CRUSTAL RADIOACTIVITY ON MARS CONSTRAINED BY INSIGHT DATA AND GEODYNAMIC MODELING

C. Michaut[1,8], A.-C. Plesa[2], H. Samuel[3], M. A. Wieczorek[4], S. McLennan[5], B. Knapmeyer-Endrun[6], M. Panning[7], S. Smrekar[7], B. Banerdt[7] and the InSight Science Team. [1]ENS Lyon, 69007 Lyon, France chloe.michaut@ens-lyon.fr, [2]Institute of Planetary Research, German Aerospace Center (DLR), 12489 Berlin, Germany ana.plesa@dlr.de, [3]Université de Paris, Institut de Physique du Globe de Paris, CNRS, F-75005 Paris, France samuel@ipgp.fr, [4]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, France, [5]Department of Geosciences, Stony Brook University, NY 11794-2100, USA, [6]Bensberg Observatory, University of Cologne, Vinzenz-Pallotti-Str. 26, 51429 Bergisch Gladbach, Germany, [7]Jet Propulsion Laboratory, California Institute of Technology; 4800 Oak Grove Dr., M/S 183-301, Pasadena, CA 91109, USA, [8]Institut Universitaire de France.

Introduction: Constraining the bulk crustal radioactivity is key to understand the formation and evolution of planetary crusts. Indeed, radioactive heat producing elements concentrate into the liquid phase during melting or differentiation events. Crust-mantle radioactivity partitioning is also crucial for the interior dynamics and mantle melting, and hence, places important constraints on a planet's thermochemical history.

Seismological methods identifying reflected and converted seismic phases on subsurface interfaces and applied to high quality marsquakes recorded by the InSight station on Mars have constrained the local structure of the crust below the landing site. Despite uncertainties, the crust below InSight appears to be either thin (~20-23 km), and composed of two layers, or thicker (~40-45 km) and composed of three different layers [1,2,3]. Such local crustal thickness constraints below InSight combined with the inversion of gravity and topography data have allowed improving the crustal thickness estimates of Mars [4]. While, up to now, average crustal thickness estimates reach 100 km [5], new crustal thickness models show a smaller global average value ranging between ~29-32 km for the thin two-layer crust scenario and between ~50-63 km for the thicker three-layers crust scenario, with a crustal density constrained below 3100 kg m^{-3} [4].

Here we use crustal thickness estimates of Mars, considering both the global average and the lateral distribution to place constraints on the content of heat-producing elements in the Martian crust and mantle, and to assess the implications of these scenarios on the crustal evolution and thermo-chemical history of the planet. Additionally, assuming a progressive formation of the Martian crust over time by volcanism, we investigate the initial thermal state of the planet and the rheology of the mantle that are able to produce the average crustal thickness inferred from gravity and topography inversion.

Methods: We use two complementary approaches that explore the possible thermo-chemical histories of Mars. First, to exploit the relationships between the present-day global average crustal thickness and the planetary history, we conducted an intensive exploration of the possible thermo-chemical histories of Mars. We modeled the evolution of a Mars-like planet for 4.5 Gyr using parameterized convection calculations [6], which takes into account the heat transfer and the chemical element partitioning within the main planetary envelopes (Fig. 1).

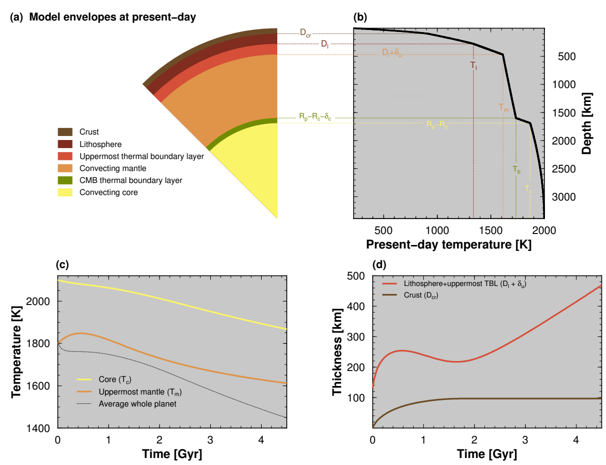

Figure 1: Example of a parameterized evolution model of Mars with an evolving crust. (a) Present-day structure and (b) areotherm. (c) Evolution of Core-Mantle boundary temperature T_c, uppermost convecting mantle temperature T_m and average planet temperature. (d) Evolution of crustal (D_{cr}) and total lithosphere thickness ($D_l+\delta_u$).

The second approach relies on the relationships between the present-day crustal structure and the observations of recent lava flows at the surface of Mars, visible in the vicinity of the Tharsis province [7,8]. We conducted a second intensive exploration of the possible thermal histories of Mars using a constant crustal thickness in time but accounting for spatial variations and seeking for models where only localized partial melt occurred at the present-day below the Tharsis Province. Using parameterized convection models that consider the crustal thickness at various locations corresponding to different geological provinces and, hence, leading to different thermal structures [9], as well as 3D spherical convection simulations with lateral variations in crustal thicknesses [10], we tested for the occurrence of partial melt below the lithosphere by comparing the local temperature to the solidus [10] (Fig. 2). For both approaches, the bulk heat-producing element content is taken from Wänke and Dreibus [11], and we varied the enrichment of the crust relative to the primitive (*i.e.*, not depleted) mantle.

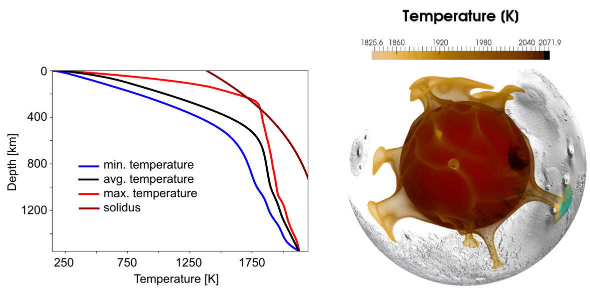

Figure 2: Example of 3D spherical calculations. Left: comparison of the minimum, maximum and average temperature profile at the present-day with the solidus. Right: present-day temperature structure of Mars showing melting below Tharsis (cyan color).

Results: Our two complementary approaches provide consistent results. Our parameter search constrains the initial temperatures of the mantle and the reference mantle viscosity. Both approaches constrain the crustal enrichment factor to similar ranges of values that depend on the crustal structure. For the second approach that tests for the presence of melt below different geological provinces on Mars, the results from the 1D parameterized exploration are in good agreement with fully dynamical 3D simulations (Fig. 3). In both 1D and 3D models, melting occurs only below Tharsis if more than half of the bulk radioelement content is stored in the crust (Fig. 3). This means that a thinner crust would require a larger concentration of heat-producing element to allow for only localized melting below Tharsis when compared to a thicker crust. For the two-layer (thin crust) scenario, a GRS-derived concentration in heat-producing elements for the bulk crust [12] amounts to ~30% of the bulk radioelement content in the crust and would lead to widespread melting (yellow star on Fig. 2 for a crustal thickness of 29.5 km).

Conclusion: The thin crustal end-member scenario requires a larger concentration of radioelements in the crust than the thicker one in order to reduce the amount of shallow mantle melting (hence crustal production) over time, and to restrict the occurrence of present-day melting to specific regions only (*i.e.*, the Tharsis province). The heat-producing element concentrations we deduce for these two types of crustal structures with our different approaches allow placing constraints on the formation scenario of the Martian crust.

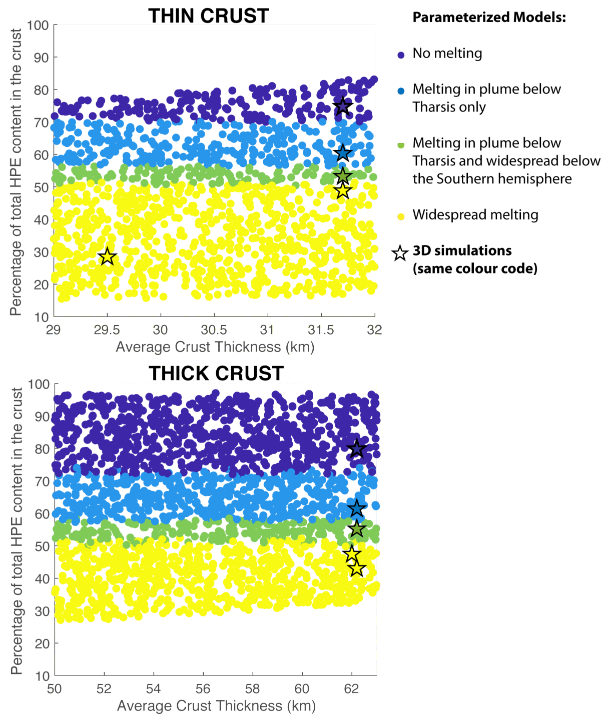

Figure 3: Results of parameterized and 3D convection modeling testing for melting in a plume below Tharsis. with models randomly sampled in terms of crustal density and northern crustal thickness. A priori ranges are given by topography and gravity data inversion [4].

References:

[1] Knapmeyer-Endrun B. et al (2020) *LPS LI,* Abstract #1914. [2] Panning M. et al (2021) *LPS LII, Seismic Constraints on the crustal thickness and structure of Mars from InSight.* [3] Panning et al (2021) *LPS LII, Results from InSight's first full martian year*. [4] Wieczorek M. et al. (2021) *LPS LII,* Abstract #1412. [5] Baratoux D. et al (2014) *JGR, 119,* 1707-1727. [6] Samuel H. et al (2019) Nature 569, 523–527. [7] Hartmann W. et al (1999) Nature 397, 586–589 [8] Neukum G., et al. (2004) Nature 432, 971-979. [9] Thiriet M. et al, (2018) JGR Planets 123, doi: 10.1002/2017JE005431. [10] Plesa A.-C. et al (2018) GRL 45, 12,198-12,209. [11] Wänke H. and Dreibus J. (1994) Philos. Trans.: Phys. Sci. Eng. 349, 285-293. [12] Taylor S. and McLennan S. (2008) Cambridge University Press, doi:10.1017/CBO9780511575358.