# PETROLOGY AND CHEMISTRY OF THE MAGNESIAN SUITE: FURTHER EVIDENCE OF LIQUID IMMISCIBILITY AND METASOMATISM IN THE WESTERN HIGHLANDS OF THE MOON

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The lunar magma ocean (LMO) was probably formed at the Moon's birth (at 4.5 Ga) and persisted for 150-200 Ma. After 60-80% of the LMO had crystallized, plagioclase became a liquidus phase and subsequently floated to form the ferroan anorthosites of the nascent lunar crust. During the latest stages of LMO crystallization, at approximately 4.36 Ga [1], the residual liquid was enriched in Fe, Si, P, K, and the REE and was trapped in the upper mantle and/or lower crust of the Moon where it crystallized to form urKREEP. This evolved residual LMO liquid is ripe for splitting into two immiscible silicate liquids and may have done so at that time. Being enriched in radioactive heat-producing elements such as K, U, and Th, this urKREEP could also readily re-melt at some later date and differentiate until it underwent silicate liquid immiscibility (SLI). The basic portion of SLI (which was REE- and P-rich, so-called "REEP-frac") was then available to metasomatize portions of the lunar crust. At least as early as 4.2 Ga, the interior of the Moon was also beginning to melt and produce primitive mafic magmas [2]. These mafic magmas could have precipitated troctolitic, gabbroic, and anorthositic cumulates in the crust and were also variedly metasomatized by the available REEP-frac. This produced Mg-suite rocks which contain primitive mineral compositions, are enriched in the REE and P, but are depleted in the alkali metals K, Rb, and Cs. Alkali anorthosites also were produced at about this time (possibly a little later), but were formed directly from the re-melted urKREEP as cumulates.

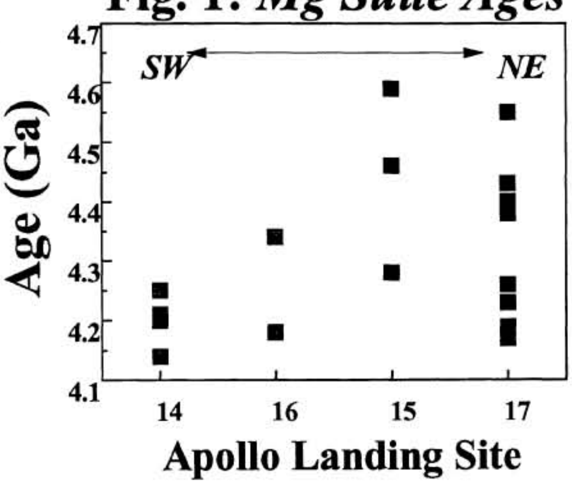
**INTRODUCTION** -- The study of rocks from the Apollo 14 landing site has led to important discoveries of evolved samples (e.g., [3,4]) which have added to our understanding of such processes as liquid immiscibility and metasomatism in the lunar environment. Mg-suite rocks are enigmatic in that they exhibit primitive mineral chemistry and evolved trace-element compositions. Lindstrom et al. [5] pointed out the problems with the urKREEP assimilation hypothesis for Mg-suite anorthosites, namely that other incompatible elements (besides the REE) such as Zr, Hf, Rb, and Cs are not enriched in the Mg-suite anorthosites and that interstitial mafic grains should be more Fe-rich, only if they crystallized from an evolved trapped liquid. These problems led them to postulate that REE-rich metasomatic fluids had infiltrated primitive troctolitic plutons in the lunar crust and percolated upwards into the anorthositic portions. These anorthositic portions of the plutons then were sampled as the magnesian anorthosites. The presence of phosphates (especially whitlockite) in the magnesian anorthosites were the only petrographic evidence of this metasomatic event [5].

**CHRONOLOGY OF Mg-SUITE CUMULATES** -- Nyquist and Shih [6] compiled age information from the lunar highlands Mg-suite and indicate that these ages range from 4.61 ± 0.07 to 4.17 ± 0.02 Ga. However, ages (with the exception of one Rb-Sr determination) for the most plagioclase-rich clasts (troctolites) fall in a range from 4.27 to 4.16 Ga. A compilation of U-Pb zircon ages for Apollo 14 Mg-suite rocks (14066,47: gabbronorite = 4141 ± 5 Ma; 14305,91: norite = 4211 ± 5 Ma; 14306,150: troctolite = 4245 ± 75 Ma; 14306,60: gabbronorite = 4200 ± 30 Ma; [7]) yields a possible range of 4136 to 4320 Ma and a weighted average age of 4191 ± 4 Ma. Thus, an age of ~4.2 Ga is considered reasonable for Apollo 14 magnesian suite rocks and is used in calculating initial isotopic ratios.

Shih et al. [8] recently have determined precise Sm-Nd ages for two Mg-suite norites (15445,17: 4.46 ± 0.07 Ga; 15445,247: 4.28 ± 0.03 Ga) and a Rb-Sr age on one other (15455,228: 4.55 ± 0.13 Ga) from the Apollo 15 landing site; these ages indicate that at least some magnesian suite rocks are in excess of 4.4 Ga old. Obviously, precise age information is needed for more Mg-suite rocks. Current isotopic data indicate that magnesian suite rocks were produced by a variety of parental magmas over an extended period of early lunar history, although *the bulk of magnesian suite rocks are younger than the ferroan anorthosites.*

Furthermore, as Figure 1 suggests, it is possibile that Mg-suite magmatism was initiated at different times in different regions of the Moon. In fact, the pattern in Figure 1 could lead to the interpretation that Mg-suite magmatism on the near-side occurred first in the northeast and then swept slowly to the southwest over a period of some 300-400 Ma. Granted, reliable age data are sparse, especially at landing sites 14, 15, and 16. However, if this age pattern is found to be real, we speculate that this regional progression could be due to the progressive freezing, and release of latent heat needed for melting, of the final residual liquids of the lunar magma ocean. This final liquid layer spread beneath the surface on the lunar near-side and was deepest, and therefore hottest, where the largest

**Fig. 1:** ***Mg Suite Ages***

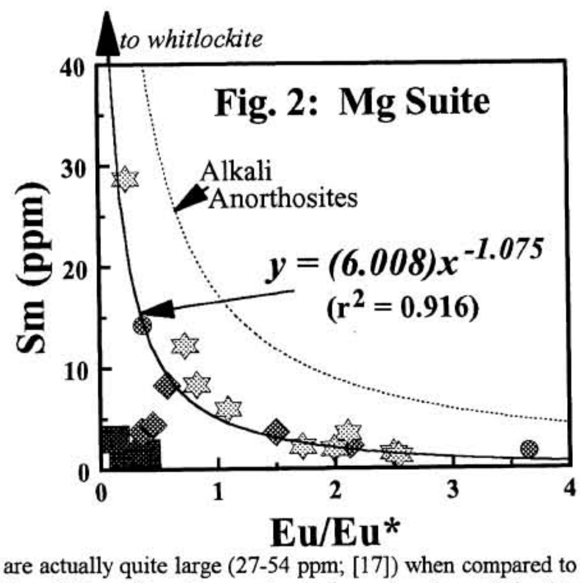


concentration of urKREEP has been found – at Apollo 14. As this final liquid layer crystallized, it did so from northeast to southwest, and culminated in the production of the most evolved KREEPy liquids beneath the Apollo 14 landing site.

**PETROGENESIS OF Mg-SUITE CUMULATES** – Magnesian anorthosites exhibit mineral chemistry consistent with their derivation from a primitive source, have REE contents consistent with an evolved parentage, but are relatively depleted in the alkali metals (e.g. K and Rb). REE contents vary widely, but in all cases, the REE are at least an order of magnitude higher than those in ferroan anorthosites [5]. The enriched Nd isotopic signature for anorthosite 14303,347 ($\varepsilon_{Nd}$ = -1.0 at 4.2 Ga) obviates a derivation from depleted mantle cumulates alone (which would have exhibited *positive* $\varepsilon_{Nd}$ values at 4.2 Ga) and suggests the possible presence of some KREEP-like component, from which its Nd isotopic signature ($\varepsilon_{Nd}$ = -1.0) is indistiguishable at this time. Therefore, the Mg-suite could represent re-melted portions of the Moon's deep interior which have been contaminated (assimilated? metasomatized?) by a component which is enriched in the REE. However, KREEP is not only enriched in the REE, but also in other incompatible elements such as the alkali metals, K and Rb [9]. The very low K (in many cases below detection limit by INAA of <0.055 wt.% $K_2O$; [5]) and Rb (0.494 ppm for 14304,347) contents and low $^{87}Sr/^{86}Sr$ initial ratio (0.69915 at 4.2 Ga) of the magnesian anorthosite, preclude KREEP as an important component. [Note that this $^{87}Sr/^{86}Sr$ ratio at 4.2 Ga is indistinguishable from that of alkali anorthosites, suggesting a similar source for the two types of anorthosites]. Furthermore, other evolved rock-types, such as QMD and lunar granite which have much higher $K_2O$ and Rb abundances (1.4-2.1 wt.% and 28-52 ppm, and 1.6-6.5 wt.% and 37-152 ppm, respectively; [10-12]) can also be ruled out as the added component.

An appropriate component, albeit only hypothesized, is found in the basic liquid fraction produced during the process of silicate liquid immiscibility (SLI). Neal and Taylor [12,13] have argued that some phosphates in some lunar highlands rocks are indicative of the process of metasomatism. Rb, Sr, and REE abundances, along with an enriched Nd isotopic signature, of 14304,347 support this conclusion for the metasomatism of the magnesian anorthosites.

Lindstrom et al. [5] noted that "magnesian anorthosites have larger negative and smaller positive Eu anomalies than the alkali anorthosites." Warren et al. [14] and Snyder et al. [15] have shown that the mineralogy and trace-element characteristics of alkali anorthosites can be explained by precipitation of plagioclase from an evolved QMD-like liquid with up to 20% of the liquid trapped in the cumulate. The greater the proportion of trapped liquid, the larger the negative Eu anomaly. However, the alkali anorthosite with the greatest proportion of trapped QMD-like liquid has a Eu/Eu* (0.24) which is still in excess of that for the more evolved magnesian anorthosites (0.094; Figure 2). Therefore, the magnesian anorthosites indicate addition of a component which has a Eu/Eu* that is as low, or even lower, than QMD (which has Eu/Eu* = 0.05-0.10). This component also has an elevated Sm abundance as indicated by the well-defined mixing hyperbola ($r^2$ = 0.916) traced by magnesian anorthosites on Figure 2 [this mixing hyperbola also includes two troctolites (circles) and several gabbronorites (diamonds)]. Only one component is known in the lunar environment which has a high Sm abundance combined with such a large negative Eu anomaly – the mineral whitlockite.




Lindstrom et al. [16] measured REE concentrations in lunar whitlockites from magnesian anorthosite 14321,1211 (,1273 = ion probe sample) using the ion microprobe and found average Sm abundances of 3315 ppm and a Eu/Eu* of 0.015. Assuming the Sm abundance of this whitlockite to be that of the component alluded to in Figure 2, one can calculate the Eu/Eu* value of the component. The calculated Eu/Eu* = 0.0028, approximately 5x smaller than actual measured whitlockites from anorthosite 14321,1211. Although, Eu values for whitlockite are exceedingly small relative to the other REE, they are actually quite large (27-54 ppm; [17]) when compared to any other lunar mineral (except possibly plagioclase). Therefore, the addition of small amounts of other minerals could lead to an extremely REE-enriched component with a lower Eu/Eu* than that of whitlockite. Therefore, it is considered likely that the trace-element abundances in the magnesian anorthosites are determined in large measure by whitlockite which may have been precipitated by the upward percolating REEP-fraction of Neal and Taylor [12].

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