

## UREILITE PARENT BODY IGNEOUS PROCESSES AND BULK COMPOSITION: CONSTRAINTS FROM PLAGIOCLASE STABILITY DURING PARTIAL MELTING OF CHONDRITIC MATERIALS

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**Introduction:** Ureilites, the second largest group of achondrite meteorites, are fragments of the residual mantle of an unidentified carbon-rich planetesimal. They are mainly composed of olivine and low-Ca pyroxene (usually pigeonite) with a lesser amount of graphite, metal and accessory sulfides and chromite. The chemistry, mineralogy and texture of Ureilites indicate that they were equilibrated at high temperatures (from 1200 to 1300°C [1]) and lost a large amount of Al-rich silicate melt.

Despite having been heated to high temperatures the Ureilite Parent Body (UPB) was never fully homogenized. The compositions in oxygen [2] and carbon [3] isotopes are variable and likely represent nebular heterogeneities preserved in the parent body. The forsterite content (Fo) of olivine (74-95) also seems to covary with O- and C- isotopes. If ureilites originated from a small (<400 km in diameter) partly differentiated planetesimal, graphite should have set the redox conditions to the C-CO buffer, which is strongly pressure and temperature dependent. High temperatures and low pressures would have reduced and driven the FeO out of the silicate minerals. This process of simultaneous melting and reduction is often called smelting by analogy with the metallurgical process. The detailed analysis of chromite and Cr valences in olivine [4] is consistent with equilibration around the C-CO buffer (IW to IW-2) at relevant P-T conditions (3-10 MPa, 1100-1300 °C). It is therefore unclear to what extent variations in the Fo content of olivine cores result from initial heterogeneities and to what extent they result from igneous processing and smelting reactions in particular.

The major element starting composition of the UPB remains largely unconstrained. The presence of graphite and O-isotopes are consistent with a carbonaceous chondrite affinity. However, other isotopic ratios (Cr, Ni, Ti) are more akin to ordinary chondrites [5]. Si-isotopes are consistent with a Mg/Si in the range between ordinary and carbonaceous chondrites [6].

We performed experiments using a variety of chondritic materials under P-T-redox conditions relevant to igneous processes within the UPB. Our experiments show that subtle variations in the Ca-Al and Na-K concentrations of the starting materials have a dramatic influence on the stability of plagioclase and therefore on the melting behavior of different chondrites and on the composition of their first melts.

**Experimental approach:** We performed experiments using the synthetic equivalents of CM, H and LL chondrites and a CM composition depleted in FeO and enriched in CAI type A (CHIS+4, Table 1). Experiments were run in a MHC pressure vessel, filled with CO and placed in a vertical tube furnace. The starting materials were loaded in graphite capsules with a Pt outer capsule. The Pt capsule was triple-crimped but not sealed to ensure equilibrium with CO [see 7]. Up to 4 starting materials were equilibrated in each experiment. In order to increase the size of glass pools at low temperature (<1150°C), the temperature was first raised to 1300 °C for 1 h and then dropped to the final run temperature and the CO-pressure was adjusted. Experiments were run for 6-7 days.

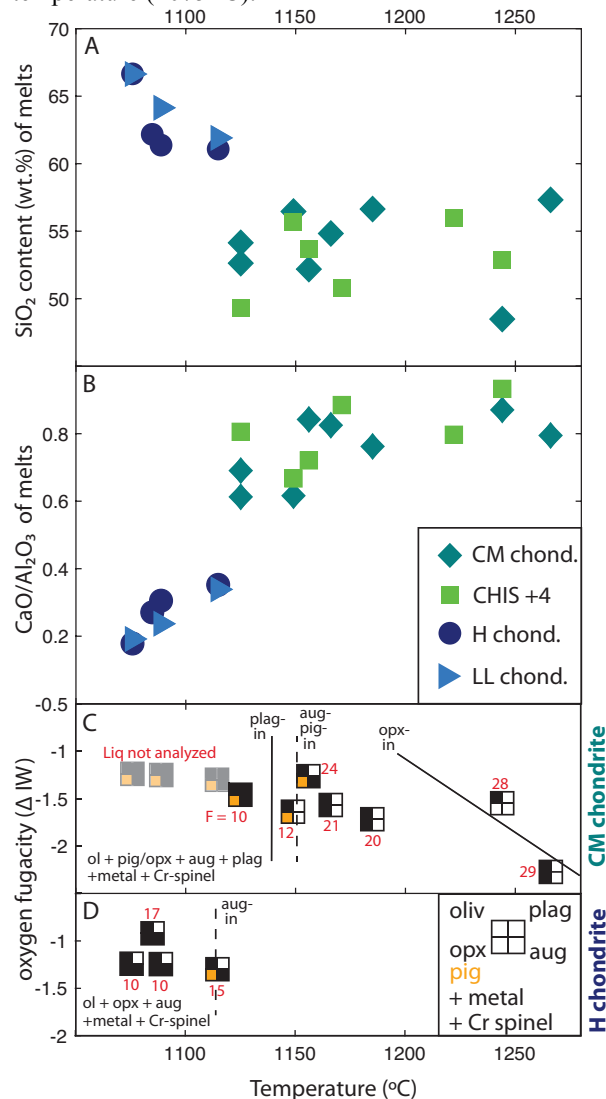
	CM	CHIS+4	H	LL
SiO <sub>2</sub>	37.34	43.62	37.63	43.51
TiO <sub>2</sub>	0.16	0.14	0.12	0.14
Al <sub>2</sub> O <sub>3</sub>	2.89	4.61	2.22	2.45
Cr <sub>2</sub> O <sub>3</sub>	0.55	0.67	0.51	0.57
FeO	28.53	19.17	30.80	21.84
MnO	0.33	0.32	0.31	0.37
MgO	25.62	25.91	23.78	26.76
CaO	2.41	4.20	1.78	2.10
Na <sub>2</sub> O	0.61	0.79	0.89	1.00
K <sub>2</sub> O	0.07	0.07	0.10	0.11
P <sub>2</sub> O <sub>5</sub>	0.30	0.35	0.26	0.24
NiO	1.20	1.51	0.90	0.10

**Table 1:** Starting material compositions modified from [10] by subtracting FeS. CHIS+4 modified from CM by subtracting 40 wt.% FeO and adding 4 % CAIs.

**Approach to equilibrium:** Most experiments display equilibrium textures with small unzoned equant crystals. Occasionally, larger crystals of olivine or pyroxene formed during the temperature overshoot (Fe-poor cores) were observed. Such crystals are not in equilibrium and are present in small quantities (<5%), which do not modify the phase equilibria. The efficiency of the quench (described in [7]) is variable and depends on the size of the glass pools and the viscosity of the melts. To exclude quench-modified melts, only liquid compositions with a K<sub>D</sub> Fe-Mg ol-liq of 0.24-0.34 are plotted in Fig. 1. For these experiments, phase proportions calculated by mass-balance are consistent with BSE images. Our experimental design completely prevents alkali losses, which are common in 1-atm experiments with gas fluxes below the IW buffer [8].

**Phase assemblage and plagioclase stability:** All experiments contain olivine (Fo<sub>75-80</sub>) and a metal

phase. Most of them also contain at least one pyroxene: orthopyroxene at high temperature and opx/pigeonite + augite at lower temperature (Fig. 1C-D). Small quantities of Cr-rich spinel were observed in all experiments but mostly as rare and small crystals ( $<2 \mu\text{m}$ ). The main difference between experiments performed from CM and H-LL chondrites is the temperature of plagioclase saturation. With CM and CHIS+4 starting compositions, plagioclase is stable at high temperature (1140-1160 °C). With H-LL starting compositions, no plagioclase is observed at the lowest temperature (1075 °C).



**Figure 1:** [A,B] composition of experimental melts vs temperature. [C,D] Phase assemblage as a function of oxygen fugacity and temperature for 2 of the 4 starting compositions. Oxygen fugacity is calculated from the position of the CCO buffer at 3-10 MPa and expressed relatively to the IW buffer. All experiments contain olivine, metal, Cr spinel  $\pm$  opx, pig, aug and plag. The

melt fraction (F) for each experiment is represented in red.

**Liquid composition:** The absence of plagioclase has a large effect on the liquid compositions. In H-LL experiments, the liquids are rich in  $\text{Al}_2\text{O}_3$ , poor in CaO (low  $\text{CaO}/\text{Al}_2\text{O}_3$ , Fig. 1B), rich in  $\text{SiO}_2$  (Fig. 1A) and rich in  $\text{Na}_2\text{O}$ . The melt fraction at a given temperature is also much smaller for CM experiments. The melt compositions in CM experiments could not be analyzed under 1125 °C ( $F < 10 \text{ wt.}\%$ ). In H experiments, the melt fraction is 10% at  $\sim 1075 \text{ }^\circ\text{C}$ .

**Implications for the formation of ureilites:** Ureilites cannot have formed by batch melting of CM chondrites. Most Ureilites only contain olivine ( $\text{Fo}_{77-80}$ ) and a singular pyroxene, typically pigeonite, and no plagioclase. However, this phase assemblage only occurs in a narrow field around 1150 °C (Fig. 1C), which is lower than the temperature of Ureilites equilibration ( $>1200 \text{ }^\circ\text{C}$ ; [1]). Adding CAIs to the starting composition (CHIS+4) only increases the stability of plagioclase and does not expand the ol+pig stability field. Instead, changing the bulk composition to H-LL chondrites and the melting regime from batch to fractional should increase the temperature interval of the ol+pig stability field. The temperature of plagioclase saturation is lowered by at least 50 °C, and the equilibrium low degree melts ( $\sim 10\%$ ) in the absence of plagioclase are highly enriched in Al and Na but are poor in Ca. If such melts were progressively extracted from the UPB (i.e., by fractional melting), the Ca/Al of the residue would go up and pigeonite would be stable at higher temperature. Albitic plagioclase fragments similar to [9] would also easily precipitate out of such Al- and Na- rich melts. Ureilite-like melting residues are thus best explained by the progressive fractional melting of C-rich chondritic materials but with CAI and alkali contents similar to ordinary chondrites. This will be tested experimentally by subtracting  $\sim 5\%$  of the low degree melts from the H chondrite starting material and performing experiments at high temperature (1200-1300 °C).

**References:** [1] Singletary S. J. and Grove T. L. (2003) *MAPS*, 38, 95-108. [2] Clayton R. N. and Mayeda T. K. (1996) *GCA*, 60, 1999-2017. [3] Barrat J.-A. et al. (2017) *EPSL*, 478, 143-149. [4] Goodrich C. A. et al. (2013) *GCA*, 122, 280-305. [5] Warren P. H. (2011) *GCA*, 75, 6912-6926. [6] Dauphas N. et al. (2015) *EPSL*, 427, 236-248. [7] Singletary S. J. and Grove T. L. (2006) *GCA*, 70, 1291-1308. [8] Jurewicz A. J. G. et al. (1995) *GCA*, 59, 391-408. [9] Goodrich C.A. et al. (2017) *LPSC*, #1196 [10] Lodders K. and Fegley B. (1998) *The planetary scientist's companion*, 400 pp.