THE SOURCES OF MARE BASALTS REVISITED: A MODEL INVOLVING LUNAR MAGMA OCEAN CRYSTALLIZATION, PLAGIOCLASE ENTRAINMENT, AND TRAPPED INSTANTANEOUS LIQUID Gregory A. SNYDER, Lawrence A. TAYLOR, & Clive R. NEAL, Dept. of Geological Sciences, University of Tennessee, Knoxville, TN 37996-1410.

The magma ocean concept has been an integral part of the lunar literature since the return of the first lunar samples [1]. Many variations of the concept have been proposed (e.g. [2-3]), and we offer here a further refinement to this fundamental concept. Several parameters must be considered when developing a model for the mare basalt source regions: (1) the bulk composition of the initial LMO; (2) the relevant phase equilibria with depth for crystallization paths; (3) the degree of perfect fractional crystallization of the LMO; (4) the efficiency of crystal-crystal and crystal-liquid separation in the LMO during its evolution; and (5) the depth in the cumulate pile at which melting must occur to generate a mare basalt parent magma. We have dealt with (5) elsewhere and will concentrate on points (3) and (4) here.

A model for crystallization of the Lunar Magma Ocean (LMO) has been developed which is analogous to what is believed to have occurred in terrestrial layered mafic intrusions. In this model, the LMO is allowed to fractionally crystallize. Crystallization occurs in the upper portion of the moon-wide melt layer, due to the high heat flux near the lunar surface, and mafic crystals settle to the bottom. At successively greater stratigraphic heights, a variable proportion of <u>instantaneous residual liquid</u> is trapped in the cumulate pile. In our model, 1-10% trapped instantaneous residual liquid (TIRL) is used, and we assume that perfect adcumulates do not exist.

The trapped liquid is required to elevate the extremely low REE abundances found in the mafic cumulates alone. Only prohibitively low degrees of melting (<<1%) could generate a liquid with the appropriate <u>abundances</u> of the REE seen in mare basalts. However, at these extremely low degrees of partial melting, derived liquids would be extremely LREE enriched and would not match the analyzed REE <u>patterns</u> of mare basalts.

The fractionation sequence used in this model is modified from that used by Hughes et al. [3], as deduced from Walker et al. [4] and utilizing the program MAGMAFOX [5]. This sequence is preferred on the basis of known mineralogy and phase equilibria. The sequence used is: 0-40% = olivine; 40-55% = opx; 55-85% = 53% plag + 47% opx; 85-95% = 53% cpx + 38% plag + 9% pig; 95-100% = 50% cpx + 36% plag + 8% pig + 6% ilm. After approximately half of the LMO has crystallized, plagioclase becomes a liquidus phase [3]. This plagioclase is subsequently floated, and generally does not become part of the *mafic cumulate + TIRL* pile. However, perfect crystal-crystal separation may not occur, allowing the entrainment of the more buoyant mineral plagioclase into the mafic cumulus pile. This combination of TIRL and entrained plagioclase in the mafic pile is what makes this model unique.

The mafic cumulate + TIRL source (*sans* plagioclase) begins to take on a pronounced negative Eu anomaly once plagioclase becomes a liquidus phase (>45% LMO fractional crystallization). This can be seen in Figure 1, where (La/Sm)n is plotted versus Eu/Eu*. As the percentage of TIRL decreases, the more LREE depleted the source becomes. As crystallization proceeds (Eu/Eu* decreases) LREE depletion decreases initially, levels off, and then takes a drastic drop where cpx becomes a liquidus phase. Simply by varying the percentages of TIRL and the degree of fractional crystallization of the LMO, a wide range of sources which are LREE depleted, and exhibit a negative Eu anomaly, may be generated.

Figure 1

Assuming the parental liquids for the high-Ti basalts had trace element compositions as proposed by Snyder et al. (1990), an upper limit may be imposed on the (La/Sm)n of the source (=0.44). This is due to the fact that all plausible mafic minerals have LREE-depleted partition coefficient patterns. The lower the % melting the greater the LREE depletion required in the source. Limits can also be placed on the *mineralogy* of the cumulate residue after melting. Assuming as a lower limit that the residual minerals left in the residue

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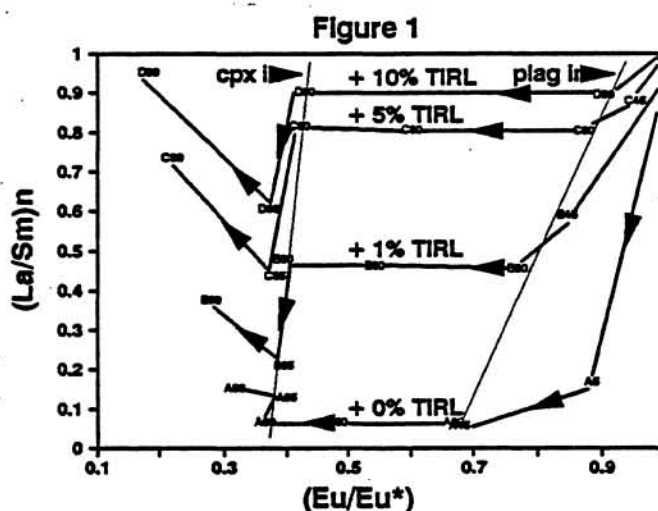
of melting to form the high-Ti parent had a bulk D = 0, minimum REE abundances in the residue may be calculated. This calculation was performed at 1-10% melting and at the point where the LMO was 90 per cent solids (PCS).
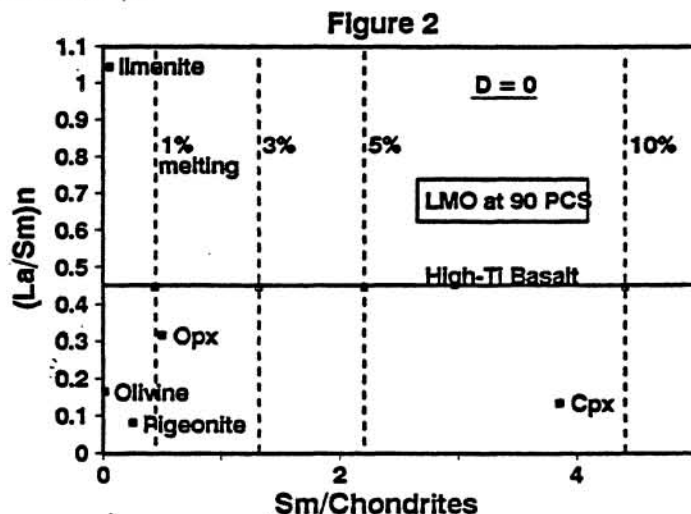
Figure 2

The minimum residue abundances are also plotted on Figure 2 as a family of dashed lines for 1,3,5, and 10% melting. Sm abundances and (La/Sm)n ratios were then calculated for the plausible cumulus minerals in equilibrium with the residual LMO liquid at 90 PCS. As is indicated, only one mineral gives the requisite abundance of Sm as well as the appropriate (La/Sm)n for the HT source – CLINOPYROXENE (CPX). This does not mean that the other minerals cannot occur in the source, but that a proportionately large amount of CPX is required. At greater percentages of melting, more severe constraints are placed on the mineralogy of the residue (i.e., requiring more CPX).

As an example, the trace elements in the source region for a group of high-Ti mare basalts (Apollo 17, Type C and Apollo 11, Type B3) has been successfully modeled using our proposed approach (Figure 3, [6]). However, approximately 9 wt% of the major oxide Al_2O_3 is also required in the high-Ti basalt parent. The mafic cumulate will contain a vanishingly small amount of this oxide and the residual LMO contains only $\leq$ 7 wt% Al_2O_3 at high PCS. Addition of approximately 15wt% plagioclase in the melt during non-modal melting of the source will solve this problem. This plagioclase could have been entrained into the mafic cumulate as it sank in the LMO.

Figure 3

Complicated models involving convective overturn of the LMO cumulate pile and selective addition of a late-stage "KREEPy" liquid [3] are not required. In general, sources for mare basalts can be generated by simple fractional crystallization of the LMO, settling of the mafic phases with the entrainment of a small amount of TIRL and/or plagioclase in the latter stages.
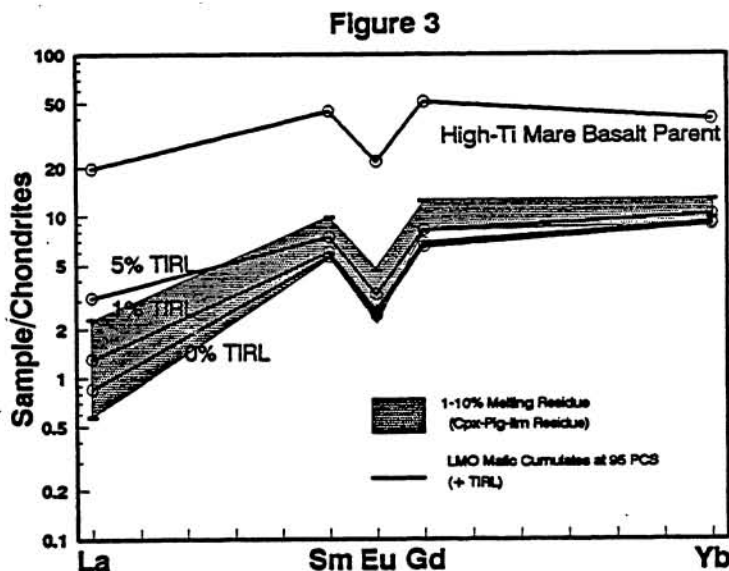
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