GEOCHEMICAL CONSTRAINTS ON THE EXISTENCE OF A LUNAR CORE

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The highland crust is widely believed to have originated in a global-scale melting and differentiation event which affected the outer few hundred kilometers of the moon about 4.4 b.y. ago. Mare basalts are believed to be derived by complex processes involving subsequent partial melting of the deep lunar interior, perhaps combined with assimilation of mafic cumulates from the 4.4 b.y. major differentiation event (1). Small quantities of iron-rich metal phase occur widely in lunar highland rocks and in mare basalts. It has often been assumed, therefore, that the mafic cumulates underlying the crust and the source regions of mare basalts might likewise contain significant amounts of an iron-rich metallic phase. Several workers (2) have ascribed the depletion of indigenous siderophile elements in mare basalts and lunar crustal rocks to separation of a metal phase in the lunar interior prior to formation of the lunar crust and/or mare basalts. This evidence, believed to favour the widespread occurrence of metal phase within the moon, combined with global-scale lunar differentiation, has been used to support the proposal e.g. (2) that the moon might possess a small iron-rich metallic core.

Low-Ti mare basalts are believed to represent the most primitive type of basaltic liquid derived from within the moon, and accordingly, to carry the most direct chemical evidence concerning the compositions of their source regions (1). Detailed studies of olivine-metal relationships in low-Ti mare basalts e.g. (3,4) have demonstrated that (a) liquidus olivines contain as much as 500ppm Ni and 250ppm Co, (b) the very earliest liquidus olivines to crystallise do not co-precipitate with a metal phase, (c) subsequent liquidus olivines may co-precipitate with a metal alloy of unusual composition (up to 55% Ni). These observations show that the most primitive low-Ti liquids were far from being saturated with Fe-rich metal prior to eruption, and it thus follows that the source regions of these basalts likewise were not saturated with Fe-rich metal. Moreover, our electron microprobe study of Green Glass has shown that the high nickel content (180ppm) is not attributable to a dispersed metal phase but in fact occurs as NiO, uniformly distributed throughout the glass. A nickel content of around 180ppm is much too high for Green Glass ever to have been in equilibrium with metallic iron at near-liquidus temperatures. Finally, we have demonstrated (5) a good correlation between total Ni and MgO/(MgO+FeO) ratios in low-Ti basalts, which requires that nickel was present dominantly as the oxidised species prior to eruption and that nickel abundances were controlled by olivine fractionation. It appears that the most primitive mare basalts, essentially unaffected by olivine fractionation, probably contained over 200ppm Ni and 40ppm Co as oxidised species and were similar in this respect to terrestrial oceanic tholeiites (5). The enormous depletion of some siderophile elements such as germanium (5) cannot therefore have been due to prior separation of a metallic iron phase. Moreover, since the source regions have never been in equilibrium with metallic iron, the chemical justification for proposing the existence of an iron core on these grounds appears decidedly weak.
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In lunar highland rocks, a strong co-variance of W with La, and of P with La, extending over 2 orders of magnitude in concentration range, is observed Figs. 1 and 2. This co-variance was clearly caused by incompatible crystal chemical behaviour of W and P during magmatic differentiation process and requires that W and P were dominantly present as oxidised species in the original lunar highland rock system. The partition coefficient for W between metallic iron and silicate melts has been measured by (6). We have measured the partition coefficient for P at 1300°C between metallic iron, and a parental highland magma as described by (7). Both W and P are found to be strongly siderophile under these conditions with metal-silicate partition coefficients exceeding 20. It follows that the major lunar differentiation which formed the highland crust and the subsequent magmatic fractionation processes which gave rise to KREEP basalts did not occur in the presence of a metallic iron phase. There are no grounds, therefore, to suppose that an iron-rich lunar metallic core resulted from this early differentiation process.

Some workers e.g. (8) have proposed that the lunar core consists of an FeS-Fe liquid alloy, close to the minimum melting composition. We have measured the solubility of FeS in low-Ti mare basalts over a wide range of P02, temperature and pressure conditions. We find that these basalts are grossly undersaturated with FeS and conclude that they could never have been in equilibrium with a residual FeS-rich phase in their source region. Further arguments against the existence of an FeS-rich lunar core are provided by cosmochemistry. If a small lunar core of FeS corresponding to the upper bound set by seismic observations were assumed, the moon would contain about 0.4 percent of sulphur. Compared to the primordial abundances, this would imply that the moon successfully accreted about 3 percent of the primordial complement of sulphur, an extremely volatile element in the solar nebula. This may be compared with the corresponding proportions of other elements believed to have condensed in the moon, on the basis of their abundances in low-Ti mare basalts (5): Cs 1.5%, F 1.4%, Zn 0.5%, Ag 0.2%, As 0.1%, Au 0.01%, Ge 0.006%. All of these elements are much less volatile in the solar nebula than sulphur. It is therefore very difficult to conceive of conditions under which the moon formed that would permit sulphur to have been accreted so much more effectively than these other much less volatile elements. Several of these (e.g. Zn, Ge, F) are not chalcophile, so that their depletions cannot be ascribed to preferential partition into a hypothetical FeS core.

Geophysical evidence relating to the occurrence of a lunar metallic core is generally regarded as being highly equivocal. The geochemical evidence discussed above does not favour the existence of a core comprised dominantly of metallic iron or of iron sulphide. This evidence would not necessarily be inconsistent with the presence of a core composed dominantly (>60%) of metallic nickel which, theoretically, could separate under conditions of much higher oxygen fugacities than would be possible for an iron core. However, a nickel-rich core amounting to 1-2 percent of the lunar mass would raise many more geochemical problems than it would solve. These include the constraint arising from the relative vapour pressures of metallic iron and nickel - that metals condensing from the solar nebula cannot contain more than 15 atomic percent of Ni (9).
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Finally, we re-emphasise the significance of the strong depletions of W and P in the moon relative to the primordial abundances as pointed out by (6, 10, 11), Figs. 1, 2. These depletions cannot be ascribed to volatility. Since we have demonstrated that primitive mare basalts and highland basalts have never been in equilibrium with metallic iron, their depletions cannot be ascribed to segregation in a lunar iron core. Moreover, W and P are not strongly chalcophile so that their depletions cannot be due to segregation in a hypothetical FeS lunar core. However, the abundances of W and P in lunar rocks are very similar to those in terrestrial rocks as indicated by W/La and P/Liratios in both systems (6, 10, 11). This similarity is most readily explained if the material now constituting the moon was ultimately derived from the Earth's mantle.

REFERENCES