THE Mg-SUITE AND THE HIGHLAND CRUST: AN UNSOLVED ENIGMA

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Most of the rocks returned from the highlands are polymict breccias, pulverized by the massive bombardment. However, some monomict breccias with low siderophile element contents are considered to be "pristine" rocks that represent the original igneous components making up the highland crust. Three principal pristine constituents make up the lunar highland crust: ferroan anorthosites, the Mg-suite and KREEP.

Ferroan anorthosite, typically coarsely crystalline with cumulate textures, is the single most common pristine highland rock type, making up probably 80% of the highland crust. The pristine clasts in lunar meteorites are mostly ferroan anorthosites. The major component (95%) is highly calcic plagioclase, typically An_{95-97} with a pronounced enrichment in Eu (Eu/Eu* ~50). Low-Mg and low-Ca pyroxene is the next most abundant mineral, but the mafic minerals are usually minor constituents in this dominantly monomineralic feldspathic rock.

An age of 4440 ± 20 m.y. has been obtained for the Apollo 16 anorthosite 60025 [1] and this is taken to represent the crystallization of ferroan anorthosites from the lunar magma ocean and the flotation of the feldspathic highland crust as "rockbergs." Alternatively, this date represents the "isotopic closure age" during cooling of the crust. Their old age, primitive $^{87}Sr/^{86}Sr$ ratios, uniform composition, Eu enrichment, presence of large massifs of pure (<3% mafics) anorthosite [2] and their global extent all combine to suggest that the ferroan anorthosites crystallized from a magma ocean.

KREEP originated as the final 2% or so melt phase from the crystallization of the magma ocean [3] and is strongly enriched in those "incompatible" trace elements excluded from the major mineral phases (olivine, orthopyroxene, clinopyroxene, plagioclase, ilmenite) during crystallization of the bulk of the magma ocean. This residual phase was the last to crystallize, at about 4360 m.y. and apparently pervaded the crust, with which it was intimately mixed by cratering. Its presence tends to dominate the trace element chemistry of the highland crust. Extreme REE enrichment up to 1000 times the chondritic abundances are known.

The Mg-suite comprises norites, troctolites, dunites, spinel troctolites and gabbro-norites [4]. Some are granulites, possibly from deep within the crust. These rock types are characterized by higher, and so more primitive Mg/Mg+Fe ratios compared to the ferroan anorthosites. They have a range in ages from about 4.43 b.y. down to about 4.17 b.y. although the older limit may be 4.37 b.y. The crucial point is that available data suggest that typical ages are 100-200 m.y. younger than those of the ferroan anorthosites.

The Mg-suite is petrographically distinct from the older ferroan anorthosites and does not appear to be related directly to the crystallization from the magma ocean. It makes up a minor, but signicant proportion (perhaps 20%) of the highland crust. It has two distinct and contradictory components in terms of conventional petrology. It is Mg-rich, commonly with Mg#>90 and so primitive in terms of igneous differentiation, but also contains high concentrations of incompatible elements, typical of highly evolved or differentiated igneous systems. The Mg-suite rocks typically contain REE at 15 to 100 times chondritic. The REE patterns are parallel to those of KREEP and ferroan anorthosites [5]. This KREEP signature does not represent post-crystallization contamination of Mg-suite plutons by KREEP, but was present in the magma from which the Mg-suite crystallized.

The contradictory characteristics of the Mg-suite suggest an origin by mixing of these two distinct components, one primitive to account for the major elements (particularly the high Mg/Fe), and the other evolved to account for the trace element characteristics. The source of the highly evolved component is clearly KREEP. The source of the "primitive" Mg-rich component is less clear. Conventional theories propose that the Mg-suite arose as separate plutons which intruded the crust as separate igneous intrusions. However, all Mg-suite rocks have parallel REE patterns [5], a characteristic compatible with mixing, but not expected to occur with such regularity in multiple separate igneous intrusions. Furthermore, it is of interest that the Mg-suite contains Mg-rich orthopyroxene, a mineral that is lacking in mare basalts.

Clearly the Mg-suite sources were distinct from those of the mare basalts. During crystallization of the magma ocean, Mg-rich minerals, (e.g. olivine and orthopyroxene) are among the first to crystallize and accumulate on the bottom of the magma chamber, in this case at depths exceeding 400 km. It is sometimes suggested that massive overturning has occurred to bring these within reach of the surface [6]. The isotopic systematics of the mare basalts show that their source regions were solid by 4400 m.y. The only melt remaining was the residual KREEP liquid, which solidified by 4360 m. y. Thus the magma ocean had completed crystallization by 4400 m.y. with only the minor KREEP component remaining liquid until about 4360 m.y. so that the lunar interior was mainly solid at the time of the formation of the Mg-suite. It seems difficult to envisage a massive overturning of the upper 400 km of the lunar interior after 4400 m.y. Other arguments have been advanced for only localized overturning during crystallization of the magma ocean [7].

There is no obvious internal source of energy for remelting early refractory Mg-rich cumulates. Subsequent melting to produce mare basalts took place in more differentiated cumulates and produced lavas with a different mineralogy, without the primitive and evolved characteristics of the Mg-suite. The total amount of mare basalt melt was probably about 0.1% of lunar volume. The melting, fueled by variable amounts of K, U and Th trapped in the cumulates, occurred over a period exceeding 1 b.y. in over 20 separate locations and was essentially trivial on a Moon-wide scale.

The Mg-suite, constituting at least 20% of the highland crust, or 2% of the Moon, has a volume about 20 times that of the mare basalts, and was produced in less than 20% of the time that the Moon took to produce the mare basalts. It requires a major energy source.The problems with the Mg-suite are thus to provide both a large volume of a primitive component (taking the evolved component as KREEP) and a source of energy to produce a magma.

We argue that large-scale overturning of the lunar mantle is unlikely to produce the voluminous and compositionally distinct magmas required to produce the Mg-suite. If the primitive compositions cannot come from the interior, perhaps they came from above. The giant impact hypothesis for lunar origin provides a ring of debris of primitive lunar composition from which the Moon accreted. Sweepup of some leftover objects at relatively low velocities following the formation of the lunar crust might result in mixing of whole Moon compositions with the residual KREEP liquid and with some remelted ferroan anorthosite. Such early impacts at about 4.3 b.y. into hot crust might differ significantly from later basin-forming events in cold crust (e.g. Imbrium, Orientale; note that gravity anomalies are confined to young basins and that the old highlands are in isostatic equilibrium). The resulting magmas could then pond beneath the ferroan anorthositic crust and subsequently intrude the crust. The amount of material added to the Moon need amount only to about 2% of lunar volume. Such a model can account for the mineralogy of the Mg-suite, with orthopyroxene and plagioclase, for the old ages (but younger than the accretion of most of the Moon) and provide both the primitive "whole Moon" component and a sufficient energy source.The production of igneous-textured rocks like 14310 may also be expected.

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