

FRACTIONATION TRENDS OF EVOLVED LUNAR MAGMAS, J. Longhi,
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A current concern of lunar petrologists is how the suite of evolved pristine rocks (EPR), which include alkali-norites, alkali-anorthosites, and felsites, developed their characteristic mineralogy and compositions. Most of the EPR samples are clasts from breccias; larger samples of pristine rocks define two major suites (1): ferroan anorthosites (FA), which seem to be a fairly homogeneous assembly, and Mg-rich cumulates, which have been subdivided into two groups (2): magnesian norites (MN) and gabbro-norites (GN). Although the EPR appear to have little in common with the FA in terms of mineral assemblages and compositions, some of the EPR have apparent affinities with the MN, whereas others appear related to the GN (3). These relationships suggest that the EPR might be differentiates of the Mg-suite magmas. An alternative hypothesis is that some EPR might be the plutonic complements to KREEP basaltic magmatism (4). Some time ago I proposed that Mg-suite parent magmas were hybrids produced by assimilation of variable amounts of FA and KREEP into primitive, high-Mg magmas (5). More recently, (6) proposed that KREEP basalt magmas were also hybrids produced by assimilation of anorthosite and more primitive KREEP. If these latter two hypotheses are correct, then the hypotheses of (3) and (4) are in fact one in the same. To examine these possibilities I have modeled the fractional crystallization path of a MN parent magma and a KREEP basalt. To investigate how primitive KREEP may have developed, I have modeled the crystallization of a FA parent magma.

Much of the petrological data on EPR's has been tabulated by (4) and some of this data is illustrated in the *Mg vs An* plot in Fig. 1. Numbers signify landing sites; capital letters are abbreviated rock names (see caption). Also shown in Fig. 1 are calculated paths of mineral compositions for low-pressure fractional crystallization of three starting compositions: KREEP basalt 15386 (7), a Mg-Norite parent magma modified from (8), and a ferroan anorthosite parent magma also modified from (8). The abbreviated mineral names mark the onset of crystallization of the indicated phase (plag is always present). The first appearance of opx or pi marks the disappearance of ol; pi marks the disappearance of opx, if present; and fa marks the disappearance of pi. The slopes of the three calculated trends steepen from left right as explained by (8).

The FA curve passes through the field of ferroan anorthosite mineral compositions (not shown) and mimics the reappearance of Fe-rich olivine (fa) noted by (1). The FA curve does not pass through the field of EPR mineral compositions -- a fact that illustrates simply what is well known, viz., that EPR's have little in common with ferroan anorthosites or their residual liquids. Regardless of whether ferroan anorthosites formed atop a magma ocean or in serial intrusions, the rocks that crystallized from their residual liquids (olivine-tridymite ferro-gabbros with $An > .90$) have not been described among the returned samples. Remelting of such ferroan compositions would not produce suitable parent liquids for the EPR's either. The onset of ilmenite crystallization, which in and of itself has no special significance, represents 93 mol% crystallization of the FA parent. If we allow that the FA parent developed after 60% crystallization of a magma ocean or other primitive magma source, then the ilm point represents 97% crystallization of the original magma. Even such advanced crystallization is nowhere near sufficient to produce KREEP-like enrichments of incompatible elements (9). By the time that fractionation produces KREEP-like enrichments of incompatible elements the residual magma is nearly devoid of MgO and has a temperature $\leq 1000^\circ\text{C}$. The density of such hyper-ferroan liquids decreases rapidly once ilmenite crystallizes, primarily because alkalis are increasing rapidly. For example, at 93% (ilm) $\rho=3.09$, but at 99.3% (whl) $\rho=2.78$. During this interval concentrations of incompatible elements would increase dramatically and Ti/Sm would decrease precipitously, yet there is little reason to expect that these residual liquids (=ur-KREEP?) would intrude upward in the crust. Continued crystallization would drive density still lower, but would involve whitlockite precipitation. Modeling of REE abundances in KREEP suggests that phosphate was not involved (10), so it appears that the residual liquids did crystallize much beyond the appearance of whitlockite. Previous thermal calculations (11) suggest that even if these residual liquids were deeply buried, the enrichment in heat-producing radiogenic elements would primarily prolong the cooling and crystallization process and not lead to any significant remelting of the surroundings. Consequently, there seems little reason to expect ur-KREEP/crust interactions; rather it seems possible that ur-KREEP would have remained molten in isolated pockets at the base of the crust for tens or possibly hundreds of millions of years; some of it may even have been swept back down into the underlying mantle. It has been recognized for some time that most Mg-norites have KREEP affinities, e.g., low Ti/Sm (12). The present calculations are consistent with previous models that explained these affinities in terms of magma-mixing (12) or assimilation (5) of KREEP into primitive highly magnesian liquids.

The MN composition was devised so that: a) its mineral trend would pass through the compositions of the troctolite 76535 and norite 78235; b) ol would be replaced by opx between the troctolite and norite points; and c) augite and ilmenite would crystallize relatively late. It is not meant to be a unique estimate of the parent magma composition of these rocks, but rather an example of a typical liquid composition. At first glance there is little to distinguish the MN and 15386 trends other than the offset in *An* composition and the absence of ol in the KREEP trend. However, differences in TiO₂ concentration reflected in the appearance of ilmenite at very different *Mg* values are probably real inasmuch as most Mg-norites lack ilmenite (2) whereas KREEP basalts commonly have ilmenite (13). If one accepts the premise of KREEP mixing/assimilation into magnesian liquids, then the differences between the MN (lower Na and Ti) and 15386 (higher Na and Ti) compositions are probably due to differences in the parental magma composition, which in turn may be due to differences in degree of partial melting, differences in source composition, or variable assimilation of anorthosite (5,6). Anorthosite assimilation was originally invoked as means to allow highly magnesian, low-Al₂O₃ liquids to crystallize early ol + plag and then opx + plag, however, it may play an important role in determining alkali and Ti concentrations as well.

An important feature of the EPR mineral composition trends is the sequence of cumulus phases. In the center of the array of EPR mineral compositions are Ap14 norites and anorthosites, an Ap14 ilmenite-gabbro, and a cluster of Ap16 gabbro-norites. On the basis of *Mg-An* relationships alone, these rocks represent at least three distinct magma types, none of which lays along the MN line of descent. Relative to the MN composition, the Ap14 N and A magmas probably had lower lower SiO₂ relative to *Mg* (this would allow ol to persist to lower *Mg* and delay the appearance of sil); the Ap14 I-G magma had higher TiO₂ and CaO; and the Ap16 gabbro-norite magma had much lower SiO₂ relative to *Mg*. With the notable exception of K-

feldspar, which appears to crystallize at too low an *Mg*, a parent of 15386 seems readily capable of fractionating so as to crystallize rocks like the Ap15 granites, such as 15405. Given the difference in ages between 15386, 3.9 b.y. (14), and 15405, 4.36 (15), a direct match should not be expected. However, it seems quite possible that 15405 crystallized from a magma derived from a 15386-like parent. Analogously, the Ap12 and 17 felsites could have crystallized from a KREEP basalt-like magma, but one that was more sodic than any that are presently known.

In summary, the EPR appear to have crystallized from numerous Mg-rich parent magmas separable in terms of major element compositions. Variable degrees of KREEP contamination is probably responsible for differences in their incompatible element abundances; whereas different degrees of partial melting, assimilation of *ur*-KREEP, and probably assimilation of anorthosite are necessary to explain the differences in the major element compositions. The only link between the EPR and promordial differentiation appears to be that anorthosite and *ur*-KREEP were produced during that epoch.

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Figure 1. Plot of atomic Mg/(Mg + Fe) [*Mg*] in olivine or low Ca pyroxene versus Ca/(Ca + Na + K) [*A_N*] in plagioclase. Boxes, bars and filled hexagons are mineral compositions in evolved pristine rocks after (4). Apollo 14 norites (4 Na-g): 14318c2; 14318c1; 14305, 396; 14361c; 14304g; 14303, 44; 14311c. Apollo 14 anorthosites (4Aa-c): 14066; 14321c; 14305c91; 14047c; 14305c2. Apollo 14 ilmenite-gabbro (4I-Ga): 14311, 96. Apollo 14 gabbro-norite (4G-Na): 14313c. Apollo 12 anorthosite (2Aa): 12073. Apollo 12 felsite (2 Fa): 12033, 57. Apollo 15 granitic rocks (5 Gra-b): 15405, 12; 15405QMD. Apollo 17 ilmenite-gabbro (7I-Ga): 72275. Apollo 17 felsites (7Fa-b): 72215; 73215. Apollo 16 alkali-gabbro-norites (filled hexagons a-f): 67975, 131N; -86; -44Nm; -42N; -14; -136N; -44Nf. Dotted box (2 Fa) is plotted on the basis of *Mg* in augite. Dashed lines are calculated mineral compositions produced during plagioclase-saturated fractional crystallization. Starting compositions are KREEP basalt 15386 (7), Mg-norite parent (MN) after (8), and ferroan anorthosite parent (FA) after (8). Filled symbols and abbreviations mark the onset of crystallization of various phases and the disappearance of others. For example, olivine disappears at the first appearance of opx or pi, opx disappears at the first appearance of pi, and pi disappears at the reappearance of olivine (fa). The calculated spinel is Cr-rich.

