GLOBAL CHARACTER OF THE MARTIAN CRUST AS REVEALED BY INSIGHT SEISMIC DATA.
M. A. Wieczorek[1], B. Knapmeyer-Endrun[2], M. P. Panning[3], A.-C. Plesa[4], S. M. McLennan[5], F. Nimmo[6], S. Gyalay[6], C. Michaut[7], A. Broquet[1], H. Samuel[8], A. Rivoldini[9], S. Smrekar[3], W. B. Banerdt[3], and the InSight Science Team; [1]Observatoire de la Côte d'Azur, Nice (mark.wieczorek@oca.eu), [2]University of Cologne, Cologne, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, [4]German Aerospace Center (DLR), Berlin, [5]Stony Brook University, Stony Brook, [6]University of California Santa Cruz, Santa Cruz, [7]Ecole Normale Supérieure de Lyon, [8]Institut de Physique du Globe de Paris, Paris, [9]Royal Observatory of Belgium, Brussels.

Introduction: The crust of Mars formed as a result of differentiation processes that occurred early in solar system history and subsequent magmatic processes that continue to the present day. If the average thickness of the crust were known, it could be used as a key constraint on deciphering the time-integrated thermal evolution of the planet [1]. Several studies have attempted to estimate the thickness of the crust of Mars by modeling the relationship between gravity and topography, but depending on the assumed crustal and upper mantle densities, estimates for the average thickness range from values as low as 30 km to values that exceed 100 km [2-4].

The InSight mission [5] has been making seismic measurements on the surface of Mars since early 2019. By using methods that search for both reflected and converted seismic phases from subsurface interfaces, it has been possible to constrain the depth of the crust-mantle interface (the Mohorovičić discontinuity, or just "Moho") beneath the landing site [6]. Based on preliminary analyses of the available data, two possible models can account for the seismological observations [7]. In one, two distinct crustal layers are present and the local thickness of the crust is 20-23 km. In the other, three distinct layers are present and the local crustal thickness is 40-45 km. The degeneracy in the interpretation of the data is a result of the small number of large amplitude quakes that have been detected at this stage of the mission.

In this work, we extrapolate the preliminary local InSight crustal thickness estimates globally using spacecraft derived gravity and topography data. This provides not only a map of the lateral variations in thickness of the crust, but also constrains the average thickness of the crust and the range of allowable crustal densities. The two possible InSight Moho depths give rise to two distinct classes of models for the composition and origin of the Martian crust.

Methodology: Our global crustal thickness modeling employs standard methods that have been applied previously to the terrestrial planets and Moon. The observed gravity field is assumed to be the result of surface relief, relief along the crust-mantle interface, and hydrostatic relief of density interfaces in the mantle and core. In the models presented here, the crust has a constant density, with the exception of the low-density polar ice-cap deposits. We make use of 15 *a priori* density profiles of the mantle and core [8-9] that span the range of plausible Martian compositional models and core radii.

Three key parameters have a large influence on the global crustal thickness models: (1) the upper mantle density, which is specified by the interior reference model, (2) the density of the crust, and (3) the measured crustal thickness at the InSight landing site. Once these parameters are fixed, our inversion procedure adjusts iteratively the average thickness of the crust until the thickness at the InSight landing site matches the observed value. Models that give rise to unphysical negative crustal thickness are excluded. Tests show that the inclusion of a constant thickness near-surface layer of lower density materials does not affect significantly the inversion results [10].

Results: For a given InSight crustal thickness, the parameter that has the largest impact on the global crustal thickness models is the difference in density between the upper mantle and crust. We find that the average thickness of the crust increases with increasing crustal density, and as the density contrast across the crust-mantle interface decreases, the variations in relief along the crust-mantle interface become increasingly prominent. The maximum allowable density occurs when the crustal thickness becomes zero at some place on the planet. Though our inversions cannot constrain the minimum allowable crustal density, we make use of a conservative lower bound of 2550 kg m^{-3} that is consistent with independent gravity inversions [11].

The average crustal thickness is plotted as a function of crustal density in Fig. 1 for the two best-fitting thicknesses at the InSight landing site: 21 km and 42 km. Model results are plotted for all interior reference models, demonstrating that the results are only modestly affected by the employed mantle and core density profile. When using the 21-km InSight seismic constraint, the range of allowable crustal densities is small, 2550-2750 kg m^{-3}, and the average crustal thickness is well constrained to 29-32 km. In contrast, for the 42-km thick InSight seismic constraint, the range of allowable crustal densities is larger, 2550-3100 kg m^{-3}, and the average crustal thickness is 50-63 km.

When the uncertainties on the InSight seismic constraints are considered the crustal thickness ranges increase somewhat: 28-36 km for the two-layer seismic model, and 48-68 for the three-layer seismic model. A representative crustal thickness map is presented in Fig. 2 using the 42-km InSight seismic constraint. Models that include an increase in crustal density north of the dichotomy boundary give rise to somewhat thinner average crustal thicknesses, but the maximum crustal density and maximum average thickness are unchanged.

Implications: The InSight seismic constraints allow us to exclude certain classes of models of the crust of Mars. In particular, for both InSight seismic models, the maximum allowable crustal density is substantially less than would be expected based on the average basaltic composition of surface materials that have an estimated density of about 3300 kg m^{-3} [4]. The average crustal densities are also less than the bulk densities of the young volcanic edifices as derived from gravity data, which are approximately 3200 kg m^{-3} [12]. As a result of this, the average crustal thickness of Mars (<68 km) is considerably thinner than models that assume denser crustal materials [4]. These results have important implications regarding the fractionation of heat producing elements between the crust and mantle, and the thermal evolution of the planet [13].

One explanation for the lower-than-expected bulk crustal densities is the presence of significant crustal porosity. For the two-layer seismic model, the required porosity (assuming a pore-free density of 3300 kg m^{-3} with porosity filled by air) would correspond to more than 16%, and for the three-layer model it would be more than 6%. These values are broadly compatible with the bulk porosity of the impact fractured crust of the Moon [10]. As the crust of Mars was affected by nearly the same impact bombardment as the Moon, the generation of a similar porosity would not be surprising. Nevertheless, this initial porosity would likely have been filled (at least partially) by fluids or aqueous alteration products at a later time. Elevated temperatures within the Marian crust early in its evolution could also have removed porosity by viscous deformation of the host rock at depths greater than about 10 km [14].

An alternative explanation for the low density of the Martian crust is that the composition of the average crust is more felsic than the basaltic near-surface materials. Though there is ample evidence for the existence of evolved rocks on Mars, thus far these compositions have been observed only as a minor component of the near surface materials [15-16]. The InSight data would instead require that they comprise a substantial portion of the deep Martian crust.

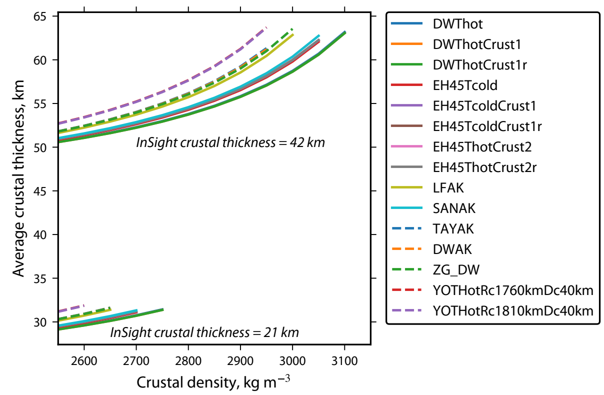

Figure 1. Average thickness of the Martian crust as a function of crustal density. Each curve corresponds to a different interior reference model that specifies the density profile of the mantle and core (legend). Shown are two suites of models that satisfy two possible seismic thicknesses at the InSight landing site of 21 and 42 km.

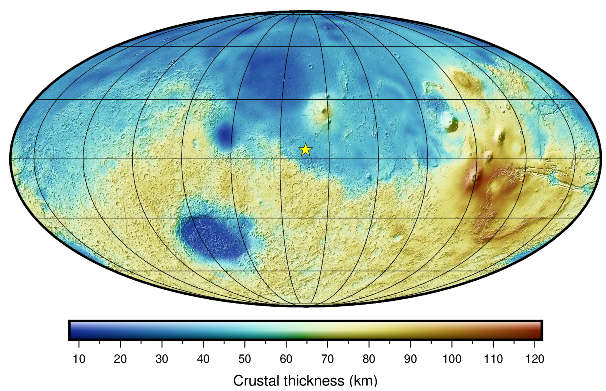

Figure 2. A representative global crustal thickness model of Mars. This model uses the TAYAK reference interior model [8], a crustal density of 2900 kg m^{-3}, and a 42-km thickness at the InSight landing site (yellow star). The average crustal thickness for this model is 59 km, the minimum thickness is 8 km, and the maximum thickness is 121 km.

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