obliquity of 40° either ricocheted or penetrated to a depth, measured from the surface, of about 0.50 that given by Eq. 1. For obliquities of 30°, the high-velocity projectiles did not ricochet, and penetrated to a depth below the surface of 0.65 that given by Eq. 1. Iron meteorites are rough and irregularly shaped objects that may strike with obliquity and are likely to turn sideways or break. If all these factors are considered, the penetration of an iron meteorite may be estimated to be about one-third to one-half of the value calculated for smooth spheres, or about 7 to 11 diameters.

When inert projectiles strike concrete or stone, a wide shallow crater is formed with a cylindrical penetration hole beyond the bottom of the crater. The diameters c of the craters formed in the tests being analyzed fit the relation

$$\left(\frac{c}{d}\right) = 2.70 \left(\frac{\frac{1}{2}mV^2}{Sd^3}\right)^{1/3} \qquad (2)$$

and there is no evidence of failure of the one-third power scaling for craters from 5 to over 200 cm in diameter and projectile kinetic energies from 400 joule to 10 mjoule. For the values listed above, ($\frac{1}{2}mV^2/Sd^3$) is 336 and we find that $c/d = 19$.

I shall extrapolate these relations to craters the size of the largest lunar maria. This involves extrapolation from the largest craters in concrete, about 2 m in diameter, to maria a few hundred kilometers in diameter. The observed diameter of a mare is used as c in Eq. 2 to determine the diameter of the impacting object, assumed spherical, and this diameter is used to calculate the depth, using the empirical Eq. 1. It is assumed that the meteorite is rough and irregular in shape and may penetrate to only one-third to one-half of the depth calculated. The calculations (Table 1) are the result of a very great extrapolation, but there is no way to avoid this. We do not have detailed data to evaluate the term ($\frac{1}{2}mV^2/Sd^3$) for lunar or terrestrial meteoritic craters. We do have data for projectiles over a range of 12:1 in diameter and 5000:1 in mass, and a scaling law that fits these data. The great extrapolation over several powers of ten must be recognized for what it is, with results that are suggestive and are not to be considered as accurate predictions. The results of this extrapolation are presented here because of the very good agreement with the suggestion by Muller and Sjogren.

Ronca (*3*) described the possibility of magma formation by cratering, and his figure 1 can be used to find the depth

Table 1. Sizes of meteorites to form lunar maria.

Mare	Meteorite		
	Diam. (km)	Depth (km)	Mass ($\times 10^{15}$ kg)
Imbrium	61.2	450 – 670	930
Serenitatis	36.7	270 – 400	200
Crisium	27.2	200 – 300	82
Humorum	21.3	155 – 233	39
Nectaris	16.0	116 – 175	17
Ptolemaeus	10.0	73 – 109	4

of penetration, in the earth, needed so that the resulting pressure release at this depth would lead to melting. A diagram similar to Ronca's figure 1 was drawn for the moon, with the use of temperatures from Fricker, Reynolds, and Summers (*4*). Using Ronca's value for melting, 1000°C with $dT/dP = 10°/$kb, I find that penetration to a depth of 200 km into the moon would release pressure so that the solid material would melt. If I use the melting value of 1350°C with $dT/dP = 6°/$kb, as given by Fricker, Reynolds, and Summers, I find that penetration to a depth of 290 km is needed to release the pressure so that the material will melt. In either case, the increase in volume will cause the magma to flow up into the crater.

These results suggest that the lava-filled maria were formed when very large iron objects struck the surface of the moon at a velocity so low that there was no immediate fracture of the object. The impact produced a very large crater, and the object penetrated to such a depth that deep material was melted by pressure release and flowed to the surface to fill the crater. The interior of the moon must have been solid when these events occurred, because otherwise the dense iron meteorite would have sunk into the molten material. Each mare is formed by one large iron object, and this dense object under the mare is the mascon discovered by Muller and Sjogren.

The suggestion by Muller and Sjogren is very reasonable. However, the depth of the mascons, which they take as 50 km, seems to be considerably underestimated. The depth of an impact crater, measured to the bottom of the shattered material in the crater instead of to the top of this debris, is approximately one-fourth of the crater diameter. This means that if the maria are filled craters, the depth of Imbrium is about 300 km and the depth of Humorum is about 100 km. Meteorite diameters and penetrations listed in Table 1 indicate that the depth to the bottom of these objects is a few hundred kilometers and that the top of the mascons is below the bottom of the broken material in the crater.

Muller and Sjogren give 20×10^{-6} lunar masses for the largest mascon. The largest meteorite listed in Table 1 has a mass about two-thirds this value, corresponding to a sphere of diameter only 14 percent smaller than that of an iron sphere of mass 20×10^{-6} lunar masses.

If the mascons are deeper, as I suggest, then they must also be more massive to produce the observed gravity anomalies. If the objects are very irregular in shape, the depth of penetration may be considerably less than that predicted for spheres of the same mass, but in any case the mascons may be expected to be as deep as the shattered material in the bottom of the crater.

J. GORDON STIPE
Department of Physics, Boston University, Boston, Massachusetts

References and Notes

1. P. M. Muller and W. L. Sjogren, *Science* **161**, 680 (1968).
2. J. G. Stipe, in preparation.
3. L. B. Ronca, *Icarus* **5**, 515 (1966).
4. P. E. Fricker, R. T. Reynolds, A. L. Summers, *J. Geophys. Res.* **72**, 2649 (1967).
5. I thank G. S. Hawkins for discussion.

30 August 1968; revised 14 October 1968

Lunar Mascons: A Near-Surface Interpretation

Muller and Sjogren (*1*) have presented data on the gravitational field of the moon obtained from the spacecraft Lunar Orbiter V. Positive anomalies, on the order of 100 to 200 mgal, are shown over the circular maria. The rapid fall-off of the fields from the center leads them to suggest that, as one possibility, the anomalies are caused by masses buried at depths of 25 to 125 km. This could be taken as evidence in support of Urey's description (*2*) of maria structure and structural evolution. Interpretation of gravity data is always somewhat ambiguous, and we wish to point out an alternative model which also produces anomalies of the magnitude and form observed. We feel it is a reasonable one, in view of the known structure of impact craters.

It is not difficult to show that near-surface slab-like models produce anom-

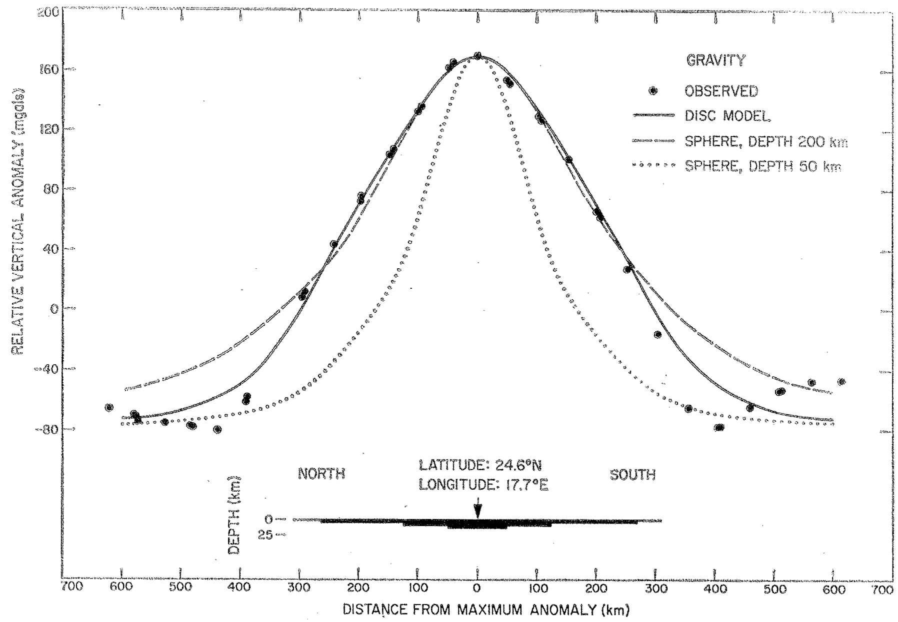

Fig. 1. Mare Serenitatis: theoretical and observed values. The observed gravity profile over the center is from the data of Muller and Sjogren (*1*), orbit 31. The diameter of the mare is taken as 620 km. Four disks are used in the model of Fig. 1 as follows: radius 310 km from 0 to 2 km in depth; radius 265 km from 2 to 5 km in depth, radius 150 km from 5 to 9 km in depth, and radius 50 km from 9 to 14 km in depth. The density contrast is uniformly 1.1 g/cm³.

alies of the magnitude observed. We suppose that the maria fill can be represented by a thin circular disk of dense rock at the lunar surface, embedded in less dense material. To compute the anomaly expected from such a model of Mare Serenitatis, we assume the basin fill to be 600 km in diameter, 8 km thick, with a density of about 3 g/cm³, embedded in material whose density is about 2 g/cm³. The formula for the on-axis vertical component of gravity outside the disk g_z is 6.66 $\Delta\rho t\omega$, where $\Delta\rho$ is the density contrast, t the slab thickness in kilometers, and ω the solid angle subtended by the cylindrical midsection. Using the above values, we obtain g_z in excess of 200 mgal for the magnitude of the central anomaly, which is in the order of that observed.

In order to match the observed gravity profiles of Muller and Sjogren (*1*) in an approximate fashion, a more elaborate model is required. We have used an arrangement of disks representing radial variation in thickness of the mare fill for Mare Serenitatis. The model is shown in Fig. 1. The curvature of the lunar surface has been neglected, but in view of the possible errors in data reduction, our model is adequate. These errors may be a high as 20 percent (*3*). Each disk is approximated by a 12-sided polygon of appropriate thickness and the same density contrast. Any low-density surface layer that may be present in the mare is neglected. We have adopted a value for maximum thickness of fill in the maria of 14 km, based on Urey's estimate (*4*) of the depth of Serenitatis obtained from Baldwin's empirical formula (*5*) for the relation between diameters and depths of impact craters.

The gravity profile for this model is computed by a program supplied by Dr. M. Talwani based on techniques of (*6*) and (*7*) (see Fig. 1). A north-south profile across the center of Mare Serenitatis is taken from the normalized data of Muller and Sjogren and is plotted in Fig. 1. In matching the curves, we have assumed a maximum anomaly of 250 mgal, as estimated from the data of Muller and Sjogren (*1*). The density contrast then required to match the anomaly, if we use a depth of 14 km, is 1.1 (*8*). If the density contrast is decreased, the model thickness must be increased. Thus a contrast of 0.5 would require a thickness of 30.8 km.

The geologic reasoning behind the tabular model is as follows. The submare and adjacent rim material are of low density because they have been brecciated and pulverized by continued impact. The mare fill is denser material, perhaps solid basalt. The form of the original impact basin is taken to be generally that of other large impact craters. This high-density fill may have its origin in several ways: in flows; a local melting on impact and subsequent solidification to higher density; or high-density material brought to the moon by the impacting body. The present gravity data appear consistent with any of these. Further refinement and study on a broad lunar scale, including the problems of topography and isostasy, will serve to eliminate some of these possibilities (*9*). Although the mass required to produce the anomaly is quite large, the low value of lunar gravity reduces the loading on the moon from that which the same mass would produce on the earth. In our model, the maximum shear stress on the moon is approximately 56 bars at a depth of roughly 80 km beneath the center of the load (*10*).

Curves are also shown for spherical masses buried at depths of 200 and 50 km below the surface. It is seen that the sphere at depth 50 km falls too rapidly on either side of the maximum value to give a satisfactory fit, while the deep sphere appears a definite possibility for the north-south profile. Further refinement of gravity data may permit a distinction between the tabular and spherical models.

It is clear from these simple examples that matching the entire pattern of any observed anomaly would require a three-dimensional body of some complexity, but for a first approximation the plate model appears to be satisfactory and geologically reasonable (*11*).

J. E. CONEL
G. B. HOLSTROM
Jet Propulsion Laboratory, Pasadena, California

References and Notes

1. P. M. Muller and W. L. Sjogren, *Science* **161**, 680 (1968).
2. H. C. Urey, in *Vistas in Astronomy*, A. Beer, Ed. (Pergamon Press, London, 1956), vol. 2, pp. 1676-1677.
3. W. L. Sjogren, personal communication. We are presently computing a series of models to fit the unnormalized gravity data.
4. H. C. Urey, *The Planets* (Yale Univ. Press, New Haven, 1952), p. 38.
5. R. B. Baldwin, *The Face of the Moon* (Univ. of Chicago Press, Chicago, 1949).
6. M. K. Hubbert, *Geophysics* **8**, 215 (1948).
7. M. Talwani and M. Ewing, *Geophysics* **25**, 203 (1960).
8. R. F. Scott [*J. Geophys. Res.* **73**(16) p. 5469 (1968)] obtained a density of 1.5 to 2.0 g/cm³ for the lunar surface material from Surveyor measurements. To estimate behavior under compression, we use data for shale [H. D. Hedberg, *Amer. J. Sci.* **31**, 241 (1936)] since this is a highly compressible earth material. We obtain a density between 2.0 and 2.5 g/cm³ at 14 km on the moon for this surface density range, with an average density between 1.7 and 2.24 g/cm³. Taking an average value for the density of basalt of 2.9 g/cm³ leads to a density contrast $\Delta\rho$ between the fill and surrounding material of 0.65 to 1.2 g/cm³.
9. H. C. Urey and J. O'Keefe, personal communications.
10. The pressure effects of additional mass added to the surface can be roughly estimated from solutions for axially symmetric surface loads

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 $p_0 = \Delta\rho g h$. 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.

12 September 1968

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*)

$$-\delta g = 2\pi G \rho h \tag{1}$$

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

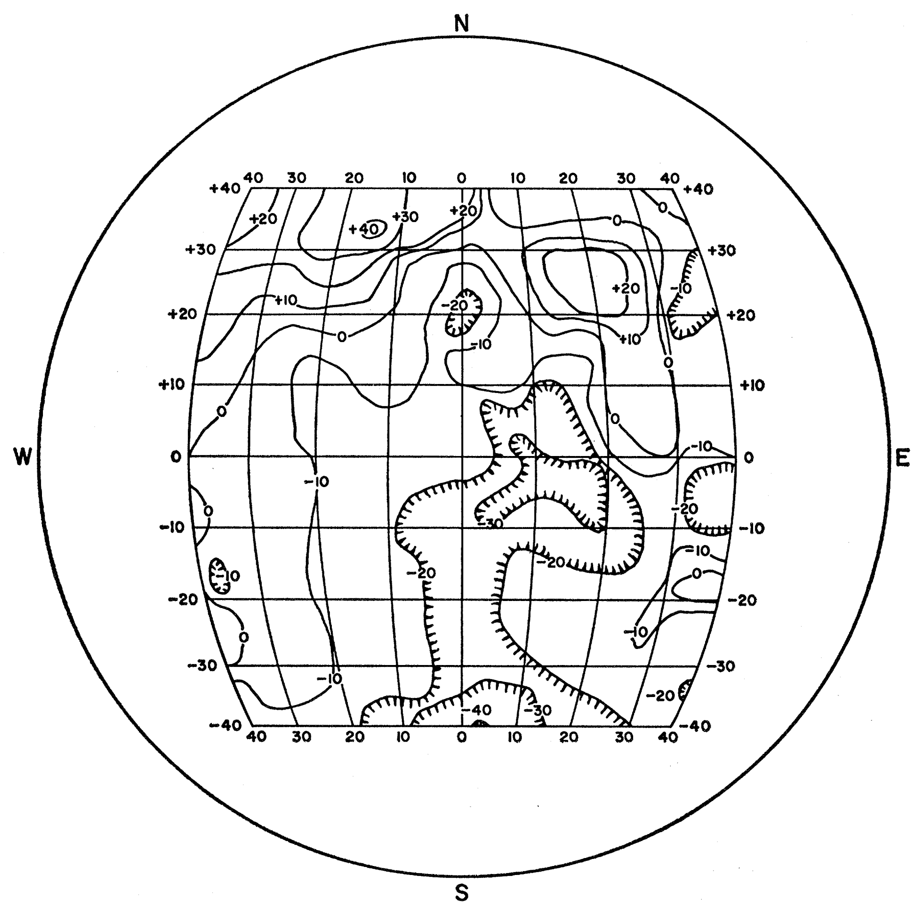

Fig. 1. Bouguer anomaly map of moon. Unit, 10 mgal. To be compared with the map of Muller and Sjogren (*1*). Allowance for the gravitational effects of the topography has produced a much rougher map, indicating that the topography is compensated by underground variations of density.