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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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 could not account for what is observed on the moon.

The question arises: what lava flows would be possible on a moon which supports such an immense submerged mass. If a lava flow is to occur, the rocks must sink in order to displace the liquid, and it seems likely that if the rocks can sink to displace lava, they should be able to sink in order to equalize the mass per unit area produced by the great collision which apparently has supplied this great mass to the areas below the surface of the maria. In fact, it would appear that if one has extensive lava flows, then there cannot be very large areas in which isostatic equilibrium is not established, at least for long periods of time. This would lead to the conclusion that the great smooth maria areas of the moon are not lava flows, but owe their existence to some other process, and that no liquid masses exist below the moon's surface.

This conclusion need not be in disagreement with observations of limited volcanic activity reported by Greenacre (*3*) and by Middlehurst (*4*). Such features may represent very mild and limited activity. It is contended here only that massive eruptions producing comparable gravity anomalies to those observed are not possible. (It might be argued that only recently, that is, in the last century, the last million years, or some other time, has the moon acquired sufficient temperature to begin to acquire isostasy, but this would be a very special assumption which is not made here.)

Yet the compositions of some regions on the moon are similar to that of basalt which is produced on the earth in lava flows, and, in fact, we observe no terrestrial rocks of this kind produced by any other method. This leads many to conclude definitely that the smooth areas of the moon are lava flows and even to suggest that they may be recent. The simultaneous presence of apparent lava flows and a cold rigid moon requires some attempt at a physically acceptable explanation of the difficulty.

There are very good arguments supporting the view that the intense collisional activity on the surface of the moon occurred in the very early history of the earth-moon system, before the earliest sedimentary rocks of the earth were laid down some 3 or 3.5 billion years ago. These terrestrial rocks show no evidence of having been disturbed by collisional processes such as would be expected if they had been subjected to the intensity of collisional processes exhibited in the southern part of the moon or in the rear areas of the moon. Also, the Canadian shield would be covered with very many large craters if half of the density of large lunar craters had been produced on the earth during the 2.5 billion years since the shield originated. This leads to the conclusion that these collisional processes occurred early in the history of the solar system. It is also probable that the collision maria occurred at the same time, though it is not possible to be quite so definite in regard to the arguments.

However, there are numerous craters which can be reasonably regarded as postmare. I counted some 34 craters of moderate to large size, in the neighborhood of Mare Imbrium, covering 9 percent of the lunar surface which are surely postmare in age. On this basis an equal density on the igneous rocks of eastern Canada should have about 20 such craters if they were formed at a uniform rate during the last 4.5 billion years. Only Chubb Crater, about 3 km in diameter, was observed in this area. It was suggested that a bay on the eastern side of Hudson Bay may be of collisional origin. It is very probable that the collision maria are part of the terminal stage of accumulation of the moon and earth (*5*).

Although it may be claimed that the material from the maria has been transported to the surface of the moon during recent geologic times, this cannot explain the observations of the material north of Tycho. Here, essentially basaltic material was observed in a region in which great collisions in great numbers have occurred (*6*). According to the argument presented above, these collisions must have occurred early in the history of the earth-moon system. But then, of course, the basaltic material was produced before the intense collisional processes that have supplied the many craters on this area of the moon. It appears likely that some type of differentiation process other than lava flows produced this material in the terrae regions of the moon, and it seems likely that this might also hold for the material in the maria.

Many people compare what is observed on the moon to the earth, but it seems also to be desirable to consider what we see on the moon in comparison with what we observe in the meteorites. The enstatite achondrites consist of nearly pure magnesium metasilicate. It would appear that in order to produce this material one needs to remove the element iron from primordial material almost completely by a melting and reduction process in a gravitational field, and then subject the remaining liquid silicates to a fractionation process which would divide it into two fractions—one having the enstatite achondritic composition which has the greater density and the higher melting point, and a second fraction similar to basalt without any iron content, that is, containing increased amounts of calcium, potassium, sodium, aluminum, and silicon, and a decreased quantity of magnesium. Material of not quite this basaltic-like composition was observed north of Tycho. The iron content however was not negligible, but some of the materials observed might indeed have a low iron content (*7*). In order to produce the fractionation of the primordial material into two fractions, one might suppose one of two processes; either a fractional crystallization process with the basaltic type material crystallizing at the top, or a solidification of the pool of the silicates and then a partial remelting producing basaltic-like material. The remelting process requires a second source of heat which is difficult to devise. A precisely similar process would apply to other achondrites containing oxidized iron, except that the reduction process was not complete or did not occur at all. In setting up models of this kind for the meteorites, a very definite limitation exists. These objects have potassium-argon ages in the neighborhood of 4.5 billion years, and the processes, whatever they were, occurred in a short period of time at the very beginning of the solar system.

The fact that the surface of the moon can reasonably be argued to be older than 3.5 billion years and possibly 4.5 billion years suggests that possibly the processes which occurred on the surface of the moon are similar to those which occurred to produce the achondritic meteorites, and they may have occurred at the same time. In fact, we may have a situation in which melting in a gravitational field, a recrystallization of the silicate fraction over a period of time, possibly some millions of years, produced material of lunar type at the surface. Establishment of the Widmanstätten figures in the iron meteorites requires slow cooling during something like 100 million years. Thus the achondritic materials and their accompanying basalts may have had a very long period of time in which to produce the postulated fractionation.

This model for the origin of the achondritic meteorites may suggest some mechanism by which basalt would be produced on the surface of the moon and yet not have lava flows on the surface. According to such a model the moon would have accumulated slowly and under conditions which made the interior of the moon cold, the center of the gas sphere at low temperature, for example, or the accumulation of solid objects over a long period of time, for example. This was followed by a heating process at the surface together with a reduction process in some cases. The heating might have been produced by highly compressed gases, or perhaps an intense bombardment process, or a high temperature sun. The iron oxide may have been reduced by hydrogen gas or carbon, or both, if iron oxide had not been present. It was then stored under an insulating atmosphere for a very considerable length of time, and produced a basaltic layer at the surface and an ultrabasic layer below. Then the atmosphere was lost, the surface cooled down, the moon was captured by the earth, and during this series of events it was subjected to the intense bombardment process. The terrae were thereby highly covered with many craters of moderate size and a few places were subjected to collisions with large iron-nickel objects which produced the circular maria. Other large collisions of this type may have been covered by the smaller crater collisions, for example, the mascon near Sinus Medii. The collisional processes produced a dust cloud of the basaltic-type material that settled over the maria areas and into many of the craters, or the collisions produced melting which supplied basaltic lava, or both. The moon at the time was so cold that no sinking of the iron-nickel mass to the deep interior occurred, and the heating processes within the moon since that time have not been sufficient to cause these nickel masses to sink enough to produce an isostatic situation on the moon. Short-lived radioactive elements could not have supplied the heat for the early melting process, because in this case the interior of the moon must have been at a high temperature, and it therefore could not have supported the subsurface high-density masses. This model for the origin of these meteorites and incidentally of the moon has been given by Urey (*8*).

A general bombardment with large and small objects containing some amounts of nickel-iron may have produced a widely spread layer of dispersed metal at some distance below the surface in addition to the mascons. If my suggestions here are correct, seismic studies of the lunar surface should be able to reveal such a layer. Also, if these effects occurred during the very early lunar history, the materials of the surface should be as old as the meteorites.

It is very reasonable to expect that (i) large objects have collided with the moon in its early history; (ii) these large objects should be similar to meteorites in composition and density; and (iii) if the moon has sufficient rigidity to support any extra masses of any kind, then it is reasonable to expect that these objects added additional mass in a localized area to the surface of the moon and are indeed responsible for the positive gravitational anomalies.

Could a moon meeting the requirement of high-density masses have escaped from the earth? If the earth accumulated from solid objects with the iron-nickel core material distributed uniformly throughout, and then it melted rather suddenly (as seems likely), the change in moment of inertia could have produced an unstable condition resulting in the loss of a body such as the moon. Its composition would approximate that of the moon as has been recognized for many years. However, if it separated as a single body, it would be hot throughout, would not cool off, and probably could not support the mascons. If the material escaped as small objects from the equator, they may have lost their temperature and accumulated slowly into the moon, and thus a low temperature moon might have been formed. In this case one must ask for the source of the basaltic materials on its surface, and possibly the high-energy collisional processes at the final stage of the accumulation process produced the required molten material on the surface. However, it is difficult to account for differentiation of basaltic-like material in a quiet liquid pool and at the same time keep it molten by an intense collisional process. Possibly a very energetic sun produced melting at the surface. Very serious objections to the separation theory have been advanced by several authors (*9*).

It is difficult to devise a lunar history which provides the low temperatures required to account for the lack of isostasy and the low electrical conductivity, and at the same time for melting processes required to produce the basaltic material on the surface of the moon. But it is just such requirements that may lead to definite conclusions in regard to the problems of lunar history and eventually to the early history of the solar system. It seems probable that the moon is a primitive planetary object and hence is of immense importance for the study of these problems, and will justify the immense efforts that are being made by so many scientists and engineers in the space program. The observations of Muller and Sjogren (*1*) are very important for the understanding of early lunar and terrestrial history.

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