Lunar Science: The Moon provides a unique opportunity to study fundamental questions about the origin and evolution of the inner solar system. While it is widely believed that the Moon was created by the collision of a large object with the Earth during early planetary formation, this has not been conclusively proven. Furthermore, the mechanisms and processes by which this may have occurred are not well understood. An investigation of the composition and structure of the deep interior of the Moon may help answer some of these mysteries [1].

The Lunar interior serves as a time capsule providing clues to its initial composition, differentiation, crustal formation and possible ancient magnetic dynamo. The best, and in some cases the only way to determine the composition and structure of the deep crust, mantle and core is to conduct geophysical measurements [2]. The NRC report, The Scientific Context for Exploration of the Moon – Interim Report, finds that “Long-duration geophysical stations … implemented at multiple (six or more) sites are required to provide comprehensive subsurface information” [3].

Figure 1: Location of the Apollo lunar landing sites and the passive seismometer experiments.

While the Apollo Lunar Surface Experiments Packages (ALSEP) contained a variety of different experiments that produced significant information regarding the nature of both the lunar surface and interior, the impact of this data has been limited by the fact that the ALSEP stations were geographically clustered in the near side equatorial regions and each mission did not carry the same experimental package. Globally distributed long-term measurements would give rise to a wealth of knowledge from regions heretofore inaccessible using the Apollo database. Data collected over a period of at least 6 years (covering one lunar tidal cycle) would yield information on the nature and evolution of the lunar interior using a combination of seismic, heat flow and magnetic field instruments. Globally distributed simultaneous seismic measurements are particularly important for understanding the current structure of the deep lunar interior.

Seismology. The Apollo Passive Seismic Experiment (PSE) deployed seismometers at every landing site except Apollo 17 [4,5]. The instrument at Apollo 11 failed after 21 days, presumably because it did not contain the thermal blanket that later versions did. Thus, a network of four seismometers was completed in April 1972 (Fig. 1), and operated until 30 September 1977. During the time when the network was operational, it clearly demonstrated that the Moon was seismically active, albeit on a smaller scale than Earth [6,7]. The Moon does, however, exhibit seismic activity on a similar scale to that of an intraplate setting on Earth [6,8-10]. Four distinct types of lunar seismic events have been defined from the Apollo PSE seismic database: (1) Thermal Moonquakes – the smallest of all seismic events, related to diurnal temperature changes [11], (2) Deep Moonquakes – originating 700-1200 km within the Moon, (3) Meteoroid Impacts - surface seismic events that exhibit characteristic amplitude variations with distance, and (4) Shallow Moonquakes – with inferred focal depths of 50-200 km.

While a large volume of data was collected by the PSE network, major scientific questions still remain unresolved, and require additional data. The narrow area covered by the PSEs means that comparisons cannot be made between seismic waves from the same event that passed through the deep interior of the Moon versus those that did not. Furthermore, due to the small spacial extent of the PSEs, the resolution of seismic interpretation decreases deeper into the mantle. Variations in the lunar crust (mineralogical and thickness) have been difficult to estimate away from the PSE network sites. Finally, little is still known about the global variability and the nature of the lunar mantle.

Heat Flow. While heat flow experiments were attempted on Apollo 15-17 [12,13], only Apollo 15 & 17 successfully obtained measurements from two locations each [12]. To determine the interior heat flux to an accuracy of ±5 mW m⁻², multiple heat flow measurements in a given geologic environment are required to
average out local variations due to topography and subsurface variations. Two of the successful Lunar heat flow measurements were made within several hundred meters of each other and differed by a factor of two [12]. Ideally three or more measurements should be made in holes spaced 10s to 100s of meters apart, at depths that extend from the surface to below the penetration depth of the annual thermal wave.

Scientific questions that are unresolved with regard to lunar heat flow center around better definition of the global heat flow budget for the Moon in order to better constrain the thermal evolution and bulk composition in terms of heat-producing elements.

Magnetism. The Lunar Surface Magnetometer (LSM) was deployed as part of the ALSEP by Apollo 12, 15 and 16. The network was switched off on 14 June 1974. [14] The LSMs, along with Apollo subsatellites, were used to study the properties of the lunar interior and the lunar environment.

Unfortunately, the LSM measurements were obtained at locations that were not ideal for testing hypotheses about the origin of the lunar crustal magnetic field. Remaining scientific questions concerning lunar magnetism include: Are basin ejecta the sources of lunar magnetic anomalies? What is (are) the origin(s) of the unusual albedo markings associated with strong lunar magnetic anomalies? What is the electrical conductivity profile of the Moon?

Shallow Moonquakes & Lunar Exploration:
The exact locations and origin(s) of shallow moonquakes are unknown. While they appear to be associated with boundaries between dissimilar surface features (e.g. impact basin rims) [15], the exact origin of these events is still unclear. Shallow moonquakes are the largest of the lunar seismic events. The Apollo PSEs recorded 28 events, with seven events registering the largest of the lunar seismic events. The Apollo

Enabling Architecture: The Lunar Exploration Architecture greatly enables the geophysical science investigation of the Moon. Small, low mass, low power geophysical probes may be developed using existing technology and flight proven instrumentation, allowing them to be easily transported and deployed within the framework of both robotic and human exploration missions. Probes may be a payload on either an orbiter or lander. With proper packaging, orbital deployment allows probes to be placed anywhere on the surface of the Moon, thereby achieving the critical global coverage not afforded by the Apollo ALSEP.

While development of low-mass, long-lived power supplies is needed, these self-sufficient lunar geophysical probes can be designed to store data and periodically downlink it to a lunar base or to Earth by using the already planned Lunar Communications Architecture. The low data rate and periodic communication requirements of the probes should impose a negligible load on the planned high bandwidth infrastructure.

References: