A REE-IN-PLAGIOCLASE-CLINOPYROXENE THERMOMETER FOR MAFIC AND ULTRAMAFIC ROCKS FROM THE EARTH, MOON, AND OTHER PLANETARY BODIES. C. Sun and Y. Liang, Department of Geological Sciences, Brown University, Providence, RI 02912 (Chenguang_Sun@Brown.edu).

Introduction: Distributions of REE between two co-existing minerals depend on temperature and mineral compositions [1-5]. Based on parameterized lattice strain models for REE partitioning between pyroxene and basaltic melts, we have developed a REE-in-two-pyroxene thermometer for mafic and ultramafic rocks [4-7]. Temperatures derived from the REE-in-two-pyroxene thermometer are in excellent agreement with those derived from major element-based two pyroxene thermometers for well-equilibrated spinel peridotites from stable continental regions [4-5]. Due to the differences in diffusion rate between trivalent REE and divalent Ca, Mg, and Fe in minerals, the REE-based thermometer can potentially record thermal events more close to magmatic temperatures for mafic and ultramafic rocks during a fast cooling process.

Plagioclase (plg) and clinopyroxene (cpx) are common rock-forming minerals in mafic and ultramafic rocks. Partitioning of REE between coexisting plg and cpx may be used as a thermometer for the mafic and ultramafic rocks. In this study, we first develop a predictive model for REE partitioning between plg and basaltic melts based on partitioning data from our experiments [8] and those from literatures. We then formulate a REE-in-plg-cpx thermometer by combining the independently calibrated REE partitioning models for plg and cpx. Application of the REE-in-plg-cpx thermometer to pyroxenites from Bushveld complex and cumulate eucrites produces equilibrium temperatures consistent with those calculated using the REE-in-two-pyroxene thermometer of [4-5]. The internal consistency between these two REE-based thermometers inspires a broader application of the new thermometer to lunar ferroan anorthosites (FANs) and Mg-suite rocks, as well as refractory inclusions in chondrites (CAI: Ca-Al-rich inclusions; POI: plagioclase-olivine-rich inclusions).

A predictive model for REE partitioning between plagioclase and basaltic melts: In general, the trace element partition coefficient between mineral and melt is a function of pressure (P), temperature (T), and compositions of mineral and melt (X). REE partition coefficients from a given mineral-melt partitioning experiment can be quantitatively described by the lattice strain model [9]. Following the procedures described in [6-7], we have analyzed published REE partitioning data between plg (An# = 52.6 ~ 98.2) and basaltic melts, and parameterized key partitioning parameters in the lattice strain model (D_0, r_0 and E) as

functions of P, T and X. We find that D_0 is positively correlated with Ca abundance in plg and negatively correlated with T, and that r_0 and E can be treated as constants. Figure 1 shows the excellent agreement between the predicted and observed REE partition coefficients (D) between plg and basaltic melts from partitioning experiments reported in the literature as well as those measured in our laboratory [8].
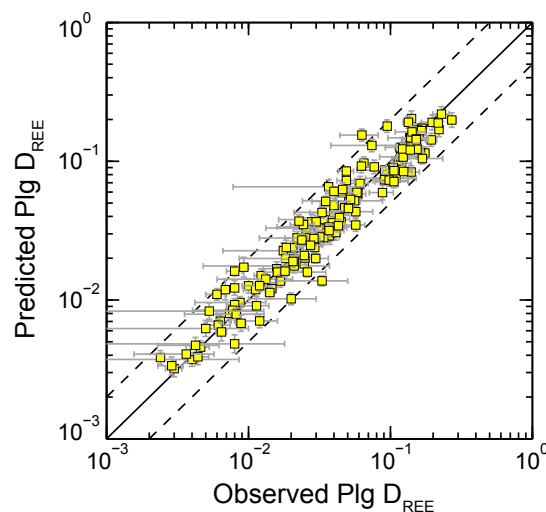

Figure 1. Predicted vs. observed D of REE between plagioclase and melts from partitioning experiments. The predicted and observed D values tightly follow the 1:1 lines.

A REE-in-plg-cpx thermometer: The temperature and composition dependent mineral-melt partition coefficient for trace element i can be written as
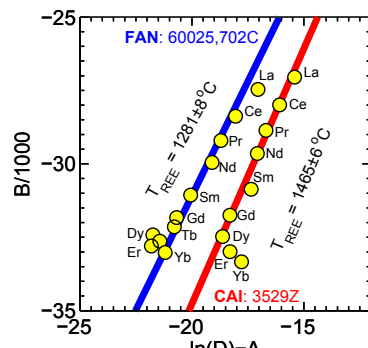
$$\ln D_i^{plg} = A_i^{plg} + \frac{B_i^{plg}}{T} \;,\; \ln D_i^{cpx} = A_i^{cpx} + \frac{B_i^{cpx}}{T}$$

where A and B are functions of ionic radius of element i and major element compositions of plg or cpx, and can be deduced from the lattice strain model. A predictive model for REE partitioning between cpx and basaltic melts has been proposed in [6]. Combining the above equations for plg and cpx, we obtain a temperature-dependent partitioning model for element i between these two minerals,

$$\ln D_i^{plg/cpx} = A_i + \frac{B_i}{T} \;,\; A_i = A_i^{plg} - A_i^{cpx} \;,\; B_i = B_i^{plg} - B_i^{cpx}$$

The temperature-dependent REE partitioning model for plg and cpx, in turn, can be used as a thermometer to calculate equilibrium temperature (T_{REE}) if REE abundances in plg and cpx are known. As shown in Fig. 2, the equilibrium temperature can be deduced from the slope in a plot of ($\ln D_i - A_i$) vs. B_i through a linear least squares analysis of the REE and Y parti-

tioning data. By treating REE as a group, we can reduce analytical uncertainties in trace element analysis during the temperature inversion. Figure 3 summaries T_{REE} for selected plg-cpx bearing samples from the Earth, Moon, and other planetary bodies.

Figure 2. Inversion diagram showing the application of REE-in-plg-cpx thermometer to a FAN sample from [10] and a CAI sample from [11].

Mafic cumulates from Bushveld complex and eucrites: Model validation. We apply the REE-in-plg-cpx thermometer to intercumulus plg and cpx in pyroxenites from the Lower and Lower Critical Zones of Bushveld complex [12]. The equilibrium temperatures based on the REE-in-plg-cpx thermometer for the pyroxenites range from 1068 ~ 1169 ºC, which are consistent with those calculated using the REE-in-two-pyroxene thermometer (1071 ~ 1226 ºC) [4]. The internal consistency between these two REE-based thermometers is further demonstrated by cumulate eucrite samples from [13] (cf. Fig. 3a in [4] and Fig. 3 in this study).

Refractory inclusions in chondrites (CAI and POI): REE and major element abundances in primary anorthite and high-Ca pyroxene in a type B1 CAI sample from the Allende meteorite was reported in [11]. The calculated T_{REE} for this CAI sample is 1465 ºC. Interestingly, the calculated T_{REE} for a POI sample of [14] is 1361 ºC lower than that of CAI. These are consistent with the phase equilibria studies of [15].

Lunar ferroan anorthosites and Mg-suite rocks: It has been shown that REE redistribute between coexisting anorthite and pyroxene in FANs and Mg-suite rocks during subsolidus re-equilibrium [8, 10, 16, 17]. The equilibrium temperatures for FANs were calculated using REE abundances reported in [10] and [17] and major elements reported in [18]. T_{REE} for all the FAN samples vary within a small range (1281 ~ 1361 ºC), and are about 50 ~ 100 ºC higher than the MAGFOX-derived plagioclase crystallization temperatures (1235 ~ 1261 ºC) in a lunar magma ocean (LMO) model [19]. The small temperature range for all FAN samples suggests that the high T_{REE} is a global feature for the lunar highland crust. If the high T_{REE} is the crystallization temperature of FANs in LMO, it suggests that anorthite becomes saturated in LMO earlier

than that predicted by MAGFOX. The early saturation of anorthite may result from more complicated LMO crystallization processes than that assumed in MAGFOX calculation or a difference in initial LMO composition from that used in MAGFOX calculation of [19]. Alternatively, the high T_{REE} may indicate a global thermal perturbation in the lunar highland crust, which reset the equilibrium temperature of REE-in-plg-cpx.

In conclusion, the REE-in-plg-cpx thermometer can be used to study the thermal and magmatic history of mafic and ultramafic rocks from the Earth, Moon, and other planetary bodies. This is further demonstrated by a final example in which T_{REE} for two lunar troctolite samples from [16] (1298 ºC and 1378 ºC) are comparable to their crystallization temperatures.
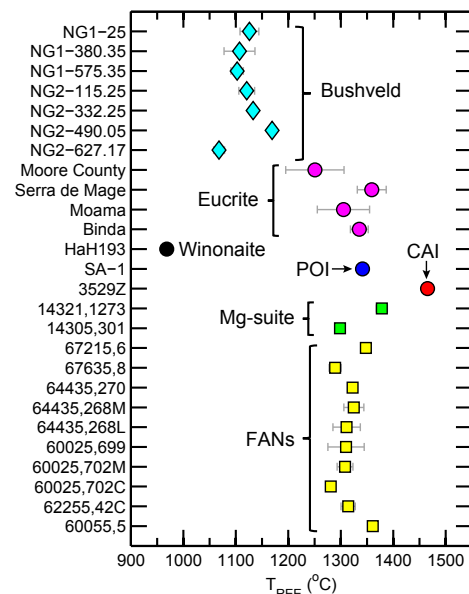

Figure 3. Variations of T_{REE} for lunar FANs [10], Mg-suite rocks [14], pyroxenites from Bushveld complex [12], achondritic meteorites (eucrites [13] and a winonaite [20]), CAI [11] and POI [14].

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