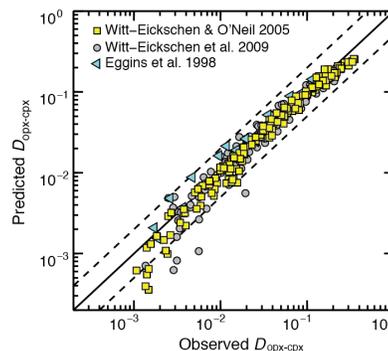


**A REE-IN-TWO-PYROXENE THERMOMETER FOR MAFIC AND ULTRAMAFIC ROCKS FROM THE EARTH, MOON (FANS AND Mg-SUITE ROCKS), AND OTHER PLANETARY BODIES: PROMISES AND CHALLENGES.** Y. Liang, L. Yao, C. Sun, and P. C. Hess (Department of Geological Sciences, Brown University, Providence, RI 02912, email: yan\_liang@brown.edu).

**Introduction:** In two recent studies we examined published experimental data for REE partitioning between pyroxene and mafic melts and parameterized REE & Y partition coefficients for clinopyroxene (cpx) and orthopyroxene (opx) as functions of temperature ( $T$ ) and pyroxene composition using the lattice strain model [1, 2]. To test internal consistency of the two partitioning models, we calculated opx/cpx REE partition coefficients using major element compositions from three suites of well-equilibrated spinel lherzolite and harzburgite xenoliths [3-5] and the two-pyroxene thermometer of [6]. Fig. 1 shows the excellent agreement between our model-derived opx/cpx partition coefficients and those calculated directly from REE & Y abundances in coexisting opx and cpx measured by LA-ICP-MS. (The outliers are La, which likely results from its low abundance in opx and poor analytical precision.) This excellent agreement is significant considering our two partitioning models for pyroxene/basalt were calibrated at magmatic conditions, whereas mantle xenoliths were equilibrated at subsolidus  $T$ .

Intrigued by the excellent agreement, we turned the problem around and calculated “equilibrium temperatures” for the aforementioned xenoliths using our opx/cpx partitioning model and major and trace element compositions of opx and cpx reported in the three studies. Fig. 2b demonstrates the surprisingly good agreement between temperatures calculated using our opx/cpx partitioning model ( $T_D$ ) and the major element based two-pyroxene thermometer of [6] ( $T_{BKN}$ ). This leads to the obvious questions: Can REE partition coefficients for coexisting opx and cpx be used as a thermometer for ultramafic and mafic rocks from the Earth, Moon, and other planetary

bodies? Should  $T_D$  always be the same as  $T_{BKN}$ ? If not, at what conditions would we expect the two thermometers to be different?



**Figure 1.** Comparison between model-derived opx/cpx REE partition coefficients and directly measured values from three suites of spinel lherzolite and harzburgite xenoliths reported in the literature [3-5].

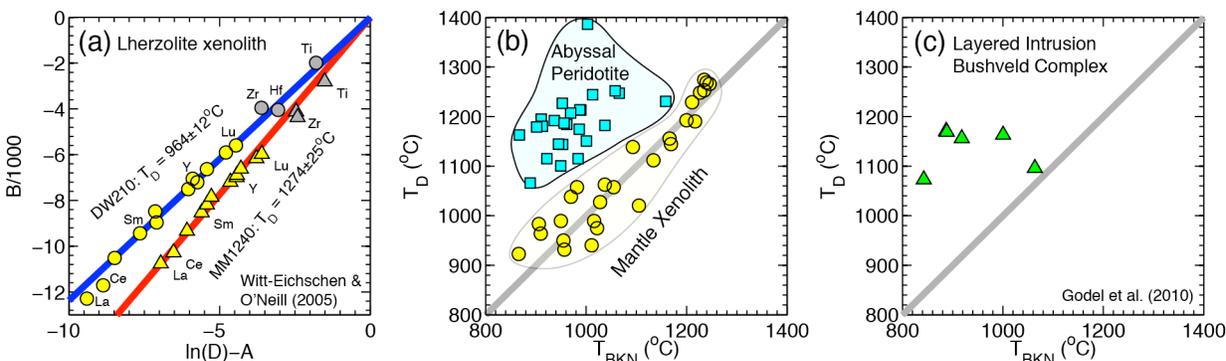
**The model:** The temperature and composition dependent pyroxene/melt partition coefficient ( $D$ ) for element  $i$  can be written as

$$\ln D_i^{cpx/melt} = A_i^{cpx} + \frac{B_i^{cpx}}{T}, \quad \ln D_i^{opx/melt} = A_i^{opx} + \frac{B_i^{opx}}{T}$$

where  $A_i^{cpx}$ ,  $A_i^{opx}$ ,  $B_i^{cpx}$ , and  $B_i^{opx}$  are functions of ionic radius of  $i$  and major element compositions of the two pyroxenes, and can be deduced from expressions given in [1, 2]. Combining these two equations, we have a  $T$ -dependent partitioning model for element  $i$  between opx and cpx,

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

The slope in a plot of  $(\ln D_i^{opx/cpx} - A_i)$  vs.  $B_i$ , which can be obtained through a linear least squares



**Figure 2.** (a) Application of REE-in-two-pyroxene thermometer to two spinel lherzolite xenoliths from [4]. Comparison between REE-derived temperatures ( $T_D$ ) and temperatures calculated using the major element based two-pyroxene thermometer of [6] ( $T_{BKN}$ ) for (b) abyssal peridotites [7, 8] and spinel peridotite xenoliths from stable continental lithosphere [3-5], and (c) mafic samples from Bushveld Complex [9].

analysis of the REE & Y (also Ti, Zr, Hf) partitioning data, is the equilibrium temperature for the REE-in-two-pyroxene thermometer. An example of temperature inversion is given in Fig. 2a for two spinel-lherzolite xenolith reported in [4].

**Mafic and ultramafic samples from the Earth:** Figure 2b shows that  $T_D$  for three suites of well-equilibrated spinel lherzolite and harzburgite xenoliths are comparable to  $T_{BKN}$  derived from Ca-Fe-Mg based two-pyroxene thermometer of [6]. However,  $T_D$  for two suites of abyssal peridotites (Gakkal Ridge and Southwest Indian Ridge) [7, 8] are 100–300°C higher than major element based  $T_{BKN}$ . Furthermore,  $T_D$  for five mafic samples from the Bushveld Complex are also higher than the major element based  $T_{BKN}$  (Fig. 2c).

One possible explanation of the difference in the trace element and major element based two-pyroxene temperatures is the difference in diffusion rate between trivalent REE and divalent Ca-Mg-Fe in pyroxene. In general, diffusivities of Ca, Mg, and Fe are one to two orders of magnitude larger than diffusivities of REE in pyroxene. Hence, to the first order, we would expect closure temperatures for the 2+ and 3+ cations to be different for a given cooling rate [13]. When the cooling rate is very small, temperatures derived from the trace element (3+) and major element (2+) based thermometers are expected to be similar (or identical). This may be the case for mantle xenoliths from continental lithosphere. When the cooling rate is moderate to high, the 3+ cation based two-pyroxene thermometer is more likely to record a higher temperature than the 2+ cation based thermometer. This may be the case for abyssal peridotite (and layered intrusions), as cooling rates at the base of Moho for the oceanic lithosphere are considerably faster ( $10^{-1} \sim 10^{-5}$  °C/yr, [14, 15]).

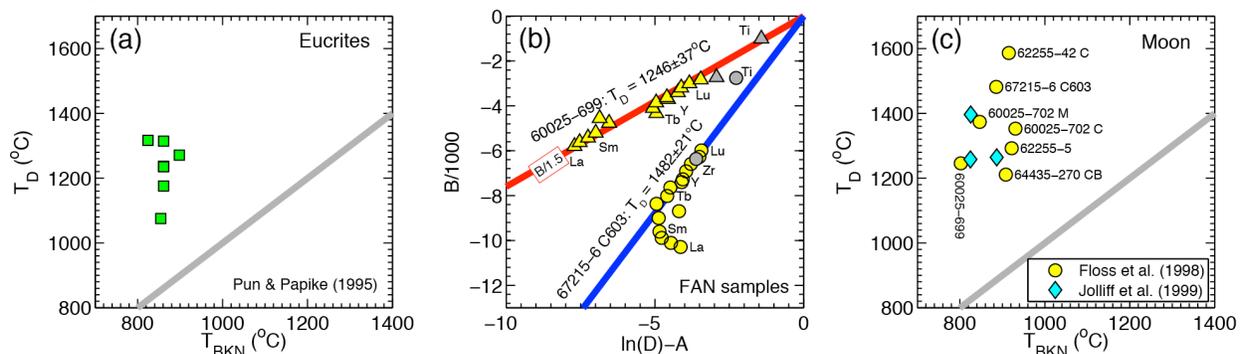
**Eucrites:** The fast cooling rate may also explain the apparent high  $T_D$  for the cumulate eucrites reported in [10] (Fig. 3a). The calculated  $T_D$  for the eucrites are

consistent with phase equilibrium studies of [16,17].

**Ferroan anorthosites:** Perhaps the most surprising results of the present study is the calculated  $T_D$  for FANs using major and trace element data reported in [11]: All the FAN samples have  $T_D \geq 1200^\circ\text{C}$  (Fig. 3c). If pyroxenes in the FAN samples were derived from interstitial melts trapped within a solidifying anorthosite mush at a late stage of LMO, the calculated  $T_D$  should be less than the crystallization temperature of plagioclase which is below  $1200^\circ\text{C}$  [18]. This poses a serious problem.

**Discussion:** Potential explanations of the higher than crystallization temperature include: (1) inaccuracy of our REE-in-two-pyroxene thermometer; (2) disequilibrium partitioning of REE between opx and cpx; (3) thermal perturbation; and (4) FANs are not the product of LMO. (1) may be assessed through additional partitioning experiments. REE in melts derived from coexisting plagioclase and opx in FANs and Mg-suite rocks are discordant [11, 19]. Impact followed by fast cooling may reset REE, resulting in a higher temperature or disequilibrium partitioning of REE between two pyroxenes. LREE in 62255-42C and 67215-6 C630 deviate from linear trend (Fig. 3b) and were perturbed by secondary process. Hence, (2)-(3) may have important implications for the age of FANs and Mg-suite rocks.

**References:** [1] Sun and Liang (2012) CMP doi: 10.1007/s00410-011-0700-x. [2] Yao et al. (2012) CMP, in revision. [3] Eggins et al. (1998) EPSL 154, 53-71. [4] Witt-Eickchen and O'Neill (2005) Chem. Geol. 221, 65-101. [5] Witt-Eickchen et al. (2009) GCA 66, 3647-3656. [6] Brey and Köhler (1990) J. Petrol. 31, 1353-1378. [7] Hellebrand et al. (2005) CMP 150, 486-504. [8] Seyler et al. (2011) G-Cubed doi: 10.1029/2011GC003585. [9] Godel et al. (2011) Lithos 125, 537-552. [10] Pun and Papike (1995) GCA 59, 2279-2289. [11] Floss et al. (1998) GCA 62, 1255-1283. [12] Jolliff et al. (1999) Am. Mineral. 84, 821-837. [13] Dodson (1973) CMP 40, 259-274. [14] Coogan et al. (2002) EPSL 199, 127-146. [15] Van Tongeren et al. (2008) EPSL 267, 69-82. [16] Stolper (1977) GCA 587-611. [17] Longhi & Pan (1988) LPSC 459-470. [18] Longhi (2003) JGR doi: 10.1029/2002JE001941. [19] Papike et al. (1996) GCA 60, 3967-78.



**Figure 3.** Comparison between REE-derived temperatures ( $T_D$ ) and temperatures calculated using the two-pyroxene thermometer of [6] for (a) cumulate eucrites [10], and (c) lunar ferroan anorthosites [11] and whitlockite monzogabbro [12]. (b) Application of REE-in-two-pyroxene thermometer to two FAN samples (60025 and 67215) from [11]. Note the disequilibrium in LREE.