

Petrogenesis of Augite-Bearing Ureilites: A LA-ICP-MS Approach. S. Huang^{1,2}, M. Humayun¹, H. Downes³, S. Singletary⁴, J. A. Van Orman⁵ and S. B. Jacobsen² ¹National High Magnetic Field Laboratory and Department of Geological Sciences, huang17@fas.harvard.edu; ²Department of Earth and Planetary Sciences, Harvard University; ³School of Earth Sciences, Birkbeck University of London; ⁴Department of Natural Sciences, Fayetteville State University; ⁵Department of Geological Sciences, Case Western Reserve University.

Introduction: Ureilites, which form the second largest achondrite group, are ultramafic meteorites, and mainly consist of olivine, pyroxenes, carbon and metals [e.g., 1]. Ureilites can be classified into two divisions: unbrecciated monomict olivine-pigeonite ureilites vs. brecciated polymict ureilites with variable pyroxene assemblages. There are large ranges in the major element contents and isotopic ratios in ureilites. For example, the Fo contents of ureilite olivine cores range from 75 to 93% [e.g., 2], and are correlated with $\Delta^{17}\text{O}$ [3]. Despite numerous studies, the petrogenesis of ureilites leaves much to be understood. For example, Guan and Crozaz [4] found a large range (up to x10) in REE abundances in augites from North Haig, but they provided no interpretation. Singletary and Grove [5] used partial melting experiments to show that the major element compositions of monomict ureilites can be explained with a fractional melting process. In contrast, some augite-bearing ureilites may be partially of cumulate origin [6]. In order to better understand the petrogenesis of ureilites and to constrain the relative role of garnet and spinel peridotites in the petrogenesis of ureilites, we determined the major, minor and trace element compositions of olivine and pyroxenes in three ureilite thick sections, LAR 04315, FRO 93008 and North Haig, using LA-ICP-MS at Florida State University (FSU).

Analytical Methods: Polished thick sections were analyzed for major, minor and trace elements using LA-ICP-MS. The analyses were conducted on the mineral cores using the Finnigan Element[®] 1 ICP-MS coupled with a New Wave[®] UP 213 Nd-YAG 213 nm laser system at the National High Magnetic Field Laboratory, FSU. The laser ablation system was used in spot mode with a repetition rate of 10Hz. The energy output of the laser during the course of analysis was 0.15-0.20 mJ. Major and minor elements were determined at medium resolution (R=4000) using a 40 micron spot size, and trace elements at low resolution (R=400) using 100-250 micron spot sizes on the same mineral grains. Each spot was ablated for ~10 sec to an estimated depth of ~10-20 microns. Measured intensity ratios with respect to ⁵⁷Fe or ²⁴Mg were converted to elemental ratios with respect to FeO or MgO using MPI-DING glass standards for calibration [7].

Results: In a Fe/Mg-Fe/Mn plot (Fig. 1), ureilite olivine, low-CaO pyroxene and high-CaO (>10%) pyroxene (augite) form three linear trends, pointing to-

ward the origin, consistent with electron probe data [2]. At a given Fe/Mg, olivines have the highest Fe/Mn, and high-CaO pyroxenes the lowest Fe/Mn.

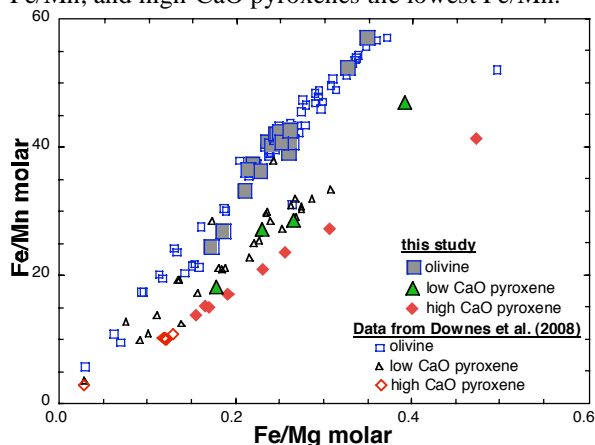


Fig. 1 Fe/Mg vs. Fe/Mn (molar ratios) of ureilite olivines and pyroxenes. Data from Downes et al. [2] are shown for comparison.

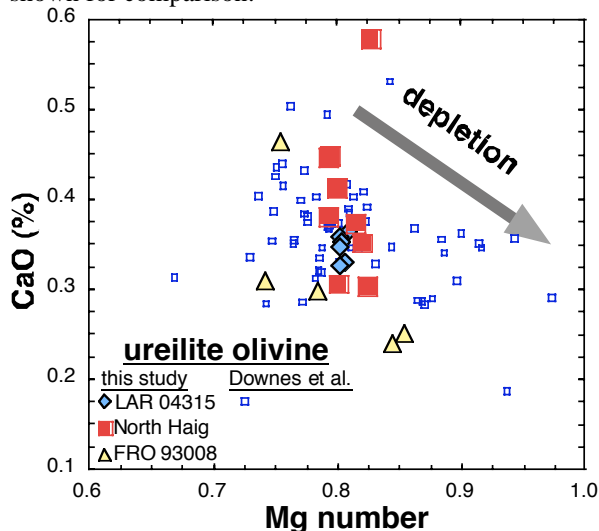


Fig. 2 Mg number (molar ratio of Mg/Mg+Fe) vs. CaO (%) of ureilite olivines. Data from Downes et al. [2] are shown for comparison.

Discussion: Within ureilite olivines Mg numbers are negatively correlated with CaO content (Fig. 2). Trace element abundances are also correlated with major elements in ureilite minerals: within ureilite olivines Yb abundance is positively correlated with CaO content (Fig. 3) and negatively correlated with Mg num-

ber. Within ureilite augites Yb abundance is negatively correlated with Mg number (Fig. 4). These major-trace element correlations of ureilite minerals are consistent with ureilites being the restites after partial melting [5]. That is, a larger extent of partial melting/smelting results in lower CaO and Yb contents and higher Mg number in the melting/smelting residues.

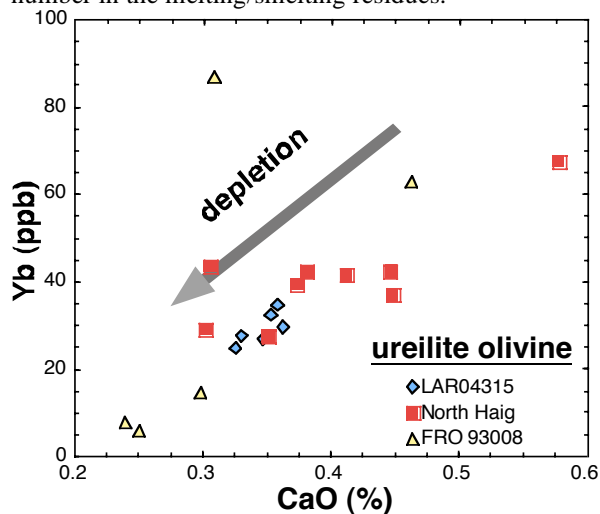


Fig. 3 CaO (%) vs. Yb (ppb) of ureilite olivines.

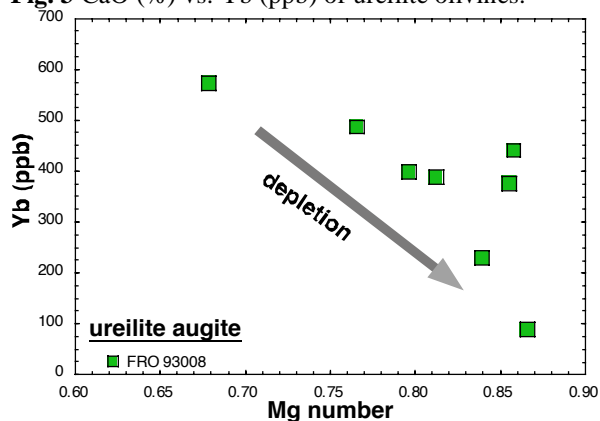


Fig. 4 Mg number vs. Yb (ppb) of ureilite augites.

Ce/Yb is positively correlated with Dy/Yb within ureilite augites (Fig. 5). This correlation is shown in both our LA-ICP-MS data on FRO 93008 and ion microprobe data on North Haig [4]. North Haig is a polymict ureilite, but the piece we obtained is augite-free. The difference between our FRO 93008 data and the North Haig data may reflect real compositional difference. The important observation is that both datasets show positive Ce/Yb-Dy/Yb correlation in ureilite augites. Because $K_{Dy/Yb}^{CPX/melt} \sim 1$ and $K_{Dy/Yb}^{X/melt} \ll 1$ (X =garnet, orthopyroxene and olivine) [e.g., 8], Dy/Yb cannot be fractionated if clinopyroxene dominates the partitioning of REEs. The positive Ce/Yb-Dy/Yb trend, as well as the REE abundances, of FRO 93008 augites can be modeled using augite compositions in equilibrium with partial

equilibrium with partial melts from either a garnet peridotite or a depleted spinel peridotite with 5% CPX (Fig. 5), with the starting compositions of $Ce/Yb_{CI}=0.5$, $Dy/Yb_{CI}=0.85$, $[Yb]_{CI}=6$ for the garnet peridotite and $Ce/Yb_{CI}=0.35$, $Dy/Yb_{CI}=0.95$, $[Yb]_{CI}=0.4$ for the spinel peridotite. Since it requires a depleted REE pattern but enriched REE abundances in the starting composition of the garnet peridotite partial melting model, we regard this as unrealistic.

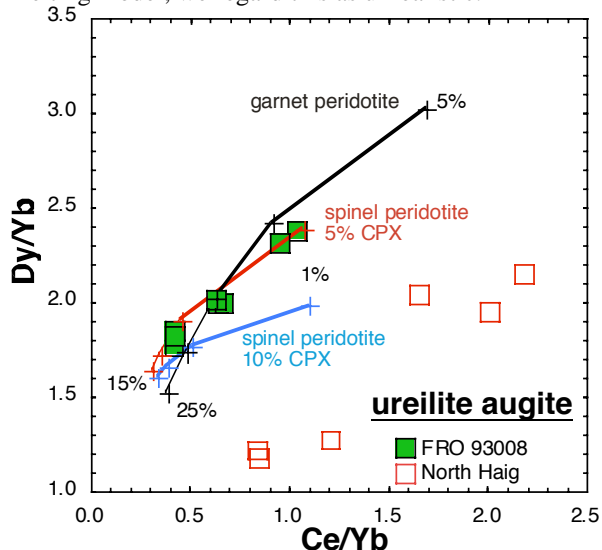


Fig. 5 Ce/Yb vs. Dy/Yb of ureilite augites. Modeling lines of augite compositions in equilibrium with partial melts from two spinel peridotites (5% CPX and 10% CPX) and a garnet peridotite are shown. The melting increment is 5%, with the minimum and maximum melting extents labeled at both ends. Data for FRO 93008 are from this study, and North Haig from [4].

Conclusions: 1. The major-trace element correlations shown in ureilite minerals can be explained as melting depletion trends, consistent with ureilites being melting/smelting restites. 2. The positive Ce/Yb-Dy/Yb trends and REE abundances in ureilite augites can be explained as a result of partial melting of a depleted spinel peridotite, but not garnet peridotite.

References: [1] Mittlefehldt D. W. et al. (1998) *Reviews in Mineral.* 36, 4-1-4-195. [2] Downes H. et al. (2008) *GCA.* 72, 4825-4844. [3] Clayton R. N. and Mayeda T. K. (1988) *GCA.* 52, 1313-1318. [4] Guan Y. and Crozaz G. (2001) *Meteorit. Planet. Sci.* 36, 1039-1056. [5] Singletary S. and Grove T. L. (2006) *GCA.* 70, 1291-1308. [6] Goodrich C. A. et al. (2001) *GCA.* 65, 621-652. [7] Jochum K. P., et al. (2006) *Geochem. Geophys. Geosysts.* 7, Q02008. [8] Salters V. J. M. (1996) *EPSL* 141, 109-123.