DEGREE OF AQUEOUS ALTERATION OF THE CM CARBONACEOUS CHONDRITE AGUAS ZARCAS: IMPLICATIONS FOR UNDERSTANDING RYUGU AND BENNU. P. M. C. Martin[1] and M. R. Lee[1], [1]School of Geographical and Earth Sciences, University of Glasgow, G12 8QQ, U.K. (p.martin.2@research.gla.ac.uk).

Introduction: The origin of Earth's water is one of the most prominent questions of planetary science. Ambitious projects such as the JAXA Hayabusa2 and the NASA OSIRIS-REx sample collection missions aim to help provide answers to this question. The targeted asteroids, *Ryugu* and *Bennu*, respectively, are thought to be of similar compositions to carbonaceous chondrites, more particularly CMs (Mighei-like) **[1-2]**. These meteorites have a relatively high water content (~ 9 wt%; **[3]**) and have undergone various degrees of aqueous alteration. This alteration is thought to have stemmed from a heating event that affected the parent-body **[4]**. To this day, the nature and length of this heating process remains poorly constrained.

Here we present preliminary results from characterization of the CM chondrite *Aguas Zarcas* using the method described by **[3]** and refined in **[5]**, which employs simple and accessible petrological and geochemical techniques to define their degree of aqueous alteration. We also describe a rare compound chondrule-CAI (calcium-aluminium-rich inclusion) found within this meteorite, which is a target for future study.

Materials and Methods: After its confirmed fall on the 23rd of April 2019 near Alajuela in Costa Rica, *Aguas Zarcas* was classified as a CM2 carbonaceous chondrite according to Garvie's (Arizona State University, USA) petrographic description and Ziegler's (University of New Mexico, USA) oxygen isotopic analysis **[6]**. This study has used three polished thin sections and two polished blocks. All thin sections were studied using an Olympus BX41 petrological microscope. After ~10 nm of carbon coating, one thin section and both polished blocks were imaged using a Zeiss Sigma SEM operated at 20 kV, and analysed by energy-dispersive X-ray spectroscopy (EDS). Several locations were further mineralogically characterised by Raman spectroscopy using a Renishaw InVia coupled with a 512 nm laser source and 2400 mm grating (maximum power of 45W). The laser was used at 0.5% of its power in order to avoid any alteration by heating of the samples.

Petrological observations: *Aguas Zarcas* has been described previously as being composed of two main lithologies: one chondrule-rich (20 areal%) and the other chondrule-poor (80 areal%) **[6]**. The samples studied seem to all be within the chondrule-rich lithology. All of the samples studied display a distinct micrometric-thick fusion crust indicating that they haven't been extensively affected by terrestrial alteration. This is further confirmed by the absence of rinds of oxides around sulphides **[7]**.

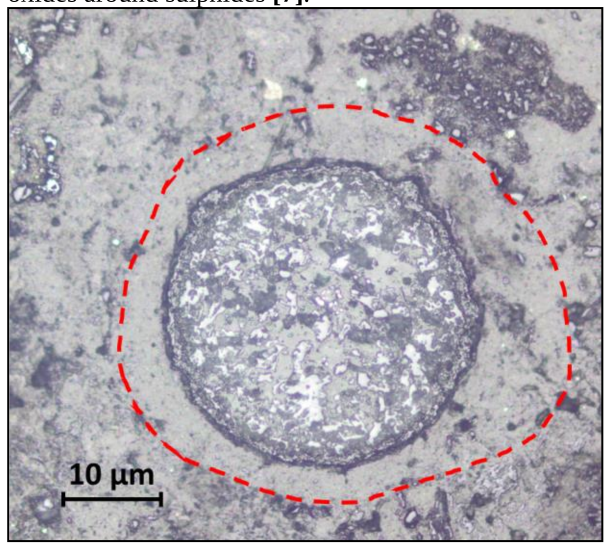

Fig. 1. *Reflected light image of a micrometric circular chondrule surrounded by a fine-grained rim (FGR; circled in red).*

Petrographic observations reveal extensive aqueous alteration. The meteorite has numerous chondrules displaying various degrees of mafic phenocryst fragmentation. Despite the well preserved shape of the chondrule in **Figure 1**, Raman spectroscopy has revealed the presence of dolomite and calcite, indicating that the fine-grained rim (FGR) surrounding was permeable enough to permit aqueous alteration of the contents of the chondrule. The mesostasis within chondrules had been completed altered and replaced with silicates (probably phyllosilicates) **[3, 5]**. This observation was confirmed with EDS analysis (cf. **Figures 2** and **3**) and is consistent with previous studies concerning highly altered CM chondrites **[4]**.

***In situ* geochemical mapping (EDS):** Several areas of interest were chemically analysed including the rare compound chondrule-CAI (calcium-aluminium-rich inclusion) object in **Figure 2**. Such objects have been described in previous studies of multiple chondritic groups (CO **[8]**, CV **[9]**, CH **[10]**, and L, LL, H **[11]**) but only once from the CM chondrite Paris **[5]**. This meteorite is classified as a CM 2.7, and considered to be among the least aqueously altered CMs according to **[5]**. The *Aguas Zarcas* compound chondrule-CAI is therefore an extremely rare case and requires further investigation to determine the timeline of the formation of its components.

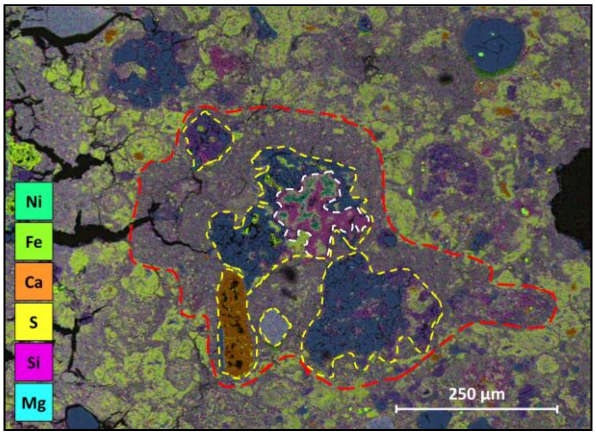

Fig. 2 *EDS layered image of a compound chondrule-CAI.*

The core of the refractory inclusion (circled in white) is dominated by spinel (blue-green at centre of the image, **Fig. 2**) surrounded by a rim of diopside (light purple). The CAI is within a fragmented chondrule (parts circled in yellow), mainly composed of forsterite with inclusions of iron-nickel sulphides (e.g. pentlandite). A single grain (orange) of Ca-carbonate (probably calcite) may have formed by replacing olivine during the parent-body aqueous alteration event **[3]**. Next to it is a single grain of forsteritic olivine (light blue). These grains are enclosed by a fine-grained rim (circled in red) composed mainly of iron sulphides and potentially serpentine. The inter-chondrule matrix is Fe-rich, as also seen in **Figure 3**, which may correspond to TCI clumps (tochilinite-cronstedtite intergrowth).

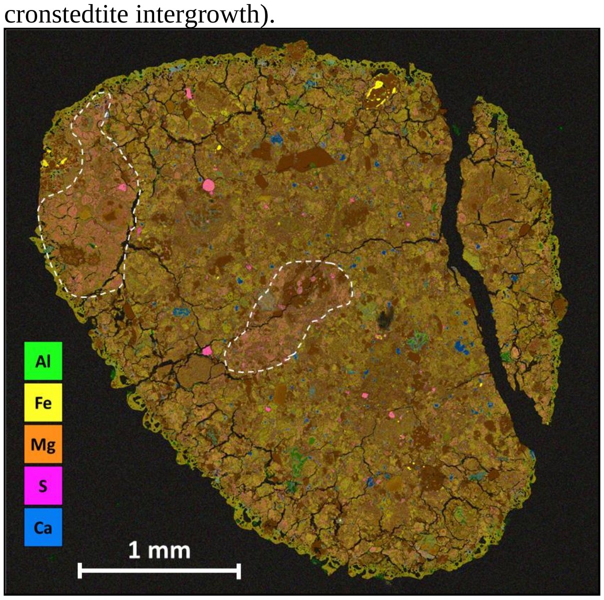

Fig. 3 *EDS layered image of a polished block of Aguas Zarcas. The circled areas are particularly rich in S and may correspond to large altered clasts or tochilinite-rich TCI areas (tochilinite-cronstedtite intergrowth). Subsequent work using Raman spectroscopy will be carried on to precise the nature and composition of these areas.*

Conclusions: Using our petrographic observations and *in situ* geochemical analyses, we have obtained these principal diagnostic characteristics:

Absence of chondrule mesostasis. They have been completely altered and replaced by silicates (probably phyllosilicates, as it has been observed in numerous previously studies (e.g., **[3, 5]**).

Matrix is dominated by phyllosilicates and iron sulphides. All petrologic subtypes (CM 2.0-2.7) in **[3]** and **[5]** have a phyllosilicate-rich matrix, which is consistent with our observations (cf. **Figures 2** and **3**).

Metallic Fe-Ni bearing phases remain scarce throughout the sample but can be found within chondrule remnants. The exact proportion has yet to be quantified precisely, but likely within the 0.03-0.30 vol% range.

Mafic silicate phenocrysts within chondrules have been almost completely altered and, in some cases, replaced by calcite or dolomite.

Large TCI clumps seem to account for about 10-15 vol% of the fully mapped samples. In order for their exact nature and composition to be confirmed, further Raman spectroscopy analyses are required.

Sulphides occur within chondrules and the matrix. Fe-Ni sulphides, such as pentlandite occur in chondrules. Pyrrhotite has not been identified in our study, although its presence is possible and would indicate a lesser degree of aqueous alteration **[3, 5]**.

According to the scale defined in **[3]** and **[5]**, the described characteristics indicate that the *Aguas Zarcas* meteorite is a CM 2.2 (±0.1). Future work includes comparisons and correlations with other popular meteoritic classifications (e.g. **[12]**).

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