STRUCTURE AND EVOLUTION OF THE LUNAR INTERIOR.

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Introduction: Early in its evolution, the Moon underwent a magma ocean phase leading to its differentiation into a feldspathic crust, cumulate mantle, and iron core. However, far from the simplest view of a uniform plagioclase flotation crust, the present-day crust of the Moon varies greatly in thickness, composition, and physical properties. Recent significant improvements in both data and analysis techniques have yielded fundamental advances in our understanding of the structure and evolution of the lunar interior. The structure of the crust is revealed by gravity, topography, magnetics, seismic, radar, electromagnetic, and VNIR remote sensing data. The mantle structure of the Moon is revealed primarily by seismic and laser ranging data. Together, this data paints a picture of a Moon that is heterogeneous in all directions and across all scales, whose structure is a result of its unique formation, differentiation, and subsequent evolution. This brief review highlights a small number of recent advances in our understanding of lunar structure.

Shallow structure: Crust and upper mantle. The surface varies in composition on both local and regional scales [1], including the concentration of incompatible elements within the Procellarum KREEP terrane (PKT) [2]. Remote sensing data show that pure anorthosite is limited to rare small outcrops [3], while much of the upper crust outside the maria is dominated by a mixed feldspathic layer [4].

Gravity data reveal large variations in crustal thickness, primarily associated with impact basins and the nearside-farside asymmetry [5,6]. The upper crust has a mean density of ~2550 kg/m^3 and porosity of 12% [5], with an increase in density with depth [7]. A wide range of smaller structures exist within the crust including linear dike-like intrusions [8], ring-dikes around basins, a quasi-rectangular pattern of structures surrounding the PKT [9], magma chambers beneath volcanoes [10], density anomalies beneath craters [11], and pervasive small-scale density anomalies [12].

Seismic data show a low velocity and low density megaregolith, overlying a higher velocity and density crust. The strongest seismic constraints on crustal structure come from analysis of the signals generated by the crash landings of the lunar module ascent stages and the Saturn S-IVB booster stages, resulting in crustal thickness estimates of ~30-35 km in mare regions, and 40-50 km in highland regions [13].

Deep structure: Mantle and core. Exposures in impact basins indicate that the uppermost mantle is rich in either orthopyroxene (representing the top layer of magma ocean cumulates) [14] or olivine (representing the post-overturn mantle) [15]. Constraints from joint consideration of the mean density and Love numbers (GRAIL) and the moment of inertia (Lunar Laser Ranging) of the Moon result in a family of models which support the presence of a solid inner and liquid outer core [16], and possibly a deep mantle low shear velocity zone interpreted as partial melt [17]. Deep seismic reflections also support a partial melt layer overlaying a fluid outer core and solid inner core, with radii of ~480, 330, and 240 km, respectively [18]. The Lunar Prospector magnetometer detected an induced moment in the Earth's geomagnetic tail, supporting the existence of a conducting metallic core of radius 340+90 km [19], or 1 to 3% of the lunar mass.

Thermal evolution and geodynamics. The early thermal and geodynamic evolution was dominated by the equilibration and loss of accretionary heat, leading to early global expansion followed by contraction [8]. Subsequent evolution has been heavily affected by the concentration of heat producing elements in the Procellarum KREEP terrane [20] and the secular decline in radiogenic heat, resulting in relaxation of ancient basins [21] and declining rates of volcanism [20].

References: [1] Cahill, J. T. S. et al. (2009) *JGR* 114 1–17. [2] Jolliff B. L. et al. (2000) *JGR* 105 4197-4216. [3] Ohtake M. et al. (2009) *Nature* 461 236–240. [4] Hawke B. R. (2003) *JGR* 108 doi:10.1029/2002JE001890. [5] Wieczorek M. A. et al. (2013) *Science* 339 671–675. [6] Neumann G. A. et al. (2015) *Sci. Adv.* 1 1:e1500852. [7] Besserer J. et al. (2014) *GRL* 41 5771–5777. [8] Andrews-Hanna J. C. et al. (2013) *Science* 339 675–678. [9] Andrews-Hanna J. C. et al. (2014) *Nature* 514 68–71. [10] Kiefer W. S. et al. (2013) *JGR* doi:10.1029/2012 JE004111. [11] Soderblom J. M. et al. (2015) *GRL* 42 6939–6944. [12] Jansen J. C. et al. (2014) *LPSC* 45 Abstract 2730. [13] Chenet H. et al. (2006) *EPSL* 243 1–14. [14] Nakamura R. et al. (2012) *Nat. Geosci.* 5 775–778. [15] Yamamoto S. et al. (2010) *Nat. Geosci.* 3 533–536. [16] Matsuyama I. et al. (2016) *GRL*. 43 8365–8375. [17] Williams J. G. et al. (2014) *JGR* 119 1546–1578. [18] Weber R. C. et al. (2011) *Science* 331 309–312. [19] Hood L. et al. (1999) *GRL*. 26 2327–2330. [20] Laneuville M. et al. (2013) *JGR* 118 1435–1452. [21] Kamata S. et al.

(2013) *JGR* 118 398–415.