**TEMPERATURE AND THERMAL HISTORY OF HED AND SNC METEORITES AS DEDUCED FROM THE REE-IN-PLAGIOCLASE-CLINOPYROXENE THERMOMETER.** Y. Liang[1] and C. Sun[1,2], Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912; Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543. (Yan_Liang@Brown.edu)

**Introduction:** Plagioclase and clinopyroxene (cpx) are major rock-forming minerals in mafic and ultramafic rocks from the Earth and other planetary bodies. Distributions of rare earth elements (REE) between plagioclase and cpx depend on temperature and plagioclase and cpx major element compositions [1, 2], which can be calibrated as a thermometer. Here we quantify the temperature- and composition-dependent REE partitioning between plagioclase and cpx and outline the thermodynamics basis for the REE-in-plagioclase-cpx thermometer. We verify the new thermometer using field data from the Bushveld Complex and discuss the significance of calculated temperatures for the SNC and HED meteorites. Since diffusion rates of REE in plagioclase and cpx are very slow, the REE-based thermometer has a greater chance to record and preserve high temperature magmatic event(s) than Ca-Mg-Fe based thermometers. Integrated applications of the major element- and REE-based thermometers to mafic and ultramafic rocks from meteoritic samples can shed new light on the thermal state and thermal history of their parent bodies.

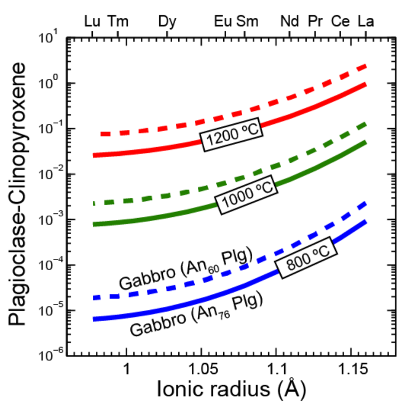


**Figure 1.** Onuma diagram showing the temperature- and composition-dependent plagioclase-cpx REE partition coefficients. Solid and dashed curves are for two different bulk compositions.

**A model for REE partitioning between plagioclase and cpx:** It has been demonstrated recently that the partitioning of REE between major rock forming minerals (pyroxene, garnet, olivine, and plagioclase) and basaltic melts are functions of pressure ($P$), temperature ($T$), and mineral compositions ($X$) [3]. Effect of melt composition is either unimportant or indirect. The $T$-$X$ dependent mineral-melt partition coefficient ($D_i$) of trace element $i$ can be written as

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

where $A$ and $B$ are functions of ionic radius of element $i$ and major element compositions of plagioclase (plg) or cpx, and can be deduced from the lattice strain model [4]. In three recent studies [1, 2, 5], we developed parameterized lattice strain models for cpx-basalt and plagioclase-basalt REE partitioning. We parameterized the lattice strain parameters ($D_0$, $r_0$, and $E$) as functions of cpx or plagioclase compositions. We find that $D_0$ in the plagioclase-melt model is positively correlated with Ca abundance in plagioclase and negatively correlated with $T$, and that $r_0$ and $E$ can be treated as constants. Combining the above equations for plagioclase and cpx, we obtain a $T$-$X$ dependent partitioning model for element $i$ between these two minerals,

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

Figure 1 shows the effects of $T$ and anorthite content ($An_{60}$ vs. $An_{76}$) on plagioclase-cpx REE partitioning for two gabbroic rocks.

**A REE-in-plagioclase-clinopyroxene thermometer:** The temperature-dependent REE partitioning model for plagioclase and cpx can be used as a thermometer. As shown in Fig. 2, a temperature ($T_{REE}$) 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 partitioning data. By treating REE as a group, we can reduce analytical uncertainties in trace element analysis during temperature inversion. Figure 3 summaries $T_{REE}$ for selected plagioclase-cpx bearing samples from HED and SNC meteorites.

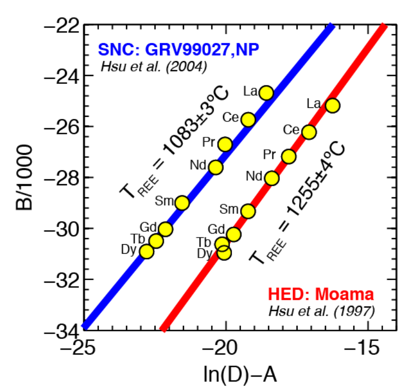


**Figure 2.** Inversion diagram showing application of the REE-in-plagioclase-cpx thermometer to a SNC sample from [6] and a eucrite from [7].

**Model validation: Mafic and ultramafic cumulates from the Bushveld Complex.** We apply the REE-in-plagioclase-cpx thermometer to intercumulus plagioclase and cpx in pyroxenites and gabbronorites from the Bushveld Complex using REE and major element data reported in [8, 9]. The temperatures based on the REE-in-plagioclase-cpx thermometer for the samples range from 1069~1193ºC, which agrees very well with those calculated using the plagioclase liquidus thermometer of [10] (1105~1183ºC). Interestingly, for the same Bushveld samples reported, temperatures ($T_{Mg}$) calculated using the Mg-in-plagioclase-cpx thermometer of [11] are significantly lower (651~830°C). The lower temperatures are likely due to fast diffusion of Mg in plagioclase: the closure temperature of Mg is significantly lower than those of REE in plagioclase [12].

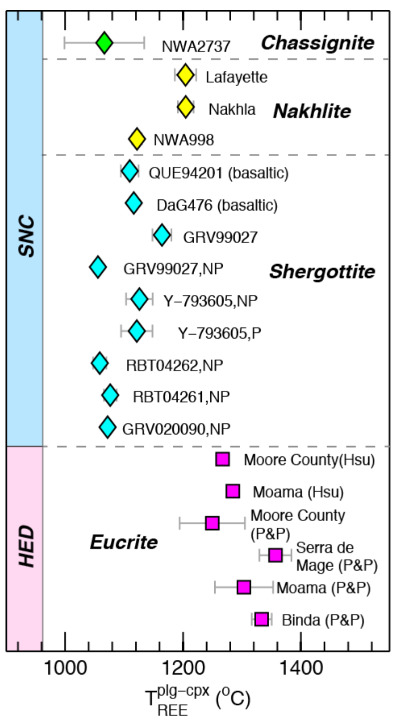


**Figure 3.** Summary of $T_{REE}$ for HED and SNC meteorites.

**Temperatures and thermal history of SNC and HED meteorites:** Although there is a long and distinguished history of geochemical studies of SNC and HED meteorites [13, 14], only a handful of studies reported REE abundances in coexisting minerals (Eucrites: [7, 15, 16]; SNC meteorites: [6, 17-27]). Figure 3 displays calculated temperatures for eucrites (An = 88~99, cpx Mg# = 61~76) and SNC meteorites (An = 31~63, cpx Mg# = 63~83) using our REE-in-plagioclase-cpx thermometer and published data cited above. The first order observation is that $T_{REE}$ for eucrites (1250~1357°C) are consistently higher than $T_{REE}$ for SNC meteorites (1056~1205°C). Figure 4 compares $T_{REE}$ with temperatures derived from the Mg-in-plagioclase-cpx thermometer of [11] for part of the samples shown in Fig. 3 that reported Mg content in plagioclase. The Shergottites appear to be "well-equilibrated", falling on or very close to the 1:1 line in Fig. 4, whereas Nakhlites and a Chassignite appear to have experienced cooling (i.e., $T_{REE} > T_{Mg}$). Eucrites are basalts and basaltic cumulates formed in the crust of their parent body (4-Vesta). Hence their $T_{REE}$ may be (very) close to plagioclase liquidus temperatures. Interestingly, their $T_{Mg}$ are significantly lower than those of SNC meteorites. The small 4-Vesta is likely to have experienced fast cooling during and after magma ocean solidification. Closure temperature of Mg in plagioclase may be used to constrain cooling rates of eucrites and diogenites, which in turn may shed new light on the thermal and chemical evolution of their parent body.

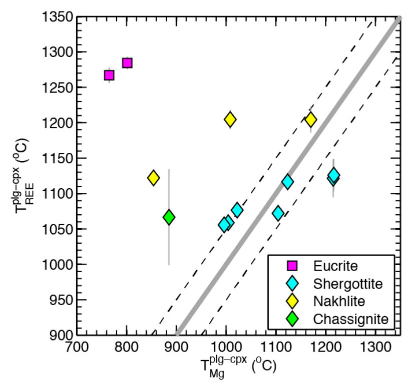


**Figure 4.** Correlation between $T_{REE}$ and $T_{Mg}$ for selected HED and SNC meteorites displayed in Fig. 3 in which Mg abundances in plagioclase were available in the literature.

**References:** [1] Sun & Liang (2013) *44th LPSC*, 1627. [2] Sun (2014) PhD thesis, Brown University. [3] Sun & Liang (2014) *Chem. Geol*. 372: 80-91. [4] Blundy & Wood (1994) *Nature* 372, 452-454. [5] Sun & Liang (2012) *CMP* 163:807-823. [6] Hsu et al. (2004) *MPS* 39: 701-709. [7] Hsu et al. (1997) *GCA* 61: 1293-1302. [8] Godel et al. (2011) *Lithos* 125: 537-552. [9] Vantongeren & Mathez (2013) *J. Pet*. 54: 1585-1605. [10] Thy et al. (2013) *Am. Min*. 98: 1360-1367. [11] Faak et al. (2013) *GCA* 123: 195-217. [12] Cherniak (2010) *RiMG* 72: 691-733; [13] Mittlefehldt et al. (1998) *RiMG* 36: 4. [14] McSween & Treiman (1998) *RiMG* 36: 1. [15] Pun & Papike (1995) *GCA* 59: 2279-2289. [16] Pun et al. (1997) *GCA* 61: 5089-5097. [17] Wadhwa & Crozaz (1995) *GCA* 59: 3629-3645. [18] McSween et al. (1996) *GCA* 60: 4563-4569. [19] Mikouchi & Miyamoto (1997) *AMS* 10: 41-60; [20] Wadhwa et al. (1999) *AMS* 12: 168-182. [21] Wadhwa et al. (2001) *MPS* 36: 195-208. [22] Wadhwa et al. (2004) *AMS* 17: 97-116. [23] Lin et al. (2005) *MPS* 40: 1599-1619. [24] Treiman (2005) *CdE* 65:203-270. [25] Beck et al. (2006) *GCA* 70: 2127-2139. [26] Usui et al. (2010) *GCA* 74: 7283-7306. [27] Jiang & Hsu (2012) *MPS* 47: 1419-1435.