

**DISEQUILIBRIUM FRACTIONAL MELTING ON THE UREILITE PARENT BODY.** C.A. Goodrich<sup>1</sup>, J. Van Orman<sup>2</sup> and L. Wilson<sup>3</sup>, <sup>1</sup>Dept. of Physical Sciences, Kingsborough Community College, Brooklyn, NY 11235 USA (cgoodrich@kingsborough.edu), <sup>2</sup>Dept. of Geological Sciences, Case Western Reserve University, Cleveland, OH 44120 USA, <sup>3</sup>Environmental Science Dept., Lancaster University, Lancaster LA1 4YQ, UK

**Introduction:** Ureilites are carbon-rich ultramafic achondrites [1] thought to represent the mantle (residues and minor cumulates) of a parent body that was stratified in *mg*, pyroxene abundance, and pyroxene type due to the pressure dependence of smelting [2]. Because there are no basaltic ureilites, we lack direct information about melts on the ureilite parent body (UPB). Insights from feldspathic clasts in polymict ureilites suggest that melting may have been a fractional rather than batch process [2-4]. Rapid, fractional melt extraction may explain the preservation of oxygen isotopic heterogeneity on the UPB [1], despite high-T igneous processing. We have modelled modes and rates of melt migration on the UPB based on its physical characteristics and a thermal model for its heating [5]. Here we examine implications for trace element fractionation on the UPB.

**Thermal and Physical Modelling:** Our results [5] show that melts on the UPB would have begun to migrate from their source regions (principally upwards under buoyancy forces) after only ~0.5-1.5% melting, and thereafter would have migrated continuously in thin veins, the thin veins coalescing upwards into fatter veins and eventually dikes. Full vein inter-connectivity would have been established very quickly, and thereafter the melt content of the vein network at any time would have been at most only ~0.3%. Furthermore, melt migration rates were high, with the time required for a given batch of melt to pass through the system to the surface being in the range 2 months to 1 year. From a geochemical point of view, the process suggested by these calculations is perfect fractional melting (melt extraction rate  $\geq$  melt production rate). However, Warren and Kallemeyn [6], hereafter WK, modelled REE patterns of ureilites and concluded that they are not consistent with fractional melting.

**Equilibrium Fractional Melting:** We have reexamined REE fractionation on the UPB under the following assumptions. 1) A reevaluation of available REE patterns for ureilites suggests that the only reliable representatives of the UPB mantle immediately following melt extraction are one pattern obtained for an acid-leached sample of Kenna [7], and a similar pattern constructed in modal proportions from *in-situ* measurements of Kenna olivine and pigeonite [8]. Therefore, we focussed our modelling on Kenna formation conditions ( $P \sim 100$  bars). 2) We believe that only olivine+low-Ca pyroxene ureilites are residues [2,9]. Therefore, the residue should not contain augite (the WK residue has 5% augite). 3) We specify the

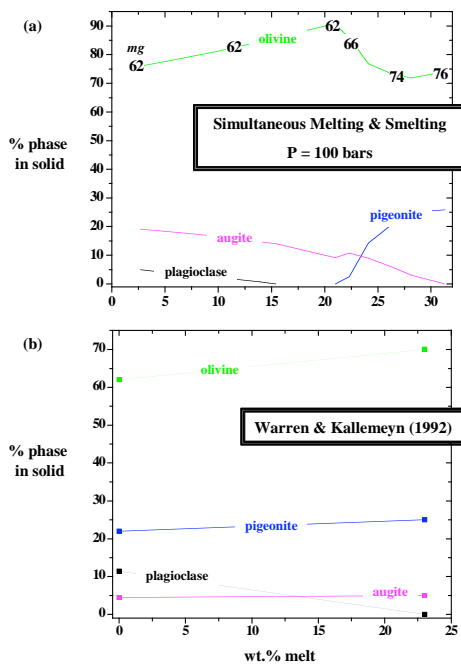
bulk chemical composition of the starting material, following [10], and obtain its mineralogy at the solidus (Fig. 1a) from MAGPOX. Comparison to the starting mineralogy of WK (Fig. 1b) shows significant differences: less plagioclase, more augite, and the absence of low-Ca pyroxene. 4) We calculated melting sequences that incorporate progressive smelting, and are therefore pressure-dependent (Fig. 1a shows the 100 bar sequence). In contrast, WK assumed modal melting (Fig. 1b). 5) We evaluated REE distribution coefficients ( $D$ 's) and made a selection of values based on [11] as most appropriate for ureilites.  $D$ 's for Eu assume  $fO_2$  of  $\sim 1W/10$  (Kenna conditions). 6) Fractional melting was simulated by incremental batch melting [12]. The REE pattern of the residue ( $C_R/C_0$ ;  $C_0$  assumed chondritic) was calculated for  $n$  (# of equal-sized steps of melt extraction) up to 75 (as  $n \rightarrow \infty$ , results approach those for pure fractional melting).

Fig. 2 compares results obtained for the 100 bar melt-smelt sequence and for the melting sequence of WK, using the "best" values of all  $D$ 's. The main differences are: 1) The melt-smelt sequence produces negative Eu anomalies for all  $n$  (consistent with the negative Eu anomalies in olivine-pigeonite ureilites), whereas the WK mineralogy produces positive Eu anomalies for  $n > 2$ ; and 2) for  $n = 1$  (batch melting) our residue has lower REE and a steeper slope than the WK residue, while for  $n > 1$  our residues have higher REE and shallower slopes. Despite these differences, the two sets of results lead to similar conclusions, when compared to the Kenna patterns. Both suggest that in an incremental batch melting model, only a small # of steps of melt extraction could have been involved ( $n \sim 2$  for our mineralogy,  $n \sim 4$  for the WK mineralogy).

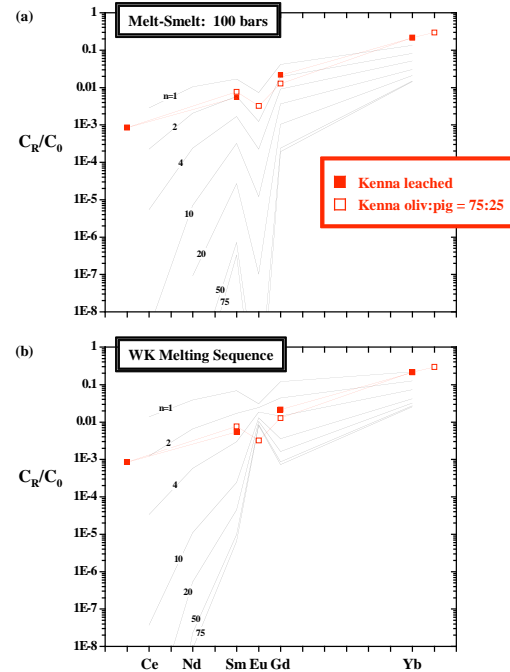
**Disequilibrium Melting:** Incremental batch melting is an equilibrium model. It assumes that equilibrium partitioning occurs between melt and residue ( $D$ 's are obeyed), even in the case of perfect fractional melting where each infinitesimal amount of melt is instantaneously removed from the residue. However, Van Orman et al. [13] have modelled diffusive chemical fractionation during melting, and shown that when partitioning is diffusion-limited, REE are fractionated less efficiently than under equilibrium conditions. This effect becomes more pronounced as melting rate and grain size increase. With increasing degree of disequilibrium, the composition of the residue produced by fractional melting approaches that of a solid produced by batch melting.

We modelled disequilibrium melting on the UPB using the numerical model described in [13], with diffusion coefficients for trivalent REE from [14] for augite and from [15] for plagioclase (labradorite). Diffusion coefficients for  $\text{Eu}^{2+}$  were assumed similar to those for  $\text{Pb}^{2+}$  [16,17]. Diffusion coefficients in augite were corrected for  $f\text{O}_2$  according to the expressions in [14,16]. Because diffusion in low-Ca pyroxene is sufficiently slow to be negligible on the timescales relevant to melting of the UPB [16], we assume that there is no exchange of REE between pigeonite and melt following their uptake, as pigeonite crystallizes late in the melting sequence. We have not included olivine in the model: REE D's for olivine are so low that olivine can safely be neglected for all but Yb.

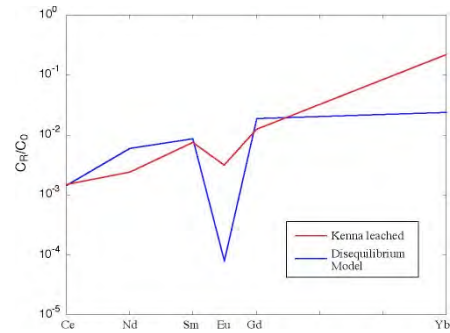
Figure 3 shows the result of the disequilibrium model, compared to Kenna. It is clear that this REE pattern closely resembles that expected from batch melting (Fig. 2), and thus provides a much better match to the ureilite REE data than equilibrium fractional melting. The model currently underestimates Eu, relative to Kenna, possibly indicating that diffusion of Eu in augite is significantly slower than that of Pb. It also underestimates Yb, but we expect this to be rectified by inclusion of olivine. We conclude that, due to extremely efficient melt extraction, REE partitioning was diffusion-limited on the UPB.



**Fig. 1.** (a) Initial mineralogy and progressive melt-smelt sequence for Kenna-like source region (100 bars). (b) Initial mineralogy and melting sequence used in WK modelling.



**Fig. 2.** Results of incremental batch melting for (a) 100 bar melt-smelt sequence, and (b) WK melting sequence [6].



**Fig. 3.** Results of disequilibrium fractional melting model using 100 bar melt-smelt sequence and the thermal model of [5]. The blue curve represents the residual solid after 30% melting. Mineral grains are 1 mm in radius initially.

**References:** [1] Mittlefehldt D.W. et al. (1998) In *Planetary Materials*, *RIM* **36**. [2] Goodrich C.A. et al. (2004) *Chemie de Erde* **64**, 283. [3] Kita N.T. et al. (2004) *GCA* **68**, 4213. [4] Cohen B.A. et al. (2004) *GCA* **68**, 4249. [5] Wilson L.W. et al., this vol. [6] Warren P.H. and Kallemeyn G.W. (1992) *Icarus* **100**, 110. [7] Spitz A.H. and Boynton W.V. (1991) *GCA* **55**, 3417. [8] Guan Y. and Crozaz G. (2000) *MAPS* **35**, 131. [9] Goodrich C.A. et al. (2006) *MAPS*, submitted. [10] Goodrich C.A., this vol. [11] Jones J.H. (1995) In *Handbook of Physical Constants*, *AGU Ref. Shelf* **3**, 73. [12] Allegre C.J. and Minster J.F. (1978) *EPSL* **38**, 1. [13] Van Orman J.A. et al. (2002) *EPSL* **198**, 93. [14] Van Orman J.A. et al. (2001) *CMP* **141**, 687. [15] Cherniak D.J. (2003) *Chem Geol* **193**, 25. [16] Cherniak D.J. (2001) *Chem Geol* **177**, 381. [17] Cherniak D.J. (1995) *CMP* **120**, 358.