THE COMPOSITION OF TWO UREILITES STUDIED USING X-RAY POWDER DIFFRACTION

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Introduction: Planetary formation occurred in different steps in which the first planetesimals accreted to produce planetary embryos [1]. The growth of chondritic undifferentiated asteroids produced achondritic bodies, and one example is the Ureilite Parent Body (UPB) [2]. The meteorites known as ureilites are the second largest group of achondrites [2]. Most of the ~550 known ureilite meteorites are monomict (unbrecciated) ultramafic rocks, coming from the mantle of a partially melted (~25–30%), C-rich asteroid probably larger than 250 km in diameter [3]. The formation scenario of the different classes of ureilites invokes the early disruption of a moderately large UPB [3]. Before the UPB differentiation was complete, a catastrophic collision produced its break-up into many asteroid fragments. Consequently, ureilites are ultramafic achondrites that exhibit heterogeneity in Mg modal abundance and O isotope ratios [4]. The UPB probably grew mainly from carbonaceous chondrite progenitors, and the heterogeneous composition can reveal significant clues about the growing process and its relative timescale. This heterogeneity can be tested using the X-ray powder diffraction (XRD) technique, with the goal of investigating the bulk mineralogical composition of ureilites. The XRD technique is mainly used for phase identification of crystalline minerals and can also provide significant information about modal abundances and phase compositions [5]. The XRD technique is particularly relevant for achondrites exhibiting complex mineralogy, which could be consequence of secondary processes like e.g. collisional gardening and aqueous alteration. In particular, it has been demonstrated a shock-induced origin for nanodiamonds found in ureilites [6].

Experimental procedure: For the present work, two different ureilite meteorites were studied: Elephant Moraine 96042 (EET 96042), and Miller Range 090031 (MIL 090031) (see Table 1). XRD measurements on capillary powder samples of the two ureilities were performed by using a powder diffractomer equipped with a Mo X-ray souce (λ=0.709 Å). This experimental configuration allowed us to minimize preferential orientation effects as well as to significantly reduce the X-ray fluorescence signal from iron, relative to XRD measurements performed with a standard Cu X-ray tube. Phase identification was performed using DIFFRAC.EVA software together with the Powder Diffraction File PDF-2 and the Crystallography Open Database (COD). Quantitative phase analyses (QPA) were carried out with the Rietveld method [5] using the TOPAS 4.2 program from Bruker. From the refined structural data, information about the Fe/Mg composition of both the olivine (ol) and pyroxene (px) minerals was also obtained. For this analysis, the data of Ref. [7] are employed. Two thin sections of both samples were additionally investigated in order to confirm the validity of the XRD results.

Meteorite	Weathering degree	%Fa	%Fs
EET 96042	A/B	14-18	-
MIL 090031	B/C	16	17

Table 1. The ureilites studied in this work. The fayalite (Fa) and ferrosilite (Fs) mol percent are also indicated.

Results and discusion: Our XRD measurements allowed us to identify the minerals listed in Table 2. The QPA results obtained with the Rietveld method, displayed in the table, suggest that the px/(px+ol) ratio is slightly larger in MIL 090031 (~0.4) than in EET 96042 (~0.3). The lattice parameters thus extracted allow us to infer that olivine grains in the former have a larger core forsterite content (95% vs 81% in mole%). Similarly, pyroxene in MIL 090031 is found to have very low Fe content. In contrast, ferrosilite core content in EET 96042 is ~11% in mole%. Goethite, arising from terrestrial weathering of ureilites, is only found in MIL 090031. EET 96042 in thin section shows silicate grains rimmed by moderately-weathered carbon-rich material containing traces of metal and troilite. The meteorite mineralogy seems to be well preserved and exhibits little presence of oxides (Table 2). The silicates are fractured and olivine grains exhibit undulatory extinction, thus suggesting a low degree of shock. In turn, MIL090031 in thin section is found to consist of an aggregate of large olivine and pyroxene grains up to 2 mm across. Individual olivine grains are rimmed by carbon-rich material containing traces of metal and oxides. The olivines were mosaicized by shock.

Mineral	EET 96042	MIL 090031
Forsterite (Fo%)	64.8 (81)	51.2 (95)
Goethite	-	9.9
Pyroxene (Wo%/En%)	28.5 (10/79)	34.9 (8/92)
Kamacite	2.3	2.1
Troilite	1.6	-
Graphite	1.6	1.3
Cristobalite	1.2	0.4
Total	100	100

Table 2. The main components of the studied ureilites in modal percent as obtained by XRD.

Some urelites only exhibit parent asteroid aqueous alteration, but this could be absent in others. As an example of the latter, EET 96042 lacks evidence of oxides and contains metal and troilite despite having suffered a significant degree of shock (Fig. 1a). MIL 090031 olivine grains have pervasive fine veins and strings of metal+goethite, produced by terrestrial oxidation of iron and troilite (see Fig. 1b).

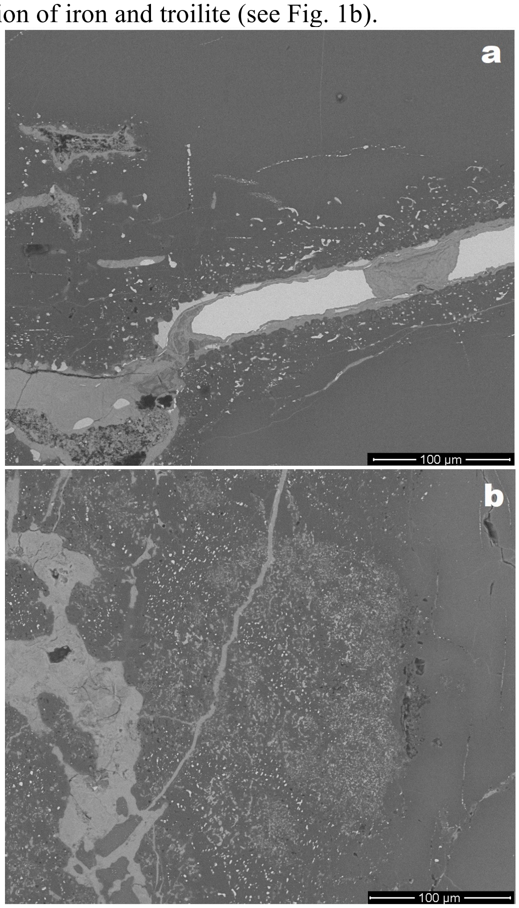

Figure 1. SEM backscattered electron image of selected ROIs. a) EET96042 and b) MIL 090031.

It has been described that the terrestrial weathering of the fayalitic part of the olivine is a multistage process, similar to the oxidation of troilite [8]. Pervasive oxidation produces Fe-hydroxides, like e.g. the goethite found in MIL 090031 (Fig. 1b) [9].

Conclusions: The study of ureilites is highly relevant to better understand the collisional evolution of asteroids. The impact that disrupted the UPB produced different asteroid fragments that suffered distinctive collisional evolution. The two samples analyzed here exemplify the mineralogical diversity, further accentuated by terrestrial weathering. While EET 96042 can be considered to have a pristine mineralogy, terrestrial weathering is important for other ureilites (like e.g. MIL090031). As a consequence, the role of oxidation during their stay in the Earth's oxidizing environment needs to be taken into account. In this sense, the use of the XRD technique presented here is very valuable to study the complex mineralogy of ureilites, and particularly to identify pristine ureilites that have escaped terrestrial weathering. Identifying such weathered ureilites is the key to establishing a reliable scenario for the formation and evolution of the UPB, and its fragmental asteroid family.

Acknowledgements: We acknowledge support from the Spanish Ministry of Science and Innovation (project PGC2018-097374-B-I00, PI: JMTR). US Antarctic meteorite samples are recovered by the Antarctic Search for Meteorites (ANSMET) program which has been funded by NSF and NASA, and characterized and curated by the Department of Mineral Sciences of the Smithsonian Institution and Astromaterials Acquisition and Curation Office at NASA Johnson Space Center.

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