LETTERS TO NATURE

PHYSICAL SCIENCES

Model of Early Lunar Differentiation

IT has been suggested that one of the first major chemical differentiations in a planetary body such as the Earth will involve segregation of an Fe-FeS liquid[1,2]. This is because the eutectic temperature of this system (referred to here as Fe-S) is 990° C and is much lower than the temperature required to melt silicates (~1,100° C). The eutectic temperature is relatively insensitive to pressures[3] of at least 30 kbar.

The surface regions of the Moon have been melted and silicates differentiated at ~4.6 billion yr ago[4,5]. It is certain, that any Fe-S present will melt long before the silicates and because of its greater density will sink into the interior. Because of the small gravitational size of the Moon and because of the time required to accumulate any radiogenic heat, the interior of the Moon at the time of surface melting must have been cold; thus the sinking Fe-S liquid will be trapped at some depth.

Sonnett *et al.*[6] have described evidence for a layer of high electrical conductivity in the Moon at a depth of 250 km. They suggest that this is caused by compositional or phase change. It is improbable that phase changes, caused by partial melting in the silicate compositions appropriate to the Moon, can result in an electrical conductivity increase of three orders of magnitude. More probably, a major compositional change is involved. We suggest that this is an Fe-S layer (Fig. 1). In a Moon containing, as in some meteorites, about 5% by weight of FeS, melting of the outer 200 km will produce an Fe-S layer roughly 10 km thick.

If the Moon was an Earth satellite in synchronous rotation at the time[7] of melting, tidal forces and the then rapid rotation of the Moon would produce bulges in the Fe-S liquid layer both towards and away from the Earth with associated thinning at the poles. Further, differential gravitational effects between the rigid interior and the surrounding Fe-S liquid layer could introduce a basic asymmetry in the mass distribution of the Fe-S layer, the mass being greatest in the Earth-facing side (Fig. 2), analogous to models suggested by Baldwin[8] and Smith *et al.*[9]. Such a distribution of mass in the Fe-S layer is in qualitative agreement with the three unequal lunar moments of inertia[10]. Hydrodynamic instabilities of the type described by Elsasser[11] can produce downward bulges in the layer and consequent localized concentrations of Fe-S. We shall refer to these Fe-S concentrations as "fescons". We expect the fescons to be preferentially located on the near side of the Moon, reflecting the asymmetry of mass in the Fe-S layer caused by the tidal forces.

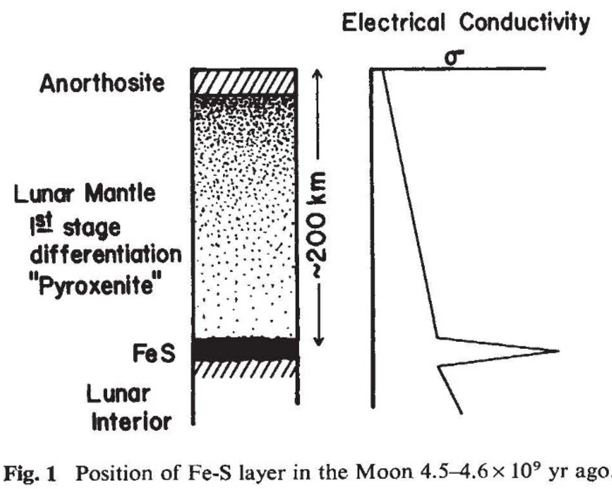

Fig. 1 Position of Fe-S layer in the Moon 4.5–4.6 × 10^9 yr ago.

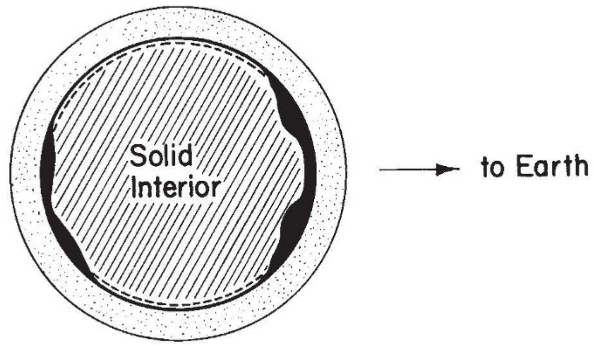

Fig. 2 "Droplets" of Fe-S form fescons at sites of tidal bulges.

The Moon's observed principal moments of inertia cannot result from a homogeneous body having the Moon's known shape. Muller and Sjogren[12] have shown that the circular maria are associated with positive gravity anomalies attributed to excess mass (mascons) under these regions. Mascons near the surface[13–15] can explain quite precisely the known ratios between the lunar moments of inertia. But their masses are a factor of ten too small to account for the magnitude of the moments of inertia[16]. In our model, variations in the thickness of the deformed Fe-S layer from 10–20 km produce fescons of sufficient mass (10^{21}–10^{22} g) to explain the observed moments of inertia.

Using the treatment of Morgan[17] and assuming a viscosity in the lunar interior of 10^{26} poises[18], a fescon of mass 10^{22} g would sink only 40 km in 4.5 billion yr, even if the mass were in the form of a uniform sphere. Because the fescons would probably be disk-shaped, the excess pressure, and hence the rate of sinking, would be appreciably less. Any minor sinking would tend to produce subsidence of the overlying material resulting in shallow circular basins.

It has been argued recently that in conditions of Fe-S segregation, the normally lithophile alkali metals, K, Rb and Cs, may exhibit chalcophilic behaviour[19,20]. In the Moon, therefore, we might expect that the segregation of Fe-S from the surface materials has impoverished them not only in chalcophile and siderophile elements, but in the alkalis as well. Heat production in the fescons by decay of ^{40}K with a half life of 1.3 billion yr would be most pronounced in the first billion years or so of lunar history, while the U and Th heat production in the outer zone of silicates would be both more uniform with

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time and more efficiently lost from the surface. Such a decoupling of the short lived and long lived radioactivities at 4.5 billion yr ago from the outer 200 km of the Moon might be expected to have considerable effect on the Moon's subsequent history. Because of the localized concentrations of ^{40}K in the fescon, local pockets of basaltic liquids associated with fescons would be formed. Impact-triggered eruptions could result in flooding of the regions above the fescons (Fig. 3) with spillage into adjacent areas. The mascons themselves may be primarily a result of near-surface effects associated with mare formation[14,15], but the distribution of circular maria on the lunar surface and the production of basaltic liquids a billion years after the origin of the Moon result from the formation of fescons.

Many workers have noted that the mare basalts show gross depletions of the alkalis, and several chalcophile and siderophile elements relative to chondrites. The depletion of alkali elements has been attributed to volatilization from the Moon[14,21] and to pre-lunar fractionation processes[22,24]. Evidence obtained from Pb-U and Rb-Sr isotopic techniques[4,25] shows that these fractionations have occurred before or during the first few million years of the Moon's history. Strong arguments against volatilization following lunar accretion as an exclusive source of these fractionations have been presented[22]. In our model, the Fe-S liquid segregation will cause a depletion of the chalcophile, siderophile, and alkali elements, in addition to any pre-lunar fractionations.

Following the initial melting 4.6 billion yr ago, the outer regions of the Moon underwent extensive fractional crystallization[9], producing the anorthositic crust by flotation of plagioclase cumulates[15] accompanied by sinking of pyroxene and ilmenite. The net result of this fractional crystallization process would be a mineralogically and chemically zoned outer region of the Moon, grading from Fe, Ti rich material in the lower parts to residual material near the top enriched in trace elements such as K, Ba, rare-earths, U and Th, overlain by an anorthositic crust.

About 1.0–1.5 billion yr later, the heat generated in the fescons by ^{40}K would partially melt the already chemically differentiated outer layer, producing the ferro-basalts of the maria. Thus, the abundances of many trace elements such as Ba, U, Th and the rare earths in these mare basalts would have been controlled both by the enrichments in fractional crystallization in the initial melting and the partial melting about a billion years later. The alkalis, in contrast, would have been depleted in the initial melting because of the Fe-S liquid segregation, but would be somewhat enriched in the later partial melting.

Assuming a uniform thermal gradient from 200 km depth to the surface and a conductivity of 10^{-2} calories/cm s °C, approximate calculations show that to produce and maintain silicate melting temperatures ($\sim$1,000° C) (at the depth of the Fe-S layer) during the first billion years would require the extraction of $\sim$100 p.p.m. of K from the overlying silicate material into the Fe-S layer. A 5% FeS content in the Moon initially would lead to a K concentration of 0.2% in the Fe-S layer. Estimating the K content of the source regions of the mare basalts at $\sim$200 p.p.m.[26] we obtain an initial abundance of 300 p.p.m. K in the outer parts of the Moon, significantly less than that in ordinary chondrites. An entire Moon of this K content would not undergo melting in the interior regions, as Urey and MacDonald showed[27].

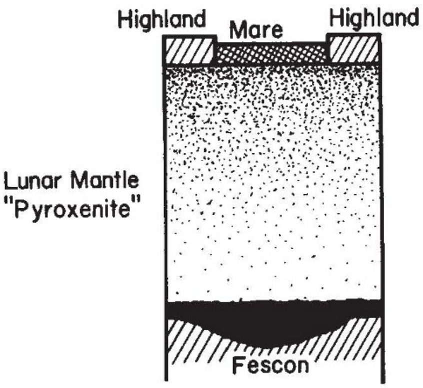

Fig. 3 Fescon and mare 3.0–3.6 × 10^9 yr ago.

The hypothesis of Fe-S segregation and formation of fescons used in our model of early lunar differentiation can be tested in future lunar missions. Seismic studies bearing on the interior structure of the Moon should in principle detect the Fe-S layer and the fescons. The localized concentration of ^{40}K in the fescons may be reflected by higher heat flow in the circular mare areas and can be verified by heat flow studies.

We suggest that Fe-S segregation plays a major role in the early chemical and physical history not only of the Moon and Earth[20] but of other terrestrial planets as well. Thermal histories of the planets attendant on a possible early segregation of K from U and Th remain to be studied.

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V. RAMA MURTHY
N. M. EVENSON
H. T. HALL

Department of Geology and Geophysics,
University of Minnesota,
Minneapolis,
Minnesota

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