



# Partial melting of a C-rich asteroid: Lithophile trace elements in ureilites

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## Abstract

Ureilites are among the most common achondrites and are widely believed to sample the mantle of a single, now-disrupted, C-rich body. We analyzed 17 ureilite samples, mostly Antarctic finds, and determined their incompatible trace element abundances. In order to remove or reduce the terrestrial contamination, which is marked among Antarctic ureilites by light-REE enrichment, we leached the powdered samples with nitric acid. The residues display consistent abundances, which strongly resemble those of the pristine rocks. All the analyzed samples display light-REE depletions, negative Eu anomalies, low  $(\text{Sr}/\text{Eu}^*)_n$ , and  $(\text{Zr}/\text{Eu}^*)_n$  ratios which are correlated. Two groups of ureilites (groups A and B) are defined. Compared to group A, group B ureilites, which are the less numerous, tend to be richer in heavy REEs, more light-REE depleted, and display among the deepest Eu anomalies. In addition, olivine cores in group B ureilites tend to be more forsteritic ( $\text{Mg}\# = 81.9\text{--}95.2$ ) than in group A ureilites ( $\text{Mg}\# = 74.7\text{--}86.1$ ). Incompatible trace element systematics supports the view that ureilites are mantle restites. REE modeling suggests that their precursors were rather REE-rich (ca.  $1.8\text{--}2 \times \text{CI}$ ) and contained a phosphate phase, possibly merrillite. The REE abundances in ureilites can be explained if at least two distinct types of magmas were removed successively from their precursors: aluminous and alkali-rich melts as exemplified by the Almahata Sitta trachyandesite (ALM-A), and Al and alkali-poor melts produced after the exhaustion of plagioclase from the source. Partial melting was near fractional (group B ureilites, which are probably among the least residual samples) to dynamic with melt porosities that did not exceed a couple of percent (group A ureilites). The ureilite parent body (UPB) was almost certainly covered by a crust formed chiefly from the extrusion products of the aluminous and alkali-rich magmas. It is currently uncertain whether the Al and alkali-poor melts produced during the second phase of melting reached the surface of the body. The fact that initial silicate melting of ureilitic precursors would have produced relatively low density liquids capable of forming an external crust to the UPB casts doubt on models that invoke chondritic outer layers to achondritic asteroids.

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## 1. INTRODUCTION

The early history of the Solar System was marked by the accretion of numerous asteroid-sized bodies (large asteroids and embryos). Many of them underwent rapid internal heating, leading to melting and subsequent differentiation. Among the most significant issues for understanding the differentiation of rocky bodies are the exact processes of melting, the compositions of the generated magmas and how these were then segregated from their sources. Melt migration may have involved ascent to the surface to form a crust, or alternatively escape to space by explosive volcanism. It has recently been argued that partial melting of carbonaceous chondrite-like bodies (e.g. CV or CM), could have produced melts too dense to erupt through buoyancy alone. Consequently, the differentiation of such bodies could have generated distinctive internal structures, with a preserved chondritic carapace at the surface covering an igneous layer, and possibly a metallic core at their centers (Weiss and Elkins-Tanton, 2013; Fu and Elkins-Tanton, 2014). If true, these bodies could have harbored magnetic dynamos when their cores were still molten. The discovery that some CM and CV chondrites recorded ancient magnetic fields has strengthened such a view, although the origin of these fields, whether internal or linked to an early stage of solar activity, remains a matter for debate (e.g. Carporzen et al., 2011; Cournède et al., 2015).

The structure and differentiation history of C-rich bodies can be studied directly using meteorite samples. Unfortunately, no representative sampling of a single body, i.e. from the core to the crust, is currently available. However, the ureilites, one of the largest families of achondrites (ca. 400 different meteorites and 17% of the known achondrites currently reported in the Meteoritical Bulletin Database), represent a unique collection from the mantle of a single, now-disrupted, C-rich body (Downes et al., 2008). These rocks are usually coarse-grained peridotites, consisting chiefly of olivine and pyroxene (pigeonite, and more rarely augite and orthopyroxene), abundant carbon (up to 7 wt%, graphite and diamond), with accessory metal and sulfides (e.g., Mittlefehldt et al., 1998). It is noteworthy that these peridotites are virtually devoid of feldspar.

Ureilites have been the focus of many geochemical studies. Even though uncertainties remain concerning the differentiation of the UPB, thermal modeling and extinct isotope systematics make it possible to reconstruct its overall history (e.g., Wilson et al., 2008; Budde et al., 2015; Goodrich et al., 2015). It accreted no more than 1.6 Ma after CAIs, i.e. later than the parent bodies of the magmatic irons, and about half a million years before most of the chondrite parent bodies. The UPB was definitely C-rich, but was isotopically distinct from the carbonaceous chondrites (Yamakawa et al., 2010; Warren, 2011). However, it contained enough  $^{26}\text{Al}$  to be heated by the decay of this isotope, which allowed the segregation of S-rich metallic melts (e.g., Warren et al., 2006; Rankenburg et al., 2008; Budde et al., 2015), more likely before the onset of silicate melting (Barrat et al., 2015). Subsequent extraction of silicate melts is demonstrated by the presence of feldspar-rich rock debris in ureilitic breccias (e.g., Ikeda et al.,

2000; Cohen et al., 2004; Bischoff et al., 2014), but the melting experienced by the UPB was more limited than in other early bodies, such as the angrite parent body or Vesta, where magma oceans homogenized the O isotope compositions (Greenwood et al., 2005). Indeed, ureilites display a wide range of  $\Delta^{17}\text{O}$  values which are well correlated with various mineral compositions (Clayton and Mayeda, 1996, and Fig. 1). Systematics of short-lived isotopes ( $^{53}\text{Mn}$ – $^{53}\text{Cr}$ ,  $^{182}\text{Hf}$ – $^{182}\text{W}$ ,  $^{26}\text{Al}$ – $^{26}\text{Mg}$ ) indicate that the differentiation occurred between 3 and 7 Ma after the CAIs (Yamakawa et al., 2010; Goodrich et al., 2010; Bischoff et al., 2014; Budde et al., 2015). It stopped soon after, with the catastrophic breakup of the body following a large impact, while its mantle was still hot.

Although it is now widely accepted that most ureilites are mantle restites (e.g., Boynton et al., 1976; Takeda, 1987; Warren and Kallemeyn, 1992; Scott et al., 1993; Warren et al., 2006; Goodrich et al., 2015 among others), the melting processes and the involvement of C during their formation are matters of intense debate. During the ureilite disruption event, C locally reduced olivine crystals, and produced their distinctive iron-depleted rims and veins (e.g., Miyamoto et al., 1985). Except for these rims and veins, olivines are quite uniform in Mg# number [=100 Mg/(Mg + Fe), atomic] within any given ureilite. However, between different samples their compositions display a huge variation, as shown by the olivine-core Mg# (=forsterite content), which range from 74 to 97. The Fe/Mn ratios (ranging from 3 to 57) are correlated with

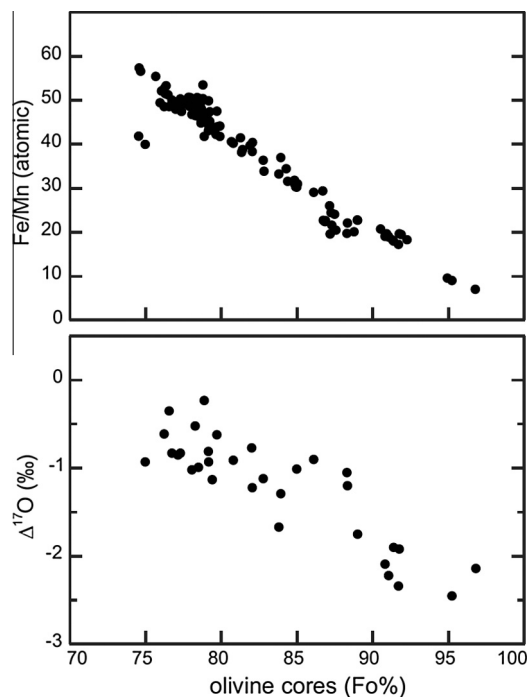


Fig. 1. Plots of molar Fe/Mn ratios in olivine cores and  $\Delta^{17}\text{O}$  (Clayton and Mayeda, 1996) vs. the composition of the olivine cores (data mainly from Singletary and Grove, 2003; Goodrich et al., 2006; Downes et al., 2008; Barrat et al., 2015 and references therein).

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