COMBINED EQUILIBRIUM AND FRACTIONAL CRYSTALLIZATION OF A MAGMA OCEAN AND FORMATION OF THE UPPER MANTLE OF THE MOON  Gregory A. Snyder, Lawrence A. Taylor, and Clive R. Neal, Dept. of Geological Sciences, University of Tennessee, Knoxville, TN 37996; now at Dept. of Civil Eng. and Geol. Sciences, University of Notre Dame, Notre Dame, IN 46556.

Lunar mare basalts are generally considered to have originated by the melting of a cumulate mantle formed during the crystallization of an early Moon-wide magma ocean (LMO) or magmasphere. However, the nature and chemistry of this cumulate mantle and the logistics of its origin have remained elusive. In fact, many workers have suggested that the stratigraphy of the lunar upper mantle has been overprinted during subsolidus convection due to inherent density contrasts in the cumulate pile [1,2,3]. This convective overturn has been proposed on mineral/chemical grounds to explain the relatively high Mg# (as reflected in mare basalts) of late-stage ilmenite-bearing LMO cumulates. However, large-scale convective overturn of the lunar mantle may not be required if equilibrium crystallization was an important process in LMO differentiation [4].

CRYSTALLIZATION OF THE LUNAR MAGMA OCEAN -- Early in the evolution of the lunar mantle, when the LMO still was largely liquid, it is possible that vigorous convection was an important factor in crystallization. Such convection would allow crystals to remain suspended in chemical equilibrium with the LMO for relatively long periods of time. During this interval, equilibrium crystallization would control the differentiation of the LMO. However, plagioclase began to crystallize and float late in the evolution of the LMO (when convection was less vigorous) and was effectively separated from the rest of the cumulate. At that time, fractional crystallization would take over as the controlling mode of differentiation.

Extensive studies of terrestrial layered mafic intrusions over the past sixty years have emphasized the imperfection of fractional crystallization and attendant crystal-crystal and crystal-liquid separation in a convecting magma chamber. These separations were similarly inefficient during evolution of the lunar magmasphere, allowing for the trapping of interstitial melt and entrainment of a small proportion of less-dense plagioclase into the more-dense mafic cumulate mush. Indeed, petrography of lunar highlands samples demonstrates this well (e.g., anorthosites with 1-10% olivine). Therefore, we propose a "realistic" model for the late-stage evolution of the lunar mantle, by taking into account the imperfect fractional crystallization of the lunar magma ocean.

UPPER MANTLE STRATIGRAPHY -- The proposed chemical model assumes a starting composition for the LMO similar to the proposed bulk moon composition of Buck and Toksoz (Mg#=82, Al2O3=5.0wt.%, CaO=3.83 wt.%, TiO2=0.4wt.%; [5]). An initial magma ocean depth of 400 km is specified. The model includes equilibrium crystallization for the first three-quarters of LMO differentiation during rapid convection (at 6 kbar pressure), followed by low-pressure in situ fractional crystallization of the magma ocean. This latter phase was accompanied by trapping of remaining residual liquid and entrainment of 1 modal% plagioclase [once it became a liquidus phase at 78 Per Cent Solid (PCS)]. Most of the crystallizing plagioclase floated to the lunar highlands. The fractionation sequence, as determined by using modified output from the programs MAGFOX and MAGFOX (Longhi), is as follows:

(a) 0-40 PCS = olivine; (b) 40-78 PCS = orthopyroxene (with some olivine resorption); (c) 78-86 PCS = 53% plagioclase + 25% olivine + 22% orthopyroxene; (d) 86-95 PCS = 38% clinopyroxene + 56% plagioclase + 26% orthopyroxene; (e) 95-99.5 PCS = 34% orthopyroxene + 31% plagioclase + 24% clinopyroxene + 11% ilmenite. This extended crystallization of orthopyroxene (up to 78 PCS) with only minor olivine resorption may at first seem counterintuitive. However, Longhi has pointed out that, with increasing pressure, the reaction curve between olivine and orthopyroxene moves toward the olivine corner in the olivine-anorthite-silica pseudoternary phase diagram [6]. This effectively decreases the proportion of olivine resorption with increasing pressure. Since the equilibrium crystallization calculations were performed at 6 kbar, the amount of olivine resorption is smaller than it would be at low pressure. Likewise, the cotectic with plagioiclas moves away from the olivine corner with increasing pressure.

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thereby delaying the appearance of plagioclase on the liquidus.

The stratigraphy of the upper mantle, which is a product of the equilibrium/fractional crystallization model presented here is similar to others previously presented (Fig. 1). The major difference is the relatively late appearance of clinopyroxene (after plagioclase) in the present model (at 86 PCS). Ilmenite begins to precipitate above 95 PCS, as opposed to 92-93 PCS in other models [7,8,9].

MAJOR ELEMENT EVOLUTION OF THE LMO -- Extended equilibrium crystallization of the LMO leads to the "buffering" of the liquid at relatively high Mg#. How this is achieved, when it appears that only a small proportion of olivine is resorbed, is still not completely understood. At 86 PCS the Mg# of the liquid has still only fallen to 49 (Fig. 2). The Mg# of the mafic cumulate at 86 PCS is 73. However, from this point on the Mg# of the liquid, and the corresponding Mg# of the mafic cumulate, drops off markedly (due to fractional crystallization of the liquid). Ilmenite does not become a liquidus phase until 95 PCS, at which point the Mg# of the liquid is 15 and that of the corresponding mafic solid is 27. Mixing of a mafic cumulate at 95 PCS with that at 86 PCS, in a 90:10 ratio, will yield a cumulate which is fertile for melting and generation of high-Ti mare basalts (see Snyder and Taylor, this volume [4]). This mixing could be accomplished by small-scale density overturning.

TRACE-ELEMENT EVOLUTION OF THE LMO -- Trace-element evolution of the residual liquid and the mafic-cumulate, trapped-liquid, and entrained-plagioclase pile are illustrated in Figures 3 and 4, respectively, and labelled with the respective PCS values. Extended equilibrium crystallization (for 78 PCS) is nearly indistinguishable from the trace-element evolution of the LMO displayed by simple fractional crystallization [7,8]. This is due to the fact that most trace elements are incompatible with mafic minerals. Due to the low kps, resulting in low bulk Ds for the cumulates, equilibrium crystallization mathematically reduces to fractional crystallization.

It is evident in Figure 3 that late-stage, magma-ocean, residual liquids are similar to lunar high-K KREEP [10]. Above 90 PCS, the mafic cumulate takes on a pronounced LREE-depleted signature, due in part to the crystallization of clinopyroxene (Fig. 4). Melts taken from above this level would retain relatively depleted Nd isotopic signatures over time.

SUMMARY -- Extensive equilibrium crystallization of the LMO will not alter its trace element evolution, but will have an important "buffering" effect on the major elements, specifically Mg and Fe. Whether equilibrium crystallization was as prolonged as presented herein is debatable. However, it is plausible that equilibrium crystallization played a major role in the differentiation of the LMO.