SINKING THE LUNAR MAGMA OCEAN: NEW EVIDENCE FROM METEORITES AND THE RETURN OF SERIAL MAGMATISM.

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Abstract: Current understanding of lunar evolution is built on the Lunar Magma Ocean (LMO) hypothesis, which is based on the returned Apollo samples of ferroan anorthosites and the assumption that they are globally distributed. However, compositions of anorthositic clasts in lunar meteorites are inconsistent with a global LMO, and more consistent with crustal anorthosites forming from serial emplacement of massifs.

Introduction: The 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.

The 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 the Moon's highland crust is anorthositic[6-8], which is consistent with a global distribution suggested by the LMO model. The later basalts show a strong Eu depletion, suggesting that their source region(s) are complementary to the ferroan anorthosites[9], consistent with flotation and thus removal (by flotation) of plagioclase.

Tests of the global distribution of LMO products are provided by lunar meteorites; samples from random areas across the lunar surface[10]. Most of the feldspathic meteorites are breccias, and most of those do not contain ferroan anorthosites, KREEP, or Mg-suite rocks. This alone suggests that these hallmarks of the LMO are not globally distributed. Here we present new data on lunar feldspathic meteorites ALHA81005 and NWA2996, and review literature data on others. These data show that ferroan anorthosite is probably abundant only in the Imbrium basin and its ejecta, and thus that the global LMO model as currently envisioned cannot be correct.

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.

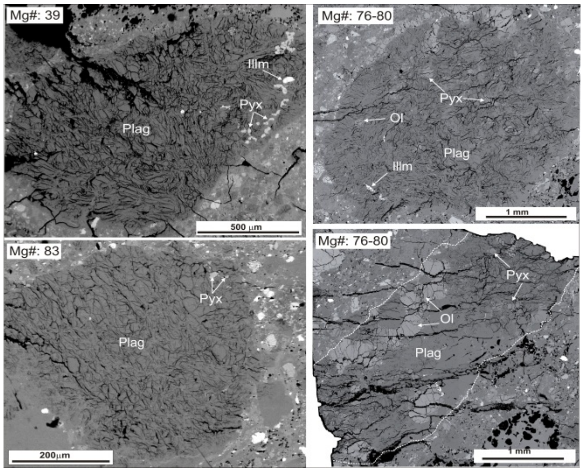

Fig. 1: BSE images of four typical anorthosite clasts in ALHA81005 (left side) and NWA2996 (right side).

Geochemistry: Mineral compositions are uniform within each clast, 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 continuum of Mg#s in anorthosites from both meteorites not only spans the gap between rocks of the Apollo ferroan anorthosite suite and the Mg-suite (Fig. 2A), but actually 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; but fragments of Mg-suite rocks are very rare.

Discussion: ALHA81005 and NWA2996 do not match the prediction of the LMO model. Their anorthosites that are too magnesian to have crystallized from a global LMO, and they contain little or none of the other characteristic LMO products, i.e., Mg-suite rocks and KREEPy material. In fact, most of the lunar feldspathic meteorites are similarly inconsistent with the LMO model. Of the 43 known feldspathic lunar meteorites, data on 19 are adequate to evaluate the composition of their anorthosites[11]. Five contain ferroan anorthosites comparable to those of Apollo samples, but 14 contain magnesian anorthosites (with Mg#s up to 90), and little or no ferroan anorthosite, Mg-suite rocks or KREEP (Fig. 2B).

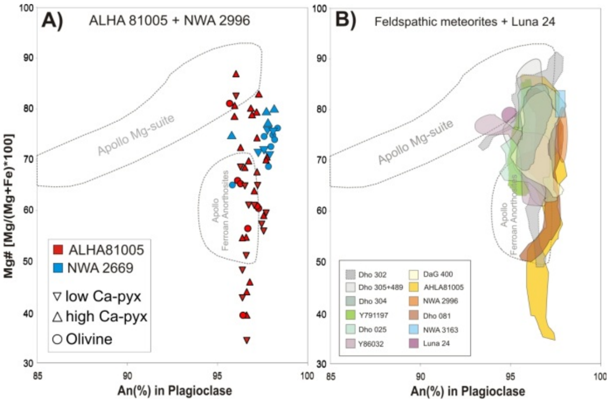

Fig. 2: A) Graph of anorthite (mol%) in plagioclase versus Mg# in mafic minerals in lunar samples. A) Anorthosite clasts in ALHA81005 (red symbols) and NWA2996 (blue symbols); B) Fields of anorthosite clasts in some feldspathic lunar meteorites and Luna 24, each color represents a different meteorite.

These meteorite data show that ferroan anorthosites are not globally distributed. The Apollo landing sites are all strongly influenced by the continuous ejecta of the Imbrium basin [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 cannot be extrapolated to the whole Moon or to a global LMO. The lunar meteorites provide further support for this idea. Of the 19 feldspathic highlands meteorites with adequate data, approximately only 1/4 contain ferroan anorthosite; this proportion is approximately the same as the proportion of the lunar highlands that is affected by continuous Imbrium ejecta.

How did the lunar plagioclase-rich crust, as we see it today, form? 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, heat from the Moon's interior allowed plagioclase-rich cumulates from the intrusions to 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 and differentiate continuously over time. The range of crystallization ages of ferroan anorthosites [2,5], inconsistent with a single LMO, is a natural consequence of this serial diapirism in which anorthosite diapirs form 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 (Fig 3). The sources of mare basalts and magnesian suite rocks would form as mixtures of primitive mantle with the sinking diapirs of mafic material [18]. Portions of each mafic diapir would bear the element signatures of plagioclase co-crystallization (i.e. Eu depletion), of late ilmenite cumulates, and of late magmatic differentiates (KREEP). Each potential source area for mare basalt would have a unique mafic diapir input, and thus a unique degree of Eu depletion, Ti enrichment, and KREEP enrichment, contributing to the compositional diversity of mare basalts. Thus it is not surprising that we see a range of Eu depletions [23] (Fig. 4).

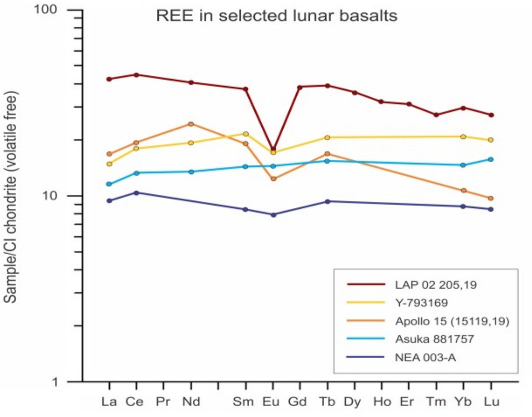

Fig. 3: Range of REE in selected lunar basalts. After [23].

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