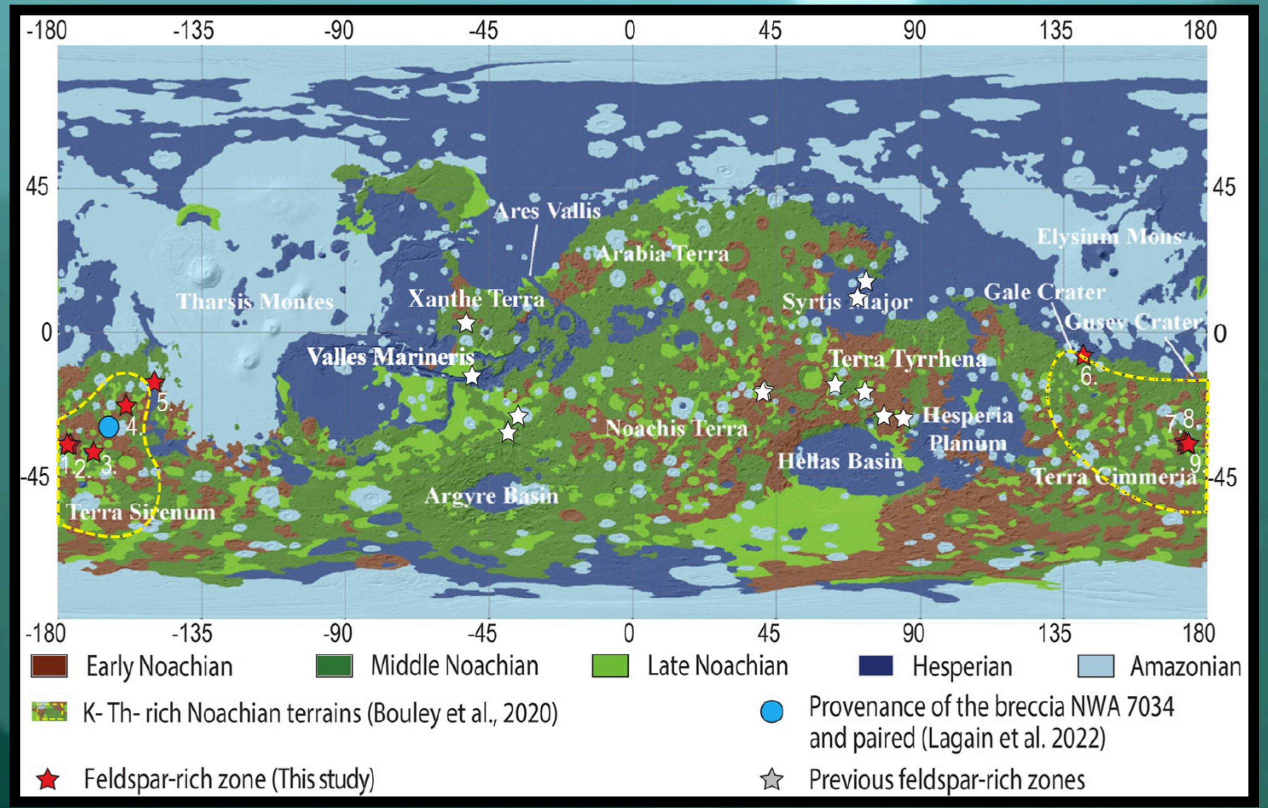
Differentiation of the Martian Highlands during its formation.

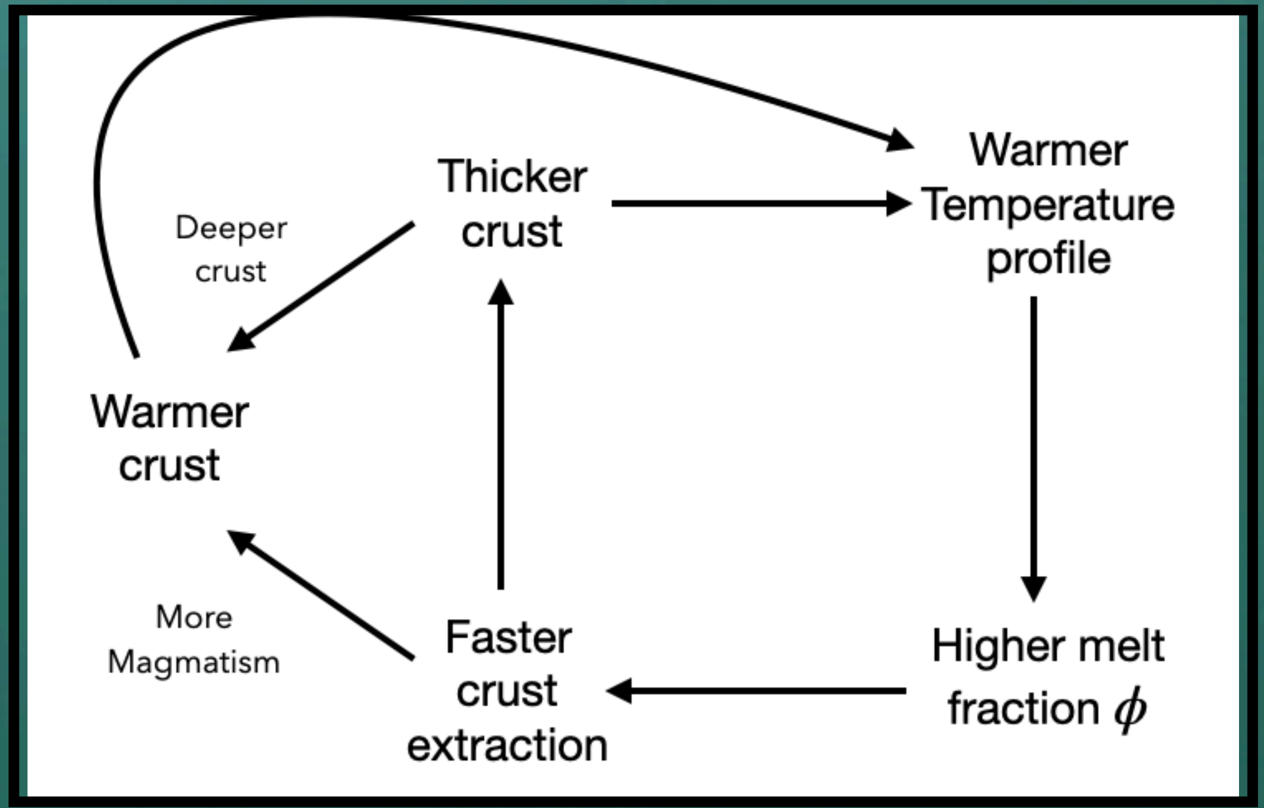
Valentin Bonnet Gibet,
Chloé Michaut, Thomas Bodin, Mark Wieczorek, and Fabien Dubuffet

Personal website

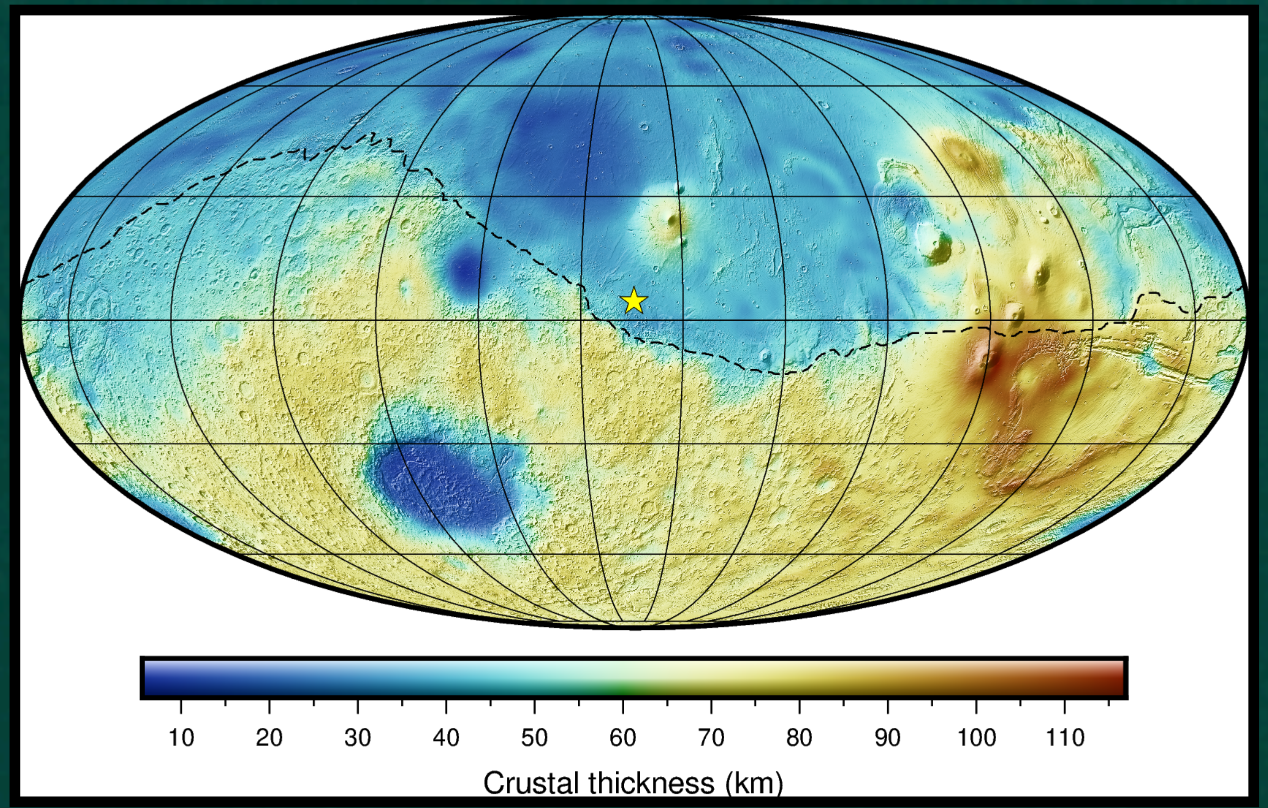
Crustal felsic Component



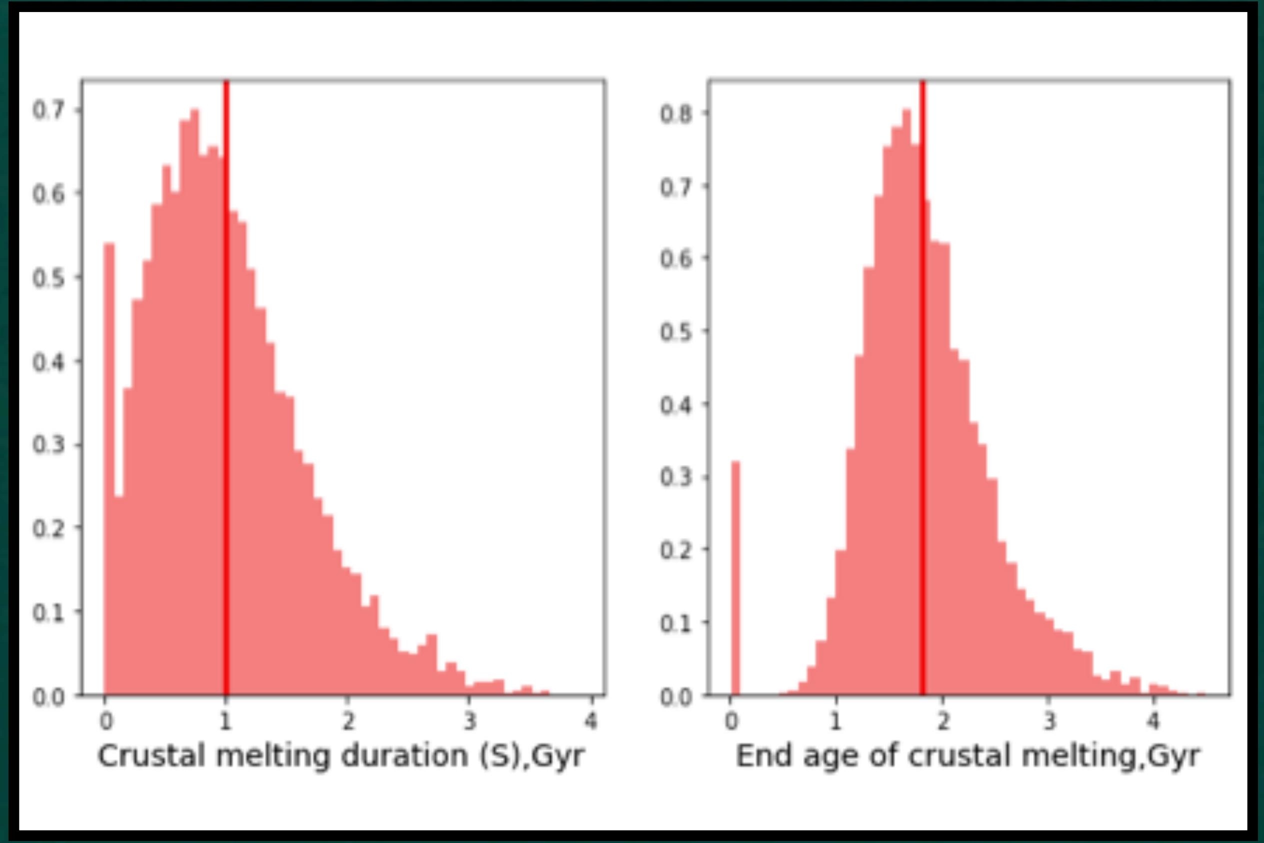
Mechanism & Model



Bayesian Inversion



Inversion results



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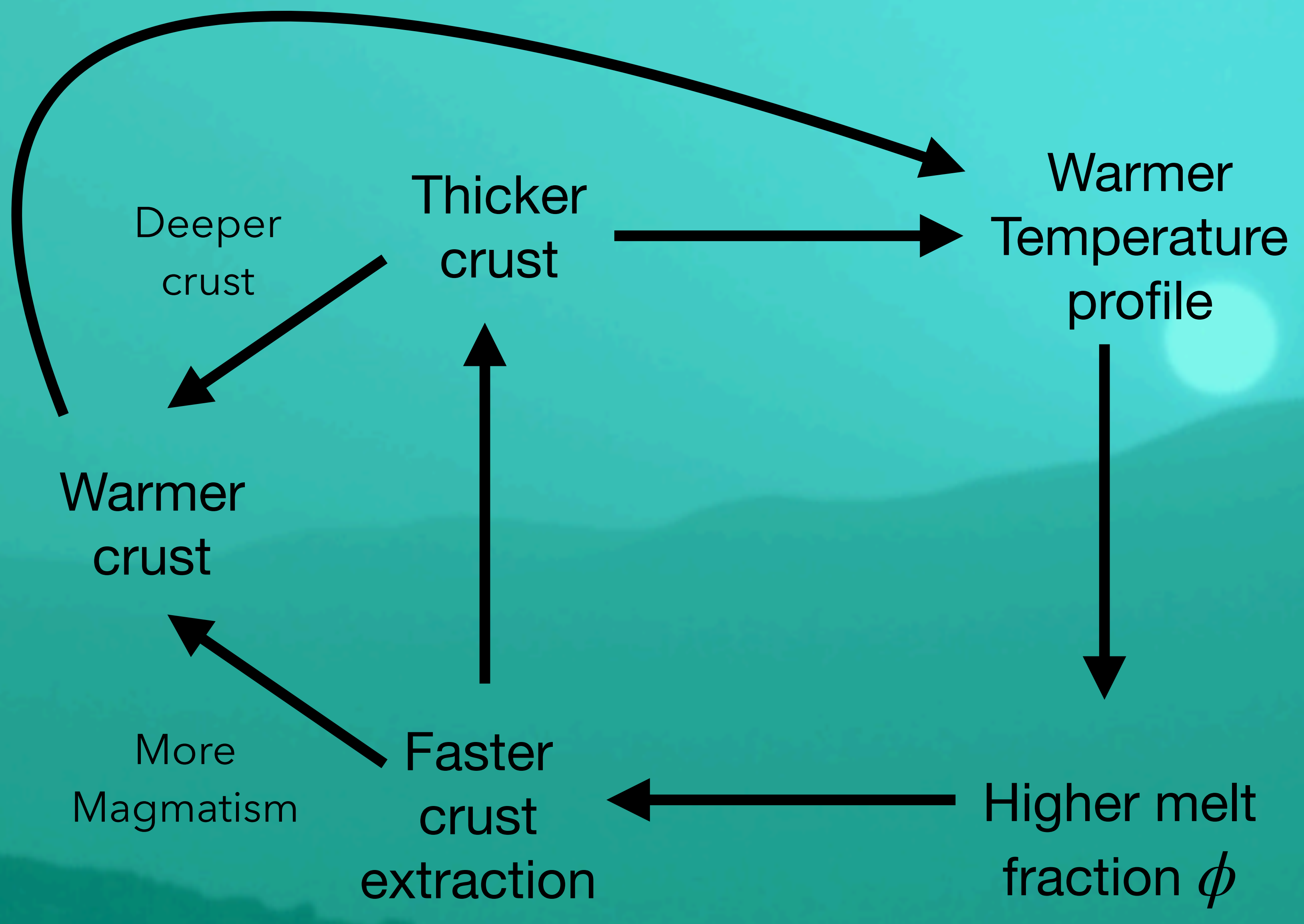
EGU23 Abstract

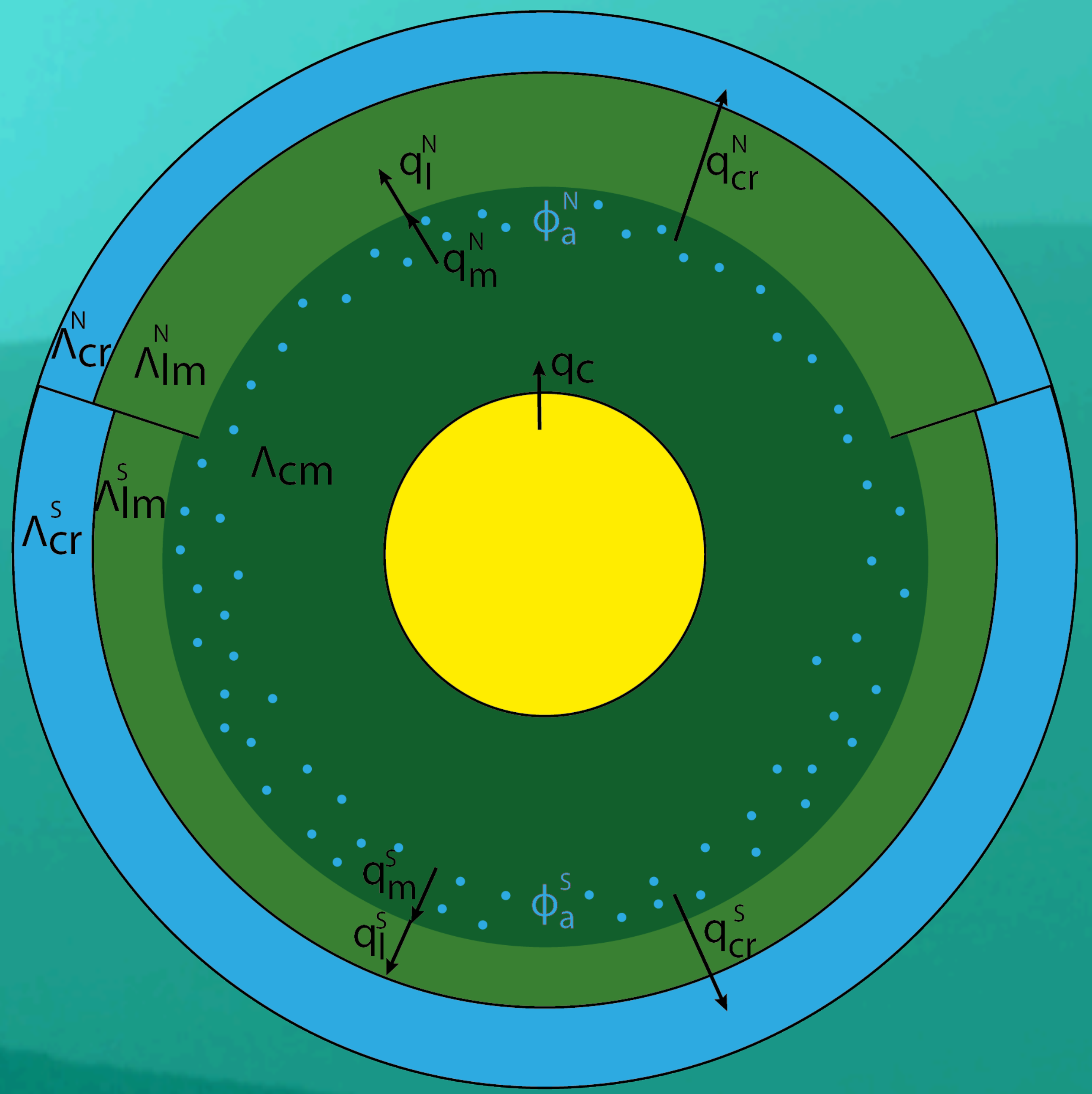
Key points

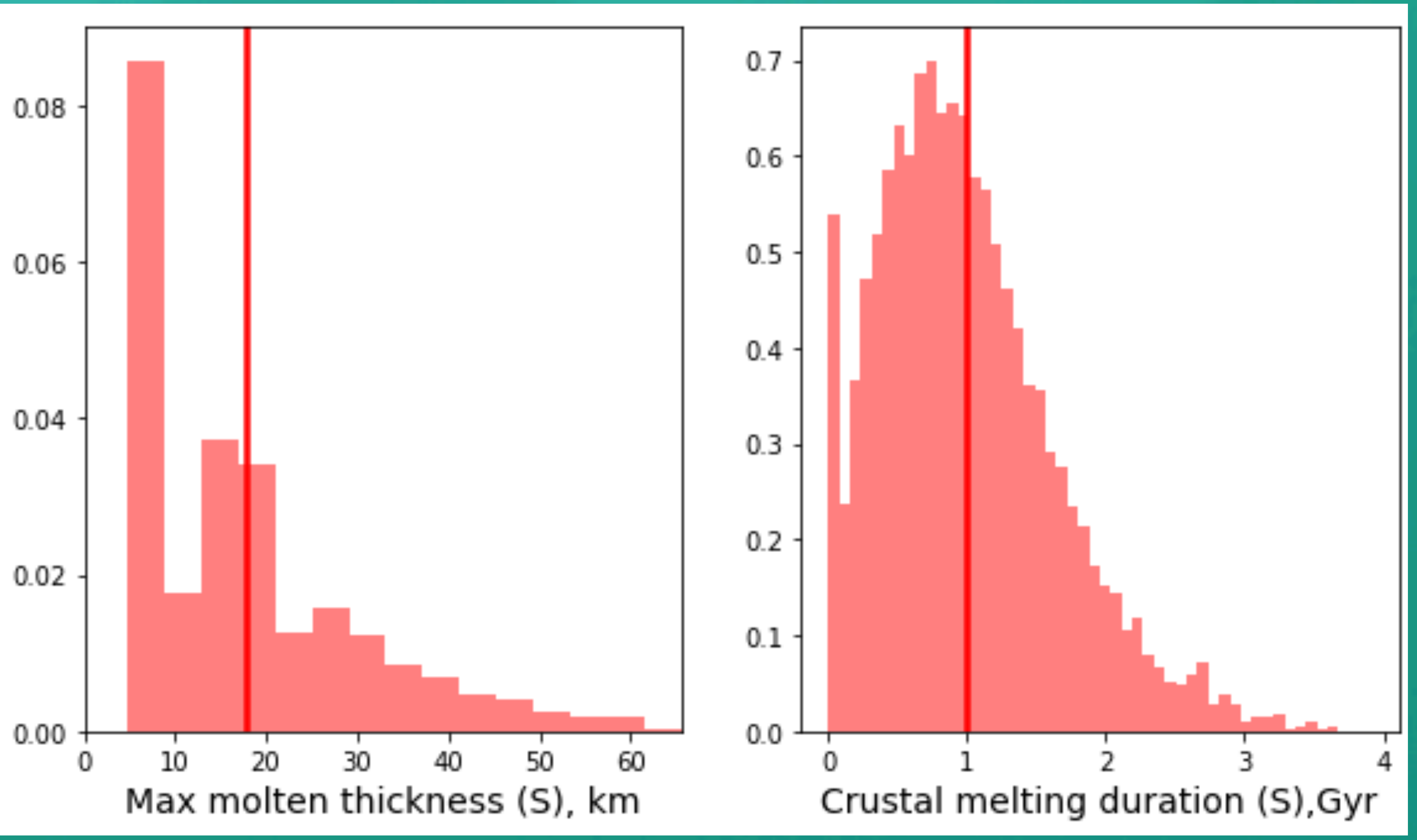
Conclusion

Differentiation of the Martian Highlands during its formation.



➡ **Crustal thickening and crustal temperatures are larger where the crust is thicker.**



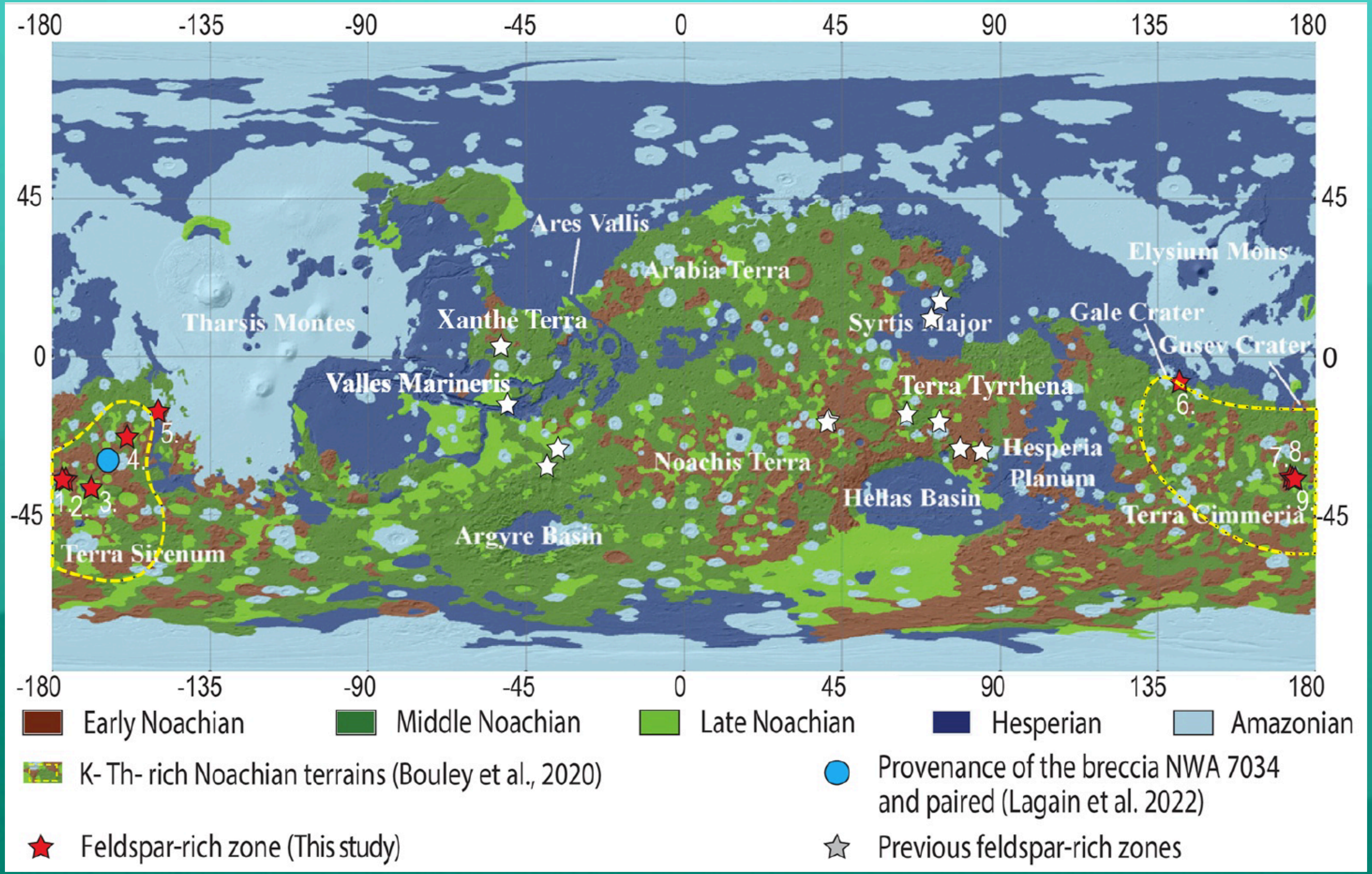


❖ A positive feedback mechanism that could explain the formation of a crustal dichotomy provides the conditions for Highlands differentiation.

❖A Bayesian inversion of a two-hemisphere parameterized thermal model gives us a collection of models that fit the InSight observations.

❖ Some of these models (10%) show partial melting in the Highlands for an average duration of 1 Gyr and over a vertical extent of several tens of kilometres.

Observations of felsic rocks in the Southern highlands of Mars



Payré et al, JGR 2022

- Gale crater: large variety of igneous rocks from basaltic to rhyolitic.
- NWA 7034: felsic clasts from trachy-andesitic to monzonitic.
- Terra Sirenum Cimmeria: felsic outcrops and possible origin of NWA7034.
- Other outcrops showing an evolved compositions found in many parts of the Highlands.

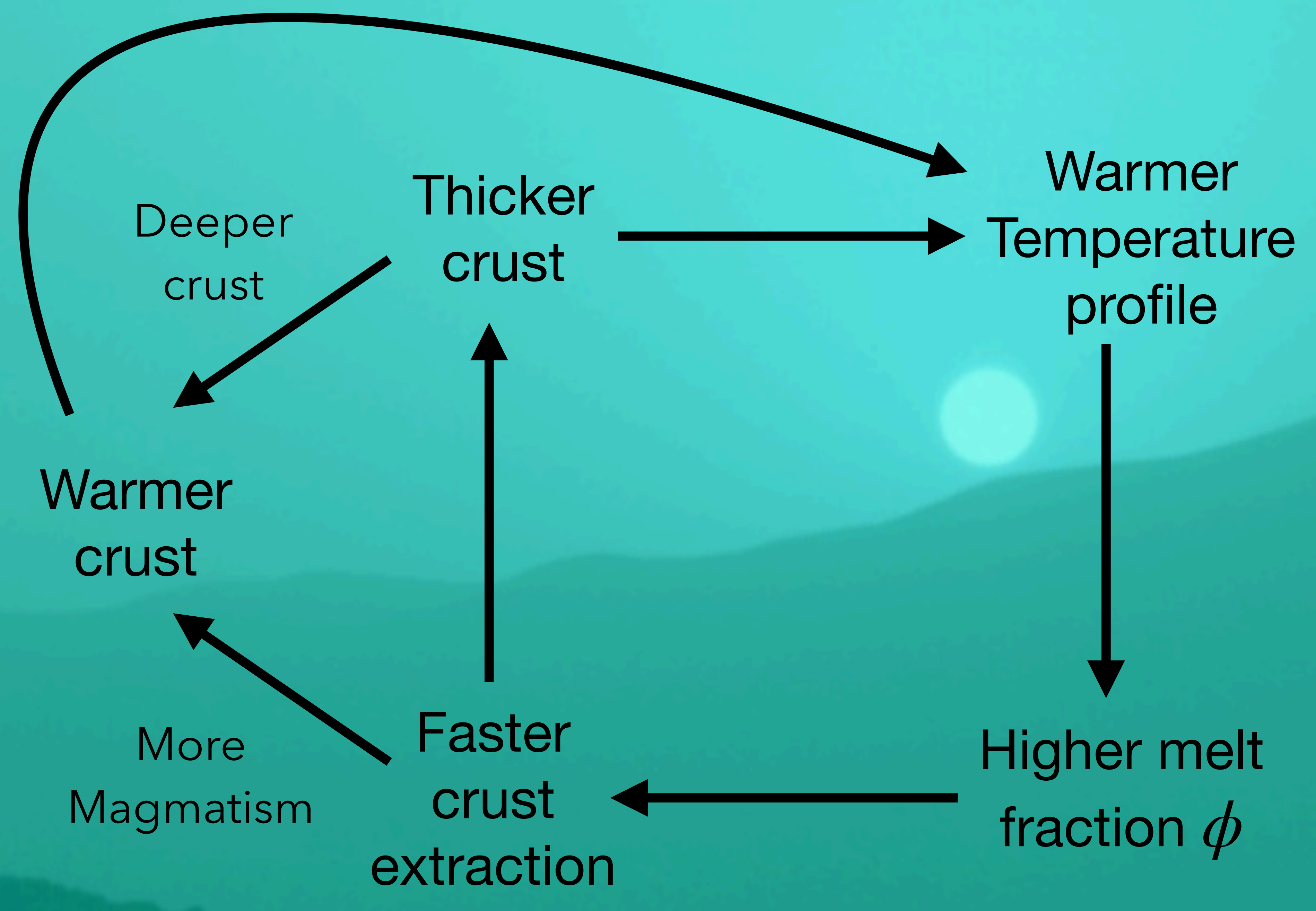
What origin? What mechanism?

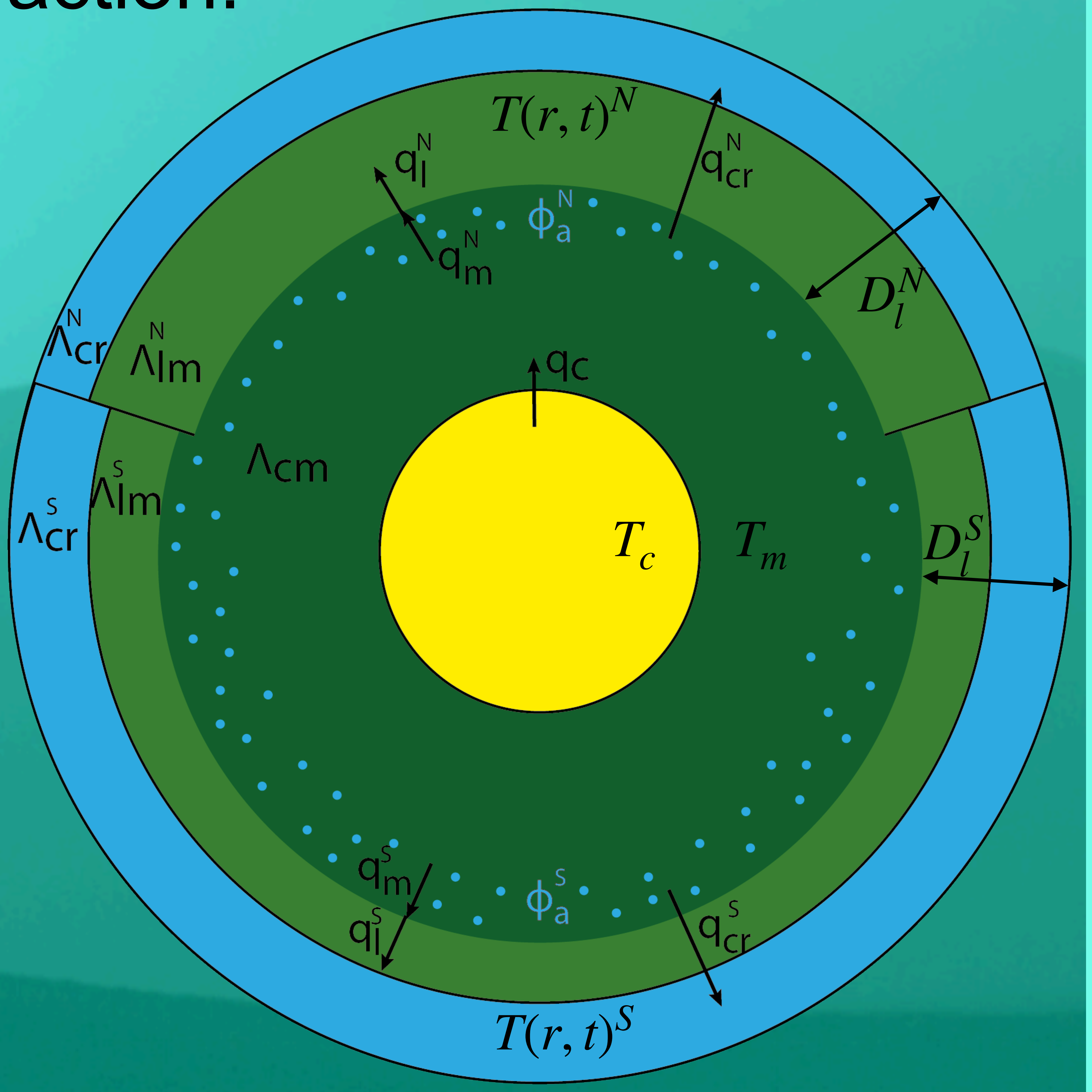
➡Primary, from a global magma ocean?

➡Secondary by fractional crystallization of a basaltic melts?

What extent in time and volume ?

A positive feedback mechanism between crustal thickness and melt extraction.





➡ **Crustal thickening and crustal temperatures are larger where the crust is thicker.**

Mechanism favoring the growth of a hemispheric perturbation

This mechanism can explain the growth of the martian crustal dichotomy.

Parameterised thermal evolution for stagnant lid convection with two hemispheres

Melt extraction from Darcy flow

Crust melting, magmatism and advection

A positive feedback between crustal thickness and melt extraction for the origin of the Martian dichotomy,
Bonnet Gibet et al, JGR 2022

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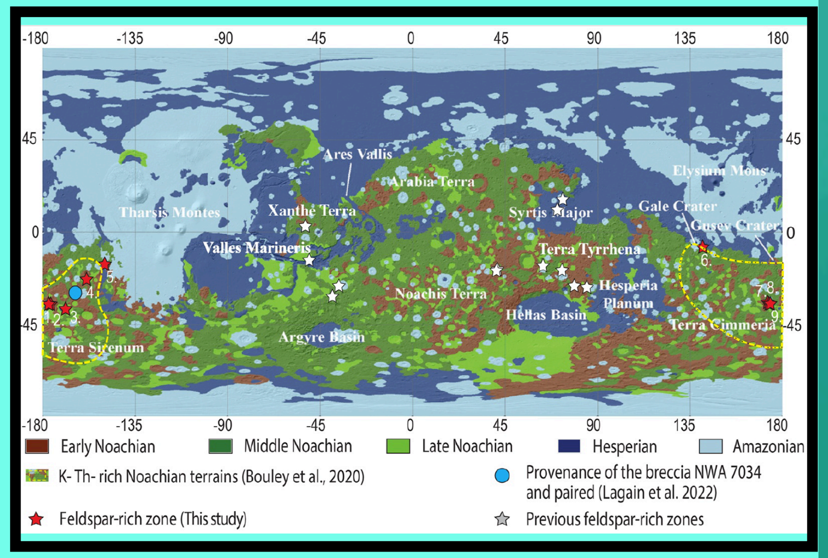
Crustal felsic Component



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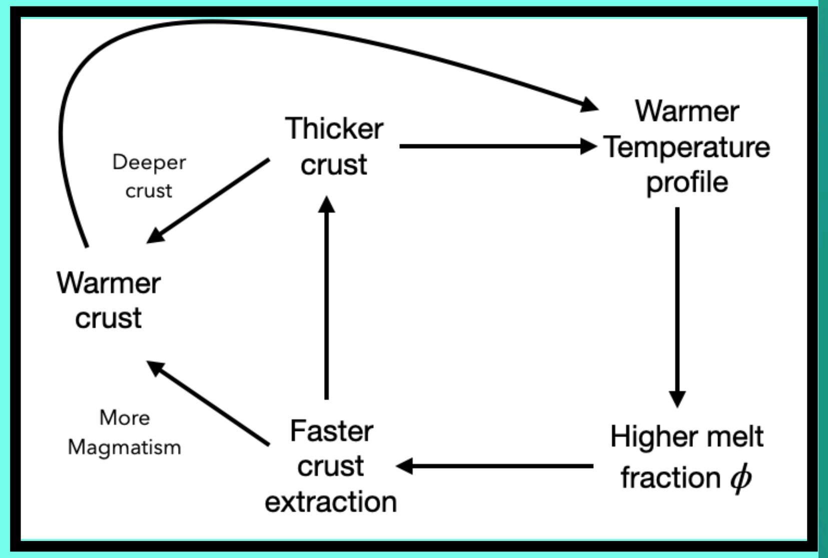

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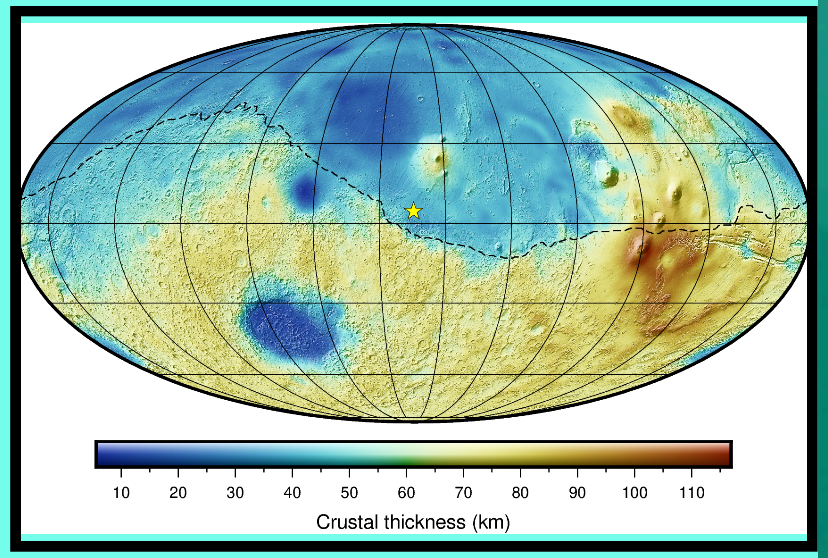

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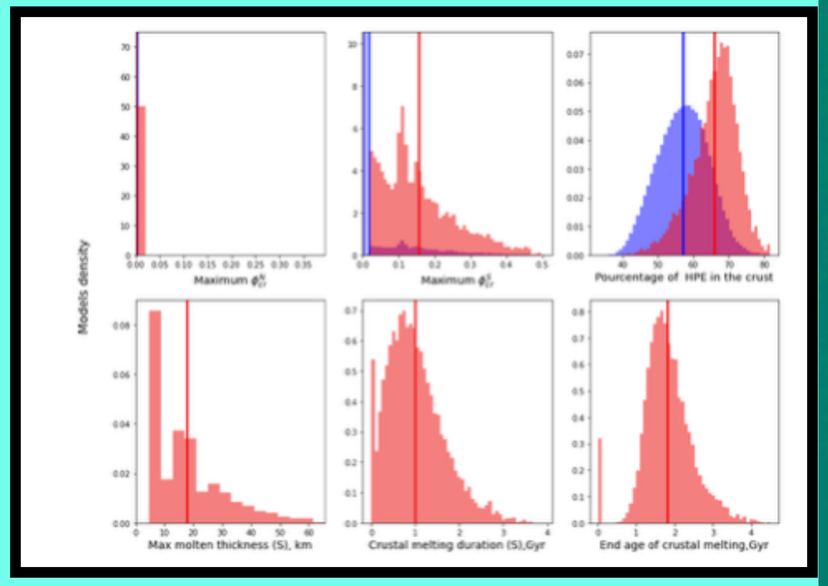


Bayesian inference and inversion.

Model parameters
$(\eta_0,\ k_0,\ \rho_{\mathrm{cr}}\ \ldots)$
+
Initial conditions
$(T_m^0,\ D_l^0,\ \Delta D_l^0\ \ldots)$

Forward problem →

Thermal evolution calculated for 4.5 Gyr

Model forecast →

Dichotomy amplitutde: $\Delta D_{\mathrm{cr}}^{\mathrm{N/S}}$

Crust thickness: $D_{\mathrm{cr}}^{\mathrm{avg}}$

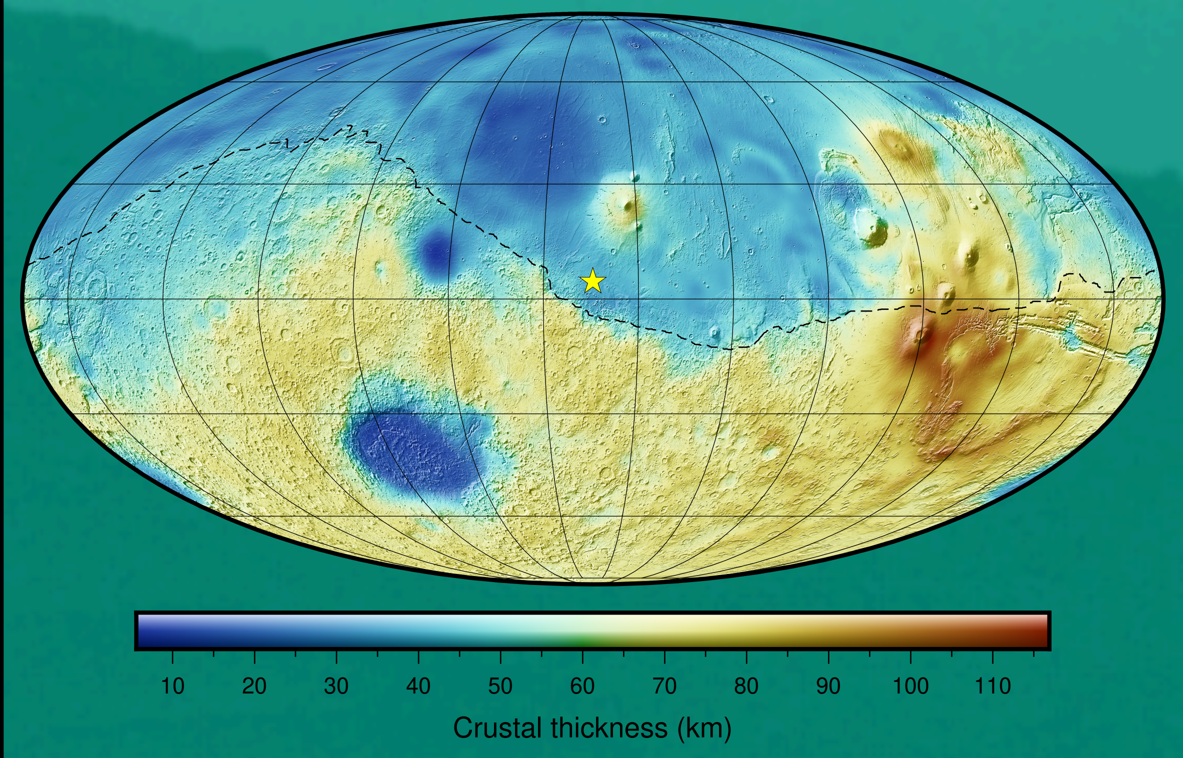
Lid thickness: D_l^{avg}

Potential temperature: T_p

$+\max(\phi_{cr}^{N/S})$

Likelihood based on geophysical observations from InSight

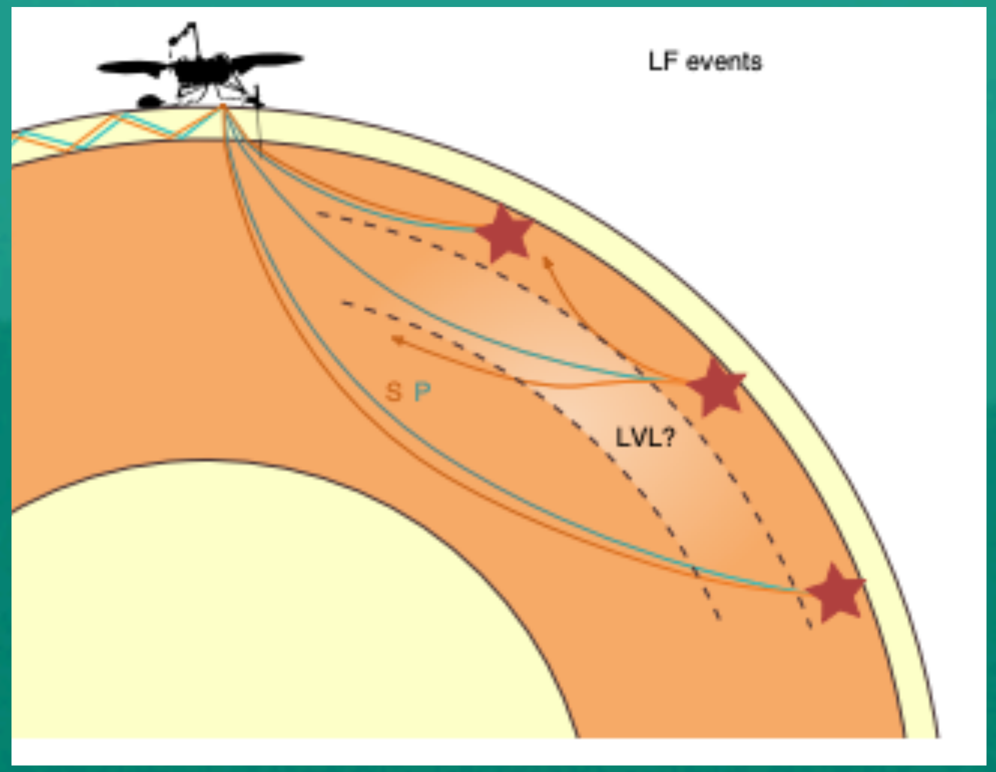
Constraints on crustal thicknesses from gravity and topography inversions and receiver function analysis below InSight



$$D_{\mathrm{cr}}^{\mathrm{avg}} = f(D_{\mathrm{cr}}^{\mathrm{InS}}, \rho_{\mathrm{cr}})$$

$$\Delta D_{\mathrm{cr}}^{\mathrm{N/S}} = f(\rho_{\mathrm{cr}})$$

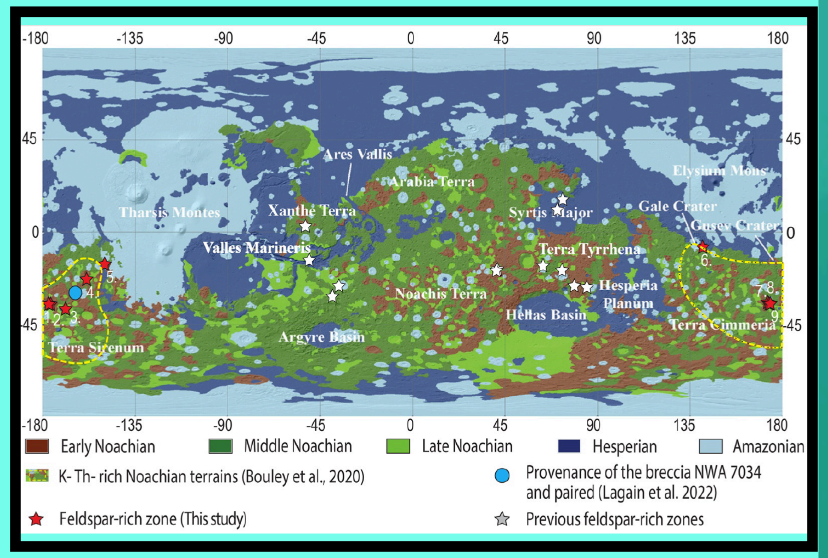
Constraints on lithosphere thickness and mantle potential temperature from seismological data.

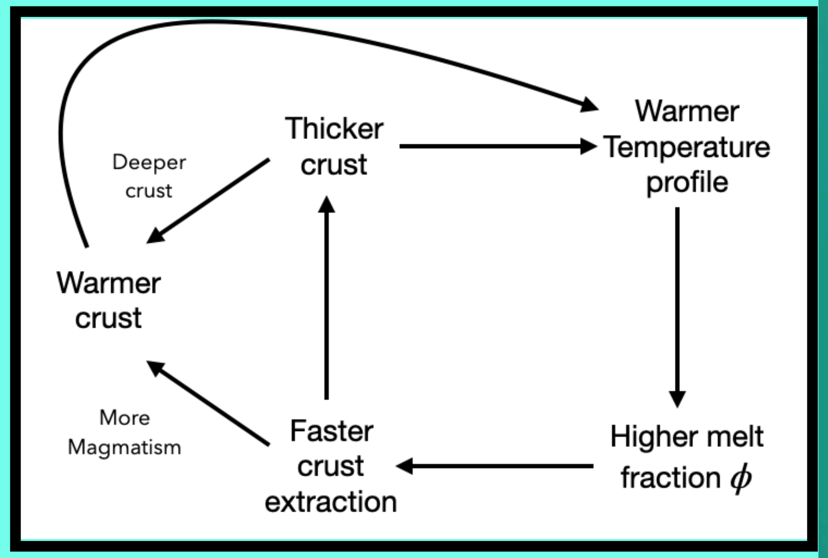


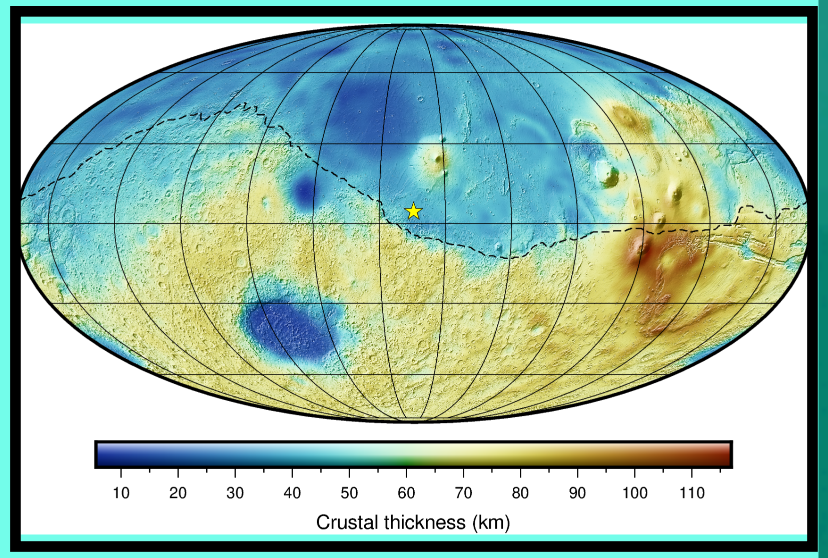
$$D_l^{\mathrm{InS}} = 450 \pm 100 \text{ km}$$

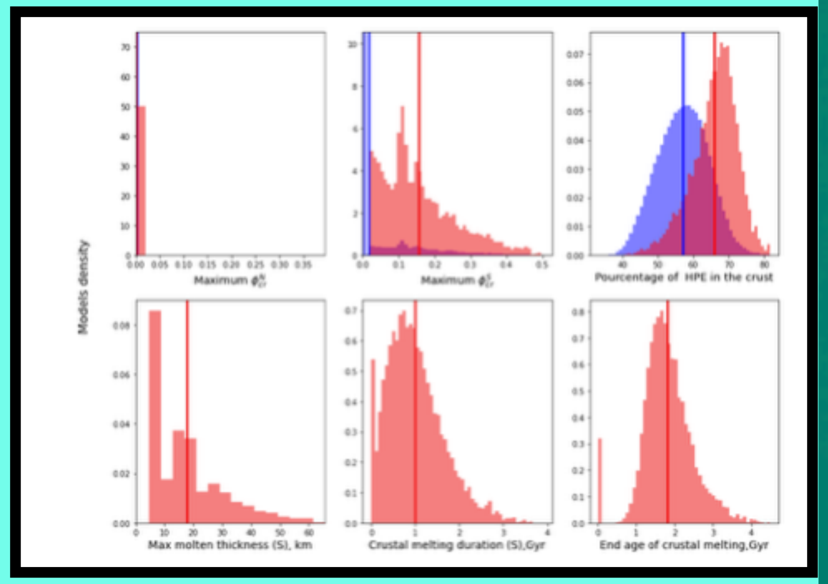
$$T_p^{\mathrm{InS}} = 1605 \pm 100 \text{ K}$$

Inversion : Monte Carlo - Markov chain sampling algorithm





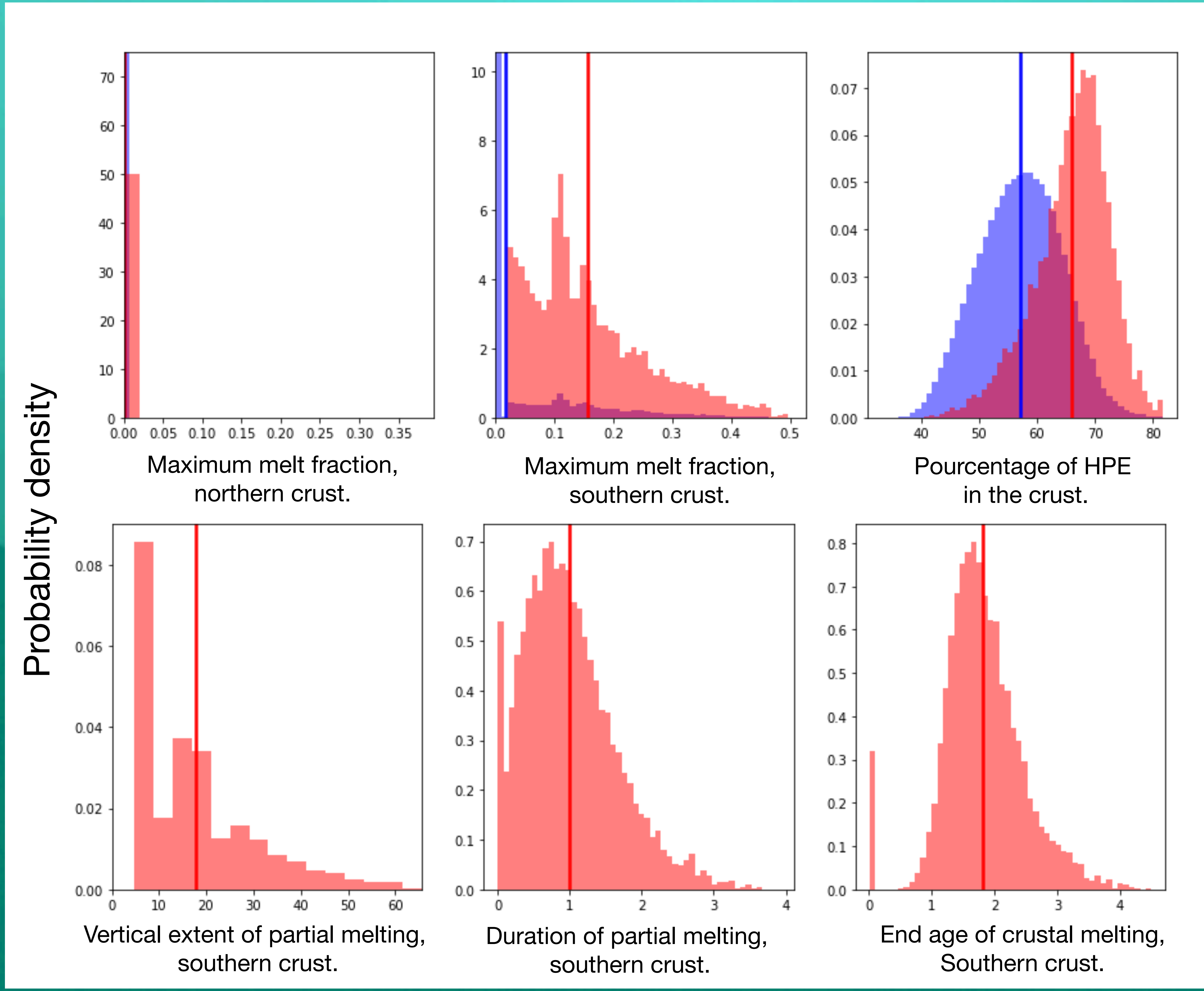




Conclusion

Inversion results

Model Outputs

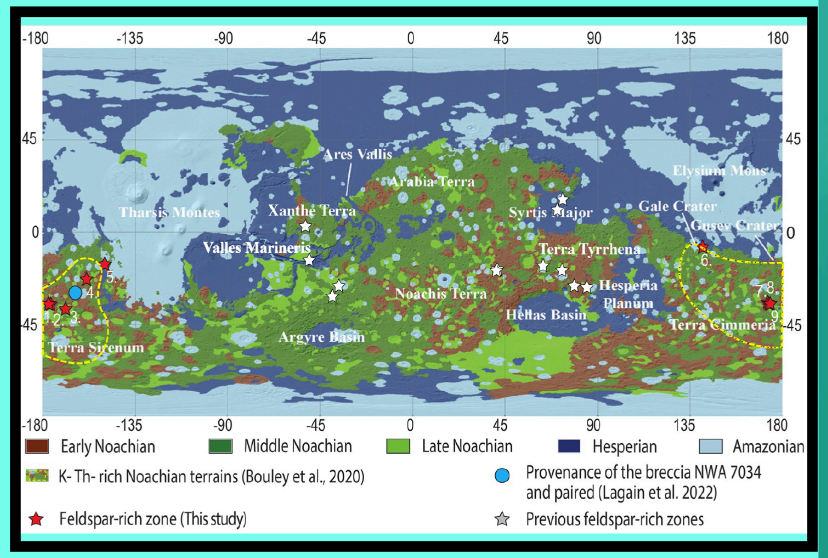


- The result of the inversion is a collection of models that fit the likelihood. We display the probability densities for different model outputs.
- Partial melting of the southern crust occurs in 8-10% of all selected models while partial melting of the northern crust occurs in less than 1% of them.
- For these models, Partial melting can be significant both in duration (~1 Gyr) and vertical extent (10s of km) .

Inverted parameters
More output aposteriori
Examples of thermal evolution

Home page

Crustal felsic Component



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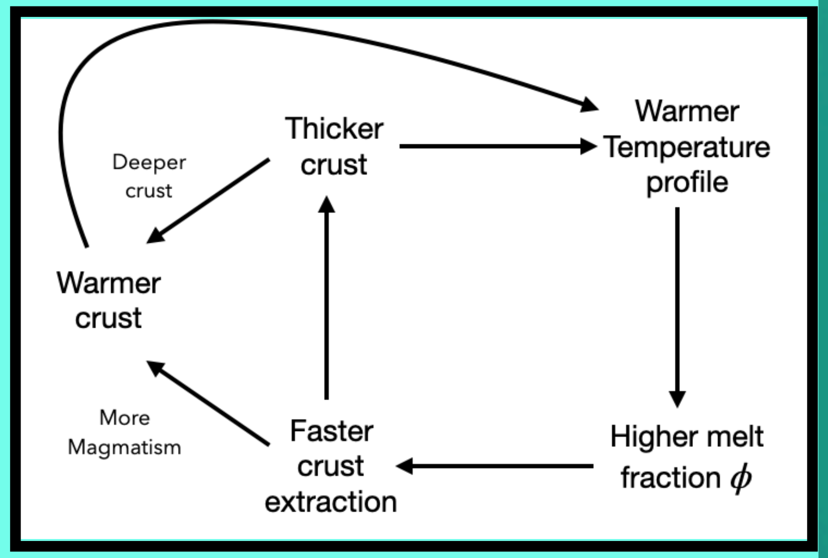

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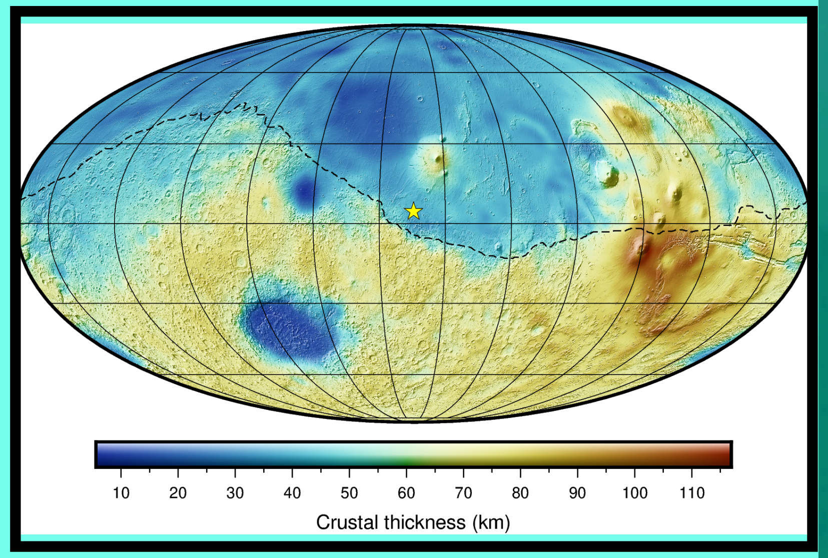

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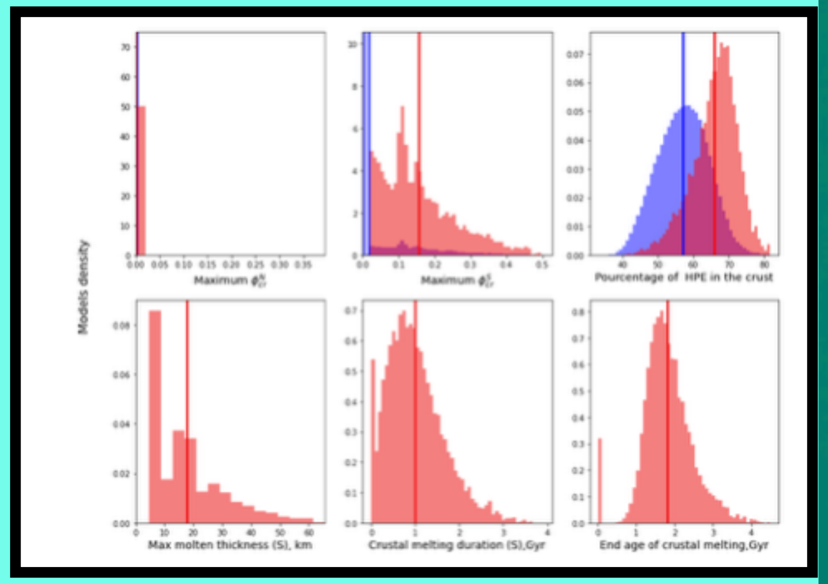

Conclusion

❖ The Martian crust can remain partially molten during its formation over a long duration (~1 Gyr) and large vertical extent (10s of km).

❖ A significant fraction of the selected models (i.e. compatible with the internal structure revealed by InSight) provides the conditions for the formation of felsic rocks by fractional crystallization.

❖ In the frame of our mechanism, felsic rocks form in regions of thick crust, as suggested by observations.

❖ A secondary origin for the differentiated rocks would in turn provide strong constraints on the thermal evolution of Mars.

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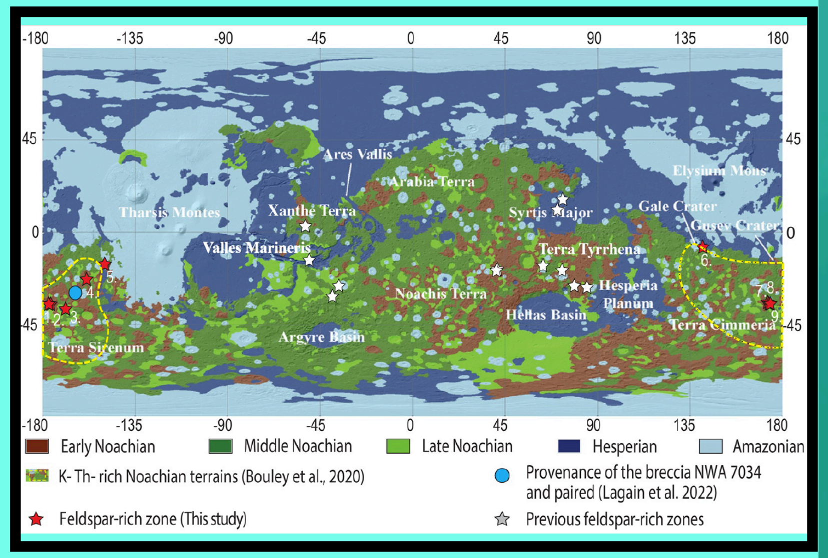

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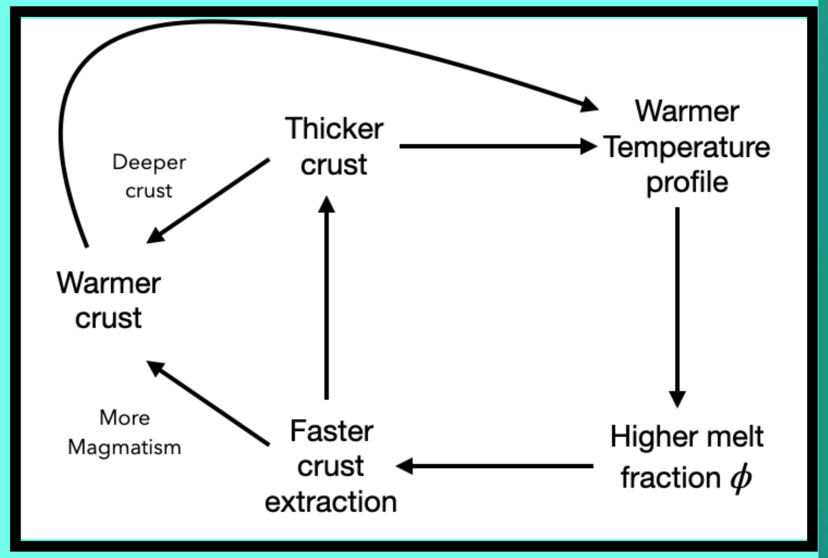

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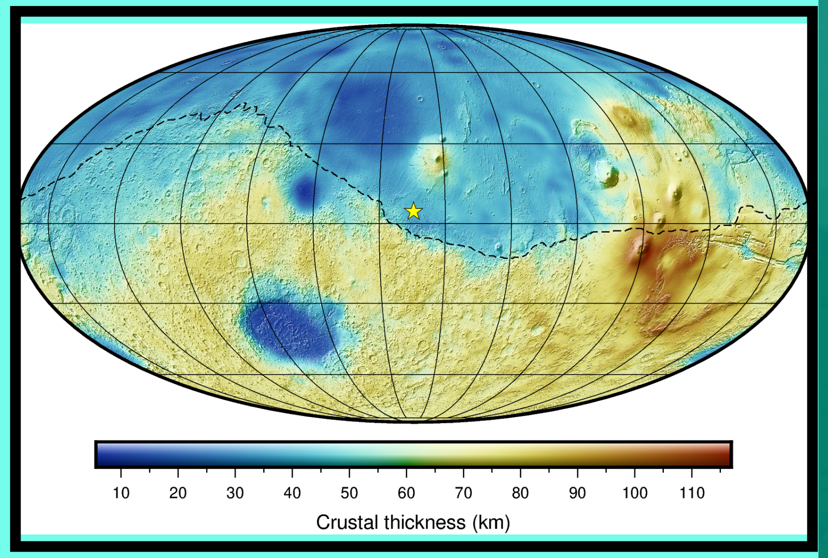

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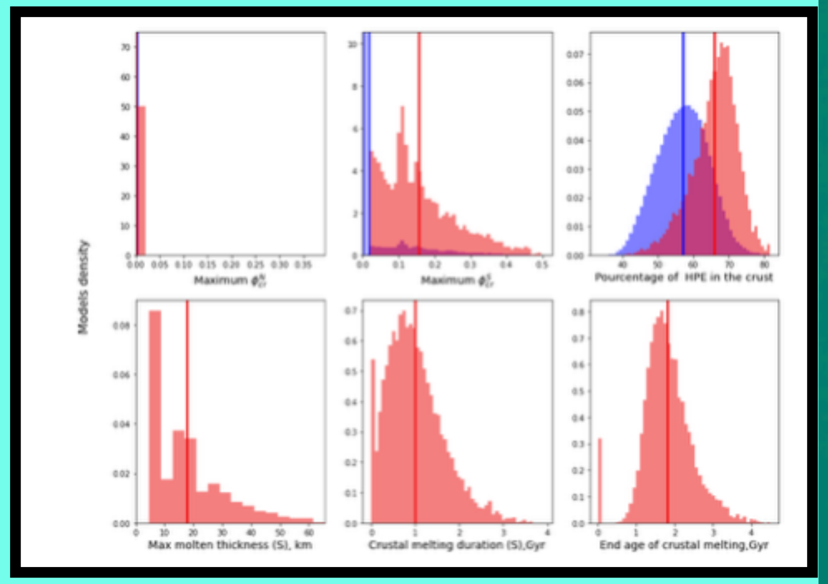
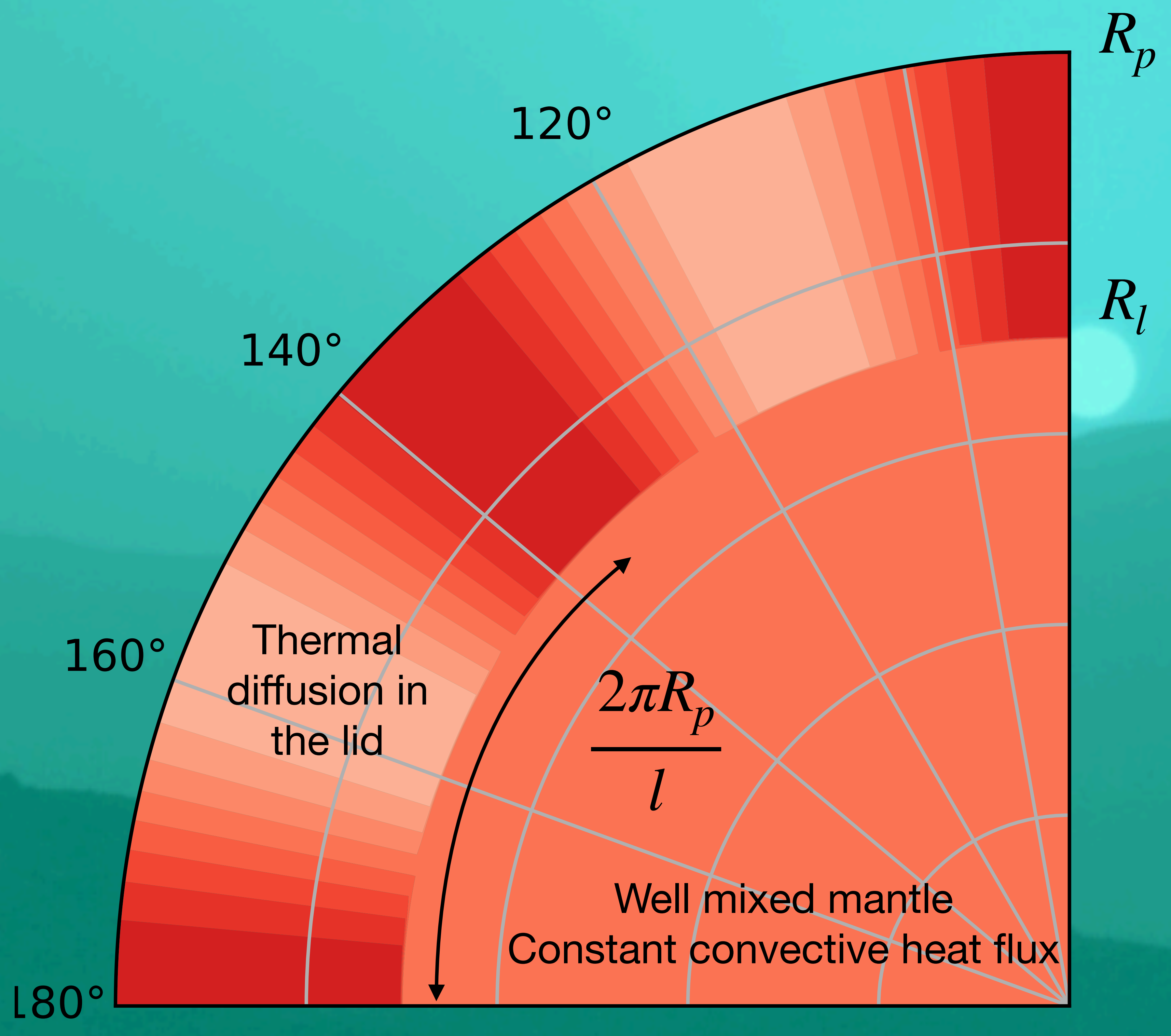
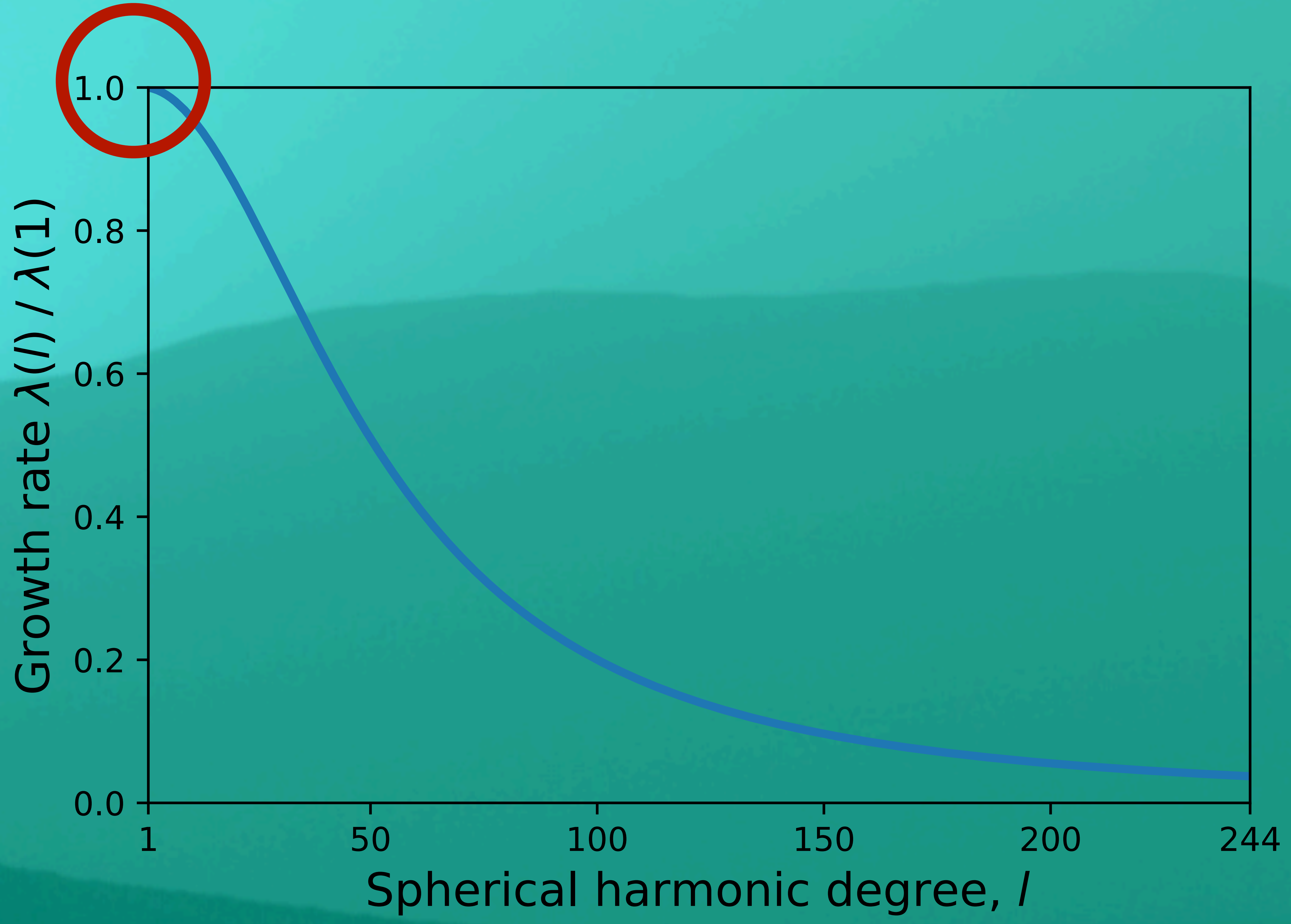


Mechanism favoring the growth of a hemispheric perturbation

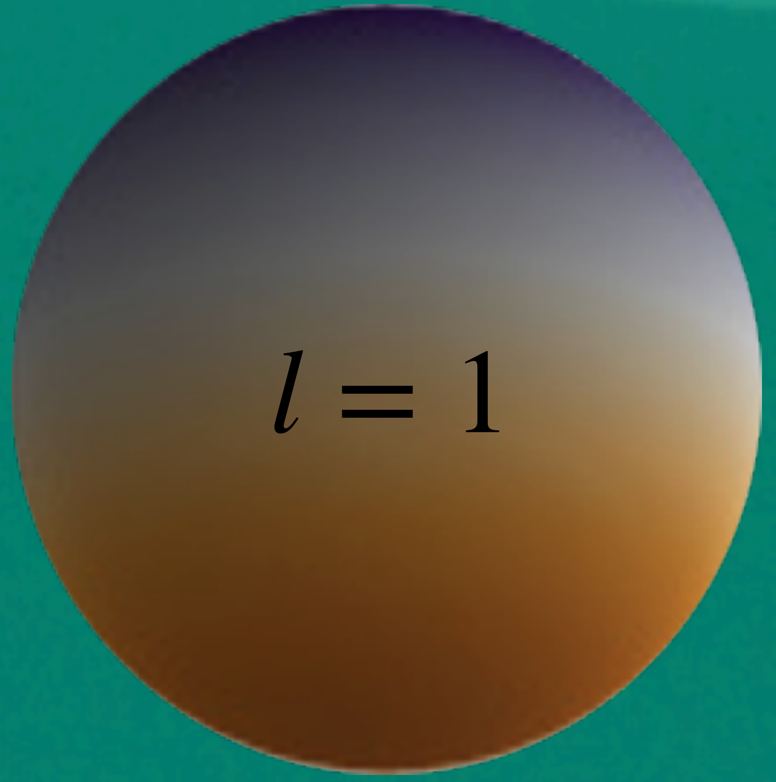




Growth of Small Lateral perturbations in temperature or/and heat production ?

$$H(\theta, \phi, t) = H^0(t) + \epsilon H^1 Y_{lm} e^{\lambda(l)t}$$

A positive feedback between crustal thickness and melt extraction for the origin of the Martian dichotomy, Bonnet Gibet et al, JGR 2022



A hemispheric perturbation is favored because smaller ones are more attenuated by lateral thermal diffusion.

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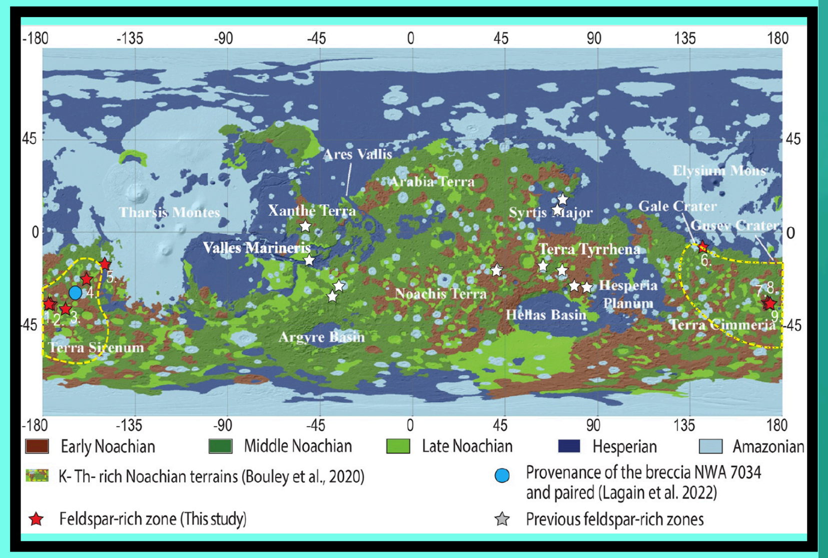

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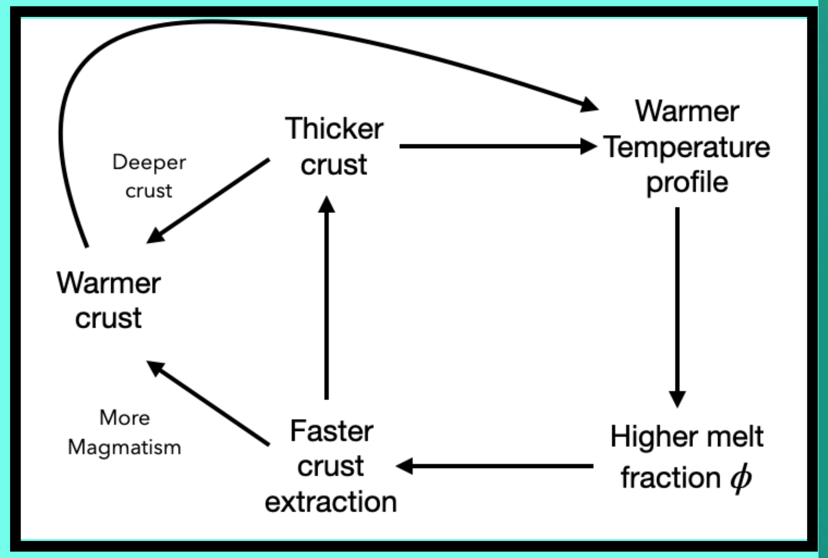

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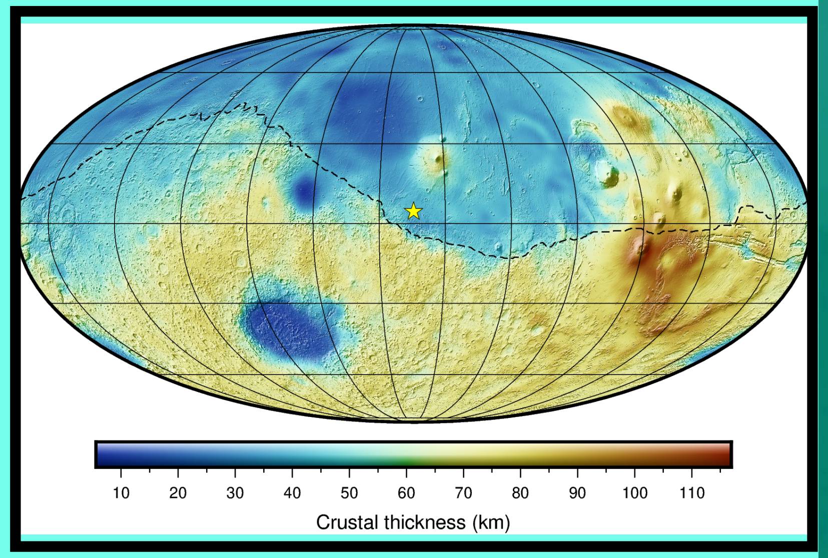

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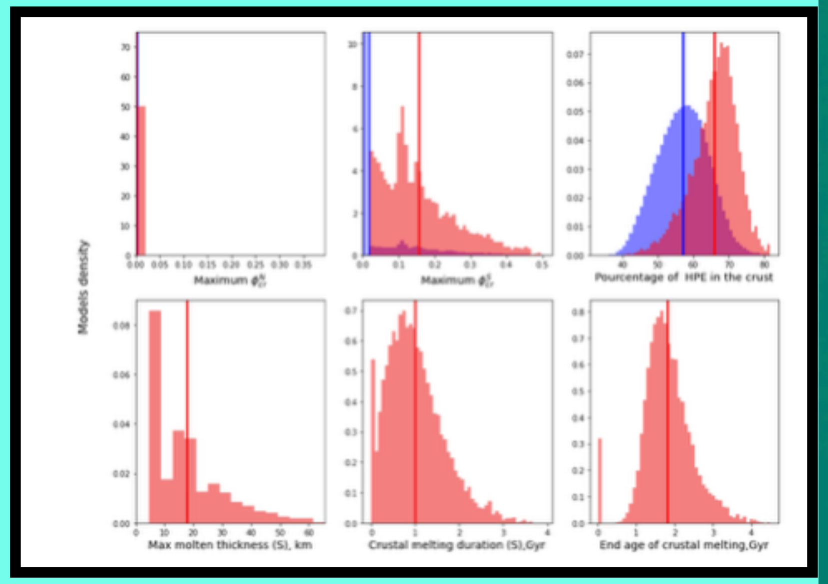
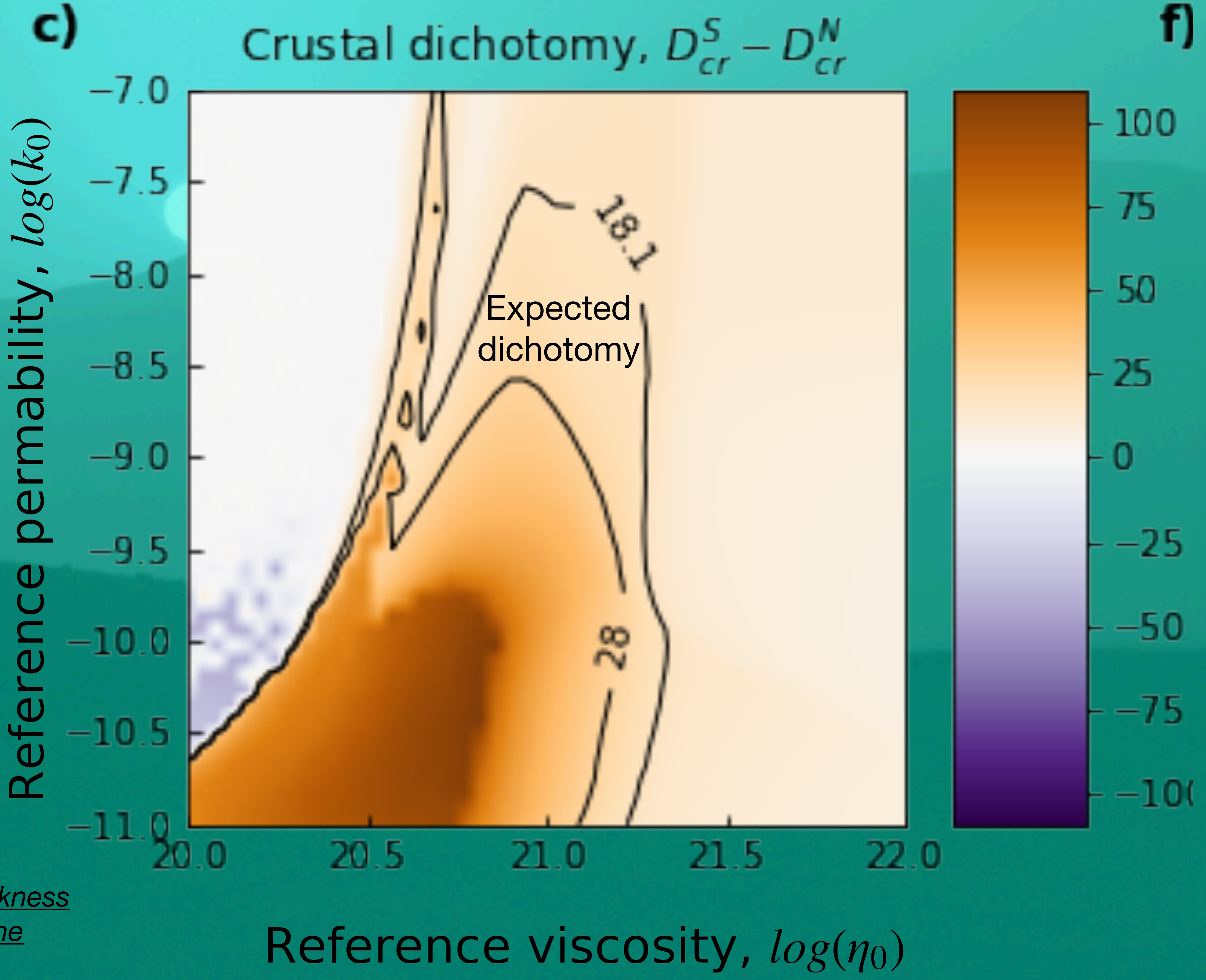


This positive feedback mechanism can explain the observed crustal dichotomy amplitude.

➢A significant crustal dichotomy can form for a large set of (k_0, η_0).



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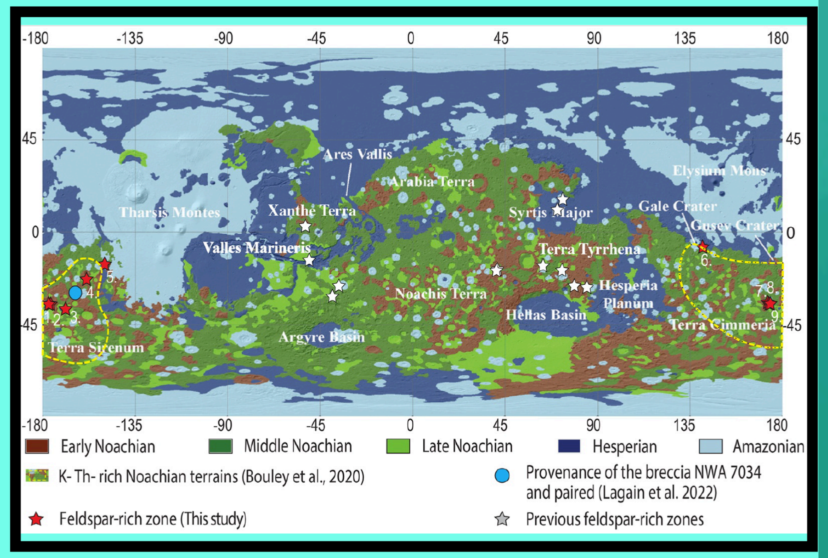
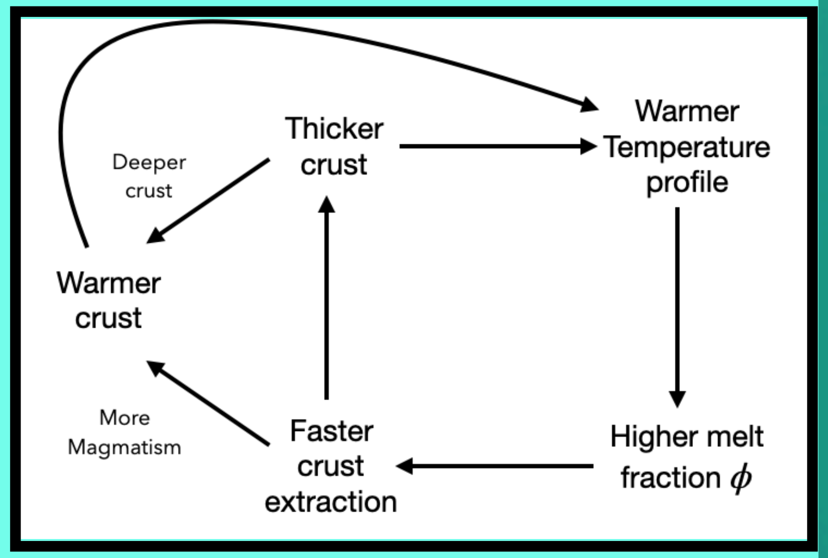
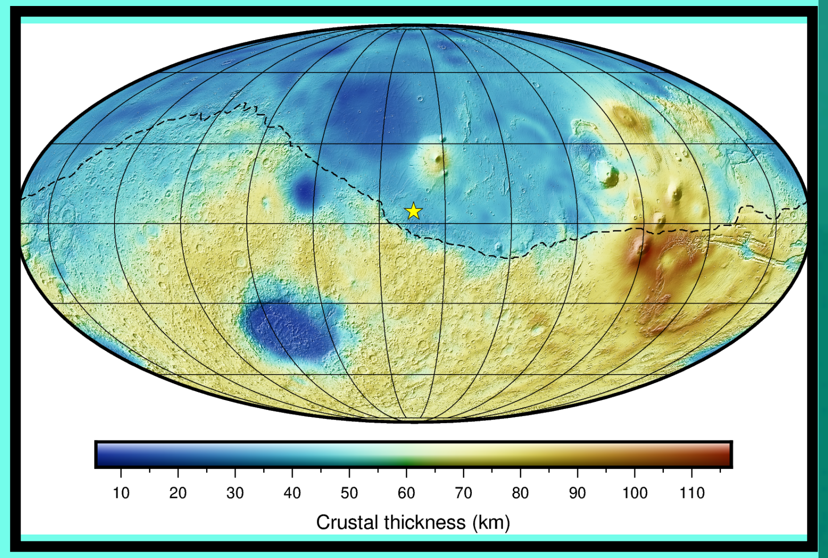
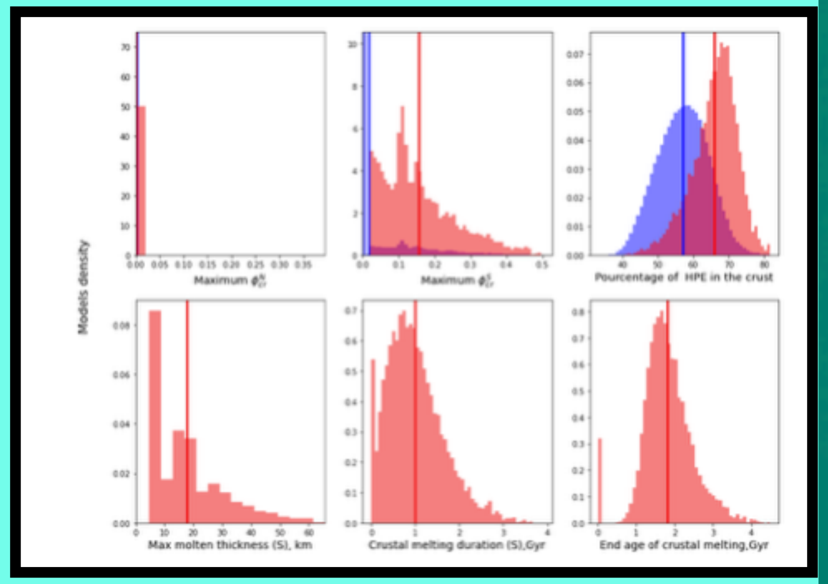
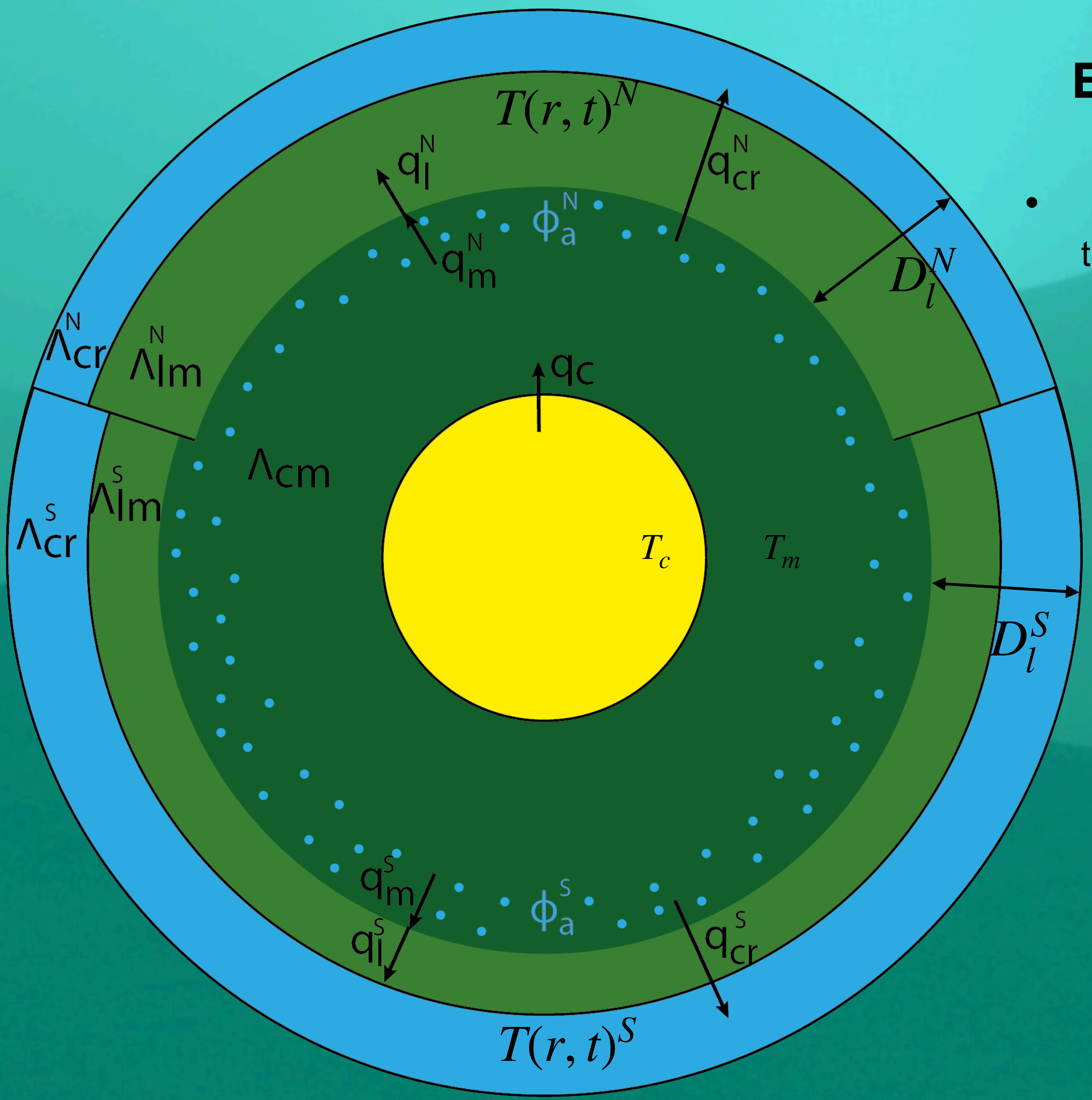








Parameterised thermal evolution for stagnant lid convection with two hemispheres



Energy conservation in the different layers

- Heat conservation in the convective mantle and core gives the temperature at the top of the mantle (T_m) and core (T_c) :
  - ➡ Parametric description of the convective heat flux q_m (Davaille et Jaupart, 1992).
  - ➡ Viscosity law: $\eta(T,P) = \boldsymbol{\eta_0} \exp(\frac{A+PV}{RT} - \frac{A+P_0V}{RT_0})$
  - ➡ Radiogenic heat production (Wänke and Dreibus, 1994)

- Two different lids for each hemisphere (N/S) :
  - ➡ Two different thermal profiles $T(r,t)^{N/S}$ obtained by solving thermal diffusion in each lid.
  - ➡ Heat budget at the lithosphere base gives the thickness of the two different lithospheres $D_l(t)^{N/S}$.

A positive feedback between crustal thickness and melt extraction for the origin of the Martian dichotomy,
Bonnet Gibet et al, JGR 2022

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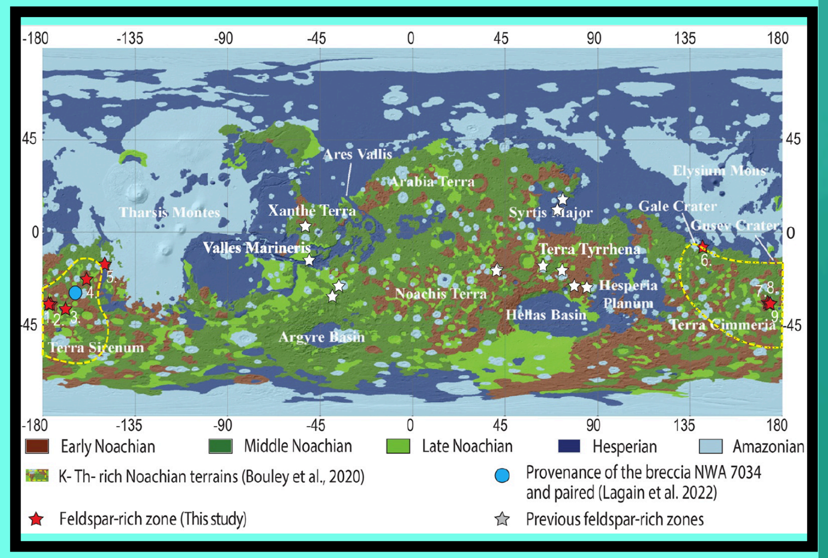
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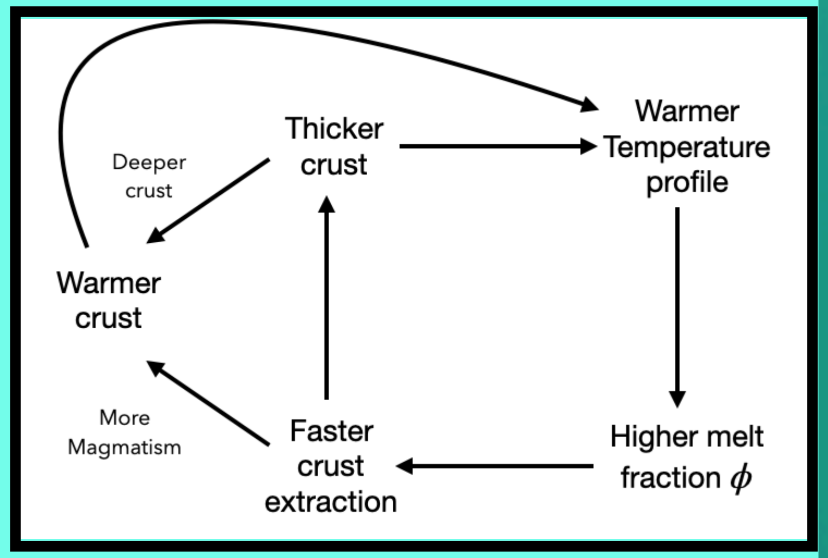

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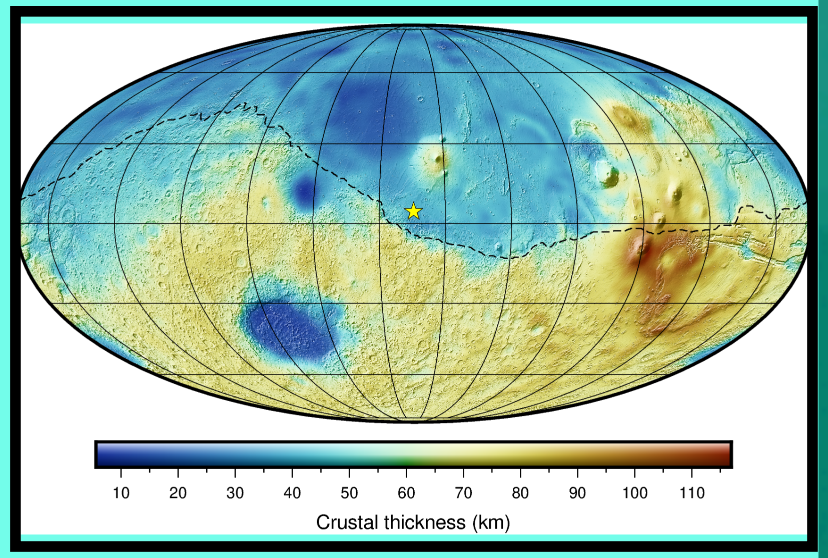

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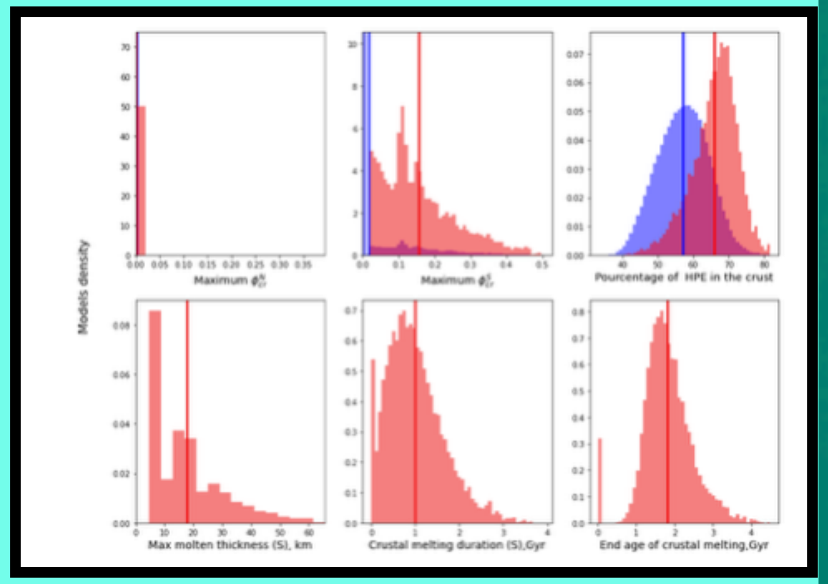
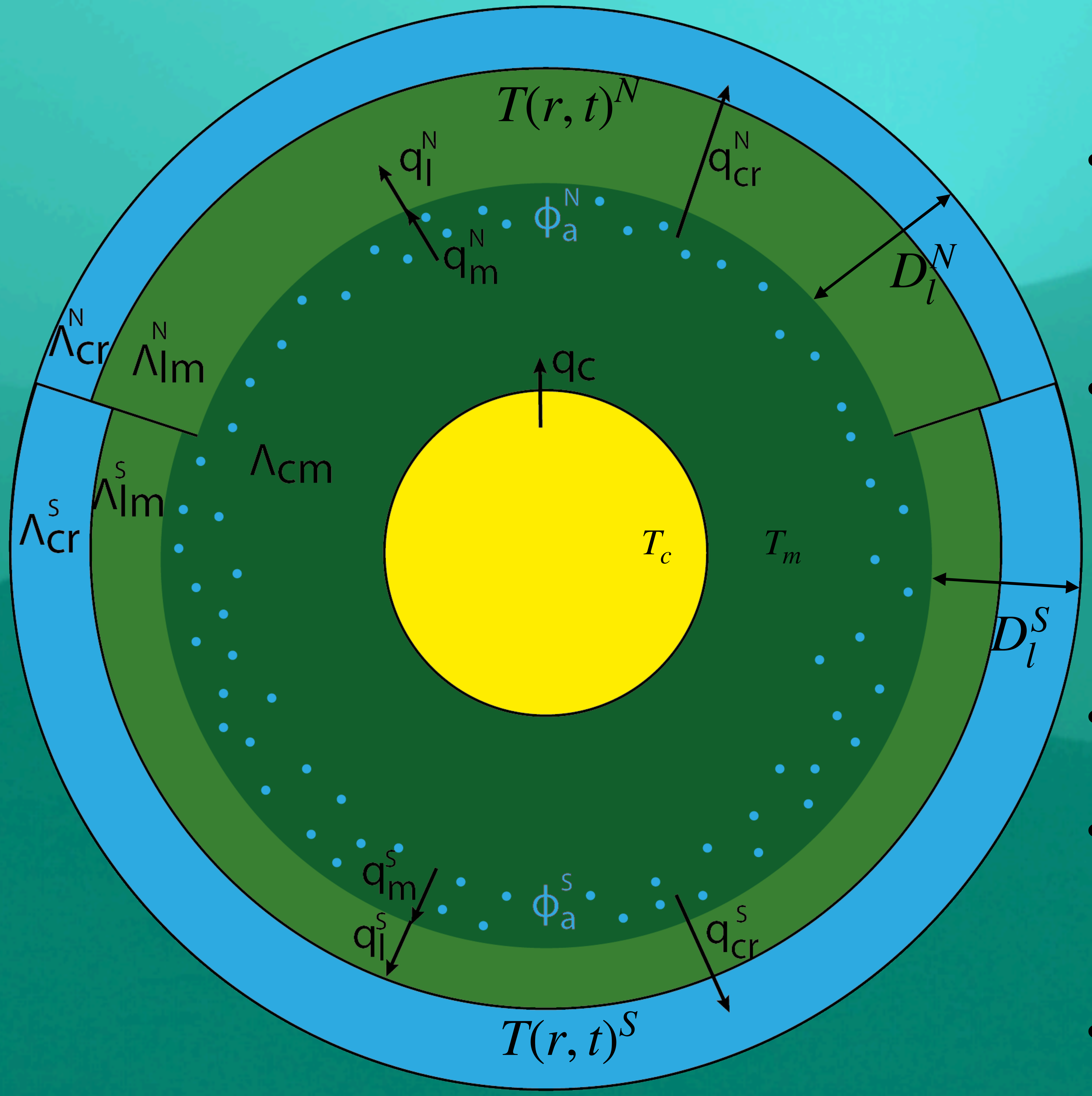


Mantle melt extraction by Darcy flow



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Crust extraction and HPE partitioning

- Average melt fraction calculated below each lid $\phi_a^{N/S} = f(T_m, D_l^{N/S})$
- Melt output velocity from the mantle : $$w^{N/S} = \frac{\mathbf{k_0}\phi_a^{N/S^3}\Delta\rho g}{\eta_l}(1-\phi_a^{N/S})$$
- Crustal growth : $$\frac{dD_{cr}}{dt} = w\left(\frac{R_l}{R_{cr}}\right)^2$$
- Heat flow out of the mantle due to crust growth: $$q_{cr}^{N/S} = \frac{dD_{cr}}{dt}\rho_{cr}\left(C_{cr}(T_m - T_l) + L\right)$$
- Heat producing element partitioning depends on partition coefficient D_i and melt fraction $\phi_a^{N/S}$.

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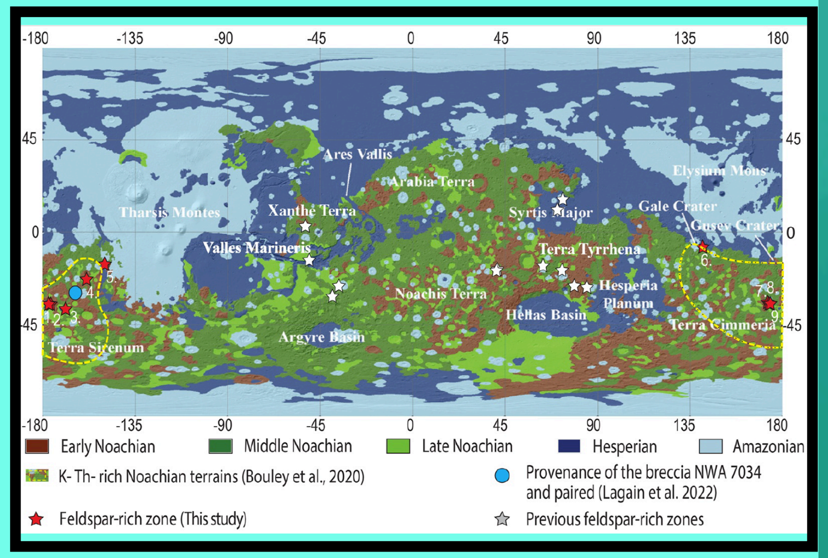

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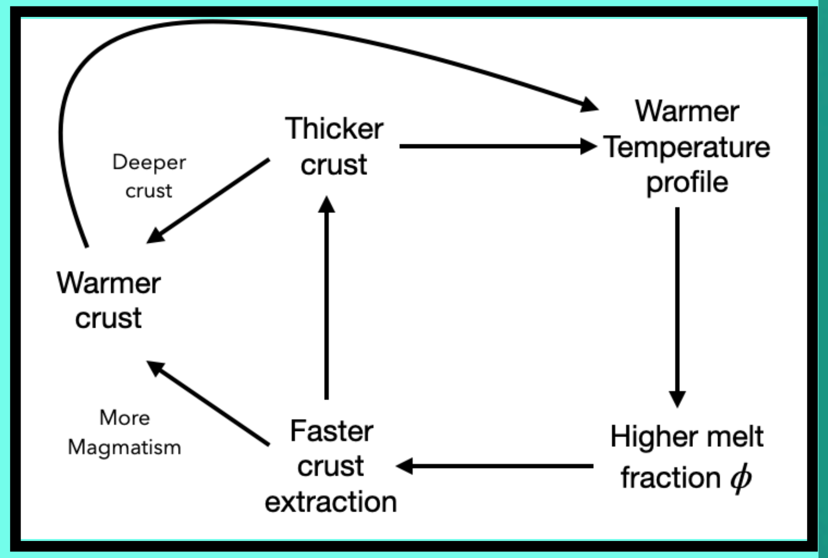

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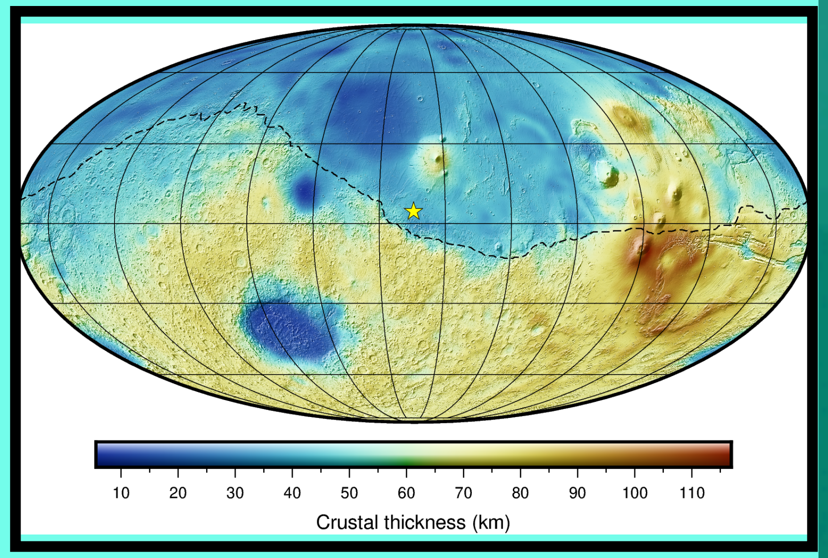

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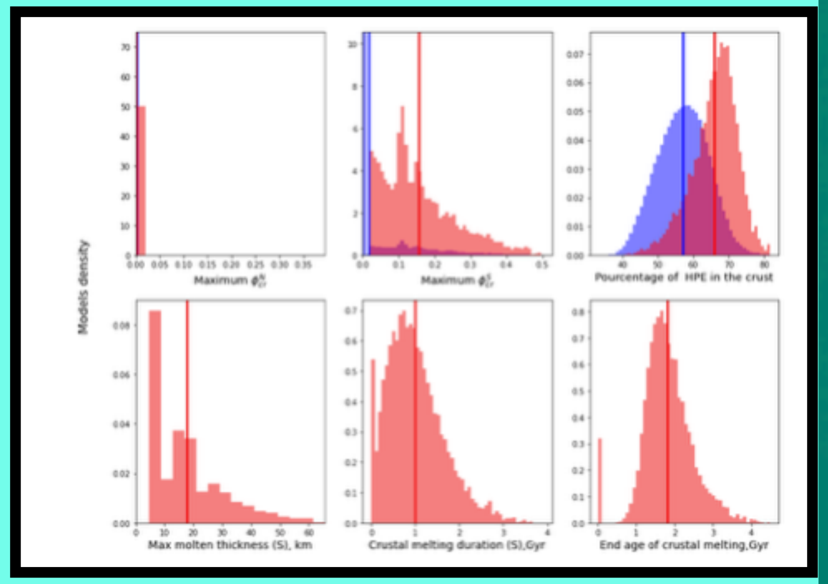
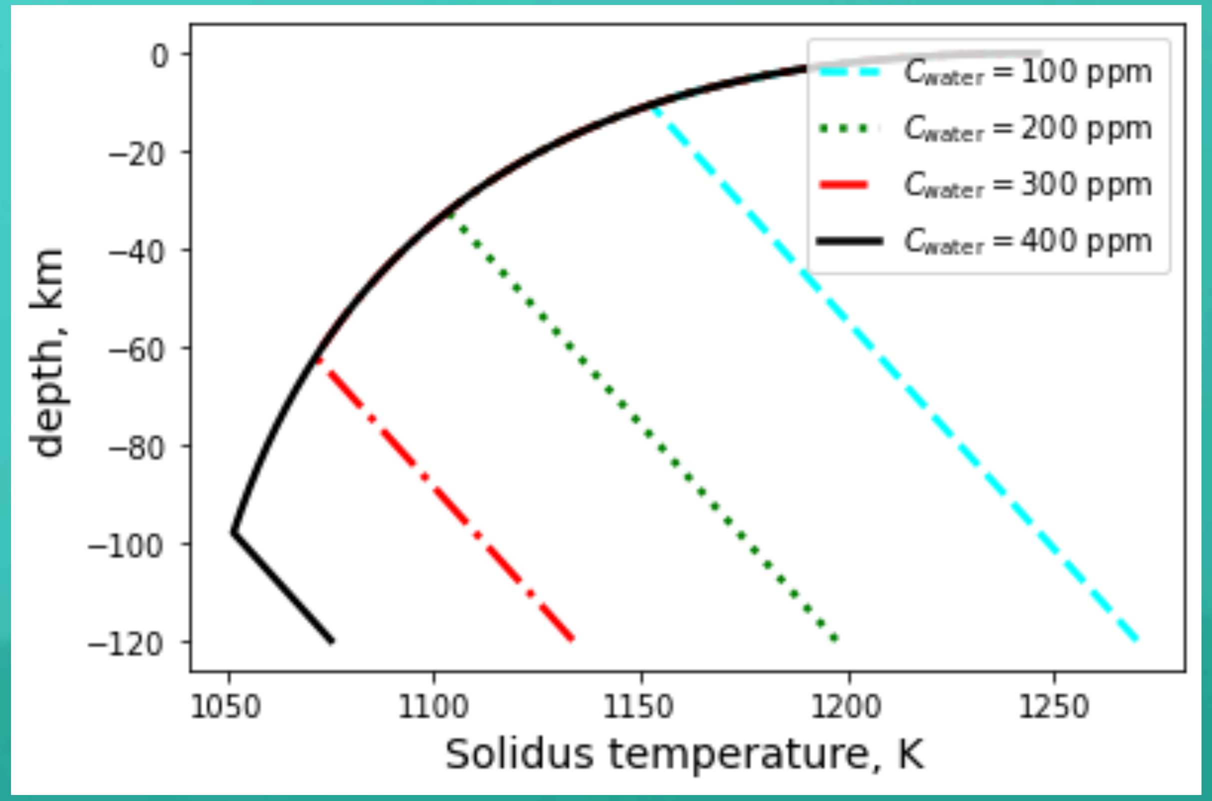


Crust melting, magmatism and downward advection

- We construct a solidus for the crust using the parametrization of *Katz et al (2003*).

- The solidus depends on pressure and on the water content of the crust.



$$u(r > R_{cr}) = (1 - f_{\mathrm{mag}}) \times w \left(\frac{R_l}{r}\right)^2 - (1 - f_{\mathrm{base}}) \times f_{\mathrm{mag}} \times w \frac{R_l^2}{r^2} \frac{R_p^3 - r^3}{Rp^3 - R_{cr}^3}$$

$$u(r \le R_{cr}) = w \times \left(\frac{R_l}{r}\right)^2$$

$$\rho_m \left(C_m(T_m - T_l) + L\phi_a^{N/S}\right)\left(\frac{dD_l^{N/S}}{dt} - w^{\mathrm{N/S}}\right) = -q_{cm}^{N/S} - k_m \frac{dT}{r}\Bigg|_{r=R_l}^{N/S}$$

- Crust extraction causes downward advection of the lithosphere below which depends on the deposition mode (fmag, fbase).

- Downward advection of the lithosphere results in a cooling term in the conduction and lid thickness equation.

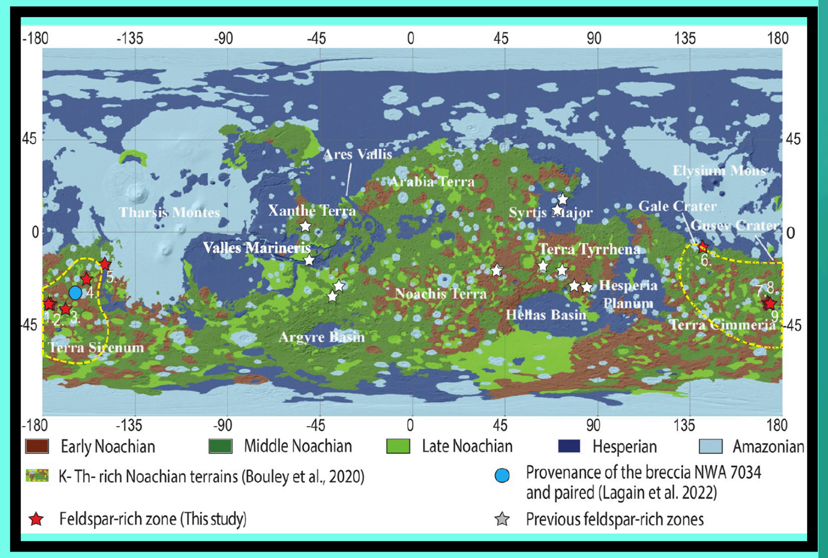
- Heating induced by magmatism depends on the magma and crust temperature and on the deposition modes.

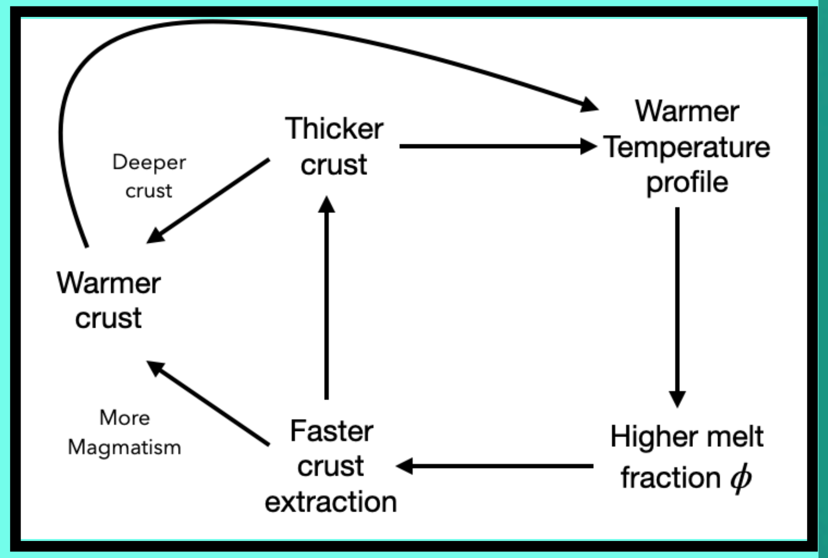
$$H_{\mathrm{lat}}^{\mathrm{N/S}}(r > Rcr) = w^{\mathrm{N/S}} \frac{A_{cm}^{\mathrm{N/S}}}{V_{cr}^{\mathrm{N/S}}} \rho_{cr} \Big[L + C_{cr}\Big(T_l - T(r)\Big)\Big] f_{\mathrm{mag}}(1 - f_{\mathrm{base}})$$

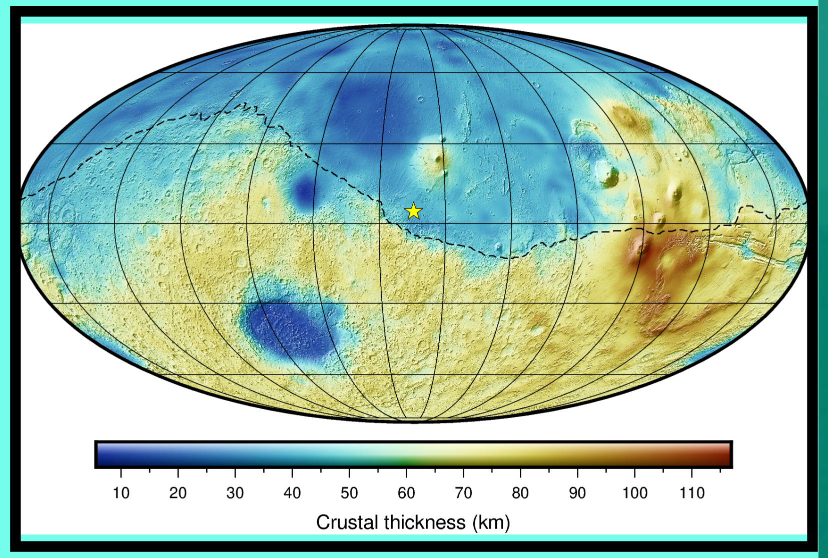
$$H_{\mathrm{lat}}^{\mathrm{N/S}}(R_{cr}) = w^{\mathrm{N/S}} A_{cm}^{\mathrm{N/S}} \rho_{cr} \Big[L + C_{cr}\Big(T_l - T(R_{cr})\Big)\Big] f_{\mathrm{mag}} \left(\frac{(1 - f_{\mathrm{base}})}{V_{cr}^{\mathrm{N/S}}} + \frac{f_{\mathrm{base}}}{dV_{cr}}\right)$$

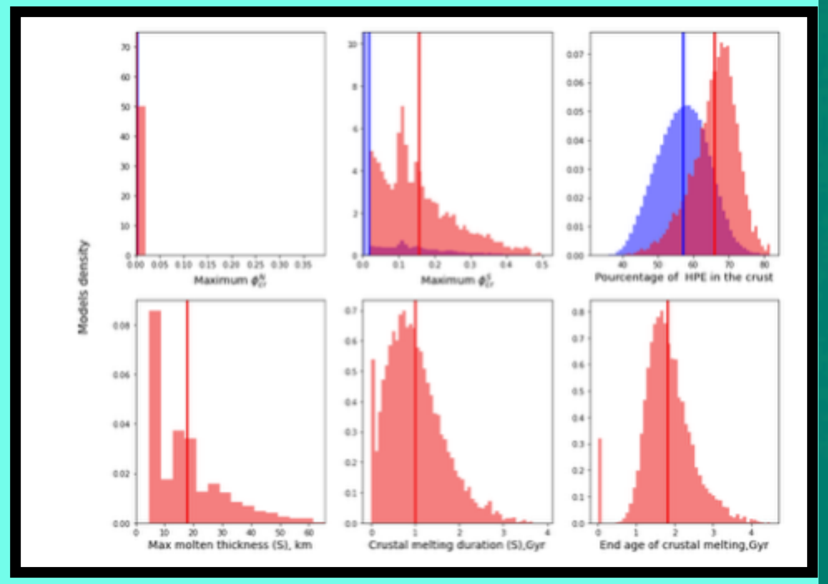
Deposition modes :

- (1-fmag) : fraction of melt deposed through volcanism (instantaneous cooling.)
- f_{base} fraction of magmatism (fmag) depose at the base of the crust.
- The rest (1-f_{base}) is depose on the bulk volume of the crust.

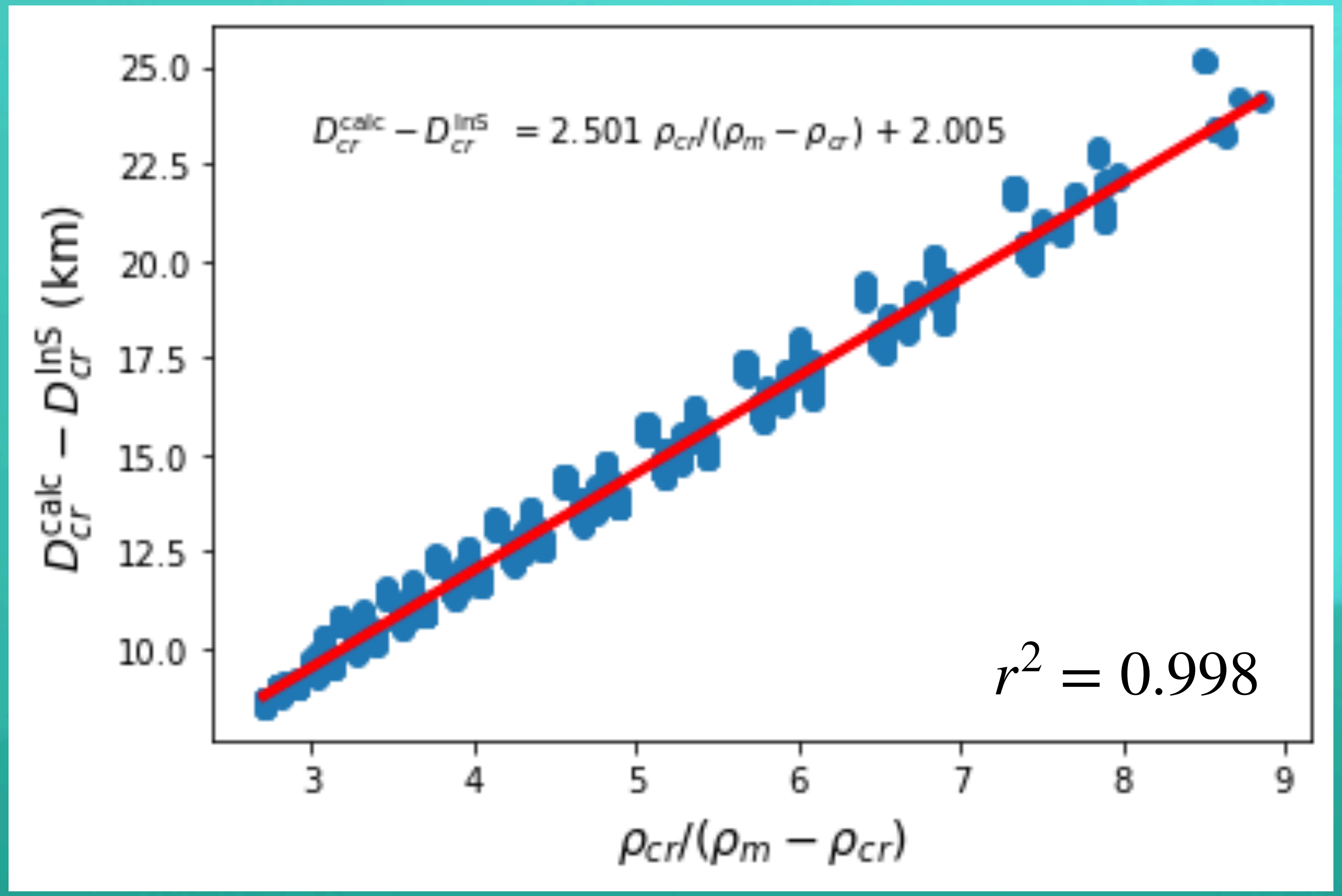




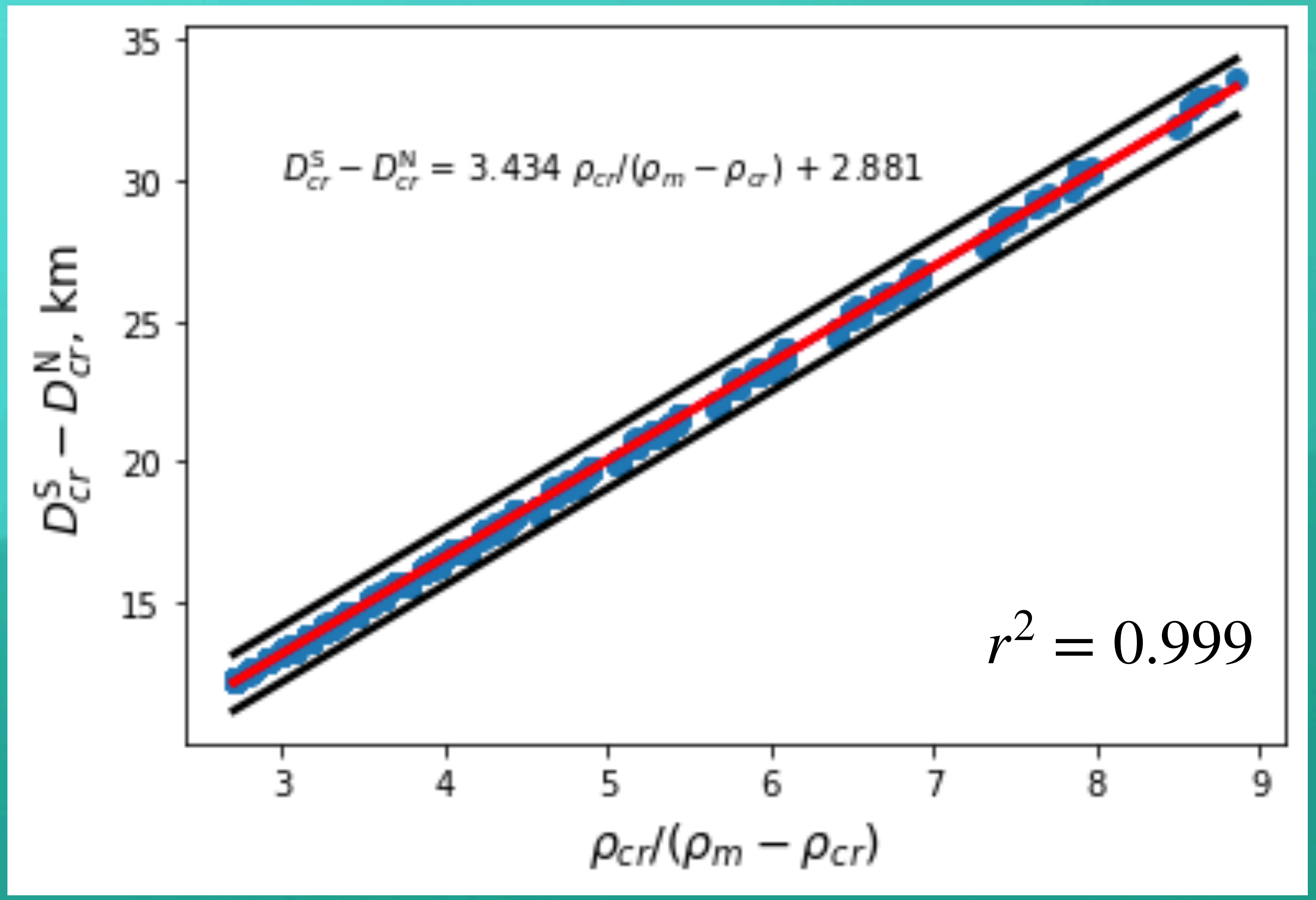




Likelihood from inversions of topography and gravity data.



Knapmeyer-Endrun et al, 2021



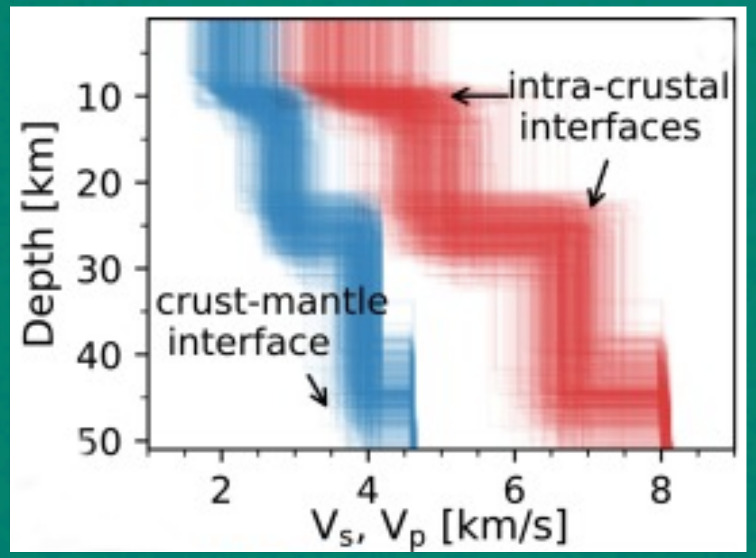
Knapmeyer-Endrun et al, 2021

Forecasted value from the model

$$D_{cr}^{InS} = D_{cr}^{calc} - 2.501\left(\frac{\rho_{cr}}{\rho_m - \rho_{cr}}\right) - 2.01 \text{ km}$$

$$\Delta D_{cr}^{calc} = D_{cr}^{S} - D_{cr}^{N}$$

Expected value from InSight mission



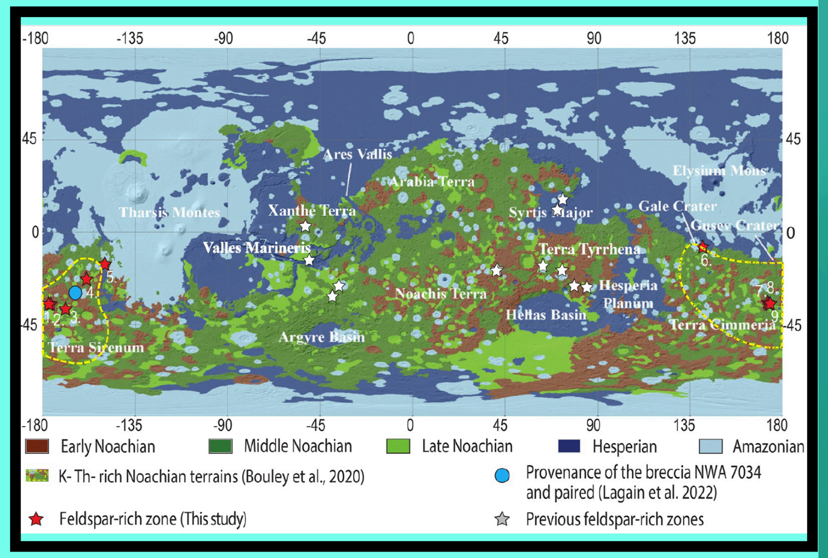
$$D_{cr}^{InS} = 42 \pm 5 \text{ km}$$

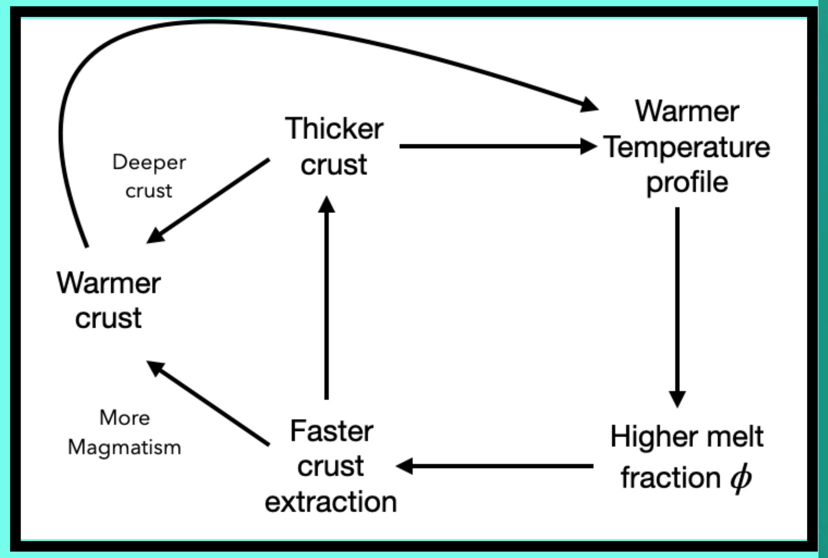
Durán et al, 2022

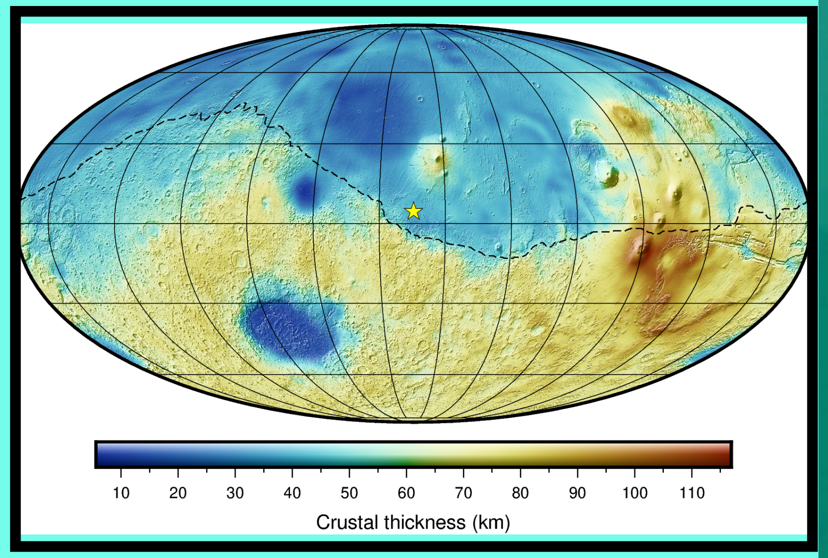
$$\Delta D_{cr} = 3.434\left(\frac{\rho_{cr}}{\rho_m - \rho_{cr}}\right) + 2.881 \;\; \pm 2 \text{ km}$$

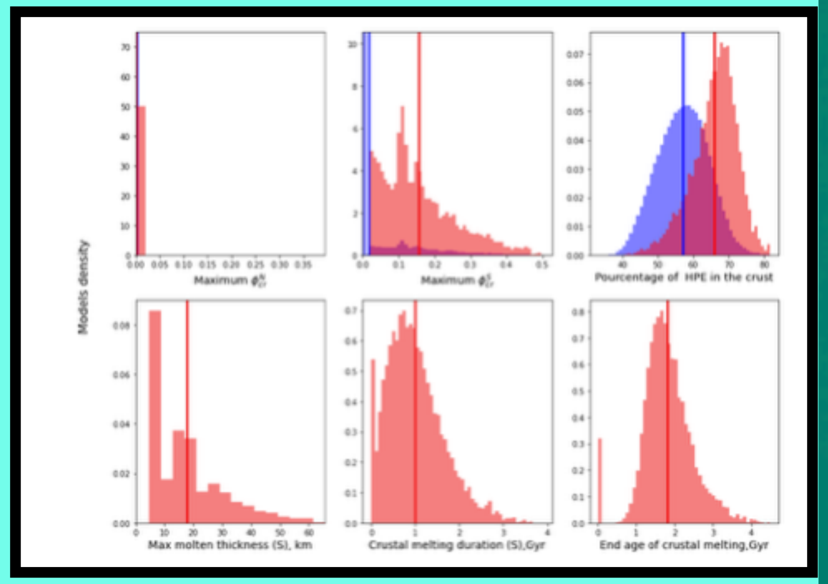
Knapmeyer-Endrun et al, 2021

- We use a gaussian probability distribution around the mean value.



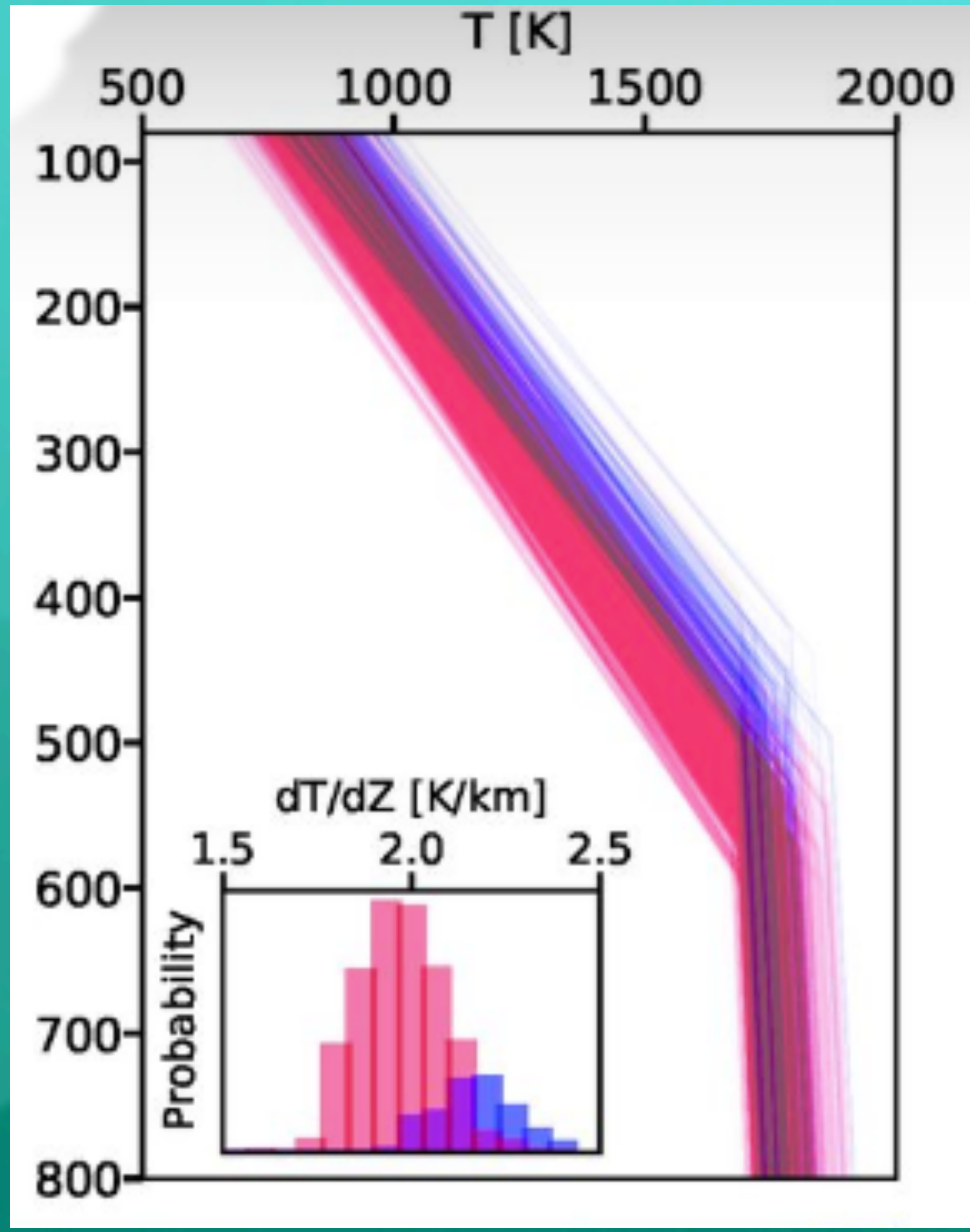






Seismological results on the current thermal state of the Martian mantle.

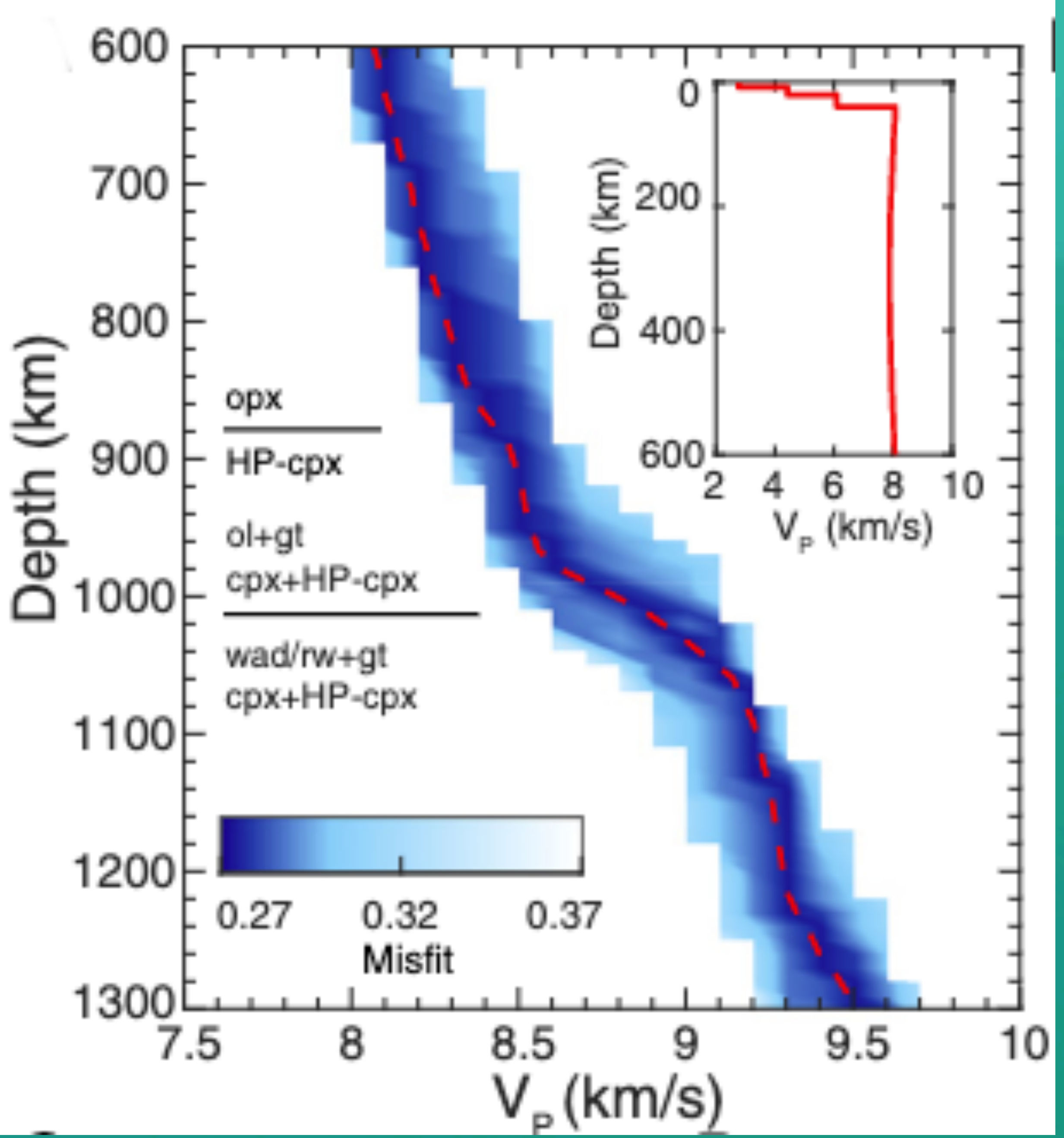
Khan et al, 2021 & Durán et al, 2022



The inversion of travel time provide the semis velocity profile and can be interpret As a temperature profile. This profile reveal the potential temperature and a lid thickness of the martian mantle.

$$D_l^{\mathrm{InS}} = 450 \pm 100 \text{ km}$$

Huang et al, 2022

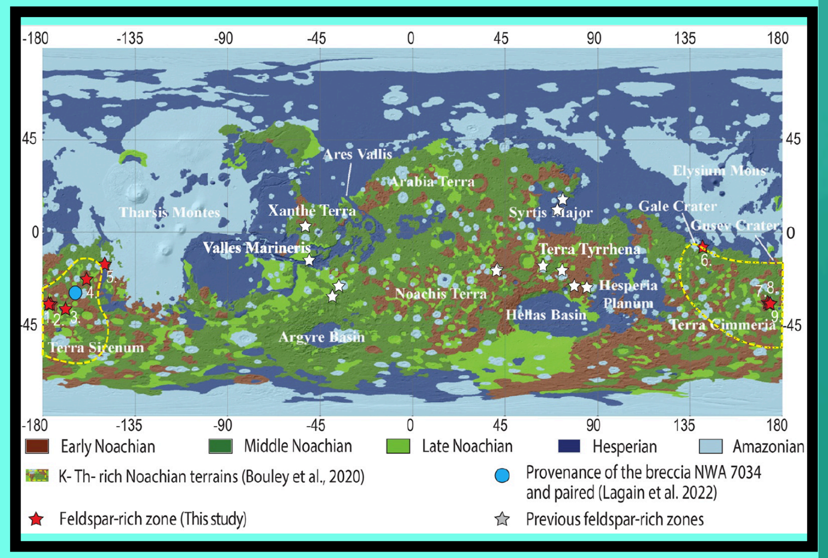


The depth of the mantle transition zone (Olivine to wadsleyite) provide, for a given mineralogical model, the temperature of the convective mantle.

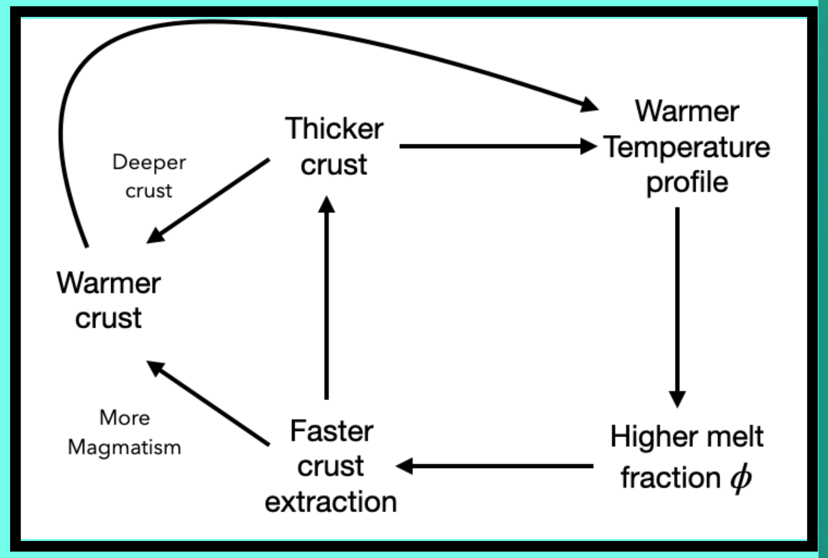
$$T_p^{\mathrm{InS}} = 1605 \pm 100 \text{ K}$$

Home page

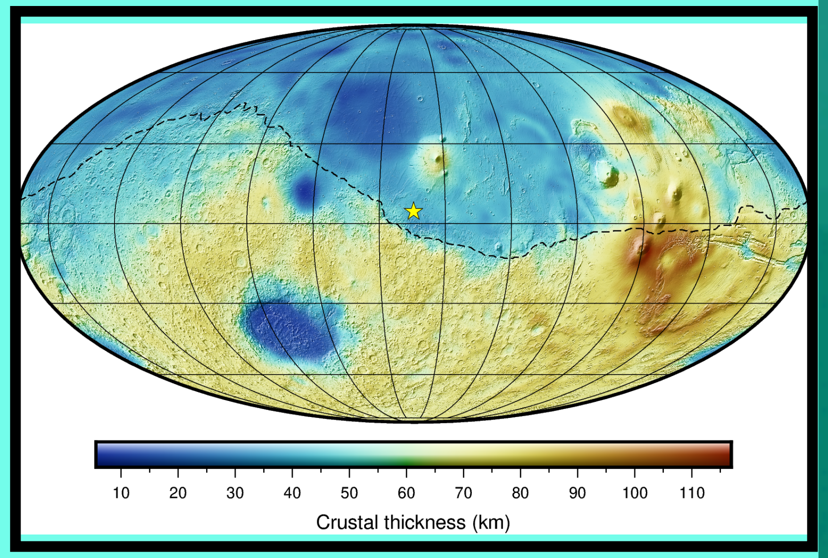
Crustal felsic Component



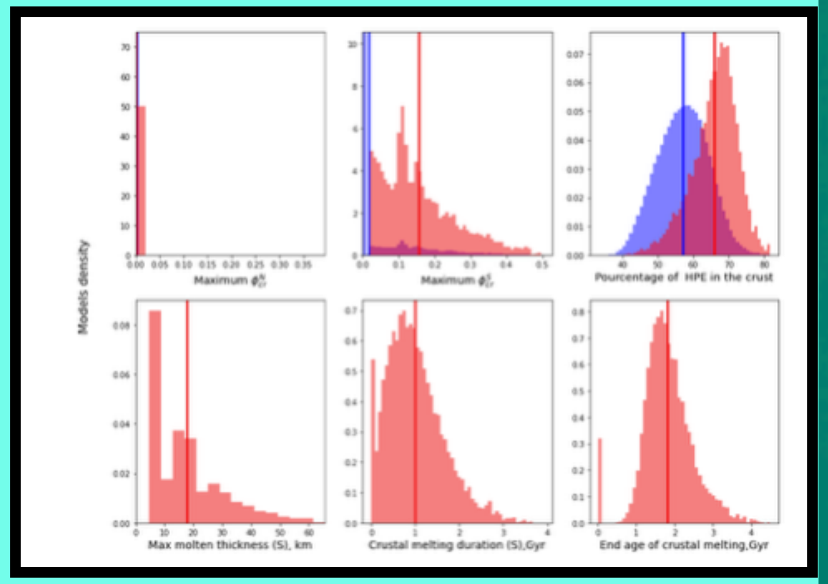
Mechanism & Model



Bayesian inversion



Inversion results



Monte Carlo - Markov chain sampling algorithm

Calculation of the 1st model $p_1 = f(\boldsymbol{m})$

↓ For N models

Write model $\boldsymbol{m}$

↓

Gaussian perturbation

Proposition of a new model $\boldsymbol{m}' = g(\boldsymbol{m}')$

↓

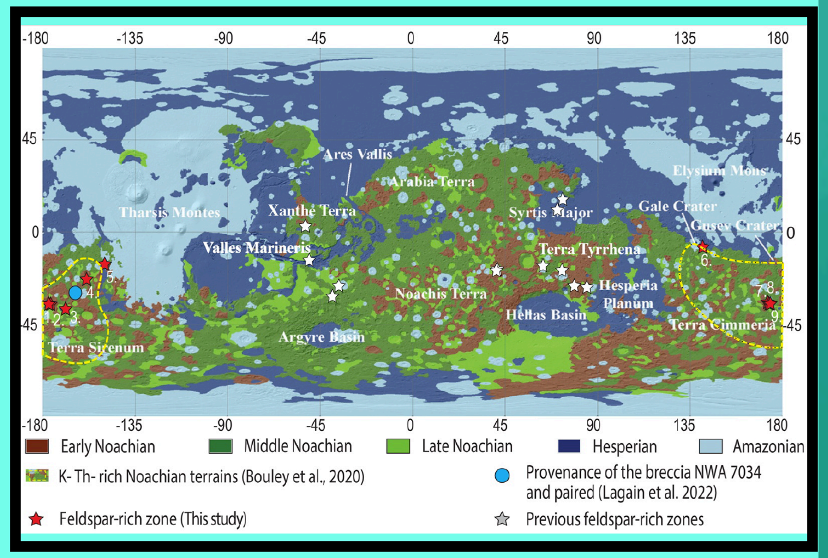
Calculation of the new model $p_2 = f(\boldsymbol{m}')$

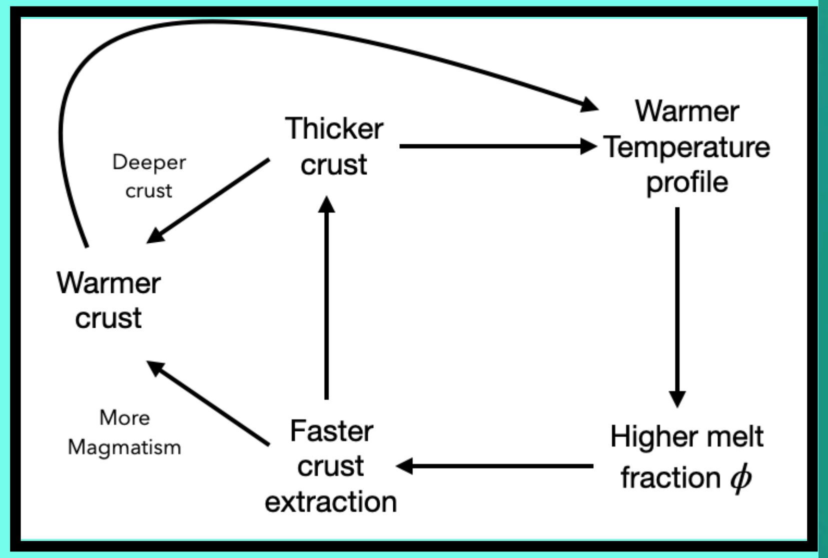
↓

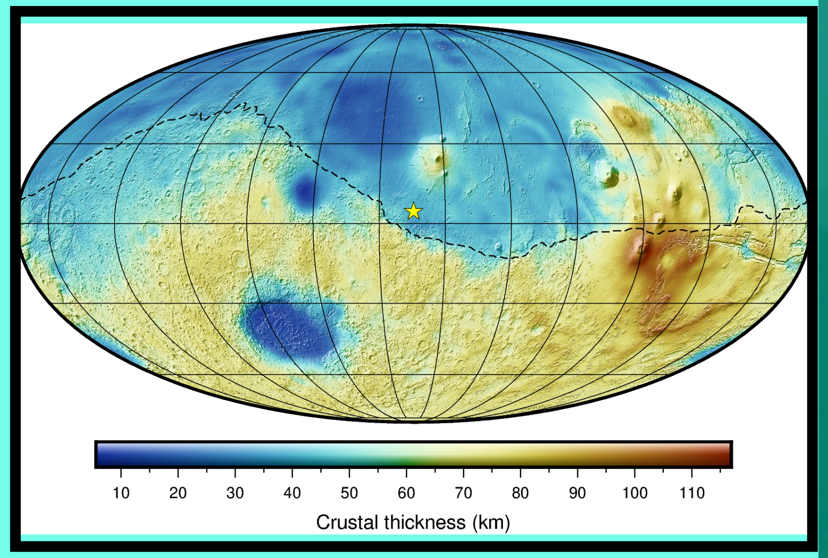
$\frac{p_2}{p_1} >$ rand(0,1)

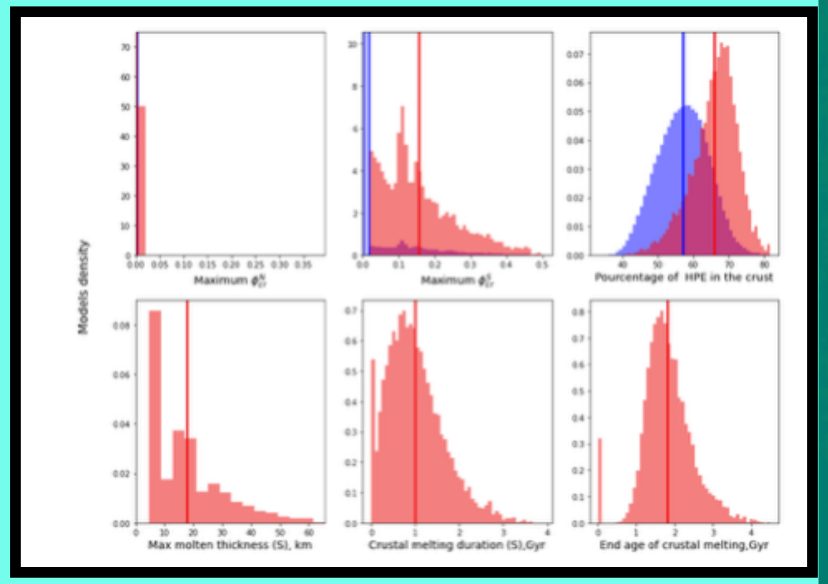
True → $\boldsymbol{m} = \boldsymbol{m}'$ & $p_1 = p_2$ → back to "Write model $\boldsymbol{m}$"

False → back to "Write model $\boldsymbol{m}$"

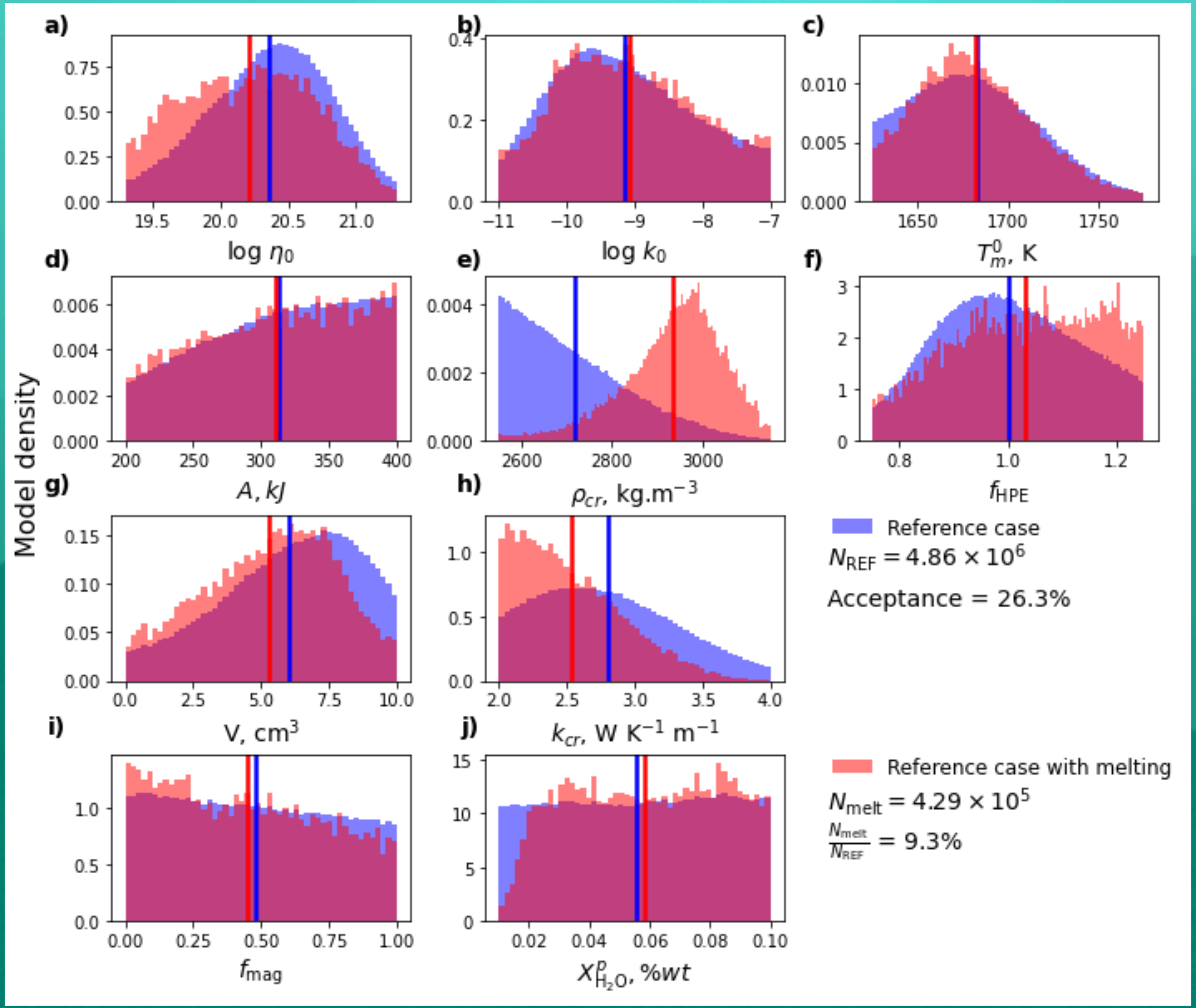








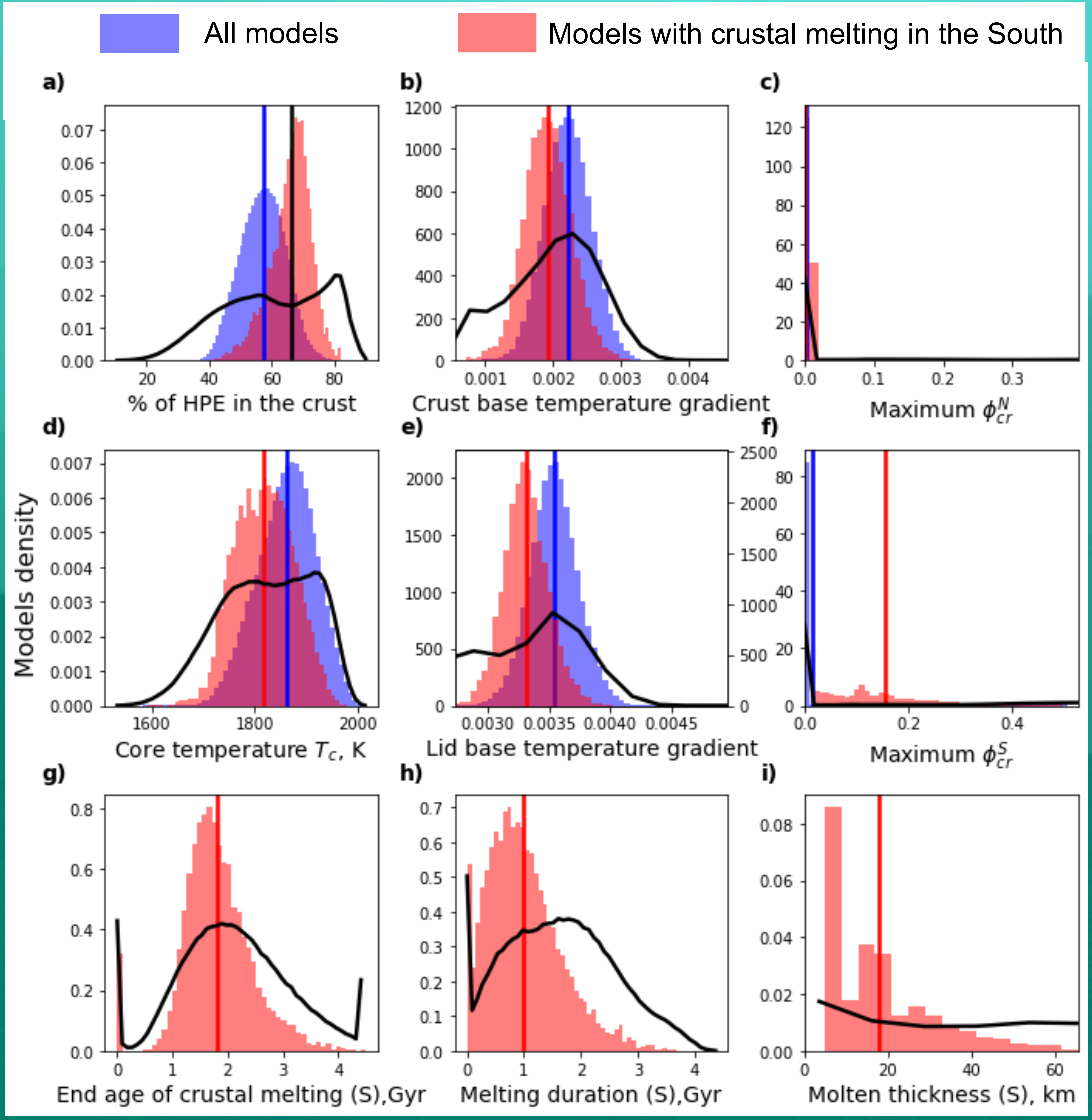
More results: inverted parameters



Caption : A poster distribution of the inverted parameters. Blue histograms represent all models and red histogram model with crustal melting only in the South. The coloured lines represent the averages of the corresponding distributions.

a) η_0 reference viscosity (log scale), **b)** k_0 reference permeability (log scale), **c)** T_m^0 Initial mantle temperature (K), **d)** A Activation energy (kJ), **e)** ρ_{cr} crustal density (kg.m^{-3}), **f)** f_{HPE} factor on the concentration of heat-producing elements, **g)** V activation volume (cm^{-3}) **h)** k_{cr} crustal thermal conductivity (W/m/K), **i)** f_{mag} fraction of magmatism deposition mode, **j)** $X^p_{\mathrm{H_2O}}$ water content of the primordial content.

More results: A posteriori output



<u>Caption :</u> Output a posteriori from the inversions. Blue histograms represent all models and red histograms model with crustal melting only in the South. The vertical lines represent the averages of the corresponding distributions. The black curve represent the a priori distribution.

a) Fraction of the total heating that occurs in the crust **b)** $\left.\frac{dT}{dz}\right|_{R_l}$ Temperature gradient at the base of the lid **c)** $\max(\phi_{cr}^{N/S})$ Maximum melt fraction in the Northern crust **d)** Core surface temperature. **e)** $\left.\frac{dT}{dz}\right|_{R_{cr}}$ Temperature gradient at the base of the crust **f)** $\max(\phi_{cr}^{N/S})$ Maximum melt fraction in the Southern crust **g)** Age of the last melting in the Southern crust. **h)** Duration of melting in the southern crust. **i)** Maximum thickness of partially molten crust in the southern hemisphere.

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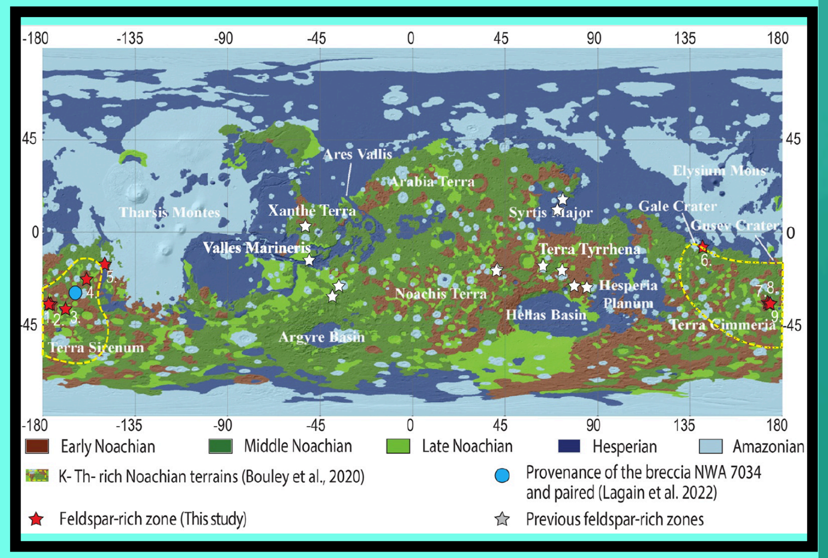
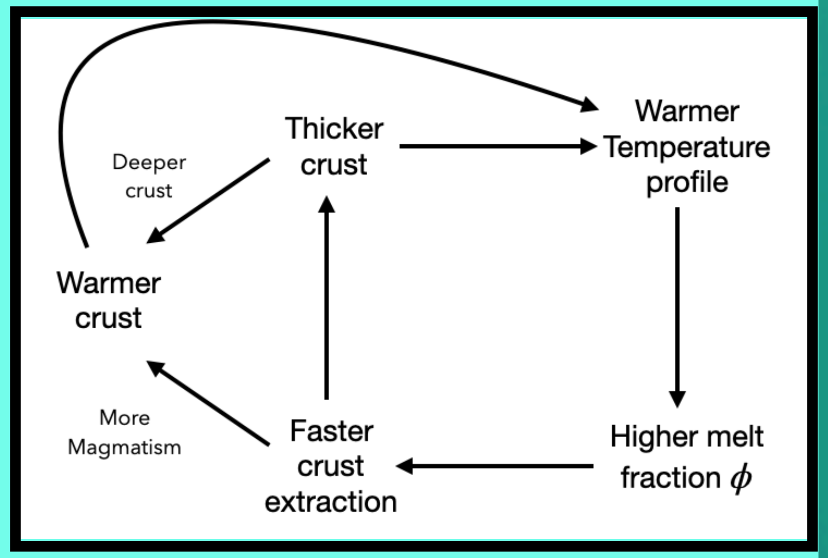
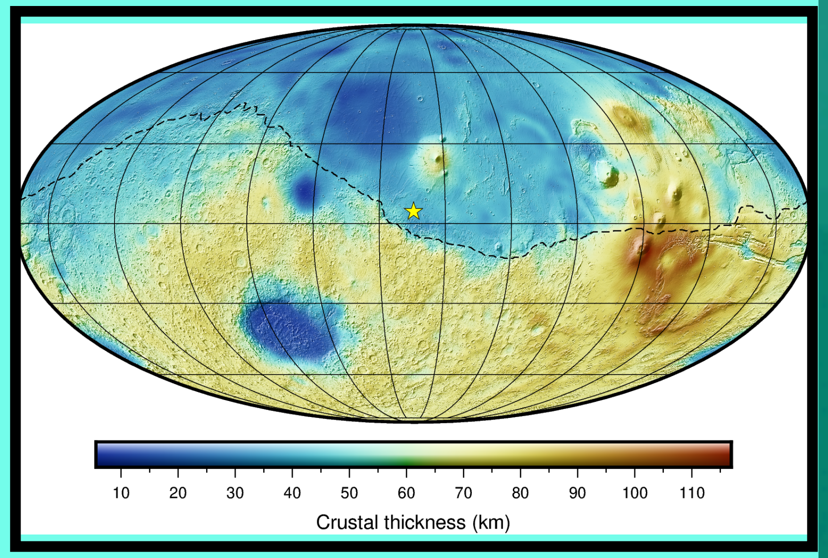
Crustal felsic Component



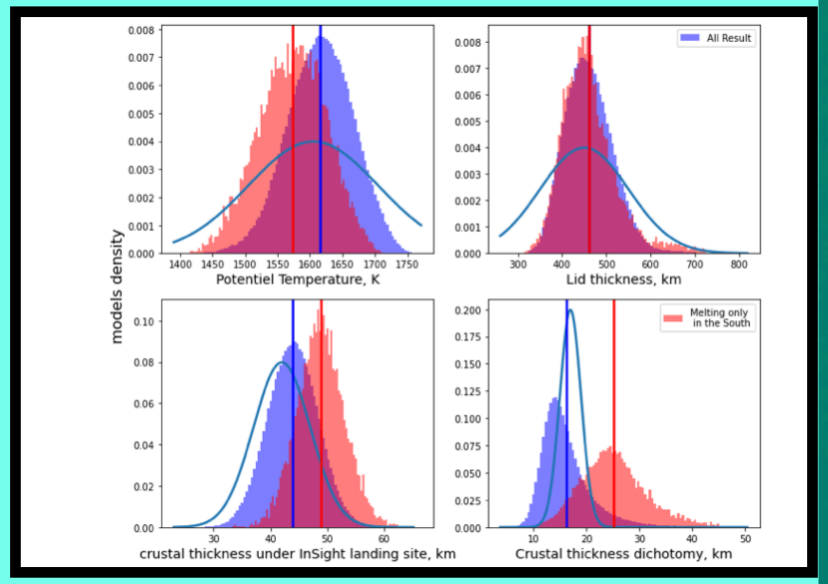
Mechanism & Model



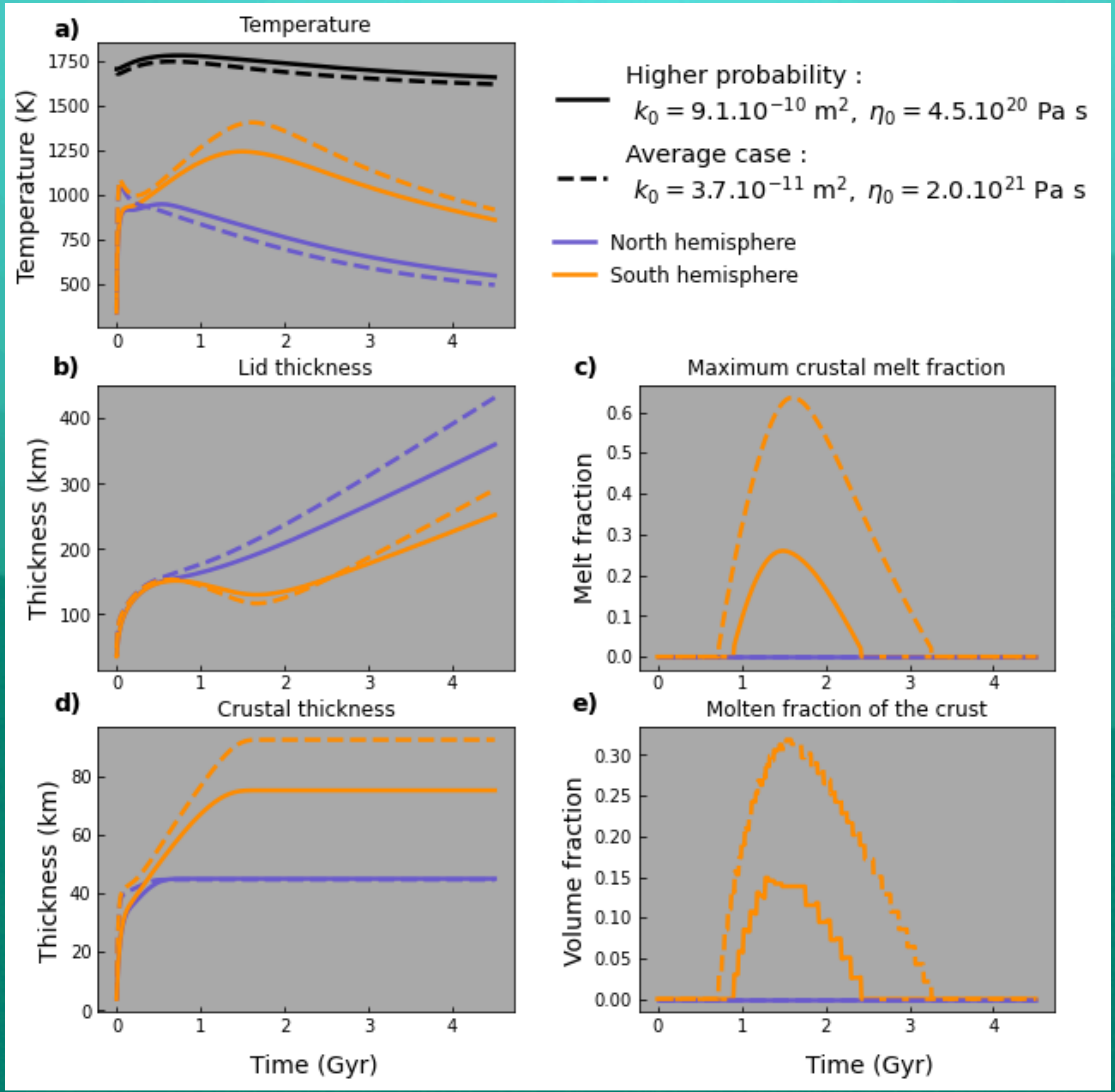
Bayesian inversion



Inversion results



Two thermal evolution examples



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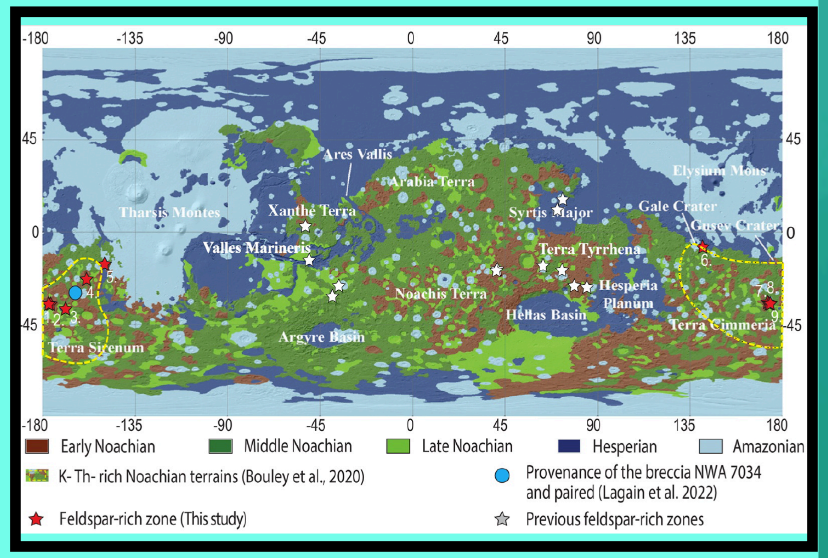
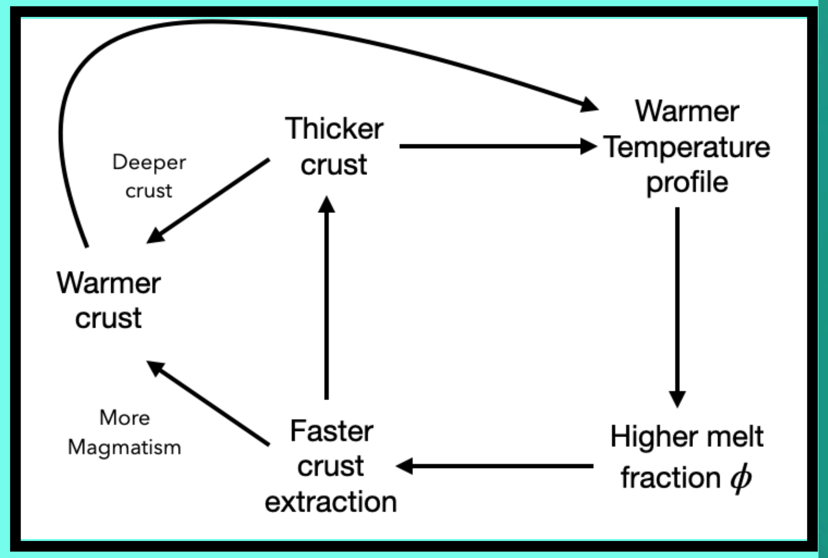
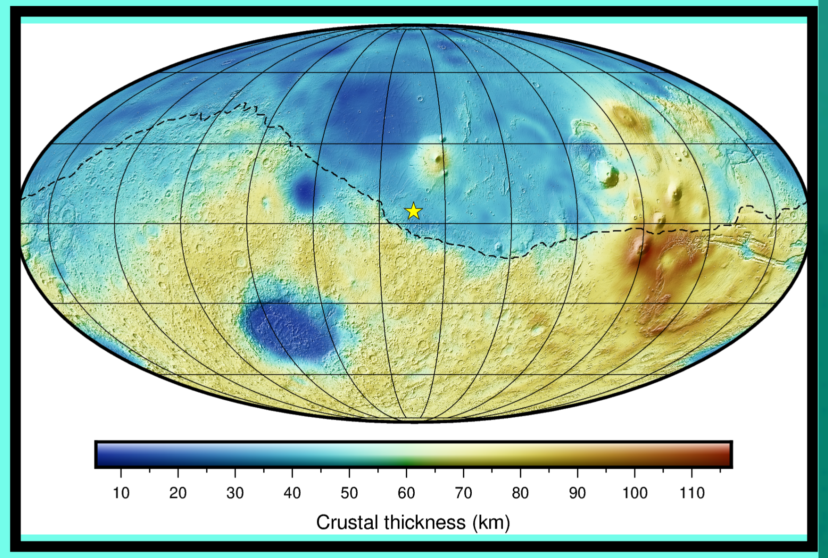
Crustal felsic Component



Mechanism & Model



Bayesian inversion



Inversion results