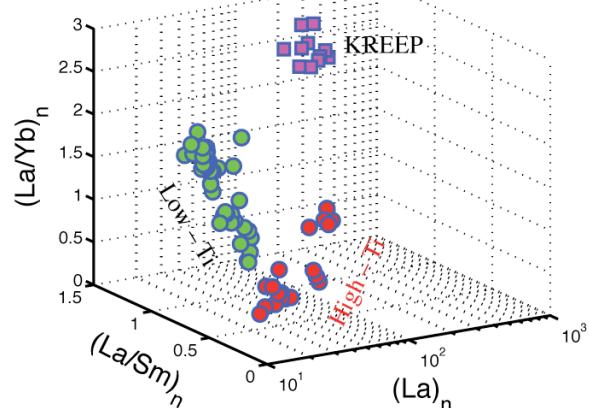


**SIMPLE MODELS FOR TRACE ELEMENT FRACTIONATION DURING MELTING AND MELT MIGRATION IN AN UPWELLING HETEROGENEOUS LUNAR MANTLE.** Y. Liang and P. C. Hess (Department of Geological Sciences, Brown University, Providence, RI 02912, email: yan\_liang@brown.edu).

**Introduction:** It has long been recognized that lunar mantle is chemically, isotopically, and lithologically heterogeneous. The heterogeneities are ancient and were formed during large-scale differentiation events, such as the solidification of a globally distributed lunar magma ocean (LMO) and subsequent lunar cumulate mantle overturn [1-3]. Mixing of distinct early and late LMO cumulates results in a hybrid cumulate mantle [4]. Evidence for a heterogeneous lunar mantle is overwhelming, including major element data (low-Ti to high-Ti basaltic samples), incompatible trace element patterns (e.g., REE), selected incompatible trace element ratios (e.g., La/Sm, La/Yb, Fig. 1), and isotopic variations and co-variations (Sr, Nd, Hf, and Pb isotopes) [1-3]. At least three distinct components in the (overturned) lunar mantle have been identified: early harzburgitic cumulate, late ilmenite-bearing cumulate, and KREEP, although the lithologies of the latter two and the length scale and spatial distribution of these mantle components are not known.



**Figure 1.** Variations of C1-normalized La, La/Sm, and La/Yb in mare basalts [5] and KREEP [3]. Note the distinct trends for the low- and high-Ti mare basalts. Similar trends also exist in picroitic glasses [3].

It is well known that melt transport processes can affect compositions of mantle-derived melts. Continuous re-equilibration or partial re-equilibration during grain-scale porous flow in a partially molten lunar mantle results in chromatographic fractionation among elements of different compatibility [6]. The chromatographic effect is especially important when chemical heterogeneities are involved [7-9] and must be included in any chemical models for melting and melt migration in a heterogeneous lunar mantle.

The importance of assimilation or melt-rock reaction during magma transport in the lunar mantle has long been recognized in the lunar science

community. Petrologic and phase equilibrium considerations, peridotite dissolution experiments, and geological field observations of the mantle section of ophiolites suggest that channelized melt flow (via high-porosity dunite channels or melt-filled fractures) has played an important role in magma migration and melt-rock reaction in the (terrestrial and lunar) mantle. Formation of high-porosity dunite channels in the lunar mantle involves porous melt flow and preferential dissolution of pyroxene and Fe-Ti oxides and is a viable mechanism for assimilation during magma transport in the lunar mantle [10,11].

Figure 1 compares chondrite-normalized La/Sm, La/Yb, and La abundances in Apollo 11 and 17 high-Ti mare basalts (red circles), Apollo 12 and 15 low-Ti basalts (green circles), and KREEP (squares). It can be demonstrated that melting of a homogeneous mantle source cannot generate the two distinct trends, i.e., the high- and low-Ti basalts were likely from different mantle sources or/and modified by different melt transport and melt-rock reaction processes. Further, melting of a homogeneous mantle source cannot produce the range of La/Sm and La/Yb variations within each trend, i.e., at least two components are needed in each case. This is corroborated by the available Nd and Hf isotopic data for the mare basalts that also display two distinct trends for the high- and low-Ti mare basalts in the  $\epsilon_{\text{Nd}}$  vs.  $\epsilon_{\text{Hf}}$  diagram [1,2,12]. Although the notation of a heterogeneous lunar mantle has been widely accepted in the lunar sciences community, simple models for trace element fractionation during concurrent melting, melt transport, and melt-rock reaction in an upwelling, heterogeneous lunar mantle has still not been developed. Consequently, melting and assimilation processes in a heterogeneous lunar mantle are still difficult to assess and quantify.

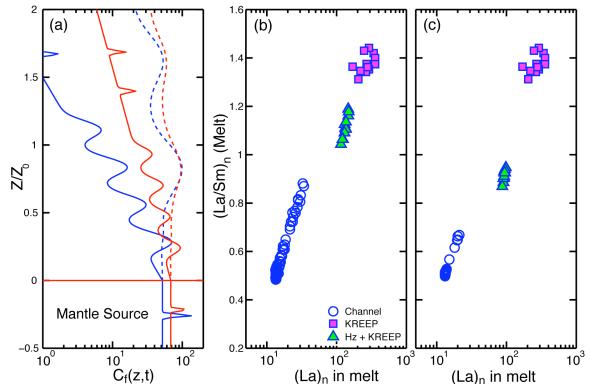
**Simple models:** We have recently developed a simple model for trace element fractionation during concurrent melting and melt migration in an upwelling, chemically heterogeneous, two-porosity double lithology melting column that consists of dunite channels and harzburgite matrices [9]. Analytical solutions for the abundance of a trace element in the harzburgite matrix and the dunite channel were obtained under the assumptions that (1) the crystal and melt are in local equilibrium; and (2) the porosity, melt and solid velocities, and solid-melt partition coefficients are constant and uniform. Chemical source heterogeneities of arbitrary size and shape were integrated into the simple melting model by allowing trace element abundance in the source

region to vary as a function of time and space. This is in essence a generalized dynamic melting model.

**Melting in a heterogeneous mantle:** The first order geochemical characteristics can be summarized as follows. (1) Concurrent melting and melt migration in a heterogeneous mantle is characterized by superposition in which time-dependent concentration patterns produced by melting of heterogeneous source regions are superimposed on a reference concentration distribution established by melting of the ambient mantle (Fig. 2a). (2) The size and spatial distribution of heterogeneous regions are important in determining the variation of trace element and isotopic ratio in the matrix and channel melts (cf. Figs. 2b and 2c). (3) Chromatographic fractionation is important for the matrix melt when heterogeneities are involved, giving rise to a significant phase-shift or anti-correlation between two incompatible trace elements in the matrix melt. (4) Mixing is the chief mass transfer process in the dunite channel where chromatographic effect is negligible for most of the incompatible trace elements. (5) Compatible trace element (defined with respect to olivine) abundances in the channel melt depend strongly on matrix dissolution. In general, the compatible trace element abundances in the channel melt are lower than those in the average matrix melt. (6) Incompatible trace element abundances in the matrix melt are very sensitive to the depth of high-porosity melt channel initiation, and the magnitude of melt flow rate to solid upwelling rate. (7) And finally, the incompatible trace element abundance in the channel melt is dominated by the less depleted small-degree melts from the lower part of the melting column and not very sensitive to the details of how matrix dissolution rate vary spatially in the mantle (dashed lines in Fig. 2a).

**Numerical examples:** As an illustrative example, we consider La and La/Sm variations in extracted melts during melting and melt migration in a two-component lunar mantle that consists of heterogeneously mixed harzburgite cumulates (ambient mantle) and KREEP. This scenario has been considered before except we treat heterogeneities explicitly using a prescribed spatial distribution. For purpose of demonstration, we assume the enriched mantle consists of 0.1~1wt% KREEP + 99.9~99% harzburgite. Other parameters used in the calculations are similar to those used to construct Fig. 8 in [9]. Fig. 2a shows a snap shot of the matrix (solid lines) and channel (dashed lines) melt compositions for La (blue) and Sm (red) in the melting column. The mantle first experienced 1~3% batch melting below  $z < 0$  (red line). Dynamic melting starts at  $z = 0$  and terminates at  $z = 2$  where the degree of melting experienced by the solid matrix is 20%. Note the

contrasting behaviors between the matrix and channel melts. Fig. 2b displays the correlations between La and La/Sm in the channel melt collected at the top of the melting column (blue circles). For reference, compositions of KREEP tabulated in [3] and the small degree melt derived from the enriched mantle are shown as squares and triangles. La (0.2~0.9) and La/Sm (0.02~0.15) are more depleted in the matrix melt (not shown) with compositional pattern similar to that reported in Fig. 8b in [9]. Fig. 2c is calculated using a set of parameters similar to that for Figs. 2a and b, except the amplitude and wavelength of the heterogeneities are smaller. Consequently the compositional variations in the channel melt are also smaller in the latter case.



**Figure 2.** (a) Variations of La (blue curves) and Sm (red) in the matrix melt (solid lines) and the channel melt (dashed lines) in the melting column. (b) Variations of La and La/Sm in the channel melt collected at the top of the melting column. (c) Same as (b) except the amplitude and wavelength of the heterogeneities are smaller.

**Discussions:** The similarities between La and La/Sm variations in our model calculations (Fig. 2b) and those observed in high-Ti mare basalts (Fig. 1) are encouraging. To conduct more detailed calculations, it is essential to know the chemical composition, lithology (e.g., peridotite vs. garnet pyroxenite), and thermodynamic phase relationships of the “enriched” mantle component(s). To assess the role of assimilation in producing compositional diversities in mare basalts and picritic glasses, it is necessary to include Fe-Ti oxide-bearing harzburgite dissolution in the simple models.

**References:** [1] Snyder et al. (2000) In: *Origin of the Earth and the Moon*. pp361-396. [2] Shearer et al. (2006) In: *New Views of the Moon*. pp365-518. [3] Papike et al. (1998) In: *Planetary Materials*. Chapter 5, pp1-234. [4] Ringwood and Kesson (1976) *PLPSC* 7th, 1697-1722. [5] Neal (2001) *JGR* 27,865-27,885. [6] Navon and Stolper (1987) *J. Geol.* 95, 285-307. [7] McKenzie (1984) *J. Petrol.* 25, 713-765. [8] DePaolo (1996) *JGR* 101, 11,855-11,865. [9] Liang (2008) *GCA* 72, 3804-3821. [10] Beck et al. (2006) *GRL* 33, 1029/2005GL024008. [11] Liang and Hess (2006) *LPS* 37, #1943. [12] Beard et al. (1998) *GCA* 62, 525-544.