

A SEISMIC SEARCH FOR THE LUNAR CORE. R. C. Weber¹, P. Lin², and E. Garnero², ¹United States Geological Survey, Astrogeology Science Center, Flagstaff, AZ (rweber@usgs.gov), ²Arizona State University, School of Earth and Space Exploration, Tempe, AZ.

Introduction: Despite recent studies that have furthered many areas of lunar science through the analysis of the Apollo seismic data [e.g. 1,2,3,4], important deficiencies remain in our current understanding of the lunar interior. One such deficiency is the lack of a seismic constraint on the size and state of the lunar core. The radius, composition, and present state (liquid or molten) of the lunar core are key variables in lunar formation and thermal evolution models, as well as possible indicators of an early dynamo for magnetic field generation. Current (indirect) constraints on core properties arise from moment of inertia considerations, the Lunar Laser Ranging experiment, magnetic induction studies, and from analyses of elemental abundances in mare basalts [5]. However, these estimates vary widely, with proposed radii between ~200 and 460 km.

As with terrestrial investigations, direct observation of core reflections provides the strongest constraints on core radius. We therefore analyze Apollo seismograms using array processing methods to search for the presence of a P-wave reflection from the core-mantle boundary (the seismic phase called PcP), which can be used to constrain the lunar core radius as well as the seismic velocity contrast of the core-mantle boundary. Lunar core reflections have not been observed to date. In this study, we present two techniques for processing the Apollo seismograms, aimed at enhancing coherent energy reflecting from the lunar core.

Polarization filter: Lunar seismograms are characterized by emergent rather than impulsive arrivals and by long P and S-wave codas caused by the scattering of seismic energy, which tend to mask later arrivals. The application of a polarization filter to artificial impact seismograms has been shown to successfully reveal surface reflections masked by the P-wave coda [6]. We apply this method to the larger catalog of deep moonquakes [7], with the goal of enhancing reflected core phases such as PcP.

The polarization function (M) is given as the averaged cross product of the vertical (Z) and radial (R) or transverse (T) seismogram components, e.g.

$$M_j = \sum_{i=-n}^n R_{j+i} Z_{j+i}$$

where j is the time step and n determines the length of the averaging window (we used $n=6$ samples). The output of the filter (S) is the product of M and R (or T):

$$S_j = R_j M_j$$

Since deep moonquakes originate from discrete source regions that produce repeatable waveforms, their seismograms can be stacked to improve signal-to-noise ratios and enhance the P and S arrivals. However, stacking raw data does not improve the visibility of putative core phases. Application of the polarization filter to stacks of events from these clusters, however, reveals discrete arrivals (Figure 1), which we investigate as possible core arrivals.

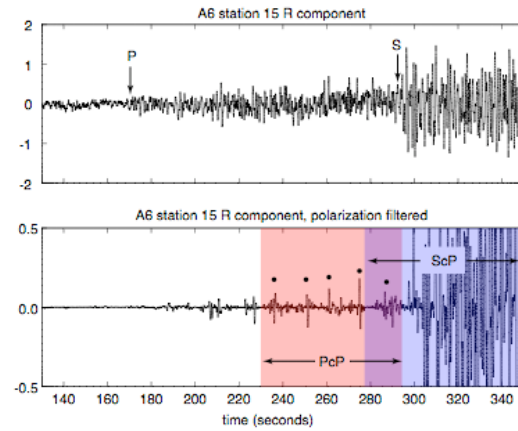


Figure 1: (top) R-component raw seismogram stack from the A6 cluster (latitude 43.5°N, longitude -36.6°E, depth 844 km) as recorded at Apollo station 15. The P-wave (S-wave) coda precludes definitive identification of arrivals between P and S (after S). (bottom) The same trace after application of the polarization filter. Several arrivals between P and S are evident (dots). The predicted PcP and ScP arrival windows [8] using the velocity model of [1] and assuming core radii between 200 and 500 km, are shown in pink and blue, respectively.

Double array stacking: Researchers in terrestrial seismology use a technique to stack seismograms that have been time-shifted to the predicted arrival time of a hypothetical reflection of interest (e.g. PcP) in order to enhance and detect subtle arrivals. This method permits stacking of an entire data set (in this case the 65 clusters with constrained depths), which further enhances coherent signals [9]. We search for lunar core reflections by summing the deep moonquake stacks along predicted PcP arrival times. Using only those traces for which the S arrival is prominent and easy to pick, the individual stacks are first normalized in time and amplitude to the S wave. The S arrivals are shifted to the reference model predictions to minimize time uncertainties as we search for core reflections. Traces

are then shifted so the arrival of interest in every trace (e.g. PcP) aligns at a new reference time of $t=0$. Finally, the records are summed within a 30-second time window centered on the PcP prediction. If the Moon has a core, it is expected to reflect seismic energy, which should be present in the Apollo data. Thus we conduct our stacking experiment for a suite of core radii, permitting an investigation of the core radius producing the most coherent PcP energy.

Results using the polarization-filtered R-component deep moonquake stacks, aligned on the predicted PcP time, are shown in Figure 2. Core radius predictions between 200 and 500 km are shown, for 10km increments. These plots suggest a strong coherent arrival crossing at time $t = 0$ for a core radius of 300km.

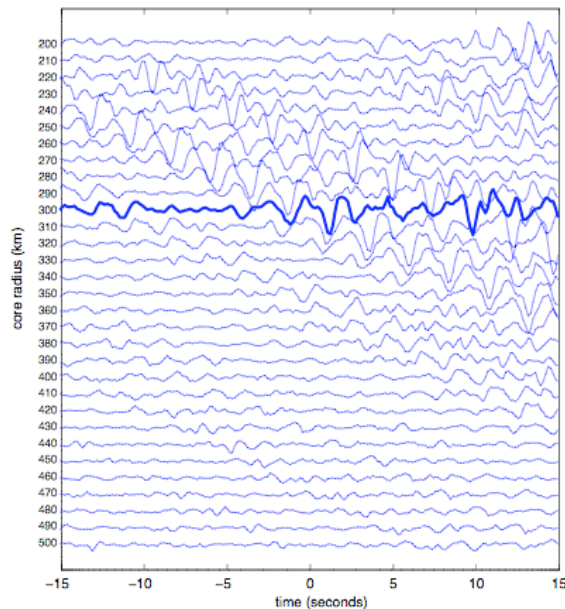


Figure 2: Polarization-filtered R-component deep moonquake stacks summed on the predicted PcP arrival time for a range of hypothetical core depths. The strongest arrival crossing at time $t = 0$ occurs for a core radius of 300 km, marked in bold.

To further investigate the result shown in Figure 2, we examined each of the PcP stack members contributing to the 300 km result shown in bold. These are shown in Figure 3. It appears that a single trace from station 14 is strongly influencing the result. Removing the spurious trace from the PcP stack also removes the strong arrival at $t=0$ (Figure 4). Many of the other traces, however, have energy between 4 and 10 seconds that is consistent with intermittently observable PcP arrivals.

Conclusions: Our initial results suggest a lunar core radius of 300 km. However, additional work is

required to assess the robustness of the result, as well as consistency with other known core reflections (namely ScS and ScP).

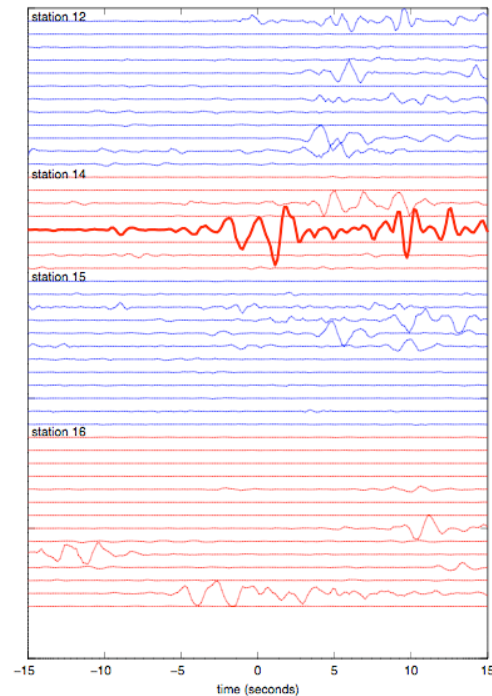


Figure 3: Stack members from each of the four Apollo stations (alternating colors) contributing to the 300 km core radius result in Figure 2. Note the spurious trace (bold) that strongly influences the stack and produces a false arrival at time $t = 0$.

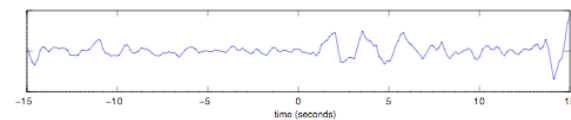


Figure 4: Revised 300 km PcP stack with the spurious trace from station 14 removed. Now the arrival appears to have shifted in time, suggesting a larger core radius.

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