LUNAR FELDSPATHIC METEORITES: CONSTRAINTS ON THE GEOLOGY OF THE LUNAR FARSIDE HIGHLANDS, AND THE ORIGIN OF THE LUNAR CRUST.

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Introduction: The Lunar Magma Ocean (LMO) hypothesis holds that, early in its history the Moon was wholly or mostly molten [1,2]. Mafic minerals (olivine and pyroxene) crystallized first from the magma and sank to form the mantle, enriching the remaining magma in Fe and incompatible elements. Later, plagioclase floated in the dense Fe-rich magma [3,4], and concentrated at the Moon's surface to form a global crust of ferroan anorthosite. The LMO residue became strongly enriched in incompatible elements and produced abundant ilmenite and residual melt enriched in KREEP to form new basaltic magmas that then intruded the global ferroan anorthosite, now represented by Mg-suite plutonic rocks and mare basalts.

This global LMO hypothesis is consistent with most petrologic and geochemical data from the Apollo returned samples. Most Apollo anorthosites are ferroan. Crystallization ages of the anorthosites are ancient [2,5], consistent with formation early in the Moon's history. Orbital remote sensing shows that all of the Moon's highland crust is anorthositic [6-8], as required by the LMO model. Mare basalts show a strong Eu depletion, complementary to the strong Eu enrichment of ferroan anorthosites[9], and consistent with flotation and thus removal of plagioclase from the mare basalts' source regions.

Lunar meteorites, ejected from the lunar surface by impact events, provide additional tests of the global distribution of LMO products. The meeorites come from random sites across the lunar surface [10]. About 2/3 of the meteorites are feldspathic, 1/3 are basaltic, consistent with the proportion of the lunar surface covered by highland material and mare basalts [10]. Feldspathic lunar meteorites, such as ALHA81005 and NWA 2996, represent these highland materials.

Samples and Method Meteorites ALHA81005 and NWA2996 are feldspathic, polymict, regolith breccias composed of rock and mineral fragments from the lunar highlands [11,12] with very little (NWA2996) to no (ALHA81005) KREEP component [13,14]. In thin section both meteorites contain fragments of anorthosites, 300μm to 3.5mm in diameter (Fig. 1), with 90-98 vol% plagioclase and 2-10 vol% olivine, low- and high-Ca pyroxenes, and/or accessory ilmenite.

Quantitative mineral analyses were obtained with a Cameca SX100 at NASA Johnson Space Center. Operating conditions were: 15kV accelerating voltage, 20nA beam current, 1μm beam diameter for olivine and pyroxene, and 5μm for plagioclase.

Geochemistry: Mineral compositions are uniform within each clast in these meteorites, but vary widely among clasts: plagioclase ranges from An_{96-99}; Mg# range from highly magnesian (Mg#=86) in both meteorites, to hyper-ferroan (Mg#=39) in ALHA81005 (Fig. 2A), a far larger range than the 'typical' Apollo ferroan anorthosites (Mg#=50-70; Fig. 2A). The range of Mg#s in anorthosites in both meteorites spans the gap between the Apollo ferroan anorthosite suite and Mg-suite (Fig. 2A), and is concentrated in this gap (Mg# 65-85). These meteorites also contain mineral fragments and granulites with the same Mg# range as the anorthosites, impact glasses, and basalts. Fragments of Mg-suite rocks are very rare.

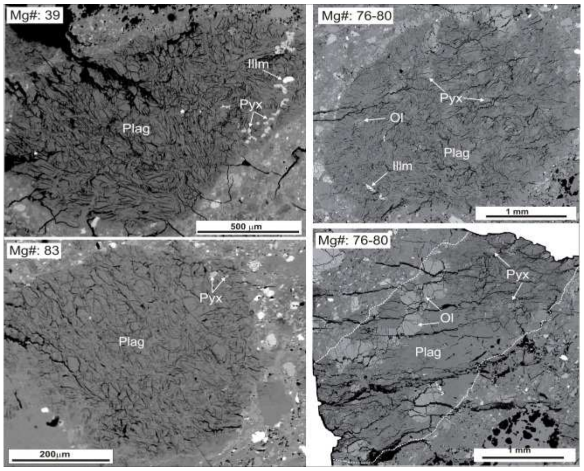

Fig. 1: BSE images of four typical anorthosite clasts in ALHA81005 (left side) and NWA2996 (right side).

Lunar Magma Ocean products?

ALHA81005 and NWA2996 and most lunar feldspathic meteorited [26] are not obviously consistent with predictions of the LMO model.

1) Most Anorthosite clasts in lunar feldspathic meteorites are too magnesian (Mg#>70) to have formed from flotation cumulates on a global LMO. Of the 43 known feldspathic lunar meteorites, data on 19 are adequate to evaluate the composition of their anorthosites [11]. Of those 19 about 2/3 contain magnesian anorthosites (Mg# >70; Fig. 2B), and the reminder 1/3 contain ferroan Anorthosite clasts comparable to those of the Apollo sites.

2) No known lunar meteorite is a 'pure anorthosite' (>95% plagioclase), and 'pure anorthosite' clasts are rare in feldspathic breccias [24]. Thus, 'pure anorthosite' may not be widespread across the lunar surface as suggested by remote sensing [25].

3) Most feldspathic meteorites contain little KREEP, consistent with the Th distribution on the lunar surface (concentrated in the nearside Procellarium KREEP Terrain, PKT). This alone suggests that a hallmark of LMO models KREEP, is not globally distributed.

4) Clasts of Mg-suite rock are rare in lunar feldspathic meteorites. Nearly all clasts that plot in the Apollo Mg-suite field (Fig.2) are magnesian anorthosites and noritic anorthosites that appear continuous with the range of other anorthositic clasts. Very few clasts in the feldspathic meteorites fall along the Mg-suite trend of decreasing An and Mg# (Fig.2).

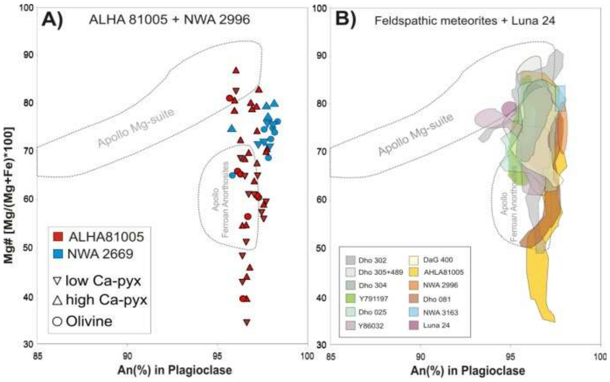

Fig. 2: A) Graph of anorthite (mol%) in plagioclase versus Mg# in mafic minerals in lunar samples. A) Anorthosite clasts in ALHA81005 (red symbols) and NWA2996 (blue symbols); B) Fields of anorthosite clasts in some feldspathic lunar meteorites and Luna 24, each color represents a different meteorite.

Lunar Farside Highlands: The lunar feldspathic meteorites suggest that magnesian anorthositic rock is a major component of the lunar highland crust and is the dominant material over most of the Moon. Only 1/3 of the feldspathic meteorites are ferroan, which is approximately the same as the proportion of the lunar highlands that is affected by the continuous Imbrium ejecta [3,16]. Only the Luna 20 and 24 missions returned samples from outside the continuous ejecta of Imbrium, and their highlands materials are dominated by magnesian anorthositic rocks, not ferroan anorthosites [17]. Thus, it seems reasonable to suggest that ferroan anorthosite, as well as KREEP and Mg-suite rocks, reflects processes localized in the Imbrium area and that magnesian anorthositic material is characteristic of the remaining 2/3 of the lunar crust. So, how did that remaining 2/3 form? By analogy with the Imbrium ejecta, and by impact modeling [27], that surface is likely underlain by ejecta from the South-Pole-Aitkin basin (SPA). SPA is the largest and oldest recognized lunar impact basin, and its ejecta blanket was kilometers thick over the whole lunar surface [27]. This ejecta, mostly of mid- and deep-crustal material, should be dominant at the lunar surface, except where covered by younger deposits (basin ejecta or basalt). Thus, it seems reasonable that the materials of most feldspathic highlands meteorites should be principally derived from mid- and deep crustal materials of the SPA target, and the remainder of highlands meteorites should consist mostly of Imbrium ejecta.

If the surface of the lunar highlands as we see it today is a continuous blanket of the Imbrium and SPA ejecta then **how did the original lunar crust form and evolve?** The long-standing alternative to the LMO hypothesis is serial magmatism – that the observed lunar crust is the product of multiple intrusions of basaltic magma, each differentiating during and after emplacement so that any primordial LMO crust is obscured[18,19]. In that model, plagioclase-rich cumulates from intrusions that rise into the crust as diapirs [18,20-22], while the complementary mafic layers sank back to the mantle [18]. Our data and the literature data are consistent with a modified version of this model, in which layered intrusions are emplaced close to the surface, differentiate and rise continuously over time. Each diapir is expected to have its own unique chemistry, Mg# range and plagioclase composition, depending on the physical and chemical characteristics of its source region and the duration of ascent and fractionation of interstitial melt within the diapirs [23]. During the SPA impact event those diapirs, close to the lunar surface, were then distributed onto and over the lunar surface.

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