INCREMENTAL MELTING IN THE UREILITE PARENT BODY: TEMPERATURE, MELT COMPOSITIONS AND INTERNAL STRUCTURE M. Collinet[*] and T. L. Grove, Massachusetts Institute of Technology, Department of Earth, Atmospheric and Planetary Sciences, 77 Mass Ave, 02139, MA. *current affiliation: Institute of Planetary Research, German Aerospace Center, Berlin, Germany (max.collinet@dlr.de).

Introduction: Ureilites are ultramafic achondrites mostly made of olivine and pigeonite and containing a few percent of carbon polymorphs, metal and sulfide. The emerging consensus is that pigeonite-olivine ureilites (> 80% of ureilites) are melting residues representing the mantle of a planetesimal from which sulfide and silicate melts (15-30 wt.%) were removed. Isotope systematics (e.g. O, C, noble gases) indicate that nebular heterogeneities were preserved in the ureilite parent body (UPB) despite partial melting. The UPB was catastrophically disrupted, which enabled rapid cooling of ureilites and quenching of their high-temperature equilibrium state.

We have performed experiments to constrain the initial major element composition of the UPB, the composition of the silicate melts that were produced and the style of melting (i.e. batch vs. incremental) [1]. We have previously reported that the initial UPB was not depleted in alkali elements relative to the sun's photosphere (high NaK# of 50, where NaK# = (Na+K)/(Na+K+Ca)*100) and had a high Mg/Si ratio, most similar to CI chondrites [2]. Upon melting, the UPB first produced Si- Al- and alkali-rich melts similar to the trachyandesite ALM-A [3].

Here, experimental results are used to calibrate a precise thermometer based on the partitioning of Cr between olivine and low-Ca pyroxene (LCP). The resulting temperature distribution of ureilites is used to constrain the style of melting, the composition of the "late-stage" silicate melts and the location of different ureilite groups within the UPB. All experiments were performed in MHC-pressure vessels from various synthetic chondritic materials and were designed to simulate batch and incremental melting (see [1-2] for detail of the methods).

Ureilite geothermometry: 2-pyroxene and olivine-chromite thermometers have been used to estimate the equilibration temperature (T_E) of ureilites [4-5]. However, most ureilites only contain one pyroxene and lack chromite. To estimate the T_E of the most common ureilites, a pigeonite thermometer has also been developed [6]. The new experiments highlight that the latter is not accurate. It produces large offsets (up to 100 ºC) relative to the experimental temperatures. A new precise thermometer is needed to better constrain the petrogenesis of ureilites.

The concentration of Cr in the liquid increases with the experimental temperature. Cr becomes less compatible in both olivine and LCP. In addition, the distribution coefficient of Cr between olivine and liquid ($D_{Cr}^{oliv-liq}$) decreases slower than the $D_{Cr}^{LCP-liq}$ with temperature. As a result, the ratio $D_{Cr}^{oliv-liq}/D_{Cr}^{LCP-liq}$ (i.e. the $D_{Cr}^{oliv-LCP}$) increases linearly with temperature (Fig. 1). This behavior is independent of the bulk composition of the system, the fO_2 (between IW -1 and IW -2.5) and the type of additional phases present (e.g. augite, chromite). Therefore, the $D_{Cr}^{oliv-LCP}$ can be used as a precise geothermometer for all groups of ureilites.

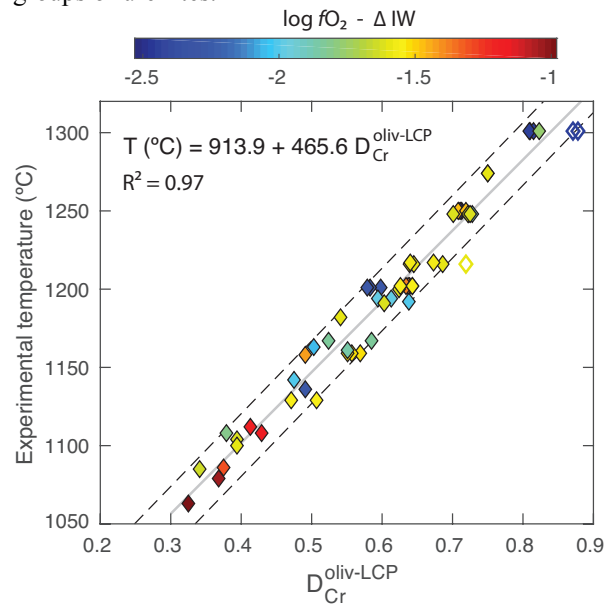**Figure 1:** $D_{Cr}^{oliv-LCP}$ geothermometer calibrated on 60 experiments with 10 contrasting bulk compositions (CI, H, LL chondrites and various residual mantles). The dashed lines represent a ±15 ºC uncertainty.

New temperatures of equilibration: The Cr_2O_3 concentration of olivine and pyroxene are available for 75 of the ~550 known ureilites. They are used to calculate the T_E distribution of ureilites (Fig. 2). All pigeonite-olivine ureilites are characterized by T_E above the minimum temperature of pigeonite stability [7], which confirms the validity of the new thermometer. FeO-rich pigeonite-olivine ureilites (Mg# 77-84) equilibrated over a large range of temperature (1140 to 1280 ºC), which overlaps with the range of T_E of reduced ureilites (Mg# 90-95; 1180-1250 ºC). Augite-bearing ureilites (with Mg# < 90), characterized by poikilitic textures and high bulk CaO concentrations, display lower T_E (1060-1160 ºC).
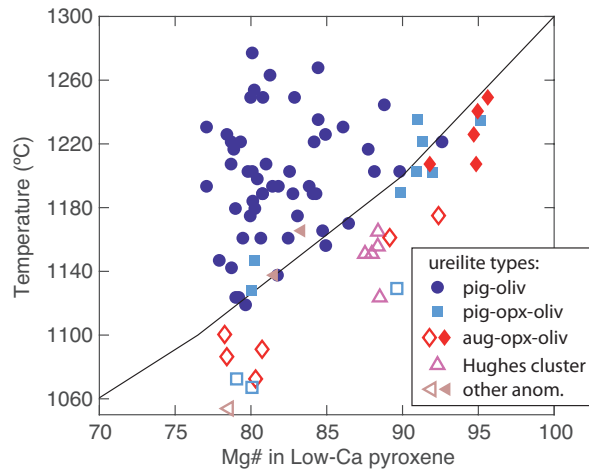
Figure 2: Equilibration temperature of ureilites calculated with the $D_{Cr}^{oliv\text{-}LCP}$ thermometer. The solid line represents the minimum temperature of pigeonite stability from [7]. Open symbols: anomalous low-T and pyroxene-rich ureilites (including poikilitic ureilites).

Discussion: The T_E of pigeonite-olivine ureilites (Mg# 77-84) correlates negatively with the Al_2O_3 and Wo contents of pigeonite and bulk concentrations of rare-earth elements [8]. The negative correlations with incompatible elements indicate that the samples having experienced the highest temperature have also lost the largest fraction of silicate melt. This suggests that the T_E represents the peak temperature and that the UPB was likely melting at the time of its disruption. The overlapping T_E of ureilites with Mg# of 77-84 and 90-95 could indicate that both groups derive from distinct mantle reservoirs but located at similar depths within the parent body. Therefore, despite being heterogenous, there is no evidence that the UPB had a compositionally stratified mantle.

Pigeonite-olivine residues can be produced by batch or incremental melting of chondritic-materials with a NaK# of 50 (i.e. alkali undepleted). During batch melting, pigeonite is replaced by orthopyroxene at 1170-1200 ℃ but, if melting is incremental, it remains in the residue up to 1270 ℃. The presence of pigeonite in ureilites up to 1250-1270 ℃ further supports an incremental melting process [1].

If melting was incremental, the composition of the last melts produced in the UPB must have been radically different from the composition of low-degree batch melts, which are rich in Al_2O_3 and alkali elements but poor in CaO. We use an experimental calibration of the $D_{Ca}^{oliv\text{-}liq}$ to calculate the CaO concentration of "late-stage" incremental melts in equilibrium with ureilites (Fig. 3). The CaO concentration is identical to that of batch melts from alkali-undepleted chondrites at low temperature but quickly increases to 12 wt.% at ~1250 ℃. Such CaO-rich melts could have

reacted with cooler melting residues during their upward migration and form the anomalous low-T and augite-bearing ureilites (Fig. 4).
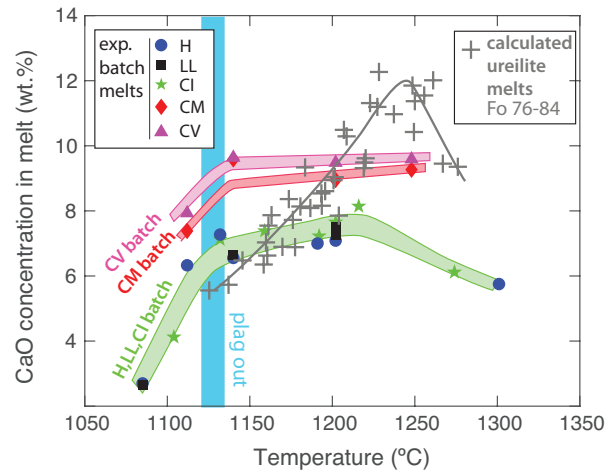

Figure 3: CaO concentration of "late-stage" incremental melts in equilibrium with ureilites (+) compared to the batch melts of different chondritic compositions.

mantle residue, FeO-rich (IW -1.3)
mantle residue, FeO-poor (IW -2.5)
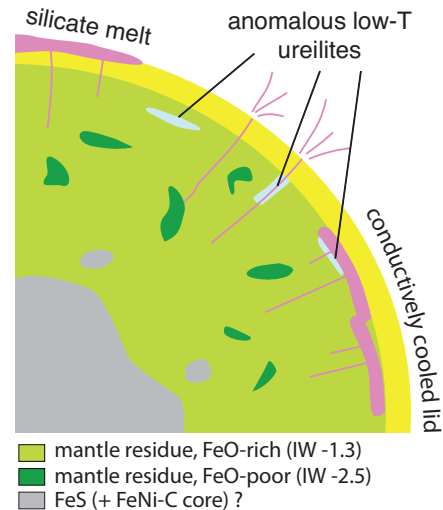FeS (+ FeNi-C core) ?

Figure 4: Summary: sketch of a UPB with a heterogeneous but non-stratified mantle with sources characterized by different isotopic compositions and fO_2. Low-T and augite-bearing ureilites record the migration of late-stage CaO-rich melts.

References: [1] Collinet M. and Grove T. L. (under review) *MAPS*. [2] Collinet M. and Grove T. L. (2019) *50th LPSC*, 3229. [3] Bischoff A. et al. (2014) *PNAS, 111,* 12689-12692. [4] Sinha S. K. et al. (1997) *GCA, 61,* 4235-4242. [5] Goodrich C. A. et al. (2014) *GCA, 135,* 126-169. [6] Singletary S. J. and Grove T. L. (2003) *MAPS, 38,* 95-108. [7] Sack R. O. and Ghiorso M. S. (1994) *Contrib. Min. Petrol., 116,* 287-300. [8] Barrat J-. A. et al. (2016) *GCA, 194,* 163-178.