on elastic half spaces given by Nadai [*Theory of Flow and Fracture of Solids* (McGraw-Hill, New York, 1963), vol. 2, p. 235]. A bell-shaped and radially symmetric surface pressure distribution $p(r)$ for which the integrals given there can be evaluated exactly is

$$p(r) = p_0 \ (1 + r^2/a^2)^{-3/2}$$

where p_0 is the maximum pressure and a is chosen so that $p(r)$ is an approximation for the pressure distribution to our model ($a \cong 160$). For this function, the maximum shear stress occurs at a depth below the load of $a/2$ and has the value $2p_0/9$. The maximum increase in load due to the presence of higher density slabs near the surface is $p_0 = \Delta\rho gh$. If we take values from our model, $p_0 = 250$ bars, and the maximum stress difference is 56 bars at a depth of about 80 km beneath the lunar surface.

11. Recent calculations using unnormalized data indicate that a density contrast of 0.95 will match the chosen north-south profile with a fill depth of 14 km. Our north-south profile was chosen because it is an orbital track. Along this path there are small negative anomalies to the north and south of the mare. However, profiles nearer east-west do not show these, and the size of the anomaly which we have used may therefore be somewhat overestimated. These other profiles show 180 to 200 mgal, and the required density contrast may thus be 0.7 to 0.8 g/cm^3 with a fill depth of 14 km.

12. We thank P. M. Muller and W. L. Sjogren for supplying their raw gravity data, and for other important contributions. R. A. Lyttleton and A. A. Loomis made many helpful suggestions. Research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract number NAS 7-100.

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Isostasy on the Moon

Muller and Sjogren (*1*) have performed the astonishing feat of providing a relatively detailed though preliminary gravimetry of much of the front surface of the moon. The data from which they worked is in no sense marginal; the perturbations of the Orbiter satellites which they used are so large as to have been an operational nuisance before they were understood. The internal agreement of their data seems to justify the general aspects of their gravimetric map; and, although much can still be done to improve the data, it is not too soon to see what can be deduced from it.

The material consists of measures of the intensity of gravity referred to a height of 100 km, and determined for points within a radius of about 50° of the center of the moon's visible face. The unit used by Muller and Sjogren is approximately 10 mgal. The principal results are: (i) Over the continental regions of the moon and the noncircular maria, gravity is constant within about 50 mgal. (ii) Over the circular maria, there are excesses of gravity up to 200 mgal.

The interpretation suggested to Muller and Sjogren by the papers of H. C. Urey, and tentatively adopted by them, attributes the mass excesses in the mare regions to mass concentrations, perhaps remnants of colliding iron asteroids, of the order of 100 km in diameter, buried under the lunar surface. On the other hand, both observation and experiment indicate that impact at normal meteor velocities leads to the scattering of the impacting mass as a result of shattering and vaporization. Even if it is supposed that the circular maria were made by bodies already in orbit around the earth, and hence having relative velocities of only a few kilometers per second, there remains a difficulty in supporting the mass. The pressure exerted by such a body on its base would be of the order of 8 kb (110,000 pounds per square inch); this exceeds the crushing strength of granite. It is reasonable that a mass of this kind would crush its way to the center of the moon.

To study the effects of internal variations in density on the gravitational field of a body, the first step is to remove the effects of the visible topography. This correction is known as the Bouguer correction. Where, as here, the effects of the topography are smoothed by distance from the moon, it is possible to apply the Bouguer correction by finding the mean height h around any point; the Bouguer correction (δg to lunar gravity g) is then (*2*)

$$-\delta g = 2\pi G\rho h \qquad (1)$$

where G is the absolute constant of gravitation and ρ the density. Accordingly, Bouguer corrections were calculated with a map from the Army Map Service (*3*). Although there is considerable disagreement about the precise values of heights on the lunar surface, it appears that so long as one is interested in heights within half a kilometer, and does not care about precise values at a single point, but only heights averaged over an area, it makes little difference which map is used (*4*).

For the density the highland value of 3.0 g/cm^3 was assumed in accordance with the calculations of the Surveyor

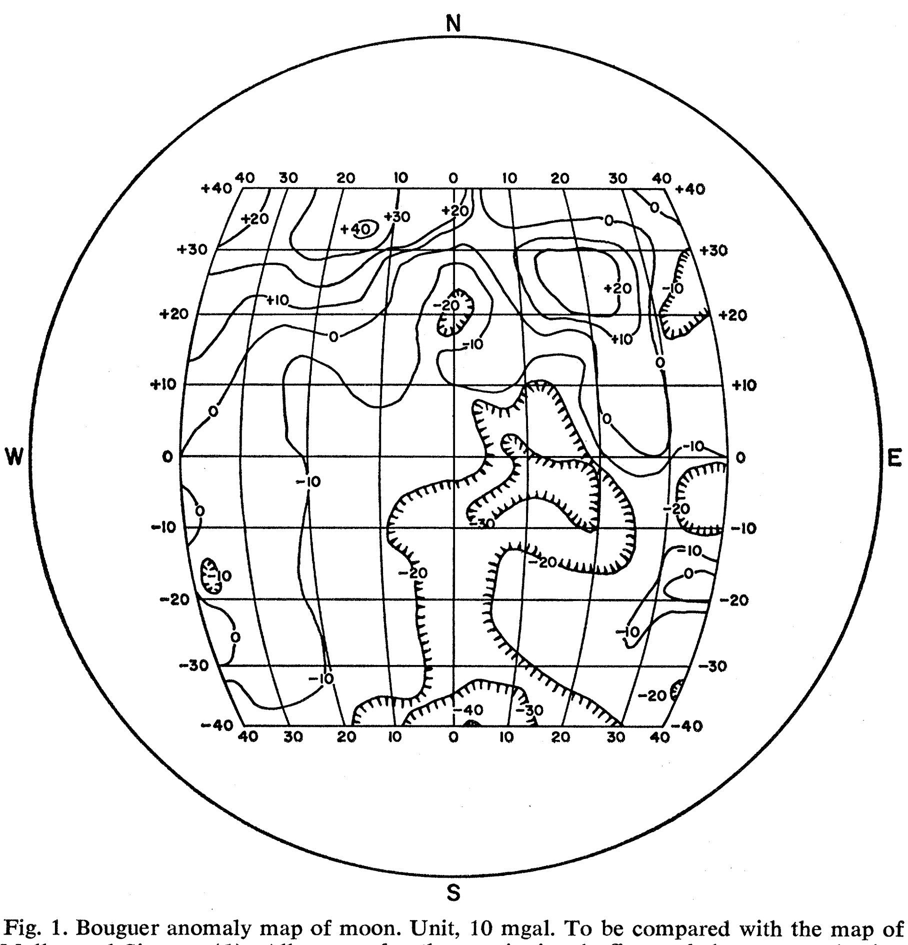

Fig. 1. Bouguer anomaly map of moon. Unit, 10 mgal. To be compared with the map of Muller and Sjogren (*1*). Allowance for the gravitational effects of the topography has produced a much rougher map, indicating that the topography is compensated by underground variations of density.

working group on lunar theory and processes (*5*). If the corresponding mare value of 3.2 g/cm^3 had been adopted in whole or in part, the Bouguer corrections would have been increased by at most 7 percent, which would slightly strengthen the conclusions of this paper.

Equation 1 yields the result, in milligals and kilometers: $\delta g = 126\ h$. Allowing for the 100-km height of the spacecraft above the lunar surface, the relation becomes $\delta g = 110\ h$; and this is the correction applied. The value of h used here was obtained by subtracting 7 km from the map height.

The resulting chart of Bouguer anomalies, obtained by applying the Bouguer correction to the anomalies found by Sjogren and Muller, is shown as Fig. 1.

The fact which leaps to the eye is that the Bouguer anomalies are much larger, in both directions, than the anomalies determined by Sjogren and Muller, which are essentially free air anomalies. In the 18th century, a similar situation was noted in the Andes by Bouguer (*6*). It is as if the topography were massless; and, in fact, Bouguer suggested that the volcano Chimborazo might have enormous caves. Later work has indicated a different conclusion; but let us first consider the possibility that the lunar matter is highly porous.

We first remark that a detailed examination of several thousand Orbiter images, and several tens of thousands of Surveyor images has shown no instances of the mouths of caves, or of overhanging or even vertical slopes, except those on individual boulders a meter or so in height. Hence, the porosity, if it exists, must be due to granularity.

Second, let us note that the porosity at the lunar surface, or very near it, was found to be not over 50 percent (*7*). At depths of a few meters solid rock is encountered (*8*). The solid layers may be interleaved with lower layers of granular material (*8*).

But, as we descend into the interior of the moon, the porosity must lessen, because larger areas of contact are necessary between grains in order to support the overlying load. It is probably safe to say that 2 g/cm^3 is a lower limit to the density of the lunar crustal material at depths of the order of kilometers. Our conclusion would not be substantially altered if a density of 2 g/cm^3 were used in Eq. 1 instead of 3 g/cm^3.

We are thus compelled, like terrestrial geologists, to assume that the subcrustal density variations in the lunar structure are inversely correlated with the height of the topography (*9*, pp. 178–79). The meaning of this phenomenon has long been known: the topography is isostatically compensated. In some sense, the crust floats on a mechanically weak interior, so that the principle of Archimedes is approximately obeyed. In the maria, we have deviations from isostatic compensation; but they are of relatively small amount and extent. To a rough first approximation, the moon is in isostatic equilibrium.

The observed range in the Bouguer anomaly amounts to about 600 mgal. This implies that the crust of the moon is, at least in the highlands, lower in density than the interior (so that it can float). The regional variations in Bouguer anomaly could mean either regional variations in crustal density (the Pratt-Hayford theory of isostasy) or regional variations in the thickness of the crust (the Airy-Heiskanen theory), or both. It can be said, however, that, in order to produce the observed range of about 600 mgal, it is necessary that, in the highlands, the crust be several tens of kilometers thick even if the crust in the maria is of zero thickness. If the crust in the highlands is 10 percent less dense than the lunar interior then it must have a thickness of 50 kilometers; if it is 20 percent less dense, the thickness must be 25 km.

It follows that the highlands cannot consist of ultrabasic rocks, as suggested by Vinogradov *et al.* (*10*). A veneer of ultrabasic rocks over a mass of lighter material is not excluded by these results, but does not fit well with the results of Turkevich *et al.* (*11*).

The excess mass in the maria over what would be called for by isostasy may be connected with the fact that the maria are filled with some sort of material, which has arrived there after the formation of most of the highland topography, as indicated by superposition relationships around the mare borders.

Baldwin (*12*) has discussed this idea in a way which fits the new data remarkably well. O'Keefe and Cameron (*13*) and O'Keefe (*14*) also suggested that the maria are in the process of sinking under the additional load. Evidence of sinking is furnished by the inward inclination of craters on the mare borders, and especially by the ring-fault around Mare Humorum, with the downthrow side toward the mare.

At 110 mgal per kilometer of rock, it is clear that the largest of the gravity anomalies shown on the map of Sjogren and Muller imply loads on the crust equivalent to about 2 km of rock, or, under conditions of lunar gravity, about 100 bars. Jeffreys (*9*, p. 202) has pointed out that surface loads imply stress differences in the interior of one-half to one-third of the surface loads. It thus appears that there are internal stress differences, at depths of the order of a few hundred kilometers, which amount to 30 to 50 bars. These are somewhat greater than the loads implied by the second harmonics of the moon's figure, but they are of the same order of magnitude. They definitely fall below what would be expected for solid cold rock (up to 1 kb); and imply that, at these depths, the lunar interior approaches the melting point.

Finally, it should be pointed out that the material which flooded the circular maria must have come from points which were hundreds of kilometers away, either downward or sidewise. If they had simply poured out on the surface from a depth of 50 km or so, as possible for the noncircular maria, there would have been no net effect on the gravity over the region of the mare. The most likely guess is that they came from depths of 500 km or more inside the moon.

JOHN A. O'KEEFE

Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, Maryland

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