

PREFERENTIAL ASSIMILATION DUE TO MELT-ROCK REACTION IN THE LUNAR MANTLE: A LABORATORY AND OPHIOLITE FIELD PERSPECTIVE. Y. Liang and P. C. Hess (Department of Geological Sciences, Brown University, Providence, RI 02912, email: yan_liang@brown.edu).

Introduction: Assimilation has been called upon in numerous occasions to explain various petrologic and geochemical observations of the igneous rocks on the Moon. A well known example is the assimilation of ilmenite-bearing late cumulates (and KREEP) to the low Ti primary magmas at shallow levels, that has been used to explain the high Ti magmas observed on the lunar surface [1]-[3]. An alternative to the assimilation model is the mixing of ilmenite to the cumulate mantle during lunar mantle overturn, that has been proposed to explain the characteristics of the source region of the VLT to high Ti picritic to basaltic samples from the Apollo landing sites [4]-[10]. In general it is difficult to distinguish these two models because both have been treated as simple mixing or mass balance problems. In detail, the processes of assimilation are more complicated.

The primitive lunar picritic magmas are not saturated with pyroxene and ilmenite at their liquidus at pressures below multisaturation. Once segregated from their source regions, the picritic magmas will have a strong tendency to interact, both thermally and chemically, with their surrounding mantle and crust at shallower depth. In a recent experimental study we examined the thermo-chemical consequences of picritic magma and anorthosite reaction in the lunar crust [11]. Here we explore the physical and chemical processes of assimilation during picritic magma transport in the lunar mantle. Our discussions are based on laboratory reactive dissolution studies and geological field observations of the mantle section of ophiolites on Earth.

Melt-rock reaction in the Earth's mantle: Like picritic magmas on the Moon, terrestrial primitive mid-ocean ridge basalts (MORBs) are not in equilibrium with residual harzburgite or lherzolite mantle at low pressure (e.g., [12]). The mechanisms and processes of melt-rock reaction in the Earth's mantle are relatively well understood through thermodynamic calculations, laboratory dissolution studies, and geologic field observations. They involve preferential dissolution of clinopyroxene (cpx) and orthopyroxene (opx) and precipitation of olivine, as olivine normative basalts percolate through a harzburgite or lherzolite matrix [13]-[17]. Figure 1 shows an experimental example of lherzolite reactive dissolution in an alkali basalt at 1300°C and 1 GPa [17]. Reaction between lherzolite and alkali basalt produces a reactive boundary layer that consists of a zone of melt-bearing, pyroxene-free dunite and a cpx-free harzburgite. This is very similar to the dunite, harzburgite, lherzolite, and plagioclase

lherzolite (DHL-PL) sequence that is abundant in the mantle section of the Trinity ophiolite in northern California [13]. An important observation of the DHL-PL sequence at Trinity (and also several other ophiolites on Earth) is that the dunite, harzburgite, and lherzolite are plagioclase-free. The formation of the DHL-PL sequence is consistent with a model that involves preferential dissolution of plagioclase, followed by cpx, and finally opx, as olivine normative basalts percolate through a plagioclase-bearing lherzolite. Hence disproportionately more plagioclase and cpx are assimilated to, whereas olivine is subtracted from, the reacting basaltic melt. This selective rather than bulk assimilation is the hallmark of melt-rock reaction in the Earth's mantle.

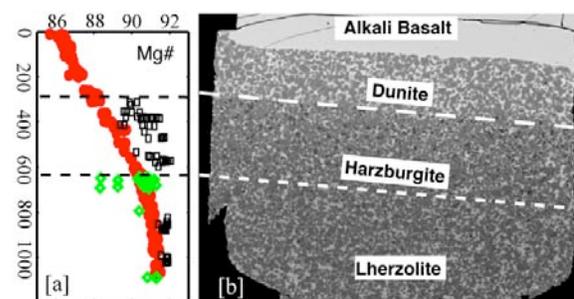


Figure 1. Lherzolite reactive dissolution in alkali basalt (1300°C, 1 GPa, 8 hrs). [a] Variations in Mg#s of olivine (red circles), opx (open squares), and cpx (green diamonds) in the reaction zone as a function of distance (μm) in the charge. [b] BSE image of the charge with dash lines marking the sharp boundaries between the three lithologic units. The original lherzolite-basalt interface is marked by the capsule offset in graphite (black walls in this image).

Melt-rock reaction in the lunar mantle: The lithology of lunar mantle is less well constrained compared to that of the Earth's mantle but is probably dominated by harzburgite (olivine + opx \pm cpx \pm ilmenite) after mantle overturn. Since picritic magmas (green, yellow, orange, red and black glasses) have only olivine on their liquidus at pressures below multisaturation [2, 3, 19, 20], it is inevitable that melt-rock reaction takes place during transport of the picritic magmas through the harzburgitic mantle. Indeed preferential dissolution of opx and precipitation of olivine were observed in a series of Apollo 15 red glass and harzburgite (olivine + opx \pm melt) reactive dissolution experiments [18] (1385°C and 1-2 GPa). The dunites produced in the red glass-harzburgite dissolution runs (see Fig. 2 in [18]) are melt-bearing and opx-free, similar to the dunite shown in Fig. 1b and those formed in the alkali basalt-harzburgite dissolution experiments reported

in [16] (1250-1290°C and 0.6-0.75 GPa). The rate of dunite formation, hence opx dissolution and olivine precipitation, depends on the extent of opx undersaturation with respect to the reacting melt, which is a strong function of pressure, temperature and melt composition. For example, the rate of dunite formation at 1 GPa is 6 times faster than that at 1.6 GPa, while the rate of dunite formation is essentially zero at 2 GPa in the red glass-harzburgite dissolution runs (all at 1385°C).

Depending on the efficiency of convective mixing during mantle overturn, the lunar harzburgitic mantle may contain ilmenite. The primitive lunar picritic magmas are not saturated with ilmenite at their liquidus at pressures below multisaturation. Hence reaction between the picritic melts and ilmenite-bearing harzburgite is also inevitable during magma transport in the lunar mantle. Based on phase relationships [2, 3, 19, 20] and our red glass-harzburgite dissolution experiments [18], it is possible to deduce that reaction between an ilmenite-bearing harzburgite and a picritic melt may produce an ilmenite-free dunite-harzburgite sequence that is surrounded by the ilmenite-bearing harzburgite (Fig. 2), similar to the DHL-PL sequence at the Trinity ophiolite. If the abundance of ilmenite is large, local ilmenite saturation may be established in the newly formed dunite. Reaction between the ilmenite-rich harzburgite and a picritic melt then would produce an ilmenite-free dunite surrounded by ilmenite-bearing dunite and harzburgite. The later sequence was observed in a preliminary dissolution run in which the reacting harzburgite contains ~25wt% ilmenite (1325°C and 1.2 GPa).

Consequences of melt-rock reaction in the lunar mantle: Figures 2a and 2b are schematic diagrams showing the relative TiO₂ abundance in the interstitial melts in the dunite, harzburgite, and ilmenite-bearing harzburgite sequence produced by reaction between a low Ti picritic magma and an ilmenite-bearing harzburgite in either a (shallow) magma conduit or a (deep) porous lunar mantle. These concentration profiles are produced by a combination of dissolution, diffusion, and melt flow and in general cannot be accurately modeled by simple mixing calculations. Preferential dissolution of ilmenite and opx and precipitation of olivine selectively assimilate TiO₂, FeO, and SiO₂ to the reacting picritic magma. This is broadly consistent with the simple mass balance calculations of Wagner and Grove [2] who proposed a petrogenetic model for high Ti lunar ultramafic glasses that involves ilmenite, cpx, and pigeonite assimilation and olivine subtraction at shallow levels. However, assimilation of cpx may not be necessary or as much as those proposed in [2] because CaO and Al₂O₃ can also be

added to the picritic magmas later during their ascent through the lunar crust where melting and dissolution of anorthositic rocks are likely to take place [11, 21]. Hence preferential assimilation due to melt-rock reaction at various depths in the lunar mantle and crust is a viable mechanism through which some of the compositional diversities of the picritic glasses were produced. Preferential dissolution also has important implication for the interpretation of multisaturation depth, a topic that will be explored in the future (see discussion in [18]).

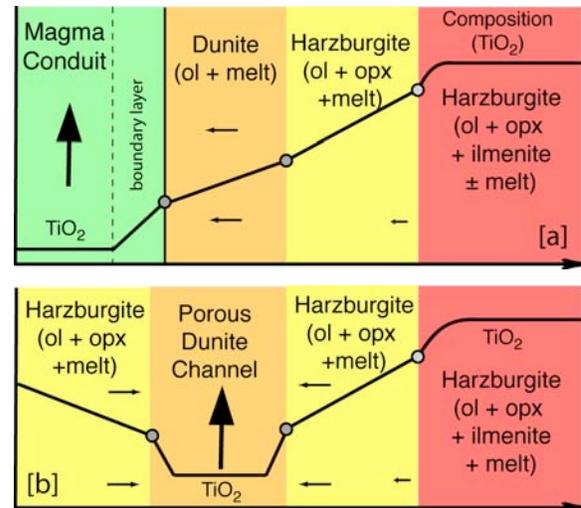


Figure 2. Schematic diagram showing a sequence of dunite, harzburgite, and ilmenite-bearing harzburgite formed during reaction between a low Ti picritic magma and an ilmenite-bearing harzburgite in the lunar mantle. Case [a] is likely to occur in the relatively cold lunar lithosphere where fractures can develop. Case [b] may occur in the deep lunar mantle just above the source region of the low Ti picritic magma where the ilmenite-bearing harzburgite may be partially molten. Relative TiO₂ abundance in the picritic magma and the interstitial melts in the peridotite sequence are shown as solid black lines (cf. Fig. 1a). Arrows indicate local melt flow direction.

References: [1] Hubbard and Minear (1975) *Lunar Sci.* VI, 405-407. [2] Wagner and Grove (1997) *GCA* 61, 1315-1327. [3] Elkins et al. (2000) *GCA* 64, 2339-2350. [4] Ringwood and Kesson (1976) *Proc. 7 LPSC*, 1697-1722. [5] Delano (1986) *JGR* 91, B4, D201-D213. [6] Ryder (1991) *GRL* 18, 2065-68. [7] Spera (1992) *GCA* 56, 2253-2265. [8] Hess and Parmentier (1995) *EPSL* 134, 501-514. [9] Van Orman and Grove (2000) *Meteoritics Planet. Sci.* 35, 783-794. [10] Elkins Tanton et al. (2002) *EPSL* 196, 239-249. [11] Liang et al. (2005) *LPSC* #1706. [12] Stolper (1980) *CMP* 74,13-27. [13] Quick (1981) *CMP* 78, 413-422. [14] Kelemen (1990) *J. Petrol.* 31, 51-98. [15] Kelemen et al. (1995) *Nature* 375, 747-753. [16] Morgan and Liang (2003) *EPSL* 214, 59-74. [17] Morgan and Liang (2005) *CMP* 150, 369-385. [18] Beck et al. (2006) *GRL* 33, 1029/2005GL024008. [19] Longhi (1992) *GCA* 56, 2235-2251. [20] Longhi (1995) *GCA* 58, 8375-8386. [21] Finnilla et al. (1994) *JGR* 99, 14,677-14,690.