CRUSTAL STRUCTURE OF EARLY MARS WITHOUT IMPACT BASINS AND VOLCANOES. S. Bouley[1], J. T. Keane[2], D. Baratoux[3], B. Langlais[4], I. Matsuyama[5], F. Costard[1], R. Hewins[6], V. Sautter[6], A. Séjourné[1], O. Vanderhaeghe[3], B. Zanda[6]. [1] Géosciences Paris Sud (Univ. Paris-Sud, CNRS, Université Paris-Saclay, Rue du Belvédère, Bât. 504-509, 91405 Orsay, France; sylvain.bouley@u-psud.fr); [2]California Institute of Technology (Pasadena, CA 91107, USA; jkeane@caltech.edu); [3]Geosciences Environnement Toulouse (UMR 5563 CNRS, IRD & Université de Toulouse, 14 Avenue Edouard Belin, 31400, Toulouse, France); [4]Laboratoire de Planétologie et Géodynamique (CNRS UMR 6112, Université de Nantes, 44322 Nantes cedex 3, France); [5]Lunar and Planetary Laboratory (University of Arizona, Tucson, Arizona 85721, USA); [6]Institut de Minéralogie, de Physique des Matériaux, et de Cosmochimie (Sorbonne Université, Muséum National d'Histoire Naturelle, UPMC Université Paris 06, UMR CNRS 7590,IRD UMR 206, 61 rue Buffon, 75005 Paris, France);

Introduction: Understanding the origin and character of Mars's crust is critical, as Mars occupies an intermediate state between worlds dominated by primary crust formed shortly after accretion (e.g., the Moon, Vesta), and planets with long histories of crust generation and alteration (e.g., Earth, Venus).

The present-day crustal structure of Mars is dominated by an enigmatic hemispheric dichotomy, several large impact basins, and igneous provinces. While previous studies have quantified how Tharsis the largest volcanic province—contributes to the crustal structure [1–3], no study has quantified how impact basins affect Mars's global crustal structure.

In this work, we reconstruct the crustal thickness of Mars before the formation of the largest impact and volcanic provinces. The reconstructed crustal thickness map provides new insight into the origin of the dichotomy and of the global structure of the martian crust.

Methods: There are many methods for isolating, characterizing, and removing the signature of impact basins and volcanoes from the gravity fields, shapes, and crustal structures of planets [1–5]. In this work, we develop a simple method for removing these features from crustal thickness maps [6–7]. We assume that (1) impact basins are largely axisymmetric and reshaped the crust in a way that approximately conserved crustal mass. The same approach is applied to the volcanoes for simplicity, though it clearly ignores the mantle contribution. In essence, we "re-filled" the impact basins, and spread out the volcanoes over a large area so the mantle contribution becomes negligible. Figure 1 shows an example of this procedure applied to Hellas. In order to model the structure of Mars's primary crust, we applied an iterative parameter-space search, and removed sequentially each feature not considered to be part of it.

Using this technique, we sequentially isolated and removed the axisymmetric crustal thickness structures associated with the four largest impact basins (Hellas Planitia, Argyre Planitia, Utopia Planitia, and Isidis

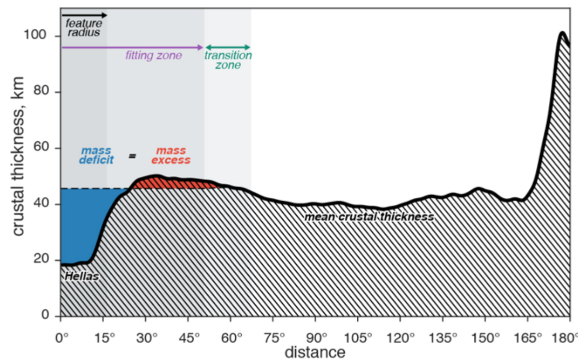

Figure 1. The radial crustal structure of Hellas Planitia. Azimuthally-average crustal thickness about Hellas (solid black line with hatching beneath). The grey boxes delineate the fitting and transition zones used for finding the mass-conserving crustal reconstruction. The volume above the mass-conserving crustal thickness (dashed line) is equal to the volume below it.

Planitia), the Elysium Mons, and the Tharsis rise, including the five largest individual volcanoes (Olympus Mons, Arsia Mons, Pavonis Mons, Ascraeus Mons, Alba Patera). We also considered the hypothetical Borealis impact basin.

Mars without Impact Basins and Volcanoes: Figure 2 shows the crustal structure of Mars with, and without, impact basins and volcanoes. This process reveals an early Mars with more subdued crustal thickness variations. In this reconstruction, the distribution of crustal thickness suggests that the crust can be divided into three distinct components (instead of two): (1) thin crust (<35 km), associated with the present-day northern lowlands; (2) intermediate thickness crust (35–45 km), associated with most of the present-day southern highlands; and (3) a previously unrecognized thick crustal component (>45 km) restricted to the region of Terra Cimmeria–Sirenum.

While impact basins contribute to the hemispheric dichotomy, the dichotomy clearly exists independently of the basins. For example, the crustal volume in the southern highlands is roughly four times larger than the crustal deficit within Hellas. The only crustal reconstructions that removed the hemispheric dichotomy were those that included the giant (albeit debated) Borealis impact basin [2, 8–9].

The Unusual Character of Cimmeria–Sirenum: The Terra Cimmeria–Sirenum crustal block shares many of the geophysical and geochemical signatures of terrestrial continental crust. Cimmeria–Sirenum coincides with the strongest crustal magnetic anomalies that might depict tectonic features (Figure 2d) [10–13]. Cimmeria–Sirenum is associated with the lowest inferred crustal densities inferred in gravity analyses [7]. Cimmeria–Sirenum is associated with high abundances of incompatible elements, like potassium and thorium [14].

While continental crust-like material has been previously identified in specific outcrops or samples [14–18], our study identifies the first regional scale crustal block (covering 10% of Mars) with geophysical and geochemical affinities with the terrestrial continental crust.

We hypothesize that Cimmeria–Sirenum is analogous to terrestrial continental cratons, formed by the accretion of smaller crustal nuclei. Since this terrain is overprinted by Hellas, Argyre, and Tharsis, it is likely the oldest segment of the martian crust. Subsequent meteoritic impacts and tectono-volcanic processes further altered the crustal structure, yielding the Mars we see today.

The InSight mission will soon provide definitive measurements about Mars's interior structure, which will be critical for testing this hypothesis and improving our understanding of Mars's crustal evolution.

References: [1] Zuber, M. T. and Smith, D. E. (1997) *JGR*, 102, 28673-28686. [2] Andrews-Hanna, J. C. et al. (2008) *Nature, 453*, 1212–1215. [3 3] Matsuyama, I. and Manga, M. (2010), *JGR*, *115*, 12020. [4] Keane, J. T. and Matsuyama, I. (2014) *GRL*, *41*, 6610–6619. [5] Garrick-Bethell, I., et al. (2014) *Nature*, *512*, 181–184. [6] Genova, A. et al. (2016) *Icarus*, *272*, 228–245. [7] Goossens, S. et al. (2017) *GRL*, *44*, 7686–7694. [8] Wilhelms, D. E. and Squyres, S. W. (1984) *Nature*, *309*, 138–140. [9] Frey, H. and Shultz, R. A. (1988) *GRL*, *15*, 229–232. [10] Connerney, J. E. P. et al. (2001) *GRL*, *28*, 4015–4018. [11] Arkami-Hamed, J. A. (2004) *JGR*, *109*, E09005 10.1029/2004JE002265. [12] Langlais, B. et al. (2004) *JGR*, *109*, E02008. [13] Langlais, B. et al. (2019) in prep. [14] Boynton, W. V. et al. (2007) *JGR*, *112*, E12S99. [15] Sautter, V. et al. (2015) *Nature Geoscience*, *8*, 605–609. [16] Humayun, M. et al. (2013) *Nature*, *503*, 513–516. [17] Bouvier, L.C. et al. (2018) *Nature*, *586*, 586-589. [18] Christensen, P.R. et al. (2005) *Nature*, *436*, 504-509.

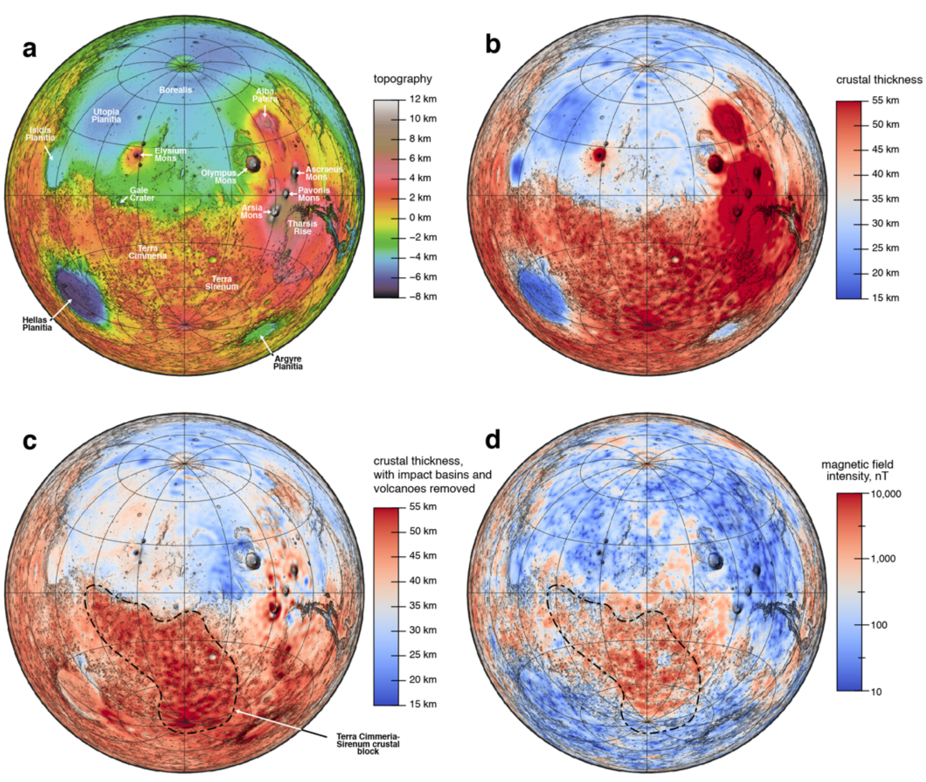

Figure 2. Global view of the crustal structure of Mars. a*, MOLA topography of Mars with features of interest labelled.* ***b****, crustal thickness of Mars [7].* ***c****, the crustal thickness of Mars after removing all the large impact basins and volcanic features. The Cimmeria–Sirenum crustal block is enclosed by a dash-dot line.* ***d****, magnetic field intensity, evaluated at the surface of Mars [13]. Maps are in Lambert azimuthal equal-area projection, centred on 0°E (left column) and 180°E (right column). Each map covers all of Mars except for a small region antipodal to the map centre. Maps are draped over present-day topography for reference. Grid lines are in increments of 30° of latitude and longitude.*