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Apollo Lunar Seismic Experiment—Final Summary

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Processing and initial analysis of the entire set of Apollo lunar seismic data collected continuously from 1969 through 1977 have now been completed. Recent results include: 1) better defined deep moonquake locations, which appear to be bounded rather sharply between about 800 km and 1000 km depths with concentrations near both boundaries; and 2) middle mantle (~500 to 1000 km depth) seismic velocities of $V_p = 8.3 \pm 0.4$ km/sec and $V_s = 4.6 \pm 0.2$ km/sec, which are significantly higher than previous estimates and represent an increase of velocities from the upper mantle as opposed to a decrease in previous estimates.

INTRODUCTION

The four-station seismic network on the moon, established during the Apollo lunar landing missions from 1969 through 1972, continued to operate until September 30, 1977, when reception of transmitted data was suspended. The data collected continuously for eight years and took several more years to process. We have now completed the processing of all Apollo Lunar Surface Experimental Package (ALSEP) data, including those collected in the listening (passive) mode from Lunar Seismic Profiling Experiment (LSPE) at the Apollo 17 station.

Results already published both by the University of Texas (Galveston) group and by the MIT group represent analyses of partial data sets. We have now completed analysis of the entire data set. This paper summarizes mainly the results of the Galveston group, covering several topics. We emphasize highlights of some recent results, details of which are being published elsewhere. Also included in this summary are some results which have not been published before because they are either extensions of previous results or are results reflecting what we now view as the limitations of the data set.

PROCESSED DATA SET

The data received from the lunar surface stations were initially recorded on instrumental tapes at NASA space communication stations around the world, and were processed to produce computer-compatible digital tapes. From the latter tapes, several convenient subsets of the data were then produced (Table 1). Processing details can be found in *Nakamura et al.* [1980]. Most of these data sets, including a catalog of detected events, microfilm copies of seismograms, and sets of magnetic tapes containing selected major events, are now available on request from the National Space Science Data Center (NSSDC), Goddard Space Flight Center, Greenbelt, Maryland, 20771. Descriptions of the available data sets are found in *Vostreys* [1980].

Analysis of the data begins with the detection and identification of seismic events. Table 2 gives a summary of more than 12,000 catalogued seismic events detected on the long-period seismograms during the operation of the network. Most of our analyses were done using these events. There is a much larger group of events detected only on short-period seismograms, but they have not yet been catalogued. Unclassified events include those which are too small to be classified by type of source and many suspected deep moonquakes which remain unclassified as to source region.

SEISMICITY

Four distinct types of natural seismic sources have been identified. They are deep moonquakes, shallow moonquakes, thermal moonquakes, and meteoroid impacts (Figure 1). They reflect the present dynamic state of the lunar interior and the interplanetary environment around the moon.

Deep Moonquakes

These, the most abundant type, are small-magnitude events that occur at depths about halfway between the surface and the center of the moon. Their occurrence is strongly correlated with the tides raised on the moon by the earth and the sun. Since the last comprehensive study by *Lammlein* [1977], many new sources have been identified, and a large number of additional events have been found at previously identified sources. The total number of distinct source regions identified to date is 109.

The nearly identical waveforms of individual moonquakes from a given source region allow us to use a stacking technique (addition of amplitudes of many seismograms) to improve the signal-to-noise ratio of seismograms. We used an optimum stacking technique described by *Robinson* [1970], wherein the signal-to-noise ratio is maximized by appropriately weighing individual seismograms. The use of P and S arrival-time readings from these newly stacked seismograms and the use of an improved velocity model (described later) have allowed us to locate source regions more accurately than before. Of 109 source regions identified by distinct waveforms, 52 have been located (Table 3). For nine of these source regions, the arrival-time data are not sufficient to determine the depths, thus they have been assumed.

Several features of the epicenter distribution (Figure 2), such as linear patterns, are now more conspicuous than in earlier maps. In addition to the two deep seismic belts identified by *Lammlein et al.* [1974], i.e., the east-northeast-to-west-southwest belt and the south belt, two more belts are

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TABLE 1. Processed Lunar Seismic Data

Data	Quantity	Event Catalog	Digital Data	Compressed Seismogram	Expanded Seismogram	Others
Continuous data	8 years		N	N		
All long-period events	12,558 events	N	N	N	G	
Selected events						
All artificial impacts	9 events	N	N	N	N	G
All shallow moonquakes	28 events	N	N	N	G	G
Major meteoroid impacts	98 events	N	N	N	G	G
Major deep moonquakes	1074 events at 33 hypocenters	G	G	G	G	G
Storage Medium		print microfiche card magtape	magtape	paper microfilm	paper microfilm	

N = complete set available from NSSDC; G = complete set available only in Galveston; Others include filtered, rotated and stacked seismograms and Fourier-transformed data.

now discernible in the northwest quadrant extending toward west and west-northwest. An apparent near symmetry of epicenter distribution in the northern hemisphere about the prime meridian perhaps reflects the bilateral symmetry of the tidal force which produces seismicity of this type.

We have previously noted the curious lack of locatable deep focus moonquakes in most of the southeastern quadrant. Deep moonquakes may truly be absent beneath this mostly highland region, or a localized high attenuation zone underneath the southeastern quadrant may be responsible for the absence of locatable deep moonquakes in this region. The fact that a large number of moonquakes were detected only at station 16, which is located within the southeast quadrant, gives support to the latter hypothesis.

The almost complete absence of located deep moonquakes on the far side of the moon (only the A_{33} source region is located on the far side beyond the eastern limb) also sustains similar speculations. The inferred existence of a partially molten zone in the lower mantle [*Nakamura et al.*, 1973] certainly can explain our inability to locate deep moonquakes on the far side [*Nakamura et al.*, 1976*b*]. However, this does not rule out the possibility that deep moonquakes are absent in the far side, which is again mostly covered with highland regions.

The improved locations of deep moonquake foci also show an interesting distribution inside the moon (Figure 3). Most foci occur within a clearly defined region between depths of 800 km and 1000 km. There also exist concentrations of foci near the top and the bottom of this region, suggesting the possible existence of two distinct deep moonquake zones. The histogram of Figure 4 displays this depth distribution more clearly, showing two peaks with fairly sharp drop-offs above 800 km and below 1000 km depths. This contrasts with the distribution inferred in previous studies, which found a broadly diffused zone of foci bounded below by the partially molten lower mantle. Earlier suggestions that deep moonquakes are caused by stress concentration due to a high contrast in rigidity or by fluid injection from below [*Nakamura et al.*, 1973] can explain only the deeper moonquakes near 1000 km depth. It now appears that we need another mechanism to explain the group of deep moonquakes occurring just below 800 km depth.

The process that causes deep moonquakes has been a subject of considerable discussion [e.g., *Toksöz et al.*, 1977]. Several lines of evidence now suggest that these quakes are not caused by tectonic stresses in the moon but rather represent dissipation of tidal energy in the moon generated by the relative motions of the earth and the sun [*Nakamura*, 1978; *Koyama and Nakamura*, 1980]. Tidal stresses concentrated at certain heterogeneities in the deep lunar interior appear to cause deep moonquakes to occur there, although more detailed studies are needed to clarify the mechanism.

TABLE 2. Catalogued Events

Type	Number of Events
Artificial impacts	9
Meteoroid impacts	1,743
Shallow moonquakes	28
Deep moonquakes	3,145
Unclassified	7,633
Total	12,558

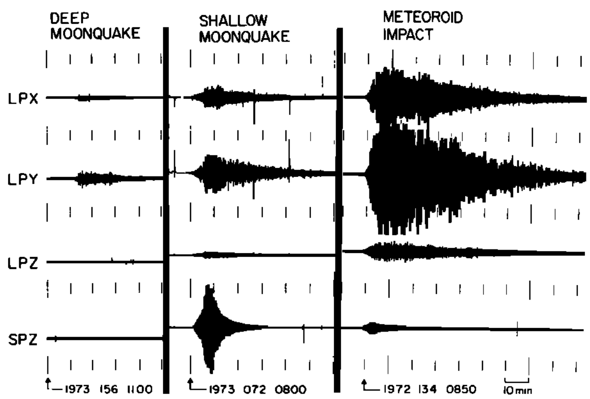

Fig. 1. Representative lunar seismograms in compressed time scale [from *Nakamura et al.*, 1974*b*]. All of these are for signals detected at the Apollo 16 station. LPX, LPY, and LPZ stand for three orthogonal components of a long-period instrument, and SPZ stands for a short-period vertical component. A typical thermal moonquake, not shown, would appear as a signal of very short duration on SPZ only on this type of display.

Shallow Moonquakes

Shallow moonquakes are the most energetic seismic sources we observed on the moon although they are rare compared with all the other types of seismic events. Their occurrence is not clearly correlated with the tides as in deep moonquakes, so they are quite likely to be tectonic in origin. Most, if not all, of them occur in the upper mantle of the moon [*Nakamura et al.*, 1979].

TABLE 3. Deep Moonquake Hypocenter Coordinates

Source A−	Latitude deg N	+−	Longitude deg E	+−	Depth km	+−
1	−16.6	2.7	−39.8	5.4	920.	29.
5	20.4	1.2	−41.0	3.6	703.	30.
6	42.8	2.8	55.0	9.7	853.	32.
7	24.6	1.6	53.8	7.5	875.	27.
8	−36.0	8.4	−36.4	7.2	*	
9	−7.7	2.5	−16.5	2.9	995.	66.
10	−47.6	8.5	−23.5	10.2	*	
11	7.1	0.6	8.1	1.4	825.	63.
14	−24.7	12.3	−36.6	7.1	*	
15	−3.8	1.5	0.5	0.6	817.	68.
16	8.6	1.3	4.3	1.6	1153.	88.
17	25.5	2.3	−22.0	2.8	814.	40.
18	22.9	2.4	32.1	5.4	915.	47.
19	14.3	1.3	35.9	6.1	807.	41.
20	24.2	2.5	−34.6	6.0	969.	47.
21	−13.0	2.7	−38.6	5.6	969.	32.
24	−35.3	4.3	−40.3	6.4	987.	27.
25	35.9	1.8	65.9	11.5	961.	33.
26	15.5	2.8	7.6	2.3	1132.	86.
27	22.2	3.1	19.8	4.3	1047.	68.
28	11.2	7.0	28.6	8.4	1052.	86.
30	11.9	1.1	−34.9	4.6	918.	39.
31	15.9	3.2	9.7	3.0	1181.	91.
32	24.7	2.9	33.0	5.6	941.	47.
33	4.6	2.4	116.5	9.1	898.	112.
34	7.7	0.9	−7.7	1.4	993.	74.
36	66.7	9.5	−15.2	8.2	1016.	26.
39	−18.8	3.9	−9.2	1.6	939.	57.
40	−1.4	1.3	−11.8	1.6	898.	62.
41	17.9	1.4	−33.0	4.0	801.	35.
42	24.4	1.6	−54.8	6.9	925.	27.
44	61.6	3.7	52.7	12.6	930.	42.
50	9.7	1.0	−53.2	5.0	832.	26.
51	10.6	2.1	33.2	7.6	1179.	69.
53	−31.0	11.4	−32.2	7.1	*	
54	8.7	1.4	−60.1	6.7	968.	27.
55	−35.7	12.5	−8.7	10.2	*	
56	11.3	1.3	−42.3	6.2	966.	36.
57	−49.9	8.4	−27.1	14.6	*	
60	28.8	2.2	−81.9	9.1	*	
61	23.7	2.1	44.5	6.1	805.	34.
70	32.4	3.5	50.2	10.6	983.	32.
71	13.0	1.6	−11.8	2.1	947.	75.
82	24.8	2.3	30.4	4.4	871.	43.
84	−12.7	2.4	−31.7	4.1	877.	34.
85	28.7	1.3	69.7	7.1	819.	58.
90	−35.7	14.1	12.0	3.6	*	
94	−46.0	22.2	−25.2	16.9	*	
97	0.8	1.3	17.0	3.6	960.	77.
101	19.7	1.7	−28.6	3.6	777.	41.
106	40.8	2.4	51.3	6.8	835.	36.
109	6.8	1.5	44.5	7.5	1065.	45.

The numbering of source regions follows that of *Lammlein* [1977]. His source regions A45, 46, 47, and 48 are not listed separately here because they are in the same source region as A1 [*Nakamura*, 1978]. Similarly, A62 of *Goins et al.* [1981] is the same as A6.

Columns headed by +− indicate the ranges of one standard error.

*Assumed to be 933 +− 109 km, the mean and standard deviation of the determined depths of the other 43 source regions.

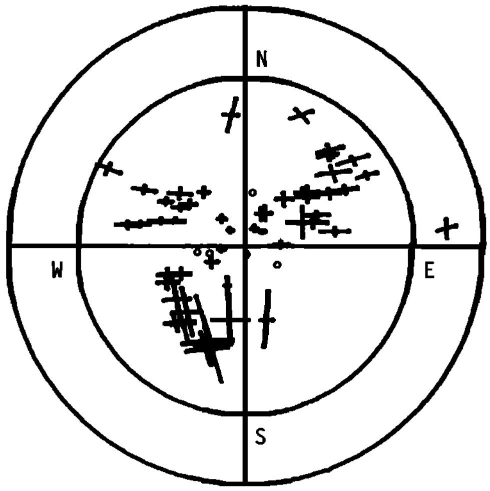

Fig. 2. Distribution of deep moonquake source regions. Each source region contains a large number of epicenters. The base map is the entire surface of the moon in an equal area projection. N and S represent the north and the south poles, respectively, the inner circle is the limb of the moon and the outer circle is the antipode. The length of crosses equals one standard error. Seismic stations are indicated by small circles.

Nakamura et al. [1980] have shown that several characteristics of shallow moonquakes are common to those of intraplate earthquakes. For example, both shallow moonquakes and intraplate earthquakes appear to occur in zones of preexisting weakness in a lithospheric plate; also the relative abundances of large and small quakes are similar, suggesting that similar mechanisms generate them on both planets. Shallow moonquakes may be quite representative of the tectonic quakes one would expect to find in the lithosphere of a single-plate planet.

Thermal Moonquakes

These are the very small seismic disturbances caused by temperature variations at or near the surface of the moon [*Duennebier and Sutton*, 1974*b*]. They are detectable only at distances up to a few kilometers from a seismic station. The mechanism for their generation is not well understood, though they seem to originate at young craters and large rocks [*Duennebier*, 1976]. They probably represent thermal degradation processes acting upon relatively young lunar surface features.

Meteoroid Impacts

The origin of meteoroid impacts is clearly not internal to the moon, and thus they do not represent true lunar seismicity. However, meteoroid impacts observed by the lunar seismometers are an important source of information on the interplanetary environment. Those meteoroids detected by the long-period seismometers (Table 2) have estimated masses in the range from 500 g to 50 kg [*Duennebier et al.*, 1975], while the much more numerous impacts detected by short-period seismometers [*Duennebier and Sutton*, 1974*a*] and the LSPE geophones represent those of smaller masses.

The seismic data clearly show that the large meteoroids are not distributed evenly in the surrounding interplanetary space, but show clustering [*Duennebier et al.*, 1976]. Some of these clusters may be related to known meteor showers [*Dorman et al.*, 1978]. Statistical studies of the distribution

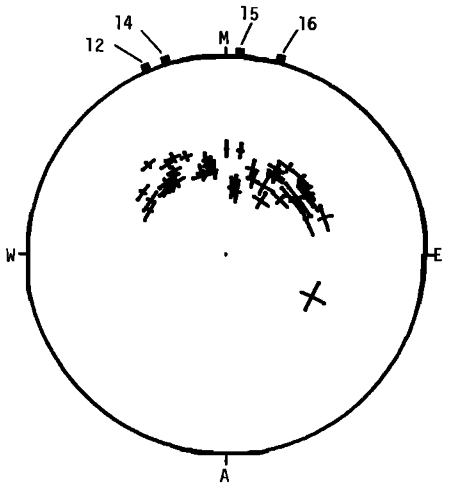

Fig. 3. Distribution of deep moonquake foci in depth and longitude. M, A, E, and W indicate prime meridian, anti-prime meridian, east limb and west limb, respectively. Small squares with numbers indicate the locations of Apollo seismic stations. The length of crosses equals one standard error.

of these impacts reveal many interesting features. For example, the distribution of intervals between consecutive detections of impacts (Figure 5) indicates that about 20% of the impacts detected by the long-period seismometers during the final five years of the network operation (after the installation of Apollo 16 station to complete the network) were actually concentrated within 3% of the time, while the remaining 80% of the detected impacts were distributed more or less randomly throughout the entire time period. Further analysis of the details of the distribution of impacts should reveal more about the nature of these small bodies in interplanetary space.

INTERNAL STRUCTURE

Seismic arrival times from various types of events, mostly from those listed as selected events in Table 1, have been the primary source of data from which to estimate the seismic velocity profile of the lunar interior. In addition, some secondary information such as amplitude has also been used. Because of the paucity of seismic stations and of usable seismic events, the uncertainties in the estimates are rather large. Despite this problem, earlier estimates based on more limited data than now available were remarkably successful in elucidating the major features of the lunar interior [e.g., *Nakamura et al.*, 1976*a*; *Goins et al.*, 1981].

The more complete data base we now have allows us to make a more accurate estimation of the velocity profile, and

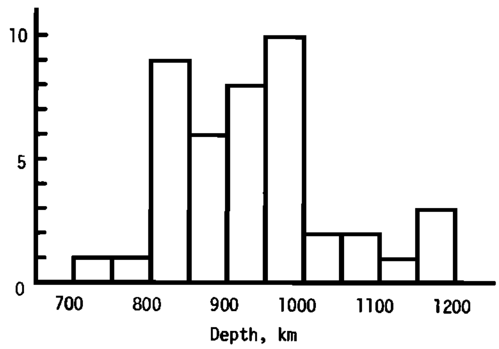

Fig. 4. Histogram of deep moonquake depth distribution.

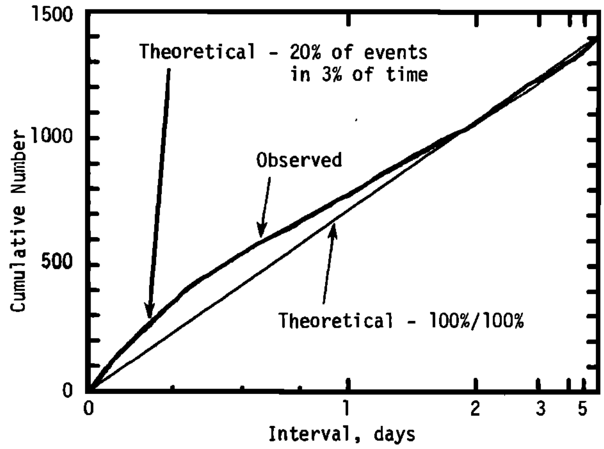

Fig. 5. Distribution of intervals between consecutive observations of meteoroid impacts on the moon from April 21, 1972, through September 30, 1972, on long-period seismograms. The horizontal scale is proportional to 1–exp (–rt), where r is the average rate of impact observations per unit time and t is the observed interval. The straight line marked 'theoretical—100%/100%' represents a completely random distribution for all impacts. The other theoretical curve, almost indistinguishable from the observed curve, represents 20% of impacts concentrated within 3% of the time.

we have just completed an inversion of the entire available arrival time data set (Table 4 and Figure 6). We used a linearized least-square inversion technique, a detailed description of which is outside the scope of this summary (a paper in preparation). All indicated discontinuities except the one at the crust/mantle boundary (58 km) are introduced for the convenience of calculation, and therefore should not be taken as being real.

For depths less than 500 km, the new result is similar to previous results. This is to be expected because the amount of arrival-time data that have direct relevance to this part of the lunar interior increased only modestly from the last such computation. For depths below 500 km, however, improvements in both the quality and the quantity of the relevant deep-moonquake data have significantly altered the result from previous estimates, as described below.

The new results differ from the structure determined by *Goins et al.*, [1981] 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 based on the amplitude data [*Nakamura et al.*, 1979*a*], but now it is confirmed by the arrival time data. A decrease of seismic velocities with depth is expected for a lunar upper mantle of uniform composition [*Nakamura and Latham*, 1969]; thus this result is consistent with such a model.

Second, the seismic velocities for both P and S waves below 500 km depth are significantly higher than those in the

TABLE 4. Arrival Time Inversion Result

Depth km	V_p km/sec	V_s km/sec
0–1	0.51	0.30
1–15	4.90	2.84
15–30	6.25	3.62
30–58	6.68	3.87
58–270	7.74 ± 0.12	4.49 ± 0.03
270–500	7.46 ± 0.25	4.25 ± 0.11
500–1000+	8.26 ± 0.40	4.65 ± 0.16

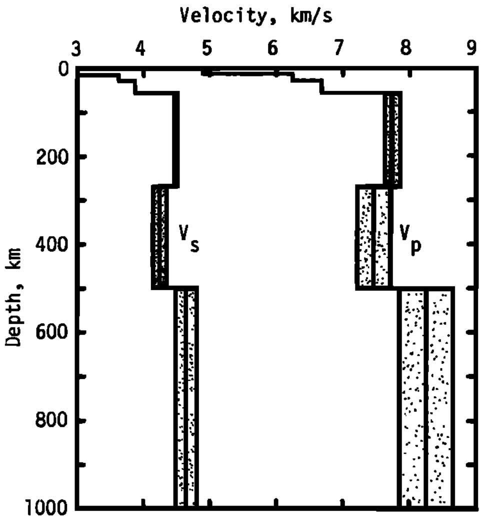

Fig. 6. Seismic velocity profile of the moon above 1000 km depth estimated from the arrival time data. Shaded areas indicated the ranges of one standard error.

upper mantle. This is contrary to most earlier results, which indicated that velocities in this zone are lower than those in the upper mantle. Since the expected pressure at these depths is certainly not enough to cause a large velocity increase in a mantle of uniform composition, the newly found increase of velocities in the middle mantle indicates that lithology for this part of the lunar mantle differs from that of the upper mantle.

Further variations in the velocity profile between 500 and 1000 km depths may well exist considering the sudden disappearance of deep moonquakes above about 800 km depth as discussed above. However, they could not be determined from the available arrival time data.

The seismic velocity structure below the level of the deep moonquakes is less well determined because few large seismic events were sufficiently distant from the seismic stations to produce seismic rays penetrating below the 1000 km depth. The available data indicate no significant variations in the P velocity at least down to a depth of about 1400 km [*Nakamura et al.*, 1974*a*]. In contrast, S waves penetrating below about 1000 km depth are not observed. This indicates that the lunar mantle below this depth maybe in a partially molten state [*Nakamura et al.*, 1973].

One important question which might be answered by seismology is whether the moon has a metallic core. Analysis of observations from a single farside impact has suggested the possible existence of a small low-velocity core [*Nakamura et al.*, 1974*a*]. However, no additional distant impacts occurred to confirm this possibility before the termination of the experiment.

The periods of free oscillations of the moon, if known, would be relevant to the question of the possible core. An earlier attempt by *Loudin* [1979] to extract free oscillation periods from the seismograms of two large meteoroid impacts was inconclusive. We recently searched for possible weak excitation of free oscillations through the entire interval when the long-period instruments were operated in the flat mode (instrumental response extended to low frequencies) in 1976 and 1977. We found no evidence of such excitation. Thus the question of the existence of a metallic core remains unresolved.

Table 5 and Figure 7 summarize our best estimates of the seismic structure of the lunar interior. Uncertainties of velocities are large, especially at great depths. The boundaries between the various zones are not clearly defined except for the crust/mantle interface. Nevertheless, the overall structural divisions are clearly indicated. The limited depth ranges within which moonquakes occur also show the zoned nature of the lunar interior. The seismic Q's in the upper mantle are extremely high, especially for shear waves. Furthermore, the shear wave Q is also frequency dependent [*Nakamura and Koyama*, 1982].

It is interesting to compare the lunar interior with that of the earth. In physical terms (as opposed to mineralogical terms, which seismology can address only indirectly), the entire lunar interior may be considered to be equivalent to the upper few hundred kilometers of the earth's interior. The pressure at the center of the moon (about 5 GPa; the radius of the moon is 1738 km) is reached at about 150 km depth in the earth. Thus the physical behavior of rocks in the deep lunar interior may be quite similar to those of the upper mantle of the earth.

The entire lunar interior may be viewed as a stretched version of the top 150 km of the earth's interior. The upper 1000 km of the lunar interior may be compared to the lithosphere of the earth, and the partially molten lunar interior below about 1000 km depth may be comparable to the terrestrial asthenosphere. The thick lithosphere of the moon is unlikely to break up into several plates as in the earth, thus creating a single-plate situation for the moon. Shallow moonquakes, which are like intraplate earthquakes, occur within and near the top of this single-plate lithosphere; while deep moonquakes, for which we find no terrestrial counterpart, occur near the bottom. Although the depths of deep moonquakes are greater than those of any observed earthquakes (deepest at about 700 km), the physical conditions at the depths of deep moonquakes are similar to those found about 100 km below the earth's surface.

TABLE 5. Summary of Lunar Structure

Depth km	Zone	V_p km/sec	V_s km/sec	Q_p	Q_s	Moonquakes (km)
	Crust	0.1–6.7	0.05–3.9	~6000	~6000	
55–60						
	Upper mantle	7.7–7.5	4.5–4.2	4000+	4000–7000+	Shallow (60–100)
~500						
	Middle mantle	8.3	4.6		~1500	Deep (800–1000)
~1000						
	Lower mantle	~8	—		<100	
1300–1600?						
	Core?	4–6				

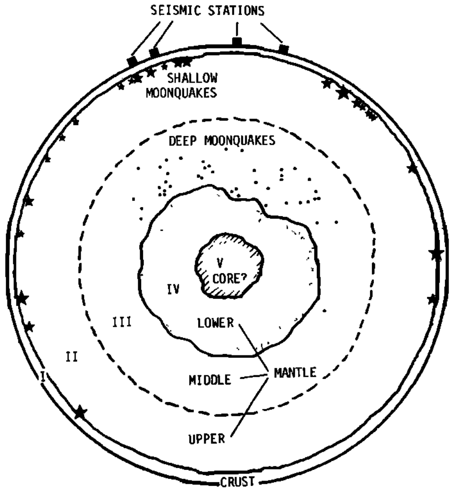

Fig. 7. Schematic diagram of the lunar interior inferred from the Apollo seismic data.

Remaining Problems

Our main research effort so far has been to determine the structure and seismicity of the lunar interior. The two most important findings are that the lunar interior is still tectonically active, and that the lunar crust is clearly differentiated from the mantle, possibly with further differentiations within the mantle. However, many other characteristics of the moon and its environment may still be investigated with the data in hand.

The more than 1700 large meteoroid impacts detected by the long-period seismometers of the station network should provide information about the detailed distribution of those interplanetary objects whose masses range roughly from 1 to 100 kg and whose orbits cross that of the earth-moon system. Much more numerous impacts recorded on short-period and LSPE seismograms can provide information about objects of smaller masses.

The focal mechanism of moonquakes has been studied for only one source region so far [*Nakamura*, 1978; *Koyama and Nakamura*, 1980]. Others, especially those which appear to lie on linear trends, also need to be investigated.

Proper interpretation of some observations will require further theoretical studies. One such problem is the intense scattering of seismic waves in the moon. A good understanding of the scattering processes near the surface of the moon undoubtedly will lead to a better interpretation of observed seismograms. This would allow better determination of the internal structure of the moon and of the focal mechanisms of moonquakes.

To solve certain other problems simply requires more data, which are not likely to be available in the near future. For example, there are several lines of evidence that indicate the presence of lateral structural variations within the moon. However, the available data are not sufficient to define them clearly. In addition, extended observations would be necessary to learn more about shallow moonquakes, the only truly tectonic quakes in the moon. Someday, we might be able to deploy a small network of seismometers for possible monitoring of aftershocks immediately following detection of a large magnitude shallow moonquake. Finally, the question of the existence and composition of the lunar core must await more observational data from sources near the antipode of a seismic array.

The Apollo seismometers on the moon could be turned on again at any time before their power supplies—radioactive thermal generators—cease operation if funding were available to record the data. Since this is not likely, we must look forward to our next chance in some distant future.

Concluding Remarks

The Apollo lunar seismic experiment has been a long-lasting project, continuing more than a decade. The results of the experiment, as summarized above, have greatly exceeded our expectations. The experiment, thus, has been a great success. However, the more we learn about the moon, the more questions we generate, and we sincerely hope that the future generations will strive to find answers to these questions using the greatly advanced technology available to them compared with the Apollo instrumentation of the 1960's.

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