AN EXPERIMENTAL STUDY OF REE AND OTHER TRACE ELEMENT PARITITIONING BETWEEN AUGITE AND FE-RICH BASALTS: A PARAMETERIZED MODEL FOR PLANETARY APPLICATIONS. N. Dygert, Y. Liang, and P.C. Hess, Brown University (324 Brook Street, Providence, R.I., nicholas_dygert@brown.edu).

Introduction: Mineral-melt partition coefficients are an important parameter in the interpretation of igneous rocks and are known to be sensitive to temperature (*T*), pressure (*P*), and the compositions of the mineral and melt (*X*). Because clinopyroxene (*cpx*) is typically the most fusible silicate mineral in the mantle of a planetary body and has relatively high capacity to store incompatible trace elements, a thorough understanding of cpx-melt partition coefficients (K_D's) is of primary importance. Although numerous studies have investigated K_D's for cpx with Mg# > 60 [Mg# = 100*Mg/(Mg+Fe) in molar fraction], very few studies have reported partition coefficients for more iron-rich systems. Oe et al. [1] measured REE K_D's by electron microprobe in nakhlite analogue experiments (yellow circles, Fig. 1a, green line, Fig. 2), while Olin et al. [2] report K_D's calculated from LA-ICP-MS analyses of Fe-rich cpx (Mg# 59-10) that crystallized in silicic natural samples (58.6-77.2% SiO_2). The REE K_D's reported in [2] are $\gtrsim$1 and not relevant to basaltic systems. Wood and Triglia [3] report K_D's for aluminous cpx with intermediate Mg#s in hydrous melts (green circles, Fig. 1a), while Pertermann and Hirschmann [4] measured cpx K_D's for anhydrous ecolgitic cpx experiments (cyan circles, Fig. 1).

While pure hedenbergite ($Fe_2Si_2O_6$) and low Mg# augite are relatively rare in natural rocks, they crystallize at end-stage solidification of magma oceans and layered intrusions, and from evolved igneous melts on bodies throughout the solar system, including Mars (the nakhlites, [5]), the Moon (lunar magma ocean cumulates, alkali suite rocks, and quartz-monzodiorites [6-8]), angrite parent bodies [9], and Earth (layered intrusions and ferroan calc-alkaline rocks [e.g. 2,10]).

Recently, a parameterized lattice strain model was developed for REE partitioning between cpx and basaltic melts [11]. This model was calibrated using available high-quality experimental data from the literature (all with cpx Mg# > 50). According to [11], REE partition coefficients primarily depend on *T* and abundances of Al on the tetrahedral site and Mg on the M_2 site of cpx. While [11] does an excellent job predicting REE K_D's within the range of the experimental data used to calibrate the model, it fails to predict the measured K_D's for Fe-rich pyroxene presented here (Fig. 2). The purpose of this study is to develop an experimental dataset of high-quality partition coefficients over the range of cpx compositions presented in Figure 1. Ultimately, this data will be incorporated into a global model similar to [11].

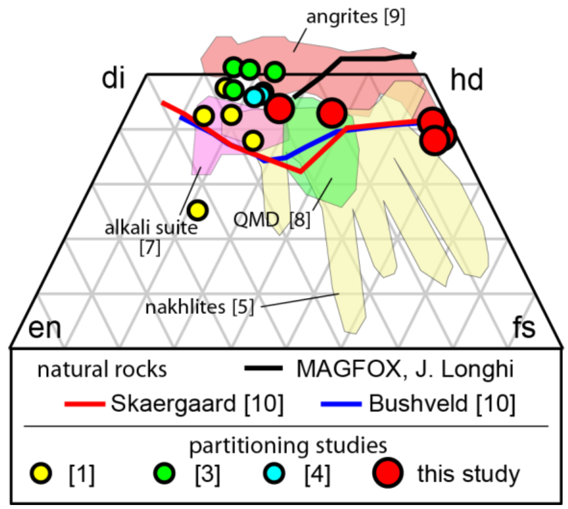

Figure 1. Pyroxene compositions fron experimental trace element partitioning studies with the lowest Mg#s (circles) and pyroxenes in samples from Earth, Mars, the Moon, and the Angrite parent body. Note the absence of partitioning studies near hedenbergite. MAGFOX is a parameterized fractionation model that calculates lunar magma ocean cumulate compositions (J. Longhi, personal communication). Cpx compositions shown are for a magma ocean 93-97% crystallized.

Experiments: The six partitioning experiments reported here were conducted in graphite-lined Mo capsules in a 19.1 mm piston cylinder apparatus. Run conditions range from 1050-1220°C and 0.8-2.2 GPa. Experimental methods are similar to those described in [12]. Starting compositions are based on an end-stage lunar magma ocean analogue melt (FR-1290) reported by Longhi [13]. Starting compositions were prepared from reagent grade oxide powders following the procedure described in [12].

Three experiments were conducted with pure FR-1290 at different *T-P* conditions (1050-1150°C, 0.8-2.2 GPa). In an additional experiment, a layer of ilmenite powder was placed at the bottom of the capsule beneath a thicker layer of FR-1290 in volume proportions of ~1:4. In the final two experiments we placed a layer of natural augite (Mg# 82) beneath a thicker layer of FR-1290 (in proportions of ~ 1:4) and ran the experiments at 1220 and 1170°C (1.5 GPa). All experiments were cold pressurized, brought above their estimated liquidus temperature, then cooled to their target temperatures at 0.1°C/min. Target conditions were maintained for at least 48 hours before an isobaric quench.

Analysis: Major elements in cpx and melt were analyzed using a Cameca SX100 electron microprobe at Brown University with beam current of 15 nA and accelerating voltage of 20 kV. Quenched melt was measured with a defocused 10 µm beam, while cpx was measured with a focused beam. Trace elements were measured by LA-ICP-MS at the University of Rhode Island using spot sizes ranging from 20-60 µm.

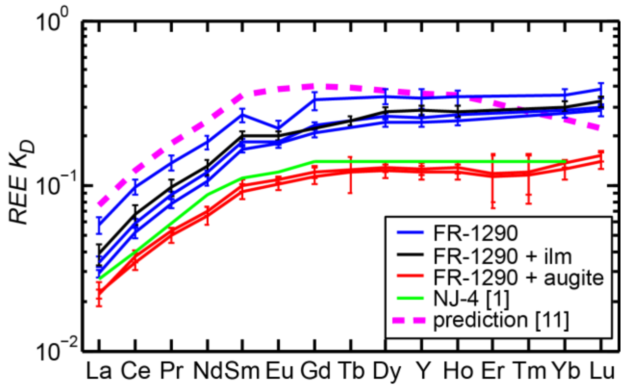

Figure 2. REE partition coefficients from this study (blue, black, and red lines). Legend identifies experimental starting composition. Also shown is an experiment from [1] (NJ-4) and a prediction from [11] for one of our FR-1290 + augite experiments (dashed magenta line). Errorbars are 2σ.

Results: Experiments generally contain just a few large (hundreds of µm) cpx crystals and melt. Cpx obtained in this study are augite and hedenbergite (Fig. 1). Augite in the two experiments (Mg# = 36-52) exhibit significant core-rim Mg# zoning, but minor and trace elements are more homogeneous throughout the crystals. The major element compositions and K_D's reported here are from analyses of the grain rims in those experiments, which should be well equilibrated with surrounding melt. Hedenbergites in the four experiemnts do not exhibit major or trace element zoning. Melt in all experiments is homogeneous and free of quench modification except immediately adjacent to crystals.

Figure 2 summarizes our measured REE K_D's and Figure 3 demonstrates the quality of our measured partitioning data through applications of the lattice strain model.

Partitioning Model: We inverted lattice strain parabolas from measured K_D's by nonlinear least squares regression for individual experiments from this study (Fig. 3) and [4]. Experimental parameters (X,T,P) were compared to unknowns in the lattice strain model (D_0, E, r_0) and correlations were noted. Finally, D_0, E and r_0 were parameterized as functions of P and the cation fraction of Ca in cpx by simultaneous inversion of the global dataset.

Predicted K_D's are in good agreement with measured values (Fig. 4). REE partitioning was found to be insensitive to Mg# or the abundance of Mg or Al in cpx lattice sites, though we caution this result is preliminary as the global dataset is currently limited to only 9 experiments.

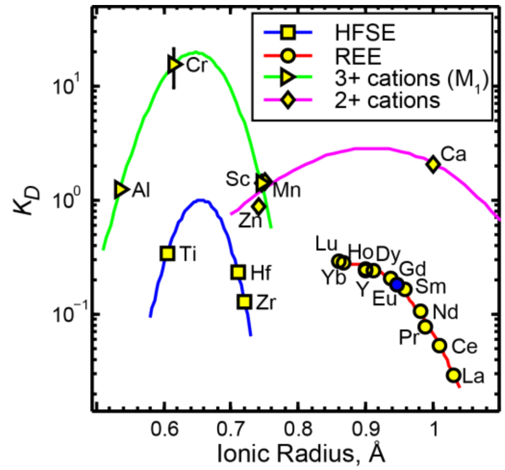

Figure 3. Lattice strain parabolas inverted from measured partition coefficients for a single experiment. Additional elements are not shown (Li, Na, K, Sr, P, V, Ni, Co, Cu, Ga, Mo, W, Nb, Ta, Pb).

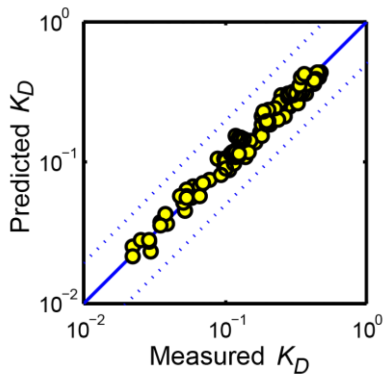

Figure 4. REE partition coefficients for Fe-rich cpx predicted by our global model compared to experimentally measured values. Solid line shows 1:1 values, while dotted blue lines show 2:1 and 1:2 values.

Potential applications: The new augite-hedenbergite trace element partitioning data and model are especially useful for the interpretation of Fe-rich rocks on Mars, the Moon, Angrite parent bodies, Earth, or other planetary bodies. They could also be used to invert parent magma compositions, calibrate a REE based geothermometer for Fe-rich systems [14], or be incorporated into magma ocean crystallization models.

References: [1] Oe et al. (2001) *LPS XXXII*, Abstract #2174. [2] Olin, P. and Wolff, J. (2010) *CMP*, *160*, 761-775. [3] Wood, B. and Triglia, R. (2001) *Chem. Geol*, *172*, 213-223. [4] Pertermann, M. and Hirschmann, M. (2002) *AmMin*, *87*, 1365-1376. [5] Udry et al. (2012) *Meteor. & Planet. Sci.*, *47*, 1-15. [6] Snyder et al. (1992) *GCA*, *56*, 3869-3823. [7] Shervais, J. and McGee, J. (1999) *AmMin*, *84*, 806-820. [8] Marvin et al. *LPSC*, *21*, 119-135. [9] Kuehner et al. (2006) *LPS XXXVII*, Abstract #1344. [10] Wager, L. and Brown, G. (1967) Layered Igneous Rocks, W.H. Freeman (San Francisco). [11] Sun, C. and Liang, Y. (2012) *CMP*, *163*, 807-823. [12] Dygert et al. (2013) *GCA*, in press. [13] Longhi, J. (2003) *JGR*, *108(E8)*, No. 5083. [14] Liang et al., *GCA*, *102*, 246-260.