MELTING AND MELT MIGRATION IN A HETEROGENEOUS LUNAR MANTLE: PHYSICAL PROCESSES AND CHEMICAL CONSEQUENCES. Y. Liang, A. Schiemenz, and E. M. Parmentier (Department of Geological Sciences, Brown University, Providence, RI 02912, email: yan_liang@brown.edu).

Introduction: Several lines of evidence suggest that the melt generation and segregation regions of the lunar mantle are heterogeneous, consisting of chemically and lithologically distinct domains of variable size and dimension. The heterogeneities were likely formed during the solidification of lunar magma ocean (LMO) and subsequent lunar cumulate mantle overturn [1-3]. Incomplete mixing of the early and late LMO cumulates results in a heterogeneous lunar cumulate mantle [2,4]. Partial melting of the hybrid mantle gives rise to a diverse range of basaltic magma erupted on the surface of the moon.

One of the important problems of lunar (and terrestrial) mantle geochemistry is the mapping of the heterogeneities observed in basalts into the chemical and lithological heterogeneities present in the mantle. Such a mapping, in general, is nonlinear and can be affected by a number of processes, including but not limited to, the size and distributions of the heterogeneity; dynamics of melting, melt migration, and melt-rock interaction. In an effort to address at least part of this problem, we have undertaken a numerical study of melting and melt migration in an upwelling hybrid lunar mantle. The basic idea behind this study is that regions containing higher abundances of the late LMO cumulates have lower solidi than their surrounding harzburgite mantle. During decompressional melting of an upwelling hybrid lunar mantle, the former starts to melt at a greater depth and therefore has higher porosity than the harzburgite mantle when the latter starts to melt at a shallower depth. Once segregated from their source regions, melts derived from both source regions will have a strong tendency to interact with their overlying mantle. Laboratory dissolution studies have shown that chemical interactions between the picritic melts and partially molten harzburgites result in the formation of high porosity orthopyroxene-free dunites [5-6]. The main objective of the present study are (1) to determine the distribution of key melt migration parameters, such as porosity and melt velocity, and their dependence on the distribution of heterogeneities in the lunar mantle, and (2) to explore the geochemical consequences of melting and melt migration in such a setting.

Model setup: We consider melting and melt migration in a 2D upwelling mantle that consists of orthopyroxene (opx), olivine, and an interconnected melt network in a gravitational field. The governing equations are similar to those given in [7], except that we include an equation tracking the abundance of opx in the harzburgite. Upwelling and percolation bring the partially molten residual mantle into the simulation domain from below. In terms of major elements, we assume that the interstitial melt and residual solid are in local chemical equilibrium and that the solubility of opx increases upward along the vertical direction. To maintain local chemical equilibrium, a melt percolating upward must dissolve opx. The dissolution rate is proportional to the vertical melt flux. An increase in local melt flux due to the presence of the late cumulates, therefore, increases opx dissolution rate, which, in turn, further increases the melt flux and opx dissolution.

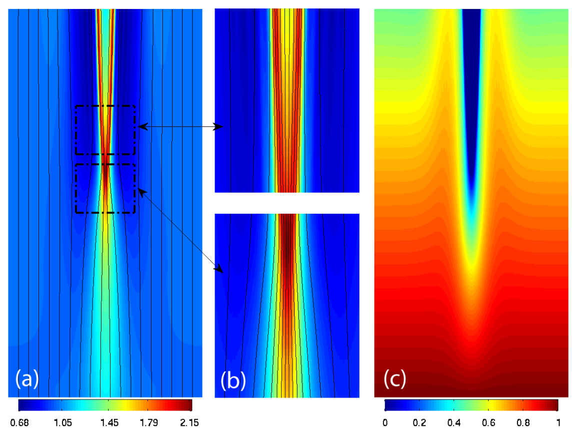

Figure 1. Stable regime: Steady-state distribution of porosity (ϕ_f) and opx (ϕ_{opx}) in the computation domain (all scaled to reference values). (a) porosity; (b) zoom in of the boxed regions in (a); (c) opx abundance. The solid lines in (a) and (b) are melt streamlines. The dark blue region in (c) corresponds to the melt-bearing dunite where $\phi_{opx} = 0$.

Melt transport processes: Linear stability analysis of a similar problem as outlined above [8] indicates that there are three physically distinct regimes for melting and melt migration in an upwelling mantle: (i) an unstable fingering regime where elongated high-porosity melt channel develops spontaneously along the melt flow direction; (ii) an unstable wave regime in which initially randomly distributed porosity self-organizes into regular wave patterns at a later time; and (iii) a stable regime in which randomly distributed porosity decays back to the 1D steady state in the absence of a sustained porosity perturbation at the bottom of the melting column. Key parameters needed to distinguish the three regimes are the opx solubility gradient and the ratio between mantle upwelling rate and melt flow rate, though none of which are well constrained for the lunar mantle. Nonetheless, for melt migration in the lunar mantle, regimes (ii) and (iii) are more likely, due to the significantly smaller gravitational field.

In the presence of a sustained or fixed porosity perturbation at the lower boundary, a 2D steady-state is established in the stable regime. Figures 1a-c show an example of calculated porosity and opx fields induced by a single time-independent Gaussian perturbation around the center of the bottom boundary. Three interesting features are noted. First, a high porosity melt channel develops immediately above the base where the sustained porosity perturbation is located (Figs. 1a-b). The lower part of the melt channel is harzburgite and the upper part is opx-free dunite (Fig. 1c). The maximum depth to which the dunite channel develops depends on the curvature of the opx solubility gradient and the amplitude of porosity perturbation. In the absence of porosity perturbation, the melt channel and dunite channel disappear and the 1D steady state is recovered. Second, the high porosity melt channel is surrounded by a low porosity compacting boundary layer that is more pronounced around the dunite channel. Third, at the point of opx exhaustion, the melt channel bifurcates into two smaller branches within the dunite as a result of compaction in the central part of the dunite channel (Figs. 1a-b).

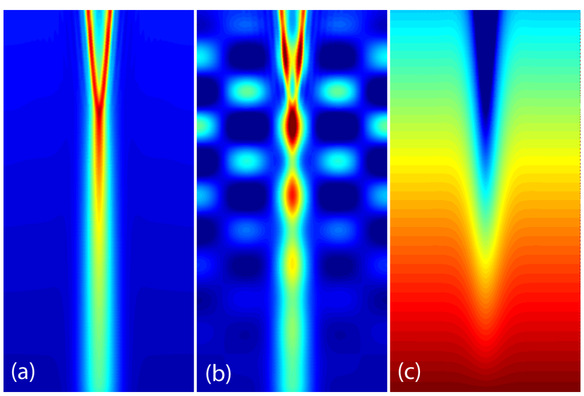

Figure 2. Wave regime: Time-dependent variations of porosity (a, early time; b later time) and opx fields (c).

Figures 2a-c show an example of the time-dependent nature of the porosity and opx fields in the wave regime. Again, a single sustained porosity perturbation is placed around the center of the lower boundary. At early times, the porosity field is dominated by the boundary perturbation and hence broadly similar to that in the stable regime, except the compacting boundary is significantly weakened in the wave regime (cf. Figs. 1a and 2a). At later times, the porosity field is self-organized into a wave-like structure. Nevertheless, the high-porosity melt channel remains visible (Fig. 2b). Distribution of the dunite channel again correlates strongly with the boundary perturbation and is not very sensitive to time and porosity variations (cf. Figs. 2b-c).

Chemical consequences: The depth of multi-saturation, which ranges from 240 to 500 km for the picritic glass melts [2,9], is an important parameter to lunar magma genesis. Here, the multi-saturation depth corresponds to the depth at which opx first disappears from the liquidus and is generally believed to represent the minimum depth at which picritic glass melts were formed. An interesting observation is that the multi-saturation depth of the lunar orange, red, and black glass melts overlap with those of the green glass melts [9]. If a significant fraction of the picritic melts is extracted through the dunite channels, the depth of the dunite channel may offer a dynamic interpretation to the multi-saturation depth. Since the depth of dunite channel initiation is sensitive to the amount of low-solidus materials, such as ilmenite-bearing cumulates, and opx present in the hybrid lunar mantle, it is not surprising that the depth of multi-saturation for the picritic glass melts vary considerably, independent of their TiO_2 content.

The spatial and temporal distributions of the porosity, mineral fraction, melt and solid velocities are essential to the interpretation of the major and trace element abundances in the melt erupted on the surface. For melt migration in the stable regime, melting in regions far away from the melt channels is equivalent to batch melting, whereas melting and melt migration in and around the compacting boundary layer is more to fractional melting. The composition of the melt extracted from the dunite channel is a weighted average of the (major element) depleted melt from the harzburgite channel, the expelled melt from the compacting boundary layer, and melt produced by opx dissolution along the sidewalls of the dunite channel. However, the trace element abundances in the channel melt may be enriched due to the presence of an enriched source (e.g., our boundary perturbation). The presence of compacting waves in and around a dunite-harzburgite channel system further complicates the melt flow field and provides new mechanisms for melt-peridotite interaction in the lunar mantle. Examples of trace element fractionation during melting and melt migration in the stable and wave regimes will be discussed.

References: [1] Hess and Parmentier (1995) *EPSL* 134, 501-514. [2] Shearer et al. (2006) In: *New Views of the Moon*. pp365-518. [3] Papike et al. (1998) In: *Planetary Materials*. 5, pp1-234. [4] Ringwood and Kesson (1976) PLPSC 7th, 1697-1722. [5] Beck et al. (2006) *GRL 33,* 1029/2005GL024008. [6] Liang and Hess (2006) *LPS* 37, #1943. [7] Spiegelman et al. (2001) JGR, 106, 2061-2077. [8] Hesses et al. submitted to J. Fluid. Mech. [9] Grove & Krawczynski (2009) Elements, 5, 29-34.