

## Elastic wave velocities of lunar samples at high pressures and their geophysical implications

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**Abstract**—Ultrasonic measurement of  $P$  and  $S$  velocities of Apollo 11 lunar samples 10020, 10057 and 10065 to 5 kbar pressure at room temperature shows a pronounced increase of velocity (as much as twofold) for the first 2 kbar. The travel times predicted from the velocity–depth curve of sample 10057 are consistent with the results of the Apollo 12 seismic experiments. At pressures below 200 bar, the samples are highly attenuating; for both  $P$  and  $S$  waves, the value of  $Q$  is about 10.

MEASUREMENT of the velocities of elastic waves in lunar samples has two objectives: (1) to provide the basic data necessary for interpreting lunar seismograms and (2) to study properties of rocks which were formed under extra-terrestrial environments. Seismic data combined with laboratory data provide the most direct clues to the understanding of the lunar interior. In addition, mechanical, thermal and chemical processes near the lunar surface may be inferred from the properties of the rocks. We present here the  $P$ - and  $S$ -wave velocities measured up to 5 kbar pressure on the Apollo 11 samples and data obtained on simulated lunar rocks with the composition obtained from the alpha scattering experiment of Surveyor V. Comparison will be made with the results obtained in the Apollo 12 seismic experiments. The samples were provided by NASA in the form of a rectangular cylinder [ $1 \times 1 \times 2$  cm, see Table 1 and NASA (1969)].

We estimated the intrinsic density of sample 10057 which contains numerous voids. Assuming that the ratio of the total cross-section area of the voids on the surface to the total surface area of the sample is equal to the porosity, we obtained a porosity of 17.4 per cent and intrinsic density of  $3.38 \text{ g/cm}^3$ . Sample 10020 has few visible voids; the intrinsic density probably does not exceed the bulk density ( $3.18 \text{ g/cm}^3$ ) by more than 10 per cent. Sample 10057 is the largest and the most uniform, though probably weakly to moderately shocked, rock return on Apollo 11 (NASA, 1969); it is similar to basalt. Sample 10020 is a fine-grained igneous rock containing plagioclase, pyroxene and minor olivine and cristobalite. Sample 10065 is a fine-grained breccia (terrestrial analogue, micro-breccia), and has a bulk density of  $2.35 \text{ g/cm}^3$ .

The standard pulse transmission technique of BIRCH (1960) with 1 MHz barium-titanate transducers for both  $P$  and  $S$  waves was used. High-pressure measurements were made in a simple piston-cylinder high-pressure cell with petroleum ether as the pressure medium. Samples were jacketed by copper foil or rubber tubing, or encapsulated with Sylgard. The average values of the results obtained by several runs with different sample-transducer assemblies are listed in Table 1. The estimated accuracy is

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Table 1. Bulk density and velocity (in km/sec) of samples

Sample		Pressure (kbar)						
		0-0	0-5	1-0	2-0	3-0	4-0	5-0
10020	<i>P</i>	3.50	4.80	5.55	6.30	6.80	7.00	7.20
$\rho = 3.18 \text{ g/cm}^3$	<i>S</i>	2.20	2.88	3.25	3.67	3.87	4.00	4.08
10057*	<i>P</i>	2.82	3.80	4.65	5.62	6.18	6.52	6.78
$\rho = 2.88 \text{ g/cm}^3$	<i>S</i>	1.70	2.45	2.82	3.20	3.39	3.50	3.62
10065	<i>P</i>	1.50	2.90	3.50	4.05	4.30	4.30	4.50
$\rho = 2.34 \text{ g/cm}^3$	<i>S</i>	1.05	1.70	2.00	2.28	2.42	2.65	2.78

\* This sample is densely pitted. The estimated intrinsic density is  $3.38 \text{ g/cm}^3$ .

2–3 per cent for *P* waves and 5 per cent for *S* waves. These accuracies are considerably lower than those normally achieved because of the small size of the samples and the high attenuation. The example given in Fig. 1 is typical of the behavior of the velocity with pressure of lunar rocks. The velocity increase of about twofold for the first 2 kbar pressure increase is much more pronounced than in earth rocks.

The elastic properties of the Apollo 11 crystalline rocks appear to be representative of the material in the Sea of Tranquillity. A second set of observations may be obtained from the data of Surveyor V, recorded about 25 km northwest of the Apollo 11 landing site. Simulated Surveyor V lunar rocks were synthesized with their chemical composition given by the alpha back scattering experiment. The mineralogical composition of the simulated rocks closely approximates that of Apollo 11 rocks. The composition (in mole%) of the simulated rocks are for plagioclase, 30–44; pyroxene, 45–60; and free silica, 6–10.

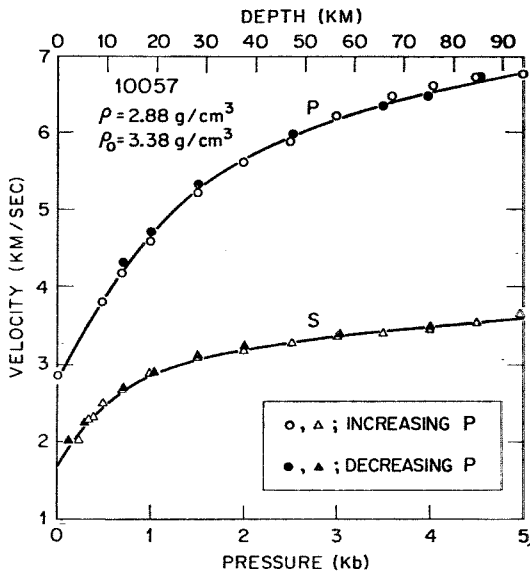


Fig. 1. *P* and *S* velocities of sample 10057 as a function of pressure.  $\rho$  is bulk density and  $\rho_0$  is estimated intrinsic density. The upper scale gives depth in the moon converted from the pressure.

Table 2. *P* wave velocities at 10 kbar, extrapolated from data in Table 1

Sample	Density (g/cm <sup>3</sup> )	<i>V</i> <sub>p</sub> at 10 kbar (km/sec)	Note
10020	3.18	7.35	crystalline
10057	2.88 (3.38)*	7.00	crystalline
10065	2.34	4.65	breccia

\* Intrinsic density.

Because the velocities of elastic waves measured on the simulated rocks ( $\rho = 2.8$ ,  $V_p = 6.2$  and  $V_s = 3.5$ ) closely approximate the intrinsic properties of the Apollo 11 rocks (extrapolated to zero pressure to eliminate the effects of microcracks), neither having been corrected for porosity, we believe that our results apply to the entire area of the Sea of Tranquillity.

The densities and the *P*-wave velocities at 10 kbar (Table 2) extrapolated from the data of sample 10057 fall on the curve of mean atomic weight of about 23 in BIRCH's (1961) diagram (Fig. 2) of velocity–density–mean atomic weight. This value of mean atomic weight agrees reasonably well with that calculated from the chemical composition (LSPET, 1969) of the Apollo 11 samples, 23.0–23.7. This agreement suggests that BIRCH's diagram can be used for the interpretation of the lunar interior.

The extremely low velocities at normal pressures are probably due to the presence of micro-cracks between grains; they may have formed either by the large temperature fluctuations of the lunar surface or by shock metamorphism. Microscopic examination of the thin sections revealed cleavage fractures, but no through-going fractures.

The lunar samples have a very high attenuation (low *Q*) at low pressures for elastic waves. Although we could not measure precisely the value of *Q*, we estimate its order-of-magnitude by measuring the ratio of the amplitude of the signal through the

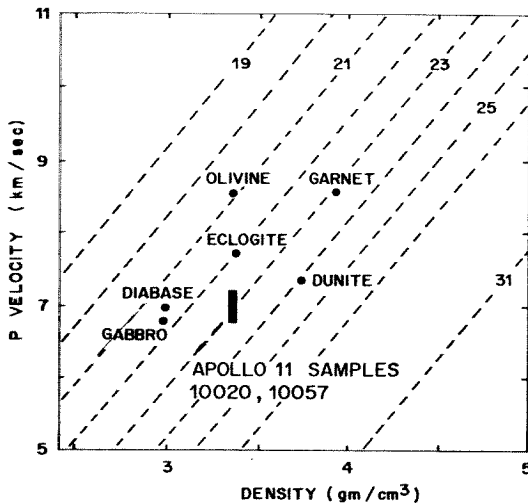


Fig. 2. Apollo 11 data in BIRCH's diagram of velocity–density–mean atomic weight. The value obtained from velocity data agrees well with that calculated from the chemical composition.

sample to that through a steel test piece having the same size and shape as the sample. If we assume that the effect of  $Q$  dominates over those of geometrical ray spreading and internal reflections and that the steel has a much higher  $Q$  than the sample, then the value of  $Q$  can be calculated approximately from the amplitude ratio  $a$  by  $a = \exp [-\pi ft/Q]$  where  $f$  is frequency and  $t$  is travel time through the sample. At low pressures ( $P = 200$  bar), the values of  $Q$  are of the order of 10 for both  $P$  and  $S$  waves for all the samples. At high pressures, all the samples, and in particular 10020, showed an appreciable increase in  $Q$ . It was not possible, however, to determine the value of  $Q$  because the assumptions made above are not valid for high- $Q$  samples.

The fact that two of the samples (10020, 10057) have densities nearly equal to the bulk density of the moon,  $3.34 \text{ g/cm}^3$ , it noteworthy; rock samples collected, at random, on the earth's surface would represent the density of neither the bulk earth

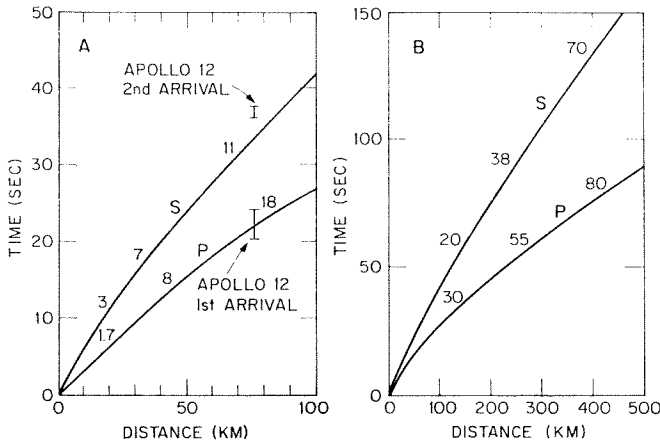


Fig. 3. The travel-time curve for the moon predicted from the velocity-depth curve of 10057 (Fig. 1), the most uniform sample. The times of the first and second arrivals in the Apollo 12 seismogram (6) are shown in A. The numbers on the curve indicate the depth (in km) of the penetration of the ray. B is the travel-time curve to a larger distance.

nor the mantle. One implication of this finding is that the vertical differentiation process in the moon may have been much less extensive than that in the earth; the structure of the moon may be relatively homogeneous without well defined crustal layers. This idea can be tested by comparing our laboratory data with the results obtained in the Apollo 12 seismic experiment. If the dense samples 10020 and 10057 are representative of the lunar material, we can predict, ignoring the temperature effect, the depth variation of seismic waves in the moon (see Fig. 1), from which the travel-time curve of seismic waves can be predicted as shown in Fig. 2. In the Apollo 12 seismogram which recorded the impact of the ascent module, two distinct arrivals were detected (LATHAM, 1969); the first at 20.1–24.1 sec and the second at 37.5 sec after the origin time. The epicentral distance is 75.9 km. As shown in Fig. 3, these arrival times agree with the predicted  $P$  and  $S$  arrival times remarkably well. Although the second arrival has not been confirmed as  $S$ , our proposed undifferentiated moon

model is at least compatible with the seismic results. This agreement also suggests that the special textures (probably micro-cracks) of the samples also prevails at depths down to 20 km or so. These micro-cracks may have important bearings on the physical processes that have taken place on the lunar surface, and deserve more extensive investigation in the future.

If the samples 10020 and 10057 are representative of the lunar material, an efficient wave guide must exist near the lunar surface because of the sharp velocity increase with depth. Calculations of surface-wave dispersion curves made for the structure predicted from the velocity–pressure curve of the sample 10057 show a relatively constant group velocity (velocity, 1.57 km/sec) of Rayleigh waves over a period range 0–5 sec. If future seismic experiments confirm this dispersion character, the evidence for an undifferentiated moon will be strengthened. If, on the other hand, significant deviation from the predicted dispersion curves is found, it will indicate the existence of structural heterogeneity at depths due to temperature, phase change and compositional change.

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