The thermo-chemical evolution of Mars with a compositionally stratified mantle

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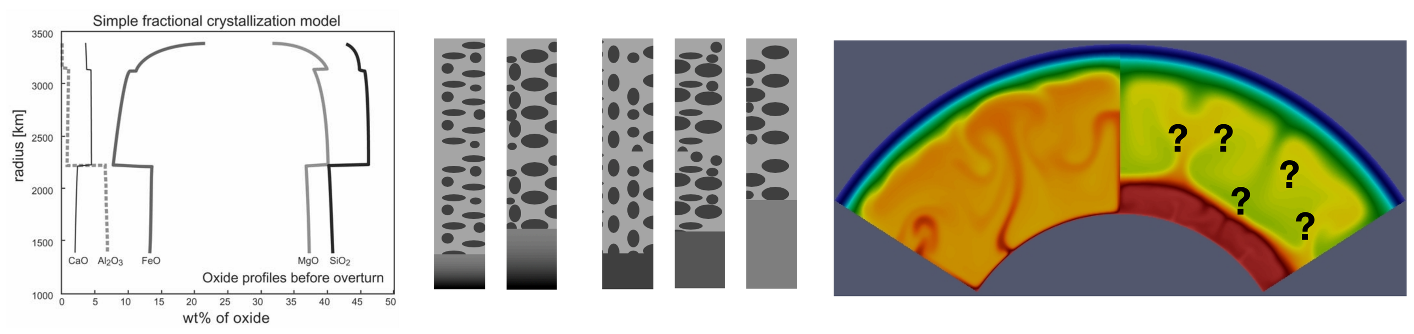
1. Motivations

To better constrain Mars' evolution, the InSight mission has recently landed on the surface of Mars to record its seismic activity, surface heat flow, magnetic field, and to refine the current estimates of Mars' response to tidally induced gravitational changes. Combining such data with geodynamic considerations provides a way to better understand and constrain the thermo-chemical history and the present-day structure of Mars.
Despite our relatively poor knowledge of Mars' early history, several indications suggest that Mars' mantle went through a global magma ocean stage. The crystallization and fractionation of such a magma ocean is likely to have led to the presence of a compositionally distinct material at the bottom of the mantle. Such a layer would have been heavily enriched in iron and Heat-Producing Elements (HPE) - with either a homogeneous or a depth-dependent enrichment - with respect to the overlying mantle. The significant iron enrichment may have led to a strongly stratified mantle with a flat interface.



[Elkins-Tanton, 2003; Ballmer et al. 2017; Maurice et al., 2018; Boukaré et al., 2018; Zeff & Williams, 2019]...

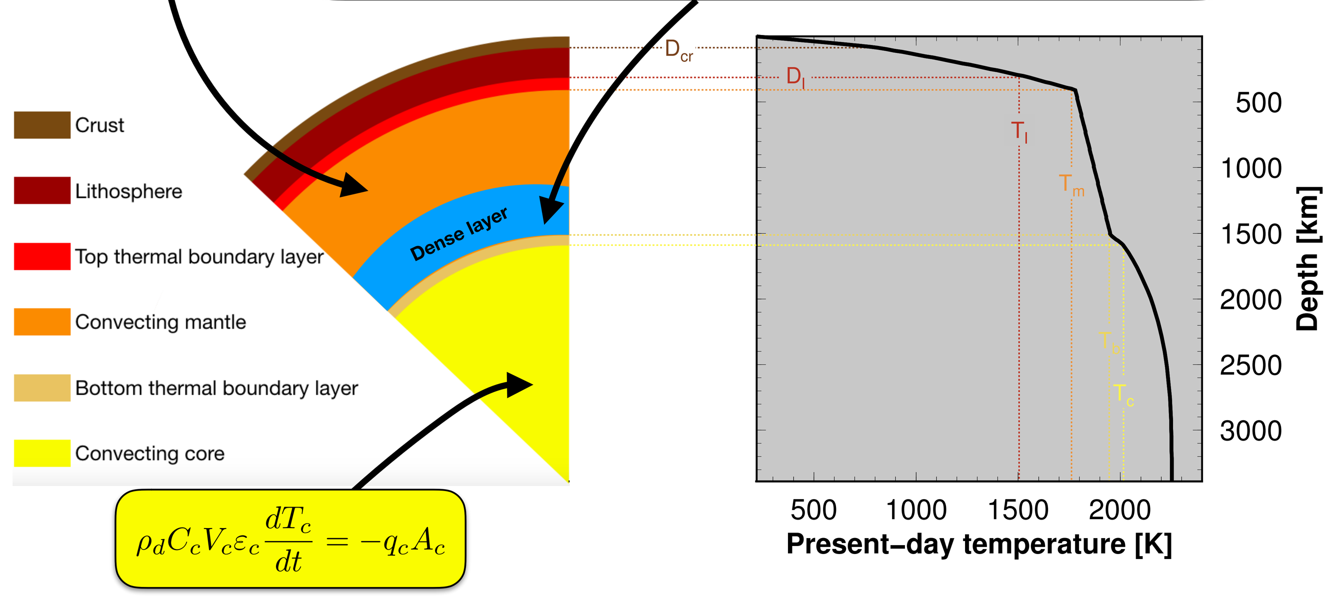
Using a parameterized convection approach, we modeled the thermochemical evolution of Mars' main envelopes: a liquid convecting core, a dense silicate layer enriched in HPE and sitting atop of the core-mantle boundary, overlaid by a less dense and more depleted silicate mantle, convecting under a stagnant lithospheric lid. The latter includes a crust building up with time and enriched in HPE with respect to the underlying silicate mantle. The dense layer is assumed to be convecting separately if its composition is homogeneous, or purely diffusing heat if its iron enrichment decreases with depth (stable stratification). Our efficient approach allows exploring a wide range of parameter space including the dense layer thickness, Mars mantle rheological parameters, Mars' initial thermal state and core size. For each case considered, we predict the obtained present-day thermal structure, heat flux, crustal thickness, degree two Love number k_2 in order to compare with available and upcoming observations from the InSight mission. This will allow interpreting InSight data to place constraints on Mars thermal evolution, but also on the initial conditions as a function of planetary accretion and differentiation.

2. Thermo-chemical evolution: Parametrised convection model

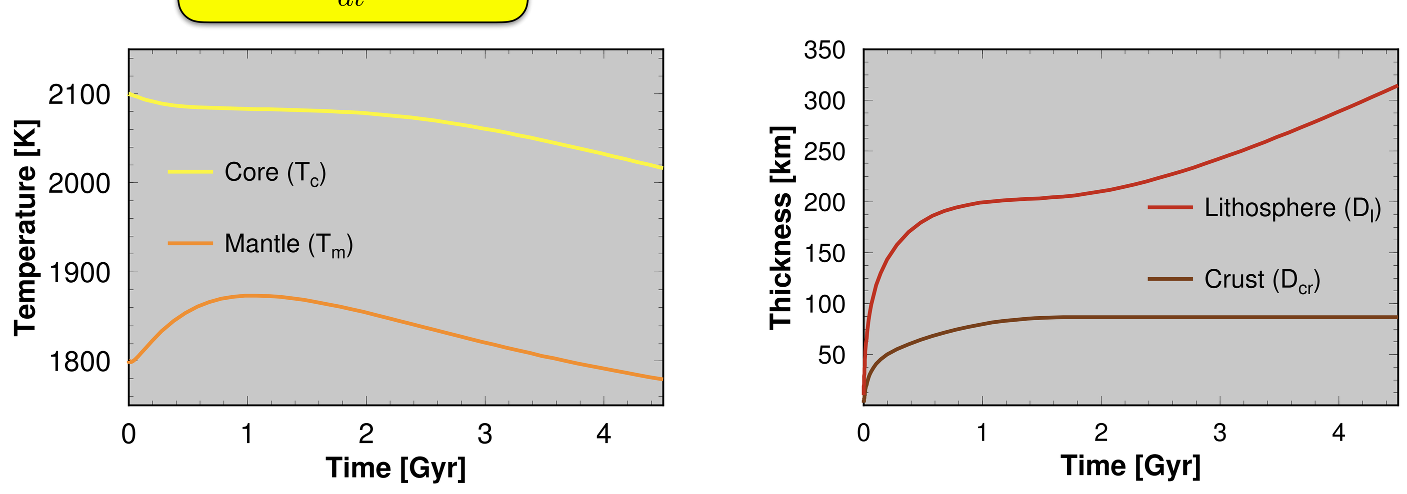
$$\rho_d C_m V_m \varepsilon_m (1+St_m)\frac{dT_m}{dt} = q_d A_d - q_m A_m + H_m V_m$$

$$\rho_d C_d V_d \varepsilon_d (1+St_d)\frac{dT_d}{dt} = q_c A_c - q_d A_d + H_d V_d \quad \text{(if homogeneous)}$$

$$\rho_d C_d \frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 k_d \frac{\partial T}{\partial r}\right) + H_d(r) - \rho_d L \frac{\partial \phi}{\partial t} \quad \text{(if stably stratified)}$$



$$\rho_d C_c V_c \varepsilon_c \frac{dT_c}{dt} = -q_c A_c$$

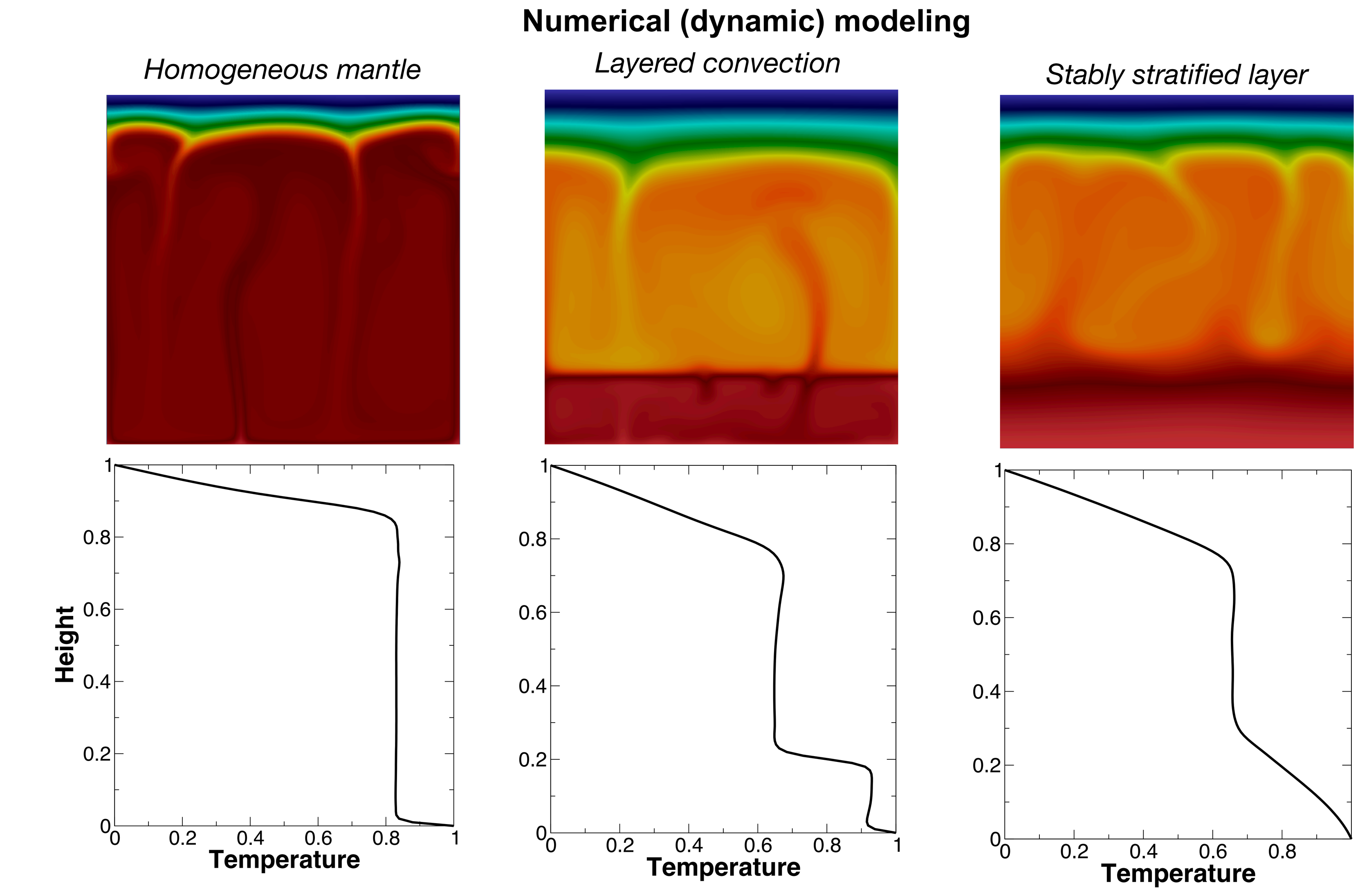


➪ Accounts for crustal and lithospheric evolution and HPE partitioning (crust/lithosphere/mantle)
➪ Accounts for latent heat effects
➪ Accounts for different types of stratification (stably stratified or homogeneous layer)

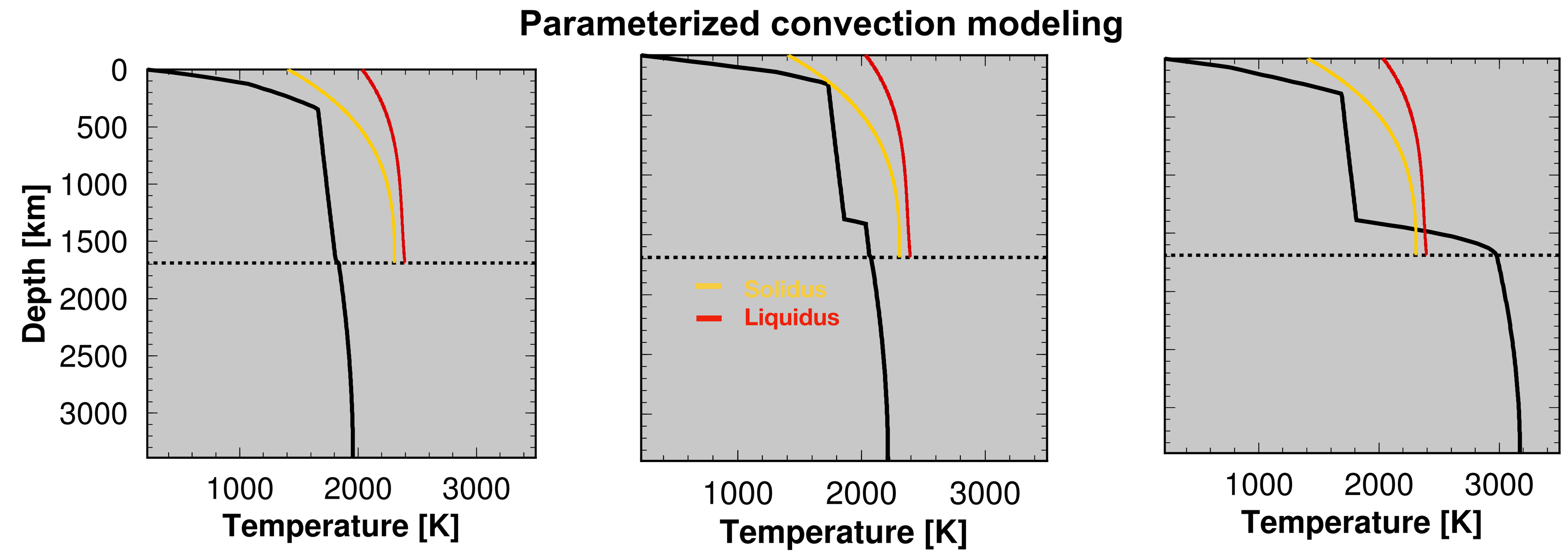
3. End-member scenarios

✓ *No layer: homogeneous mantle*
✓ *Layer with homogeneous composition ➪ layered convection develops*
✓ *Stably stratified layer (compositional gradient dFe#/dz<0) ➪ purely diffusive layer*

Numerical (dynamic) modeling



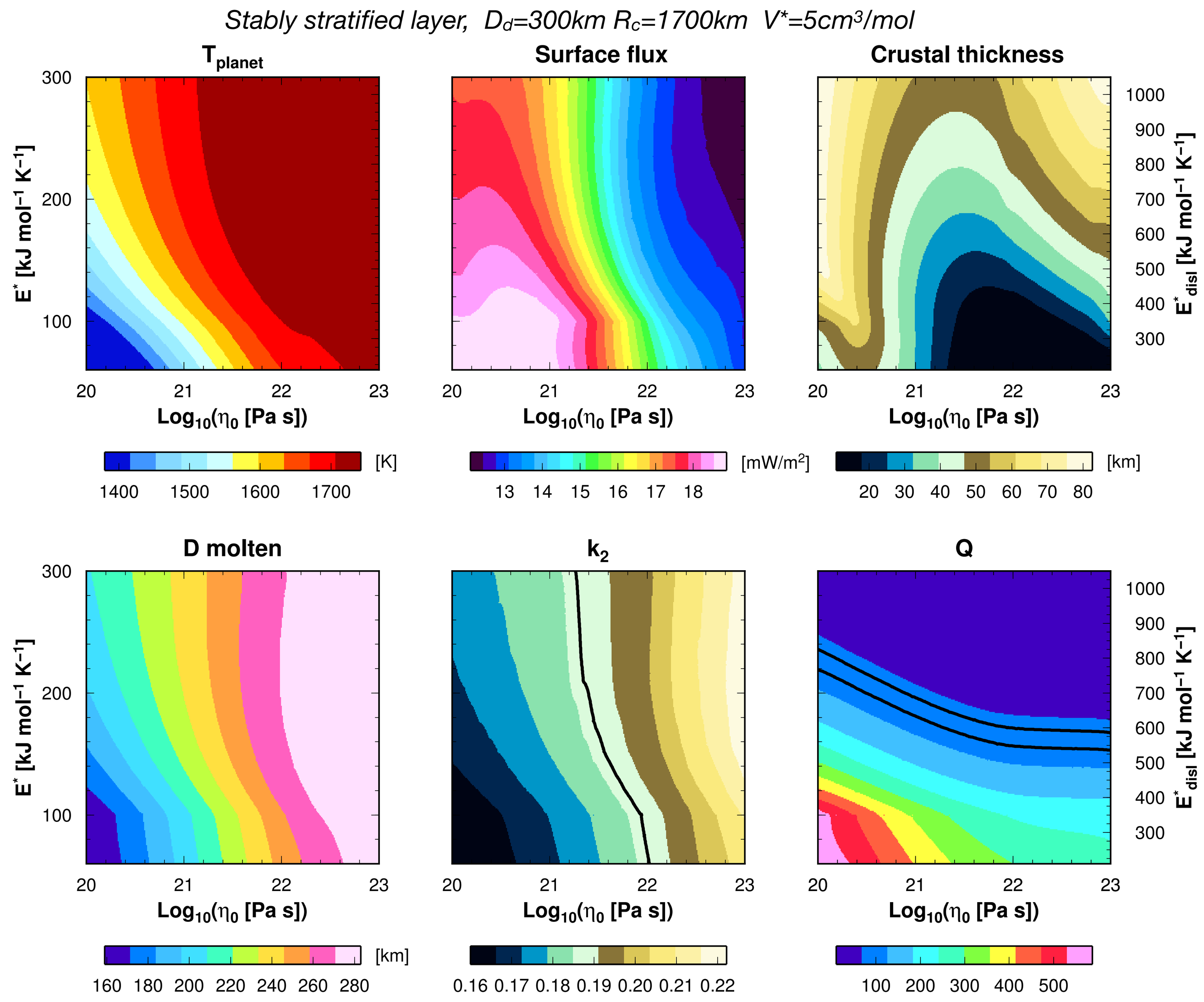
Parameterized convection modeling



Influence of the presence of a dense, HPE-enriched layer atop of the core:
➪ Increase of the deep mantle temperature ➪ melting at present-day
➪ Hotter present-day core
➪ Effects more pronounced for stably stratified dense layer

4. Systematic correlations

Stably stratified layer, D_d=300km R_c=1700km V^*=5cm³/mol

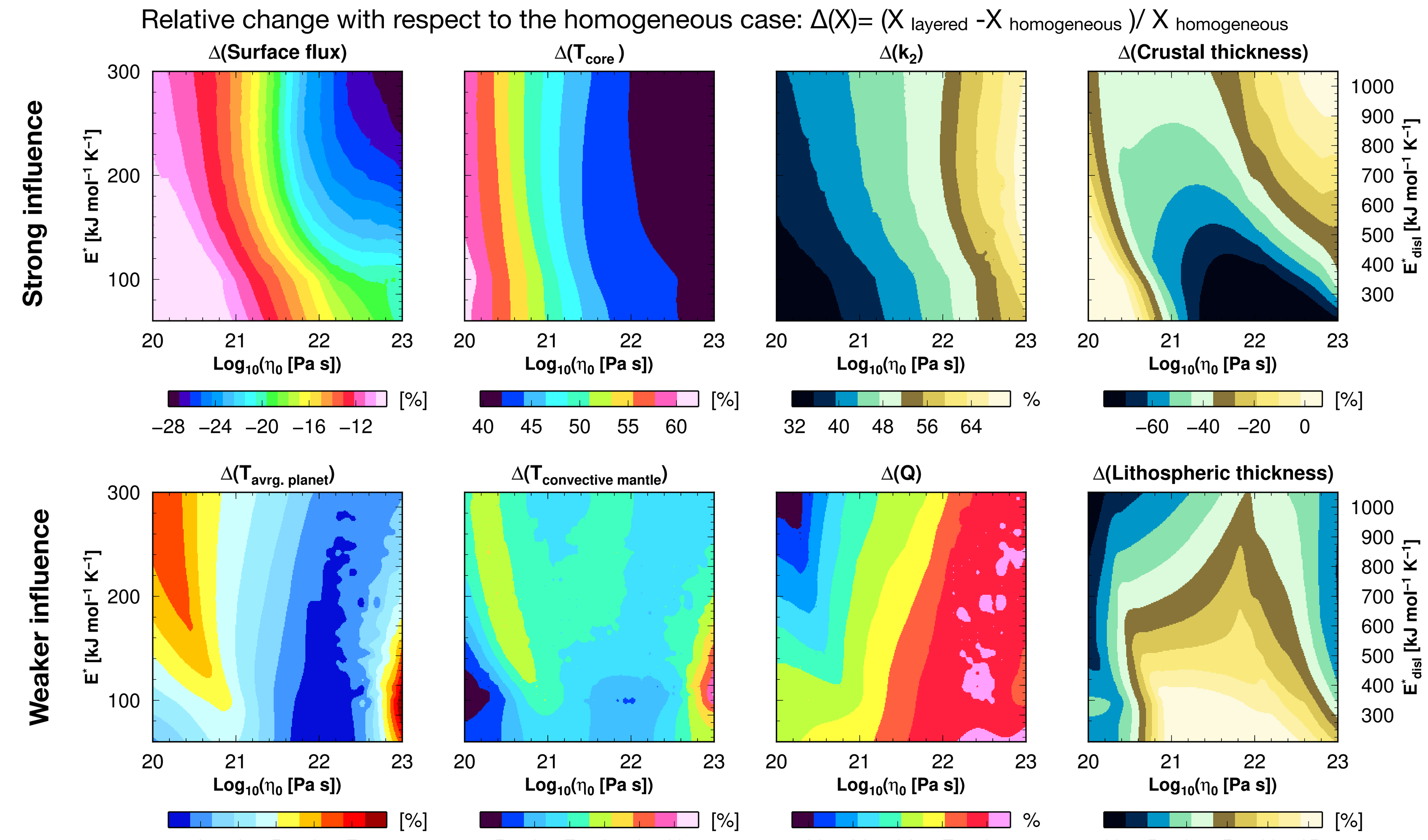


✓ Thickness of molten part of the dense layer (D_{molten}) correlate with avrg. planet temperature (T_{planet})
✓ k_2 (Andrade rheology) correlates with D_{molten}
✓ Present-day surface heat flux and Q correlate with $1/\eta_d$ (with $\eta_d = \eta(T_d)$, and $T_d \sim$ correlates with T_{planet})
✓ Present-day D_l correlates positively with T_{planet}
✓ Surface heat flux anticorrelates with D_l

➪ Despite present-day k_2 and Q constraints (k_2=0.169±0.02, Q=95±10), various possibilities for thermo-chemical structure remain, but the plausible range for E* can be reduced

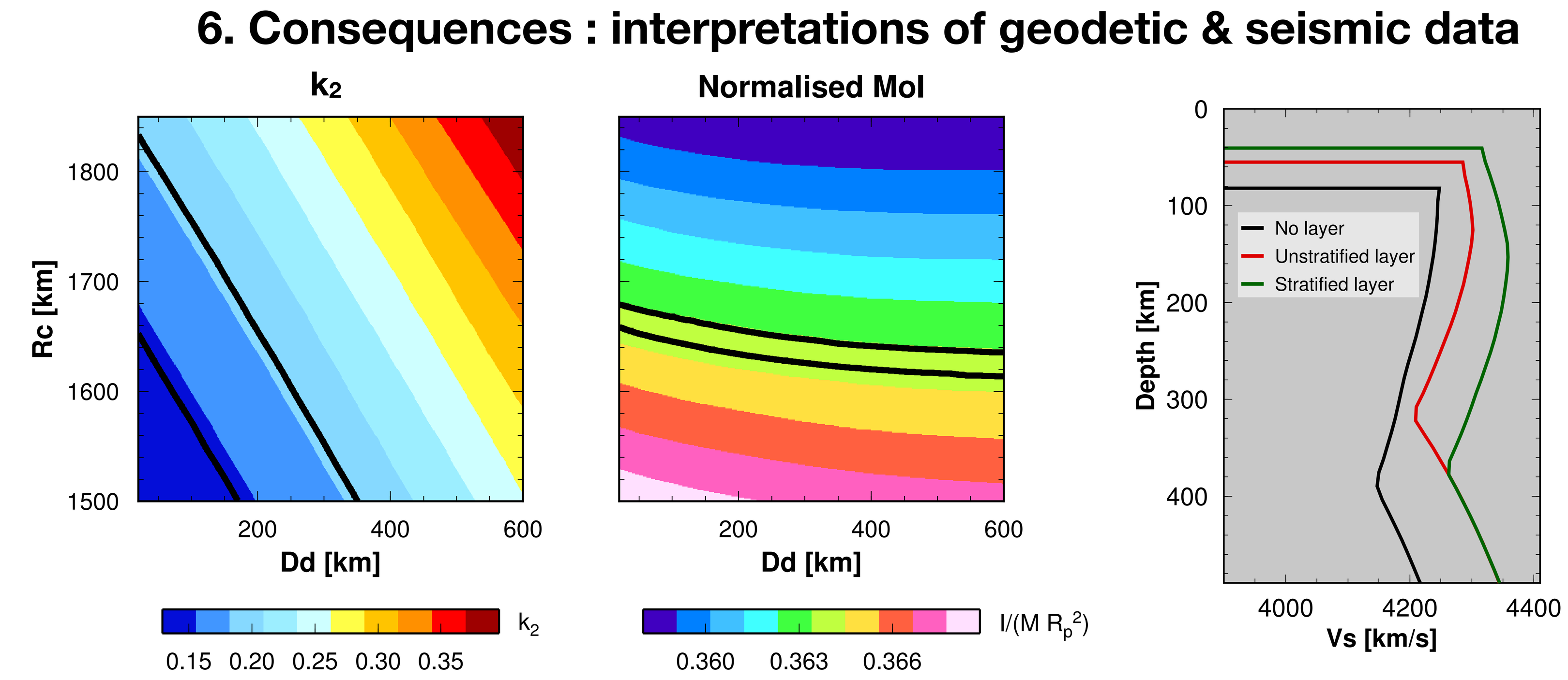
5. Differences between homogeneous and layered cases

Relative change with respect to the homogeneous case: $\Delta(X) = (X_{layered} - X_{homogeneous}) / X_{homogeneous}$



The presence of a dense, enriched (stratified) layer mostly influences:
✓ Core temperature (increase with decreasing mantle viscosity)
✓ k_2 increase (proportional to the layer thickness)
✓ Crustal thickness (increase or decrease)
✓ Surface heat flux (decrease)

6. Consequences : interpretations of geodetic & seismic data



Two distinct interpretations for k_2 :
-Homogeneous mantle with a large core
-A layered mantle with a small core

Further MoI constraints:
- Core size
- Core composition

✓ Different crustal thicknesses
✓ Distinct shape/extent of LVZ (?)

7. Conclusions

The (likely) presence of a dense, enriched (stratified) layer mostly influences:
✓ Core temperature (increase with decreasing mantle viscosity)
✓ k_2 increase (proportional to the layer thickness)
✓ Crustal thickness (increase or decrease)
✓ Surface heat flux (decrease)

Accounting for the possibility of a strong, early layering may be important:
✓ For seismic data interpretation: Mars' structure, presence of shadow zones *etc.*.
✓ For geodetic data interpretation: Core size, composition, thermal state
✓ To understand Mars' early history and formation/differentiation

References

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