MAJOR AND MINOR ELEMENT PARTITIONING IN ARMALCOLITE- AND ILMENITE-BEARING HARZBURGITE AND DUNITE: A DATA BASE FOR MODELING PARTIAL MELTING AND MELT-ROCK REACTION IN A HETEROGENEOUS LUNAR MANTLE. C. Thacker, Y. Liang, and P. C. Hess (Department of Geological Sciences, Brown University, Providence, RI 02912, email: carla_thacker@brown.edu).

Introduction: Ilmenite has played an important role in the petrogenesis of lunar high Ti picritic magmas [1-7]. In a preliminary study, we examined the stability of ilmenite in the context of lunar cumulate mantle overturn [8]. Mixtures of natural olivine + ilmenite (dunite) and olivine + orthopyroxene (opx) + ilmenite (harzburgite) were equilibrated at 1235-1475°C and 1-2 GPa. In the starting dunite mixture, ilmenite is stable in the subsolidus assemblage at least up to 1450°C and 2 GPa. The assemblage is partially melted at 1400°C and 1 GPa and at 1475°C and 2 GPa, defining the solidus for the ilmenite-bearing dunite. In the harzburgite starting mixture, ilmenite is stable at pressures greater than 1.4 GPa, and armalcolite is stable at lower pressures. Solidi were determined, and the phase boundary between ilmenite- and armalcolite-bearing harzburgite was shown to have little dependence on temperature [8]. An incompletely overturned lunar cumulate mantle is therefore lithologically stratified with armalcolite-bearing harzburgite stable at depths less than 270 km and ilmenite-bearing harzburgite stable at greater depth.

In this study we report compositions of coexisting minerals and melts in armalcolite- and ilmenite-bearing harzburgite and dunite from our experimental charges, focusing on major and minor element partitioning between high Ti oxides and silicate minerals and melt. These partitioning data are essential in modeling major and minor element abundance and distributions during partial melting and melt-rock reaction involving ilmenite- and armalcolite-bearing harzburgite and dunite.

Experiments: Experimental procedures are reported in [8]. Mineral and melt compositions were measured with a Cameca SX100 electron microprobe at Brown University. Mineral analyses were carried out using a focused beam with a 20 keV accelerating voltage and a 25 nA beam current. Melt analyses were made using a defocused beam (15 µm) with a 15 keV accelerating voltage and a 15 nA beam current.

Mineral and Melt Chemistry: Electron microprobe traverses along grains in several samples indicate that individual olivines, ilmenites, and armalcolites are homogenous in terms of major and minor elements examined, whereas opx grains show distinct core to rim compositional variations. Only opx rim compositions are discussed below.

Mg# [100MgO/(MgO+FeO), molar ratio] of olivine varies systematically with the starting composition, the final oxide present, and as a function of temperature. Olivines in samples starting with the ilmenite-bearing dunite composition tend to have a slightly higher Mg# than those starting with the ilmenite-bearing harzburgite composition (avg. 87.8 ± 0.6 vs. 86.2 ± 0.7). Additionally, a plot of Mg# of olivine vs. Mg# of the coexisting oxide shows that runs with armalcolite lie along a linear trend that is separate from a linear trend containing runs with ilmenite (Fig. 1). The TiO_2 abundance in olivine coexisting with either ilmenite or armalcolite is relatively high (0.17-0.56 wt%).

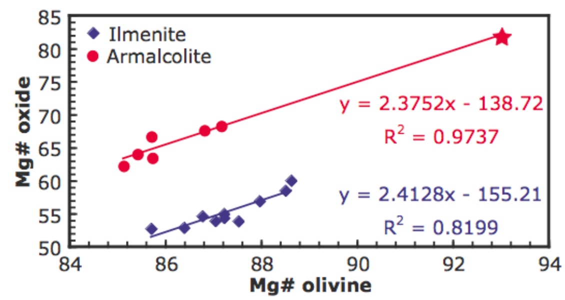

Fig. 1. Mg# of olivine vs. Mg# of coexisting oxide. Red star is from [10] with the mineral assemblage olivine + opx + armalcolite. Equations from un-weighted linear least squares analyses are given in the figure.

The Mg# of opx rims ranges from 86.9 to 87.9 and is positively correlated with the Mg# of olivine. A graph of Mg# of opx versus the Mg# of the coexisting oxide also shows two separate trends for runs with armalcolite vs. ilmenite present. Other major and minor element abundances in opx rims range from 0.87-1.4% for TiO_2, 3.5-5.8% for Al_2O_3, and 0.21-0.32% for Cr_2O_3.

Ilmenite in our experimental charges contains considerable amounts of MgO (14.1-18.0%) with Mg# ranging from 51.2 to 60.1 (Fig. 1). FeO and TiO_2 in ilmenite range from 21.3-24.9% and 54.8-57.4%, respectively. Ilmenite also contains small amounts of Al_2O_3 (0.89-2.1%) and Cr_2O_3 (0.12-1.1%).

Armalcolite was first discovered in lunar basalts as reaction rims with ilmenite [9]. We have demonstrated experimentally [8] that armalcolite can also be formed at pressures less than 1.4 GPa during lunar cumulate mantle overturn through the reaction:

$$\text{ilmenite} + \text{opx} \rightarrow \text{olivine} + \text{armalcolite}.$$

The Mg# of armalcolite produced in our experimental charges ranges from 62.4 to 68.4 (Fig. 1), with 11.3-12.3% MgO and 9.7-12.2% FeO. The TiO_2

abundance in armalcolite is characteristically high at 69.3-71.8%, while Al_2O_3 is 3.2-4.9% and Cr_2O_3 is 0.63-1.4%. The structural formula for a typical armalcolite from our experimental charge is

$$(Mg_{0.60}Fe_{0.35}Mn_{0.01}Cr_{0.02}Al_{0.04})(Al_{0.13}Ti_{1.87})O_5.$$

The linear correlation between Mg# of armalcolite and the Mg# of olivine is further extended by one datum from [10, 1360°C and 1.2 GPa] that has the assemblage olivine + opx + armalcolite (Fig. 1).

Orthopyroxene and armalcolite were completely melted in two high-temperature runs resulting in large melt accumulation at the bottom of the charges. Melt in run CT-13 (1390°C, 1.3 GPa) has average MgO of 18.6 ± 0.8%, FeO of 16.3 ± 0.3%, TiO_2 of 22.8 ± 1.1%, and Al_2O_3 of 5.5 ± 0.4%. Melt in run CT-15 (1360°C, 1.3 GPa) has an average MgO of 17.0 ± 1.5%, FeO of 16.7 ± 1.2%, TiO_2 of 23.5 ± 1.7%, and Al_2O_3 of 6.1 ± 0.7%. The TiO_2 abundance in these melts are among the highest reported in recent studies, allowing us to further constrain FeO-MgO partitioning among coexisting phases.

FeO-MgO Partitioning: Although the abundance of major and minor elements in the minerals and melts reported above depend on the bulk composition of our starting materials, key elemental ratios between coexisting phases are less sensitive to choices of starting compositions. The distribution coefficient (K_D) for FeO-MgO between the olivine and high Ti oxide phases or olivine and coexisting melt was calculated for several samples containing armalcolite or ilmenite [$K_D = (FeO/MgO)_{ol} / (FeO/MgO)_{ph}$, where ol stands for olivine, and ph refers to Ti oxide or melt]. A plot of the natural log K_D vs. inverse temperature shows that the FeO-MgO K_D between olivine and either oxide is effectively independent of temperature. For olivine and ilmenite, the average K_D is 0.182 ± 0.007, while for olivine and armalcolite, the average K_D is 0.309 ± 0.020. This is in good agreement with the datum derived from the work of [10] (see Fig. 1). Additionally, [11] found that at low X_{Fa} such as in our study, K_D for olivine and ilmenite is essentially constant. This supports our finding that K_D for FeO-MgO between olivine and ilmenite or armalcolite is essentially independent of temperature.

The K_D for FeO-MgO between olivine and liquid was calculated for runs CT-13 (0.27) and CT-15 (0.25). It is well known that this K_D is strongly dependent on TiO_2 abundance in the melt. Regression of K_D as a function of pressure, temperature, and melt composition show that a simple linear relationship, $K_D = -0.3491(X_{TiO2})+0.337$, can adequately describe our measured K_D data and those reported in or derived from [7,10,12], where X_{TiO2} is the molar fraction of TiO_2 in the melt.

Al_2O_3, Cr_2O_3, and TiO_2 Partitioning: Analysis of opx with coexisting ilmenite or armalcolite has been limited to date. Table 1 lists our preliminary data on the partitioning of Al_2O_3, Cr_2O_3, and TiO_2 between opx and coexisting oxide (K_d). Additional work is needed to further characterize the partitioning of these elements.

Table 1. Minor element partitioning between opx and ilmenite (ilm) and opx and armalcolite (arm).

	Al_2O_3	Cr_2O_3	TiO_2
opx/ilm	3.05	0.38	0.016
opx/arm	0.88	0.36	0.016
opx/arm*	0.73	n/a	0.024

*K_d of Al_2O_3 and TiO_2 derived from one datum from [10].

Potential Lunar Applications: Armalcolites reported in lunar basalts are late magmatic differentiation products that are considerably more mafic (Mg# 18.4-63.5, [13]) and contain significant amounts of Cr_2O_3 (1.3-10.3%, [13]). Their compositions may not be used directly in assimilation calculations involving armalcolite that equilibrated in the overturned cumulate mantle.

Given the bulk composition of an overturned lunar cumulate mantle, our measured FeO-MgO K_D's can be used to estimate the Mg# of coexisting Ti oxides in armalcolite- or ilmenite-bearing harzburgite and dunite (see Fig. 1). Additionally, our FeO-MgO K_D's between olivine and liquid can be used to derive melt compositions in equilibrium with ilmenite- and armalcolite-bearing harzburgite and dunite using the methods of [14-15]. Given the K_d's for the minor elements between opx and melt [10], data presented in Table 1 can be used to calculate these elements' abundance during partial melting and melt-rock reaction in the lunar mantle. An example is given in a companion study [16].

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