

Elastic wave velocities of Apollo 12 rocks at high pressures

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(Received 20 February 1971; accepted 24 March 1971)

Abstract—New results of P- and S-wave velocity measurements on two Apollo 12 rocks, 12052 and 12065, under pressures up to 10 kbars are presented. These rocks are basalt-like crystalline rocks with a bulk density of about 3.26 g/cm^3 and a mean atomic weight of 24.5. Like the Apollo 11 rocks, the velocities and the wave transmission efficiency are surprisingly low at low pressures despite their relatively tight texture; at pressures below 200 bars, Q is estimated to be less than 100. The velocities increase very rapidly with pressure and approach 7.0 km/sec (P wave) and 3.9 km/sec (S wave) towards 10 kbars. No evidence is found for an increase of Q at 1 MHz with a reduction of the ambient pressure to 3×10^{-3} torr.

THIS REPORT presents new results of P- and S-wave velocity measurements on two Apollo 12 crystalline rocks, 12052,35 and 12065,68 under pressures up to 10 kbars at room temperature. The chemical composition of these rocks has been given by LSPET (1970) and KUSHIRO and HARAMURA (1971). These two rocks closely resemble one another in composition and are, on the whole, of basaltic composition. The mean atomic weight of these rocks as calculated from the data given by KUSHIRO and HARAMURA is 24.5 and is significantly larger than that of ordinary terrestrial basalts.

The measurement method described by MIZUTANI *et al.* (1970) and the high-pressure system used by KANAMORI and MIZUTANI (1965) are employed. Since the method of MIZUTANI *et al.* was originally devised for very small samples (several millimeters in dimension), it ensures a high accuracy when applied to samples the size of the Apollo 12 rocks; the approximate dimension of the samples is $1 \times 1 \times 2 \text{ cm}^3$. At pressures above 1 kbar, the accuracy of the present measurement is probably better than 0.7% for P waves, and 1.5% for S waves. At pressures below 200 bars, however, the wave transmission efficiency is so poor (low Q) that the onset of the signal becomes blunt and the accuracy drops considerably.

The results are summarized in Table 1 and Figs. 1 and 2; Figs. 1 and 2 give the original readings, and Table 1 lists the smoothed values. Because the samples have large compressibilities, the correction for the pressure shortening of the sample is estimated. This correction is made according to COOK (1957) but the difference between the isothermal and adiabatic bulk modulus is ignored. In such case the true P- and S-wave velocities $\alpha(P)$ and $\beta(P)$ at a pressure P can be obtained from the

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

Sample	Wave	Pressure (kb)								
		0.0	0.2	0.5	1.0	2.0	3.0	5.0	7.0	10.0
12052 $\rho = 3.27 \text{ g/cm}^3*$	P	4.30	4.90	5.55	5.93	6.32	6.55	6.80	6.90	7.01
	S	2.59	2.70	2.84	3.03	3.34	3.55	3.74	3.82	3.88
12065 $\rho = 3.26 \text{ g/cm}^3*$	P	3.27	4.44	5.21	5.80	6.24	6.47	6.74	6.86	6.96
	S	2.14	2.42	2.73	3.04	3.38	3.54	3.72	3.82	3.86

* No correction is made for the porosity.

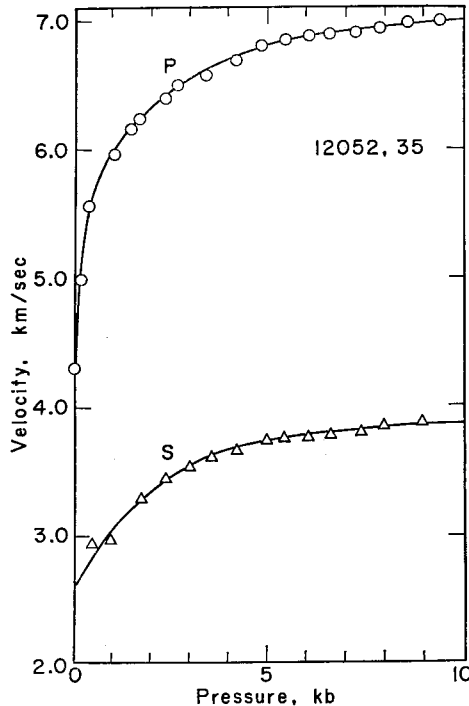


Fig. 1. The P- and S-wave velocities of sample 12052,35 as a function of pressure.

uncorrected P- and S-wave velocities $\alpha'(P)$ and $\beta'(P)$ by

$$\frac{\alpha(P)}{\alpha'(P)} = \frac{\beta(P)}{\beta'(P)} = \left[1 + \frac{1}{3\rho_0} \int_0^P \frac{dP}{(\alpha'(P)^2 - \frac{4}{3}\beta'(P)^2)} \right]^{-1}$$

where ρ_0 is the density at 0 pressure. Numerical integration of $\alpha'(P)$ and $\beta'(P)$ listed in Table 1 leads to a correction of only 0.4% at 10 kbars; this correction is therefore not meaningful in view of other experimental uncertainties. It may be argued that the static compressibility data are more appropriate for this correction than the ultrasonic data. The static compression data on the Apollo 12 rocks reported by STEPHENS and LILLEY (1971) lead to a correction of about 0.8% (at 10 kbars) which is still

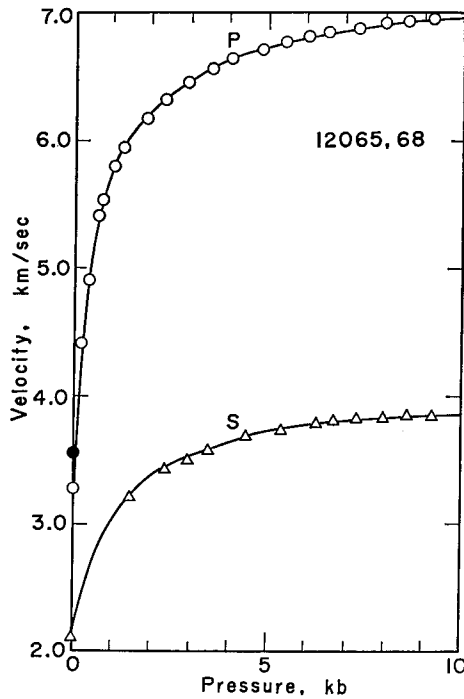


Fig. 2. The P- and S-wave velocities of sample 12065,68 as a function of pressure. The solid circle at 0 pressure indicates the velocity obtained after the pressure run.

insignificant. The densities are measured by the Archimedes method at 0 (atmospheric) pressure, and no correction is made for the porosity.

The overall elastic and anelastic behaviors of the Apollo 12 crystalline rocks are surprisingly similar to those of the Apollo 11 rocks reported by KANAMORI *et al.* (1970) and SCHREIBER *et al.* (1970). The rapid increase of the velocity for the initial 2 kbar pressure increase found for the Apollo 11 rocks is also typical of the Apollo 12 rocks. Although the velocity of the Apollo 12 rocks is slightly larger than that of the Apollo 11 rocks, it is still consistent with the travel times obtained by the Apollo 12 seismic experiments (LATHAM *et al.*, 1970), if the vertical velocity gradient beneath the lunar surface is caused by compaction alone. Thus the conclusion that the shallow part (to a depth of about 20 km) of the mare region consists of relatively homogeneous basalt-like material (KANAMORI *et al.*, 1970; LATHAM *et al.*, 1970) seems to be substantiated.

The wave transmission efficiency, at low pressures, of the Apollo 12 samples is surprisingly poor; it is much poorer than would be expected from the apparently tight textures of these samples. The wave transmission efficiency is frequently specified by the quality factor Q , where $2\pi/Q$ is the fractional loss of energy per cycle of oscillation of a vibrating system. Although the value of Q could not be measured accurately, a crude comparison of the amplitude of ultra-sonic waves transmitted through these lunar rocks with those through ordinary terrestrial rocks suggests that the value of Q

cannot be larger than 100 at pressures below 200 bars. This value may be compared with the value $Q \sim 20$ obtained by WANG *et al.* (1971) at a frequency of a few Hz, and with the value on the order of 100 obtained by WARREN *et al.* (1971) over a frequency range of 40 to 13 kHz. These values are much smaller than that required to explain the seismic ringing in terms of a diffusive and a dispersion process (LATHAM *et al.*, 1970). PANDIT and TOZER (1970) suggested on an experimental basis that, when the ambient pressure is reduced to 10^{-2} torr, the value of Q in porous terrestrial rocks increases by a factor of 5 over the value measured at 1 atmosphere. In order to see whether the pressure effect on Q is significant or not, we bonded 1 MHz transducers directly on the sample 12065,68, suspended it by a thin wire in a vacuum chamber, and observed the change with pressure of the decay rate of the ultra-sonic reverberation. No significant change of the decay rate, however, was observed over the range from 1 atmosphere to 3×10^{-3} torr. Since this experiment was made on a sample which had been subjected to high confining pressures during the velocity measurements, it is possible that the lossless "welded" contact had been destroyed and that the frictional dissipation became significant. It is also possible that the scattering at the grain boundaries is so large at such a high frequency, 1 MHz, that any pressure effect on the attenuation is masked. In any case, the increase of Q with a reduction of ambient pressure could not be confirmed in our experiment.

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