BRECCIATION ON THE AGUAS ZARCAS PARENT BODY REVEALED USING CLAST PETROFABRICS.

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Introduction: Petrofabrics within meteorites provide valuable information about the deformation history of asteroidal parent bodies. Proposed mechanisms for petrofabric development include lithostatic compaction and impacts [1, 2]. Investigations using both 2D and 3D analysis techniques have concluded that chondrule defined petrofabrics are potentially commonplace within the CM carbonaceous chondrites [2-6]. Paradoxically however, CM chondrites generally exhibit little to no evidence for shock [2].

In this study we use 3D analysis techniques to analyze chondrule shapes and orientations within the CM chondrite Aguas Zarcas. This is a well-known example of a heavily brecciated CM chondrite [7] and provides an excellent opportunity to further develop our understanding of regolith mixing and fabric development on the CM chondrite parent body/bodies.

Methods: X-ray computed tomography (XCT) was carried out on a chip of Aguas Zarcas, a CM chondrite that fell in 2019 in Costa Rica, and has a petrologic subtype of CM2.2 ± 0.1 [8]. XCT was conducted at the University of Strathclyde on a XT H320 LC instrument equipped with a 180 kV transmission source, producing a 3D volume with a final reconstructed voxel size of 12.13 µm/voxel. A total of 313 dark-toned objects were identified as chondrules, across three lithologies, hereafter referred to as L_1, L_2, L_3. Chondrules were manually segmented using a partial segmentation technique in Avizo™, fit with ellipsoids, and measured using Blob3D following the procedure set out by [4]. Orientations of the primary and tertiary axes (longest and shortest axes, respectively) of each chondrule were then visualized using Stereonet10 software [9].

Results: Within the final reconstructed volume two chondrule-bearing clasts are clearly identified. They are distinguished from the host lithology by a difference in X-ray attenuation (resulting from a greater proportion of higher atomic number minerals). The clasts are denoted L_1 (60.6 mm^3) and L_3 (49.8 mm^3), and the host lithology is L_2 [Fig. 1].

Chondrule Orientations: The orientations of the primary and tertiary axes of the chondrules within each lithology are displayed in Figure 2. Chondrules within each lithology appear to have preferred orientations with primary axis orientations plotting along a great circle girdle and tertiary axis orientations clustering. This

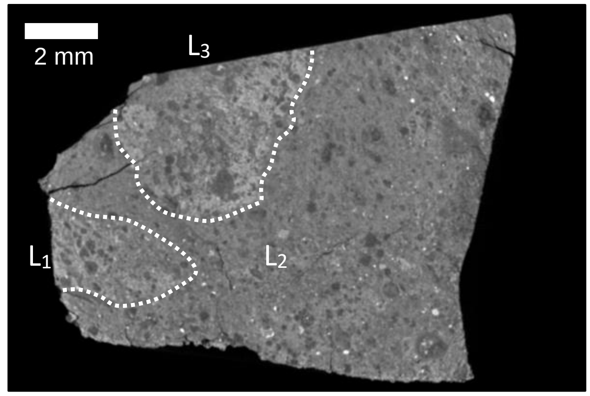

Fig 1. Cross-sectional (XY) reconstructed XCT slice of the Aguas Zarcas sample. White outlined regions represent the boundaries between lithologies.

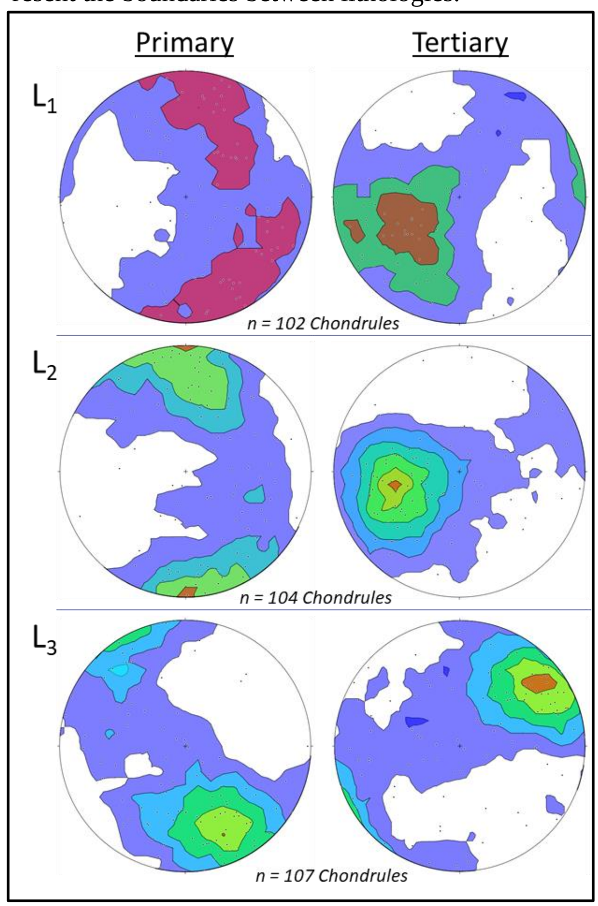

Fig 2. Equal area stereographic projections of the primary and tertiary axes of chondrules in L_1, L_2 and L_3.

pattern is indicative of a foliation fabric [10]. Slight clustering of the primary axes in L_2 and L_3 also suggests the possible presence of a weak lineation [10]. The shape (*K*) and strength (*C*) parameters of the petrofabric are listed in Table 1 where, $K < 1$ represents a girdle distribution, $K > 1$ represents a cluster distribution, *C* near 0 represents a weak fabric, and $C \geq 4$ represents a strong fabric [11]. The strength of the fabrics within the lithologies is moderately weak, with L_1 showing a slightly weaker fabric.

Figure 2 illustrates differences in foliation orientation between the three lithologies. L_1 and L_2 have similar foliation orientations, and due to the low *C* value, orientations may fall within the measurement error. L_3 has a significantly different foliation orientation likely reflecting a significant real-word change in the primary and tertiary axis orientations of the L_3 chondrules. All orientations are found to be non-random at the 99% confidence interval [11].

Table 1. Orientation shape (K) and strength (C) parameters for lithologies L_1, L_2, L_3.

Lithology	Primary Axis		Tertiary Axis	
	K	*C*	*K*	*C*
L_1	0.22	0.81	2.58	0.75
L_2	0.62	1.19	2.06	1.28
L_3	0.67	1.34	1.90	1.00

Chondrule Shape: Chondrule shape was defined using Sneed and Folk diagrams [12]. In all three lithologies the majority of chondrules measured are non-compact (L_1 = 81.37%, L_2 = 67.31%, L_3 = 75.7%), sitting predominantly within the compact bladed to compact elongate ranges [12].

Discussion: Our XCT results are clear evidence of petrofabrics within all three lithologies of the Aguas Zarcas sample. The XCT determined fabric strengths in Aguas Zarcas are similar to those recorded in the CM chondrites Boriskino (CM2) (C = 1.3) [6] and Murchison (CM2.5 [13]) (C = 1.46 and C = 2.17) [2, 4].

It has been proposed that a series of low intensity impacts on the CM parent body (<5 GPa) could produce petrofabrics whilst maintaining a low shock stage [2]. However, the heavily brecciated texture and the difference in foliation orientation between lithologies $L_1/_2$ and L_3, demonstrates significant regolith mixing on the Aguas Zarcas parent body. Therefore the absence of recorded shock features within Aguas Zarcas (shock stage S1 [7]) is surprising. Additional investigation into possible shock features within Aguas Zarcas will therefore be undertaken in an effort to reconcile this possible discrepancy.

Classification of the extent of aqueous alteration experienced by each lithology will also be carried out to investigate; the extent of heterogeneous regolith mixing, and the possible genetic link between aqueous alteration and petrofabric strength as proposed by [3].

The predominant non-compact chondrule shape observed in all three Aguas Zarcas lithologies is similar to that recorded in Murchison [2, 4]. The consistency in chondrule shape between CM chondrites is another aspect which warrants further investigation as it could provide insights into shared chondrule deformation process and/or shared chondrule origins.

Conclusions: Three lithologies of the CM chondrite Aguas Zarcas have petrofabrics that are easily identifiable by XCT. Significant differences in foliation orientations are observed between lithologies, which suggests significant regolith mixing occurring on the parent body in what is likely a very dynamic environment. The presence of these fabrics in a heavily brecciated CM chondrite and the lack of reported shock features needs further investigation to determine if these fabrics, and level of brecciation are in keeping with the multiple low-intensity impact hypothesis proposed by [2].

The use of XCT to determine true fabric orientations within CM chondrites (as opposed to the minimum orientation ascertained through 2D techniques) is crucial for correct interpretation of fabrics within meteorites. Given the likelihood that many of the CM chondrites possess petrofabrics, and that understanding these fabrics is key to our interpretation of processing on the parent body, significant further research in this area is needed.

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