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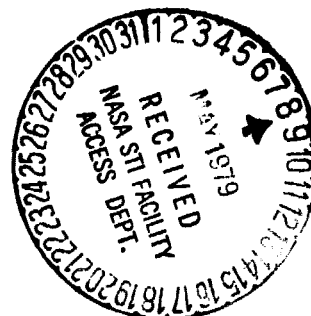
THE APOLLO PASSIVE SEISMIC EXPERIMENT

FINAL TECHNICAL REPORT

Contract NAS 9-14581

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**Passive Seismic Experiment: A Summary of Current Status**

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Abstract -- The data set obtained from the 4-station Apollo seismic network is now complete. It includes signals from approximately 11,800 events of various types. Four data sets for use by other investigators, through the NSSDC, are in preparation. Some refinement of the lunar model based on seismic data can be expected, but its gross features remain as presented two years ago. The existence of a small, molten core remains dependent upon the analysis of signals from a single, far-side impact. Analysis of secondary arrivals from other sources may eventually resolve this issue, as well as continued refinement of the magnetic field measurements. Evidence of considerable lateral heterogeneity within the moon continues to build. The mystery of the much lower meteoroid flux estimate derived from lunar seismic measurements, as compared with earth-based estimates, remains; although, significant correlations between terrestrial and lunar observations are beginning to emerge.

## Passive Seismic Experiment: A Summary of Current Status

Beginning with the Apollo 12 mission, seismic stations operated continuously on the lunar surface for nearly 8 years until the experiment was terminated on October 1, 1977. The 4-station network was completed in 1972 during Apollo mission 16, giving a total of 5-1/2 years of full network operation. The stations were operated most of the time in a peaked response mode in which vibrations of the lunar surface were magnified by nearly 20 million times, but in a narrow band of frequencies. A broader band mode of operation, giving lower peak magnification, was employed for 1-1/2 years at stations 12, 15 and 16 (late 1975 to early 1977). The intervals of station operation and categories of recorded events are summarized in Table 1.

Initial processing of all data tapes has been completed; although some reprocessing will be needed going back to March 1976. Several data sets are being produced and are available to other investigators through the National Space Science Data Center:

1. Compressed plots of all data have been produced and analyzed. These are available on microfilm.
2. Event catalogs listing the times, amplitudes, and durations of all identified seismic signals have been completed for the period through March 1977.
3. Computer tapes containing only identified seismic signals have been completed through June 1976.
4. Expanded-scale, hard-copy playouts of all events detected at station 14 have been completed through May 1976. Playouts of selected events are available for other stations.

The relatively rare, but energetic, HFT events remain a subject of great interest, for these are believed to be shallow moonquakes (Nakamura et al., 1974a). If so, they indicate that strain energy is accumulating in the outer shell of the moon as it cools. Thus, they would be the only truly tectonic quakes detected.

The population of meteoroids in earth-moon space, as determined from lunar seismic data, is nearly 10 times lower than that determined from most earth-based observations. This difference remains a mystery, and is of great importance. It is possible that many of the meteoroids that produce luminous trails in the earth's atmosphere are loosely consolidated aggregates, or contain highly volatile constituents. The luminous intensity of the trails of such objects might be greater than that of denser, or less volatile objects of the same kinetic energy, resulting in an over estimation of their masses..

Several episodes of unusually high meteoroid activity have been recorded (Duennebier et al., 1975). Possible correlations between the time-histories of terrestrial and lunar meteoroid fluxes are suggested by J. Dorman et al. (1978). They also find that the largest meteoroid impacts generally occur on the moon between early April and late July each year.

Our best model for the lunar interior remains that presented at the 7th Lunar Science Conference (Nakamura et al., 1976). As shown in figure 1, the model describes the interior in terms of five zones: the crust, between 50 and 60 km thick on the earth-facing side, an upper, middle and lower mantle, and possibly, a molten core.

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The crust-mantle interface is marked by an abrupt increase in seismic wave velocities. The elastic constants and density of the upper mantle are consistent with those expected for an olivine-pyroxene composition (Nakamura et al., 1974b). The transition from upper mantle to middle mantle, at a depth of about 300 km, is a zone in which shear wave velocities begin to decrease more rapidly than in the overlying zone, and the attenuation of shear waves increases. This is also the approximate depth at which a rapid change in conductivity is suggested by magnetic field data (Dyal et al., 1976). The MIT group places the depth of this transition at about 500 km (Goins et al., 1978). The difference between these two estimates is a consequence of differing shear wave velocities derived for the upper mantle. Goins et al. (1978) use a constant-velocity approximation for the upper mantle; whereas, the model of Nakamura et al. (1976) includes a negative velocity gradient for shear waves in this zone. We still have no satisfactory hypothesis to explain this transition. Slight melting, beginning at this depth, and the possibility that this marks the base of the zone of early melting, have been suggested, but absorption of shear waves is so low in the middle mantle that partial melting seems ruled out. On the other hand, scattering of seismic waves in the deep interior is not appreciable. It is difficult to believe that a primitive assemblage of matter, having never undergone post accretionary melting, could be without heterogeneity on a scale that could cause scattering (approximately 1 to 20 km).



The boundary between the middle and lower mantle, at a depth of about 1,000 km, is believed to be where partial melting begins at present. Deep moonquakes originate in a thin shell just above this boundary, and shear waves are highly attenuated below (Nakamura et al., 1974b).

Finally, the core is indicated with a question mark because we have only one event which generated detectable elastic waves passing through this zone (Nakamura et al., 1974b). The event was a large far-side impact that occurred in 1972. The compressional waves passing through this zone were delayed significantly. The most obvious explanation for this observation, is that the waves passed through a molten zone. If so, the maximum radius of the zone would be about 360 km, representing less than 2% of the mass of the moon. The minimum radius is about 170 km. The velocity of compressional waves through the core is between 4 and 6 km/sec. Extrapolating to lunar core pressures from data given by Anderson et al. (1977), a velocity of between 4 and 5 km/sec is expected for a molten core of iron-sulfide composition.

This model is undoubtedly a simplification of the real case. Evidence of lateral heterogeneities, possibly reflecting variations in upper mantle velocity, have been found (Nakamura et al., 1977). Further refinement of the model will undoubtedly occur. Dainty et al. (1977) e.g., have begun to use secondary arrivals to refine estimates of crustal thickness. So far, attempts to identify low-frequency signals, interpretable as surface waves or free oscillations

of the entire planet, have been inconclusive, but the search is by no means complete.

At first we were struck by the differences between the earth and the moon. The seismic activity of the moon is much lower than that of the earth and lunar signals have peculiar characteristics. Mountainous masses are perched on the lunar surface without sinking as they do on earth and there is no evidence of significant compressional or tensional forces acting at the surface. These differences now seem less astonishing and more a natural consequence of the differing dimensions of the two bodies. The moon has a crust, as does the earth, but the lunar crust is four times thicker than the average thickness of the earth's crust. The material beneath the crust, the upper mantles of the earth and the moon, has about the same density and elastic properties, implying similar compositions. Although tentatively defined in the lunar case, both planets appear to have molten cores, 4.6 billion years after their formation. Both planets are characterized by rigid outer shells - lithospheres - and underlying zones of weak, partially molten material - asthenospheres; but the lithosphere of the moon is 10 times thicker than that of the earth, and the lunar asthenosphere may extend all the way to its center rather than being confined to a thin, relatively shallow zone, as for earth. The peculiar characteristics of lunar signals are a consequence of the absence of water, leading to extremely low losses for seismic wave transmission; and the presence of a regolith, in which seismic velocity increases rapidly with depth.

Much remains to be done, but substantial progress toward understanding the lunar interior and meteoroid flux can be expected from analysis of data returned from the Apollo Seismic Experiment.

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### Figure Captions

Figure 1. Model of the lunar interior based upon analysis of lunar seismic signals.  $V_p$  = compressional wave velocity;  $\sigma$  = poisson's ratio;  $Q_s$  = quality factor for shear waves.

Table 1. PSE Data Summary

Period of Observation

1-station July-Aug., Nov. 1969 - Feb. 1971	1.27 yrs.
2-station Feb. 1971 - July 1971	0.48
3-station July 1971 - Apr. 1972	0.73
4-station Apr. 1972 - Sept. 1977	<u>5.44</u>
Total:	7.92 yrs.

Number of Seismic Events Detected

	<u>Total</u> <sup>(a)</sup>	<u>Major Events</u> <sup>(c)</sup>
Artificial Impacts	9	5
Meteoroid Impacts	1,700 <sup>(b)</sup>	95
HFT (Shallow Moonquakes)	32	7
Deep Moonquakes, Confirmed	973	9
Unconfirmed	1,800 <sup>(b)</sup>	2
Unclassified Events	<u>7,300</u> <sup>(b)</sup>	<u>0</u>
Total:	11,800 <sup>(b)</sup>	118

(a) Does not include signals detected only by the short-period seismometers of each station, or the large number of signals recorded by station 16 only.

(b) Estimated, 1977 data analysis incomplete

(c) Signals for which the amplitude of the recorded signal is greater than 10 mm at two or more stations.

