Models for the petrogenesis of lunar troctolites are severely constrained by the high Mg\textsuperscript{*} values of olivine which range from 84 to 92 and may even extend to 94\textsuperscript{(1)}. Hess\textsuperscript{(2)} critically reviewed several models for their petrogenesis but found none totally convincing. This analysis, moreover, did not address an additional constraint provided by their phase equilibria. Longhi\textsuperscript{(3)} observed that the crystallization sequence of Mg-rich suite magmas and, indeed of almost all lunar magmas, was non-tholeiitic. The crystallization sequence for the Mg-rich suite magmas is given by olivine $\rightarrow$ plagioclase $\rightarrow$ low CaO pyroxene $\rightarrow$ high CaO pyroxene i.e. one which produces troctolites, norites and gabbros in that order. In comparison, the crystallization sequence in terrestrial tholeiite basalts has high CaO pyroxene preceding low CaO pyroxene. Longhi\textsuperscript{(3)} and others have shown that terrestrial tholeiite sequence is the consequence of polybaric melting of peridotite at high pressures and the subsequent crystallization of the basaltic liquids at low pressures. Why then is the crystallization sequence of lunar basalts, and especially the Mg-rich parent magmas, so different?

Longhi\textsuperscript{(3)} proposed two solutions to this query. The most speculative suggestion was that the Ca/Al ratio of the Moon was non-chondritic. Specifically, the normative composition of the Moon was deficient in diopside relative to the composition of the Earth's upper mantle. An alternative solution is that lunar magmas evolve along the high pressure olivine-orthopyroxene boundary curve (but not too far). Such melts when brought to or onto the lunar crust will crystallize low CaO pyroxene before high CaO pyroxene. This paper will focus on this mechanism for magma generation.

The troctolite source region for a Moon must be sought in the earliest cumulates to the magma ocean. Only these rocks create source regions of Mg\textsuperscript{*} values 92 or higher. The crystallization of the magma ocean will proceed largely from the base upwards, laying down magnesian olivine cumulates if the fluid mechanical conditions so permit \textsuperscript{(4)}. The Mg\textsuperscript{*} value of the olivine cumulate is a function of the Mg\textsuperscript{*} value of the magma ocean and the pressure (depth) of fractional crystallization; the greater the pressure of crystallization, the lower the Mg\textsuperscript{*} values of the olivine which coexist with the melt \textsuperscript{(2)}. Dunite cumulates with Mg\textsuperscript{*} values greater than 90 coexist with melts with Mg\textsuperscript{*} values greater than 80 at depths $\geq$ 400km \textsuperscript{(2)}. Basalts derived by melting such cumulates have Mg\textsuperscript{*} values greater than 75 and will crystallize olivines with Mg\textsuperscript{*} values $\geq$91 under lunar crustal conditions. Such melts are therefore good candidates for the parent magmas of lunar troctolites provided that they have plagioclase close to or at their low pressure liquidus.

Where then does the normative plagioclase content of these melts come from? The dunite cumulates are too refractory to supply the normative plagioclase unless they trap sufficient quantities of intercumulus melts. MacKenzie \textsuperscript{(5)} has argued, however, then even small quantities of intercumulus liquid are likely to rise buoyantly through and escape from the crystalline matrix. In addition, thick sections of dunite cumulates should rapidly become unstable either because of thermal and or compositional convection. If such processes occur concurrently with their deposition from the magma ocean, then it is likely that the intercumulus liquid would be lost and returned to the magma ocean.

The normative plagioclase component of the dunite cumulates might be supplied by sinking parcels of the quenched crust from the convecting magma ocean \textsuperscript{(6)}. The composition of the quenched crust approximates the magma ocean at each stage of its evolution; the most primitive samples would therefore approximate whole moon compositions. Depending on the size of the sinking fragments and the degree of dissolution/melting that such fragments experience, the basal cumulate zone would become a dunite fertilized by components approximating whole moon compositions. For these rocks to be appropriate source rocks for magmas parental to lunar troctolites, the Moon must have relatively high Mg\textsuperscript{*} values.

The source with the most favorable characteristics is formed from the earliest dunite cumulates (Mg\textsuperscript{*} 92-94) and fragments of the quenched magma ocean (Mg\textsuperscript{*} 88; 4% Al\textsubscript{2}O\textsubscript{3}). A fifty-fifty mixture of these components has Mg\textsuperscript{*}$\geq$90 and Al\textsubscript{2}O\textsubscript{3} contents of 2%. The fertile dunite has a mode of about 83% olivine, 8% orthopyroxene, 8% CaO-clino.pyroxene and the rest spinel (assuming the mode is of a fertile peridotite). The melting reaction in the 1.0-2.0 GPa range is approximately (in wt\%) \textsuperscript{(7)}

\[
0.30\text{ Opx} + 0.62\text{ Cpx} + 0.08\text{ Sp} = 0.80\text{ LIQ} + 0.20\text{OL}
\]
The higher the pressure, the more CaO-clinopyroxene relative to orthopyroxene is consumed by the reaction. About 10.5% melting is required to eliminate cpx and leave only orthopyroxene + olivine in the residue. The stoichiometry of the melting reaction (for P>0.8GPa) then becomes

\[ X \text{Opx} + Y \text{OL} = \text{LIQ} \]

with X>>Y. An additional 4-5% melting eliminates Opx from the residue thereby limiting the progress of the melting path along the Opx-Oliv cotectic.

The bulk distribution coefficient for Al\(_2\)O\(_3\) at zero melting (F=0) is small, roughly D=0.08. The distribution coefficient weighted according to the phase proportions entering the liquid is significantly larger, i.e. D'=0.5. Consequently, we must consider non-modal melting which for Al\(_2\)O\(_3\) is

\[
C_L = \frac{2}{0.08+F(0.5)}
\]

Using the weight fraction of melting estimated above (F=.105), \(C_L\sim 15\%\) Al\(_2\)O\(_3\) in the melt. This liquid when erupted on the lunar surface has Mg*>91 and is close to being saturated with plagioclase. It is a suitable parent liquid for lunar troctolites. It is noteworthy, however, that the cumulate source regions derived from less primitive magma oceans cannot readily generate the troctolite parent liquids. Liquids derived from a source from a magma ocean with Mg* value of 84, for example, generate liquids that are more than 20-30% undersaturated with respect to plagioclase at low pressures.

These calculations and reasonable geochemical assumptions suggest that the source regions to the troctolite could be found in the dunite cumulates of a magma ocean of relatively high Mg* values. Indeed its difficult to conceive of any common peridotite source that can give rise to troctolites that crystallize olivines with Mg* 92 or above! Questions remain, however, as to the mechanics of magma generation in a growing cumulate pile. If pressure release melting of the dunite cumulates is to produce the lunar troctolites then the cumulate pile must not become unstable before the last remains of magma ocean have disappeared. Otherwise, melt produced in the unstable cumulate pile would simply be added back into what remains of the magma ocean.

One way around this dilemma is to rapidly crystallize the magma ocean, a possibility which is certainly consistent with the 182W isotope anomalies (8). Perhaps the foundering of the quenched crust is a sufficient energy drain to provide for rapid cooling. It is difficult, however, to avoid the slow-down in cooling of the magma ocean that would ensue after the formation of the anorthosite crust. But if the anorthosite crust never completely covered the Moon's surface rapid cooling might very well continue until the end or the near end of crystallization. The absence of FAN in the Serenitatus ejecta blanket (1) is certainly consistent with the absence of anorthosite crust in that part of the Moon.

References: