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A Morphologic & Crystallographic Comparison of CV Chondrite Matrices

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1. ABSTRACT

Meteoritic matrices are commonly classified by their modal mineralogy, alteration and shock levels. Other 'textural' characteristics are not generally considered in classification schemes, yet could carry important information about their genesis and evolution. Terrestrial rocks are routinely described by grain morphology, which has led to morphology-driven classifications, and identification of controlling processes. This paper investigates three CV chondrites- Allende (CV3.2$_{oxA}$), Kaba (CV3.0$_{oxB}$) and Vigarano (CV3.3$_{red}$)- to determine the morphologic signature of olivine matrix grains. 2D grain size and shape, and crystallographic preferred orientations (CPOs) are quantified via electron backscatter diffraction mapping. Allende contains the largest and most elongate olivine grains, whilst Vigarano contains the least elongate, and Kaba contains the smallest grains. Weak but notable CPOs exist in some regions proximal to chondrules and one region distal to chondrules, and CPO geometries reveal a weak flattening of the matrix grains against the edge of chondrules within Allende. Kaba contains the least plastically-deformed grains, and Allende contains the most plastically-deformed grains. We tentatively infer that morphology is controlled by the characteristics of the available population of accreting grains, and aqueous and thermal alteration of

the parent body. The extent of overall finite deformation is likely dictated by the location of the sample with respect to compression, the localized environment of the matrix with respect to surrounding material, and the post-deformation temperature to induce grain annealing. Our systematic, quantitative process for characterizing meteorite matrices, has the potential to provide a framework for comparison within and across meteorite classes, to help resolve how parent body processing differed across and between chondritic asteroids.

2. Introduction

Grain morphologies and size distributions are commonly described and utilized in interpreting the petrogenesis of terrestrial rocks. For example, the rates and conditions of cooling and crystallization are often determined for igneous rocks through grain size and shape analysis (e.g. Cashman & Marsh, 1988; Marsh, 1988), and the presence and direction of flow or magma chamber settling can be determined through crystallographic analyses (e.g. Boulton, 1978; Hess, 1989, Bascou et al., 2005; Holness, 2007). For sedimentary rocks, the amount of transportation from the source rock and conditions of the depositional environment can be interpreted from grain morphologies, and understanding the crystallographic orientation of grains can be used to define the direction and form of fluvial processes, for example (e.g. Visher, 1969; McLaren, 1981; McLaren & Bowles, 1985; Orton & Reading, 1993; Vandenberghe, 2013). Accurate documentation of morphologic and crystallographic parameters allows for direct comparisons between samples of the same and different rock types, and classifications can then be created from such information to interpret the geological processes at work. Such analyses are not as commonly used in application to meteoritic materials, but studies to date have demonstrated insightful outcomes, e.g.; crystal size distribution (CSD) analyses were applied to the volcanic martian meteorites (e.g. Lentz & McSween, 2000; 2005) to define the number of growth stages each sample has experienced, and allude to what processes may have been at work throughout the cooling period; chondrule size analyses performed in CO chondrites found that the mean diameter of chondrules increases with increasing metamorphic grade of a sample (Rubin, 1989); mean chondrule size distributions across meteorite groups were found to vary consistently according to class- for the carbonaceous and ordinary chondrites, CVs on average have the largest chondrules, and CM and COs have the smallest, whilst ordinary chondrite chondrules are intermediate (King & King, 1978;1979; Rubin & Grossman, 1987). Comparisons of textural properties and size distribution profiles between CV and CK chondrules found the two classes to be similar to one another and, when these data were considered alongside thermal metamorphism indicators, further supported the hypothesis that both classes originated from the same parent body (Chaumard & Devouard, 2016). However, the morphology and crystallography of meteorite matrix grains have not been investigated in a comparatively quantitative or extensive way. Nevertheless, the limited number of studies have demonstrated that the matrix holds key information regarding thermal and metamorphic processing (e.g. Scott et al., 1988; Krot et al., 2004; Watt et al., 2006; Forman et al., 2017), and illustrate that it is important to characterise the fine-grained matrices quantitatively to interpret the full geological history of chondrites.

Carbonaceous chondrites (CCs) encompass ~3% of all meteorites in global collections (Brearley and Jones, 1998). The CV class meteorites are some of the most primitive meteorites to have been studied. We are, therefore, able to gain an insight into early solar system processes by examining these rocks. We can also learn of their parent body origins and secondary processing history, both during the initial asteroid formation period and post-lithification (e.g. Rietmeijer and Mackinnon, 1985; Stöffler et al., 1991; Krot et al., 1998; Bonal et al., 2006; Cody et al., 2008; Consolmagno et al., 2008; Forman et al., 2016). Whole-rock mineralogical variations within the CV chondrite group have resulted in further classification into three subclasses (oxidized types A & B, and the reduced subtype) (McSween, 1977a; Weisberg et al., 1997), which also exhibit variations in texture and geochemistry. Such variations have been interpreted to reflect different environments or processing conditions on the same parent body (Krot et al., 1998; Krot et al., 2000; Krot et al., 2004). This makes the CV chondrites an excellent group for the purpose of this initial study, because the results can be discussed in terms of parent body processing conditions proposed in prior studies.

The average and variance in composition of a specific mineral is commonly used when describing fine-grained (matrix) of meteorites, and typically Fa (or Fo) content of matrix olivine is quoted for most chondrites (Brearley and Jones, 1998). This quantitatively constrains compositional variance within and between meteorite classes and reveals some aspect of the meteorite petrogenesis (e.g. Hua and Buseck, 1995; Hua et al., 2005). However, the microstructure of chondrite matrices have received comparatively little attention, and 2D morphology of matrix grains in chondrites is often only described qualitatively (e.g. Brearley and Jones, 1998; Scott and Krot, 2003). However, recent studies have utilized electron backscatter diffraction (EBSD) mapping to quantitatively characterize matrix microstructures over the area of a petrographic thin section, which has allowed the morphologic and crystallographic fingerprint of the matrix of Allende to be determined in detail (Forman et al., 2017). Quantification of grain size and shape statistics, intensity of intragrain crystal-plastic deformation, and crystallographic preferred orientations (CPOs) that are specific to the sample of interest can be readily characterized via EBSD mapping, which can aid in the interpretation of various processes associated with lithification, metamorphism and mechanisms of deformation (e.g. Forman et al., 2017).

In this study, we quantitatively characterize the crystallographic and morphologic microstructure of olivine matrix grains of three CV meteorites; Kaba (oxidized subtype B (CV_{oxB})), Allende (oxidised subtype A (CV_{oxA})) and Vigarano (reduced (CV_{red})) (Table 1). All CV chondrites are assumed to come from the same parent body based upon their similar textures, petrologic type and oxygen isotopes (Weisberg et al., 1997; Brearley & Jones, 1998). As an example, clasts of oxidized CV material have also been found within the reduced meteorite Vigarano, providing further evidence that all CV chondrites have the same origin (Krot et al., 2000; Weisberg et al., 2006). Previous research has inferred the relative depths of the three meteorites examined here from deepest origin to shallowest, as Allende >> Kaba ≥ Vigarano, based on a wide range of characteristics, such as magnetic properties, aqueous alteration products and the predicted maximum temperatures the samples have experienced, using various thermometry techniques (Bonal et al., 2006; Cody et al., 2008; Elkins-Tanton et al., 2011; Weiss and Elkins-Tanton, 2013). Samples have been classified to have experienced either very low bulk shock conditions (Vigarano), or little to no shock at all (Allende and Kaba) (Scott et al., 1992) (Table 1). Vigarano and Allende contain a similar ratio of matrix:chondrule (0.55 and 0.66, respectively by volume) (McSween, 1977a; Scott et al., 1992)(Table 1), whereas Kaba contains considerably more matrix material (matrix: chondrule ratio of 1.17 by volume) than either Vigarano or Allende (McSween, 1977a) (Table 1).

The purpose of this study is to (1) demonstrate the utility of EBSD mapping to quantitatively characterize fine-grained meteoritic materials; (2) provide new quantitative data for CV chondrites; and (3) to identify any preliminary links between our results and parent body processing within the context of prior work. The EBSD approach outlined in this study allows for consistent and systematic indexing of large populations of small (< 1 μm), in situ matrix grains at sufficiently high spatial resolution to measure many morphologic and crystallographic parameters. Evaluating a statistically significant number of grains in any given area provides an accurate, quantitative overview of the grains present, which can be directly compared across and between samples, meaning small variations can be identified that may not have been identified using traditional imaging techniques.

3. Materials & Methods

A thin section of Allende (Section WAM 13102, Western Australian Museum), and 1-inch epoxy mounts of Kaba (P15184, Natural History Museum, London), and Vigarano (BM192034, Natural History Museum, London) were polished using 500 nm colloidal silica in NaOH using a Buehler Vibromet II polisher. Four regions of interstitial matrix within each sample were mapped to obtain crystallographic and phase data using Tescan MIRA3 VP-FESEM with the NordlysNano EBSD detector and AZtec EDS/EBSD acquisition system situated in the John de Laeter Centre, Curtin University, Perth. Each site was surveyed by backscatter electron (BSE) imaging (Fig. 1, left column), and high-resolution secondary electron (SE) imaging (Fig. 1, four columns to the right). Two of the selected regions are proximal to chondrules (denoted by ‘P’ in site names), whereas the remaining two are situated as far as was feasible from chondrules (distal, denoted by ‘D’ in site names) to identify any variability in the morphology and crystallographic microstructure of matrix grains and their proximity to chondrules. High-resolution SE images were used to ascertain the form and general appearance of the grains at each site. Data were collected with an accelerating voltage of 16 KeV, beam intensity of 16.00, and a working distance of 20.5 mm. EBSD data were collected at a fixed step size of 0.12 μm, using high gain, 4 x 4 binning and MAD (mean angular deviation) threshold of 1.0° for all samples. Using the Oxford Instruments HKL software Channel 5.12, the EBSD data were then noise reduced by removal of isolated erroneous data points (‘wildspike’ correction) followed by a 7-point nearest neighbour zero solution extrapolation to facilitate grain definition without generating significant artefacts, as per standard procedure for this type of data (e.g. Watt et al., 2006, Forman et al., 2016; 2017).

Grains were defined based on crystallographic orientation using the automated ‘grain detect’ algorithm in Channel 5.12, based on contiguous adjacent pixels within a 10° crystallographic misorientation threshold. The threshold is assumed to represent the transition in physical properties from low-angle to high-angle boundaries, and results in minimal artefacts by visual inspection. Grains smaller than 3 pixels (each pixel is 0.12 x 0.12 μm in size) were deemed insufficiently sampled and were removed from the dataset to improve collective statistical and orientation accuracy; this is a commonly-used minimum threshold (e.g. Watt et al., 2006).

Olivine was the focus of this study given that it is the primary component of the matrices in all samples. Several grain-based parameters and their statistics, such as grain size and shape (aspect ratio), were quantified using the Tango module in

Channel 5.12 software. Grain size data from all olivine grains within each site were combined to yield statistical quantification of the ‘typical’ interstitial olivine matrix characteristics in each sample.

Grain size can be expressed in several ways; as circle-equivalent mean diameter, length of the long- or short axis of a fitted ellipse, and grain area. This study used the circle-equivalent diameter parameter, because the elongate nature of the majority of the grains implied misleading relationships between grain size and shape when other parameters were displayed. Two-dimensional (2D) grain shapes were quantified as the aspect ratio of the best-fit ellipse $(\frac{grain\ length}{grain\ width})$ for each grain using the algorithm available in Channel 5 Tango. To assess the relationship between the physical dimensions of grains and their crystallography, while also accounting for 2D cut effects of 3D grain shapes, three subsets were created to only include grains with the <a>, <b> or <c> axis parallel to the plane of the sample, and average aspect ratios were then calculated for each subset (Table 2). Because of the 2D nature of this method and subsequent treatment of the data as subsets, aspect ratios are tentatively considered as a measure of grain elongation, however cutting effects may still play a minor role in introducing bias to the measurement.

An assessment of the intensity of crystal-plastic deformation in individual matrix olivine grains utilized ‘grain orientation spread’ (GOS) maps generated using an algorithm in the Channel 5.12 software. These maps show the average angular misorientation within each grain compared to the mean crystallographic orientation of the grain (represented as Euler angles; $-\varphi2$, $-\Phi$, $-\varphi1$). All olivine grains were included in this analysis, and were color-coded to reflect the crystallographic misorientation from the mean value. Statistics derived from GOS maps for each site have been tabulated for comparison between sites and samples (Table 2).

The pattern and strength of crystallographic alignment among grains, or crystallographic preferred orientation (CPO) was quantified for olivine using EBSD data from each map. Assessment of CPO patterns involved construction of stereographic projections (pole figures) using one representative point per grain to avoid statistical bias towards larger grains. Pole figures were generated for each of the three principal crystallographic axes of olivine (<a> = <100>, <b> = <010>, and <c> = <001>) on lower hemisphere, equal area plots in the sample/map x-y-z reference frame of the arbitrarily-prepared polished surface (CS0). Pole figures were color-coded to reflect the orientation of each grain by ascribing Euler angles (i.e., -φ2, -Φ, -φ1) to red, blue and green channels, respectively. The pole figure data were also contoured for data density (using a half-width of 10°, and clustering of 5°), facilitating description of the forms- and quantification of the strengths of any CPOs. The strengths of CPOs are expressed as multiples of uniform density (m.u.d.) in this format. A more rigorous assessment of CPO strength was provided by calculation of the misorientation index (M-index) for each map (Skemer et al. 2005). This statistical calculation is defined by crystallographic alignments within the data as denoted by a number between 0-1 (0= completely random fabric, 1= single crystal orientation). Crystallographic orientations between two grains are compared and the difference defined as an angular misorientation. In this study, 10,000 uncorrelated (non-adjacent) grain misorientations were calculated for each mapped area, and the M-index values were calculated as per standard procedure defined in Skemer et al. (2005).

The Channel 5 software also allows for investigations into the relationship between the crystallographic axes and the long and short axes of the grains, by fitting each grain with an ellipse. The orientations of the long axes of the fitted ellipses for each grain were visualized as color-coded maps. One point per grain was displayed on lower hemisphere, equal area pole figures and color-coded to reflect the orientation of the long axis of the fitted ellipse were used to identify any relationships between the orientation of the long axis of the fitted ellipse and crystallographic axes. Two subsets were created to include grains with their <001> or <010> axes perpendicular to the plane of the sample respectively, so that the relative sizes of the two remaining crystallographic axes could be determined (e.g. relative lengths of the <100> and <010> axes determined within the <001> subset). This is a quantitative analysis and is semi-automated.

4. Results

4.1 Grain Morphologies and Statistics

The matrix grains of Allende are euhedral-subhedral (Fig. 1), and are predominantly lath-shaped in A-P2 and A-D1, but appear to be more angular with stronger facets in A-P1 and A-D2. The matrix is predominantly olivine (90%) with larger grains of clinoenstatite (8%) and small accessory spinel grains (~2%) (Fig. 2, Table 2) at the four sites examined. Kaba contains subhedral, small olivine grains (74%) (Fig. 1 & 2) surrounding larger clinoenstatite (22%), spinel (~2%) and magnetite grains (~2%) (Fig. 2). Vigarano contains small subhedral-anhedral olivine grains (77%) surrounding large clinoenstatite grain clusters (21%), with the addition of magnetite grains (~2%) at the proximal sites, and spinel (~2%) grains at the distal sites. Olivine is the dominant phase in all samples, however Kaba has the lowest average proportion of olivine (74%) in the matrix regions examined (Table 2). Vigarano and Allende have less variation in minor phase abundances when compared with Kaba. The abundance of non-olivine grains is also consistently higher proximal to chondrules than the distal sites in Kaba (~35% vs. ~15% respectively), Allende (~15% proximal vs. 6% distal), and Vigarano (25% proximal vs. 20% distal).

The aspect ratio statistics and grain size distributions for matrix olivine grains for each sample are displayed in Figs. 3 and 4 respectively, and summarized in Table 2. The olivine matrix grains of Allende have a markedly higher mean circle-equivalent diameter (0.96 μm) and greater variation (standard deviation of 0.98) compared to Kaba (0.48 μm, with standard deviation of 0.35) and Vigarano (0.49, with standard deviation of 0.35) (Fig. 3). Each sample preserves a log-normal grain size distribution at both distal and proximal sites (Fig. 4). All samples have narrow ranges in matrix grain size (i.e., may be referred to as 'well-sorted') (Fig. 4). However, the spread of mean circle-equivalent diameter data is greatest for Allende (Fig. 4). The proximal sites of Kaba and Vigarano contain a slightly higher proportion of large matrix olivine grains than the distal sites (Fig. 4a and 4b; Table 2). In contrast, the matrix olivine grain size frequency distribution at the distal and proximal sites of Vigarano are almost identical to one another (Fig. 4c).

Matrix grain aspect ratios are similar across all samples (Fig. 3); Vigarano has the lowest value of 1.83, compared with 1.87 and 1.93 for Kaba and Allende respectively (Table 2). There is a minimal variation of ~± 0.05 from the collective mean aspect ratio in Kaba and Vigarano between most of the subsets and whole site data (Table 2), whereas Allende shows a marginally greater variation across these subsets of up to 0.11 from the collective mean for the whole sample. If the data are considered in terms of proximity to chondrules, no clear trend in aspect ratio values are identified.

Smaller grains across all three meteorite samples generally have the largest aspect ratios, meaning these are the most elongate grains present, whereas larger grains are generally more rounded in shape with a lower aspect ratio (< 2) (Fig. 5). We define ‘elongate’ grains as those with an aspect ratio of greater than 2 in this context. The proportion of elongate grains across the sampled sites are 35%, 32% and 30% for Allende, Kaba and Vigarano respectively (Table 2). The data of Vigarano and Kaba show a gradual decrease in the mean circle-equivalent diameter as aspect ratio increases, but this trend is much weaker in Allende. The relative spread of the data between samples is evident in Fig. 5; the variation in mean circle-equivalent diameter can be described as Kaba ≤ Vigarano << Allende, whereas the variation in terms of aspect ratio can be described as Vigarano < Kaba ≤ Allende. The mean circle-equivalent diameter variation hierarchy differs slightly from the standard deviation analyses shown in Table 2, however the data points shown in Fig. 5 only include the grains for which a reliable aspect ratio can be calculated, i.e. those grains with a primary crystallographic axis parallel to the plane of the sample.

4.2 Intragrain crystal-plastic deformation

The grain orientation spread of one proximal site (P1) from each sample is shown in Figure 6 (as an example), and statistics from all sites are summarized in Table 2. Allende demonstrates the largest magnitude of GOS (average of 0.93º and standard deviation of 0.85º) and, therefore, a relatively high proportion of crystal-plastically deformed matrix grains. In contrast, Vigarano and Kaba typically contain matrix grains with lower GOS values, with sample averages of 0.66º and 0.60º, and standard deviations of 0.41º and 0.39º respectively (Fig. 6). Therefore, preserved evidence of crystal-plastic deformation is much less in these samples, and magnitude of deformation is less intense where present.

4.3 Crystallographic preferred orientations (CPOs)

Crystallographic preferred orientation data are shown in Figure 7 and summarized in Table 2. With the exception of A-D2, all sites have very low M.U.D. and M-index values indicating that the strength of CPO of matrix grains is very weak, i.e., the grains are close to randomly-oriented (Fig. 7a-c, Table 2). There is no significant correlation between M.U.D or M-Index values and the proximity of matrix grains to chondrules. The M.U.D values are highest in two sites of Allende, P1 and D2 (2.48 and 4.01, respectively). Nevertheless, the contoured pole figures demonstrate weak CPO patterns are present in most matrix sites (Fig. 7a-c). In many cases, crystallographic alignment of matrix grains is related to the presence of nearby objects, such as chondrules. For example, sites A-P1 (Fig. 7a), K-P1, K-P2, K-D2 (Fig. 7b), V-P2, V-D1 and V-D2 (Fig. 7c) all have weak point maxima in <100>, and for sites K-P1, K-P2 (Fig. 7b), V-P2 and V-D2 (Fig. 7c) this point maxima indicates that <100> is oriented perpendicular to the edges of the closest chondrules to the mapped area, i.e. <100> is pointing towards the chondrules. From the latter group, all but V-D2 also have a weak girdle maxima in <001>, which indicates that <001> lies parallel to the edge of the closest chondrule(s) to the mapped site (Fig. 7b & c). Sites A-D1, K-D1 and V-P1 have very weak girdle maxima in <100>, and A-D1 and V-D1 both have a weak point maxima in <001>, where <001> is aligned perpendicular to the plane of the sample (i.e. <001> is pointing directly out of the sample plane) (Fig. 7a-c). Site A-P2 has no discernable CPO pattern (Fig. 7a). Site A-D2 has moderately strong point maxima defined by all three crystallographic axes, where the <100> is perpendicular to the edge of the two closest chondrules, <001> is parallel to the edges of the closest chondrules, and <010> is perpendicular to the plane of the sample (Fig. 7a).

4.3 Relative length determination of crystallographic axes of olivine using EBSD data

The results of the relative length analysis of the crystallographic axes are illustrated for site A-D1 in Fig. 8. In displaying only grains with the <100> axis perpendicular to the plane of the sample (Fig. 8ai and bi), grains with the <010> axis perpendicular to the plane of the sample (Fig. 8aii and bii), and grains with the <001> axis perpendicular to the plane of the sample (Fig. 8aiii and biii), the relative grain dimensions parallel to the primary crystallographic axes at site A-D1 are revealed (Fig. 8). Green and red representative schematic grains, shown in the centers of the plots in Fig. 8b, are color-coded in accordance with how they would be displayed in Fig. 8a. These schematic grains are shown on the pole figures (Fig. 8b) to demonstrate the correlation between the longer axis of the fitted ellipse (i.e., the longer dimension in the plane of analysis), and the corresponding crystallographic axis for grains that are colored red and green in part (a). The green and red schematic grains have a 2D-defined slope of the long axis of approximately 75 º and 165 º respectively. For grains which have the <010> axis perpendicular to the plane of the sample (bii), the longer axis of the fitted ellipse corresponds to the <001> axis, and the shorter axis corresponds to the <100> axis. For grains that have <001> perpendicular to the plane of the sample (biii), the longer axis of the fitted ellipse corresponds to the <010> axis, and the shorter axis corresponds to the <100> axis. This suggests that the <100> axis is the shorter physical dimension of the olivine grains within Allende. We are unable to determine the longer axis between <010> and <001>, as there appears to be no correlation between slope of the long ellipse and crystallographic orientation of the long axis (bi). This may indicate that the <010> and <001> axes are similar in length. The results of this type of analysis are inconclusive for Kaba and Vigarano because the grains are too small to determine grain elongation by eye, and no definitive correlation to specific primary crystallographic axes could be determined.

5. Discussion

Collecting and analyzing the data reported in this study has facilitated a quantitative characterization various microstructural parameters of chondrite matrices in 2D. Grain size, aspect ratio, intragrain deformation, crystallographic preferred orientation, and an understanding of the relative lengths of the primary axes of the grains were obtained in a consistent manner at high resolution, allowing for direct comparisons of domains within and between samples. A statistically significant amount of data was collected at each site, permitting small variations between the samples to be resolved that may not be evident when using other established microanalytical or imaging techniques.

Allende contains the largest (0.96 µm (1 S.D.= 0.98) grains in circle-equivalent grain diameter (Table 2)), and the most elongate grains (mean aspect ratio of 1.93 (1 S.D.= 0.74)), and also has the greatest spread of values for both parameters (Table 2, Fig. 3 & Fig. 5). The mean diameter of the matrix of Kaba and Vigarano are approximately half that of the grains in Allende (0.48 µm (1 S.D.= 0.35) and 0.49 µm (1 S.D.= 0.35), respectively). Kaba contains slightly less elongate grains than Allende (1.87 (1 S.D.= 0.66)), and Vigarano contains the least elongate grains (1.83 (1 S.D.= 0.61)). The variation between aspect ratios according to which crystallographic axis is parallel to the plane of the sample is not consistent and no pattern can be discerned (Table 2). The mean grain size and aspect ratios recorded represent the average of statistically significant grain populations from the matrices of each meteorite (Table 2, Fig. 3 & Fig. 5), and so the differences between them are noteworthy. We can make tentative inferences between these preliminary findings and previous research. Allende has the largest grains, and the highest iron content, and Kaba has the smallest grains, and has the lowest iron content (Table 1). There does not appear to be any correlation between the composition (Table 1) and 2D aspect ratio measurements of the grains, therefore, matrix olivine aspect ratio and composition are potentially controlled by independent processes. Crystal size frequency distributions (CSD) (Fig. 4) are very similar in skewness, implying that the process controlling the overall distribution is common to all samples (e.g. Lentz & McSween, 2000; 2005). Primary accretion therefore may be the dominant cause of the distribution, as each sample has experienced differing amounts of aqueous and thermal alteration, but all samples were created from the same population of nebular material.

It is generally accepted that the wide abundance of secondary minerals such as magnetite and fayalite found in the CV chondrites was generated by heterogeneous aqueous and thermal alteration on the parent body (e.g. Krot et al., 2004; 2010a; 2010b; Ganino & Libourel, 2017). Therefore, it is reasonable to hypothesize that variations in grain size and shape may also stem from such heterogeneous alteration. We can consider our quantitative results in the context of prior qualitative mineralogical and thermochronometry studies to identify correlations and better constrain the outcomes of alteration processing in future work. Briefly, Allende is deemed to have experienced the highest temperatures of the three samples (~550 °C (Bonal et al., 2006; Huss et al., 2006; Cody et al., 2008)) and Kaba and Vigarano have experienced significantly lower temperatures (~310-370 °C (Bonal et al., 2006; Cody et al., 2008)), which positively correlates with our results of mean matrix grain size (Allende >> Kaba ≥ Vigarano (Table 2)) for example. This correlation does not necessarily indicate that grain size is controlled by the level of thermal metamorphism, but comparisons of this kind throughout the CV class and beyond would allow for a comprehensive understanding of what processes control the size and shape of the matrix grains in a sample. Aqueous alteration is less easily defined as many different secondary minerals can form as a result of interaction with the fluid. However, Allende contains the most elongate laths of olivine (Fig. 1 & 3, Table 2), which could be the result of secondary mineral formation from fluid-rock interaction as reported by Krot et al. (1998), or they may simply be the result of primary accretion of a population of more elongate grains, implying there was some variation in the population of nebular material where the CV parent body formed. Kaba contains the next most elongate grains, with an average aspect ratio of 1.87 behind that of Allende's matrix grains with an average of 1.93. Vigarano does not contain as many elongate laths (Fig. 1, Table 2), and therefore this may account for the lower observed mean aspect ratio (1.84); these observed differences in elongation imply the samples may have originated from different regions on the CV parent body. The differences in average aspect ratio between the three samples may imply that each sample did not experience the same aqueous alteration, which is supported by the observed variation in secondary minerals between the samples (e.g. Fig. 2; Krot et al., 1998). Although the difference between the measured sample aspect ratios are small, the populations of grains are large in each case, meaning the results are statistically significant and are notable. However, as this is a 2D analysis it is important to consider the effect of the sample cut and how results may become biased. Results in Table 2 imply that there is little variation in aspect ratio when examining grains in different orientations (subsets <a> <b> and <c> axes), and therefore it is unlikely that the grains are elongate but undetectable due to the cut of the sample. We recommend high resolution micro-computed tomography (μCT) scanning be used to confirm this is the case, however such analyses are beyond the scope of this study.

Deformation can be an indicator for distance from the site or source of deformation, for example impact-induced compaction (e.g. as shown by Forman et al., 2016; 2017) and potentially relative depth on a parent body. All samples are noted to have experienced very little or no shock (Table 1), which is measured from large features, such as chondrules (Stöffler et al., 1991). Therefore, any event causing crystal-plastic deformation is likely to have occurred when the matrix was highly porous (e.g. Bland et al., 2014; Forman et al., 2016; 2017), when the material may have been at higher temperatures (and consequently no brittle shock features would be produced) or at a large distance from the deformation event. Weak intragrain crystal-plastic deformation is present in matrix olivine from all samples, but Allende has the greatest abundance of deformed grains, the highest degrees of deformation (i.e., highest GOS values), and the greatest variation in amount of deformation (Fig. 6, Table 2) although overall deformation is still low in this sample. Kaba has the lowest average GOS and consequently the smallest variation in deformation (Table 2, Fig. 6). In terrestrial olivine, it has been shown that grain size exerts some control over the deformation response of individual grains (e.g. Warren & Hirth, 2006). The olivine studied by Warren & Hirth (2006) demonstrated that differing grain sizes resulted in different deformation mechanisms being activated. For fine-grained material, deformation was also reported to be localized into bands rather than a whole-rock deformation response (Warren & Hirth, 2006). However, the previously mentioned study investigated olivine within a mylonitic peridotite with 3 orders of magnitude in grain size variation- a stark difference to the fine-grained porous rocks investigated here, and therefore the controlling processes explored by Warren and Hirst (2006) are not directly applicable to chondritic rocks. Nevertheless, there is merit to exploring the relationship between deformation and grain size at a smaller scale in future work. It has also been shown that post-deformation annealing can result in lower grain orientation spread (GOS) due to dynamic grain boundary migration resulting in strain-free grains (e.g. Ruzicka et al., 2015b; Ruzicka & Hugo, 2018). In this context, then, it could be inferred from GOS values of each sample that Kaba and Vigarano experienced either slightly less deformation, and/or more post-deformation annealing than Allende. The difference in deformation (GOS) is relatively small, but given the number of grains involved at each site and the accuracy of this measurement (error < 0.5 º) (Borthwick & Piazolo, 2010; Sneddon et al., 2016), the values reported are significant. These two alternative scenarios can be tested somewhat by considering the pressures and/or temperatures that the samples have experienced, and through comparing the final porosities of the samples. As Allende experienced the highest temperatures of the three samples (Bonal et al., 2006; Huss et al., 2006; Cody et al., 2008), we predict that crystal-plastic deformation of matrix olivine would have occurred more readily than Kaba and Vigarano if such temperatures were experienced at the time of the deformation event (e.g. Idrissi et al., 2016), and evidence of post-deformation annealing would be observed. However, post-deformation annealing is likely to result in lower porosities (Ruzicka et al., 2015a; Friedrick et al., 2017), and Allende contains the highest porosity (29.1%, Macke et al., 2011)(Table 1), whilst both Kaba (3%, Corrigan et al., 1997) and Vigarano (8.3%, Macke et al., 2011) have similarly low porosities (Table 1). Therefore, some combination of the previously discussed processes could control the GOS values recorded here, but investigation with the presented dataset is beyond the scope of this study and should be explored with a greater population of samples. Mean GOS is therefore of use in quantitatively determining overall deformation throughout the matrix, and is directly comparable across a sample to determine heterogeneity, and between samples.

Grain alignment or crystallographic preferred orientations (CPOs) can be used as indicators of parent body processing such as flow (e.g. Zavada et al., 2009), impact-induced compaction (e.g. Forman et al., 2016; 2017), and grain settling in a mantle (e.g. Holness et al., 2012) for example. M.U.D and M-Index values of our samples indicate weak to no crystallographic alignment in the samples (Fig. 7, Table 2). However, weak CPO patterns are seen in Fig. 7a-c where crystallographic axes lie perpendicular or parallel to the edges of the nearest chondrules in some instances. This is especially true for most sites proximal to chondrules in Kaba and Vigarano, whereas distal sites have less distinctive crystallographic arrangements, or arrangements which do not appear to relate to the closest chondrules. On the contrary, the Allende sites P1 and P2 (Fig. 7a) display weak CPO arrangements with a more complex relationship to the closest chondrules; <100> is observed to be roughly perpendicular to the closest chondrules, however the orientation relationship isn’t as clear as can be observed in Kaba and Vigarano. Furthermore, the site with the most prominent CPO is D2 in Allende, which is situated much further from chondrules than sites P1 or P2. At this site, <100> is clearly pointing towards the two closest chondrules above and below the site (Fig. 7a), and <001> is oriented parallel to the edges of the same chondrules. The processes that created the observed CPO arrangements may therefore be different to Kaba and Vigarano, or additional processes could have affected Allende; such additional processes may have created a stronger CPO at a site distal to chondrules, and may have modified or influenced the orientation of the weak CPOs at the proximal sites.

The shorter dimension of the matrix olivine grains is parallel to <100> in Allende (Fig. 8), but is less apparent in Kaba and Vigarano due to the smaller grains not resolving sufficiently well to assign long and short axes. If this is true for all matrix grain sites in Allende, the very weak CPO geometries in P1 and P2, and more prominent CPO in D2 show <100> is approximately perpendicular to the edge of the nearest chondrules, and at site D2, <001> is approximately parallel to the edge of chondrules. This consistent with a very weak- weak flattening fabric against chondrules, which is likely to be driven by a compaction or compression event (as seen in Forman et al., 2016; 2017). Alternatively, weak granular or solid state flow may have re-aligned only the long axes of the grains where only point maxima in <001> are observed, as at Allende site D1. However, it is vital to note that these patterns in CPO are very weak and the M-Index and M.U.D values are very low, and therefore any such processes are anticipated to have only minor contributions to the total matrix microstructure in these regions, if they even occurred at all. Porosity and matrix:chondrule ratios (Table 1) may also affect the formation of any CPOs, but no patterns are evident in our data to support or investigate this relationship. It would be reasonable to assume that the longer and shorter axes are the same for Kaba and Vigarano matrix grains, and therefore a similar interpretation of a compressional alignment is implied by the CPO geometries, but further analyses at higher resolutions are necessary to investigate this assumption.

There are limitations to be acknowledged when using EBSD to attain these data, such as: (1) the effects of mapping step size thresholds and subsequent noise reduction protocols on the omission of the smallest grain size fraction due to insufficient sampling. With the introduction of new, more sensitive detectors this should not be an issue for future work, but it is important to consider that step size is the limiting factor in measuring grain morphologies, and therefore the grains of interest should be greater than 3 times the step size used for collecting the data; (2) Topography introduced to the analytical surface by polishing and differential polishing characteristics of different phases resulting in inconsistent pattern quality within a sample or across different samples. Protocols for polishing multi-mineralic samples and different samples types (thin section vs. epoxy mount for example) are limited, however the use of a minimum threshold in MAD (mean angular deviation) during imaging reduces the likelihood of incorrect indexing that may arise due to topography, and therefore increases the quality of the data. (3) Cutting effects and geometric bias inherent to analysis of a 2D surface on a 3D object. In this study, we have subsetted our data to reduce the shape bias of measuring orthorhombic grains that are crystallographically oriented oblique to the section. Only grains that have at least one crystallographic axis parallel to the plane of the sample were measured for aspect ratio, thereby improving the reliability of the measurements reported. (4) Highly heterogenous samples may not be entirely defined by the morphologic and crystallographic parameters of four regions per sample, however this assessment can be made and further regions may be characterized if sufficient variation is found between the initial four regions. The introduction of quicker and more sensitive EBSD detectors will result in larger areas being characterized and therefore more representative measurements can be obtained. Despite the limitations described, we demonstrate that microstructural analysis via EBSD mapping is a rapid, powerful tool in the characterization of meteoritic matrices, and has allowed us to quantitatively define and compare the morphologic and crystallographic fingerprint of olivine matrix grains in the three CV chondrites in this study. Grain definition via EBSD analysis is more rigorous than other imaging techniques (e.g., BSE imaging) because the grains are defined by both phase identity and crystallographic orientation. We recommend that future work should include similar characterization of matrix grains to fully encapsulate the nature of the matrix material present, and collectively insightful comparisons can be made across and between meteorite classes.

Conclusions

EBSD analyses have enabled the consistent and rapid measurement of grain size, shape, crystallographic orientation, and intragrain deformation for a significant number of grains. Allende contains the largest and most elongate olivine matrix grains (mean diameter 0.96 µm (1 S.D.- 0.98); aspect ratio 1.93 (1 S.D.- 0.74), whilst Kaba contains the smallest grains (mean diameter 0.48 µm (1 S.D. 0.35) and Vigarano contains the least elongate grains (mean aspect ratio 1.83 (1 S.D.- 0.61)). Average grain orientation spread (GOS) values are 0.93° (1 S.D.- 0.85), 0.60° (1 S.D.- 0.39) and 0.66° (1 S.D.- 0.41) for Allende, Kaba and Vigarano respectively. We propose that through comparing these parameters across a wide sample set, a deeper understanding of matrix grain formation and thermal and aqueous alteration can be gained, as alteration on the parent body was heterogeneous (e.g. Krot et al., 1995), and is a likely driver of the differences that we report here. In this instance for example, Allende appears to be the most thermally altered, which may be the reason for the larger laths present when compared to Kaba and Vigarano.

Intragrain deformation, albeit weak, is highest in Allende, perhaps indicating that it was experiencing higher temperatures than Kaba or Vigarano at the time of deformation, or that it was closer to the source of the deformation. Comparing more CV chondrites with this data would help to build a clearer picture of how the samples may have been spatially related, or infer the proximity of each sample to the source of the deformation on the parent body. Further to this, most of the sites in Allende demonstrate very weak flattening CPOs against the edges of chondrules, suggestive of weak compression or compaction, and consistent with previous findings in Allende (Forman et al., 2016; 2017). Further high-resolution investigations are required to understand the grain dimension and CPO geometry relationships of the Kaba and Vigarano matrices, however the CPO geometries are very similar to those observed in Allende. The strength of any CPOs are easily quantified using our approach, and therefore a database of this information for all CVs would improve our future interpretations of spatial relationships and compaction processing on the parent body.

This study has emphasized the importance of assessing morphologic and crystallographic characteristics of a meteoritic sample, and demonstrated what inferences can be drawn from such data. This approach, using EBSD datasets that can be obtained rapidly and over a wide area, may be easily implemented as a regular characteristic technique in addition to the traditional geochemical information, and presents information that may not be identified using qualitative analyses. A large, multi-class, standardized morphologic and crystallographic database would allow whole classes and subclasses to be compared and contrasted to identify similarities and discrepancies, and potentially reveal new grain growth and alteration features common to a number of meteorites. We propose that an approach such as this become commonplace when characterizing meteorites in future work to further our understanding of parent body processing.

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8. References

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Table & Figure Captions

***Table 1**: Collated geochemical and modal properties of the matrices in the CV chondrites Allende, Kaba and Vigarano.*

***Table 2:** Grain statistics for Allende, Kaba and Vigarano interstitial olivine matrix grains. Statistics sample grains larger than 3 pixels at each site.*

***Fig. 1:** Backscatter electron images showing site locations (left), and high-resolution secondary electron images of each site (four columns on the right). A = Allende, K= Kaba, V=Vigarano, P= Proximal, D= Distal, 1/2= Site number.*

Note that secondary electron images shown for Kaba and Vigarano are magnified to better demonstrate the appearance of the matrix grains.

Fig. 2: *Phase distribution maps of one proximal and one distal site per sample to demonstrate the general mineralogy of the matrix regions examined using electron backscatter diffraction (EBSD). A-P1/A-D1= Allende, K-P1/K-D1= Kaba, V-P1/V-D1= Vigarano. Black areas are non-indexed regions, either due to a lack of diffraction patterns or cracks/holes on the surface.*

Fig. 3: *Circle-equivalent Diameter vs. Aspect Ratio graph, showing the average dimensions calculated from combined grain data from all four sites per sample. Colored lines represent 1 standard deviation from the average, and therefore indicate where 66% of the data for each sample lies. Please note the standard deviation for circle-equivalent diameter extends below 0 µm for Allende and Kaba, but as this is purely a statistical representation of the spread of the data and is not physically possible, the range shown only extends to 0 µm.*

Fig. 4: *Grain size frequency distributions: a) Allende, b) Kaba, c) Vigarano. Sites are combined according to their proximal or distal locations with respect to chondrules, and are color-coded accordingly. The relative frequency is displayed on a logarithmic scale and normalized to the maximum value. Please note that the decrease in the frequency of grains with a diameter less than 0.25 µm for all grains is a direct result of the noise reduction and grain size thresholding performed during data processing.*

Fig. 5: *Aspect ratio vs. circle equivalent diameter for all grains with at least one primary axis parallel to the plane of the sample. This ensures accurate aspect ratio information is displayed. Note that this is a subset of the grains presented in Fig. 4 and statistics relating to this subset are shown in Table 2 as 'All axes'.*

Fig. 6: *Grain orientation spread (GOS) for olivine at sites a) A-P1, b) K-P1 and c) V-P1. The GOS is calculated as the average amount of crystallographic deviation from the mean grain orientation across each grain, indicative of the amount of deformation that has occurred.*

Fig. 7(a): *Backscatter electron images of the locations of the Allende sites are shown as representative red squares on the left. Here, the relationships with surrounding chondrules can be seen. The crystallographic orientations of each olivine grain within the sites were contoured, and the data is shown on lower-hemisphere, equal area plots on the right. M.U.D= multiples of uniform density, blue= low m.u.d, red= high m.u.d. Here, the M.U.D.max-min value given is the difference between the maximum m.u.d. and the minimum m.u.d for each site. The M-Index values were calculated using the approach of Skemer et al. (2005), whereby the crystallographic alignment can be denoted using a number between 0-1; 1 = single crystal fabric, 0= randomly oriented grains.*

Fig. 7(b): *Backscatter electron images of the locations of the Kaba sites are shown as representative red squares on the left, and corresponding lower-hemisphere, equal area plots are shown on the right. All settings and abbreviations are the same as Fig. 7(a).*

Fig. 7(c): *Backscatter electron images of the locations of the Vigarano sites are shown as representative red squares on the left, and corresponding lower-hemisphere, equal area plots are shown on the right. All settings and abbreviations are the same as Fig. 7(a).*

***Fig. 8**: a) Site A-D1 has been divided into subsets and color-coded to show 2D angle (slope) of long axis of fitted ellipse. Subsets: i) grains with a-axis perpendicular to plane of sample, ii) grains with b-axis perpendicular to plane of sample, iii) grains with c-axis perpendicular to plane of sample; b) lower hemisphere, equal area plots showing crystallographic orientations of grains in subsets (i), (ii) and (iii). Schematic green and red grains in the centres of the pole figures are overlain onto bi, ii and iii to demonstrate how grain colouring in (a) relates to the dimensions of the fitted ellipse, and the projection of longer and shorter axes in (b). For grains in subset (ii), the shorter axis of the fitted ellipse correlates to <a>, and the longer axis of the fitted ellipse correlates to <c> at this site. For subset (iii), the shorter axis of the fitted ellipse correlates to <a>, and the longer axis of the fitted ellipse correlates to <b>. For grains in subset (i), there does not appear to be a correlation, perhaps indicating the lengths of <b> and <c> are similar.*