EVIDENCE FOR ISOSTASY IN THE LUNAR MASCON MARIA

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Abstract. The pronounced positive gravity anomalies in the lunar circular maria imply lack of isostatic compensation of the lunar mascons. This lack of isostasy is hard to reconcile with the rheological properties of the lunar crust. Analysis of the negative ring anomalies that appear to surround the major positive gravity peaks indicates that associated with each mascon is a mass deficit of approximately the same size. In view of the lunar rheology these mass deficits most probably represent compensating mass deficits beneath the lunar mascon maria. Consequently, most lunar mascons appear to be near isostatic equilibrium, and the observed gravity anomalies may be essentially the superposition of positive gravity peaks due to the basaltic mare fill, and less pronounced, broader gravity lows due to the compensating mass deficits at depth.

1. Introduction

The observed positive gravity anomalies in the lunar mascon maria imply lack of isostatic compensation and are normally attributed to several kilometers of basalt held at superisostatic levels by a finite strength lunar crust (e.g., Wood, 1970; Muller *et al.*, 1974). The results of several investigations dealing with the rheological properties of the lunar crust cast some doubt on this interpretation. According to Meissner (1975), the effective viscosity of the outer parts of the Moon is in the range of 10^{27}–10^{28} poise under low stress conditions, and of the order of 10^{23} poise under high stress conditions (greater than 10 bars). Isostatic settling rates of lunar craters imply average crustal viscosities near 10^{26} poise or less (Baldwin, 1971; Kunze, 1974a), and a creep strength for the lunar crust of less than 50 bars (Baldwin, 1968; Kunze, 1974a). Yet, the crustal strength required to maintain the lunar mascons at the necessary superisostatic levels is in excess of 50 bars (Kaula, 1971; Arkani-Hamed, 1973) and thus probably exceeds the crustal creep strength. Therefore, lunar mascons should be able to adjust isostatically.

In a Newtonian viscous medium, relaxation times are directly proportional to the viscosity of the medium and inversely proportional to the linear dimension of the feature undergoing adjustment. For a typical mascon plate of 600 km diameter in such a medium of effective viscosity of 10^{26} poise, the appropriate relaxation time is less than 1 AE. Consequently, since the effective lunar viscosity in the high stress environment of mascon regions is probably less than 10^{26} poise, the major lunar mascons should have had sufficient time to achieve almost complete isostatic equilibrium in the available 3–$3\frac{1}{2}$ AE since their formation.

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2. Evidence for Mascon Compensation

According to many investigators of lunar gravity anomalies, the strong, positive gravity anomaly peaks in the lunar mascon maria appear to be surrounded wholly or partially by negative gravity anomaly rings (Gottlieb, 1970; Wise and Yates, 1970; Wong *et al.*, 1971; Phillips *et al.*, 1972). Although these negative ring anomalies are not apparent on the most recent lunar radial gravity map available (Sjogren, 1974), they are particularly well defined on the more detailed lunar radial gravity map published by Gottlieb (1970). The contours on this map represent equivalent elevations (of uniform density material) required to produce the observed anomalous spacecraft accellerations and correspond essentially to a surface density distribution which is proportional to the anomalous gravity field on that surface (Garland, 1965) and may therefore be treated as a free air anomaly pattern.

Gottlieb's lunar gravity anomaly patterns show little correlation with lunar topography, and large parts of the negative ring anomalies occur in regions of topographic highs. This indicates that these negative anomalies are largely due to mass deficits at depth. The geometric association of the negative gravity rings with the respective central mascon peaks indicates that the corresponding mass deficits at depth are closely related to the mascons and may be located below the mascon maria. In that case, the lunar mascons are at least partially compensated isostatically by mass deficits at depth. Other possibilities are discussed later in this paper.

The state of isostasy within a given region may be estimated from the existing gravity anomaly pattern. If it is assumed that all negative anomalies are due to compensating mass deficits, then, according to Gauss's theorem, the total uncompensated mass M causing a gravity anomaly $g(x, y)$ is given by the integral of the anomaly pattern over the entire surface

$$2\pi GM = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x, y)\, dx\, dy, \tag{1}$$

where G is the gravitational constant (Jung, 1937). This integral is zero in the case of perfect isostatic compensation (in thc sense that mass excesses equal mass deficits). In the lunar mascon maria the corresponding gravity anomaly integral includes contributions from the negative ring anomaly which partly cancel the positive contributions of the central anomaly peak. This implies that the uncompensated masses in the circular lunar maria are smaller than commonly assumed by most lunar investigators. A quantitative measure of the degree of isostatic compensation in a given lunar mare is provided by the ratio of the negative anomaly integral to the positive anomaly integral. If this ratio is equal to zero, then there is no isostatic compensation (no negative contributions). A ratio of 1 indicates perfect isostasy (negative contributions equal positive contributions, or mass excesses equal mass deficits).

Application of this approach to the available lunar gravity data leads to various errors of the type discussed by LaFehr (1965). The most important of these are due to the following factors:

1. *Limits of Integration.* Because the necessary integration cannot be carried out to infinity, it needs to be limited to a finite region within arbitrary boundaries. In this investigation, these boundaries were chosen around the periphery of the mascon anomaly pattern under consideration where the negative ring anomaly becomes masked by adjacent unrelated anomalies. The main effect of this truncation is to underestimate the negative part of the anomaly. The size of the error varies with the depth of the source, but the effect is distorted by the lunar curvature.

2. *The Lunar Curvature.* The integration is not performed on the flat surface assumed in the derivation of equation (1) from Gauss's theorem, but on a curved plane spanning up to 50° of arc. The mass determinations based on equation (1) are therefore either overestimates (for shallow sources) or underestimates (for deep sources). Table I shows the error in the estimate of point masses at different depths. In the present investigation the most likely effect is to overestimate the shallow mascon mass excesses and to underestimate the deeper compensating mass deficits. The expected errors are on the order of 20 %.

TABLE I

Errors in the estimate of point masses

Angular extent of regional integral	Depth of source (km)	Error in estimate of mass (percent)
40°	0	17.4
40°	10	15.8
40°	50	9.2
40°	100	0.8
40°	200	−15.8
40°	300	−31.2
50°	0	21.6
50°	10	20.4
50°	50	15.2
50°	100	8.5
50°	200	− 5.1
50°	300	−18.4

TABLE II

Gravity anomaly integrals in five lunar mascon maria

Mascon	Positive integral[a]	Negative integral[a]	Ratio
Imbrium	34.2	29.5	0.86
Serenitatis	29.7	22.7	0.76
Crisium	14.0	20.2	1.44
Nectaris	14.4	6.8	0.47
Humorum	6.5	4.6	0.71

[a] Planimeter readings without conversion of units (corrected for geometric foreshortening due to distance from subearth point).

The pertinent integrals were determined for five major lunar mascons (Imbrium, Serenitatis, Crisium, Nectaris, and Humorum) by graphic integration (utilizing a planimeter) of the appropriate anomaly patterns shown on Gottlieb's lunar anomaly map. Figure 1 is a schematic representation of these gravity patterns (according to Gottlieb's map) and illustrates the mascon anomalies of interest as well as the regional boundaries (dotted lines) used in the integration scheme. The results of the integration were corrected for geometric foreshortening due to the various distances of the anomalies from the sub-Earth point, and are shown in Table II.

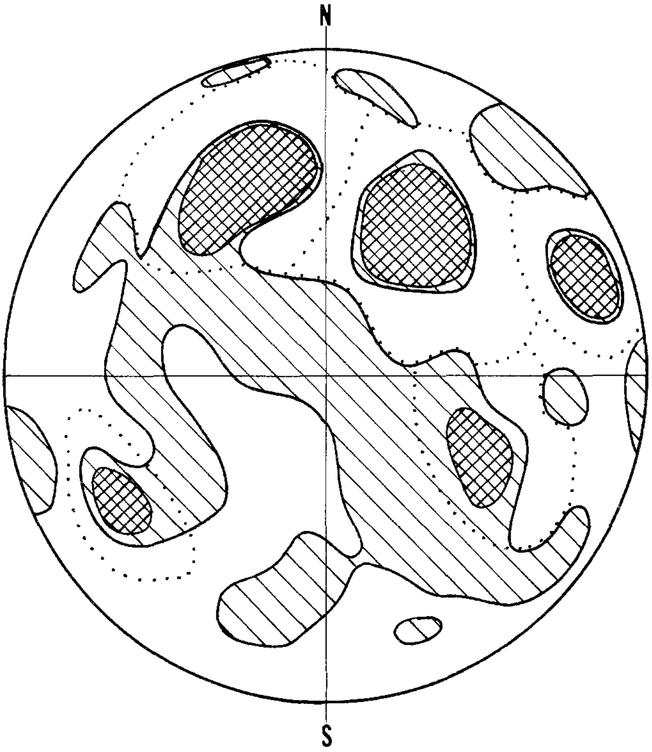

Fig. 1. Regional lunar gravity anomalies (positive anomalies shaded) and mascons (crosshatched).

3. Discussion and Conclusion

Columns 2 and 3 of Table II show that the positive gravity integrals are comparable to the corresponding negative integrals. This clearly indicates that associated with each major lunar mascon is a mass deficit of approximately the same size. It is possible that these mass deficits are unrelated to the mascons, but this is unlikely in view of their geometric relationship to the central mascon peaks. It is also possible that these mass deficits are adjacent to rather than beneath the lunar mascons and may, for instance, represent a regional downwarping of the surrounding lunar crust due to the central mascon load. But in that case the resulting crustal stress differences would be even greater than those determined by Kaula (1971) and Arkani-Hamed

(1973), and such a configuration could not persist for sufficiently long times in a medium with the rheologic properties of the lunar crust or mantle. It is more likely that most of the mass deficits are in fact compensating mass deficits located below the near surface mascon plates in a manner similar to that proposed and discussed by Hulme (1972) and Kunze (1974b). In that case, the observed gravity anomalies represent the superposition of gravity highs caused by the excess density of the basaltic mare fill, and the broader, less pronounced gravity lows produced by the compensating mass deficits below. The result is a gravity anomaly pattern of positive peaks surrounded by negative rings.

The resulting ratios of negative to positive integrals (Column 4, Table II) then indicate the degree of isostatic compensation in the given maria. In view of the errors involved, these ratios are likely to be underestimates. Hence, the results imply that most of the major lunar mascons investigated are near isostatic equilibrium. The small Nectaris mascon is probably undercompensated, and the Crisium mascon seems to be somewhat overcompensated. Mare Orientale with its strong, negative ring anomaly (Sjogren, 1974) must be greatly overcompensated.

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