PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Lunar Viscosity Models

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Lunar viscosity models

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Viscosity values as estimated from isostatic processes and from temperature and melting point-depth relations show that the Moon's outer layers are much more viscous than any geologic region on Earth. These high η-values are responsible for the survival of the very old lunar landscape. At depths below 500 km η-values increase and permit a limited convection. Moonquakes around 800 km depth seem to be connected with a limited range of viscosity values. A tentative relation between viscosity and seismic Q-values is presented.

INTRODUCTION

The physical parameter 'viscosity' plays a major role for all kinds of dynamic and quasi static processes which take place during the development of planetary bodies. For the outer layers of these bodies viscosity determines the rate of surface modifications, those of crater forms, depressions and mountains. The viscosity-depth structure is responsible for possible plate movements, diapiric rising of magmas, evaporites, and all kinds of lighter, though not necessarily less viscous, bodies. It determines the rate and shape of convection patterns and earthquake and moonquake activity.

Viscosities may be estimated in different ways. First, an average regional viscosity for the outer layers may be obtained by observing in nature quasi static processes, on Earth post glacial uplift (Haskell 1935; McConnel 1965; Magnitzky 1967; Artyushkov 1967; Post & Griggs 1973; Brennen 1974), on the Moon crater floor modification (Hulme 1974). From stress differences also for instance from those associated with the mascons certain average vicosity values may be obtained (Arkani-Hamed 1973*a*, *b*). A more detailed picture on the viscosity may be obtained from Weertman's 'temperature method'. Viscosity is related to the ratio of the melting point to the temperature (Weertman 1970). This method has been applied to the mantle of the Earth by Weertman (1970) and to the Earth's crust and the outer part of the Moon by Meissner (1974, 1975*a*). Finally, relations between viscosity and seismic Q-values (elasticity) may be found because both parameters are defect controlled and strongly dependent on the temperature.

QUASI STATIC MOVEMENTS AND RELAXATION TIMES

Deglaciated areas on Earth experience a vertical uplift strong at first and slowing down with increasing time (Post & Griggs 1973; Brennen 1974). A comparable quasi static movement is found for large craters on the Moon (Hulme 1974). The observed flattening of crater floors which may also be seen on Mercury and (much more strongly) on Mars is remarkably slower than that of depressed areas of similar dimensions on Earth. Figure 1 shows relaxation times of terrestrial deglaciated areas and those of large lunar craters. Relaxation times and average viscosities as estimated from a simple formula (figure 1) are 10^4 times smaller for the outer part of the Earth than for that of the Moon, even in the time period after the impacts. Today, average viscosities may be even higher on the Moon, as estimated by Arkani-Hamed (1973*a*, *b*), who gets a figure of 10^{26} Pa s on the basis of possible stress differences associated with mascons. These average viscosity values may be regarded as an indication of a significant viscosity difference in the outer layers of Earth and Moon.

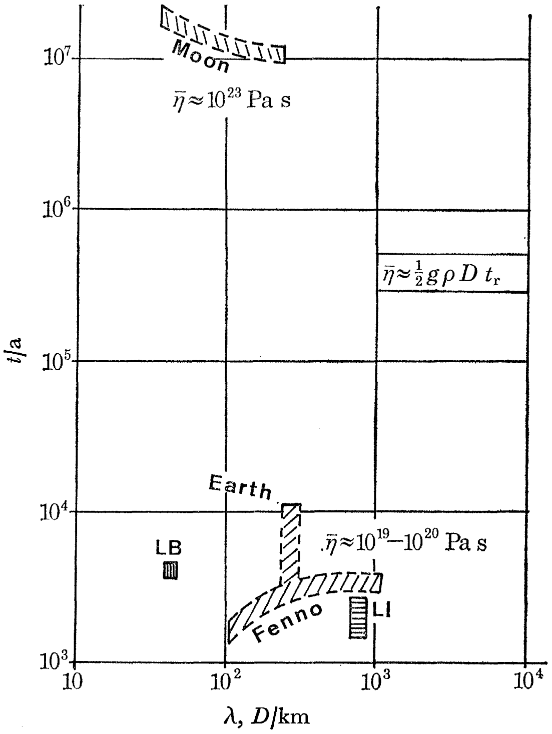

FIGURE 1

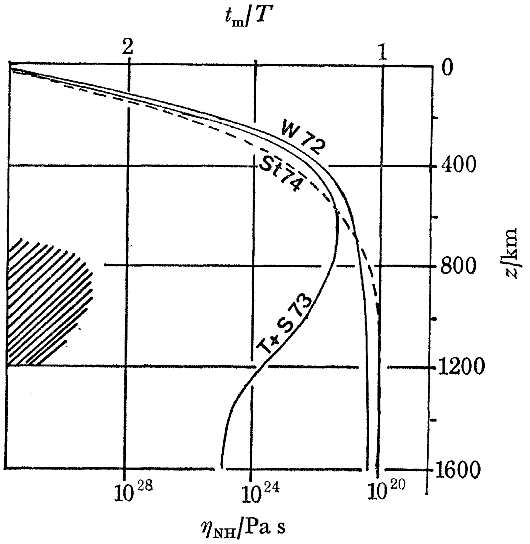

FIGURE 2

FIGURE 1. Relaxation time for the Moon against crater diameter D. Relaxation time t_r for terrestrial units against wavelength λ of uplift area. $\bar{\eta}$, average, effective viscosity; Fenno, Fennoscandian Shield after Brennen 1974; LB, Lake Bonneville; Li, Laurentide Iceshield.

FIGURE 2. Lunar viscosity-depth models. η_{NH}, viscosity values calculated assuming Nabarro-Herring creep; W 72, viscosities as derived after selenotherms from Wood (1972); T+S 73, viscosities as derived from selenotherms by Toksöz & Solomon (1973); St 74, viscosities as derived from selenotherms by Strangway & Sharpe (1974); hatched area, zone of tide generated moonquakes.

VISCOSITY MODELS AS OBTAINED FROM THE TEMPERATURE METHOD

In considering the relation between the shear stress σ and the creep rate $\dot{\epsilon}$ two competing creep processes have to be taken into account. According to Turcotte & Oxburgh (1972) and Meissner (1975*b*), the classical Nabarro-Herring or diffusion creep with $\dot{\epsilon} \sim \sigma$ (Nabarro 1948; Herring 1950) will dominate for small stresses (and small grain sizes) as found in the last stage of isostatic recovery. For the first stage of isostatic movements, especially for a fast retreat of ice or shortly after the formation of large impact craters, shear stresses are high, of the order of more than 100 bar (10^7 Pa). Here, another creep law, the so called dislocation glide, will be valid. This leads to a higher creep rate, i.e. a faster recovery rate, with $\dot{\epsilon} \sim \sigma^3$. Both creep laws depend strongly on the temperature and may be expressed by an exponential term containing the ratio of the absolute melting temperature to the temperature. Also the effective viscosity η

may be obtained in two different ways for the two creep laws. For a quasistatic, low stress case characterizing static geologic units the classical Nabarro-Herring creep should be adequate and will be considered for the following determination of viscosities (Meissner 1975*b*)

$$\dot{\epsilon} = \frac{\alpha \Omega \sigma}{KL^2} \frac{D_0}{T} \exp\left(-g\, T_m/T\right) \approx C\sigma \exp\left(-g\, T_m/T\right) \qquad (1)$$

with $\eta = \sigma/\dot{\epsilon}$,

where Ω is the atomic volume, L the average grain diameter, K the Boltzmann constant, D_0 a constant ($10^{-1} < D_0 < 10^{+1}$), g a constant ($13 < g < 25$; Weertman: $g = 18$).

From formula (1) the viscosity-depth function $\eta_{NH}(z)$ may easily be obtained by using temperature-depth functions $T(z)$ and melting point-depth functions $T_m(z)$. For the outer parts of the Moon quite reliable $T(z)$ and $T_m(z)$ curves have been calculated on the basis of the heat flow values of Apollo 15 and 17 and some assumptions about heat production by radioactive elements and about other physical constraints. $T(z)$-functions of Wood (1972), Toksöz & Salomon (1973), and Strangway & Sharpe (1974), which are similar at small depths but diverge below 500 km, have been used to calculate viscosity-depth functions.

Figure 2 shows the viscosity-depth models as obtained from formula (1), with the zone of tide generated moonquake activity indicated. These moonquakes seem to be caused by a tide generated differential movement of inner low viscosity material and inhomogeneities in the outer more viscous part of the Moon's mantle. It seems to be more a kind of tidal pumping of magma at great depths (Latham *et al.* 1972) connected with inhomogeneities than gas volcanism (Meissner *et al.* 1973). This explanation would be in accordance with the temperature calculations of Wood (1972) and Strangway & Sharpe (1974) as well as with the change in polarity of moonquake sources in the second stage of the 6 year beating period of lunar tides. Below 1000 km depth the material might be too fluid to build up the stresses necessary for quakes; for depths less than 70 km the material might be too viscous and rigid to break under the small stresses connected with tidal forces. Figure 3 gives a more detailed picture of viscosities in the outer 150 km of the Moon compared to those of geological units on Earth. This picture gives clear evidence of the large viscosity differences near the surfaces of the Moon and Earth and explains the huge relaxation times of lunar craters and the survival of the old lunar topography with mountains, depressions, and mascons.

From figures 2 and 3 it is evident that the lunar lithosphere has a thickness of about 400–600 km. Tide generated moonquakes with their small magnitude may be related to a certain range in viscosity between 10^{20}–10^{22} Pa s, a similar range to that for microearthquakes in the vicinity of oceanic ridges which occur in a similar pressure–temperature regime. It should also be stressed that convection would be possible for viscosities less than 10^{22} Pa s, i.e. for depths greater than about 500 km in the Moon (Meissner 1975*a*).

Possible relations between viscosities and seismic Q-values

It is tempting to relate the high viscosity values in the outer part of the Moon, especially those at depths of 50–100 km, to the high Q-values found from lunar seismograms (Latham *et al.* 1970; 1973*a*, *b*). Q-values of 4000–5000 have been reported which correspond roughly to the uppermost part of the lunar mantle at depth of 60–100 km. It is suspected that both η and Q are defect controlled and strongly related to the temperature, probably both proportional to an exponential function containing the ratio of the melting temperature T_m to the temperature T as in formula (1). In Figure 4 Q–η relations for the Moon are compared with some values from the uppermost mantle of the Earth. Geological units differ most strongly in temperature T and hence in T_m/T. Having established a reliable Q–η relation, one parameter may be checked or estimated from the other. The high Q-values of lunar seismograms leading to the long 'ringing' of the Moon are understood as a consequence of the high viscosity of the outer layers.

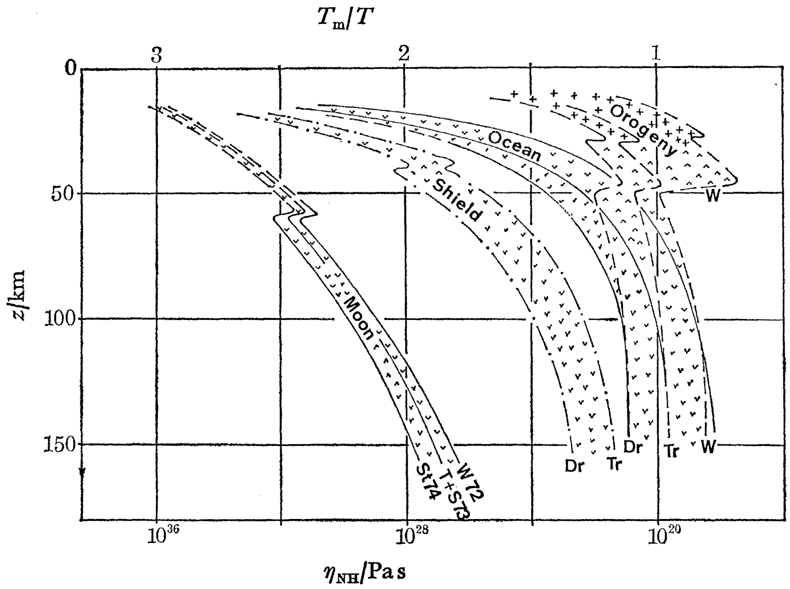

FIGURE 3

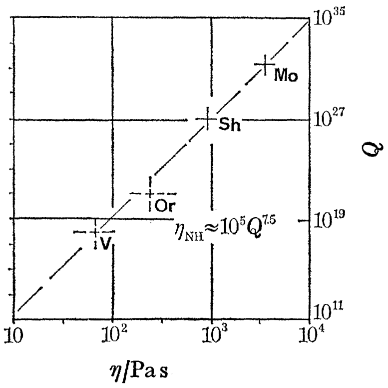

FIGURE 4

FIGURE 3. Viscosity-depth models for the outer part of Moon and Earth. W 72, viscosities as derived from selenotherms by Wood (1972); T+S 73, viscosities as derived from selenotherms by Toksöz & Salomon (1973); St 74, viscosities as derived from selenotherms by Strangway & Sharpe (1974); Dr, values based on dry solidus melting curve; Tr, values based on melting curve with traces of water; W, values based on wet solidus curve.

FIGURE 4. Possible relation between viscosity and seismic Q-values for the uppermost mantle of Moon and Earth-units. Mo, Moon; Sh, shield area; V, volcanic zones. (Q-values from Sutton *et al.* 1967.)

CONCLUSIONS

It has been shown that viscosity values determine a number of physical processes and parameters, among them the high Q-values in the outerpart of the Moon and the low Q-values below 800 km depth. High η-values near the surface are responsible for the survival of the old forms of craters, mountains, depressions and mascons, as they allow only a very slow yielding of the material to shear stresses. η-values below 10^{22} Pa s as found below a depth of 500 km might permit limited convection; values between 10^{22} and 10^{20} Pa s at depths between 500 and 1000 km might be connected with the small magnitude, tide generated moonquakes in association with tidal pumping and some inhomogeneities. Compared to the Earth where convection has played a major role during its history, the Moon with its higher overall uranium content, its lower hydrostatic pressure and lower melting point at equivalent depth behaves as a far more viscous body in the outer 500 km, but its viscosity falls to equal and lower values at greater depths.

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REFERENCES (Meissner)

Arkani-Hamed, J. 1973*a* *The Moon* **6**, 100–111.
Arkani-Hamed, J. 1973*b* *The Moon* **6**, 112–124.
Artyushkov, E. V. 1967 *Geophys. J. R. Astr. Soc.* **14**, 251–260.
Brennen, C. 1974 *J. geophys. Res.* **79**, 3993–4001.
Haskell, N. A. 1935 *Physics* **6**, 265–272.
Herring, C. 1950 *J. appl. Phys.* **21**, 437.
Hulme, G. 1974 *Nature, Lond.* **252**, 556–558.
Latham, G., Ewing, M., Press, F., Sutton, G., Dorman, J., Nakamura, Y., Toksöz, N., Meissner, R., Duennebier, F., Kovach, R. & Yates, M. 1970 *Science, N.Y.* **170**, 620–626.
Latham, G., Ewing, M., Press, F., Sutton, G., Dorman, J., Nakamura, Y., Toksöz, N., Lammlein, D. & Duennebier, F. 1972 *The Moon* **4**, 373–382.
Latham, G., Ewing, M., Dorman, J., Nakamura, Y., Press, F., Toksöz, N., Sutton, G., Duennebier, F. & Lammlein, D. 1973*a* *The Moon* **1**, 272–296.
Latham, G., Ewing, M., Press, F., Dorman, J., Nakamura, Y., Toksöz, N., Lammlein, D., Duennebier, F. & Dainty, A. 1973*b* *NASA Spec. Publ.* SP-**330**, 11-1–11-9.
Magnitzky, V. A. 1967 *Geophys J. R. Astr. Soc.* **14**, 245–249.
McConnell, Jr, R. K. 1965 *J. geophys. Res.* **70**, 5171–5188.
Meissner, R., Voss, J. & Kaestle, H. J. 1973 *The Moon* **6**, 292–303.
Meissner, R. 1974 *J. geophys.* **40**, 57–73.
Meissner, R. 1975*a* *The Moon* **12**, 179–191.
Meissner, R. 1975*b* In preparation.
Nabarro, F. R. N. 1948 Rep. Conf. Strength of solids, Phys. Soc. London.
Post, Jr, R. L. & Griggs, D. T. 1973 *Science, N.Y.* **181**, 1242–1244.
Strangway, D. W. & Sharpe, H. A. 1974 *Lunar Sci.* **5**, 755–757.
Sutton, G. H., Montronovas, W. & Pomeroy, P. W. 1967 *Bull. seis. Soc. Am.* **57**, 249–267.
Toksöz, M. N. & Salomon, S. C. 1973 *The Moon* **7**, 251–278.