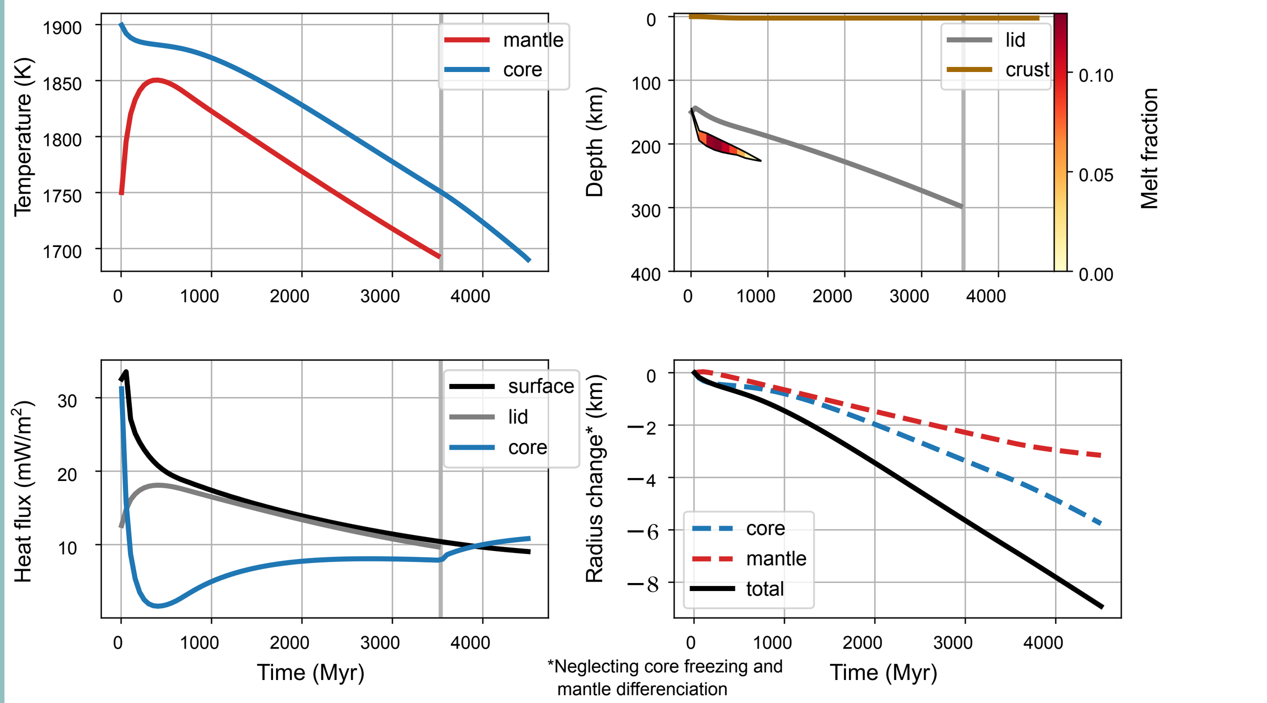
after Stixrude & Lithgow-Bertelloni (2005) with parameters from Stixrude & Lithgow-Bertelloni (2024).



Thermal evolution of end-member models

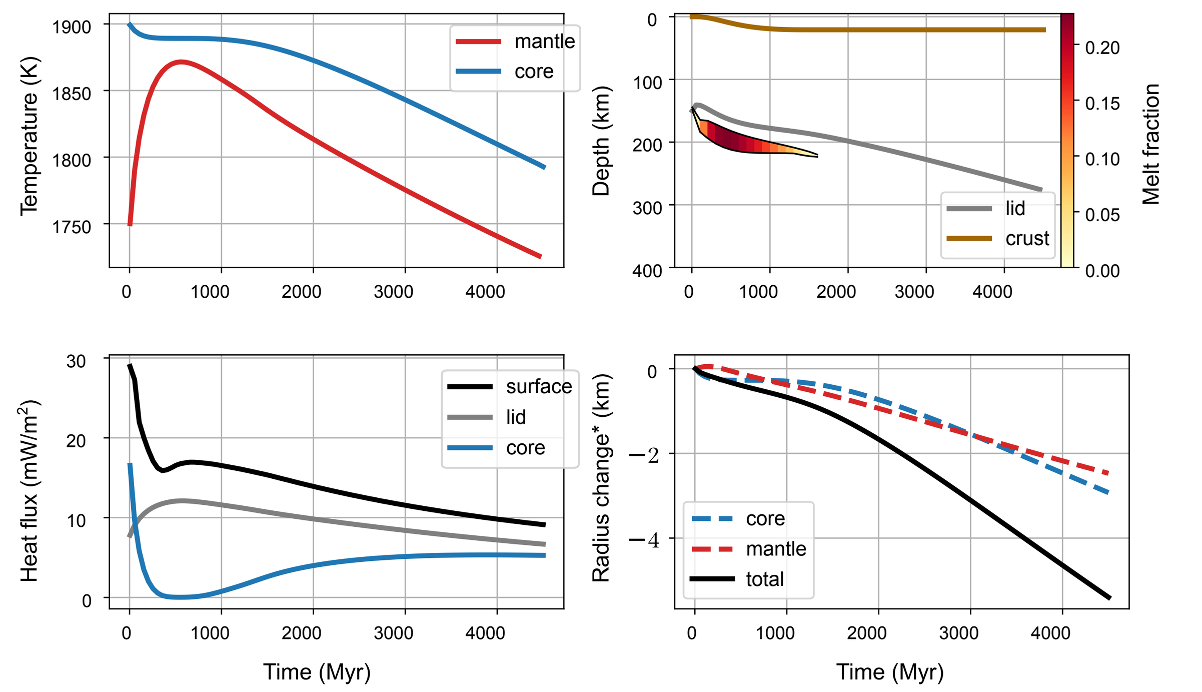
Enstatite-rich

Higher thermal conductivity
Faster cooling of the mantle and the core
Shorter duration of magma generation
Larger radial contraction



Forsterite-rich

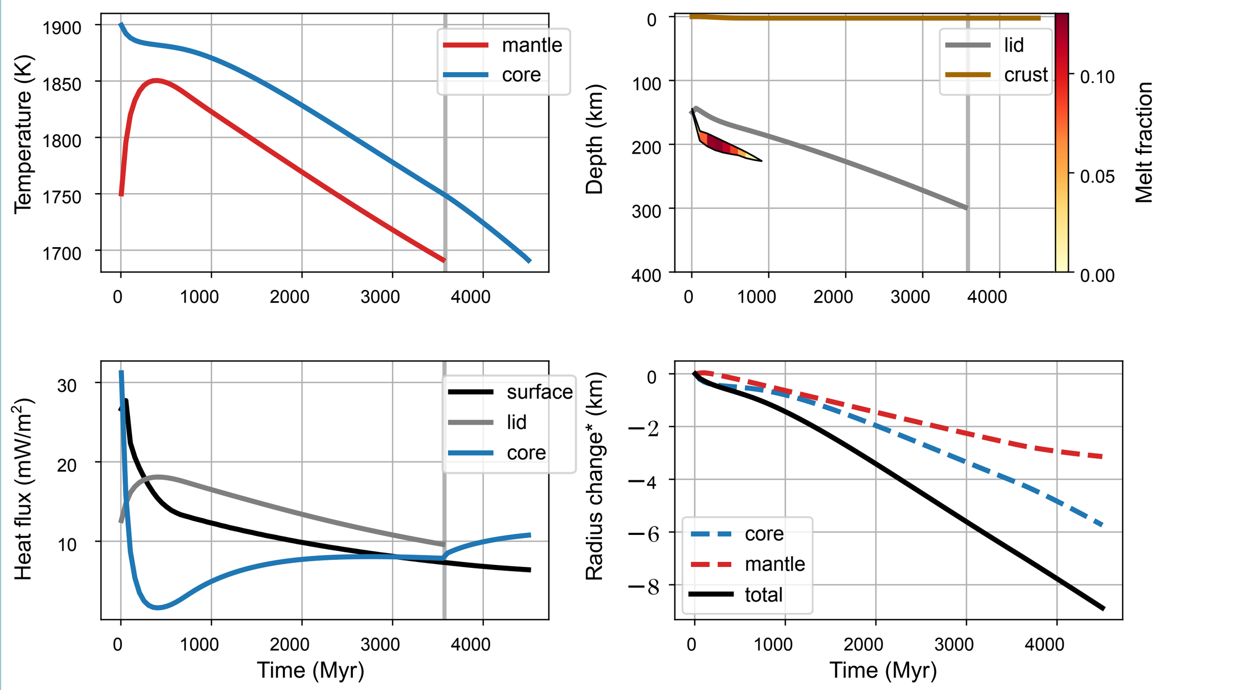
Lower thermal conductivity
Slower cooling of the mantle and the core
Longer duration of magma generation
Smaller radial contraction



Influence of crustal porosity

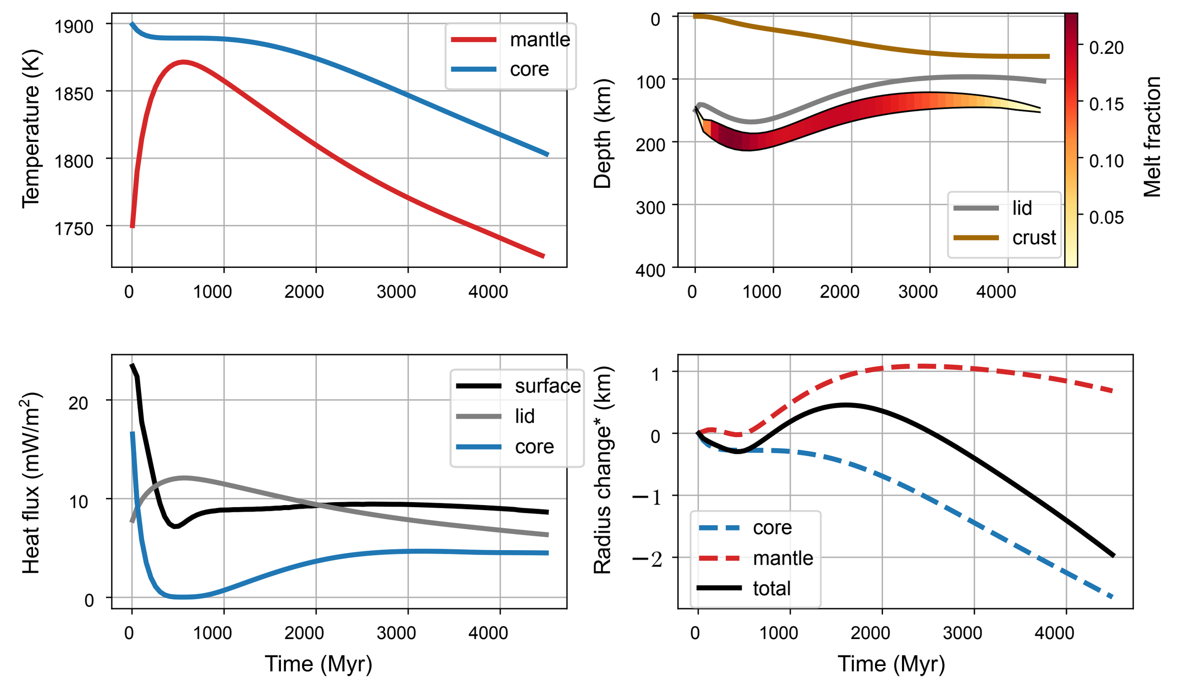
Enstatite-rich

Almost no crust produced
Nearly no effect of crustal porosity

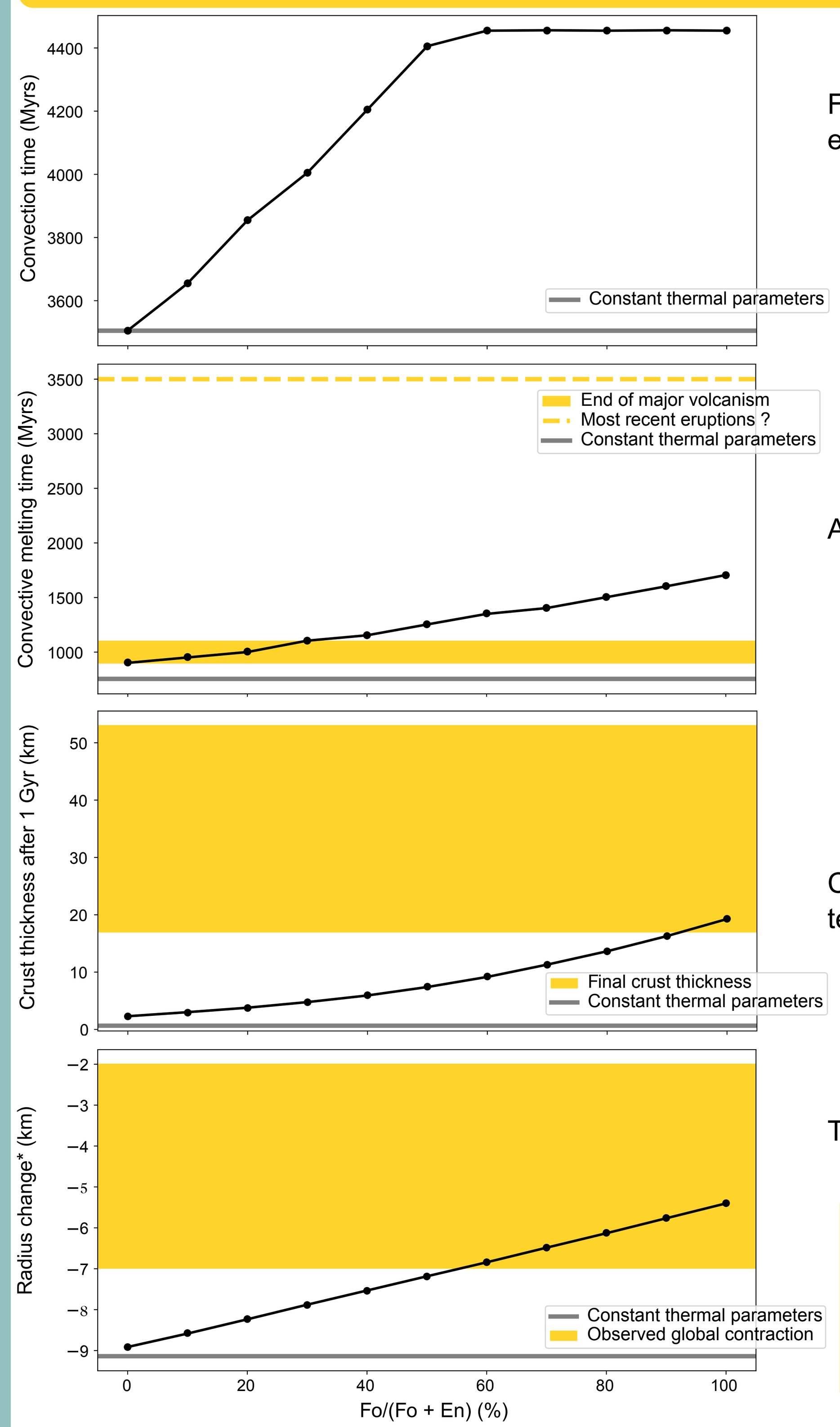


Forsterite-rich

Very low crustal conductivity
Very long duration of magma generation
Very thick crust
Delayed onset of global contraction



Influence of forsterite-to-enstatite ratios on global quantities



Forsterite has a much lower thermal conductivity than enstatite. Therefore,

- the mantle stays hotter,
- melt fractions are larger,
- the mantle convects for a longer time,
- partial melts can be produced for a longer time,
- a thicker crust is built,
- there is less thermal contraction.

According to observations from MESSENGER (2011-2015),

- the major volcanic phase should end around 1 Gyr (Byrne et al., 2016),
- the most recent volcanic deposits were formed after 3.5 Gyr (Thomas et al., 2014),
- the crust thickness is 35 +- 18 km (e.g. Padovan et al., 2015),
- the radial contraction of Mercury is between 1 and 7 km (Byrne et al., 2014, Di Achille et al., 2012, Watters, 2021)

Compared to previous models considering constant thermal properties, accounting for pressure-, temperature- and composition-dependent thermal conductivity, density, and heat capacity leads to

- longer-lived convection,
- thicker crust,
- less radial contraction.

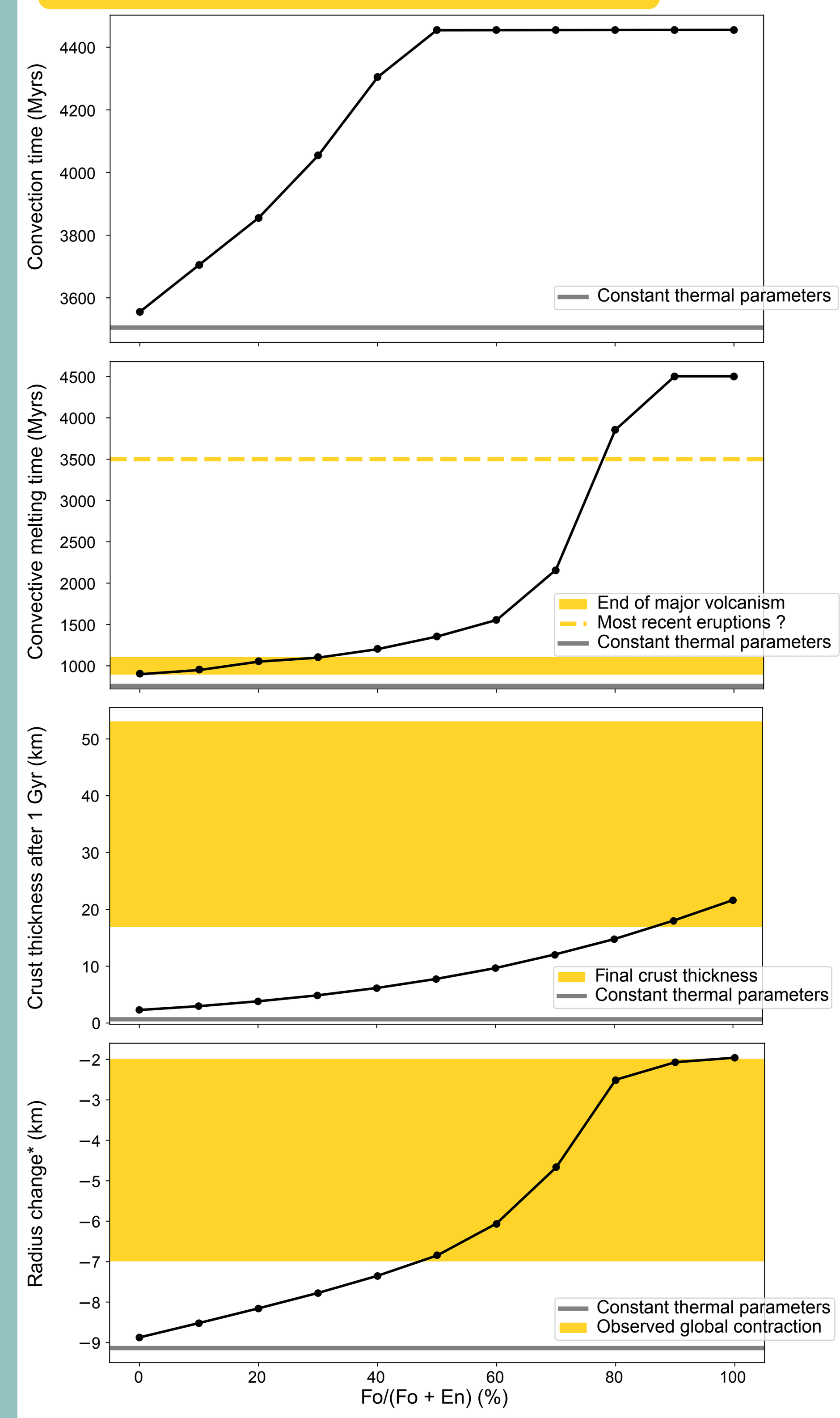
The higher the proportion of forsterite, the more enhanced are these effects.

Constant parameters

Planet radius	2440 km
Core radius	2040 km
Initial mantle temperature	1750 K
Temperature jump at CMB	125 K
Surface temperature	440 K
Surface gravity	3.7 m s^{-2}
Core density	7200 kg m^{-3}
Core heat capacity	850 J K^{-1} kg^{-1}
Mantle reference permeability	9.1 × 10^{-10} m^{2}
Melt viscosity	1 Pa s
Crustal HPE enrchiment factor	3.5
Mantle reference viscosity (1600 K)	3.1623 × 10^{-20} Pa s
Mantle thermal expansivity	2 × 10^{-5} K^{-1}
Solidus temperature (Namur et al., 2016)	1421.15 + 177 P - 12.2 P^{2}

Accounting for variations in thermal parameters due to heterogeneity in the mantle is therefore crucial in modeling planetary interiors. These factors significantly affect key parameters like crust thickness, duration of volcanism and global contraction.

Now, considering crustal porosity



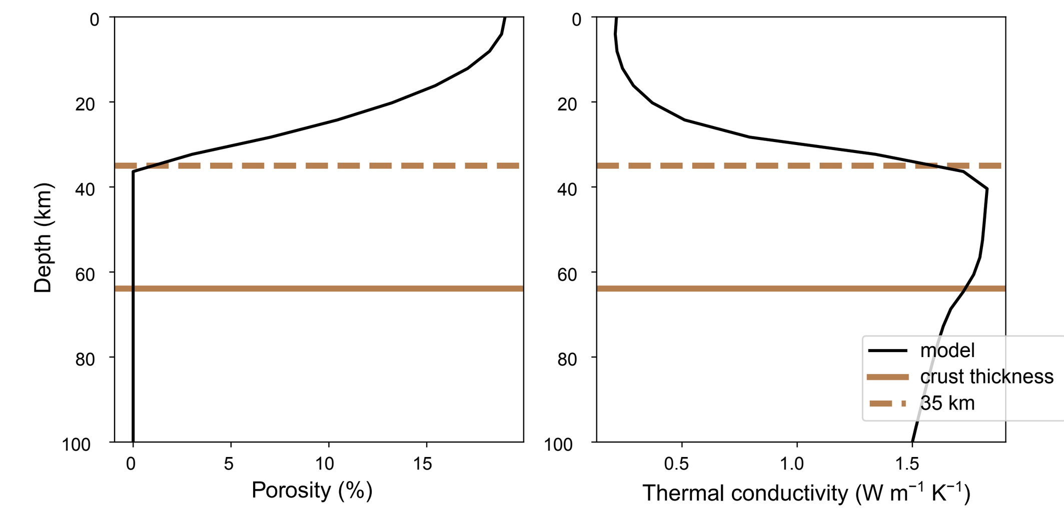
The crustal porosity (φ) of Mercury was recently estimated by Broquet et al. (2024) to an average of 13%. Porosity distribution with depth was calculated using:

$$\varphi(z) = \varphi_{surf}\,(1 - z/35)^{n}$$

where φ_{surf} is the surface porosity (set to 19%), z is the depth and n is recalculated so that the average porosity is 13%.

The porosity-dependent crustal conductivity is calculated as (Warren, 2011):

$$k = k_{basalt}\, e^{-12.46\,\varphi}.$$



The porosity effectively decreases the thermal conductivity of the crust. This leads to:

- higher crustal temperatures,
- thinner lid,
- extended melting time,
- more porous crust production,
- and less radial contraction.

These effects are marked only for forsterite-rich mantle, for which more crust is produced.

Crustal porosity emerges as a key regulator of Mercury's thermal and magmatic evolution—amplifying a self-reinforcing crust formation, particularly in a forsterite-rich mantle regime.

references