

**MELTING OF C-RICH PLANETESIMALS AND IMPLICATIONS FOR THE COMPOSITION OF THE UREILITE PARENT BODY** M. Collinet and T. L. Grove, Massachusetts Institute of Technology, Department of Earth, Atmospheric and Planetary Science, 77 Mass Ave, 02139, MA, e-mail: [collinet@mit.edu](mailto:collinet@mit.edu)

**Introduction:** Ureilites, with ~400 samples, are the second most abundant group of achondrite meteorites but their origin remains enigmatic. They display petrologic features characteristic of high-temperature igneous processing but also signs that the parent body was never fully homogenized. The large proportions of olivine and low-Ca pyroxene and the low concentrations of incompatible elements (Ti, Na, K, Al, etc.) suggest that ureilites are melting residues. Yet, ureilites are aligned on a mass-independent fractionation trend of oxygen isotopes. This implies that the mantle of the planetesimal preserved at least some heterogeneities inherited from nebular processes [1].

Ureilites also contain abundant graphite and a metallic phase. The graphite is thought to have acted as a reducing agent during the disruption of the Ureilite Parent Body (UPB) by a large impact with another planetesimal. During this event, olivine crystals developed reduced Mg-rich rims containing Fe-metal blebs. The cores of olivine crystals, unaffected by this late low-pressure C-induced reducing event (i.e. “secondary smelting”), are homogeneous but vary in composition between samples from forsterite 74 to 95. The composition of olivine cores strongly correlates with the trend of oxygen isotope fractionation and constitute one of the most striking chemical features of ureilites [1]. For some authors, this correlation shows that the forsterite contents of olivine cores directly arose from nebular heterogeneities [1, 2]. As graphite and silicate phases coexisted at igneous temperatures [e.g. 3-6], the forsterite contents of olivine cores could also be controlled by the redox conditions imposed by the CCO buffer (i.e. “primary smelting”). The extensive study of chromite and Cr oxidations states in olivine confirm that variations in forsterite contents are tied to the redox conditions [7].

The smelting reactions relevant for the petrogenesis of ureilites were calibrated experimentally by equilibrating a silicate liquid with olivine, pigeonite and metal on the CCO buffer [8] at the temperatures of ureilite equilibration (1150-1300 °C [5]). Smelting reactions are used to constrain the thermal evolution of ureilites. However, this approach provides no information on the initial composition of the UPB.

Several authors have attempted to constrain the nature of the UPB by modeling the partial melting of chondritic materials with thermodynamic/petrologic modelling programs [9-11]. However, those studies could not reach a consensus on the origin of the UPB.

In this study, we present the first experiments of partial melting performed on the composition of various chondritic materials that aim to recognize some key characteristics of the composition of the UPB. Our partial melting experiments also have implications for the thermal evolution of C-type asteroids and the formation of primordial igneous crusts on asteroids.

**Experimental methods:** Starting materials are prepared from high purity oxides and conditioned for 3 days at 1000 °C and QFM-1 in a gas-mixing furnace. Experiments are then carried out in a molybdenum hafnium carbide (MHC) cold-seal pressure vessel that is inserted in a vertical Del Tech furnace. The vessel is loaded with CO and the starting material is contained within a graphite capsule, which is placed in a Pt capsule loosely crimped at the top. The CO gas acts as the pressure medium and, together with the C-capsule, buffers the redox conditions. Experiments are run for 24 to 72 h at 25-100 bars and 1163-1266 °C. Experiments are terminated by inverting the pressure vessel and hitting it with a wrench to ensure that the capsule drops into the water-cooled head of the vessel.

**Choice of starting compositions:** Although ureilites are C-rich and plot on the CCAM line of oxygen isotope fractionation, other isotopic signatures (Cr, Ni, Ti) are closer to ordinary chondrites [12]. The bulk isotopic signature of ureilites is thus unlike any known chondritic material. The UPB could have shared characteristics of several groups of chondrites. A first set of 8 experiments (CMU) was performed from the average composition of CM chondrites [13] from which FeS was removed (Table 1). CM chondrites were chosen among carbonaceous chondrites as they have Ca and Al contents that are intermediate between CV chondrites and ordinary chondrites. The Mg/Si ratio of the UPB can be constrained from Si isotopes to  $1 \pm 0.1$  [14]. The variation in Mg/Si between carbonaceous and ordinary chondrites overlaps with this uncertainty. A second set of experiments (CHIS) is currently underway using strongly modified CM-compositions. The Mg/Si ratio is first decreased from 1.05 to 0.9 (close to the ratio of ordinary chondrites) by removing a forsterite component. The Mg# is then increased by removing 40% of the total FeO. Finally, the Ca and Al contents are adjusted by removing or adding CAI type A (Table 1) [15].

**Composition of the UPB:** At 100 bars, the residues of the CMU experiments do not contain pyroxene (Fig.1). At 50 and 25 bars, pyroxene is present but with

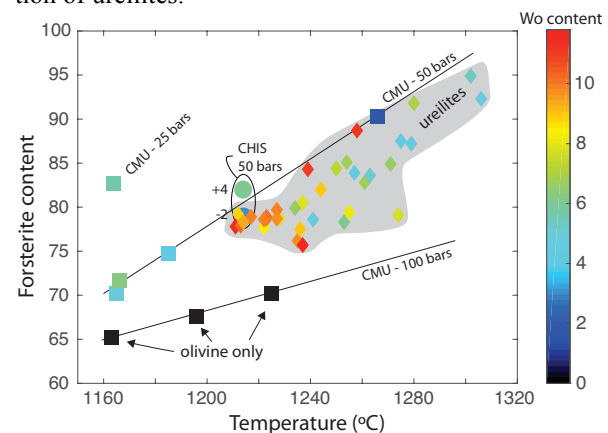
wollastonite (Wo) contents lower than those observed in ureilites at a given temperature of equilibration (Fig. 1). In addition, when pigeonite is present ( $Wo > 5$ ) it is associated with an orthopyroxene of  $Wo \sim 4$ . In the majority of ureilites, pigeonite is the only low-Ca pyroxene. In agreement with [9], CMU experiments confirm that ureilites cannot be produced by equilibrium melting of known groups of carbonaceous chondrites. A chondritic material with a larger amount of CAIs, a higher Mg#, and a slightly lower Mg/Si (CHIS6+4, Table 1) can stabilize pigeonite at a higher temperature, similar to the temperatures of ureilites equilibration (Fig. 1). However, additional experiments on this composition are necessary to determine if it is a better candidate as a ureilite precursor. We note that in all experiments containing pigeonite, the residue has a strongly super-chondritic Ca/Al of 5 to 10 times the ratio of CI chondrites. This ratio is similar to the one of ureilites and appears to be a standard Ca/Al for a melting residue. Although additional experiments are necessary, we believe that this indicates that the UPB body could have had a chondritic Ca/Al.

	CMU	CHIS-2	CHIS+4
SiO <sub>2</sub>	36.68	44.95	43.62
TiO <sub>2</sub>	0.12	0.15	0.14
Al <sub>2</sub> O <sub>3</sub>	2.88	2.69	4.61
Cr <sub>3</sub> O <sub>3</sub>	0.60	0.71	0.67
FeO	28.83	20.40	19.17
MnO	0.29	0.34	0.32
MgO	25.75	27.21	25.91
CaO	2.44	2.12	4.20
Na <sub>2</sub> O	0.71	0.84	0.79
K <sub>2</sub> O	0.06	0.07	0.07
P <sub>2</sub> O <sub>5</sub>	0.32	0.38	0.35
NiO	1.20	0.16	0.15
Mg#	61.4	70.4	70.7
CaO/Al <sub>2</sub> O <sub>3</sub>	0.85	0.79	0.91

**Table 1:** Bulk compositions of the starting materials. CMU and CHIS modified from [13]. See text for detail. CHIS-2 and CHIS+4 contains 2% less and 4% more CAI type A relative to CM chondrites, respectively. For comparison, CV chondrites would be identical to CHIS+2 (after decreasing the FeO content by 40%).

**Liquid compositions:** Most experimental liquids show signs of quench modifications (e.g.  $K_d$  Fe-Mg ol-liq = 0.16-0.24) due to the low melt fractions (< 0.3) and the variable efficiency of the quenching process. However, 3 liquids mostly escaped quench modifica-

tions ( $K_d > 0.3$  and in agreement with [16]). One of those was measured in an experiment with a melt fraction of 0.23 (CHIS-2) and is characterized by a high SiO<sub>2</sub> content (58.3 wt.%) and a CaO/Al<sub>2</sub>O<sub>3</sub> of 0.5. The liquid concentrates virtually all the Al<sub>2</sub>O<sub>3</sub> and most of the CaO of the starting material. Extraction of the liquid from the melting residue would leave a mineral assemblage with a very high CaO/Al<sub>2</sub>O<sub>3</sub> and low CaO and Al<sub>2</sub>O<sub>3</sub> contents comparable to the bulk composition of ureilites.



**Figure 1:** Comparison of mineral compositions (forsterite in olivine and wollastonite in pyroxene) between experiments (squares: CMU, circles: CHIS-2 and CHIS+4) and ureilites (diamonds). A Wo content of 0 indicates the absence of pyroxene. Ureilites data and temperature estimates are from [4] and references therein.

**References:** [1] Clayton R. N. and Mayeda T. K. (1996) *Geochim. Cosmochim. Ac.*, 60, 1999-2017. [2] Warren P. H. (2012) *MAPS*, 46, 209-227. [3] Mittlefeldt D. W. et al. (1998) *Rev. Miner. Geochem.*, 36, 4.1-4.195. [4] Singletary S. J. and Grove T. L. (2003) *MAPS*, 38, 95-108. [5] Walker D. and Grove T. L. (1993) *Meteoritics*, 28, 629-636. [6] Warren P. H. and Kallemeyn G. W. (1992) *Icarus*, 100, 110-126. [7] Goodrich C. A. et al. (2013) *Geochim. Cosmochim. Ac.*, 122, 280-305. [8] Singletary S. J. and Grove T. L. (2006) *Geochim. Cosmochim. Ac.*, 70, 1291-1308. [9] Goodrich C. A. (1999) *MAPS*, 34, 109-119. [10] Goodrich C. A. et al. (2007) *Geochim. Cosmochim. Ac.*, 71, 2876-2895. [11] Kita N. T. et al. (2004) *Geochim. Cosmochim. Ac.*, 68, 4213-4235. [12] Warren P. H. (2011) *Geochim. Cosmochim. Ac.*, 75, 6912-6926. [13] Lodders K. and Fegley B. (1998) *The planetary scientist's companion*, 400 pp. [14] Dauphas N. et al. (2015) *EPSL*, 427, 236-248. [15] Rubin A. E. (2012) *MAPS*, 47, 1062-1074. [16] Toplis M. J. (2005) *Contrib. Miner. Petrol.*, 149, 22-39.