Lunar Mascons: Another Interpretation

Muller and Sjogren (*1*) discovered that the lunar gravitational field is rough and showed that there are large mass concentrations under the six circular maria which are visible from the earth. This discovery must affect the details of any proposed history of the origin of these structures.

These authors (*1*) determined that the mascon at Mare Imbrium was centered about 50 km beneath the surface and that there was a mass excess of about 20×10^{-6} lunar masses. This is equal to a nickel-iron sphere about 70 km in diameter. They asked the questions: "Does each of these mascons represent an asteroidal-sized body which caused its associated Mare by impact?" "If not simply the original impactor itself, by what processes were they formed in the lunar interior?" "Is the presence of these objects consistent with a molten lunar interior?"

Several comments seem warranted. All the circular maria show a certain amount of asymmetry, but only Mare Imbrium and possibly ancient Mare Serenitatis depart so widely from radial symmetry as to suggest low-angle–low-velocity impacts. The minimum velocity of impact is 1.68 km/sec. Presumably these impacts were at 2 km/sec or greater, and the back pressures generated should have been great enough to cause the asteroid to lose cohesion and to "turn itself inside out." Probably a considerable fraction of the mass would have been backfired out of the crater. It is barely possible that some fraction of the mass of a nickel-iron asteroid might remain in the pit of a very low-velocity impact, but it is rather doubtful that this would occur if the body were of rock instead of nickel-iron and it is even harder to consider that much of the impinging body would remain in the pit if the velocity were high. Mare Orientale gives every evidence of having been formed in a high-velocity collision. It is quite different from the other circular maria in character as well as age, and yet it does have a buried mascon.

If the impacting velocity were very low it is highly probable that the collision was between two satellites of the earth. Thus, it would appear that the origin of the mascons should be found either in the collision effects on the lunar material or in subsequent effects on the crater.

In terrestrial meteoritic craters of much smaller sizes, the rocks below the crater are severely brecciated and are of lower bulk density after the impact than they were before. Possibly the rocks were compressed to higher densities at these giant lunar craters, but, if so, the effect should not be so sharply concentrated toward the crater centers. This leaves only postimpact effects as probable causes of the mascons.

These giant craters were formed dry (*2*; *3*, p. 305). There was some pressure melting, but the vast floods of lava came considerably after the main event. Major isostatic adjustments occurred at these sites, and the adjustments have gone both ways. The very ancient giant crater (*3*, p. 194) stretching from the Altai scarp to Werner was never lava-filled. It was almost eliminated by a rising floor and subsiding-rim type of isostatic adjustment. At best, the gravitational map shows only a very minor increase in mass within this crater, and in its southern reaches the effect is reversed. Conversely, the maximum gravitational distortions are reserved for the great circular craters which were filled with lava and where the isostatic adjustments reduced the surface levels to the lowest values observed on the moon.

On the basis of the best available data, Pike (*4*) showed that up to a diameter of about 20 km the lunar craters maintain their original contours, but above this size they become progressively more distorted, presumably by isostatic forces. From these data, a threshold strength of the lunar crustal layer of 3 to 5×10^7 dyne/cm^2 was calculated (*5*). For stresses above this limit, isostatic adjustments can occur; the larger the diameter of a crater the easier and quicker the adjustments will be made. These adjustments will be of major importance at the circular maria.

If Pike is correct in stating that the formations of all craters are isometric phenomena, then even the largest lunar craters were instantaneously of the form defined by his equations (*6*):

$$R_i = 0.155 D_r^{0.95}$$
$$R_e = 0.042 D_r^{0.98}$$

where R_i is the internal relief from crater rim to maximum depth; D_r is the rim to rim diameter; and R_e is the height of the rim above ground level.

The diameter of the Mare Imbrium central crater is 676 km, and from this we find that $R_i = 76$ km, $R_e = 25$ km, and hence the initial depth of Mare Imbrium below ground level was about 51 km. Let us postulate the following series of events.

1) Mare Imbrium was formed by a giant impact.

2) Its initial depth was approximately 50 km.

3) It was formed dry—that is, not lava-filled.

4) It began to distort isostatically, rapidly at first, then more slowly.

5) Before the basin disappeared, lavas from the body of the moon rose and began to selectively fill the low spots. There were many flows, not just one.

6) These lavas were substantially denser than other surface rocks. The outer portions of some flows were basalt-like (*7*). Basalt has a bulk density of about 2.95. It can be argued that the observed thinness of the individual flows implies that at least some were of ultrabasic rock and hence of still higher density. This is not a vital distinction here.

7) Tension cracks (rilles) on the periphery and compression features (wrinkle ridges) in the interior of Mare Imbrium and the great depth of the present surface of the central crater relative to the lava-covered surroundings are evidence that subsidence and compaction have occurred (*3*, p. 381).

8) If the prelava surface of the moon as exemplified by the continental regions is composed substantially of acidic materials, then it is probable that the density of the lava after solidification is about 0.4 g/cm^3 greater than that of the continental type rock. This assumption cannot be verified at present, but it seems highly probable. The Tycho-Surveyor measurements of rock composition cannot be used here because we do not know the origin of the rocks analyzed. They could be continental, or they could have been ejected from Tycho and highly modified.

9) Pike has shown that even the very young craters like Tycho are being modified isostatically so presumably the interior of the moon is still very hot.

10) If sufficient lava is released into a giant crater it will continuously depress the crater bottom due to the increased load of high-density matter. The original bottom of the crater may then sink back to its original position or even deeper into the moon. The cold solidified lava probably would be denser than the hot subsurface materials beneath the crater.

11) By this mechanism, a dense lens of material could be formed that was centered in the crater and capable of yielding the gravitational effects measured.

12) Some dense matter from the meteorite might also remain in the pit and would add to this effect. The tiny Arizona meteorite crater was formed by a rather low-velocity object, and a small amount of nickel-iron was found by drilling below the crater floor.

We may apply these 12 suggestions to Mare Imbrium as follows. Muller and Sjogren measured the excess as 20×10^{-6} lunar masses for a depth of 50 km. This is equal to 1.46×10^{21} g. It is assumed that the internal contour of the crater bottom is parabolic, and hence the excess mass of the lens may be expressed as $0.392\ \Delta\rho r^2 h$, where $\Delta\rho$ is the excess of density, in this case 0.4; r is the radius of the Imbrian crater, 3.38×10^7 cm; and h is the maximum depth below ground level. Solving for h, we find it to be 82 km. This value for the bottom of the high-density lens is in good agreement with the value of 50 km for the depth of the mascon that was suggested by the Orbiter observations. The concentration of excess mass toward the center of Mare Imbrium in this model is also consistent with the gravitational measures. The average depth of lava in the Imbrian crater would be only one-eighth of the maximum central depth. Smaller maria and craters should show smaller mascons with the mass excess varying with the cube of the crater diameter. The observations of Muller and Sjogren are consistent with this interpretation.

This analysis does not rule out the slight possibility that meteoritic material buried within the great craters does contribute to the observed mass concentrations, but it does suggest that a high-density lava infilling, aided by isostatic adjustments which caused the crater bottom to sink, can explain the major positive residuals of this gravimetric map.

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References and Notes

1. P. M. Muller and W. L. Sjogren, *Science* **161**, 680 (1968).
2. R. B. Baldwin, *The Face of the Moon* (Univ. of Chicago Press, Chicago, 1949), p. 211.
3. ———, *The Measure of the Moon* (Univ. of Chicago Press, Chicago, 1963).
4. R. J. Pike, Jr., *J. Geophys. Res.* **72**, 8 (1967).
5. R. B. Baldwin, "A determination of the elastic limit of the outer layer of the moon," *Icarus*, in press.
6. R. J. Pike, Jr., "Meteoritic origin and consequent endogenic modification of large lunar craters—A study in analytical geomorphology," thesis, University of Michigan, Ann Arbor (1968).
7. A. L. Turkevich, J. H. Patterson, E. J. Franzgrote, *Science* **160**, 443 (1968).

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Mascons and the History of the Moon

Muller and Sjorgren (*1*) have concluded that there are very massive objects in certain locations at the surface of the moon. Five of these occur in the collision maria and one in the mountainous area near Sinus Medii. The calculated gravity anomaly at 100 km above the surface normalized to an object 50 km beneath the surface is 230 mgal for Mare Imbrium. This is the largest one observed. They estimate the diameter of the object as some 200 km. The gravitational field at height h above the center of a flat plate of radius a and has a mass of 5.2×10^{21} g. The density than the material in which it is embedded of $\Delta\rho$ is

$$2\pi G\Delta\rho d \left[1 - \frac{h}{(a^2 + h^2)^{1/2}}\right]$$

If we use this formula with $\Delta\rho$ equal to 5 for iron-nickel in silicate materials, d should be 3.75 km if the object is in the surface, and 6.6 km if it is 50 km below the surface.

If the object is a uniform circular plate covering the inner collision area 670 km in diameter with a density difference of 1 g/cm^2, that is, H-group meteoritic material embedded in basaltic material, the object is 3.8 km thick and has a mass of 5.2×10^{21} g. The colliding object, if spherical, was 68 km in radius and if it arrived with the escape velocity of the moon, that is, 2.4 km/sec, its energy was 1.5×10^{32} erg. The formula given by Baldwin (*1a*), namely:

$$\log D\ (\text{km}) = 0.3284 \log E\ (\text{erg}) - 7.924$$

where D is the diameter of the crater, which if taken as 670 km, gives 5×10^{32} erg for the energy and a mass of 2×10^{22} g if the velocity was 2.4 km/sec. The agreement is satisfactory if we remember that all formulas and models are approximate, and the partial isostatic equilibrium has probably been established. It is probable that a deeper pool of higher density material lies near the center of the mare. The general features are entirely in accord with those presented by Urey (*1b*). It may be that such objects, as well as the smaller varieties, contributed many layers similar to the visible one and that these account for the larger irregularities noted first from the exact studies of the motion of the moon.

These "mascons," as they are called, represent a nonisostatic condition in the surface of the moon. If the Mare Imbrium situation is taken as a prime example, because it exhibits a maximum effect, we come to the conclusion that the viscosity of the moon must be higher than that of the earth by about a factor of 10^4—using a formula due to Haskell (*2*) for the time required to establish nearly complete isostatic equilibrium, namely, $T = 20\eta/\Delta\rho g l$, where T is the time, taken as 4.5×10^9 years, $\Delta\rho$ the difference in density between the mass and the surroundings, assumed to be 5 g/cm^3 in this case, g is the gravitational force at the surface of the moon, and l is the linear dimension of the material not in isostatic equilibrium. It would appear that an object collided with the moon, flattened out below the surface, and left high density masses in these locations which have remained there ever since the maria were formed. The one in the mountainous region appears to have been covered by debris due to subsequent collisions, for example, those of Maria Imbrium and Serenitatis.

Lava flows occur on the earth by a process in which a mass of solid silicates sinks and displaces a liquid silicate which rises in a column. In order for flow to occur, the mass per unit area in the solid mass which is sinking must be greater than the mass per unit area in the column area which is rising. Since the liquid has a lower density than the solid, a positive flow results which has, at times, produced very large flows of lava on the surface of the earth. This has occurred, for example, in the Hawaiian islands, in the famous Oregon basalt flows, and in the Deccan traps of India. This results in a buildup of basaltic type silicate masses whose density is lower than that of the rocks in the mantle of the earth. The liquid rises above the surface, solidifies, becomes more dense as a result of this, another breakthrough occurs, and more flows out on top. Due to the strength of the supporting crustal rocks a positive gravity anomaly can develop. This then disappears by slow settling of the mass after the volcanic activity has become quiescent. The result is that lava flows form mountainous masses and temporarily positive gravity anomalies on the earth. This is to be contrasted with what we see on the moon, where the positive gravity anomaly is in the low area of the maria, and in general the negative anomalies on the moon are in the mountainous areas. It thus appears that a lava flow