THE GROWTH & MODIFICATION OF LUNAR CRUST: KREEP BASALT CRYSTALLIZATION AND PRECIPITATION OF MG- AND ALKALI SUITE CUMULATES

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The evolution of the lunar highlands crust, as determined by returned samples from the Moon, involves two distinct stages. The first stage is the formation of anorthositic to leuconoritic crust as flotation cumulates from an incipient lunar magma ocean approximately 4.4-4.5 Ga ago. The second stage involves the modification of this early crust from 4.4 to 3.9 Ga through the crystallization of basaltic melts which have been contaminated by urKREEP -- so-called KREEP basalts. These KREEP basalts could have crystallized within the crust to form cumulate gabbros, norites, anorthosites, monzodiorites, and possibly granites, with the proportion of trapped KREEPy residual liquid determining the large-ion lithophile-element enrichment of the rock. The earliest-formed cumulates represent the magnesian suite, and later cumulates comprise the alkali suite. Generally, the proportion of trapped KREEPy liquid is small (2-20%). The broad age range for the lunar alkali-suite and magnesian-suite rocks indicates that parental KREEP basalt magmatism was not a unique event, but was an important process, possibly repeated several times throughout the first 600 to 700 million years of lunar history.

CHRONOLOGY OF THE LUNAR CRUST -- It is generally accepted that the earliest evolution of the Moon included the formation of a moon-wide magma ocean or magmasphere, crystallization of mafic minerals to form the upper mantle, and flotation of plagioclase to form the nascent lunar crust [e.g.,1]. The last dregs of lunar magma ocean (LMO) crystallization included the formation of a progressively large-ion lithophile (e.g., K, REE, P = KREEP) enriched residual liquid which was trapped in the upper-mantle cumulates and subsequently remobilized by later magmatic events, such as those which formed the KREEP basalts.

Rocks returned from the lunar surface by the Apollo missions which are thought to be remnants of the early flotation crust have been termed ferroan anorthosites or FANs. Two of these FANs have yielded ages of 4.44 ± 0.02 Ga [2] and 4.56 ± 0.07 Ga [3], attesting to the antiquity of the samples. Rocks from the lunar highlands with cumulate textures, calcic plagioclase, but more Mg-enriched mafic material were also found in the Apollo collections and reliable ages for these rocks cover a broad range (4.17 ± 0.02 Ga to 4.61 ± 0.07 Ga; [4-5]), although most are younger than FANs. Furthermore, four U-Pb zircon determinations yield ages from 4245 ± 75 Ma to 4141 ± 5 Ma [6]. These anorthositic to gabbronoritic cumulate rocks have been variously termed the mg suite or **highlands magnesian suite (HMS)**. A Sm-Nd mineral isochron for a **highlands alkali-suite (HAS)** anorthosite, 14304,267, yeilds an age of 4108 ± 53 Ma [7] which is bracketed by two zircon ages of HAS rocks from Apollo 14 (4028 ± 6 Ma and 4141 ± 5 Ma; [6]). A HAS gabbronorite from Apollo 16 yields a much older age of 4339 ± 5 Ma and indicates that HAS magmatism extended over at least 300 million years. This age span overlaps that of KREEP basalts, QMDs, and granites and allows for a direct relationship. However, the wide span of ages also suggests that the scenario of KREEP basalt magmatism and HMS and HAS cumulate crystallization was not unique in lunar history, but repeated throughout the earliest history of the lunar crust.

KREEP BASALT CRYSTALLIZATION AND THE PRECIPITATION OF HIGHLANDS CUMULATES – Snyder et al. [7] have shown that HAS cumulates can be derived from simple fractional crystallization of a KREEP basalt. Pristine KREEP basalts from Apollo 15 were used to calculate primitive precursor magmas. It is speculated that these basaltic melts are the products of deep melting in the lunar interior and subsequent assimilation of primitive KREEPy residual liquids during passage of the basalt to the lunar surface. Those basalts which did not reach the surface could have crystallized within the upper lunar crust. Using the program MAGFOX (Longhi, pers. comm.), fractional crystallization was modelled to its endpoint using this KREEP magma under 1 bar of pressure. The fractionation assemblages for nearly complete crystallization were then used to calculate mineral and trace-element compositions of successive liquids and associated cumulates [7].

Table 1: Calculated Trace-Element Compositions (in ppm) of Parental Melts for Mg Suite Cumulates* & KREEP

	P(lo)	S(lo)	P(hi)	S(hi)	KREEP
La	52	69	200	148	110
Ce	144	180	360	387	280
Nd	81	105	167	226	178
Sm	31	30.3	78	65	48
Eu	0.74	2.65	1.32	3.1	3.3
Tb		6.2		13.4	10.0
Dy	44	38	164	82	65
Er	26	25	102	53	40
Yb	20	20.5	87	43	36
Lu		2.95		6.2	5.0
Zr	861	900	1580	1930	1400
Sr	97	200	98	187	200

* Sources for calculated "data" and cumulate data: P (lo and hi) = [8]; S (lo and hi) = [11]; KREEP = [9].

The trace-element composition of these successive KREEP basalt residual liquids are shown in Table 1 and compared to equilibrium liquids back-calculated from trace-element data on HMS orthopyroxenes [8]. Note that our calculated KREEP basalt residual liquids at 0% and 55% crystallized are within the range of the HMS parental liquids calculated using the data from [8]. Furthermore, the mathematically constructed KREEP values of Warren [9] also lie approximately at the

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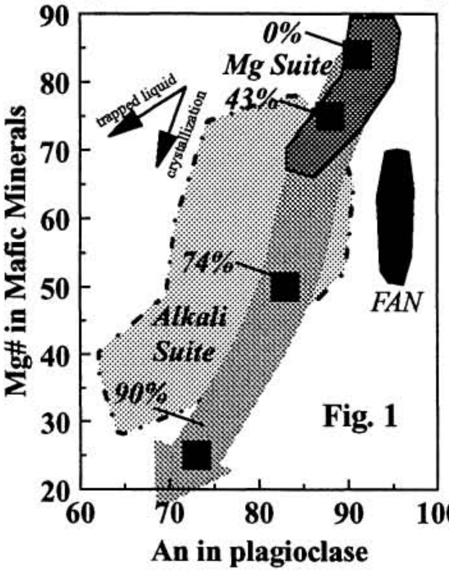
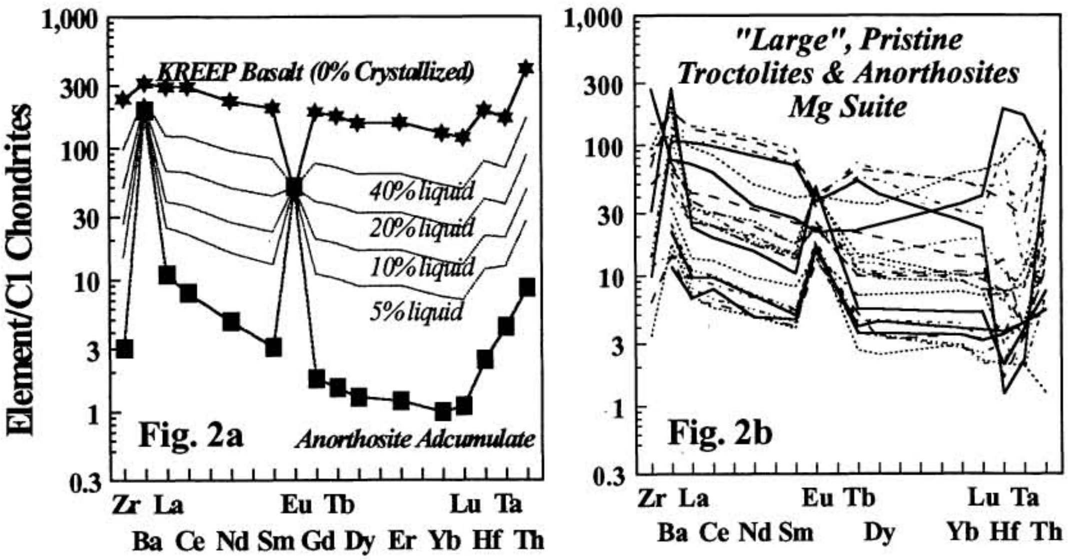
mid-point of our KREEP basalt differentiation path (i.e., halfway between the S(low) and S(high) values). Thus, the average KREEP values determined by [9] may represent an average parental magma for the HMS cumulates.



The calculated cumulate evolution path is indicated in Fig. 1, where the An content of plagioclase is plotted relative to the Mg# of either olivine or orthopyroxene (this shaded path is that for *adcumulate* compositions). As can be seen, the first cumulates to crystallize from a KREEP basalt magma are enriched in Mg (for mafic minerals) and Ca (for plagioclase) and, thus, quite primitive. In fact, the first 55% of crystallization yields cumulates which would plot within the HMS field. The next 45% of crystallization precipitates minerals with compositions which would fall in the range of HAS rocks (see Fig. 1). Addition of residual KREEP basalt liquid to a crystallizing mineral assemblage will draw compositions off of this array and result in Fe-enriched mafic minerals and more Na-rich plagioclase (see small arrows on Fig. 1). Thus, through simple fractional crystallization and retention of trapped residual liquid, the pyroxene, olivine, and plagioclase compositions of HAS cumulates can be reproduced.

EFFECT OF UNREPRESENTATIVE SAMPLING -- Many of the highlands "rocks" classified as pristine are of very small dimensions (often < 100 mg). Therefore, the modal mineralogy of these samples may not be representative of a larger rock body, but could indicate a segregation of a particular mineral assemblage (e.g.,[10]). In keeping with this idea, we have calculated anorthositic, dunitic, noritic, and gabbroic orthocumulates with variable proportions of trapped residual liquid at 0%, 55%, 60%, and 85% crystallized, and quartz monzodiorite orthocumulates at 90% crystallized. As an example of these calculations, a plot of modelled trace-element compositions for anorthosites and troctolites (Fig. 2a; at initial conditions, 0% crystallized) is compared to data for all large (>100 mg), pristine magnesian anorthosites and troctolites (Fig. 2b). The similarity between modelled anorthosites and troctolites and



the actual elemental patterns measured in samples is striking (Fig. 2; [7,11]). **Nearly all magnesian- and alkali suite rocks can be explained by simple fractional crystallization of a primitive KREEP basalt and addition of ≤ 40% trapped instantaneous residual liquid.**

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