INSIGHT'S CONSTRAINTS ON THE INTERIOR OF MARS: GEODYNAMICAL MODELS AND OBSERVATIONS. A.-C. Plesa[1], M. Wieczorek[2], M. Knapmeyer[1], A. Rivoldini[3], E. Bozdag[4], M. Walterová[1], B. Knapmeyer-Endrun[5], D. Kim[6], A. Broquet[7], S. Stähler[6], A. Mittelholz[8], D. Breuer[1], C. L. Johnson[9,10], E. Hauber[1], M. P. Panning[11], T. Spohn[1], P. Lognonné[2], S. E. Smrekar[11], W. B. Banerdt[11], and the InSight Science Team; [1]Institute of Planetary Research, DLR (ana.plesa@dlr.de), [2]Institut de Physique du Globe de Paris, [3]Royal Observatory of Belgium, [4]Colorado School of Mines, [5]Bensberg Observatory, Univ. of Cologne, [6]ETH, Zürich, [7]Lunar and Planetary Laboratory, Univ. of Arizona, [8]Harvard Univ., [9]Univ. of British Columbia, [10]Planetary Science Institute, [11]Jet Propulsion Laboratory, California Institute of Technology.

Introduction: The currently available planetary data for Mars provide us with the unique opportunity to investigate its interior with unprecedented detail. Geological data sets, gravity and topography, and, most recently, seismic measurements of the InSight mission [1] can be used to constrain global 3D geodynamical models of Mars. Below we show where InSight's new data constrain and challenge previous geodynamical reconstructions of the Martian interior.

Crustal thickness and recent volcanism: The thickness of the crust is directly linked to the long-term magmatic activity of a planet. Geological data indicate that, with time, volcanic activity on Mars declined and became more focused in Tharsis and Elysium. Young lava flows in Tharsis [2] and Elysium [3] suggest that partial melt may still be produced in the interior today.

Global crustal thickness models, derived from gravity and topography, and constrained by seismic data recorded by InSight's seismometer SEIS, indicate a thinner crust than previously estimated [4], with an average thickness between 30 and 72 km [5] (Fig. 1a,b).

Thermal evolution models that consider the most recent crustal thickness values require that the crust contains 55-70% of the total amount of heat producing elements (HPEs) [4] in order to avoid wide-spread melting at present day (Fig. 1c,d). In order to focus recent partial melt in Elysium, specifically, geodynamical models favor crustal models where the density of the southern highlands crust is lower than the northern lowlands leading to less dramatic differences in thickness between the two hemispheres [6]. Initial interpretation of surface wave travel times from three large seismic events, however, is inconsistent with large density differences between the northern and southern crust [7,8]. Thus, the combination of both seismic data and observed distribution of volcanism could provide further constraints on crustal thickness variations.

The thermal state of the lithosphere and deeper mantle: The geophysical analysis of several seismic events detected in Cerberus Fossae seems to favor a thick thermal lithosphere (400–600 km) [9] that can also explain the period of the Free Core Nutation observed by InSight's radio science experiment RISE [10], and is compatible with a crust containing a substantial amount of heat sources. This has major consequences for the temperature variations in the lithosphere [11]. Global thermal evolution models show that the crustal thickness pattern controls the temperature and seismic velocities anomalies throughout the lithosphere, and may affect depths larger than 400 km for models with cold and thick lithospheres (Fig. 1e,f) [11].

Additional constraints on the thermal state of the lithosphere come from the elastic lithosphere thickness estimates. Today, the large elastic lithosphere thickness at the north pole of Mars indicates a cold and thick lithosphere [12]. While this is consistent with seismic observations, it requires an even thicker thermal

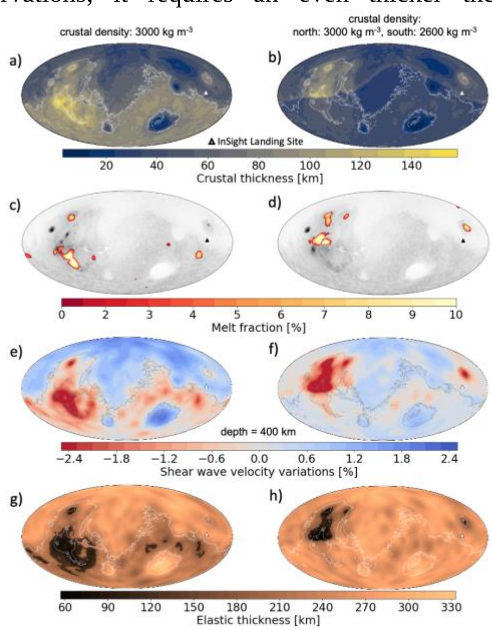

Figure 1: Present-day crustal thickness (a,b), partial melt zones (c,d), shear wave velocity variations (e,f), and elastic lithosphere thickness (g,h). Left: a model using a pronounced crustal thickness dichotomy. Right: a model with a difference in crustal density between the northern and southern hemisphere.

lithosphere at the north pole of Mars and provides one of the strongest constraints for global thermal evolution models (Fig. 1g,h), if, simultaneously, recent partial melt beneath Tharsis and Elysium is required. However, the elastic thickness might be lower if the load produced by the polar cap is not yet at elastic equilibrium [12]. Whether this is the case, depends on the viscosity of the lithosphere and mantle, and requires information from thermal evolution models.

The temperature in the deep interior, below the thermal lithosphere, is poorly constrained. Seismic detection of a deep mantle discontinuity at 1006±40 km, which is associated with the dissociation of olivine to other mantle phases, favors a cold interior with a present-day potential temperature (T_p) of 1605±100 K [13]. Studies that performed inversions of the interior structure by analysing body-wave arrivals suggest a present-day T_p of 1650-1750 K [14] and of 1740±90 K [15]. Global thermal evolution models that show large elastic thicknesses at the north pole and localized melting indicate a present-day average T_p of 1700-1830 K [4, 6, 16], a range that only partially overlaps with the values inferred from seismic data. Moreover, the temperature profile may not be adiabatic if the pressure dependence of the mantle viscosity is large. Beneath the thermal lithosphere, the viscosity was suggested to increase with pressure by 2-3 orders of magnitude to produce strong thermal variations that are able to explain both a thick elastic lithosphere at the north pole and recent partial melting of the mantle [6, 16].

Core size and the deep interior: Information on the size of the core is essential, as it determines the thickness of the mantle. This affects the mantle flow and the convection pattern (i.e., number of mantle plumes) that can be compared to volcanic and tectonic provinces.

Shear waves reflected from the core-mantle boundary (ScS) and recorded by InSight constrain the core radius to 1830±40 km, i.e., the core radius is more than half of the planet's radius. [17]. This is a strong confirmation of thermal evolution models [6, 16] that match estimates of the tidal Love number k_2 [18, 19] and in agreement with RISE [10] data.

The large size of the Martian core excludes the stability of a bridgmanite-dominated lower mantle suggesting a smaller-scale mantle convection pattern than previously thought [6]. This invalidates previous models in which hemispheric plumes could give rise to hemispheric differences in crustal thickness [e.g., 20].

The large core requires a substantial amount of light elements (S,O,C, and H) in order to match its mass [17]. The Martian core is thus likely fully molten, since its liquidus is expected to be significantly below the present-day core temperature. This suggests that the early magnetic field was thermally driven. An active dynamo at 4.5 and until at least 3.7 Gyr ago [21] places important constraints on the cooling of the interior and core thermal conductivity [22]. While parametrized thermal evolution models [22] showed that a prolonged thermally driven dynamo can be sustained, these models suggest a different mantle cooling rate than 3D geodynamical models that satisfy present-day mantle temperature constraints [4, 6].

Future steps: Recent seismicity estimates from InSight indicate that pre-InSight studies overestimated Mars' moment rate [23]. Thus, future 3D models need to revisit the mechanism linking global geodynamics to present-day seismicity of Mars, which does not seem to be dominated by contraction due to planetary cooling.

Since only a small number of seismic waveforms, from a limited number of source locations were observed by InSight, it is challenging to search for fingerprints of deviations from a 1D layered structure below the crust. Global geodynamical models need to be evaluated carefully in combination with 3D wave propagation simulations to identify possible seismic discriminators, e.g., for a mantle upwelling or plume.

The presence of a mantle plume in the Elysium Planitia region has been linked to the observed seismic activity in Cerberus Fossae [24], recent uplift, and elevated gravity and topography [25]. This has strong implications for geodynamical models, as it provides a tight constraint for the location of mantle plumes in the interior of Mars.

Laboratory experiments on core compositions and thermal conductivity [e.g., 26] combined with 3D geodynamical models that include additional constraints on the interior evolution are needed to test the generation of a thermally driven early magnetic field.

To further improve our understanding of the interior of Mars, future geophysical investigations including e.g., seismic data recorded at different locations on Mars [27], heat flow measurements [28], and electromagnetic sounding [29, 30] are essential and would greatly help to constrain the distribution of seismicity, the thermal state and bulk heat production rate of Mars, and the hydration state of its interior, respectively.

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