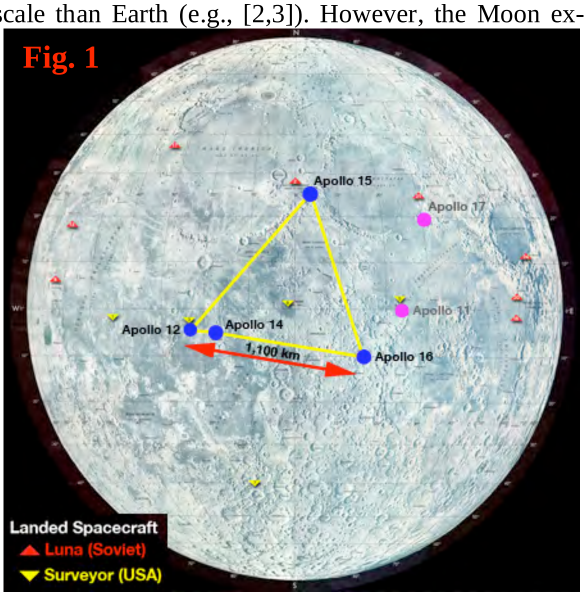
THE CASE FOR A LONG-LIVED GLOBAL LUNAR GEOPHYSICAL NETWORK - 1: SEISMIC DATA.
A. Fagan[1], C.R. Neal[1], L. Salvati[1], S. Sakimoto[1], Y. Nakamura[2], J Weinberg[3] [1]Dept. of Civil Eng. & Geo. Sci., University of Notre Dame, Notre Dame IN 46556, USA; [2]J.J. Picle Research Campus, Bldg. 196 (ROC), 10100 Burnet Rd., Austin, TX 78758-4445; [3]Ball Aerospace & Technologies Corp., PO Box 1062, Boulder, CO 80306-1062.

Introduction: The return of humans to the Moon will occur 40+ years since the last astronaut left our only natural satellite. Although there is a potentially negative public perception of "we have already been to the Moon", our current inadequate understanding of the lunar interior demonstrates that this is untrue. While the Apollo missions set up individual instruments (as part of the Apollo Lunar Surface Experiments Package - ALSEP) to collect geophysical data, the small aerial distribution of the sites (Fig. 1), coupled with the short term nature of some measurements and the fact that not all missions carried the same instruments, gave only a limited glimpse of the Moon's inner structure, composition, and thermal evolution. There is a need for a long-lived, global lunar geophysical network to address unanswered fundamental science questions (see below). It is envisaged that a seismometer be part of a network composed of lunar geophysical packages that would include a seismometer, magnetometer, and heat flow probes. Here, we concentrate on seismic data and how energy is transmitted through the regolith in order to properly characterize the nature and model the effects of Moonquakes at the lunar surface. A companion abstract [1] documents the rationale for including heat flow and magnetism measurements in this geophysics instrument package.

Background: The Apollo Passive Sesimic Network (PSN) was a network of four seismometers completed in April 1972 (Fig. 1) and operated until 30 September 1977. The data collected clearly demonstrated that the Moon is seismically active, albeit on a smaller scale than Earth (e.g., [2,3]). However, the Moon exhibits seismic activity on a similar scale to that of an intraplate setting on Earth [2,4-6]. The Apollo PSN documented 4 types of lunar seismic events: 1) *Thermal moonquakes* (the smallest magnitude event) - associated with stresses induced by lunar surface diurnal temperature changes; 2) *Deep moonquakes* (generally magnitude ≤2) - >7,000 having been recognized, generally at depths of 700-1,200 km and at regular intervals associated with Earth's tidal pull; 3) *Meteoroid impacts* exhibit characteristic seismic waveforms; >1,700 impact events (masses from 0.1 to 1,000 kg) were recorded between 1969 and 1977; 4) *Shallow moonquakes* ("high frequency teleseismic events") have "shallow" (50-200 km?) hypocenters, but exact depths and locations are unknown because all recorded events were outside the PSN. Shallow moonquakes are the strongest type of event, with 7 of the 28 recorded events being magnitude ≥5 (i.e., more than one event of magnitude ≥5 occurs per year). While these shallow moonquakes have perhaps the greatest potential for seismic hazard, they are the least understood moonquake type and their exact causes are unknown.



Lunar Internal Structure: The top few meters of the lunar regolith is highly pulverized with extremely low seismic velocities (V_p~100 m/s; V_s~40 m/s) [7,8]. Below the regolith, seismic velocities gradually increase with depth, but "normal" (coherent) rock velocity of V_p>4 km/s is reached only at depths greater than 1 km [7]. Below this, the deeper interior of the Moon beneath the PSN has a clearly identifiable crust and mantle. The crustal thickness in the Fra Mauro region near the front center of the Moon was initially estimated to be about 60 km [9], but more recent analyses tend to find thicknesses of ~ 40 km [10,11]. However, no direct crustal thickness measurements are available other than from the Apollo landing sites (**Fig. 1)** and the nature and extent of the lateral variations are still poorly constrained. Seismic velocities in the lunar upper mantle are similar to those found in the Earth's upper mantle at equivalent pressure ranges and stay nearly constant or decrease slightly with increasing depth, both in original estimates [4,12] and in more recent analyses [10,13]. There are reports of a distinct velocity discontinuity that separates upper from middle mantle at ~600 km depth [13], but its reality is uncertain. Below about 1000-1100 km depth in the mantle (below the level where deep moonquakes occur) seismic shear waves are severely attenuated, suggesting that the material below this level (the lower mantle) is either partially molten or contains significant amount of volatile material [14,15]. Whether the Moon has a liquid core is uncertain from the seismic data alone. Although there was one far-side impact that suggested the existence of a molten core (radius ≤360 km) [14], this result could not be confirmed.

Major Unanswered Questions. Although the Apollo PSN data provided a lot of information about the Moon, there remain several important unanswered questions:

1. Core: *What is the composition and size of the lunar core? Whether the Moon has a liquid core is uncertain from the PSN seismic data.*
2. Structure: *What is the internal structure of the whole Moon?*
3. Crust & Mantle: *What is the nature of global variations within the lunar crust and mantle?*
4. Very deep interior: *What are the physical properties of the very deep interior of the Moon, in particular the lower mantle and a possible core?*
5. Lateral heterogeneity: *How do crustal and mantle structures vary from one region to another?*
6. Deep moonquakes: *What is the true mechanism of deep moonquakes? How are they distributed globally, and what does this distribution mean in terms of the lower mantle structure?*
7. Strange quark matter: *Can we detect passage of nuggets of postulated strange quark matter through the Moon* [e.g., 16,17]?
8. Shallow moonquakes: *What causes shallow moonquakes? How deep are they? How much risk do they pose to future lunar bases?*
9. Meteoroid Impacts: *Are these random events or are they concentrated more in some areas than others?*

These major questions remain because global coverage is required for these key seismic measurements. Global distribution of any seismic/geo-physical network should be the utmost consideration for the next generation of seismic observations on the Moon.

Having a larger number of stations is another important factor. The four stations that constituted the Apollo seismic network were only marginally sufficient to deduce basic geophysical parameters needed to define an initial simple, radially symmetric lunar interior model. In order to model any radial or lateral changes in seismic properties and hazards, it is imperative to have sufficient stations, with at least some of these at close (1-10 km) spacings to constrain shallow moonquake epi(hypo)centers.

Relevance to Exploration: Shallow moonquakes are a potential hazard to establishing a long-term habitat on the Moon. Estimates of epicentral ground acceleration for a m_b magnitude 5.7 moonquake are 0.7-0.8 m s^{-2} for a focal depth of 25 km and 0.20-0.25 m s^{-2} for a focal depth of 100 km. Ground motion in terms of amplitude for a 5.7 magnitude quake is ~3 cm at 2 Hz to ~0.75 cm at 8 Hz, approximately 1 km from the epicenter. However, applying earthquake engineering models (e.g., [18]) to moonquake seismic spectra requires scaling factors of several orders of magnitude, which magnifies the errors to the point that results become qualitative, even unacceptably speculative. This is because: shallow moonquakes contain more energy at high frequencies than earthquakes of comparable total energy; coherent lunar materials have an extremely high seismic Q (4000-7000+) resulting in low damping of seismic energy that results in very efficient transmission and allowing the maximum signal from a moonquake to last up to 10 minutes with a slow tailing off that can last for hours. Significantly, it is not known how lunar regolith transmits seismic energy, although it is known to scatter it [19]. We will report results of resonant column tests on lunar simulant JSC-1a as a start to address this gap in our knowledge.

Summary: A global lunar seismic network that will be active for a minimum of 6 years should be established early on in the next stage of lunar exploration (i.e., before establishing the long-term lunar habitat). It would gather important engineering (and potentially critical seismic hazard safety) data as well as answer many fundamental scientific questions that still remain almost 40 years after man first set foot on the Moon. While the resonant column test data from this study helps to address major seismic assessment gaps, additional concerted efforts are required to produce codes applicable to the Moon to estimate ground motion associated with the larger moonquakes.

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