PREFERENTIAL ASSIMILATION OF ARMALCOLITE, ILMENITE, AND PYROXENE DURING MELT MIGRATION IN THE LUNAR MANTLE CAN PRODUCE THE TWO LINEAR ARRAYS OBSERVED IN PRISTINE LUNAR GLASS MELTS.

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Introduction: Systematic studies of major element abundance in pristine lunar glasses from Apollo landing sites have lead Delano [1-2] to identify two distinct compositional arrays: Array I has lower CaO and Al_2O_3 abundance and Ti/Al ratio than Array II. CaO and Al_2O_3 abundance from both arrays decrease with the increase of TiO_2 abundance in the melt and appear to fall on the linear mixing lines between two low TiO_2 components and ilmenite containing 45-54wt% TiO_2 (see Fig. 10a in [2], also Fig. 1 below). These lead Delano [2] to a petrogenetic model that involves assimilation of ilmenite into low Ti melts derived from two distinct cumulate reservoirs.
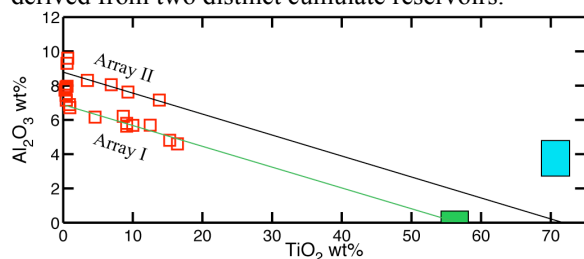

Figure 1. Variations of TiO_2 and Al_2O_3 among the 25 pristine lunar glasses reported in [2]. Fields of ilmenite (green) and armalcolite (blue) coexisting with harzburgite or dunite in high pressure experiments [3] are also shown.

Figure 1 displays the pristine picritic glass compositions from Delano [2] in Al-Ti space. Although limited in the number of data points, there appear two compositional trends within each array: one with TiO_2 abundance less than 0.5% and is controlled mainly by olivine fractionation [1-2] and the other with higher TiO_2 abundance and a shallower slope in Al-Ti space. If we extend the trends defined by data with more than 0.5% TiO_2 down to 0% Al_2O_3, they intercept TiO_2 axis at 56% and 71% which are within the range observed in ilmenite (55-58%) and armalcolite (69-72%) coexisting with harzburgite or dunite at high pressures (Fig. 1). This raises two important questions: (1) is armalcolite also involved in the petrogenesis of lunear high Ti magmas? (2) can armalcolite and ilmenite assimilation explain the two lunar high Ti trends shown in Fig. 1?
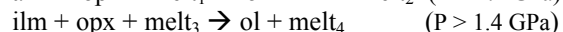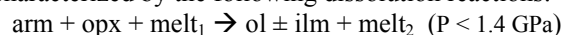
The feasibility of armalcolite assimilation can be demonstrated by a simple mass balance calculation. If we assume a starting melt has 0.5% TiO_2, other major oxide abundance in this melt can be estimated using linear trends defined by the four high Ti picritic glass data from Array II. Least squares mass balance calculations show that the major and minor (excluding Na_2O and K_2O) element abundance of the

four high Ti picritic glass melts in Array II can be derived from the low Ti melt, to within 15% relative, by adding up to 19wt% of an armalcolite equilibrated with olivine and opx at high temperatures and pressures [3]. Better mass balancing can be achieved if small amount of olivine (< 5%) is crystallized. However, our mass balance calculation is not unique: the four high Ti data in Array II can also be derived by adding orthopyroxene and ilmenite to the low Ti melt while crystallizing olivine.

Petrologic constraints: In two preliminary studies [3-4], we examined the thermodynamic stability of ilmenite and armalcolite in the context of lunar cumulate mantle overturn and outlined a petrologic framework for studying armalcolite and ilmenite assimilation during melt transport and melt-rock reaction in the lunar mantle [5]. Main results from these studies can be summarized and updated as follows: (1) In the presence of orthopyroxene (opx), ilmenite (ilm) is thermodynamically unstable at pressures less than 1.4 GPa and transforms into armalcolite (arm) through the subsolidus reaction:

$$ilm + opx \rightarrow arm + olivine. \qquad (a)$$
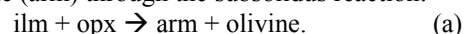
This explains the non-uniqueness of the mass balance calculations above. Depending on the efficiency of convective mixing during cumulate overturn, isolated regions of the shallow lunar harzburgitic mantle (< 270 km) may contain armalcolite and the deeper lunar mantle contains ilmenite. (2) The primitive lunar picritic magmas have only olivine on their liquidi at pressures below multisaturation [6-10]. Once segregated from their source regions, these picritic magmas will have a strong tendency to interact chemically and thermally with their surrounding harzburgitic mantle. (3) Chemical interaction involves preferential assimilation and is characterized by the following dissolution reactions:

$$arm + opx + melt_1 \rightarrow ol \pm ilm + melt_2 \ (P < 1.4 \text{ GPa})$$
$$ilm + opx + melt_3 \rightarrow ol + melt_4 \qquad (P > 1.4 \text{ GPa})$$

Preferential dissolution of opx and Fe-Ti oxides, and precipitation of olivine result in the formation of high permeability dunite channels that may serve as conduits for melt migration in the lunar mantle [5,11-12]. And finally, (4) thermal interaction likely involves partial melting of Fe-Ti oxide-bearing harzburgites whose solidus temperatures are considerably lower than the liquidus temperatures of the picritic magmas [3-4]. Densities of armalcolite or ilmenite saturated or nearly saturated melts are higher than those of olivine and opx. These Fe-Ti-rich high density melts drain downward in a porous dunite-

harzburgite network and eventually mix with the incoming low Ti picritic magmas at greater depth (see Fig. 2 in [5]). This magma mixing effect can be characterized by a melt suction rate (see below). Preferential dissolution of ilmenite, armalcolite, and opx and precipitation of olivine selectively assimilate TiO_2, FeO, and SiO_2 to the reacting picritic magma and is a viable mechanism through which some of the compositional diversities of the picritic glasses were produced.

Models: In order to quantify the processes of assimilation and melt-rock reaction during magma transport in the lunar mantle, we developed and explored two simple models: one based on a modified AFC model for a partially molten system that does not include harzburgite partial melting, and the other a double-lithology model that include the effects of dunite channel formation, harzburgite dissolution and partial melting, and buoyancy driven melt flow in both porous dunite and harzburgite [13]. Key parameters in these models include: mineral solubility or mineral/melt partition coefficient, density, porosity, and permeability, melt and solid flow rates, harzburgite melting and dissolution rates, and melt suction rate, a parameter describing the amount of melt flowing from the dissolving harzburgite into the dunite. Given the incoming melt composition and mineralogy of the lunar mantle, the governing mass conservation equations were solved numerically. Two examples are presented below.
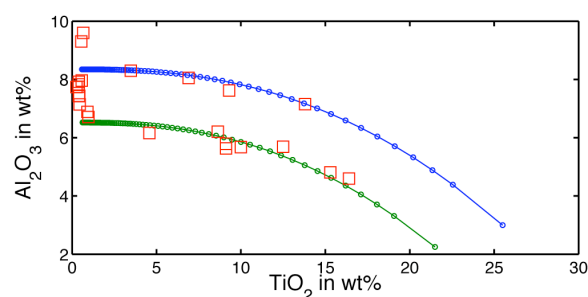

Figure 2. Results of assimilation calculations of ilmenite + opx (green line) and armalcolite + opx (blue line) into low Ti magmas. The red squares are the pristine picritic glasses from [2]. For purpose of illustration, we assume initially the Fe-Ti oxide to opx mass ratio is 1:3. Compositions of armalcolite, ilmenite, and opx are from [3]. Starting melt compositions can be read from the two ends of each curve.

Numerical results: Figure 2 displays results from two case studies using the modified AFC model: one involves assimilation of ilmenite and opx (relative dissolution rate is 1:1, green line) and the other involves assimilation of armalcolite and opx (relative dissoluton rate is 2:1).

Figure 3 presents an example of calculated melt compositions in dunite channels formed by reactive dissolution of an armalcolite-bearing harzburgite

using the double lithology model outlined above. For purpose of illustration, we considered a 10 km steady-state harzburgite column that underwent upwelling, partial melting, and melt-rock reaction. The melt suction rate and harzburgite dissoluton rate are high relative to the harzburgite melting rate (5 and 2.5, respectively) in this calculation.
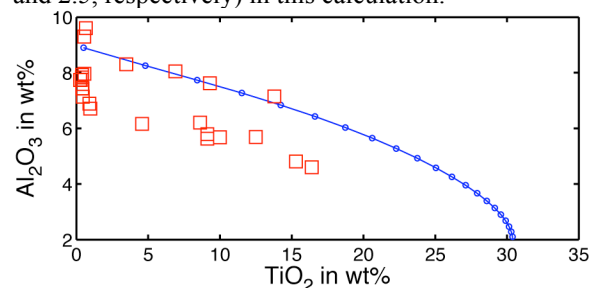

Figure 3. Covariations of Al_2O_3 and TiO_2 in interstitial melts in dunite channels formed by reactive dissolution of a harzburgite containing 15% armalcolit (blue line). The red squares are pristine picritic glasses from [2]. Compositions of armalcolite, ilmenite, and opx are from [3].

Discussions: Both the modified AFC model and the double lithology model can reproduce the two arrays of Delano [2] given proper choices of starting compositions and model parameters. The double lithology model, though having more parameters, is more consistent with the petrologic model outlined on the previous page and detailed in [5,11-12]. However, neither model can resolve the origin of the two low Ti components originally identified by Delano [2].

With the exception of TiO_2 abundance in harzburgite melt, which is buffered by armalcolite or ilmenite, the outcome of our model calculations also depend on other oxide abundance in the harzburgite melt, a parameter that needs to be further constrained in the future.

Because of the subsolidus reaction (a) on the previous page, armalcolite vs. ilmenite assimilation cannot be unambiguously resolved based on major and minor element abundance alone. Additional data, such as trace element abundance and the mineralogy of the lunar mantle may help to further constrain this problem.

References: [1] Delano and Livi (1981) *GCA* 45, 2137-2149. [2] Delano (1986) *JGR* 91, B4, D201-D213. [3] Thacker et al. (2008) *LPSC 39,* submitted. [4] Liang et al. (2007a) LPSC 38, abstract# 1076. [5] Liang et al. (2007b) LPSC 38, abstract# 1075. [6] Wagner and Grove (1997) *GCA* 61, 1315-1327. [7] Elkins et al. (2000) *GCA* 64, 2339-2350. [8] Longhi (1992) *GCA* 56, 2235-2251. [9] Longhi (1995) *GCA* 58, 8375-8386. Delano (1980) PLPSC 11th, 251-288. [11] Beck et al. (2006) *GRL 33,* 1029/2005GL024008. [12] Liang and Hess (2006) *LPS* 37, #1943. [13] Liang and Parmentier (2008) submitted.