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On the origin of mascons and moonquakes

S. K. Runcorn

Lunar Science Institute, Houston, Texas, U.S.A. and Department of Geophysics and Planetary Physics, University of Newcastle upon Tyne NE1 7RU, England

Abstract—Hydrostatic head arguments can account for the excess (compared to isostatic) filling of about 1.5 km of lava in the circular maria. With a thick rigid lithosphere, this results in the mascons. The discovery in the geometrical libration data, and in the laser altimeter records, of a systematic height difference between the surfaces of the irregular and circular maria shows that the latter have fallen 1.5 km in 3000 m.y. A cylindrical fault system extending through the lithosphere, surrounding the circular maria is postulated. Potential energy is therefore released at the average rate of 10^{18} erg/yr and this is adequate to explain the moonquakes and their properties. The clustering of the locations of lunar transient events around the circular maria are also thus explained.

1. Introduction

The discovery of positive gravity anomalies over the circular maria by Muller and Sjogren (1968) has been one of the most discussed results of the Apollo lunar exploration program. That the contours of the gravitational equipotential surface strongly correlate with the circular maria suggests that these anomalies originated in the processes that created and filled these maria and that they have since been supported by the finite strength of the lithosphere. Two main groups of hypotheses, involving essentially external and internal processes, have been put forward to explain these departures from the expected isostatic model.

It is a clear result of potential theory, supposing the nonuniformity in mass distribution lies near to the surface, that to a high degree of approximation the variation in the gravitational acceleration (g) observed over the moon depends only on the mass within a centered cone intersecting the moon's surface of unit solid angle. The problem of the mascons is to provide a physical process by which matter can be transported across the surface of such a cone, the apex of which is at the center of the moon, so that the mass enclosed can be increased in the region of the circular maria.

Urey (1968) appeals primarily to the impacting body which created the maria basin in the first place. He supposes that this iron meteorite was softened by the heat of impact and that this external mass was thus emplaced in the depths of the lunar crust: lava subsequently filling the basin to form the maria. Urey points to the rather close agreement of the extra masses required to explain the gravity anomalies and the masses of the impacting bodies, assuming they arrived at about the escape velocities, required to create craters of the dimensions of the circular maria. The merit of Urey's theory is that it provides a clear method by which excess mass could have been brought into the maria area.

Another theory which clearly meets this requirement is that of Gold (1955) who supposes that dust may be horizontally transported over the surface of the moon by an electrostatic process and collects in impact basins such as the circular maria subsequent to isostatic equilibrium being attained.

The second group of hypotheses appeal to the processes by which the circular basins were filled by magma, which petrological studies of the Apollo crystalline rocks shows to have resulted from partial melting processes at depth within the moon. Ringwood and Essene (1970) have supposed that a denser phase, eclogite, forms in the lower part of the basins while Biggar *et al.* (1972) consider that loss of volatiles and precipitation of a denser phase (iron) in the crystallization of the magma lake occurred. It has thus been assumed that the mascons can simply arise from an increase of density with depth in the impact basins when filled by lava from the lunar interior but while this may be petrologically likely, it does not obviously result in the formation of a positive gravity anomaly. *A priori* it might be supposed that the lava would rise to a height which would result in isostatic equilibrium exactly as water fills the ocean basins. The extensive outpouring of lava on the earth does not result in positive free air gravity anomalies; we have no terrestrial analogy.

2. Inferences from the Shape of the Moon

The surfaces of the maria lie below the mean surface of the highlands. Although this is now known from photographs taken in the Apollo missions, it was originally demonstrated from the analysis of heights of points on the lunar surface, determined by the method of geometrical librations, by Baldwin (1949, 1958), Runcorn and Gray (1967), Runcorn and Shrubsall (1970), and Runcorn and Hofman (1972). In the latter papers it is also shown both that the surfaces of the maria are smoother than the uplands and that the surface of the circular maria lie lower than the surfaces of the other maria. The first step in a theory of mascons is to establish whether the material filling the maria basins down to their floors is more dense than that of the surrounding highland crust. The observed densities of the returned crystalline rocks from the maria in the Apollo missions are about 3.0 and the identification of the highlands with anorthosite, which has a density of 2.7, simply fit these observations without having to make assumptions about how that the maria density varies downwards. Assuming that the circular maria are filled with a considerable thickness of lavas of which the crystalline rocks are samples, it follows, because the height of the surface of the circular maria, which are mascons, is less than those of the irregular maria not associated with gravity anomalies, that the filling of the latter basins is partly of less dense material.

Figure 1 and Table 1 shows details of the ellipsoids which best fit the heights of the lunar surface determined using the geometrical librations. The heights are separated into those of points on the highlands and on the maria, and the latter have been subdivided between those points on the circular maria and those on the other irregular maria. Though each of these surfaces has a different height, the shape of the three ellipsoids are similar: as shown by the height of the bulge toward the earth. Were the moon in hydrostatic equilibrium under the earth's

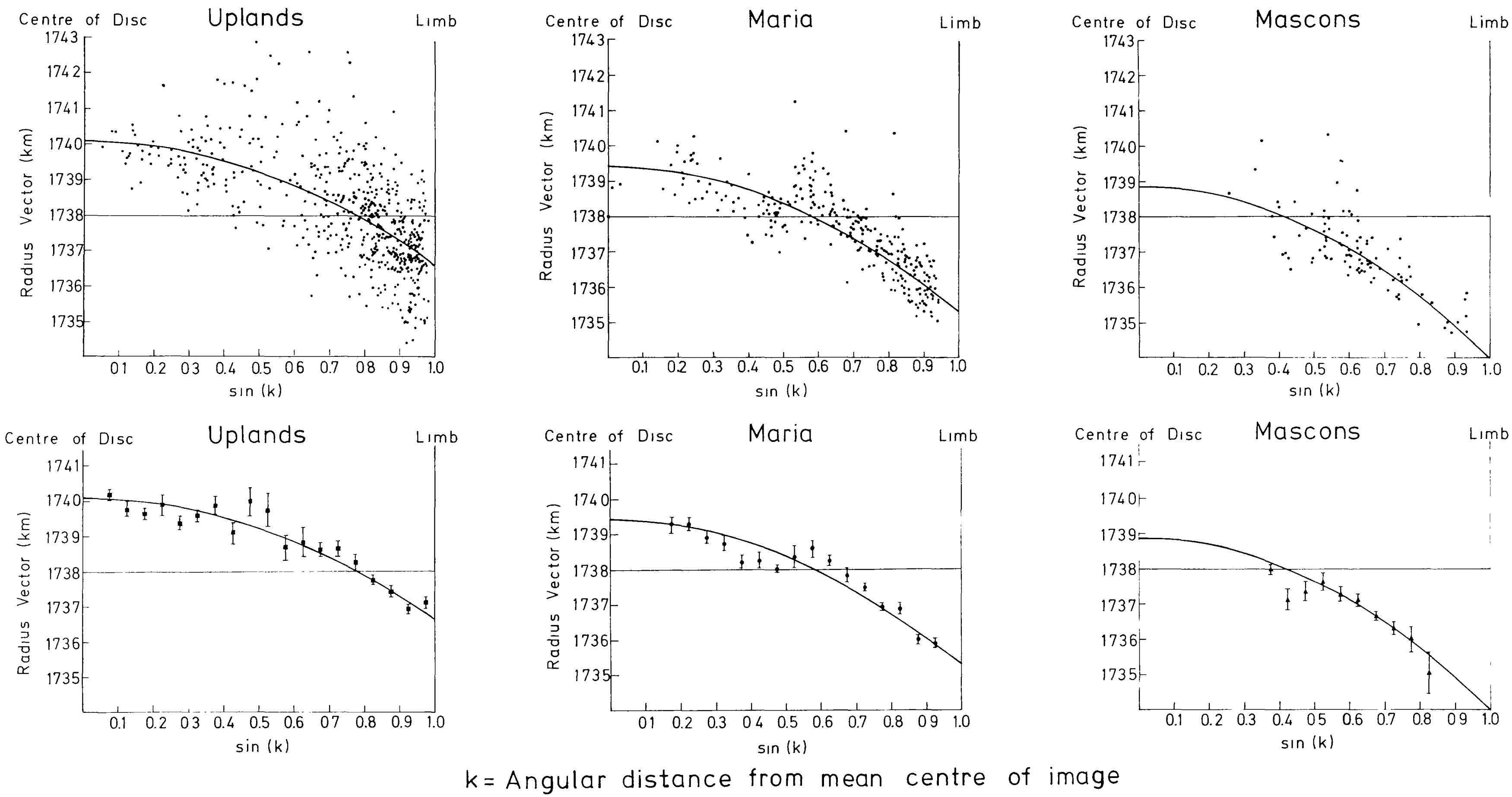


Fig. 1. Analysis of heights of lunar surface (geometrical libration data). Upper diagrams show best fitting ellipsoidal surface for the uplands, maria and the circular maria or mascons. Lower diagram demonstrates the adequacy of fit of means of points taken over equal intervals of sin (k) to the ellipsoidal surface, fitted by least squares to all the points.

Table 1. Axes of ellipsoids fitted to uplands, all maria, mascon maria, and other maria/km.

	Semi-axis toward earth a_x	Equatorial semi-axis in plane of sky a_y	Polar semi-axis a_z	$a_x - \frac{1}{2}(a_y + a_z)$	$a_y - a_z$	Number of points
Uplands	1740.2	1737.3	1736.5	3.3	0.8	532
All maria	1739.1	1736.0	1734.7	3.8	1.3	385
Mascons	1738.7	1734.5	1734.0	4.5	0.5	95
Irregular maria	1739.3	1736.1	1735.2	3.7	0.9	290

gravitational field, this bulge would equal 100 m. The nonhydrostatic figure, which has been the subject of much controversy, arose either from a distortion produced in the early history of the moon, which has since been retained by the finite strength of the interior, as Laplace and Jeffreys supposed, or it must be due to present-day convection possible because of the phenomena of solid-state creep. The latter explanation was first put forward by Runcorn (1962, 1967) and Table 1 is very strong evidence in its favor. The geochemistry of the Apollo crystalline rocks indicates that they would have had a very small viscosity when molten, which explains the relative smoothness of the maria surface previously referred to. It must, therefore, be supposed that when molten magma filled the maria basin, its surface would have been level; in coincidence with a gravitational equipotential surface of that time. It is known (Runcorn, 1973) that the present second degree harmonic gravitational equipotential surface departs considerably from the maria basin ellipsoid with only about a fifth of its ellipticity. Thus, just after the solidification of the lava flows in the maria basins the ellipticity of their surface was determined by the lunar gravity field at the time. I infer that the process which distorted the moon from the hydrostatic figure must have occurred at some time following the filling of the maria basin, otherwise the ellipticity of the mean surfaces of the highlands and the maria would now be markedly different.

The theory that thermal convection is the physical process that has distorted the lunar crust some time in the last 3000 m.y. has the merit that it is a phenomena of instability and therefore its pattern can be supposed to have changed. The present pattern of convection must have a second degree harmonic component, otherwise there would be no difference in the lunar moments of inertia—the primary data for asserting that the moon departs from hydrostatic equilibrium (Runcorn 1967). Thus I also infer that when the maria basins were filled, the moon was either in hydrostatic equilibrium or the convection currents distorting its surface were either of first degree harmonic type or at least had no second degree harmonic component. This conclusion seems reasonable because the lava necessary to fill the maria basins which are quite widespread over the nearside hemisphere of the moon is likely to have been derived from a zone rather like the asthenosphere of the earth: a spherical shell at a temperature near the melting temperature of silicate rocks. In the moon, such a zone would have to be deeper than in the earth for two reasons: (1) the greater ratio of surface to area in a body of smaller radius seems likely to result in a thicker outer shell below the temperature at which solid-state creep dominates; and (2) by whatever process the mascons were emplaced in the lunar crust, the latter must have been strong enough to support them from the time of their origin to the present day. As the phenomenon of finite strength over 10^9 yr requires, according to solid-state physics, a comparatively low temperature, less than about half the melting temperature, the thickness of the lunar lithosphere must be of the order of 200 km at least. The heat-flow measurements so far made on the moon by the Apollo 15 and 17 missions are about half that given by geothermal temperature gradient.

3. Formation of the Mascons

A spherical shell, of partial melting, rather than a number of isolated pockets of magma, seems required to generate the lavas 3–4 b.y. ago. It will be shown that a horizontal transfer of magma is required to explain the mascons. An accretional origin of the moon should result in a spherically symmetrical body, in which heat sources should not be localized. As this spherical shell was near to its melting point the lithosphere should have taken up a figure near to hydrostatic equilibrium at that time, as in the earth at present, except for anomalies of such a length scale that they can be supported by its finite strength, such as the mascons. Thus, as its rotation is slow, the shape of the moon would then have been closely spherical. The sequence of events necessary to form the maria are firstly partial melting of at least the outer part of the moon resulting in the separation of a less denser fraction, anorthosite, to form a continuous shell 2–3 m.y. after the moon's origin. If a first degree harmonic convection pattern was occurring in the moon, the thickness of this layer might be markedly greater in one hemisphere.

The thickness of the outer shell of anorthosite is restricted by moment of inertia considerations to between about 10 and 100 km, supposing it to be underlain by a mantle of ferromagnesian silicate of density nearly 3.3. Random impacts in the final stage of accretion, say 4200 m.y. ago, removed considerable areas of the anorthosite shell, leaving the mantle exposed in the area now covered by the circular maria, as shown in Fig. 2a. The floors of these large impact craters would have risen to a height at which the stress differences in the lunar lithosphere lie below the threshold for plastic deformation. Above these depressions there would at this early stage have been a free air negative gravity anomaly. Mechanics provide no reason to suppose that they are not randomly distributed, otherwise they would have occurred on the farside of the moon. Evidence for this was obtained in the photography of the far side which shows some large depressions: the large depression 20°S of the equator revealed by the laser altimeter carried by the Apollo 15 spacecraft is probably part of such a crater. There is now no reason to suppose that in respect of the infall of large objects the two hemispheres differ except as a result of the randomness of the phenomenon. However, the absence of large dark areas on the farside suggests that the process of lava filling only occurred on one hemisphere (the nearside one), and that the filling process in

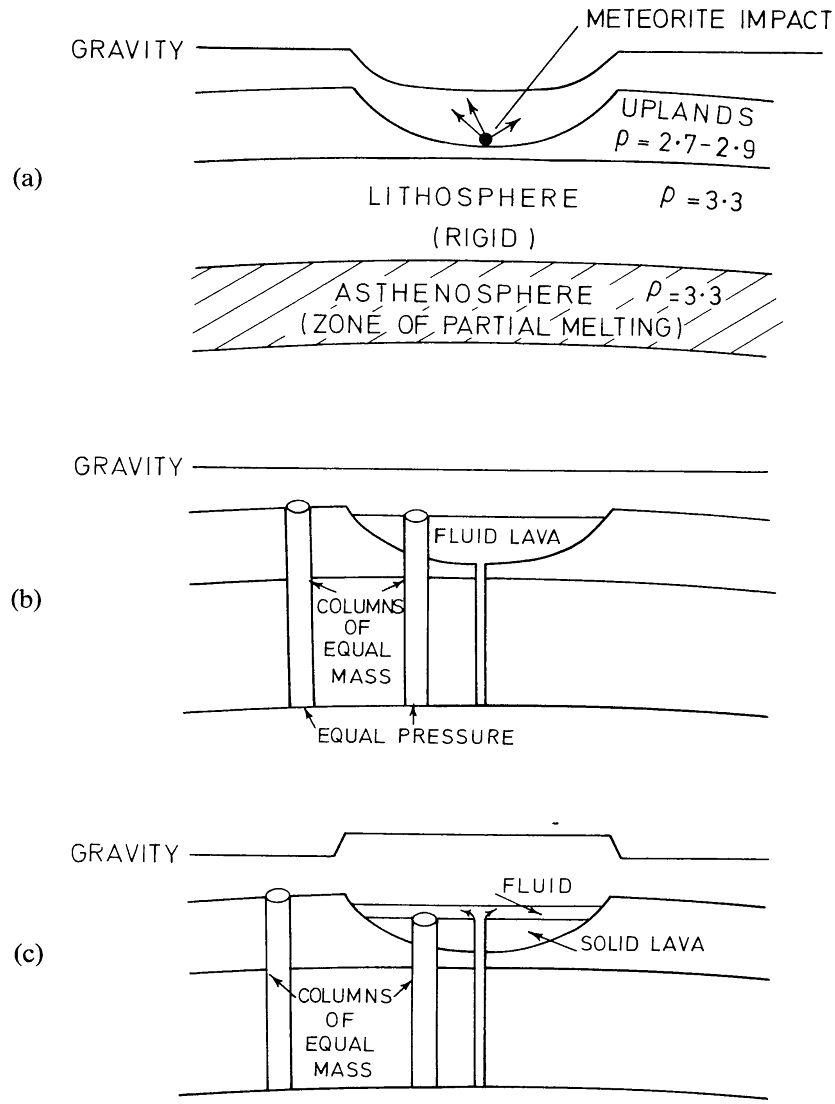


Fig. 2. Steps in the formation of the mascons: (a) Impact basins in the moon's shell. (b) Lava filling the basins from the asthenosphere. (c) Contraction of lava allowing an additional sheet of lava to form.

the circular maria resulted in positive gravity anomalies but not in the other, irregular, maria.

It is a matter of speculation why the depressions on the farside of the moon did not fill with lava, for on this basically spherically symmetrical model of the moon, the rise in temperature necessary to bring a spherical shell to near the melting point at the time (some 3–4 b.y. ago) of the filling of the nearside circular maria would hardly suggest that partial melting necessary to generate lava was only occurring in one hemisphere. Appeals have been made to tidal forces which have been supposed to operate on the nearside relatively more strongly than the farside: such suggestions are simply examples of a commonly held fallacy, the effect is only one of the third degree and appears of quite negligible importance. Thus, it is necessary to suggest a reason why lava, equally available below the two hemispheres, did not rise into the depressions on the farside. One reason is that channels to the surface were only available on the nearside: lava extrusion on the earth is generally associated with cracks in the lithosphere resulting from tensional stress in it, e.g. at the crests of the ocean rises. It is thus reasonable to infer that the tensional stresses were of much greater importance in the nearside lithosphere of the moon than in that of the farside at this early stage in lunar history. If convection is now postulated in the moon, we have concluded already that its pattern must have changed since the early history of the moon: a single cell pattern, that is, one described by a first degree harmonic, would have had the characteristic that its viscous drag on the under side of the lithosphere would have resulted in tension in one hemisphere and compression in the other. This mechanism appears to provide a satisfactory explanation for one of the most puzzling features about the moon: Runcorn (1974) has suggested that the similar assymmetry in volcanic features of the surface of Mars, revealed by the Mariner 9 photography, may be similarly accounted for. Alternatively, the possibility that the thickness of the anorthosite layer is greater on the farside is suggested by the analysis of the laser altimeter results from Apollo 15 and 16; the center of figure of the moon being displaced about 2 km further from the earth than the center of mass (Sjogren and Wollenhaupt, 1973). Magma could not rise sufficiently high to fill the basins on the farside, in which case dykes and lacoliths may exist below the farside highlands.

If the tensional forces provide channels from the asthenosphere to the circular basins, lava will fill them to a height which is determined by the hydrostatic pressure at the upper surface of the asthenosphere. It seems reasonable to suppose that this pressure must equalize itself over spherical surfaces within this "fluid" zone, see Fig. 2b. Thus, as lava rises into the basins, horizontal transfer of magma in the asthenosphere takes place. If we supposed that the lava were to remain molten in the basins it would, of course, set along a surface similar in shape to that through the surface of the highlands, i.e. nearly a sphere. However, it would be lower than the surface of the highlands because of the lower density of the anorthosite crust as shown in Fig. 2b. If the pressure at the base of the asthenosphere is p and the thickness of the uplands shell is t km, and we assume a density for the uplands of 2.7 and 3.0 for the lava, then the surface of the molten lava will be about $t/10$ km below the surface of the highlands. To a high degree of approximation no gravitational anomaly would therefore have been present over the circular maria while the lava remained fluid, nor would such an anomaly appear when the lava solidified if no further lava was welled up into the basins. If the percentage contraction in volume is α, the fall in level of the surface on solidification would be αd, where d is the mean depth of the basin. However, if the tensional forces continue to act to produce a channel from the asthenosphere to the surface of the now solidified lava in the basins, then further lava could rise and flow over the solidified surface, for the contraction of the lava in cooling would have lowered its surface below the height to which the pressure head in the asthenosphere could raise molten lava as illustrated in Fig. 2c. Thus we arrive, by a rather different argument, at the mechanism proposed by Wood *et al.* (1970) for the generation of mascons. In this argument the essential point is that, although geochemical processes resulting in an upward separation of different chemical fractions of the interior of the moon are appealed to, purely vertical redistribution of mass does not produce mascons. The process envisaged is one in which horizontal movement of material through the asthenosphere has taken place as well as vertical movement, during the filling of the maria basins.

Simple calculations, therefore, suggest that a basin which can fill with lava to a depth of about 20 km is necessary before mascon formation is possible. The additional lava sheets due to the solidification mechanism would have a thickness of about 1–2 km, as α is about 0.1. Mascon gravity anomaly, therefore, should have the shape resulting from a disk of density 3.0 exactly covering the dark area of the basin, placed at the maria surface and having a thickness of about 1–2 km. Several models of the mascon gravity anomalies have yielded essentially this result: perhaps the calculations which give the most refined test are those of Phillips *et al.* (1972).

This theory explains why the smaller circular craters filled with lava do not show positive gravity anomalies: their initial depth is too small for the shrinkage on solidification of the lava to provide space for any appreciable additional lava outflow.

The impact basins however were formed about 4.1 b.y. ago, hundreds of millions of years before the lava filled them. It is possible that after the anorthosite shell was stripped away by these impacts the moon gradually returned to isostatic equilibrium in which case the mantle, assuming its density is about 3.3 would rise to a height within these basins $t/5$ lower than the surface of highlands. As $t = 60$ km this depth would be insufficient for the above process to yield mascons. However if the density of the molten lava is 3.0, it would rise to a height in this basin below the highlands of $t/10 = 6$ km—it would therefore be possible for this shallow basin to fill with a sufficient layer of lava to account for the mascons. If the depressions on the far side which did not fill with lava are found to have negative gravitational anomalies above them this will support the view that the lithosphere was sufficiently thick when the impact basins were formed to support loads of "mascon" type. If however, no gravity anomalies are found, it can be supposed that at the time of formation 4.1 b.y. ago sufficient upwarping of the mantle occurred (to about 4.5 times the depth of the depressions i.e. about 20 km) to reach isostatic compensation. If positive gravity anomalies are found above the far side depressions, it will show that lava rose to a height of about 60 km into the anorthosite layer forming lacoliths about 20 km thick in which some mechanism like Wood's could have operated.

No tenable theory of mascons should fail to explain the absence of positive gravity anomalies over the irregular mare such as Oceanus Procellarum in spite of the height of their surfaces being greater than those of the circular maria. However, their less regular outlines strongly suggest that the impacts which removed the preexisting anorthosite crust in this region predated the impacts which created the circular maria. The geological maps of the moon also suggest the presence in Oceanus Procellarum of much brecciated material, the Fra Mauro formation, which was almost certainly deposited there by latter impacts, particu-

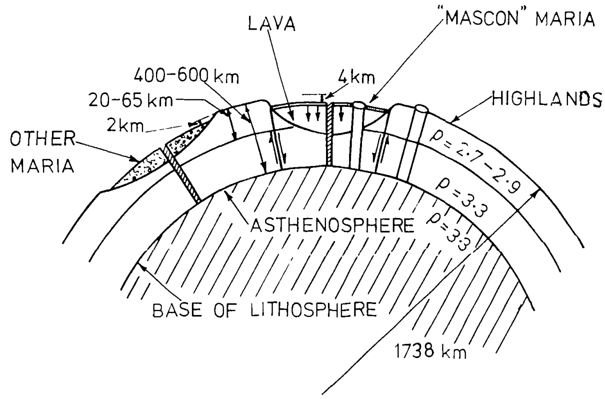


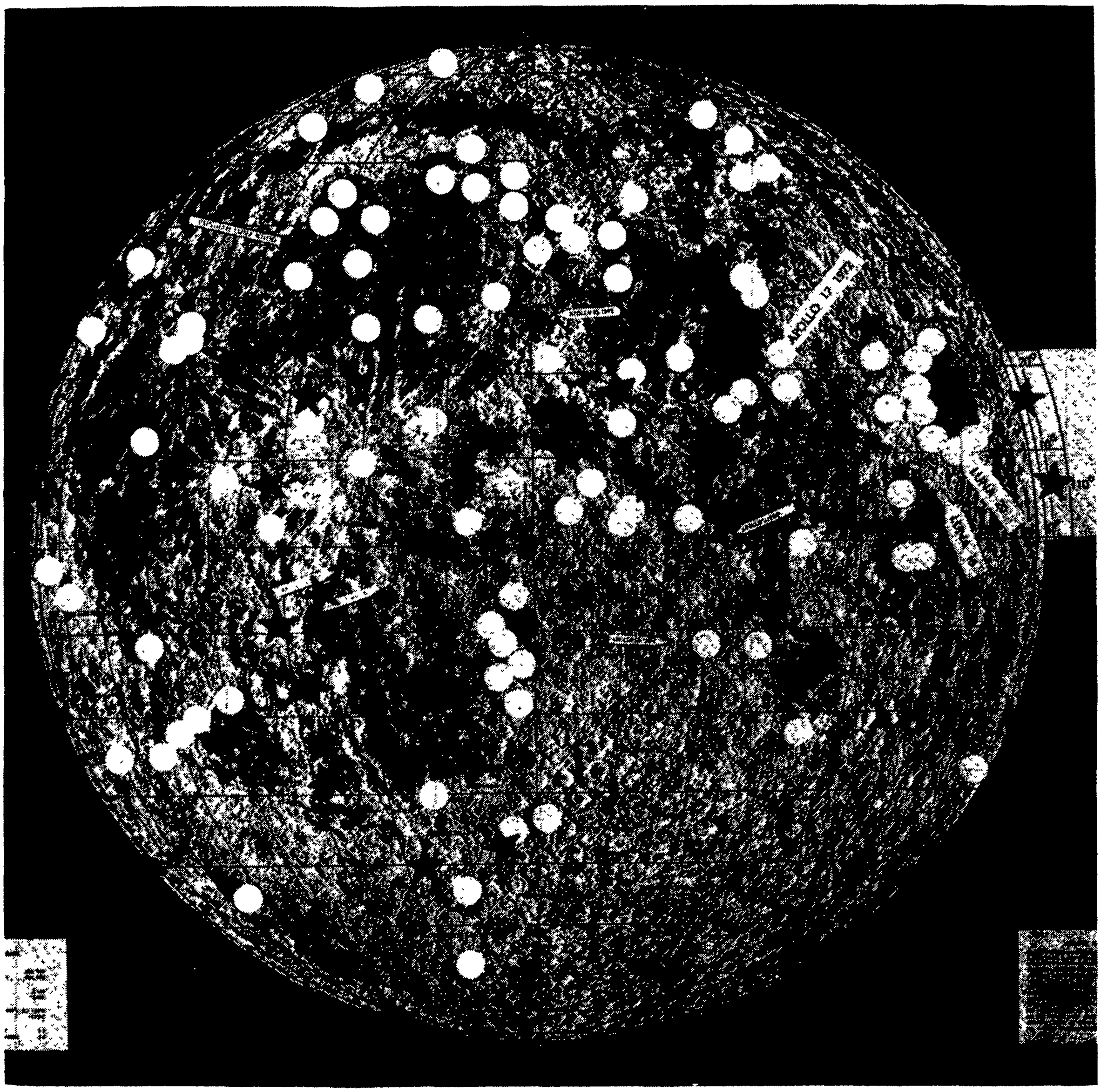
Fig. 3. The filling process of circular maria and irregular maria compared. Cylindrical fault system around circular maria responsible for moonquakes.

larly that which produced Mare Imbrium. The lava flows which have covered part, but not all, of this Fra Mauro Formation seem to cover the valleys of this preexisting terrain. The geological maps suggest that these tongues of lava are thin and consequently they only flow to a height negligibly in excess of that given by isostatic equilibrium as illustrated in Fig. 3.

4. Moonquakes

The discovery of moonquakes is one of the most unexpected results of the Apollo project. Latham *et al.* (1973) and Lammlein *et al.* (1974) showed that they occur at depths of several hundred kilometers, have a high probability of occurring at the time of highest tide; i.e. at apogee and perigee, they repeatedly occur at a number of locations having a distinctive spatial pattern and the source motions at one epicentre are normally in the same sense. We can suppose that they occur no lower than the base of the lithosphere, where strain energy can accumulate. The view of Latham *et al.* (1974) is that the strain energy released by a moonquake is that accumulated in the lithosphere in the preceding tidal period. I find this theory difficult to accept for tidal amplitudes have decreased with the time due to the retreat of the moon from the earth and it would be quite fortuitous if the present tidal strain was still just sufficient to cause rupture. I conclude that the remarkable correlation of moonquakes with the tides is more likely to be explained by the tide acting as a trigger to release other stored energy. Runcorn (1973) suggests that this latter energy is the potential energy of the mascons.

The distribution of the moonquakes is not yet finally determined. Lammlein *et al.* (1974) revise the earlier epicenter positions. Many lie near the periphery of the circular maria. Middlehurst and Moore (1967) have shown that the lunar transient phenomena (LTPs) are distributed around the circular maria and extensive crack systems and also occur at the time of highest tidal amplitude. Figure 4 shows the distribution of moonquakes and LTPs. Although the LTP recorded cover the last few centuries, and none occurs at exactly the same places as moonquakes, they do occur along the same lines, especially around the circular maria. Taken together these indications of present-day activity within the moon appear to be associated



★ PRELIMINARY POSITIONS OF MOONQUAKES ○ PLACES WHERE LUNAR TRANSIENT EVENTS HAVE BEEN OBSERVED

Fig. 4. Distribution of moonquakes and lunar transient phenomena.

with the circular maria. It is hard to see why these phenomena both correlate with the tides unless there is some path of communication between the base of the lithosphere and the lunar surface. Runcorn (1973) therefore suggested that cylindrical fault systems coincident with the boundaries of the circular maria exist through the lithosphere as shown in Fig. 3. It seems reasonable to suppose these cracks were produced by the impacts which caused the circular basins or by the subsequent uplift (see Fig. 2a). At times of perigee and apogee the lithosphere will be stretched to its maximum and this would be the most probable time for the mascons to fall downward a little. Photographs taken during the Apollo missions (e.g. of Mare Crisium) seem indeed to suggest that the mascons are cylindrical features which have descended by about 1 km through the lithospheric crust. This is exactly what we have inferred from the analysis of the heights of the lunar surface.

The potential energy released each year assuming the mascons have fallen at a constant rate is 10^{18} erg/yr. Each moonquake releases about 10^{11} erg and there are about 3000 moonquakes per year. This would imply that, with the reasonable efficiency of conversion of stored energy released to seismic energy of 0.03–0.1%, the falling mascons are quantitatively a satisfactory explanation. Further, this theory explains why the source motions are always in the same sense in consecutive events. The LTP would thus be caused by the emission at the surface of volatiles from the deep interior of the moon. Recent work of Hodges and Hoffman (1974) has shown that radon is episodically released and it is inferred that it must arise from the moon's interior. It may therefore be carried to the surface by these gases. The average rate of fall of the mascons per moonquake is 10^{-7} cm, but clearly the movement would be much greater on that part of the periphery of the cylindrical fault system which was for the time being active. The average time for which a particular part of the fault system would remain seismically active is suggested by the fact that the LTPs are fairly well spread around the circular maria. This time might therefore be some tens of years. Thus, a moonquake epicentre might continue active at each tidal maxima for such a period before migrating elsewhere. During this the mascon drops by 10 μ on an average, thus the actual movement at the epicenter would be many orders of magnitude greater.

5. Conclusions

We are now aware of three types of present-day activity originating in the interior of the moon: moonquakes, LTPs, and radon emission. They have some spatial correlation and occur episodically, the former two being correlated with tides. Much work remains to be done to examine further the nature of their association. Their correlation with the circular maria, and the evidence that the release of the potential energy of the mascons played a role in the phenomena. Figure 4 shows that many events seem to be concentrated around Mare Nubium which though not a strong positive gravity anomaly is sometimes classed as circular. It may possess a cylindrical fault system around its periphery, and may therefore have once been a mascon and at the present day its subsidence to new isostatic equilibrium may be almost—but not quite—complete. The postulated fault system could impede current flow and may explain the electrical conductivity anomaly beneath Mare Imbrium found by Schubert *et al.* (1974).

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