APOLLO LUNAR SEISMIC EXPERIMENT - FINAL SUMMARY, Yosio Nakamura, The University of Texas, Institute for Geophysics, Galveston, Texas 77550

We have finally completed all the processing and most of the analysis of the lunar seismic data collected between 1969 and 1977. Many preliminary results have already been published based on partial data sets. We have now completed analysis based on the entire data set, and this summary includes some highlights of the new results.

Processed data sets -- All ALSEP (Apollo Lunar Surface Experiment Package) data, including the 254-day data of LSPE (Lunar Seismic Profiling Experiment) in listening mode at Apollo 17 site, have now been processed to produce sets of computer-compatible digital tapes. We plotted seismic data in a compressed time scale, and picked events from these plots. Events detected on long-period seismograms (12,558 events) were transferred onto another set of tapes (event tapes), and were plotted in an expanded time scale. Most of these data sets, including a catalog of detected events and a set of tapes containing selected major events, are now available on request from the National Space Science Data Center (NSSDC).

Seismicity -- Four distinct types of natural seismic sources have been identified: deep moonquakes, shallow moonquakes, meteoroid impacts and thermal moonquakes. Deep moonquakes are small-magnitude quakes that occur at depths about halfway to the center of the moon. About 3000 of them were observed each year. Since the last comprehensive study by Lammlein (1), many new sources have been found, giving a total of 107 distinct source regions identified to date. Of these, 52 have been located (Fig. 1). A number of linear patterns in the hypocenter distribution are now more conspicuous than in earlier locations. Several lines of evidence suggest that these quakes are not caused by tectonic stresses in the moon, but represent interaction of the earth's tidal force with the heterogeneity in the lunar interior (2). The non-random distribution of the hypocenters thus indicates large-scale heterogeneities in the deep interior of the moon.

Shallow moonquakes are rare (28 detected in 8 years), but are the most energetic seismic sources in the moon. Their existence shows that the lunar interior is still tectonically active. They are comparable to intra-plate earthquakes in many respects (3). Efforts to correlate them with lunar transient events have not been successful.

Meteoroid impacts tell us about the distribution of small bodies in the interplanetary space near the earth's orbit. About 200 large impacts (estimated mass greater than 1 kg) detectable at far ranges were observed yearly. Their temporal distribution is not random, but shows clustering.

Thermal moonquakes are the very small seismic disturbances caused by temperature variations at the lunar surface, and are detectable only at distances of up to a few kilometers (4). The LSPE data just processed show a large number of events at station 17, but the data have not yet been analyzed.

Internal structure -- Seismic arrival times have been used to estimate the seismic velocity profile of the lunar interior. Because of the paucity of seismic stations and usable seismic events, the uncertainties of the estimates are rather large. Despite this drawback, earlier estimates based on more limited data than now available were remarkably successful in depicting major features of the lunar interior (5,6). The more extensive data base now available allows us a more accurate estimation of the velocity profile, and we have just completed an inversion of the entire arrival time data set. The result is given in Table 1 and illustrated in Fig. 2. All indicated discontinuities except the one at the crust/mantle boundary are introduced for the convenience of calculation and therefore should not be taken as being real.

Fig. 1. Hypocenters of deep moonquakes (equal area projection). The length of crosses equals one standard deviation.
The new result differs from the structure determined by Goins et al. (6) in two major ways. First, both P and S velocities decrease with increasing depth in the upper part of the lunar mantle. We suggested this earlier from the amplitude data (5), but now it is confirmed by the arrival time data. Second, the velocities for both P and S waves in the lower part of the mantle are significantly higher than the earlier estimates, and may indicate different lithology from the upper mantle.

The seismic velocity structure below the level of deep moonquakes is not well known. The lack of observations of shear waves penetrating below this level, however, indicates that the lowermost zone of the lunar mantle may be in a partially molten state (7).

One important question is whether or not the moon has a metallic core. The seismic arrival-time data we now have do not answer this question clearly. The periods of free oscillation of the moon, if we can determine them, would be useful in this respect. An earlier attempt by Laudin (8) using large impact and shallow moonquake data gave only an inconclusive result. We found no evidence of weak excitation of free oscillations in the entire length of the lunar seismogram we recently analyzed. Thus the question remains.

Remaining problems -- From the Apollo seismic experiment, we have learned much about the moon, about its interior as well as its environment. The two most important findings are that the crust is clearly differentiated from the mantle, possibly with further differentiation within the mantle; and that the lunar interior is still tectonically active. However, many questions still remain to be answered.

Our main effort so far has been to determine the structure and seismicity of the lunar interior. Many other characteristics of the moon that are deducible from the data still need to be investigated. For example, the more than 1700 large meteoric impacts detected by the station network should tell us about the detailed distribution of these interplanetary bodies in the mass range of roughly from 1 kg to 10 kg. Smaller impacts recorded on PSE short-period and LSPE seismograms have not yet been counted. Focal mechanism of moonquakes, especially those which appear to be on linear trends, is another subject that need to be investigated further.

Proper interpretation of some observations requires further theoretical studies. Two such problems are the intensive scattering of seismic waves on the moon and the very low attenuation of seismic waves.

To solve certain other problems simply requires more data. There are some indications of lateral structural variations within the moon, but the available data are not sufficient to define them clearly. Finally, the question of the lunar core must wait till we have more observational data.