PYROXENE STABILITY AND THE COMPOSITION OF THE LUNAR MAGMA OCEAN
John Longhi, Dept. of Geology, Univ. of Oregon, Eugene, Oregon 97403.

This study was undertaken to refine a previous model (1) for the role of pyroxene liquidus stability in low-pressure crystallization sequences of proposed whole moon compositions. We assume the existence of a primitive, global magma ocean which crystallized to form the plagioclase-rich lunar crust and complementary mafic cumulates below (2). A satisfactory magma ocean composition (herein assumed to be equivalent to a "whole moon composition") and its derivative liquids should be able to crystallize at low pressure (< 3kb) the minerals found in primitive crustal rocks in their petrographic sequence (i.e., olivine -spinel(?)-anorthite-orthopyroxene-pigeonite-waugite). A satisfactory composition should also satisfy mass balance constraints for Al2O3 caused by the presence of a 60-70 km thick, Al-rich crust overlying what was once a melt zone ~ 300 km deep (3). A previous study (1) suggested that none of the proposed whole moon compositions could satisfy all these conditions, but that compositions similar to those proposed by Ganapathy and Anders (4) and Taylor and Jakes (5) with modified, sub-chondritic Ca/Al ratios (<0.9 by wt.) could. The possibility exists, however, that extensive crystallization at the bottom of the magma ocean at pressures of 15 kb or more prior to the formation of the crust (6,7) may have altered a once "chondritic" magma ocean. The present study examines constraints placed on the composition of the magma ocean by pyroxene stability relations at low and high pressure.

We have determined the compositions of low-pressure, liquidus phase boundaries in the system Mg2SiO4-CaAl2Si2O8-CaSiO3-SiO2 shown in light solid lines in Figures 1 and 2. In Fig. 1 the solid lines are a revision of the forsterite-anorthite-silica system originally proposed by (8). Heavy dashed lines represent the compositions of multiply-saturated, natural liquids projected from Ca-SiO3, TiO2, and alkalies onto the olivine-anorthite-silica psuedo-ternary (9). Fig. 2a is a projection from anorthite of anorthite-saturated liquids onto the olivine-wollastonite-silica plane; Fig. 2b is a projection from olivine of olivine-saturated liquids onto the enstatite(or Ca-free pyroxene)-wollastonite-anorthite plane. These two projections provide information about the compositional limits of the pyroxene stability fields. The light solid lines are isobaric univariant curves; reaction curves are indicated by double arrows. We have projected the compositions of multiply-saturated, natural and synthetic lunar liquids (10,11,12,13) with atomic Fe/(Fe+Mg) ratios = 0.3-0.6 in Fig. 2 and drawn approximate saturation surfaces (heavy dashed lines) with disposition similar to those of the simpler system. Some proposed whole moon compositions are shown in projection in Figs. 1 and 2b (circled symbols); liquids derived by low pressure crystallization of the whole moon compositions up to the point of plagioclase saturation are shown in Fig.2a (symbols in squares). Also shown for reference in Fig. 2a is the average crustal composition (14). Continued precipitation of olivine + anorthite from the derivative G-A and T-J compositions at low pressure will cause high-Ca pyroxene to crystallize before pigeonite; orthopyroxene will never crystallize. The Taylor-Bence (14) and possibly the Ringwood (6) compositions will crystallize orthopyroxene, but T-B crystal-
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lizes pyroxene before plagioclase as opposed to the plagioclase-before-pyroxene sequence inferred for primitive crustal rocks such as 76215 and 76535, while R contains too little Al₂O₃ to form the lunar crust at the top of a 300 km deep magma ocean (1). Thus consideration of orthopyroxene stability, crystallization sequence and Al concentration constrain the compositions of the primitive liquids which formed the crust to have had relatively high Al₂O₃ concentrations (G-A, T-J) but sub-chondritic Ca/Al ratios, e.g. G-A". These constraints do not necessarily apply to the magma ocean as a whole, however, if significant crystallization takes place at the bottom of the ocean prior to the formation of the crust because the liquid line of descent is certain to be different at high pressure than at low pressure.

Figures 1 and 2b contain approximate phase boundaries for olivine-spinel-pyroxene equilibria (dotted lines) deduced from various high pressure phase diagrams of lunar samples. The major features of these projections are the encroachment of the olivine field by low-Ca pyroxene (Fig. 1) and the expansion of the orthopyroxene field relative to clinopyroxene(high-Ca pigeonite) with increasing pressure (Fig. 2b). Published phase diagrams (6,15) indicate that the reaction relation between orthopyroxene and clinopyroxene persists at high pressure. Thus liquids that crystallize pigeonite at high pressure will move away from orthopyroxene saturation and increase their wollastonite content. Low-Al compositions (T-B, R) will crystallize much olivine + orthopyroxene at high pressure (15), driving the liquid compositions toward An in Fig. 1, and thereby changing the low pressure crystallization of T-B if the derivative liquid were convected to the top of the ocean. However, the copious orthopyroxene crystallization would increase the wollastonite component in these liquids such that orthopyroxene could not subsequently crystallize at low pressure from either composition. More Al-rich compositions with chondritic Ca/Al ratios (T-J) will crystallize olivine, orthopyroxene, then clinopyroxene followed shortly by spinel at high pressure. Even if local accumulations of orthopyroxene were to keep the liquid saturated with orthopyroxene, crystallization of spinel would keep the wollastonite content of the liquid too high to allow orthopyroxene precipitation at low pressure. Thus it appears that a high Al (~8 wt% Al₂O₃), low Ca/Al (≤ 0.9) magma ocean composition is required to form the lunar crust whether or not extensive fractionation took place at the bottom of the ocean.


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Figure 1. The O1-An-SiO₂ psuedo-ternary. Solid lines: Fo-An-SiO₂ system (this study and [8]); dashed lines: natural system (9); dotted lines: high pressure curves for ol-low Ca pyx-spinel equilibria inferred from (6, 16 and others). Symbols refer to proposed whole moon compositions. GA" (this paper, wt%) SiO₂-42.4; TiO₂-0.43; Al₂O₃-8.29; Cr₂O₃-0.17; FeO-11.2; MgO-32.3; MnO-0.04; CaO-5.04; K₂O-0.01; Na₂O-0.10.

Figure 2. The O1-An-SiO₂-Wo psuedo-quaternary system. Solid lines: the Fo-An-SiO₂-Wo system (this study, [8] and others); dashed lines: natural system inferred from the data of (9, 10, 11, 12, 13 and unpublished) at low pressure. 2a – projection from anorthite; hexagon is average crustal composition (14); Pi= pigeonite or low-Ca clinopyroxene; squares indicate derivative whole moon composition at plagioclase saturation.

2b – projection from olivine; symbols are whole moon compositions as in Fig. 1; dotted curves are ol-low Ca cpx-sp equilibria; crystallization of ol+opx+sp drives liquid to higher Wo content.