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Structure in the upper lunar crust

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Estimates are made of the degree of lithification and of structure densities which are compatible with lunar *in situ* seismic profiles in the top 30 km of the Moon. Estimates are based on comparison of results of passive and active lunar seismic experiments with the pressure dependence of elastic moduli for various classes of lunar samples. Competent rock, such as igneous rock or recrystallized breccias with crack porosity of not more than about 0.5 % are required to satisfy velocity profiles in the depth range 1–30 km. Velocity profiles in the upper 1 km are best satisfied by comminuted material to highly fractured lithic units. These estimates constrain those thermal and shock histories which are compatible with lunar seismic results. After crystallization, or recrystallization, rock below 1 km cannot have been exposed to more than moderate shock levels. In the uppermost 1 km, an unannealed and broken rock layer would imply low thermal conductivity resulting in possible temperatures at 1 km depth of several hundred kelvins.

Introduction

As part of the lunar geophysical effort, measurements have been made of the elastic and anelastic properties of lunar samples. Many of these measurements have been made to aid in interpreting results of lunar *in situ* seismic measurements.

As is well documented in the literature, the chief characteristics of the lunar seismic observations are the very steep average velocity profile in the first 4 km of the Moon, and the extreme scattering and very low acoustic loss factors in this same region. Laboratory measurements have demonstrated that these properties are compatible with extensively outgassed and fractured rock. However, a quantitative relation is needed between ultrasonic and seismic properties on one hand, and petrographic observables on the other hand, in order to allow resolution of the rock structure. This would provide constraints on interpreting post solidus stress histories of near surface layers, and on modelling thermal and other physical properties which are dependent on rock structure.

New research is being directed towards these problems. Recently, we have shown that bulk elastic properties of lunar samples can be systematically correlated with petrographic classifications and descriptions of lithification and disaggregation (Warren & Trice 1975).

In this paper, we review the systematics and use them to estimate average degree of lithification and structure densities compatible with the observed seismic profiles in the top 30 km of the Moon. The estimates are discussed in terms of some of their implications for the thermal gradient and for annealing and fracture histories.

Systematics

Systematics in the elastic moduli-pressure relations of rock are brought out by comparing log-log plots of the data for various rocks. Data plotted in this way are bounded by power-law curves typical of soils, and by nearly pressure independent flat curves typical of good quality polycrystalline aggregates.

Data from lunar samples (crystalline, breccias, and soils) show definite correlation of curve character with petrographic descriptions of rock texture. Figure 1 illustrates some key characteristics. The compressional wave modulus C is used,

$$C \equiv V_p^2 \rho,$$

where ρ is bulk density and V_p is the compressional wave velocity.

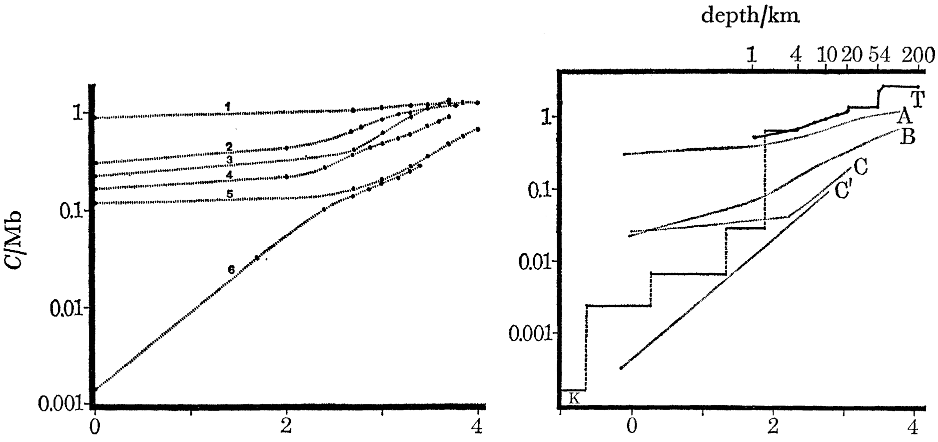

Figure 1 Figure 2

Figure 1. Curves of compressional wave modulus against pressure for six lunar samples. 1, 14311, ρ = 2.86 (Mizutani *et al.* 1972); 2, 14310, ρ = 2.86 (Trice *et al.* 1974); 3, 10057, ρ = 2.88 (Kanamori *et al.* 1970); 4, 14318, ρ = 2.81 (Todd *et al.* 1973); 5, 14313, ρ = 2.89 (Mizutani *et al.* 1972); and 6, 72161, average ρ = 2.2 assumed (Talwani *et al.* 1974).

Figure 2. Comparison of rock and seismic data. See text for description.

Sample 14311 (curve 1) is a fully recrystallized breccia. Its curve is characteristic of that for a very good polycrystalline material.

Low to moderate levels of crack damage in a good rock lowers the low pressure values of the elastic moduli, and the curve becomes S-shaped or monoclinic typified by data for kreep basalt 14310 (curve 2).

Induration and partial or mechanical welding of loose grains raises the low pressure values of the elastic moduli, as indicated by comparison of data for 14313 (a regolith breccia, curve 5) to data for soil sample 72161 (curve 6).

The data curves for low to unshocked vesicular basalts (e.g. 10057, curve 3) have characteristics somewhat similar to moderate grade unrecrystallized breccias (e.g. 14318, curve 4).

The effects of cracks can be quantitatively predicted by modelling cracks as flat flaws with sub-parallel faces which close at finite hydrostatic pressures. Typically, oblate spheroids are used. Such modelling strengthens the interpretation of S-shaped curves as being controlled by crack damage. Simmons *et al.* (1975) detail crack damage in three lunar samples including 14310.

Power law curves as observed for soils, are predicted by Hertzian theory of grain contacts. Although the texture parameters controlling the elastic properties of partially indurated rock and glassy breccias have not yet been directly established, we postulate that asperities are important. Grain bonding at asperities in low grade breccias has been shown by Christie *et al.* (1975) and Heuer *et al.* (1974). Asperities are also postulated to be important in controlling the elastic moduli of vesicular basalts. Asperity contacts at grain boundaries, rather than continuous bonding over the dimensions of the grains could result from rapid cooling and outgassing.

Seismic profile

In figure 2, C moduli against log pressure are plotted for various rock types: (A) basalt 14310, (B) medium breccia 66055, (C′) soil 69941 first compaction, (C) indurated soil 69941 (Warren & Trice 1975). Moduli based on seismic profiles of Cooper *et al.* (1974), curve K; and Toksöz *et al.* (1974), curve T, are also plotted. Densities of rock for curve T are given by the authors. Densities used to calculate C modulus for the seismic profile in the first kilometre were estimated from the published postulated rock types. The general features of curves T and K are accepted here even though other seismic profiles may be admitted by extremal inversion of the seismic data (Burkhard & Jackson 1975).

In considering the region below 1 km, it can be seen that the modulus curve for 14310 (A) is remarkably parallel to curve T, although slightly lower in absolute value. Mizutani & Newbigging (1973) point out good agreement between the seismic profile and data for 60315, a fractured, recrystallized breccia. The curve for breccia 14311 (figure 1) is slightly higher than curve T in the region of 1–20 km. It should be noted that the estimated density for curve T was 3.1 g/cm^3 while the densities of the above three rocks are approximately 2.9 g/cm^3. This, however, will have only a minor shifting effect on the curves. In general, the rocks that match the seismic profile at depths greater than 1 km can be described as fully annealed or possessing only a moderate degree of pressure sensitive damage. Model calculations for 14310 (Warren & Trice 1975) give a quantitative estimate of the crack porosity (ω_c) in the rock to be:

$$\omega_c = 0.6\,\%.$$

Above 1 km depth, *in situ* seismic data is well fitted by experimental data for compacted and indurated fine particulate material (curves C, C′). However, fines or regolith material are not necessary to account for the entire upper 1 km provided rock layers are broken up on some scale. Low *in situ* velocities may be obtained, as demonstrated by Cooper *et al.* (1974), in basalts which have higher laboratory velocities, if there is large scale disruption of the lava field. In all cases, however, it is required that material above 1 km be texturally different than material below, in that it must be essentially broken up.

In summary, velocities in the upper 1 km do not require a low density, porous medium, but they do require low grade rock, exhibiting bulk properties similar to indurated fines or low grade breccias. Based strictly on velocity, therefore, models can range from soil like to high density, fractured igneous or breccia rocks similar to model II of Schreiber *et al.* (1970). This model has velocities almost identical to breccia 14313 (figure 1), but with a higher density of 3.1–3.2 g/cm^3. The structure densities proposed are compatible with seismic scattering near the surface of the Moon (Lammlein 1974). The model here is similar to that postulated by Warren (1972), Warren *et al.* (1972), which predicts very little scattering at depths exceeding 5–10 km.

Thermal gradient

Mizutani & Newbigging (1973) point out that the velocity of sample 14321 (a complex, class A or unrecrystallized breccia, according to Heuer *et al.* 1974) has a temperature derivative of the compressional wave velocity which is two to ten times larger than compact (terrestrial) rock. Based on this, *in situ* velocities of broken rock may be lower than either laboratory measurements or model rock values based on room temperature data, if temperatures at depths of several hundred metres are sufficiently elevated.

Heat flow measurements at Apollo 15 and 17 sites give an average heat flow of roughly 0.7 μcal (3 μJ) cm^{-2} s^{-1} (Langseth *et al.* 1973, 1972). Given this heat flow, thermal conductivities of either lunar fines (1–2 μcal (4–8 μJ) cm^{-1} s^{-1} K^{-1}, Cremer & Hsia 1974) or of regolith (10–20 μcal (40–80 μJ) cm^{-1} s^{-1} K^{-1} Langseth *et al.* 1972; Horai, pers. comm.) would result in such high temperatures at only a few hundred metres of depth that the material would rapidly anneal. It is, therefore, obvious that while velocity curves for unconsolidated but compacted material could account for *in situ* seismic profiles down to 1 km, a significant thickness of this type of material would be thermally altered to give rock whose velocities would not match *in situ* velocities. Thermal conductivities of 'good' lunar rocks have been determined by a number of investigators (Horai, pers. comm.; Fugii & Osako 1973; Mizutani *et al.* 1972). Values which can be considered to be an upper bound to conductivity in the top 1 km are in the range 1–3 mcal (4–12 mJ) cm^{-1} s^{-1} K^{-1}. This yields thermal gradients of 20 K/km to 70 K/km, which may hold below 1 km depth. Reasonable thermal conductivities consistent with the large, unwelded block model may be on the order of 10^{-4} cal (4×10^{-4} J) cm^{-1} s^{-1} K^{-1} (Horai, pers. comm.). A value of 5×10^{-4} cal (2 mJ) cm^{-1} s^{-1} K^{-1} yields a thermal gradient of 140 K/km and a temperature of about 400 K at 1 km. In the cases above, we have, of course, neglected the effect of increasing temperature on the conductivity. The net result of considering this, however, would only be to slightly lower the thermal gradient with depth.

It is seen, therefore, that the present thermal gradient in the upper 1 km of the Moon is probably quite large. Moreover, assuming sufficient heat flow, at any time in lunar history that a significant thickness of unconsolidated material may have accumulated, the resultant further steepening of the thermal gradient and rise in temperature could have resulted in wide spread annealing of near surface material.

Conclusion

The published lunar seismic profiles are consistent with a sharp gradient in structure density at a depth of about 1 km, from highly fractured lithic units above 1 km, to only moderately fractured competent rock below.

Steep thermal gradients in the top 1 km and a possible temperature rise of 100–200 K at 1 km depth is reasonable assuming the measured heat flow and such a structural profile. In addition the more negative velocity-temperature derivative of fractured rock and breccias as compared to competent rock then independently suggests the large seismic step at 1 km depth.

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