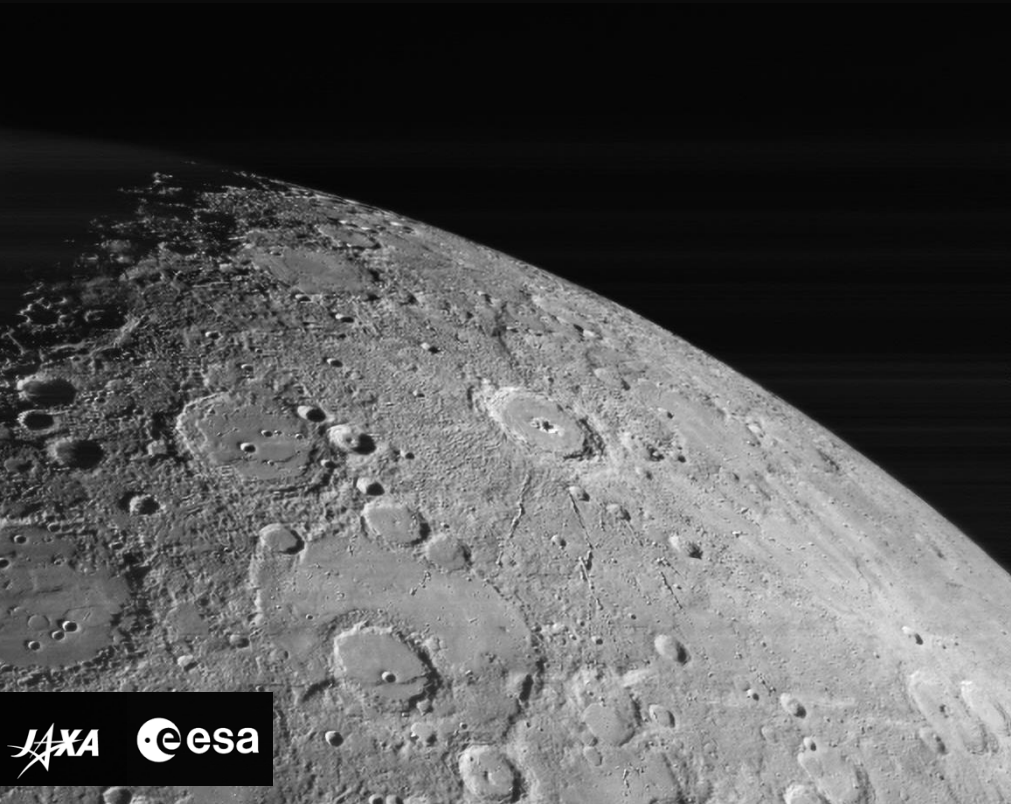


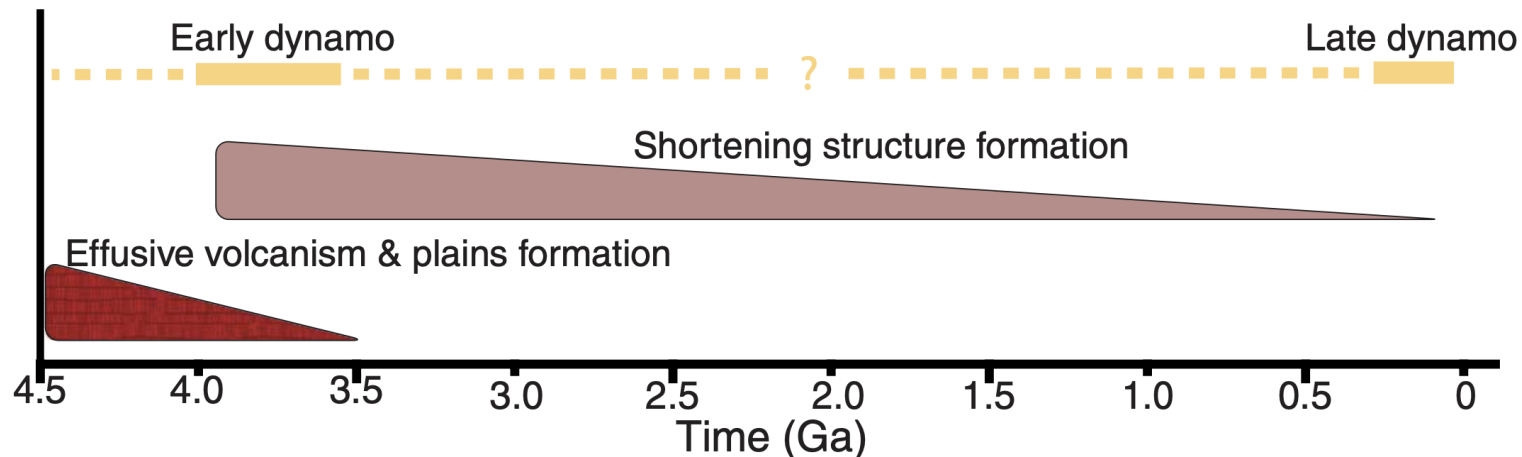
The impact of constraint selection on thermal evolution models of Mercury



M. Lécaille, N. Tosi, A. Rivoldini, P. Baumeister,
O. Namur, B. Charlier

Observations are difficult to reconcile in a single thermal evolution model

- Radial contraction e.g. Di Achille et al., 2012, Byrne et al., 2014, Crane and Klimczak, 2017, Watters, 2021, Loveless & Klimczak, 2025, Broquet and Andrews-Hanna, 2026
- Volcanic activity e.g. Padovan et al., 2015, Byrne et al., 2016, Sori, 2018
- Dynamo e.g. Johnson et al., 2015, 2026, Narret et al., 2026



We aim at refining Mercury's thermal evolution model

1. By running a set of MC simulations exploring a large parameter space
(e.g. Grott et al. 2011, Tosi et al. 2013, Davies et al. 2024, Knibbe et al. 2025)
2. A-posteriori filter the results by selecting constraints individually

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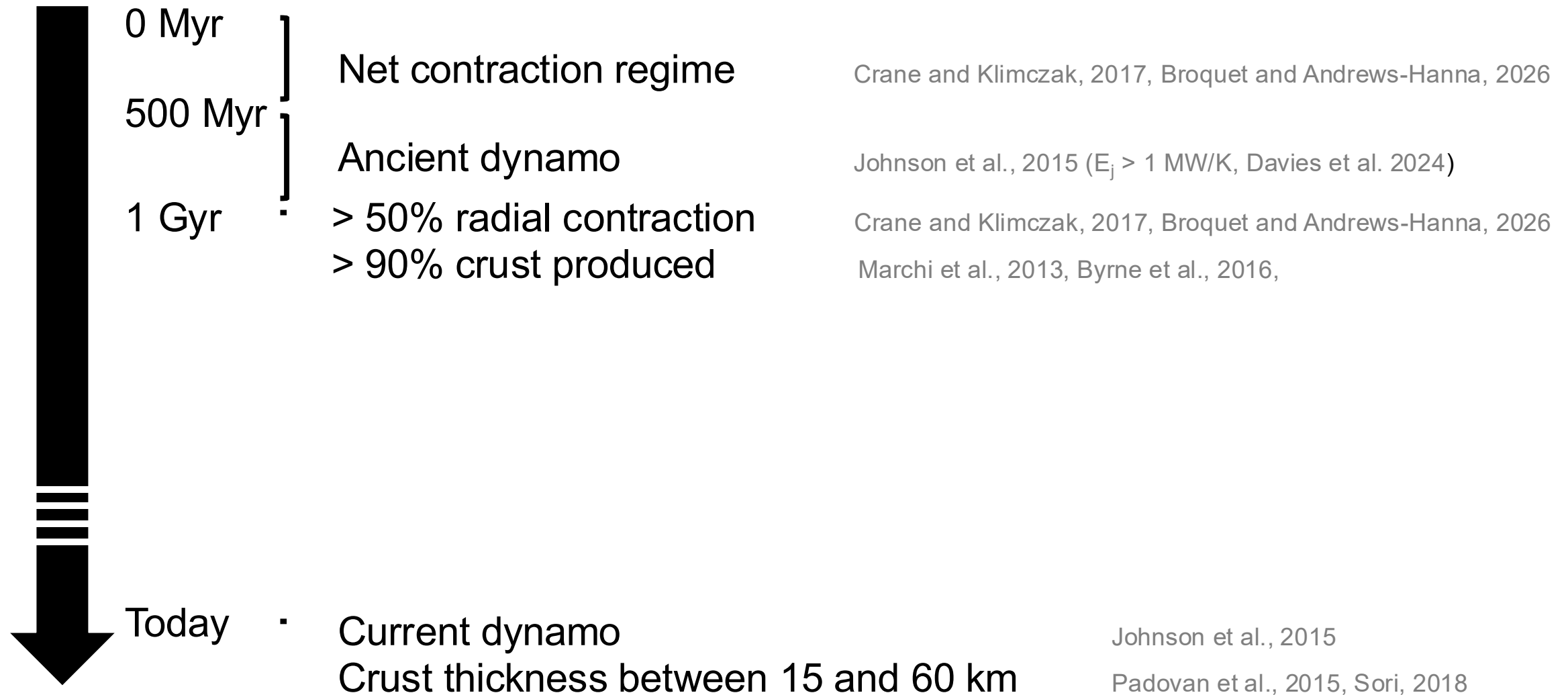
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2. A-posteriori filter the results by selecting constraints individually
3. Characterize successful models that satisfy all constraints

Very different thermal evolution models are needed to satisfy the different constraints
→ Only a few models can satisfy all constraints at once.

Constraints we considered:



1-D parameterized mantle convection model

TEMPURA code Baumeister et al. (2023)

+ Melting:

Reduced CMAS mantle Namur et al. (2016)

+ Heat-producing elements:

EH chondrite Pirotte et al. (2023)

+ Density, heat capacity, thermal expansivity:

P-T-composition dependent

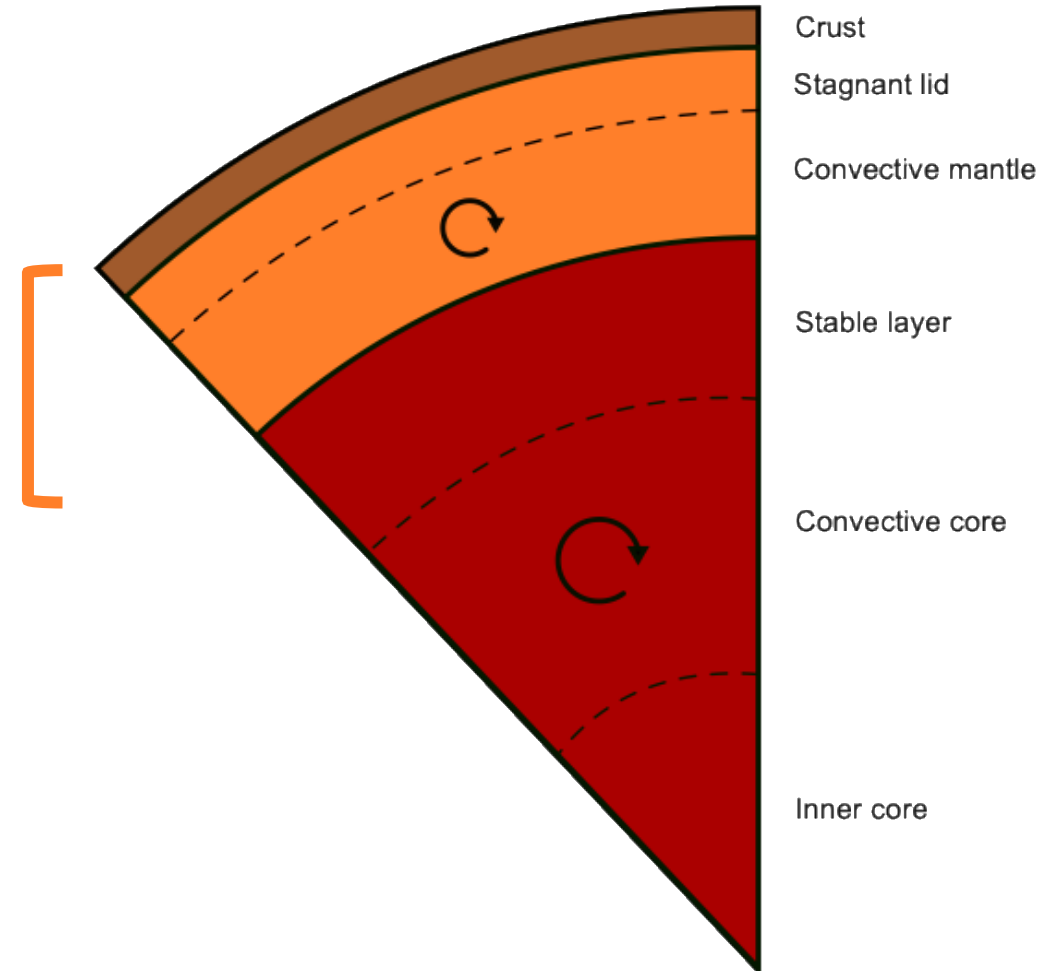
Mixture of forsterite, enstatite and diopside

Stixrude & Lithgow-Bertelloni (2005, 2024)

+ Thermal conductivity:

P-T-composition dependent

Mixture of forsterite Zhang et al. (2019),
enstatite Guo et al. (2024), and
diopside Wang et al. (2014).



Core thermal evolution model

Thermal History code Greenwood et al. (2021)

+ **self-consistent thermodynamic properties of Fe-Si alloys.**

Equations of State:

Solid inner core: Edmund et al. (2019)

Liquid outer core: Terasaki et al. (2019)

Liquidus:

Fe: Dorogokupets et al. (2017)

Eutectic: Edmund et al. (2022)

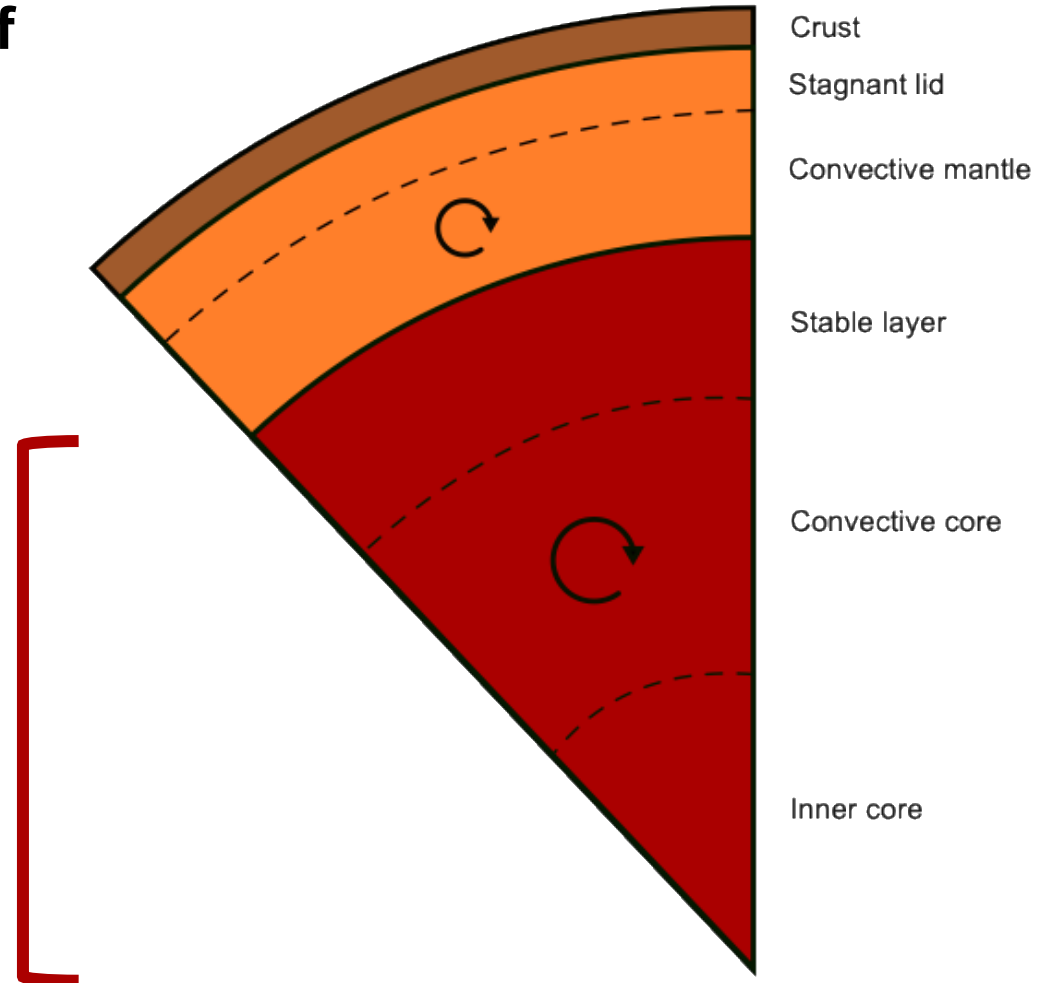
$$T(p)^{Fe-Si} = T^{Fe}(p) - (T^{Fe}(p) - T^E(p)) \times \frac{x_{Si}}{x_{Si}^E}$$

Thermal conductivity:

Fe: Edmund et al. (in press)

FeSi_{8.5wt.%}: Berrada et al. (2021)

$$k^{-1} = \frac{1 - X_{Si}/X_{Si8.5}}{k_{Fe}(p)} + \frac{X_{Si}/X_{Si8.5}}{k_{FeSi8.5}(p)}$$



Model parameters:

50,000 simulations

- Mantle reference viscosity $10^{19} - 10^{23}$ Pa s
- HPE crustal enrichment factor 2 – 20
- Enstatite-forsterite percentage 0 – 90%
(always 10% diopside)
- Initial mantle temperature 1700 – 1800 K
- Initial CMB temperature 1850 – 2100 K
- Core radius 2000 – 2020 km

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Interior structure solved:

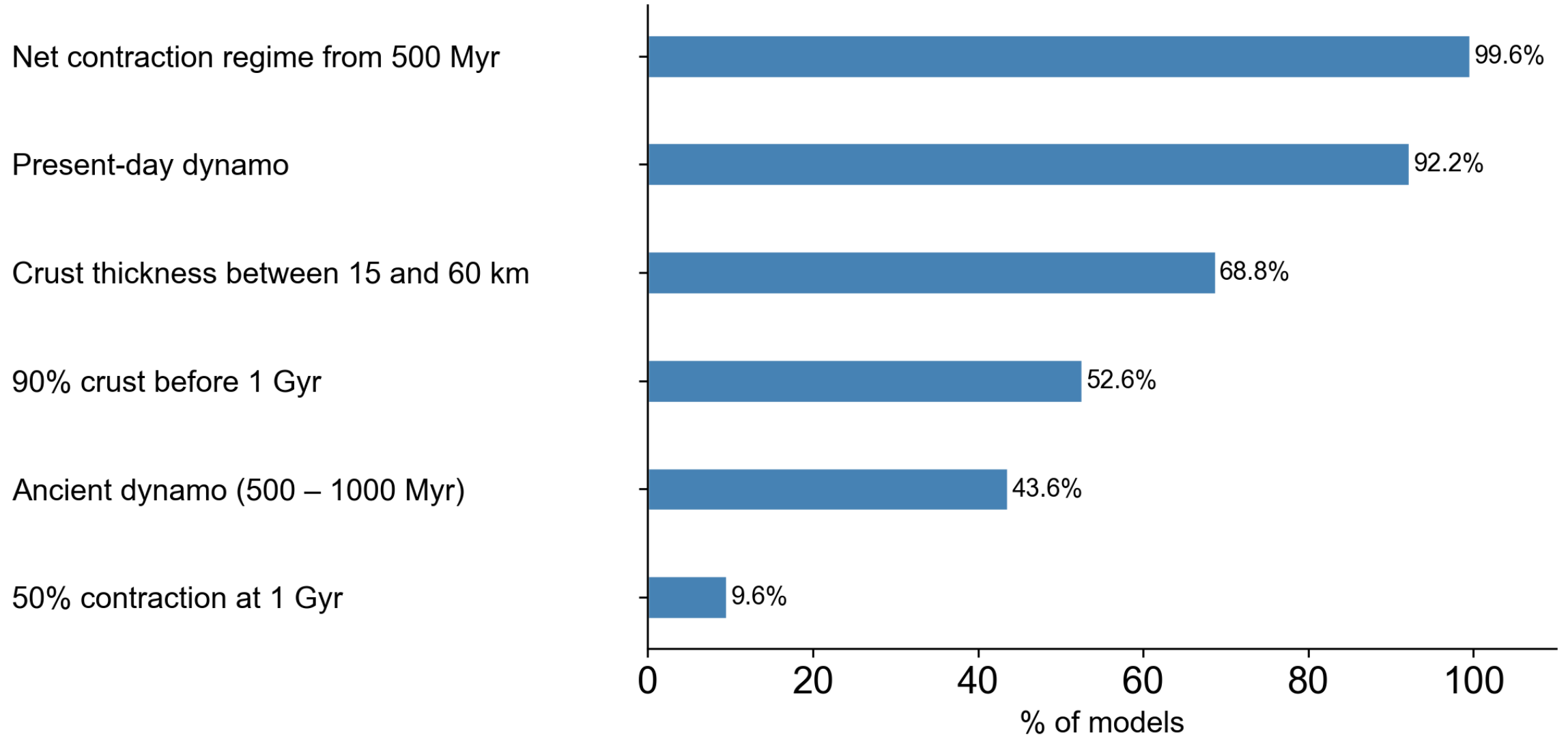
Core Si concentration adjusted
to match bulk planet density

Model parameters:

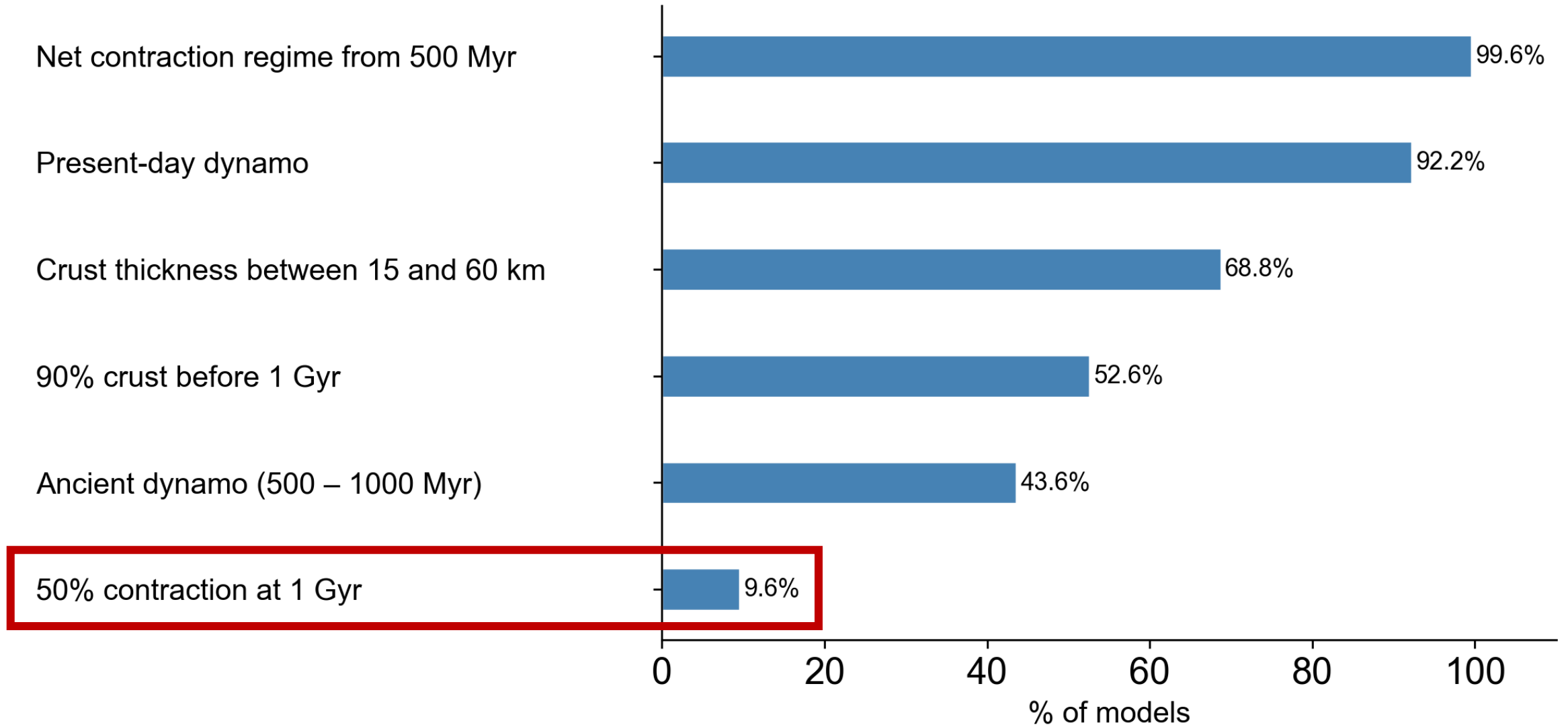
Poorly constrained core properties:

- Core thermal conductivity: varied within experimental uncertainty
At CMB: 25, 27, or 30 W m⁻¹ K⁻¹
- Core melting entropy factor: increased by a factor of up to 1.5
↳ Linked to latent heat released upon inner core growth
At CMB: 7 – 10 J K⁻¹ mol⁻¹ ; 228 – 342 kJ kg⁻¹

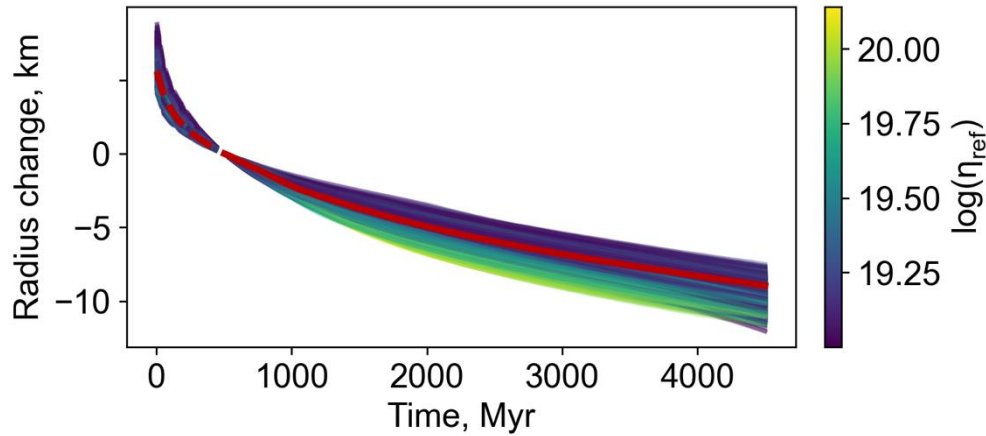
Fraction of models satisfying single constraints:



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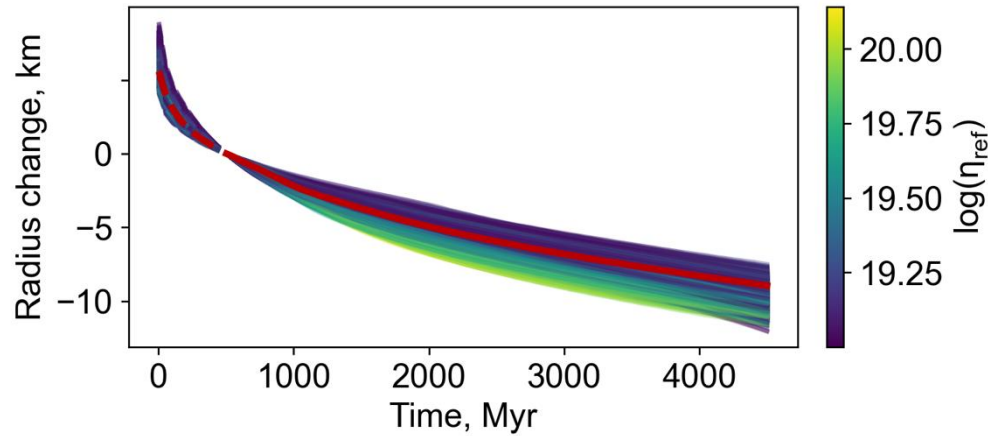


Models that reach 50% contraction by 1 Gyr are the most challenging

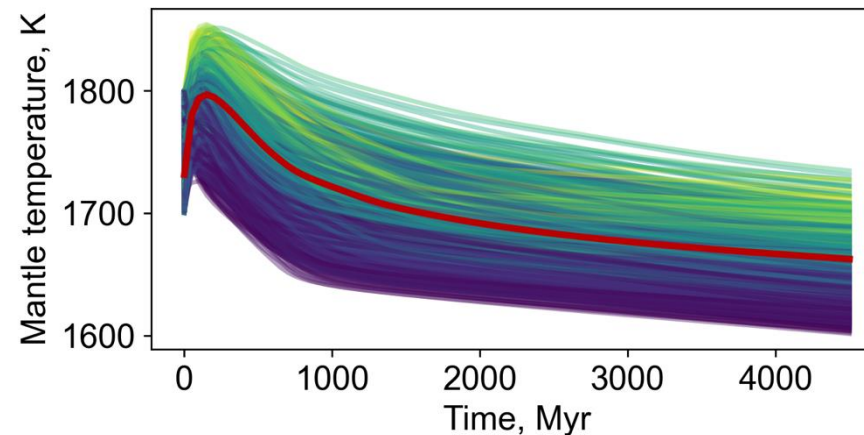
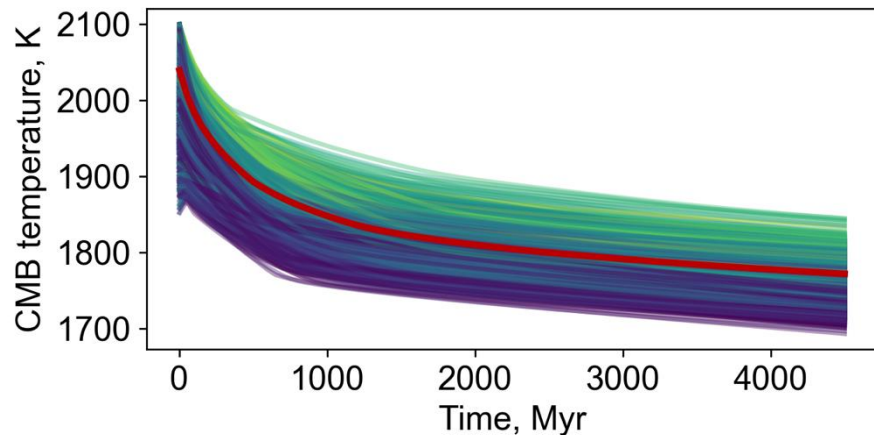


- Contract from the start.
- Core contribution to radial contraction more important than mantle contribution.

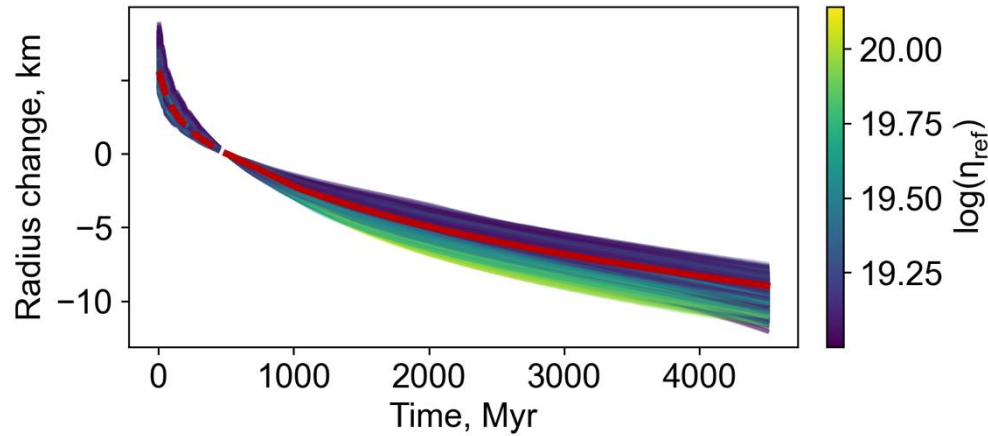
Models that reach 50% contraction by 1 Gyr are the most challenging



- Contract from the start.
- Core contribution to radial contraction more important than mantle contribution.
- Effective and fast mantle and core cooling.

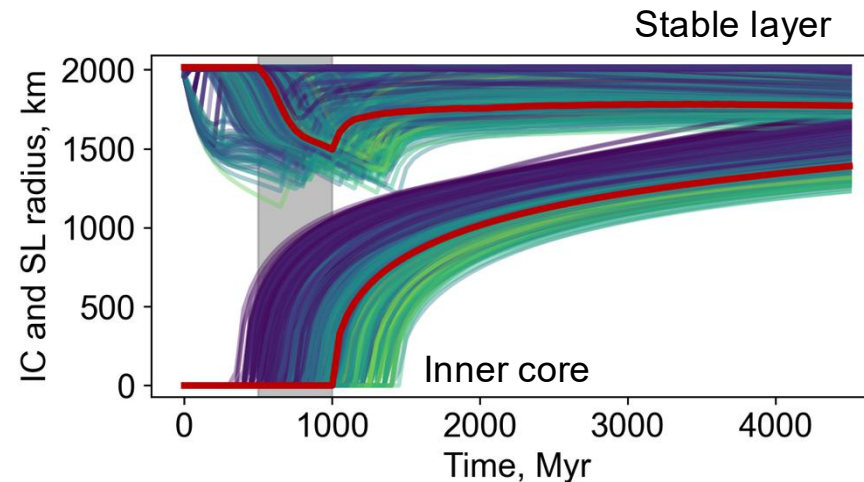
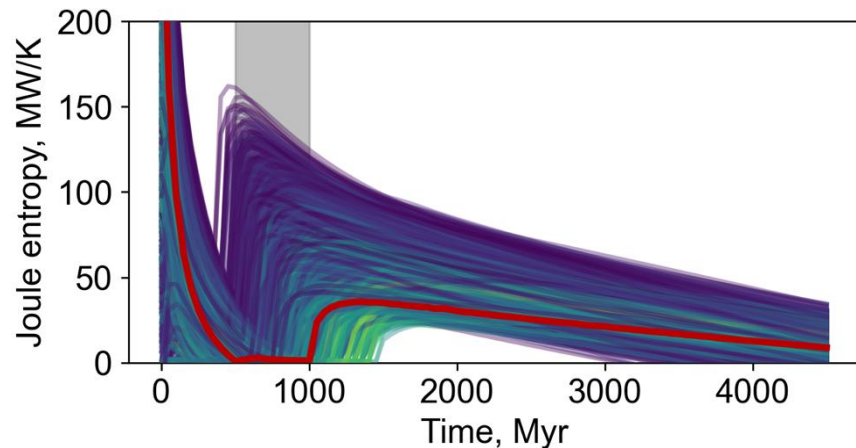


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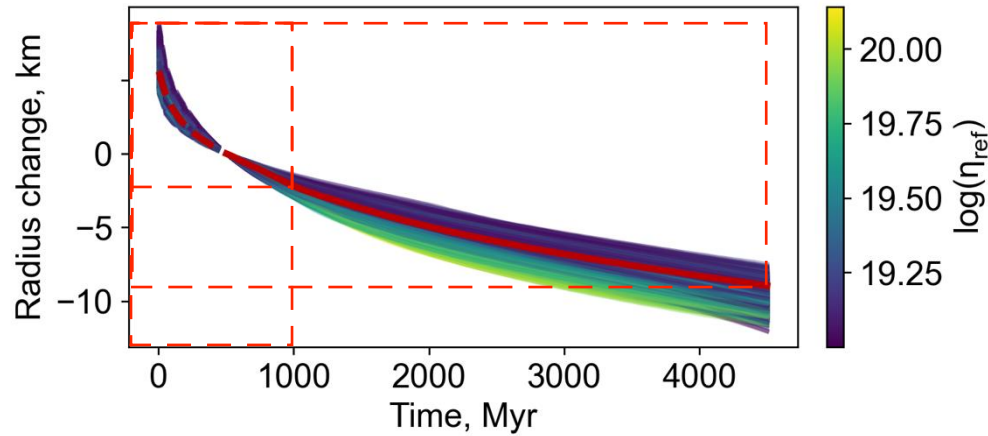


For lots of models:

- no dynamo action between 0.5 and 1 Gyr,
- or today,

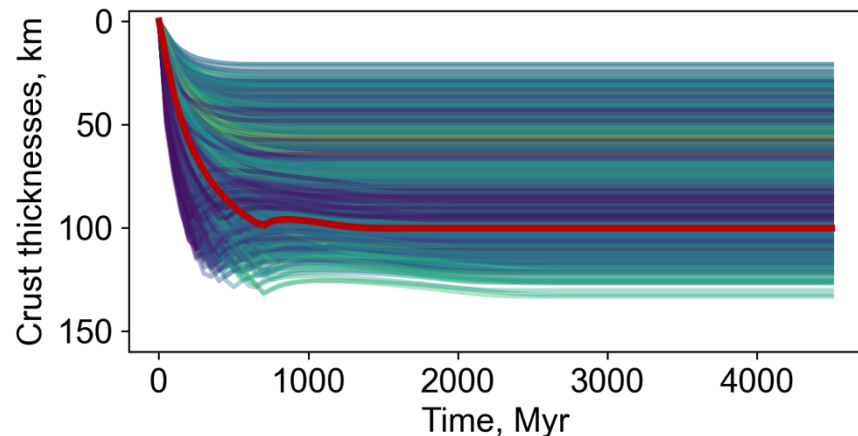


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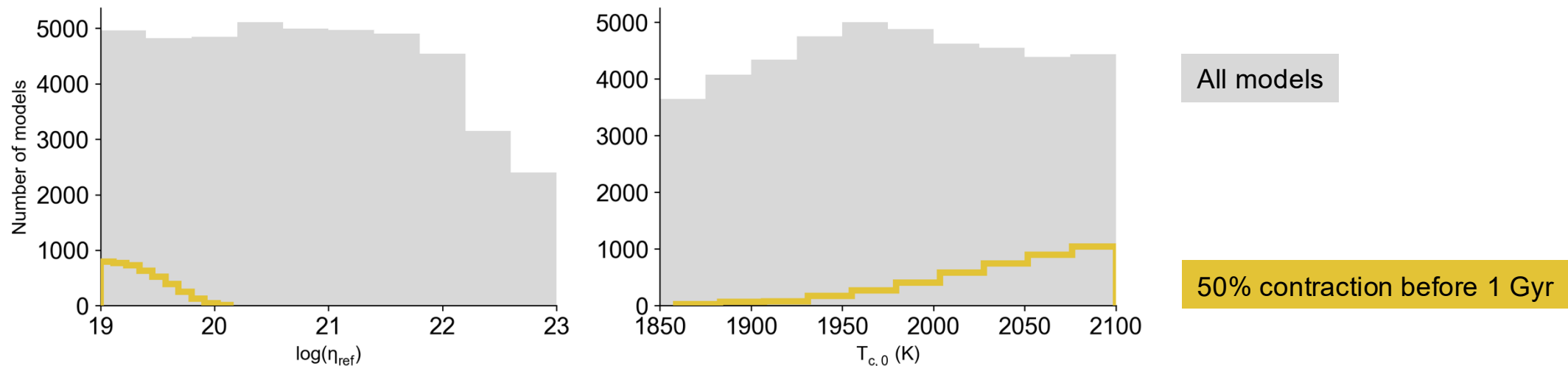
For lots of models:

- no dynamo action between 0.5 and 1 Gyr,
- or today,
- crust too thick



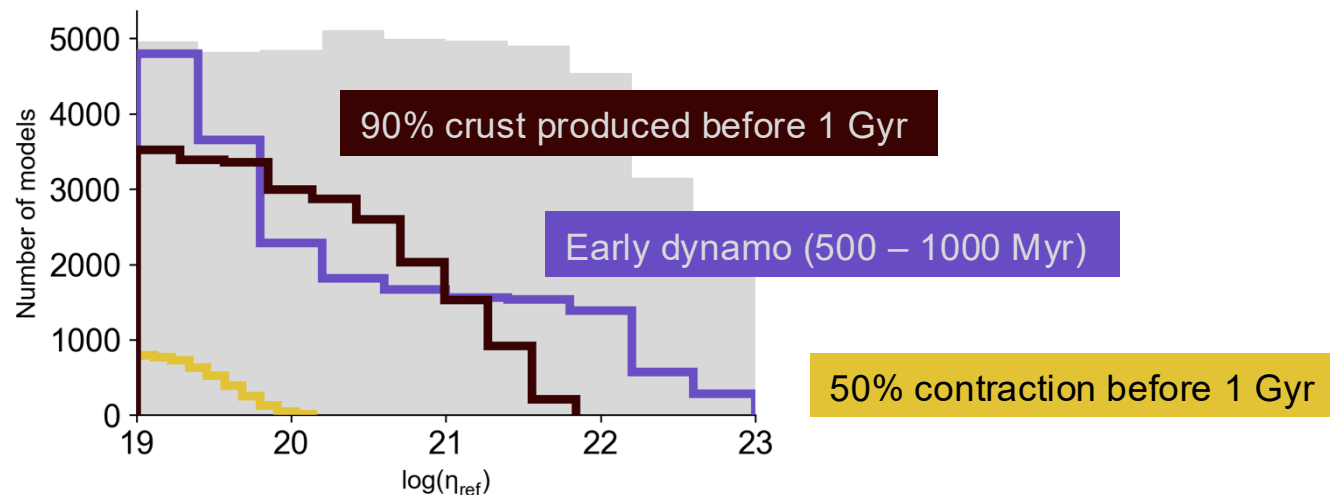
Distributions of mantle reference viscosity and initial CMB temperature for different constraints:

- To reach 50% contraction before 1 Gyr, models must have a low mantle reference viscosity and a high initial CMB temperature.



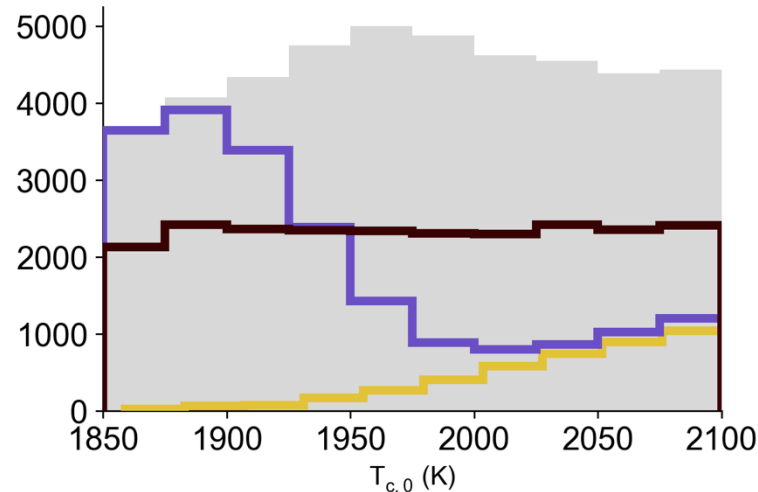
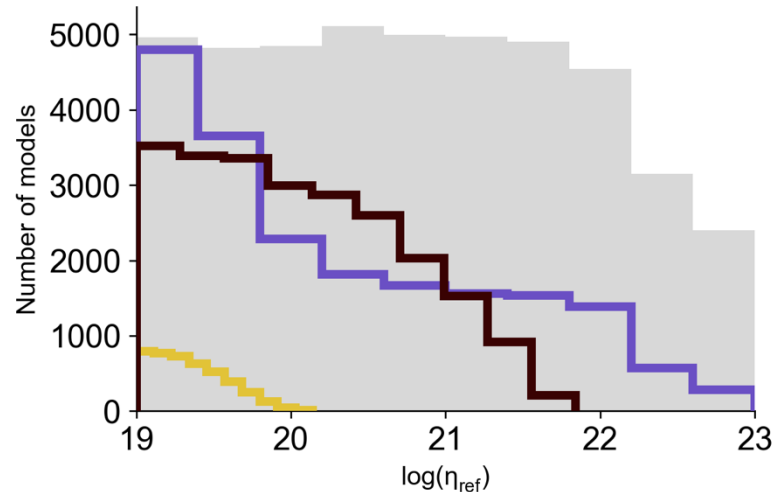
Distributions of mantle reference viscosity and initial CMB temperature for different constraints:

- To reach 50% contraction before 1 Gyr, models must have a low mantle reference viscosity and a high initial CMB temperature.
- Low mantle viscosities also helps model produce 90% of the crust before 1 Gyr and produce a dynamo between 0.5 and 1 Gyr.



Distributions of mantle reference viscosity and initial CMB temperature for different constraints:

- To reach 50% contraction before 1 Gyr: low mantle reference viscosity, high initial CMB temperature.
- Low mantle viscosities also helps model produce 90% of the crust before 1 Gyr and produce a dynamo between 0.5 and 1 Gyr.
- Early dynamo generation is facilitated by lower initial CMB temperatures.



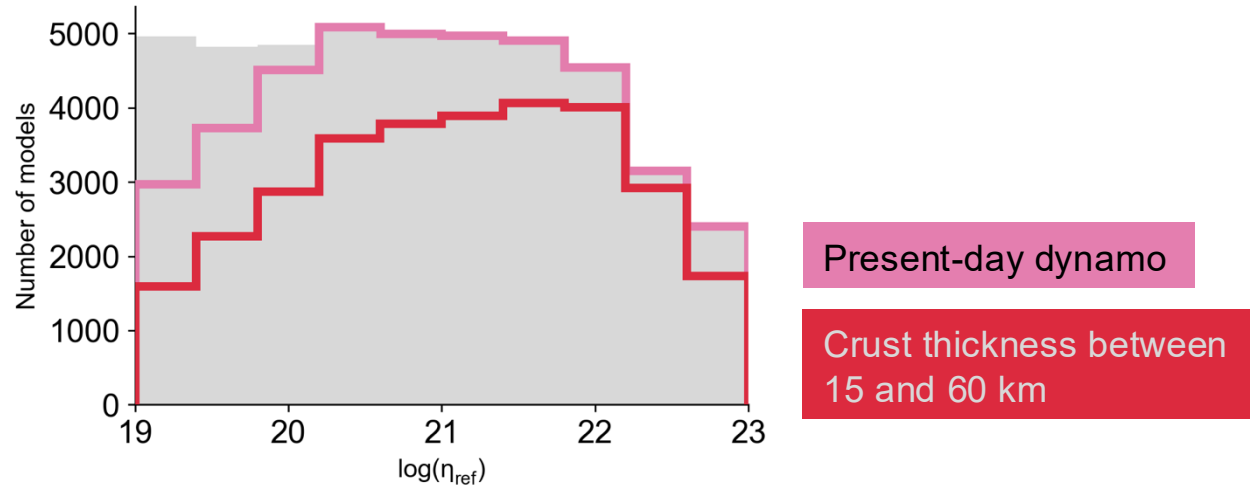
90% crust produced before 1 Gyr

Early dynamo (500 – 1000 Myr)

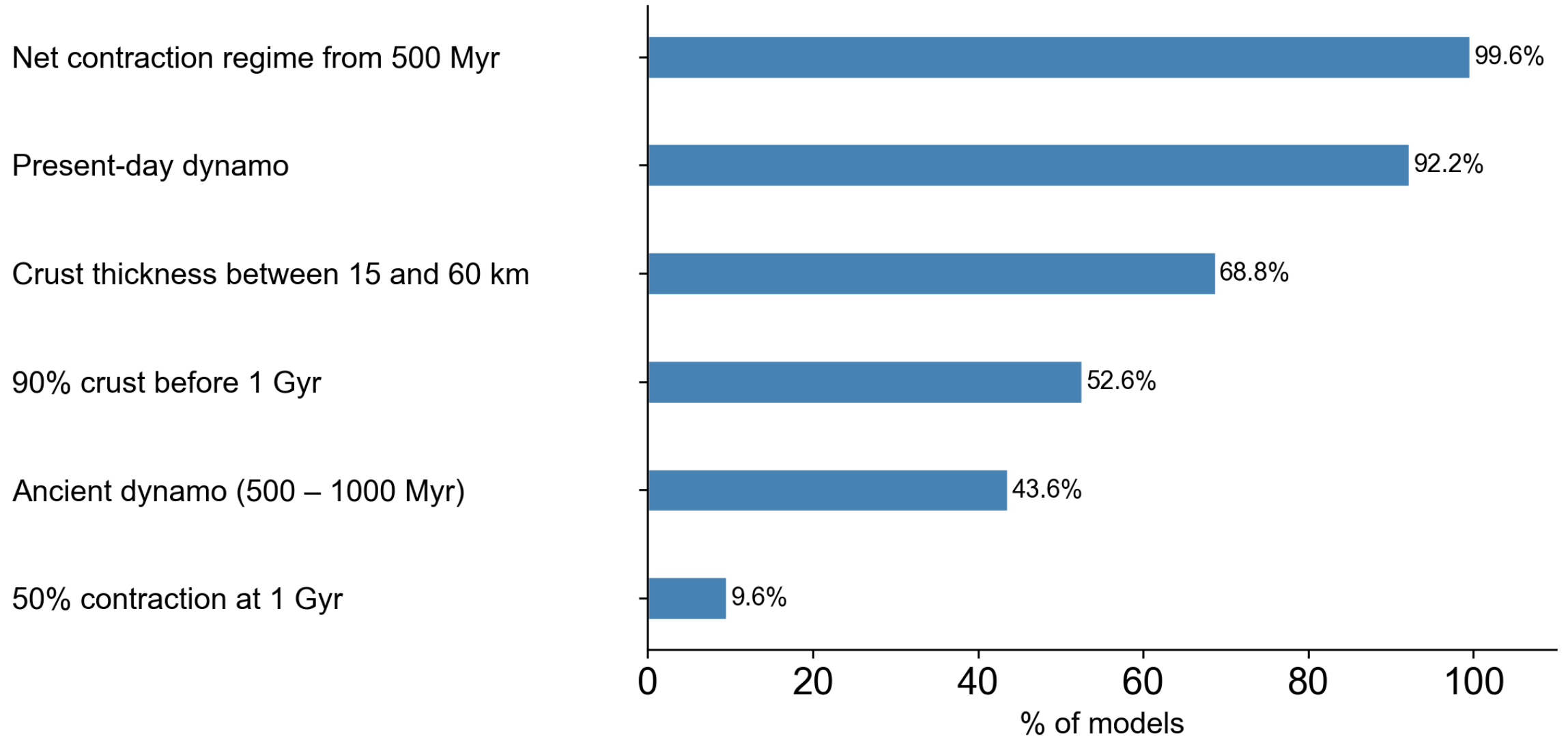
50% contraction before 1 Gyr

Distributions of mantle reference viscosity and initial CMB temperature for different constraints:

- Other constraints easier to satisfy with a larger reference viscosity:

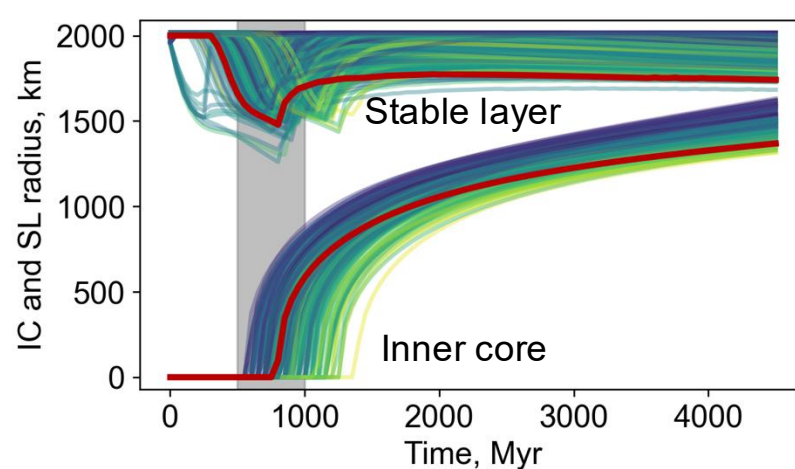
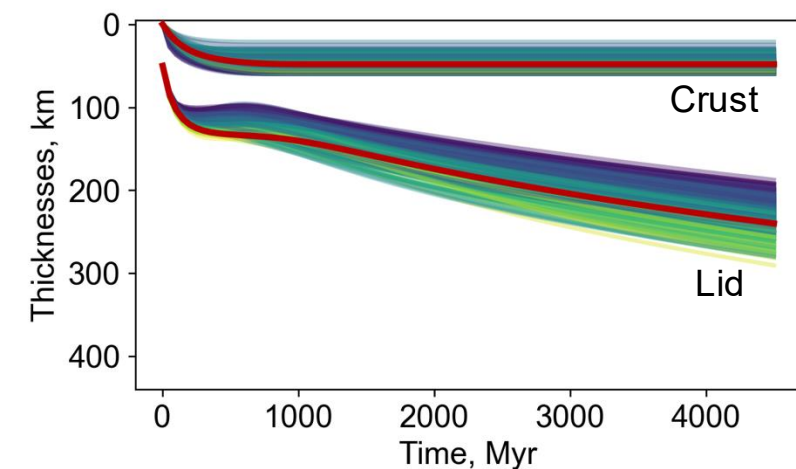
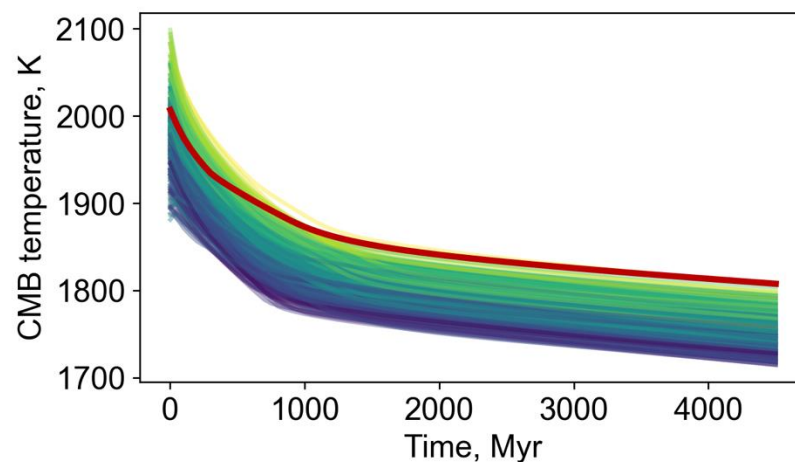
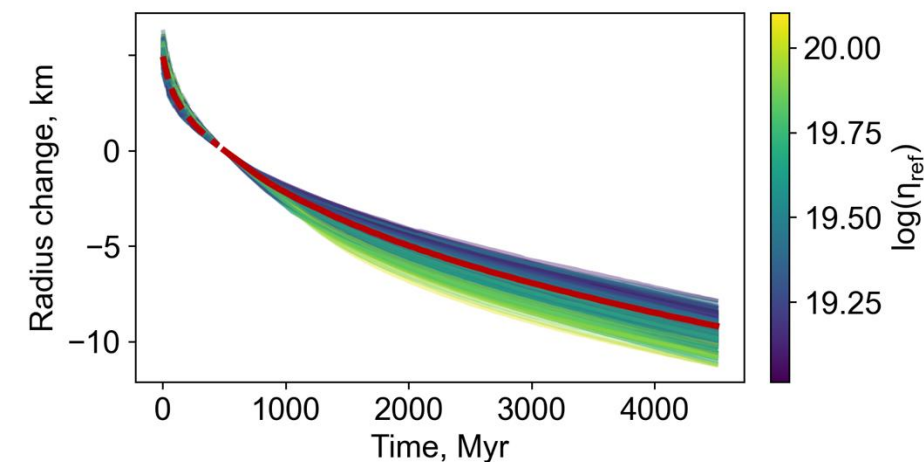


Can some models satisfy the following constraints combined?



338 models (0.8%) satisfy **all constraints**

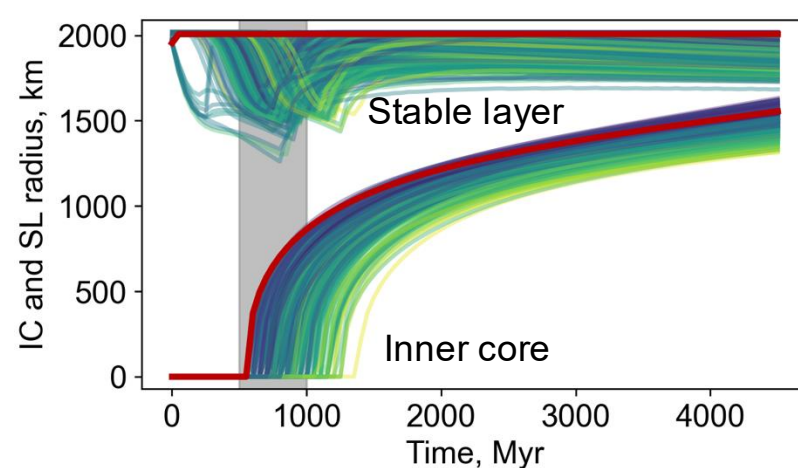
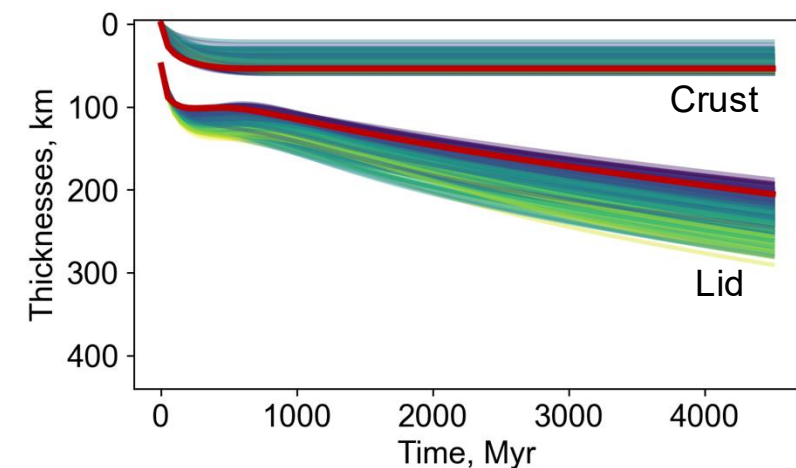
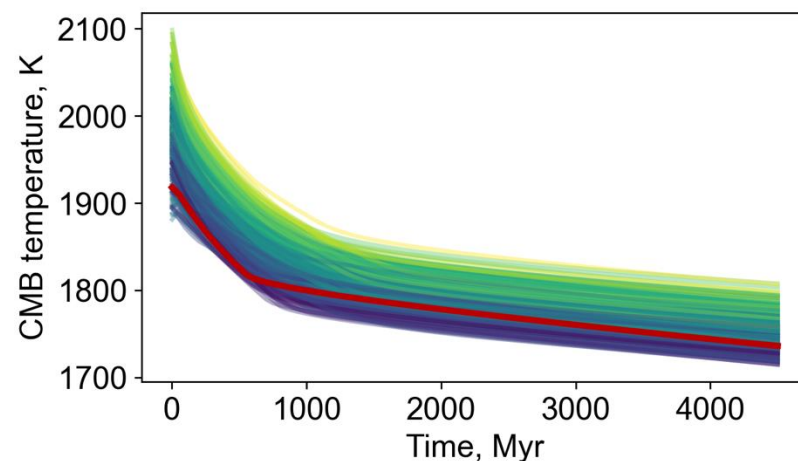
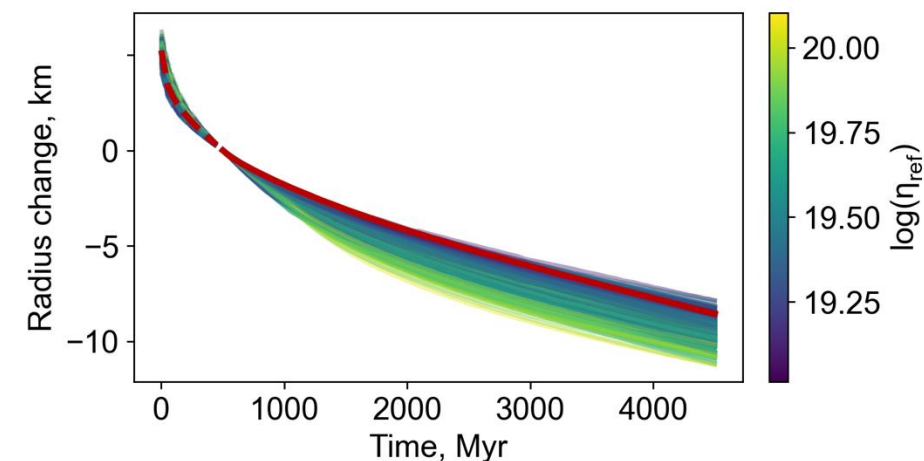
Crust thickness
Present-day and past dynamo
Early contraction regime
90% crust formed before 1 Gyr
50% contraction before 1 Gyr



- Effective cooling in the first 1 Gyr
- Decreasing rate of radial contraction
- Inner core can crystallize after 1 Gyr
- Mantle remains partially convective

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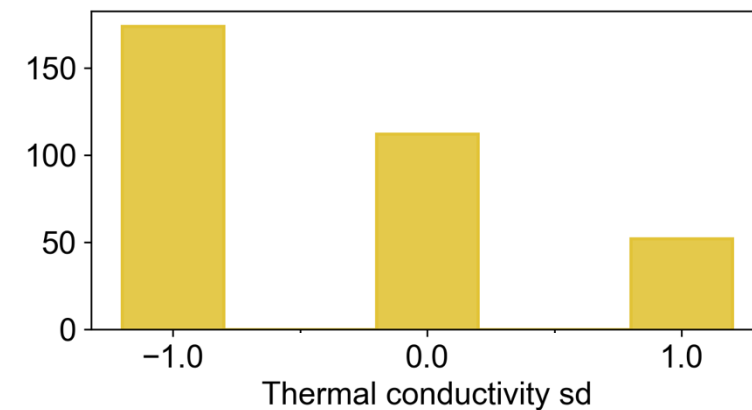
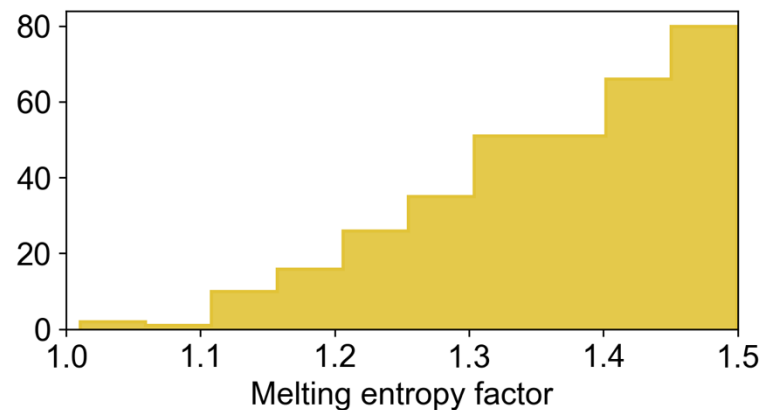
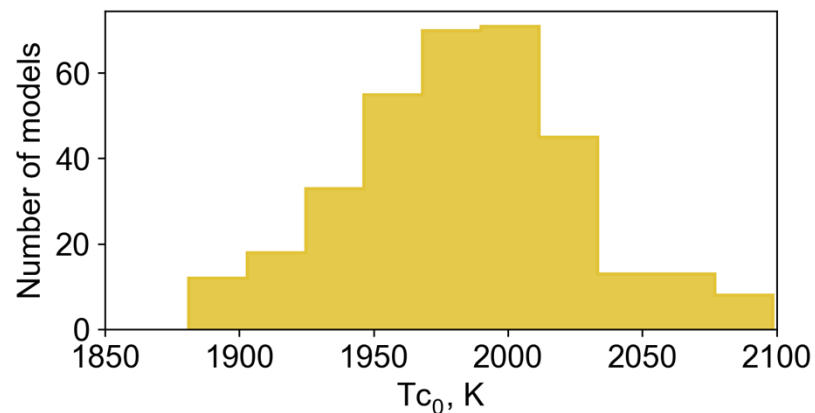
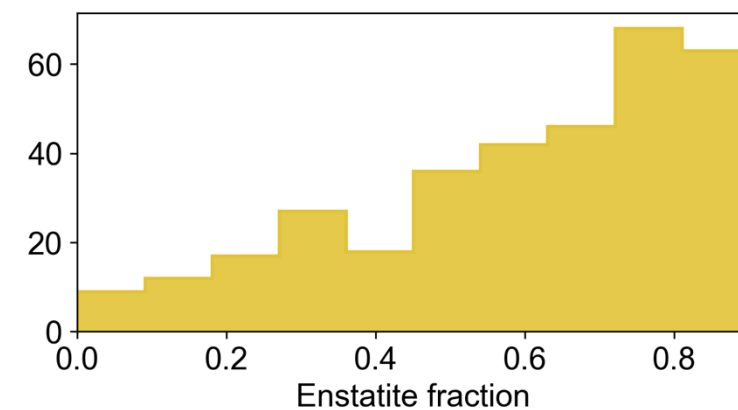
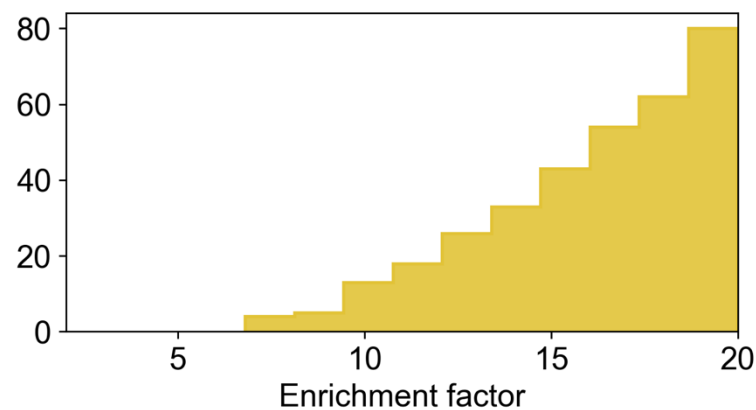
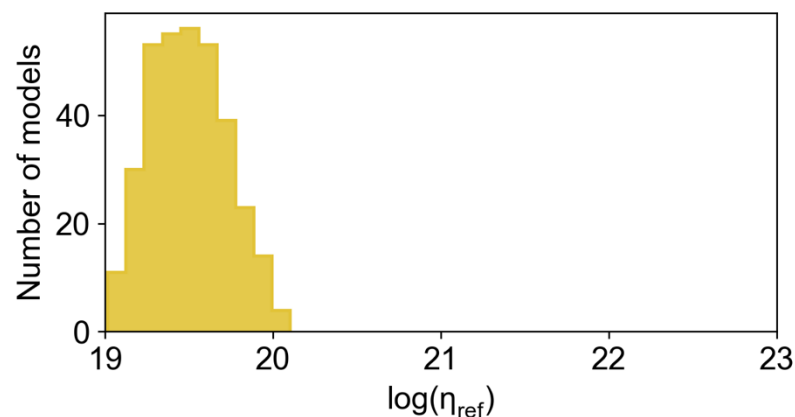
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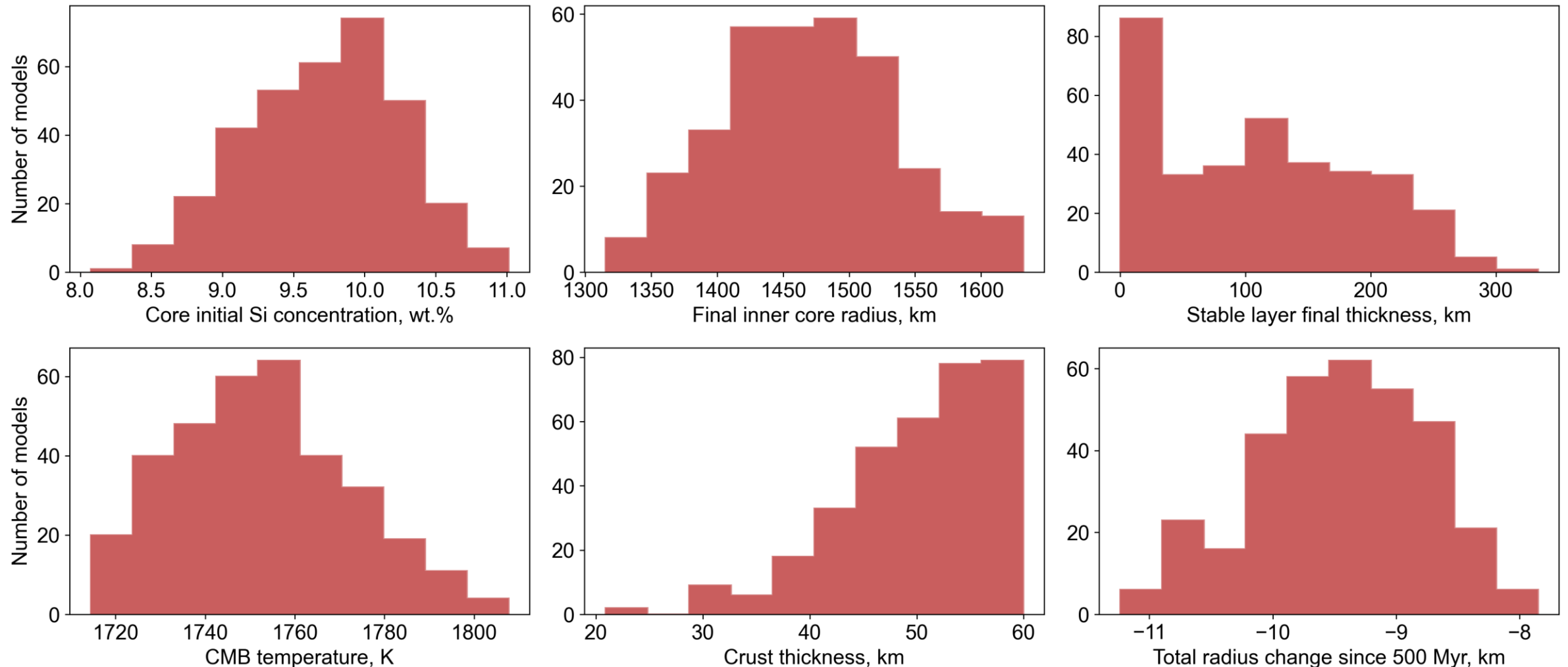
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- No stable layer

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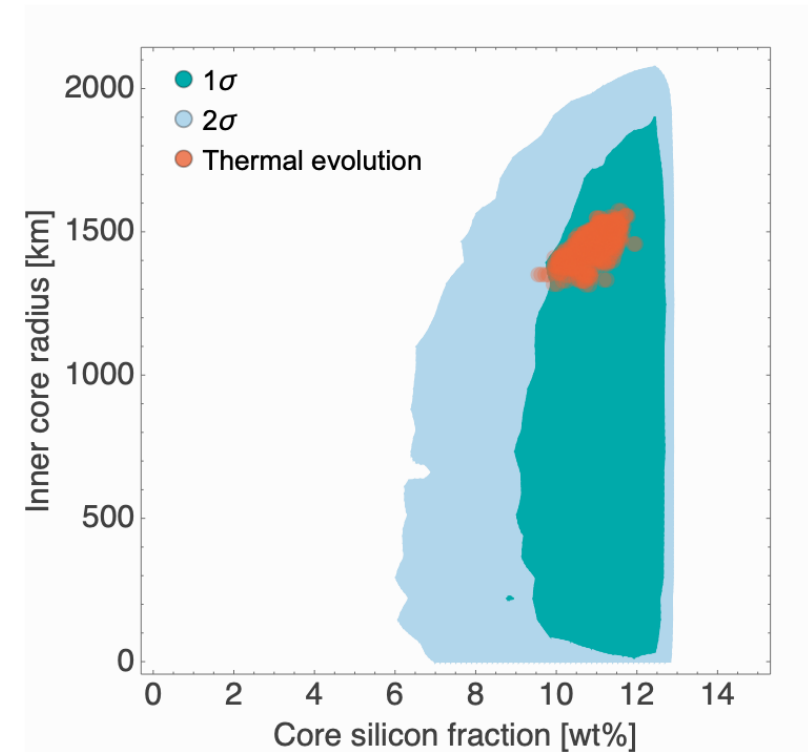
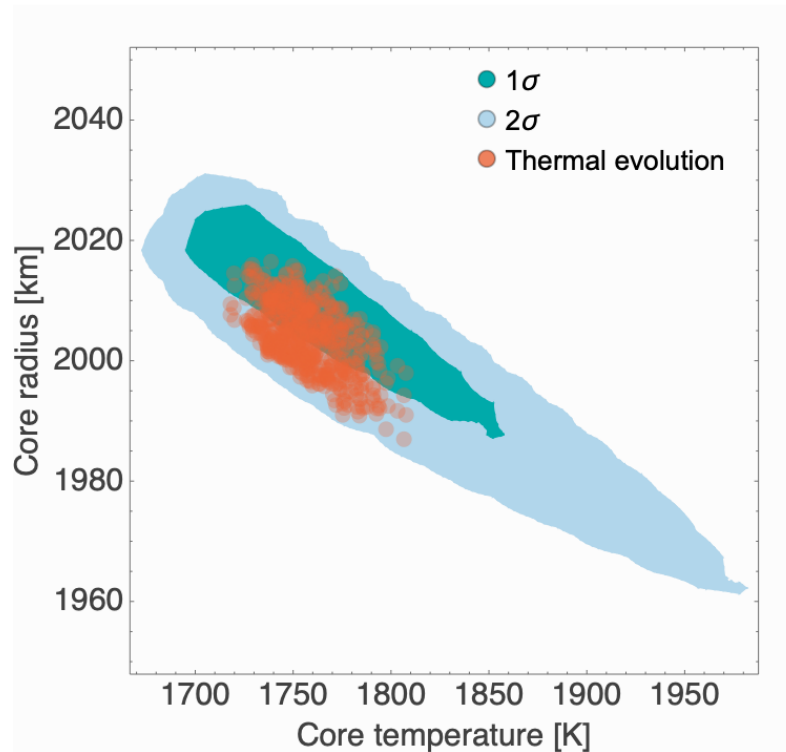
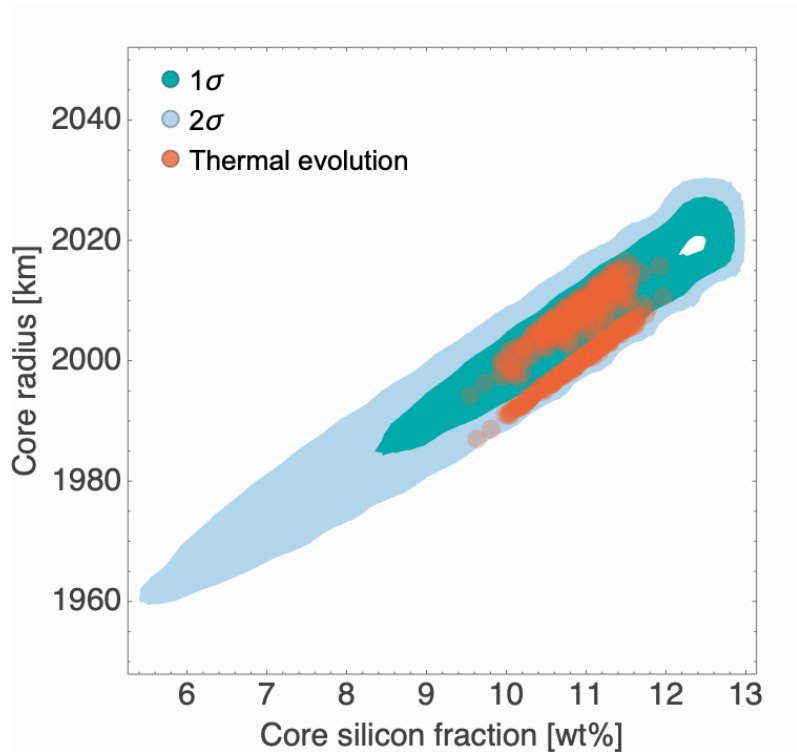
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Final state of the models satisfying **all constraints**



These models match geodesy observations (MOI, libration amplitude)



Conclusions

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Low reference viscosity

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High reference viscosity

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Low reference viscosity

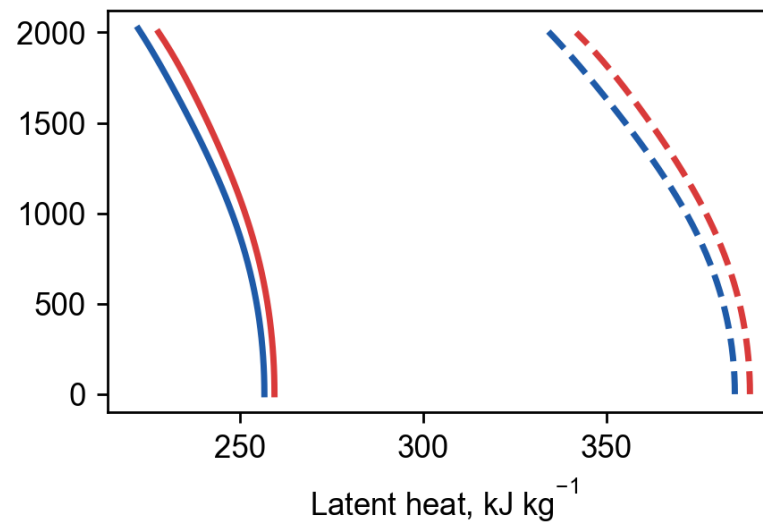
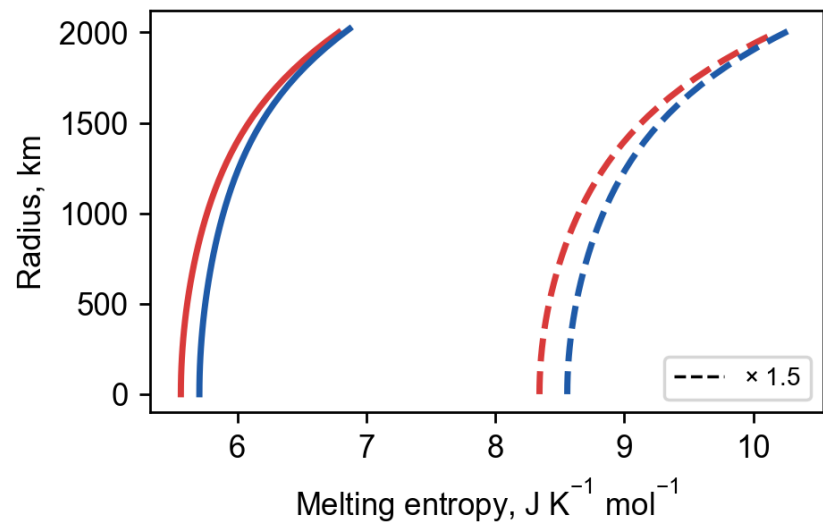
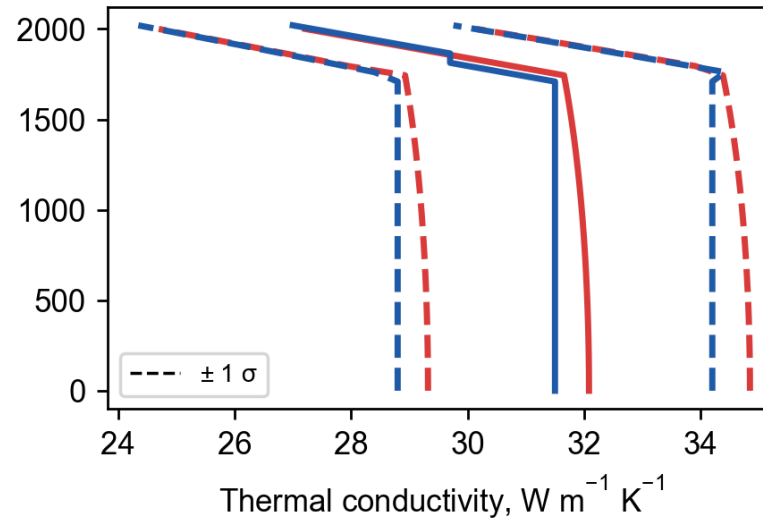
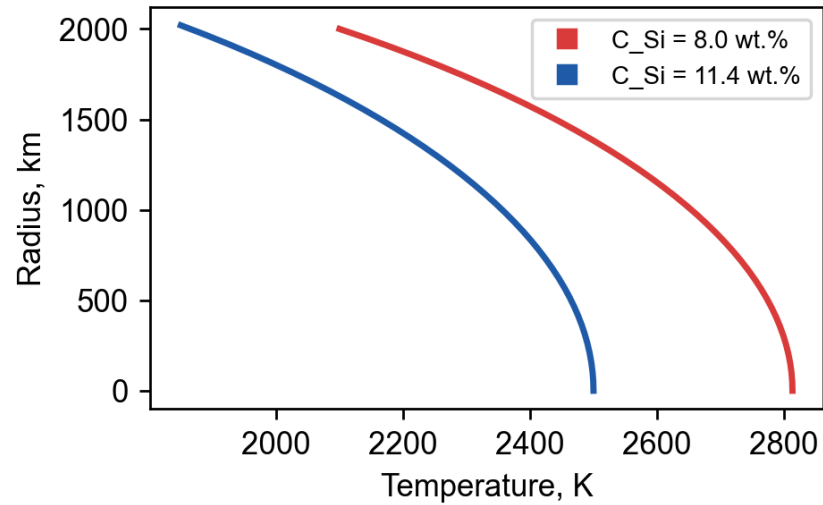
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High reference viscosity

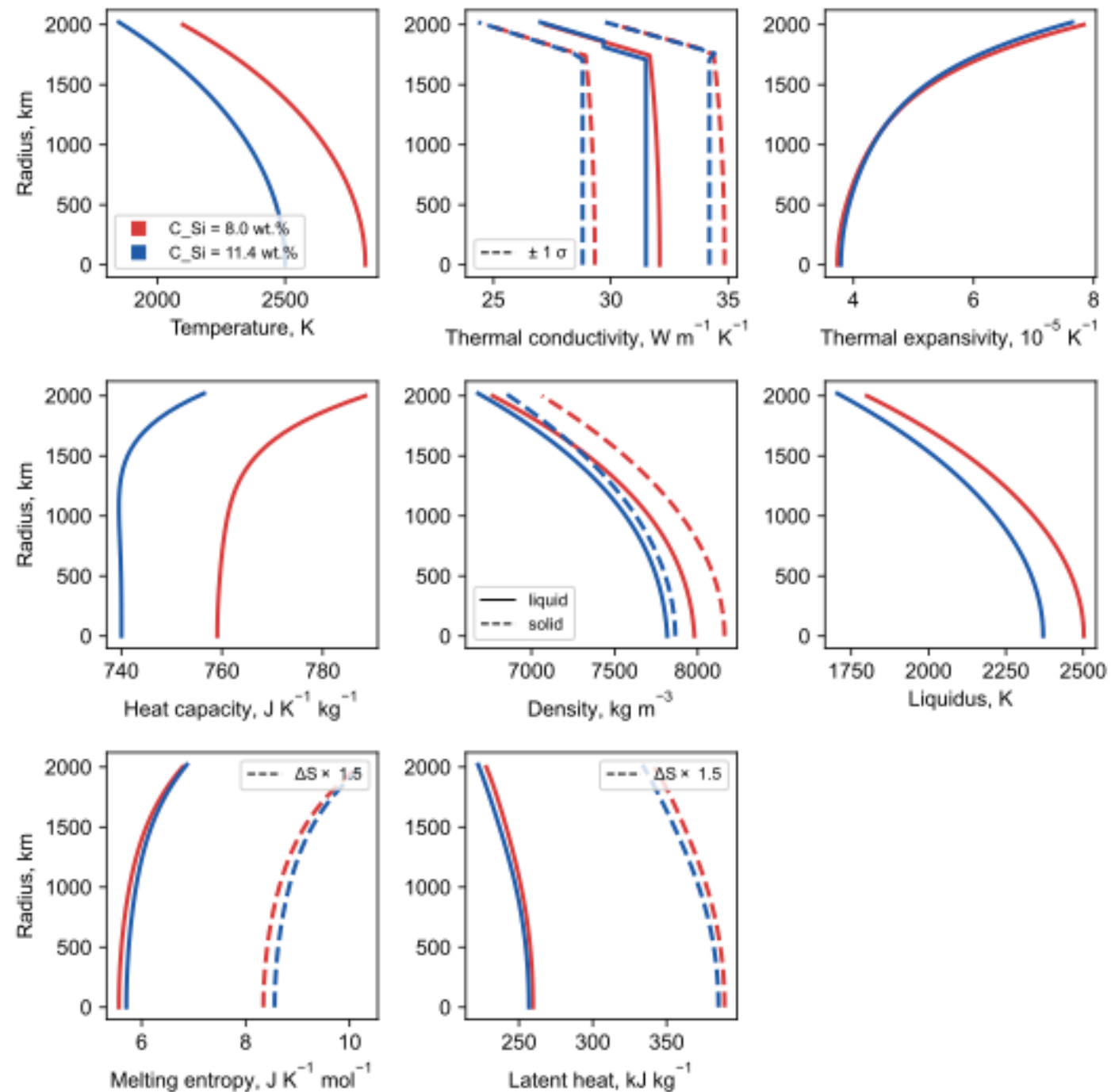
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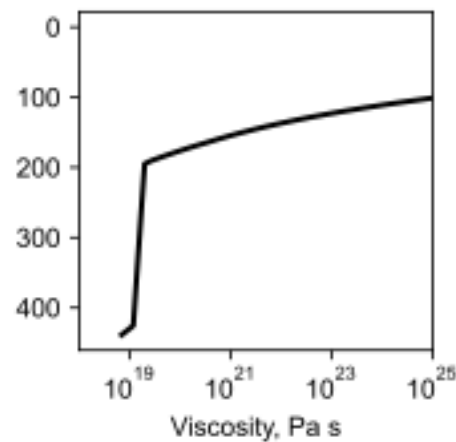
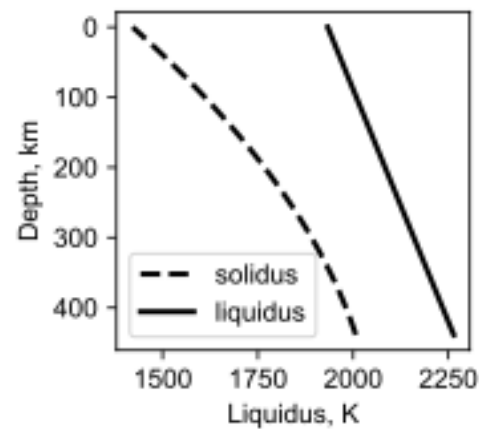
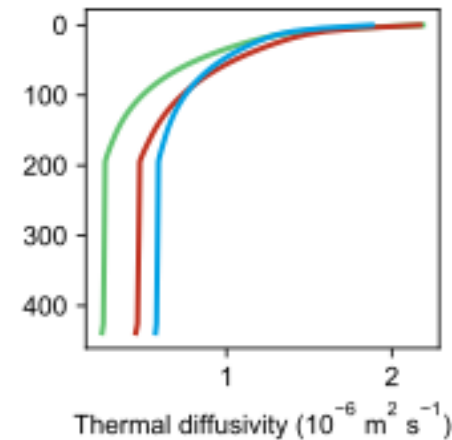
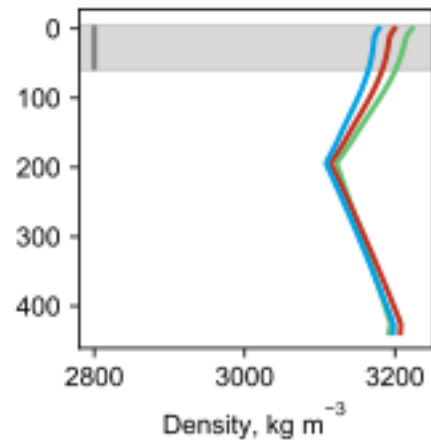
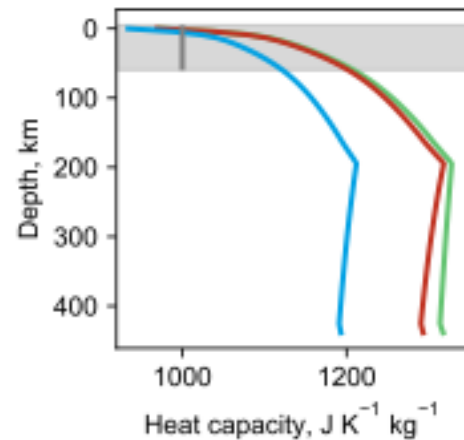
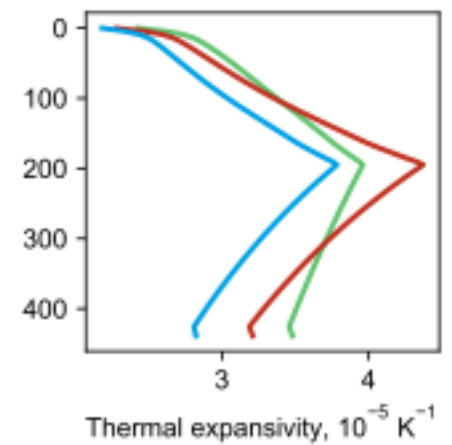
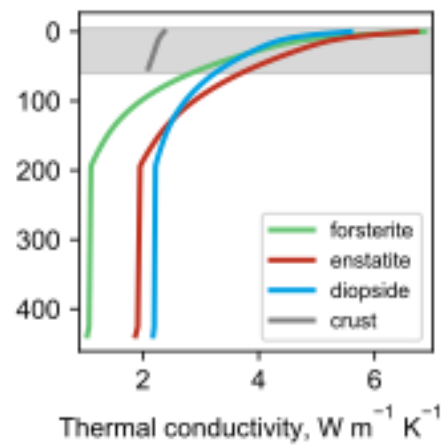
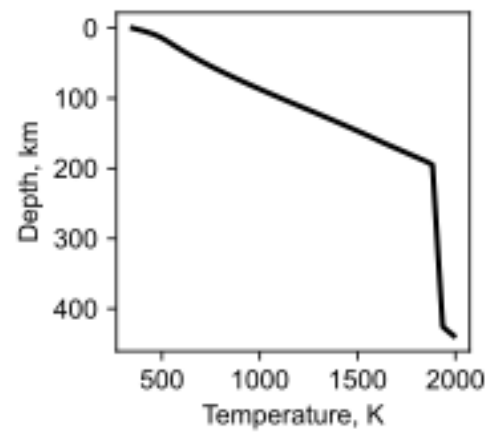
SI – kc and melting entropy profiles



SI – profiles of core parameters

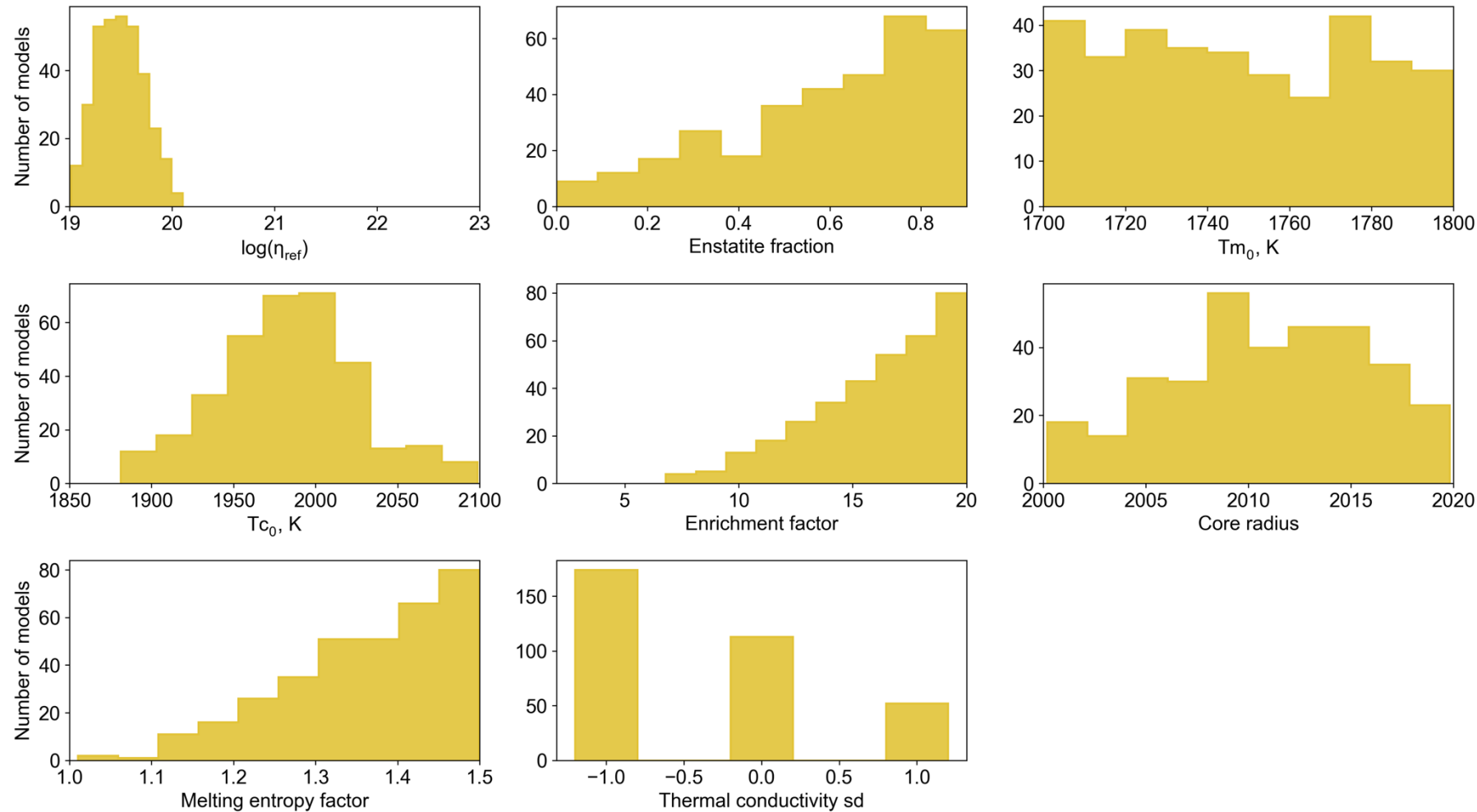


SI – profiles of mantle parameters



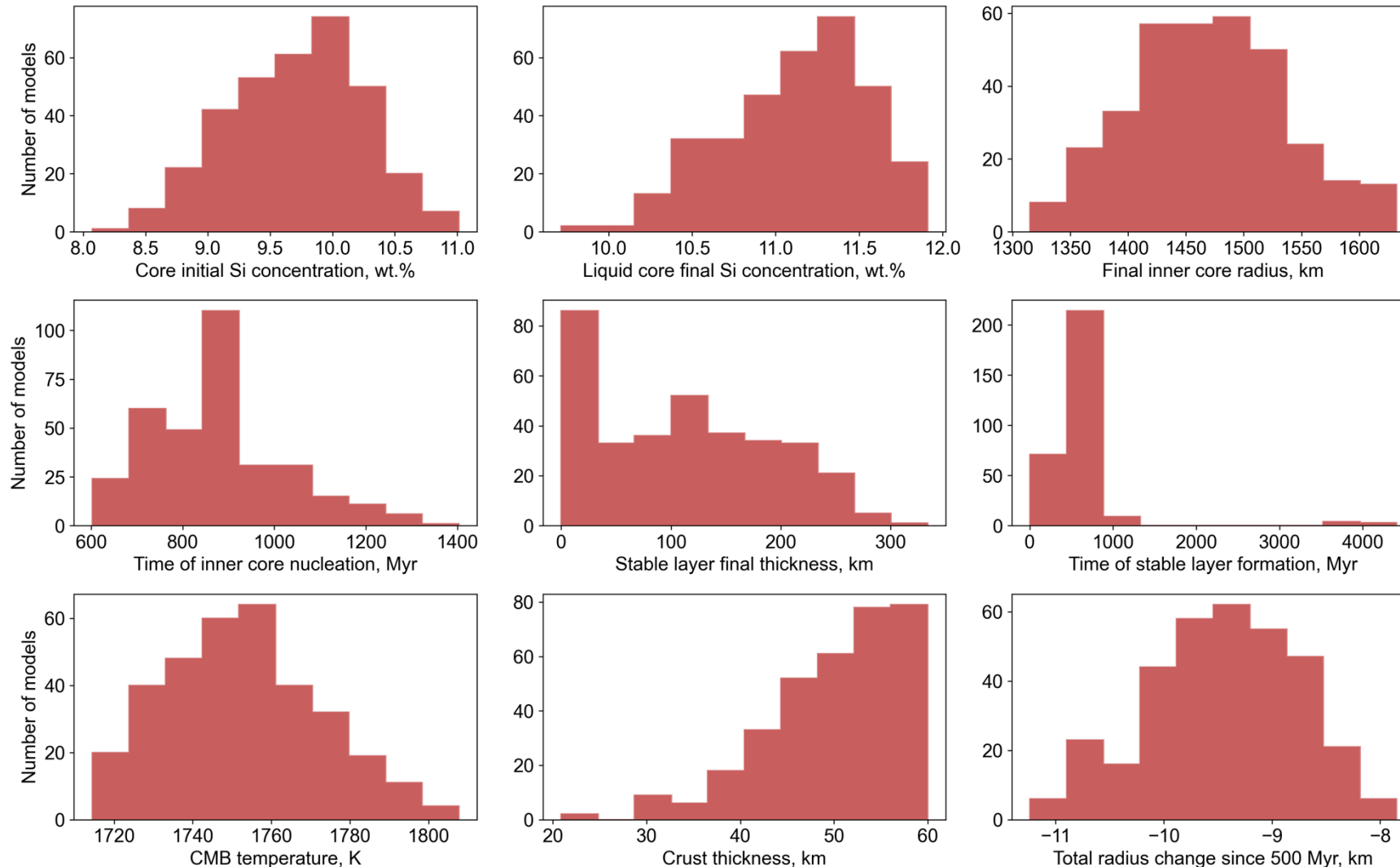
SI - Initial state of the models satisfying all constraints

Crust thickness
Present-day and past dynamo
Early contraction regime
90% crust formed before 1 Gyr
50% contraction before 1 Gyr

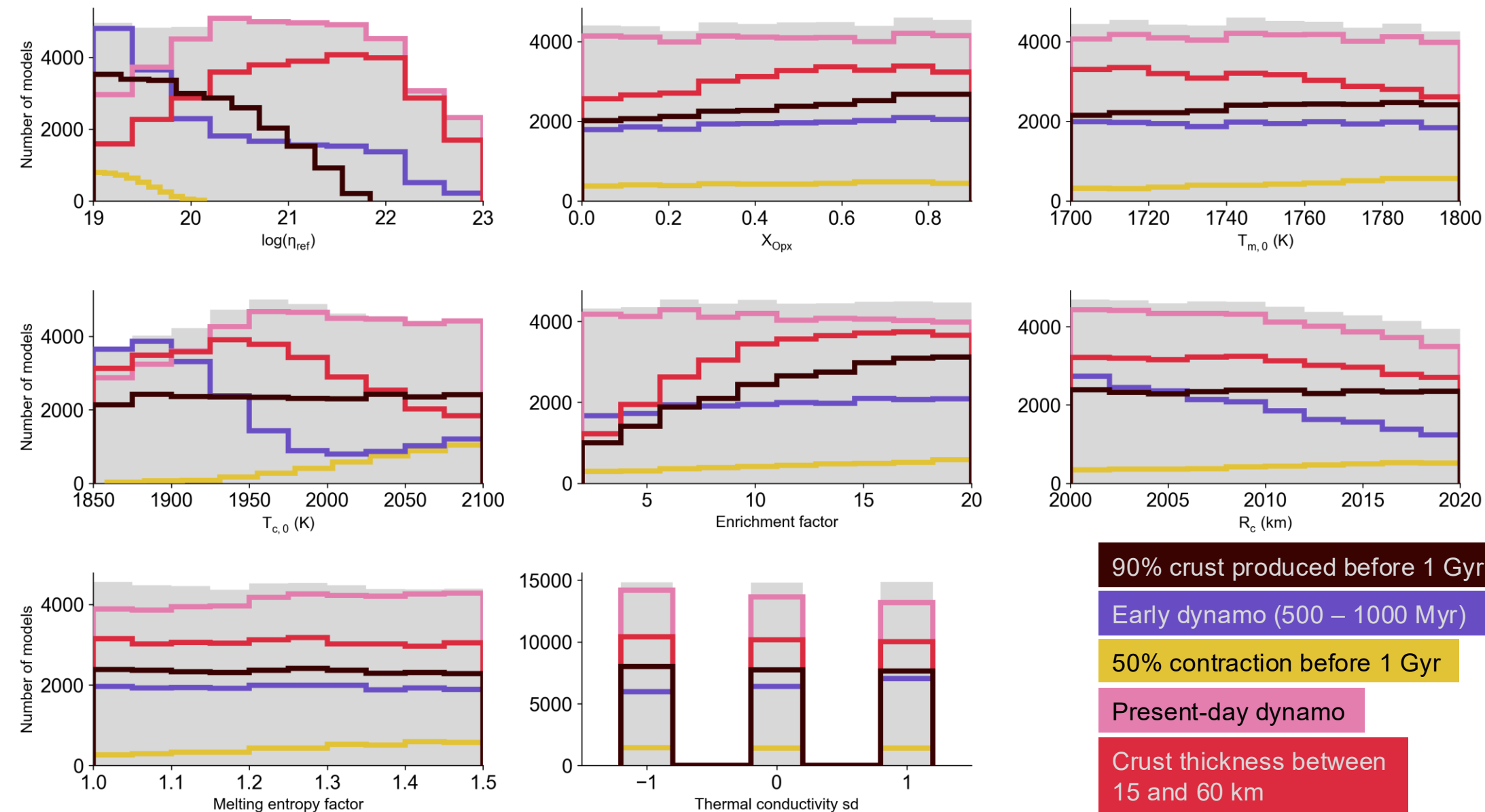


SI - Final state of the models satisfying **all constraints**

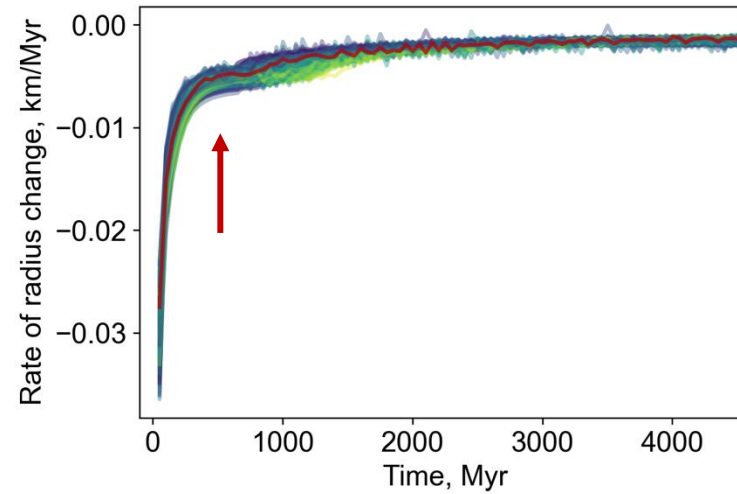
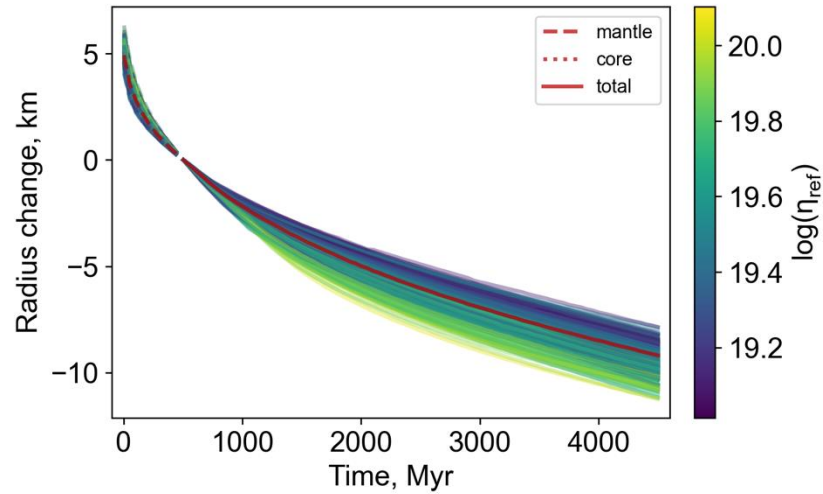
Crust thickness
Present-day and past dynamo
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SI – Histograms for all constraints individually

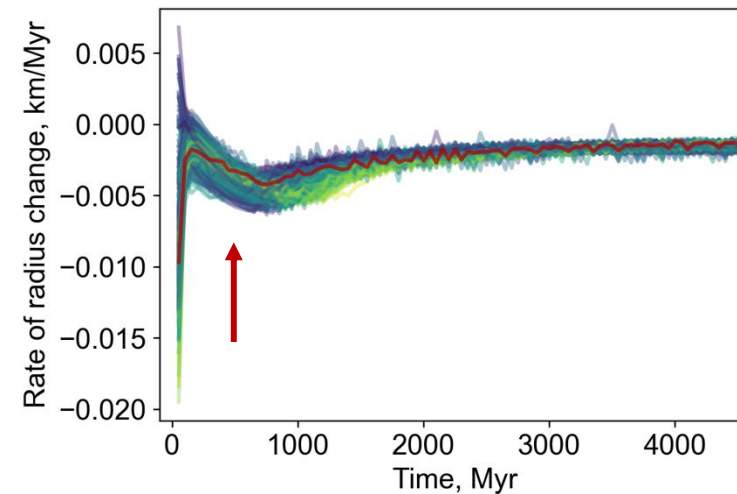
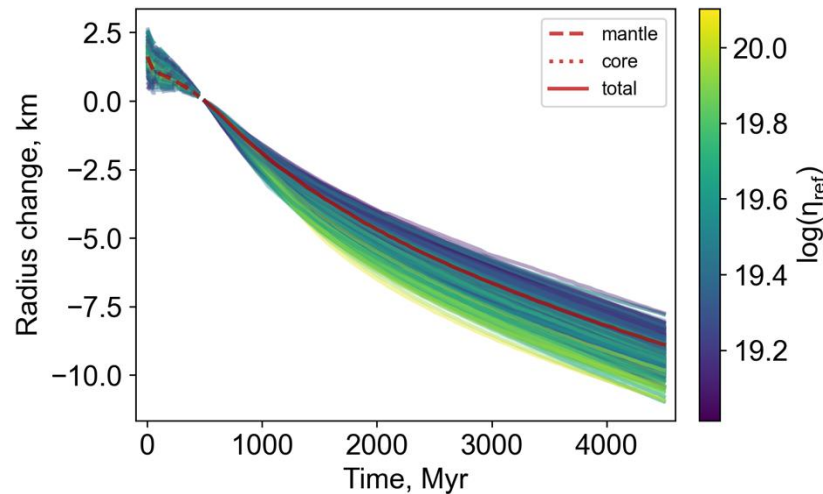


SI – Mantle differentiation effect on radius change

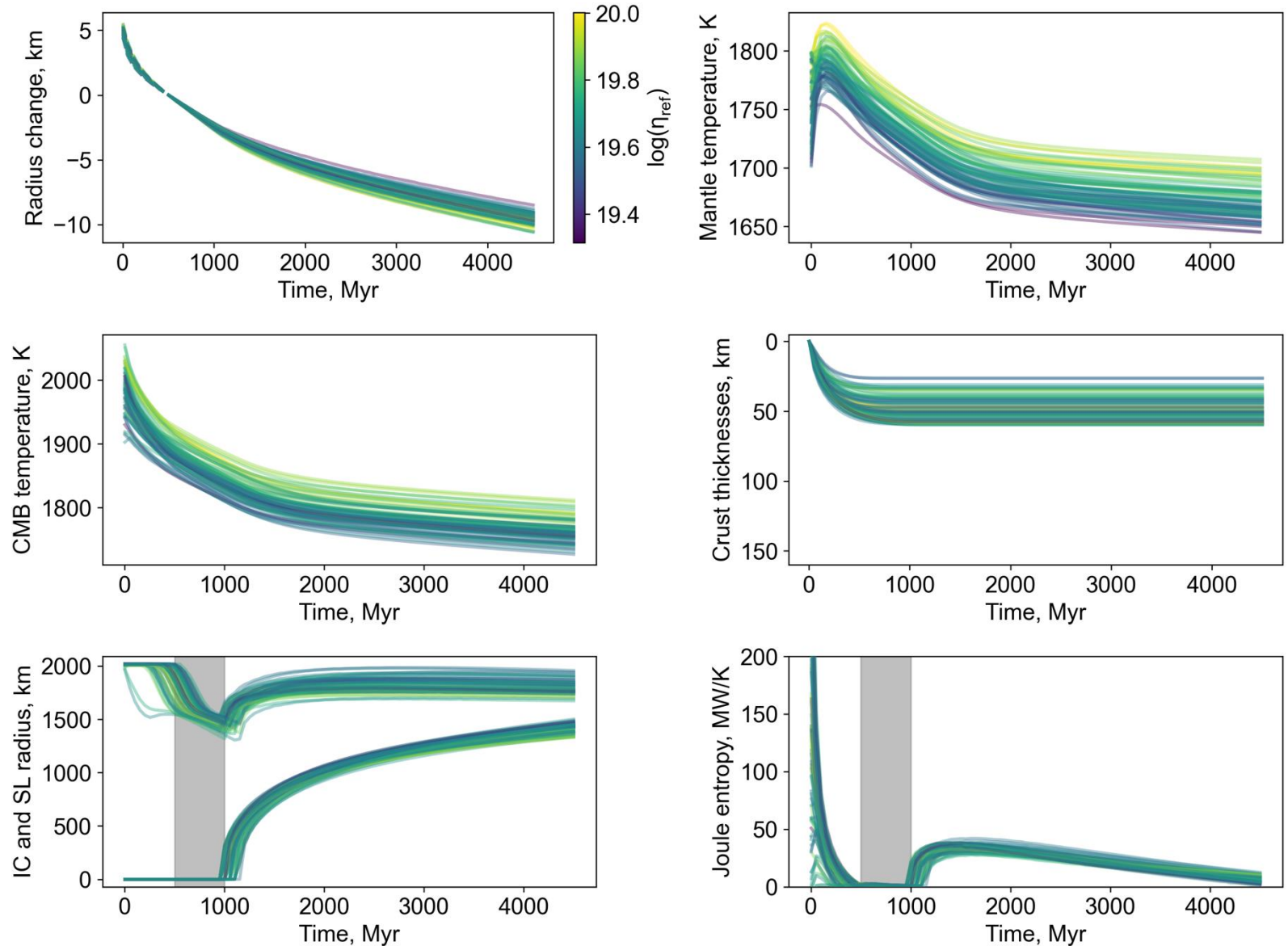


Broquet & Andrews-Hanna, 2026:
20–40 km/Gyr at 500 Myr

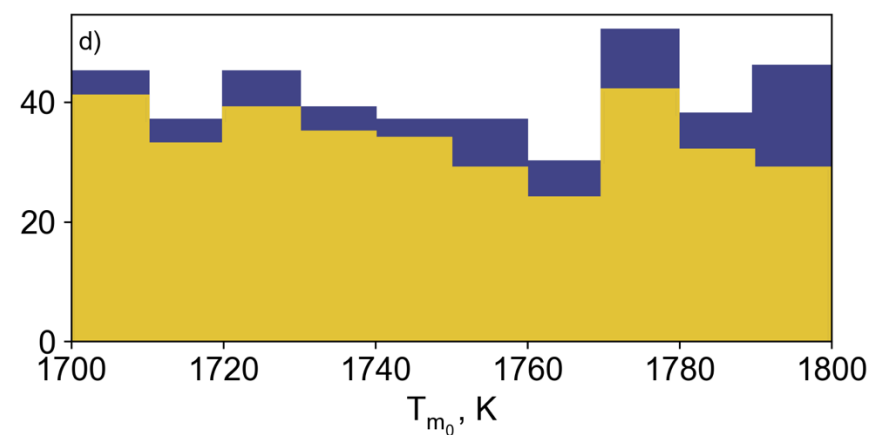
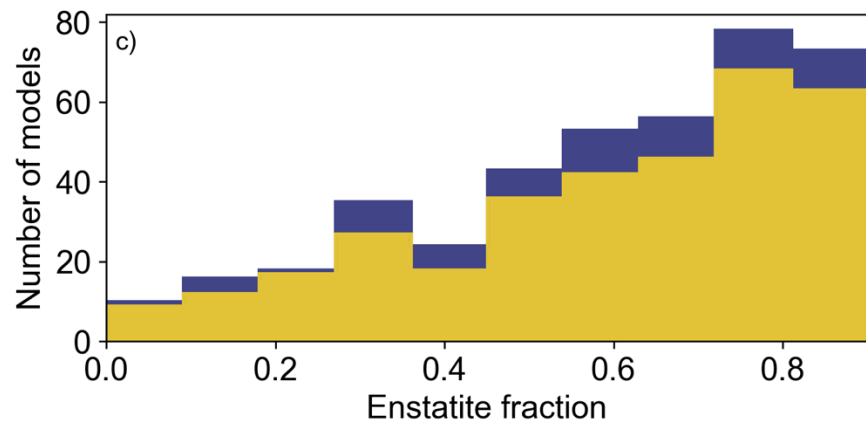
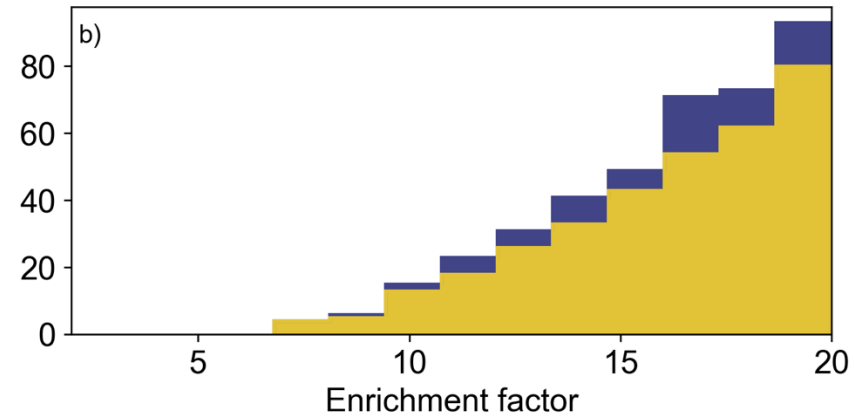
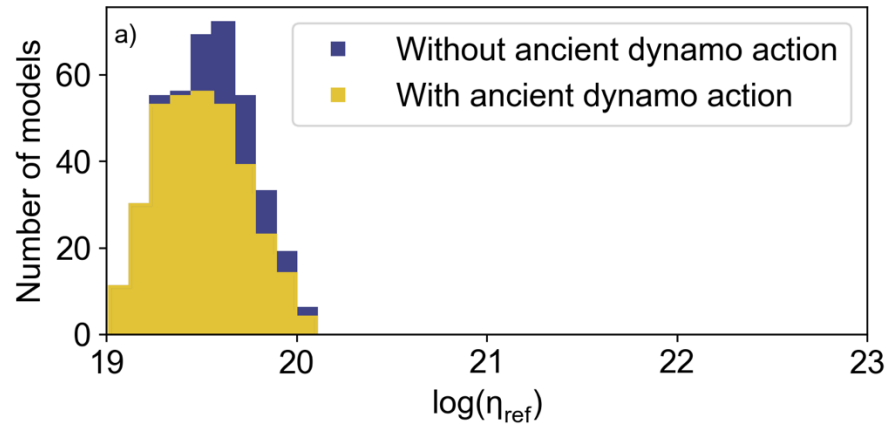
0.4 km/Gyr today



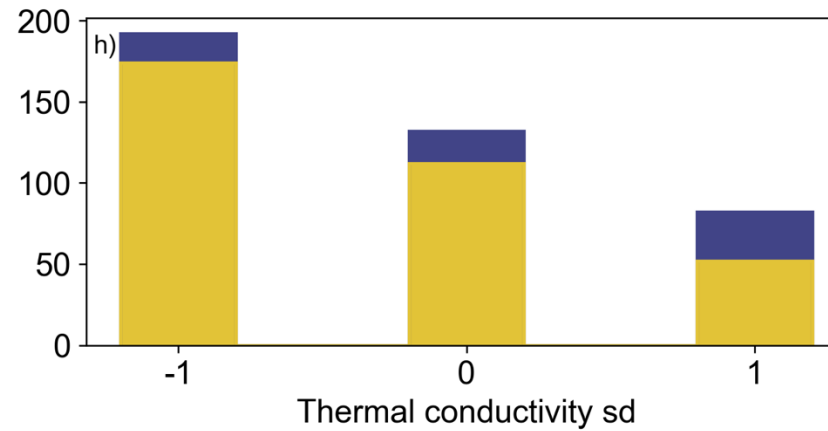
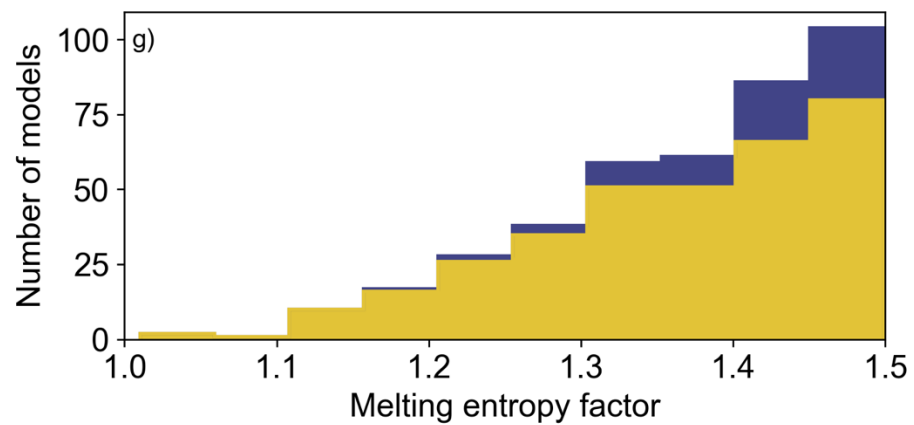
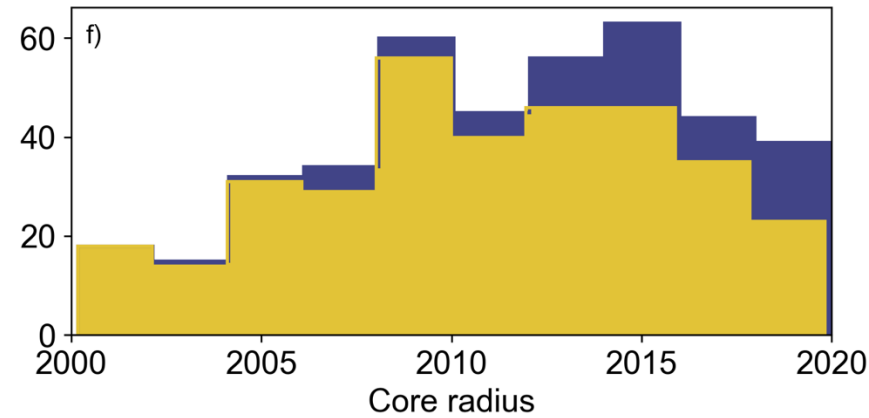
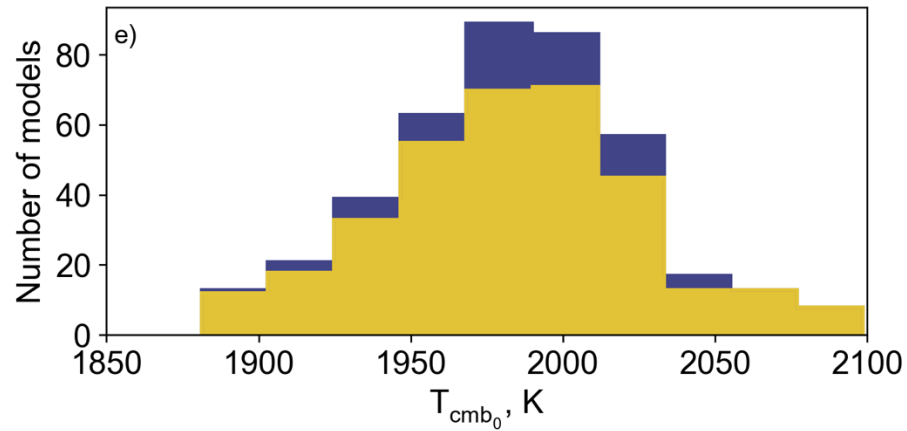
SI – Additional successful models without ancient dynamo



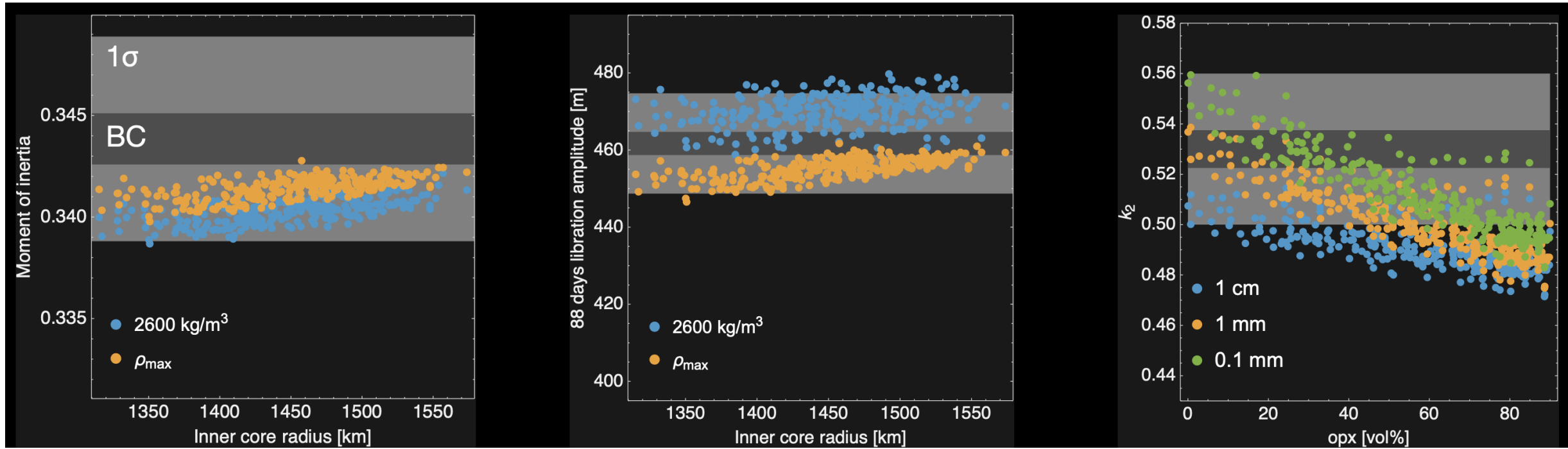
SI – Additional successful models without ancient dynamo



SI – Additional successful models without ancient dynamo



SI – Geodesy



SI – Impact of a megaregolith

SI – Mantle model

$$T_l = T_m - a_{rh} \frac{RT_m^2}{E_a}$$

$$q_l = k_m \frac{T_m - T_l}{\delta_u}$$

$$\delta_u = (R_l - R_b) \times \left(\frac{Ra_{crit}}{Ra} \right)^\beta$$

$$\eta = \eta_{ref} \times e^{\left(\frac{E_a}{RT} - \frac{E_a}{RT_{ref}} \right)}$$

$$T_{solidus} = 1421.15 + 177 \times P - 12.2 \times P^2$$

$$T_{liquidus} = 1933.28 + 64.5 \times P - 0.048 \times P^2$$

$$k_{forsterite} = 8.114 \times \left(\frac{300}{T} \right)^{1.087} \times (1 + 0.036 \times P)$$

$$k_{enstatite} = 7.667 \times \left(\frac{293}{T} \right)^{0.736} \times (1 + 0.110 \times P)$$

$$k_{diopside} = \left(2.2516 + \frac{2020.4}{T} + \frac{47362}{T^2} \right) \times \left(\frac{1 + 0.039 \times P}{1 + 0.039 \times 13} \right)$$

SI – Mantle model

$$k = \prod_i k_i^{v_i}$$

$$\rho = \sum_i v_i \times \rho_i$$

$$\alpha = \sum_i v_i \times \alpha_i$$

$$c = \frac{\sum_i c_i \times \rho_i \times v_i}{\rho}$$

$$T(z) = T_0 \times \exp\left(\frac{\alpha_0 \times g \times (z - z_0)}{c_0}\right)$$

SI – Mantle model

Parameter	Value
Time-step, Δt	2.5 Myr
Initial lid thickness, D_{lid_0}	50 km
Planet radius, R_p	2440 km
Surface temperature, T_s	350 K (Tosi et al., 2025)
Initial TBL thickness	10 km
Gravitational acceleration, g	3.7 m s^{-2}
Crust density, ρ_{cr}	2800 kg m^{-3}
Critical Rayleigh number, Ra_{crit}	450
Upper TBL thickness exponent, β^u	0.335 (Thiriet et al., 2019)
Lid temperature factor, a_{rh}	2.54 (Thiriet et al., 2019)
Convective velocity scale, u_0	$2 \times 10^{-12} \text{ m s}^{-1}$
Viscosity reference temperature, T_{ref}	1600 K
Creep activation energy, E_a	300 kJ mol^{-1}
Mantle latent heat of melting, $\mathcal{L}$	$6 \times 10^5 \text{ J kg}^{-1}$
Specific heat capacity of the crust, C_{cr}	$1000 \text{ J kg}^{-1} \text{ K}^{-1}$
Uranium concentration	35 ppb (Pirotte et al., 2023)
Thorium concentration	121 ppb (Pirotte et al., 2023)
Potassium concentration	356 ppm (Pirotte et al., 2023)

SI – Core model

$$q_c = k(T_c, P_c) \frac{T_c - T_b}{\delta_c}$$

$$\delta_c = \left(\frac{\kappa_b \eta_c Ra_{i,cr}}{\alpha_b \rho_m g (T_c - T_b)} \right)^\beta$$

$$Ra_{i,cr} = 0.28 Ra_{int}^{0.21}$$

$$Ra_{int} = \frac{\rho_m g \alpha_m (T_m - T_s + T_c - T_b) (R_p - R_c)^3}{\kappa_m \eta_m}$$

$$Q_c = Q_s + Q_g + Q_l$$

$$E_J = E_s + E_s + E_g - E_k$$

$$T_{liq}^i = T_0^i \times \left[\frac{P}{a^i} + 1 \right]^{\frac{1}{c^i}}$$

	T ₀	a	c
Fe	1810.91	15.4789	2.84968
Eutectic	1538	24.66	2.17

SI – Core model

$$T_{liq}^i = T_0^i \times \left[\frac{P}{a^i} + 1 \right]^{\frac{1}{c^i}}$$

	T ₀	a	c
Fe	1810.91	15.4789	2.84968
Eutectic	1538	24.66	2.17

$$T_{liq} = T_{liq}^{Fe} - (T_{liq}^{Fe} - T_{liq}^E) \times \frac{x_{Si}}{x_{Si}^E}$$

$$\mathcal{L} = \frac{\Delta S_{Fe-Si}}{M_{FeSi}} \times T_{liq}$$

$$\Delta S_{Fe-Si} = (1 - \chi_{Si})(S_{liq}^{Fe} - S_{bcc}^{Fe}) \times \chi_{Si} \Delta S_{liq-bcc}$$

$$k_{Fe} = (32 \pm 3) + (0.51 \pm 0.05) \times P$$

SI – Radial contraction

$$\Delta R_m = \frac{1}{R_p^2} \int_{R_c}^{R_p} \alpha(p, T)(T(r) - T_0(r))r^2 dr$$

$$\Delta R_{c,th} = \frac{1}{R_p^2} \int_0^{R_{ic}} \alpha_s(r)(T(r) - T_0(r))r^2 dr + \frac{1}{R_p^2} \int_{R_{ic}}^{R_c} \alpha_l(r)(T(r) - T_0(r))r^2 dr$$

$$\Delta R_{c,ic} = \frac{1}{R_p^2} \int_0^{R_{ic}} \frac{\rho_l(r) - \rho_s(r)}{\rho_l(r)} r^2 dr$$