THE MOON'S DEEP INTERIOR: A HOTBED FOR SEISMICITY AND THE QUESTION OF PARTIAL MELT. R. C. Weber[1], [1]NASA Marshall Space Flight Center (renee.c.weber@nasa.gov).

Introduction: Geophysical data gathered during the Apollo lunar missions revolutionized our understanding of the Moon's interior. In the intervening years, re-examination of Apollo data and sample analyses combined with a wealth of new data from Clementine, Lunar Prospector, Kaguya, Chandrayaan-1, LRO, LCROSS, ARTEMIS, and GRAIL have led to an understanding of a crust, mantle, and core that are likely spatially and compositionally heterogeneous at scales ranging from microscopic to hemispherical, reflecting the Moon's unique formation history and subsequent evolution.

Despite recent advances in lunar geophysics, many questions remain regarding the detailed global structure of the Moon's deep interior, which has bearing on its thermal, petrological, and rotational history. Recent work suggests the presence of a fluid-like transition layer between the lunar core and mantle. The Moon may therefore still be undergoing chemical segregation and thermal layering. This abstract presents a review of our understanding of the Moon's deep interior, building from the Apollo legacy and outlining some of the major remaining questions future geophysical missions to the Moon should address.

Geophysical Data: The structure of the Moon's deep interior is elucidated primarily via seismology, with gravity, heat flow, laser ranging, and electromagnetic sounding providing supporting indirect constraints. Prior to recent re-analysis of the Apollo seismic data and the GRAIL lunar gravity mission, our knowledge of the Moon's deep structure was constrained primarily using the following means:

Geodetic parameters and LLR. The Moon's moment of inertia is roughly approximated by a homogeneous sphere, so if a core is present, it must be small. Precise monitoring of the Moon's geodetic parameters via laser ranging to the Apollo retroreflectors began in 1969. Dissipation provided the first LLR evidence for a fluid core [1], with a radius of 352km (if iron), or 374km (for a Fe-FeS eutectic composition).

Magnetic induction. In April of 1998, the Lunar Prospector orbital plane was nearly parallel to the Sun-Moon line, optimally oriented for using the magnetometer to detect an induced moment when the Moon was within the Earth's geomagnetic tail lobe. Assuming that the induced field is caused entirely by electrical currents near the surface of a highly electrically conducting metallic core, the measurements could be fit by a core with radius 340±90km, although a core is not required [2]. For an iron-rich composition, a core of that size would represent 1 to 3% of the lunar mass.

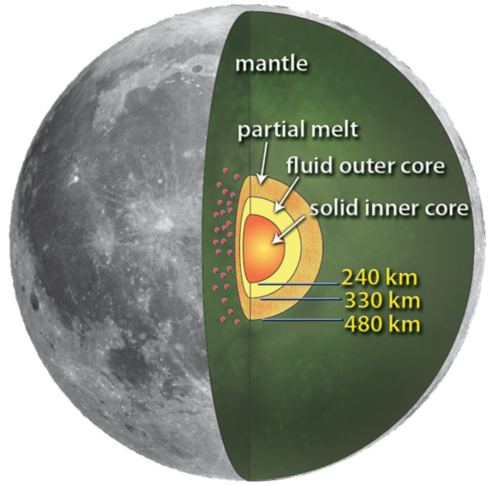

Fig. 1 The lunar interior as seen via seismology [9].

Seismology. A passive seismic experiment was deployed on the lunar near side at the Apollo 12, 14, 15, and 16 sites, and operated continuously from 1969 to 1977. Although many types of naturally occurring seismicity were recorded, no seismic energy originating from the far side penetrated the core, thus it was suggested that the core is likely attenuating [3]. The deepest moonquake sources lie between ~1200-1400km depth, so the core is likely no more than 300-500km in radius.

Due to the highly scattering nature of the lunar regolith and the overall quality of the instrumentation compared to modern seismometers, lunar seismograms are of limited quality compared to their terrestrial counterparts. Uncertainties in deep structure estimates afforded from other measurements are reflected in the seismic structure models. Crustal thickness estimates have decreased over the years as newer and more computationally expensive techniques were applied. Early models based on arrival time inversion alone [4] were supplanted by newer models using maximum likelihood estimates [5], joint seismic and pre-GRAIL gravity inversion [6], and free oscillations [7]. These newer models mostly agree that the only major discernable discontinuity in the lunar interior is the crust-mantle boundary located around 30km deep.

Recent re-analysis of seismic data, and GRAIL: Previous studies of the Apollo seismic data focused on structure constrained by direct arrivals, meaning they were only able to resolve structure to the depth of the deepest ray connecting a source to a receiver. The geographical extent of the Apollo array precluded the constraint of any core structure based on direct ray geometry. Two groups have re-analyzed the seismic data looking instead for core reflections, and separately discovered convincing evidence for the presence of a liquid lunar core [8,9] (Figure 1). The latter also constrained a solid inner core on the basis of the lack of observed SH reflections (horizontally polarized shear waves), and a partially molten layer at the base of the mantle on the basis of observed P reflections (vertically polarized compressional waves) [9].

The GRAIL mission also constrained lunar structure by sampling the lunar gravity field with extremely high accuracy and resolution. While gravity surveys and their resulting gravity anomaly maps offer optimal resolution at crustal depths, gravity in combination with lunar laser ranging permits deep structure determination through estimates of tidal energy dissipation at the solid boundaries. The combined GRAIL and LLR analysis predicted a family of deep structure models consistent with geodetic parameters, all of which possess a fluid outer core and a partial melt layer (although a solid inner core is not required to fit observations) [10].

Is a partial melt layer required? Subsequent to the re-analysis of Apollo data and GRAIL, numerous studies have emerged offering differing perspectives on the origins of the partial melt layer and whether it is required to satisfy available constraints. A melt layer is consistent with inversions of multiple geophysical data (mean mass and moment of inertia, tidal Love number, and electromagnetic sounding data) in combination with phase-equilibrium computations [11], but not required in viscoelastic dissipation models based on laboratory deformation of melt-free polycrystalline olivine [12]. The existence of a partial melt layer would inhibit core cooling [13].

Synergy with Geothermal and Paleomagnetic Measurements: Geothermal measurements track heat production and interior temperature distribution. The Apollo heat flow experiments were both emplaced within (or near the boundaries of) the Procellarum KREEP Terrane. How these areas, dominated by Th, K, and U-rich crust, came to exist depends on internal structure and the size/state of the core. Determining the physical and thermal structure of the lunar core and deep interior is critical for understanding the Moon's formation, especially the evolution of the lunar dynamo, by which the Moon may have generated and maintained its own magnetic field. Internal structure and temperature distribution also provide context for thermal emission and volcanism studies.

The Moon's dynamo history can be constrained through paleomagnetic analyses of returned samples and via crustal magnetism studies, which both suggest that the Moon once possessed a long-lived core dynamo [14]. Although multiple possible scenarios for generating and sustaining this dynamo have been proposed, no one model is yet widely accepted, with numerical models that can explain all the data only just emerging [15].

Major remaining questions: Many improvements and reduction of uncertainty in individual models could be enabled by new geophysical data from the Moon. Just as important is the need to develop a present-day physical structure model and associated model of the Moon's evolution consistent with all observations.

A longer period of observations, combined with additional surface retroreflectors, would permit inner core determination via laser ranging. A global network of long-lived broad-band seismometers would permit confirmation of the core structure, layering, and possible presence of partial melt. A seismic station on the farside would facilitate detection of core-transmitted phases, which provide information on the density and seismic velocity profiles. Such a station would also allow us to determine whether the farside is aseismic, possibly reflecting other nearside/farside dichotomies (crustal thickness, distribution of heat-producing elements, presence of mare). Mantle temperatures at local and global scales could be measured via magnetic induction with a pair of orbiting magnetometers, and via surface-deployed heat flow probes. Both were demonstrated at single points at the Apollo stations, but the need to understand lateral heterogeneity and the distribution of melt with depth persists.

To build upon the legacy of Apollo, which led to an evolution in our understanding of the Moon from a cold, dead body to a dynamic world of unending delight, the National Research Council recommends a Lunar Geophysical Network as a prioritized mission in the current planetary decadal survey. A network of least four nodes (each with a seismometer, heat flow probe, retroreflector, and magnetometer), operating continuously for at least 10 years, would enable progress towards a consistent model of the Moon's interior from crust to core.

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