Seismic investigation of the Moon: Past, Present, and Future

*Renee C Weber[1], Clive Neal[2], Bruce Banerdt[3], Sharon Kedar[3], Nicholas Schmerr[4], Mark Panning [3], Philippe Lognonne[5], Taichi Kawamura[5], Ceri Nunn[3], Angela Marusiak[4], Deanna Phillips[9], Yosio Nakamura[7], Caroline Beghein[6], Raphael Garcia[8]

1. NASA Marshall Space Flight Center, 2. Universtiy of Notre Dame, 3. NASA JPL, 4. University of Maryland, 5. IPGP Paris, 6. University of California, Los Angeles, 7. University of Texas, Austin, 8. ISAE SUPAERO, 9. University of Alabama, Huntsville

Beginning in 1969, NASA’s Apollo program successfully deployed a long-lived network of seismometers on the Moon. The resulting seismic data revolutionized our understanding of the Moon's interior. In the intervening years, re-examination of Apollo geophysical data and sample analyses combined with a wealth of new data from orbital missions 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.

The structure of the Moon’s interior is elucidated primarily via seismology, with gravity, heat flow, laser ranging, and electromagnetic sounding providing supporting indirect constraints. 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. 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. Crustal thickness estimates have decreased over the years as newer and more computationally expensive techniques have been applied. Early models based on arrival time inversion alone were supplanted by newer models using maximum likelihood estimates, joint seismic and gravity inversion, and free oscillations. These newer models mostly agree that the only major discernable discontinuity in the lunar interior is the crust-mantle boundary located around 30km deep.

Uncertainties in deep structure estimates afforded from other geophysical measurements are reflected in the seismic structure models. 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. The deepest moonquake sources lie between ~1200-1400km depth, so the core is likely no more than 300-500km in radius.

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, all located around the equator on the nearside, 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. One of these 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). The presence of a fluid-like transition layer between the lunar core and mantle suggests the Moon may still be undergoing cooling. Numerous studies have since emerged offering differing perspectives on the origins of the partial melt layer and whether it is required to satisfy available constraints.

Despite recent advances in lunar seismology, many questions remain regarding the detailed global structure of the Moon’ s deep interior, which has bearing on its thermal, petrological, and rotational history. To build upon the legacy of Apollo, the U.S. National Academies recommends a Lunar Geophysical Network as a prioritized mission in the current planetary decadal survey. A network of four nodes (each with a seismometer, heat flow probe, retroreflector, and magnetometer), operating continuously for up to10 years, would enable progress towards a consistent model of the Moon’ s interior from crust to core.

Keywords: Moon, seismology, geophysics

