THE IMPORTANCE OF TEMPERATURE ON REE AND OTHER TRACE ELEMENT PARTITIONING IN PLAGIOCLASE WITH APPLICATIONS TO LUNAR MAGMA OCEAN SOLIDIFICATION. C. Sun,1,2 and Y. Liang1. 1Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 (yan_liang@brown.edu), 2Earth Science Department, Rice University, Houston, TX 77025 (csun@rice.edu).

Introduction: Plagioclase is one of the major rock-forming minerals constituting the crusted of Earth, the Moon and other planetary bodies. The lunar highland crust is dominated by f erroan anorthosites (FANs) with >90% anorthitic plagioclase (An > 95; An = 100×Ca/(Ca+Na+K) in mol; e.g., [1-2]). According to the canonic model of lunar formation and evolution, FANs are products of crystallization and flotation of plagioclase in a global-scale lunar magma ocean (LMO; [2-3] and references therein). Thus, compositions of plagioclase record the differentiation processes of terrestrial and lunar magmas.

A key parameter for unraveling the magmatic processes involving plagioclase is the plagioclase-melt trace element partition coefficient (D), which generally is a function of temperature (T), pressure (P), and compositions of the mineral and melt (X). Since Drake and Weill’s pioneering work [4], many experimental studies have been conducted to determine trace element partitioning between plagioclase and silicate melt (e.g., [5-11]). Several empirical or semi-empirical models have also been calibrated for predicting plagioclase-melt (DREE) (e.g., [5-9, 12]). However, these partitioning models are incomplete, especially for lunar relevant melt compositions and temperatures.

In this study, we developed parameterized lattice strain models for the partitioning of 1+, 2+, 3+ cations and noble gas between plagioclase and silicate melt over a wide range of T, P, and X. These new partitioning models are broadly applicable to plagioclase-melt fractionation during terrestrial and lunar magmatism. Application of our models to LMO fractional crystallization indicates that the temperature effect on DREE is fundamental to understanding chemical fractionation during LMO solidification and must be considered in future modeling studies.

Database: Data used in our model calibration are from 29 plagioclase-melt trace element partitioning experiments from [5-11]. The 29 experiments were conducted at 1127 – 1410 °C and 1 atm to 1.5 GPa under nominally anhydrous or water-saturated conditions. Plagioclase crystals and melts from these experiments cover a large range of composition (An = 41 – 98 in plagioclase; SiO2 = 41.82 – 62.50 wt% and Mg# = 49 – 100 in melt). To ensure a self-consistent calibration dataset, we excluded partitioning experiments that are suspect of kinetics and/or analytical artifacts.

Models: Given the compiled plagioclase-melt trace element partitioning data, we developed parameterized lattice strain models for the partitioning of 1+, 2+ and 3+ cations and noble gas following a protocol that includes rigorous statistical treatment of partitioning data through parameter sweeping and simultaneous nonlinear least squares inversion of all the selected partitioning data. Fig. 1 compares our model predicted D’s with experimentally measured values. In the lattice strain model for REE partitioning, the strain-free partition coefficient (D0) is given by the expression

\[
\ln D^0_{x} = 16.05 - \frac{19.45+1.17P}{RT} 
\]

where P is in GPa and XCa is the Ca content in plagioclase per eight-oxygen. The ideal radius (ri) and effective Young’s modulus (E) for REE are constant (1.179Å and 196 GPa, respectively). The new models indicate that REE and other trace element partitioning in plagioclase depends strongly on temperature and the abundances of Ca and Na in plagioclase. Particularly, Na content in plagioclase primarily controls divalent element partitioning, while temperature and Ca content in plagioclase are the dominant factors for REE partitioning in plagioclase. For a given plagioclase composition, DREE decrease with the decrease of temperature. This is an unique and important feature of REE partitioning in plagioclase and it has important implications for REE fractionation during LMO crystallization.

Figure 1. Comparison between experimentally determined D’s and model predicted values.

Solidification of LMO: Fractional crystallization of a global lunar magma ocean was calculated using the MAGFOX program for a lunar upper mantle composition (LPM; [13]). Anorthite begins to crystalize at 78% solidification of the LMO at 1250 °C and 4.6
kbar. As crystallization proceeds from 78% to 94%, the anorthite content in plagioclase slightly decrease by ~2 mol% and the temperature drops from 1250 °C to 995 °C. Using the new partitioning models, we calculated plagioclase-melt $D$'s for three representative stages of LMO solidification ($F$): plagioclase saturation ($F = 78\%$, at 1250 °C and 4.6 kbar), spinel saturation ($F = 89\%$, at 1144 °C and 2.0 kbar), and the maximum extent solidification that MAGFOX is capable of handling ($F = 94\%$, at 995 °C and 1.0 kbar). The results are shown in Fig. 2.

![Figure 2](image_url)

**Figure 2.** Calculated plagioclase-melt $D$'s for LMO fractional crystallization. $Ar^*$ denotes the calculated noble gas $D$'s.

The partition coefficients of divalent cations (Sr, Ba, Ra, and Eu$^{2+}$) display small changes across the 250 °C temperature interval, because of the strong dependence on Ca content in plagioclase and the nearly invariant plagioclase composition; however, the small increase of albite content in plagioclase gives rise to about a factor of two decrease in $D_{Mg}$. As crystallization proceeds from 78% to 94%, the predicted noble gas $D$ increases by a factor of three, monovalent element $D$'s increase by a factor of three to four, whereas $D_{REE}$ decrease by 1.5 orders of magnitude. Given the nearly constant anorthite content in plagioclase, these variations mainly result from the 250 °C temperature reduction. Together with our recent study on REE partitioning in low-Ca pyroxene [14], the large variations of plagioclase-melt $D_{REE}$ underscore the importance of temperature and composition in quantifying trace element fractionation during LMO solidification.

**Parental melts of FANs:** Using the anorthite-melt partitioning data derived from LMO solidification (78%, 89% and 94%), we reassessed the parental magmas of FANs with reported anorthite REE data from [15-16]. Fig. 3 displays one example of the estimated parental magma compositions. For each set of $D_{REE}$, the estimated REE abundances vary by a factor of five, which may be attributed to different extents of LMO solidification (e.g., [15-16]). Because of the systematic decreases of $D_{REE}$ during LMO solidification (cf. Fig. 2), the estimated REE abundances in the parental magmas appear to increase from 100 to 2000 times chondrite values with increasing Eu negative anomalies. Interestingly, the REE compositions of FAN parental magmas calculated using $D$'s at 89% LMO solidification are comparable to those of the KREEP basalts (K, REE, and P rich; [17]).

Because temperature is the dominate factor controlling anorthite-melt $D_{REE}$, the anomalous REE enrichments and apparent Eu negative anomalies in FAN parental magmas may be attributed to (1) subsolidus re-equilibration; (2) more complicated crystallization process, or (3) inappropriate $T$ used for FAN crystallization. Assuming a higher $T$, REE abundances in the estimated parental magmas become more comparable to previous estimations (grey regions; calculated using $D$'s from [18]) and display flat patterns without significant Eu anomalies (see dashed outline in Fig. 3). Thus, determination of FAN crystallization temperatures is a prerequisite for estimating their parental magmas and further assessing formation of the lunar crust. Effects of (1) and (2) will also be assessed.

![Figure 3](image_url)

**Figure 3.** Chondrite normalized REE abundances in FAN parental magmas calculated using $D$'s at different temperatures. KREEP compositions are from [18].

**References:**