SEISMIC EVIDENCE FOR THE LUNAR CORE.
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Recent studies suggest that the Moon possesses a relatively small iron-rich core, sized between ~250 and 430 km [1]. Various indirect geophysical measurements provide supporting evidence for the presence of a core, but differ on key characteristics such as its radius, composition, and state (solid vs. molten). Constraining the structure of the lunar core is necessary for understanding the present-day internal thermal structure, the history of a lunar dynamo, and the origin and evolution of the Moon.

Seismic models of the lunar interior lack resolution in the deepest 500 km of the Moon [2,3], due to the paucity of seismic waves that penetrate this depth range identified in the Apollo seismic data. The lack of observation of far-side events recorded by the near-side array suggests the presence of a highly-attenuating region in the deep Moon [4]. This, combined with inferences from other geophysical data, has led to a widely-accepted schematic of the lunar interior containing a partially molten deepest mantle layer overlying molten outer and solid inner core layers. We apply modern array-processing techniques commonly used in terrestrial seismology to seismic data gathered during the Apollo missions in order to confirm this model.

The Apollo Passive Seismic Experiment (PSE) consisted of four seismometers deployed on the lunar near side between 1969 and 1972, which continuously recorded three orthogonal directions of ground motion until late-1977. We analyzed seismograms from previously identified deep moonquakes, which are the most abundant type of lunar seismic events. They are known to originate from discrete source regions or "clusters," with depths between 700 and 1200 km. Clusters produce repeatable seismic waveforms at each station, permitting seismogram stacking to improve the signal-to-noise ratio of the main P- and S-wave arrivals [5]. However, scattering effects presumed to originate in the lunar crust persist, manifesting as long, ringing codas that obscure subtle arrivals that may be associated with deep interfaces (Fig. 1). In addition, the small number of stations, limited selenographical extent of the network, and weak attenuation of seismic energy coupled with strong wave scattering prohibited direct observation of waves reflected off of or refracted through the core.

We suppress coda noise with a polarization filter, a time-averaged product between orthogonal components of motion, which enhances signals partitioned onto more than one component [6]. Polarization filtering enhances the main P- and S-wave arrivals, and reveals a number of intermediate arrivals (Fig. 1). Double-array stacking [7] permits investigation of deep layering as the source of these arrivals. Stacking seismograms that have been aligned on predicted core arrival times enhances small-amplitude arrivals. We searched for lunar core reflections by time-shifting the polarization-filtered deep moonquake cluster stacks to travel time predictions of reflections from specific layer depths, then summing the shifted traces. If relatively strong energy is present in a stack associated with a particular depth, this is evidence for a reflective boundary at that depth.

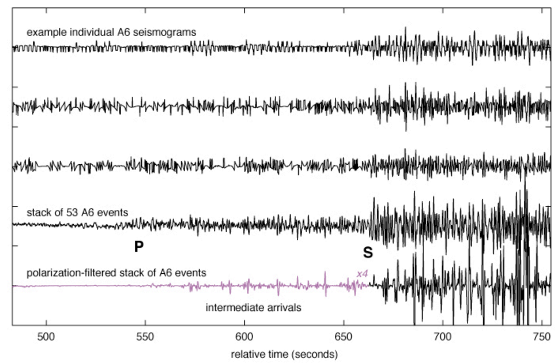

Figure 1: Sample seismograms from three A6 events (top three traces), compared to a stack of A6 events (fourth from top), and the same stack after polarization filtering (bottom). Stacking enhances the P and S arrivals, but intermediate arrivals remain masked by the P- and S-wave codas. The polarization filter reveals arrivals between P and S. The segment of the seismogram before S (purple) is magnified to increase the visibility of the intermediate arrivals.

Array seismology techniques are commonly performed relative to a reference signal, to suppress event origin errors. The direct S-wave is the largest arrival on the cluster-stacked moonquake traces. We used stacks of seismograms recorded on the four Apollo stations from all located clusters, retaining data for which S-wave onsets were clear and impulsive, resulting in 62 picks from a total of 38 clusters.

A number of significant interfaces could reflect seismic energy from deep moonquakes back to the surface. We searched the PSE data for four distinct reflection types: 1) a downward propagating P-wave that reflects and travels up to the surface as a P-wave; 2) as in 1), but a down- and up-going S-wave; 3) a downward propagating S-wave that converts to P upon reflection, traveling up as a P-wave; 4) a downward propagating P-wave that converts to S upon reflection, returning as an S-wave. We explored layered models in which we expect reflections off a partial melt boundary

(PMB), an outer fluid core or core-mantle boundary (CMB), and an inner core boundary (ICB).

Double-array stacking for models with multiple layering involves an iterative approach that seeks the best-fit radii and overlying P- and S-wave speeds of each layer, in order to produce consistency in the stacks for the four wave types (P-to-P, S-to-S, S-to-P, and P-to-S). We stacked data one interface at a time in 10-km depth increments, since resolving deeper interfaces requires knowledge of overlying structure.

We estimated the core energy of the stacks associated with each depth increment by taking the envelope of the stack and computing the area under the curve, then looking for peaks in the energy-vs-radius curve. We adopted the approach of interpreting peaks that were common to the different wave-type stacks, with relatively high record counts. A layer near 480±15 km radius is coherent in the stacks, after a slight (5% increase) perturbation in P velocities immediately above the PMB. We used a compressional wave velocity of 8.5 km/sec between 738 and 1257 km depth: this velocity likely requires the presence of garnet (at the ~20% level) at depth in the lunar mantle, which has been suggested previously [8]. Lower velocities (and hence lower amounts of garnet) are permissible as well, but produce slightly less robust stacks. We assign the layer of partial melt between the PMB and CMB with P and S velocity reductions of 10 and 30% respectively [9], corresponding to ~5 to 30% partial melt at depth, with the amount depending on the melt distribution. While these reductions are assumed, they do represent velocity contrasts that are physically reasonable, will produce notable attenuation observed for deeply-sampling seismic phases, are detectable, and are compatible with the lack of observed deep moonquakes below 1200 km depth. After fixing the PMB depth and velocities, the best-fitting CMB radius is determined to be 330±20 km. We adopt a fluid outer core P velocity of 4.1 km/sec, consistent with a liquid iron alloy under these conditions [10], resulting in a strong ICB reflection near 240±10 km radius. This deep discontinuity, which lacks S-to-S reflections, is most readily associated with a solid inner core. A transition from liquid to solid at this location implies the Moon's core is ~40% solidified. Our model [11] is summarized in schematic form in Figure 2.

The seismic velocities we have assumed for our core layers are consistent with estimates from other studies. However, these velocity assumptions affect the modeled reflector depths, since the depth of any reflector has a 1-to-1 trade-off with the velocity above the interface. Continued model velocity adjustment might result in better peak alignment between the different stacks, but the choice of velocity is not well constrained at present. Our principal results, motivated by consistencies in the stacks of different data types, demonstrate the strength of the deep reflectors and strongly suggest that the Moon has a solid inner and fluid outer core, overlain with a partially molten layer. Layer depths may plausibly vary by tens of kilometers – the exact resolution is difficult to quantify, owing to uncertainties such as moonquake location and timing errors, seismic heterogeneities that either blur stack amplitudes or affect one wave-type more than another (e.g., the CMB in the S-to-P stack), as well as fairly low record numbers for some depth regions for some wave types. We thus emphasize the need for confirmation of our result from new, broad-band seismic measurements on the Moon, such as those planned by the future mission SELENE 2 [12] and the proposed missions LUNETTE [13] and the International Lunar Network [14].

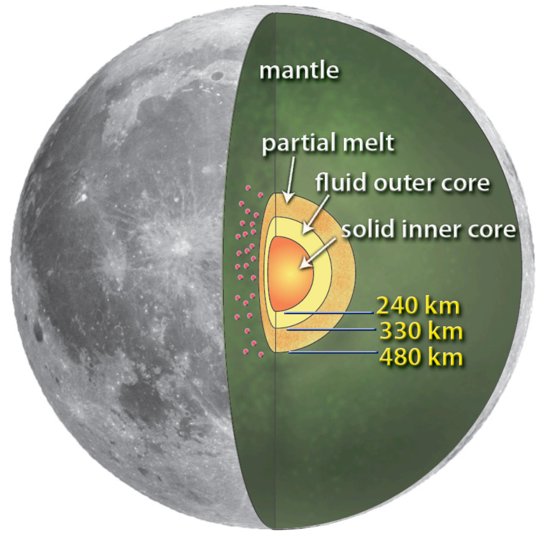

Figure 2: Schematic cross-section of the Moon [11] showing the distribution of deep moonquakes (red circles) and the radii of physical layers in the deepest lunar interior.

References: [1] M. A. Wieczorek et al., *Rev. Mineral. Geochem.* **60**, 221-364 (2006). [2] Y. Nakamura, *J. Geophys. Res.* **88**, 677-686 (1983). [3] P. Lognonné, J. Gagnepain-Beyneix, H. Chenet, *Earth Planet. Sci. Lett.* **211**, 27-44 (2003). [4] Y. Nakamura, *J. Geophys. Res.* **110**, E01001 (2005), doi:10.1029/2004JE002332. [5] R. C. Bulow, C. L. Johnson, P. M. Shearer, *J. Geophys. Res.* **110**, E10003 (2005), doi:10.1029/2005JE002414. [6] H. S. Jarosch, *Bull. Seismol. Soc. Am.* **67**, 1647-1659 (1977). [7] S. Rost, C. Thomas, *Rev. Geophys.* **40**, 1008 (2002), doi:10.1029/2000RG000100. [8] A. Khan, J. A. D. Connolly, J. Maclennan, K. Mosegaard, *Geophys. J. Int.* **168**, 243-258 (2007). [9] Q. Williams, E. J. Garnero, *Science*, **273**, 1528-1530 (1996). [10] C. Sanloup et al., *Geophys. Res. Lett.* **27**, 811-814 (2000). [11] R. C. Weber, P. Lin, E. J. Garnero, Q. Williams, P. Lognonné, *Science*, in press (2011). [12] S. Tanaka et al., *Adv. Space Res.* **42**, p. 394-401 (2008). [13] Neal, C. R.; Banerdt, W. B.; Alkalai, paper presented at the 41st Lunar and Planetary Science Conference, The Woodlands, TX, March 1-5, 2010. Sponsored by the Lunar and Planetary Institute. [14] ILN Science Definition Team Final Report (2009).