to replace. Serratosa and Bradley (7) and Bassett (8) have shown that, as long as the attractive electrical forces in the three octahedral positions which surround each hydroxyl ion are of equal strength (as in the trioctahedral micas with divalent octahedral ions), the dipole is perpendicular to the cleavage surface. But when the forces become unequal, owing to the presence of an empty octahedron [as in dioctahedral micas (muscovite)], the dipole is inclined with respect to the cleavage surface. In biotite, where one of the octahedrons may be occupied by Fe^{2+} (as in the samples studied), oxidation to Fe^{3+} disturbs the electrical balance and thus brings about a change in the inclination of the dipole.

That the difference in inclination of the dipole could cause a greater difficulty in the replaceability of K^+ from muscovite than from trioctahedral micas of equal layer charge was suggested by Bassett (8) and confirmed by Rausell-Colom and co-workers (9) and by Scott and Smith (2). Furthermore, the idea that this difference may be related to a greater negative environment surrounding the K^+ was also suggested (9); in micas which contain F^- as a replacement for OH^-, the replaceability of K^+ is inversely proportional to the F^- content, even though the layer charge is of equal magnitude.

Several important conclusions emerge from these findings: (i) Changes in the replaceability of K^+ are only an exaggerated expression of changes in the exchange characteristics of other cations in general, as measured by adsorption isotherms and equilibrium constants. (ii) In preparation for cation exchange studies, clay minerals are frequently treated with solutions which may cause either an oxidation or a reduction of the iron in the crystal lattice. Differences in results on similar materials could be accounted for by sample treatment rather than by experimental variations or errors. (iii) The persistence of species of biotite micas in many highly weathered soils could be partially accounted for by the finding that oxidation of Fe^{2+} to Fe^{3+} renders the K^+ more difficult to replace and increases the fixation capacity for K^+ by that part of the biotite which became converted to vermiculite and which thereby helps to preserve the biotite (4). Oxidation of octahedral Fe^{2+} to Fe^{3+} is an important factor in the preservation of the K^+ content of soils, even though at times K^+ may become less available for plant uptake. Under such circumstances, however, it would appear possible that the replaceability of K^+ and its availability to plants might be artificially increased without fertilization by the production of a reducing environment in the soil. This could be done by waterlogging, as frequently practiced in rice culture.

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Mascons Interpreted

Iron Meteorites as Mascons

The discovery by Muller and Sjogren (*1*) of mascons in the moon is of great interest. My investigations (*2*) allow a calculation to be made of the size and depth of the mascons in terms of the size of the mare formed by low-velocity impact of an iron meteorite. The results of these calculations are in reasonable agreement with the results reported by Muller and Sjogren.

I am currently completing an analysis of penetration and cratering of concrete and soils by steel projectiles ranging, in diameter, from 1.27 to 15.5 cm and, in mass, from 8.35 g to 44 kg. Spherical projectiles are included. At velocities of 1.0 km/sec, the projectiles do not deform in concrete but suffer only minor scratches, and they are not heated excessively when stopped in the target. One result of the analysis is that, over the range of variables in the tests, the force resisting the projectile motion increases to a constant value. For this reason, it is believed that the results may safely be extrapolated to somewhat higher velocities without difficulties due to projectile deformation and heating.

A result of the analysis is that the depth of penetration x by a projectile of diameter d and mass m striking a target of compressive strength S and density ρ, with a velocity V, is

$$\left(\frac{x}{d}\right) = 0.0615\left(\frac{\frac{1}{2}mV^2}{Sd^3}\right) + 1.10\left(\frac{m}{\rho d^3}\right)^{1/3} \quad (1)$$

where the units are such that each term in parentheses is dimensionless. This equation is the limiting case of a more complex relation and is valid at velocities so great that an exponential term in the complex relation may be neglected. At these higher velocities Eq. 1 fits more than 80 percent of 140 data points within ± 10 percent. The data include values of ($\frac{1}{2}mV^2/Sd^3$) up to 218. For iron spheres striking the lunar surface with a velocity of 2.4 km/sec and with an assumed value of S = 3500 newton/cm^2 (= 5000 pounds per square inch), the value of ($\frac{1}{2}mV^2/Sd^3$) is 336. This is only one and one-half times the maximum value in the tests being analyzed, and it is assumed that the results may safely be extrapolated this far. In the second term on the right we take m/d^3 for an iron sphere and assume a density of 3.0 to 3.5 g/cm^3 for the target material. The predicted penetration of a smooth sphere, with data as given here, is x/d = 22.

We should not expect a meteorite, having irregular shape and a rough surface and probably striking with obliquity, to penetrate as far as a smooth steel projectile striking normally. Projectiles fired normally into concrete go straight in, but those fired normally into soils often turn sideways and penetrate about 70 to 50 percent as deep as those that go straight in. Some projectiles fired into soil break into two or three pieces, and these pieces penetrate less than half as far as unbroken projectiles which go straight in. Projectiles striking at an angle from the normal may ricochet, and the limiting angle for ricochet increases with velocity. Projectiles that strike with obliquity and do not ricochet penetrate less deeply than those that strike normally. At the highest velocities used in the tests, projectiles striking with 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 $dT/dP = 6°/\text{kb}$, 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.

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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-