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Earliest rock fabric formed in the Solar System preserved in a chondrule rim

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Rock fabrics – the preferred orientation of grains – provide a window into the history of rock formation, deformation and compaction. Chondritic meteorites are among the oldest materials in the Solar System[1] and their fabrics should record a range of processes occurring in the nebula and in asteroids, but due to abundant fine-grained material these samples have largely resisted traditional *in situ* fabric analysis. Here we use high resolution electron backscatter diffraction to map the orientation of sub-micrometre grains in the Allende CV carbonaceous chondrite: the matrix material that is interstitial to the mm-sized spherical chondrules that give chondrites their name, and fine-grained rims which surround those chondrules. Although Allende matrix exhibits a bulk uniaxial fabric relating to a significant compressive event in the parent asteroid, we find that fine-grained rims preserve a spherically symmetric fabric centred on the chondrule. We define a method that

quantitatively relates fabric intensity to net compression, and reconstruct an initial porosity for the rims of 70-80% - a value very close to model estimates for the earliest uncompacted aggregates[2,3]. We conclude that the chondrule rim textures formed in a nebula setting and may therefore be the first rock fabric to have formed in the Solar System.

Large inclusions in many carbonaceous chondrites are frequently surrounded by fine-grained rims (FGR). There is a continuing debate regarding their formation. Chondrule rims are generally considered to have formed prior to the incorporation of chondrules in meteorite parent bodies, with rim particles accreting onto chondrules soon after their formation in the protoplanetary disk. Thus, rims are sometimes referred to as ‘accretionary rims’. In Allende, there appears to be a relationship between the radius of the chondrule and the thickness of the FGR[5], suggesting an accretionary origin. There is also evidence of multiple phases of FGR formation in the nebula, and multiple heating events[6]. However, many favour a parent body setting rather than a nebula one[7,8]. In a study of a CV chondrite it was suggested that impacts on a parent body generated chondrule-matrix clasts, which were then rounded by abrasion during brecciation and transportation[7]. In the CM chondrites it has been argued that rims were produced via impact-compaction of porous matrix within the parent asteroid[8]. Given that rock fabrics provide arguably the clearest window on the history of deformation and compaction in a rock, in addition to controlling porosity and permeability, it is unfortunate that abundant sub-µm material in carbonaceous chondrites renders traditional techniques unusable. Palaeomagnetic studies have revealed that several bulk meteorites contain fabrics, with anisotropy interpreted as arising from asteroidal processes (impact or gravitational compaction)[9-11]. A few studies have attempted to constrain the degree of flattening of large inclusions[10,12-14]. But detailed *in situ* imaging of fabrics in primitive meteorites has proved impossible. Fabric analysis – of the type routinely applied to terrestrial rocks – is a largely undeveloped area in meteorite studies. Here we apply a relatively new technique - electron backscatter diffraction (EBSD) - to derive precise crystallographic data on grains down to ~0.3µm in size in the CV chondrite Allende, image fabric relationships, and elucidate the origins of FGRs.

In earlier work we employed EBSD mapping to show that matrix material in Allende possesses a planar fabric defined by a preferred orientation in the *a*-axis of olivine grains 100nm-µms in size, consistent with uniaxial compaction[15]. This *a*-axis fabric has the same orientation and similar intensity on a hand-sample scale[15]. Magnetic susceptibility anisotropy in Allende[9] is also attributed to the matrix fabric. The matrix fabric arises because individual olivine grains are tabular with short *a*-axes[15], and there is a strong alignment of the tabular crystals[15]. In the current study we have acquired a representative series of EBSD maps from FGR material surrounding Allende chondrules. Figure 1a shows the position of individual maps around the first chondrule; Figure 1b shows the orientation of the background matrix fabric; and the resolution of the technique is illustrated in Figure 1c. FGR olivine grains also exhibit tabular form with short *a*-axis orientations, and tabular crystals are aligned to give a preferred orientation of *a*-axes. However, unlike the matrix fabric, the FGR fabric is spherically symmetric, centred on the chondrule (Figure 1a): olivine crystals effectively ‘tile’ the chondrule (see Supplementary Figure S1 for data from a second chondrule FGR, where the section is cut such that the background matrix fabric is in the plane of the section).

Our conceptual model for the development of the *a*-axis rim fabric is that it formed by compaction of an initially random and porous aggregate of tabular olivine crystals. We now estimate the amount of compaction and from it reconstruct the pre-compaction porosity of the aggregate: that information is valuable as a comparison to modelling and experimental work, which provide specific estimates of porosity in primary accreted aggregates of nebula fines[2,3]. As compaction progressed, each olivine rotated so that its flat face became more parallel to the chondrule surface nearby and therefore the normal to the (100) plane became closer to the perpendicular to that surface. Rocks commonly contain inequant rigid objects embedded in a softer matrix, and these “passive markers” (analogous to playing cards embedded in random orientations in syrup) will rotate as the ensemble is deformed (the cards will become aligned). The degree of alignment is related to the amount of deformation: this relationship can be quantified. To quantify the degree of alignment, we use the olivine grain orientations to construct a “dispersion tensor” (see

Methods section). To quantify deformation, the strain ellipsoid in a deformed material is defined as the shape imposed on what was, before deformation, a sphere[16]. It is characterised by three principle axes, X, Y and Z, each the ratio of an initial (undeformed) to a final (deformed) length, with X being the largest. The alignment of passive markers is governed by a combination of X/Y and Y/Z[17]. Consequently we can use the dispersion tensor, calculated from observations, to infer the strain ratios X/Y and Y/Z and then, assuming compaction in a single direction, the value of Z (see Methods section).

Table 1 shows eigenvalues and calculated strain ratios from *a*-axis pole figures for the first chondrule FGR. X/Y values are expected to be ~1 because our method assumes no strain parallel to the chondrule surface during compaction. X/Y is indeed ~1 except for two datasets (both have relatively small sample size). Apart from these, the datasets show that the uniaxial assumption is viable. The Z values, being the ratios of final length to initial length of notional lines perpendicular to the chondrule surface, define the amount of compaction, and range from 0.43-0.58 (average 0.50). Thus, the compaction has roughly halved the volume of the FGR aggregate. Bulk Allende has a current porosity of 23%[18]. As igneous inclusions or lithic fragments have minimal porosity, the bulk value will largely be a function of the porosity of fine-grained materials in this rock. Given the abundance of matrix in Allende[4,19] we calculate a potential matrix porosity of 38-61%. Allende matrix shows a similar degree of compaction to our FGR[15]. If the final (observed) porosity in the rim is ϕ, the initial porosity (when the rim olivines were randomly oriented) is given by $\phi Z + (1-Z)$. Assuming matrix and rim porosities are similar, initial FGR porosity must have been of-order 70-80%.

Our fabric studies provide a new perspective on chondrite FGR formation. Allende matrix has a uniform, planar, short-axis alignment fabric that is pervasive on a cm-scale and likely the result of a major uniaxial deformational shortening event on the parent body[15]. Gravitational compaction or impact are both possibilities. As to chondrule rims, if FGRs were formed from matrix compacted against a chondrule we would observe strain shadows: low strain areas partially protected from deformation by virtue of their proximity to a rigid object (in this case, a chondrule). Strain shadows are observed in Allende matrix away from FGRs, in areas that are entirely consistent with the overall sample-scale fabric[15], but not in the FGR itself (Figure 1a and 1b). The strength of the observed fabric varies by less than 9% around the entire FGR (Table 1), showing that deformation in the FGR was spherically symmetric.

The absence of strain shadows in this FGR, the juxtaposition of uniaxial (matrix) and spherically symmetric (FGR) stress fields, and the fact that the same FGR fabrics are present in a section cut parallel to the matrix fabric (Supplementary Material), appears to rule out both parent body models[7,8]. The uniaxial matrix fabric is not consistent with multiple impacts[8], and multiple impact would not assist in forming a spherically symmetric FGR fabric. Allende matrix is porous, and collapse of pore space during impact is an irreversible process[20] occurring at very low shock pressures (~2GPa): multiple impacts could not compact matrix against a chondrule to form a FGR, and then matrix porosity recover to record a uniaxial event. As to the clast abrasion model[7], it would require that fine-grained materials retained 70-80% porosity following accretion into the CV parent body, fragmentation and brecciation during impact, ejection of clasts, and abrasion and transportation. Instead, the unusual nature of the FGR fabric, and the extremely high initial porosities that we calculate for it, suggest that it was emplaced in the nebula: chondrule acquired FGR; FGR experienced a spherically symmetric stress field and was compacted; chondrule+FGR accreted with high-porosity matrix onto the parent body; and the whole was then subjected to a major uniaxial compressive event. The FGR fabric resisted that later uniaxial event due to earlier porosity reduction. The aggregate would also be stronger if olivines had begun to anneal and establish contacts of finite area.

Allende shows evidence for secondary hydrothermal alteration within the parent body. Rim and matrix fabrics are delineated by fayalitic olivine, and there is some debate about its origin (whether primary or secondary). But secondary compositional change does not preclude survival of primary textures or fabrics (see Supplementary Material). A plausible formation mechanism involves replacement of Mg-olivine by ferrous olivine during alteration by Fe-rich fluids[21]. This could occur without significant change to either olivine crystal habit, or primary fabrics. Our fabric data and a review of the available literature (see Supplementary Material) support this view.

It has been hypothesised that rims would have accreted with high porosity in the nebula[2,3,22]. Volume filling factors obtained in particle cluster aggregation (PCA) are ~0.15[2,3]. Given the uncertainties in measured FGR porosities and laboratory and theory estimates of volume filling factors, it is interesting that our initial porosities are so close to literature PCA volume filling factors[2,3]. The correspondence between porosity in experimentally synthesised fine-grained material[2], modelled accreted aggregates[2,3], and our estimates for initial porosity in an Allende FGR suggests that PCA rims[2,3,22] were indeed the starting point for fabric formation. Yet, accretionary rims in primitive meteorites have rather low porosity. Also, rims were robust enough to survive accretion onto meteorite parent bodies, as well as any regolith processing that occurred prior to final burial and compaction. How did nebula compaction take place?

It is suggested that FGR compaction initially occurred by means of rolling motions within the porous dust layer, and with larger collisional energies aggregates restructured and became more compact down to a filling factor of ~0.33[2,3,22]. But how did the final porosity reduction occur? An effective mechanism for additional rim compaction may derive from the currently popular idea that chondrules were melted by Mach 7 nebula shock waves[23,24]. Strong shocks would have melted chondrules, but it is plausible that weaker shocks were both more numerous and more prevalent[3] (petrographic evidence supports this view: ~50% of CV chondrules have coarse-grained rims, frequently surrounded by FGRs[6]). Chondrules and their fractal aggregates would have experienced a large number of low-intensity shocks, over a wide range of collisional velocities[25], prior to accretion onto a parent body. More energetic collisions between larger agglomerations of rimmed chondrules may also have aided compaction[3]. All of these mechanisms would be consistent with the observed rim fabric. Initial aggregate restructuring; low intensity shocks; collisions between larger

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agglomerates: all would produce uniaxial compression of an FGR region, but with the time-integrated result being spherically symmetric compression.

METHODS

Electron backscatter diffraction: Areas of chondrule, FGR, and matrix were mapped in a CamScan X500 crystal probe fitted with a thermionic field emission gun, equipped with forescatter detectors and a phosphor screen, to perform automated EBSD mapping[26]. Samples were mapped by beam movement on a grid with a fixed step of 50-200nm, to ensure that each (sub) grain contained several measurement points. The EBSD pattern from each point was indexed using the program CHANNEL 5.1 from Oxford-HKL, enabling the construction of pattern quality maps, orientation maps, phase maps and pole figure plots of crystallographic orientation. For the FGR, grain orientation data and pole figure plots were derived from specific areas of the FGR, each typically comprising several hundred thousand data points, and 300-1200 olivine grains. Because mapping of the FGR was done at very high resolution (mostly 50nm steps) it involved ~100 hours of machine time.

Strain calculations: The following assumptions are made: 1) each olivine rotates in accordance with the imposed strain, as if it were a flat object embedded as a "passive marker" in a viscous matrix; 2) the olivines do not interact mechanically with each other. In this case the statistics of the olivine orientations can be mathematically related to the strain imposed[17]. First, we derive a tensor which summarises the olivine orientations. Each olivine crystal C has a (100) normal direction described by a unit vector n_i. The unit vector has ambiguous sign; the choice made is arbitrary, so a simple vector mean is not an appropriate way to summarise the average orientation. Instead the overall orientation is described by a "dispersion tensor"

$$G_{ij} = \frac{1}{N}\sum_{C} n_i^C n_j^C$$

where N is the number of measurements, and the sum is over all the crystals C. $\boldsymbol{G}$ has a unique value regardless of signs chosen for each n_i. $\boldsymbol{G}$ is symmetric and has three eigenvalues (G_{max}, G_{int} and G_{min}) which sum to 1. For a random distribution of lines, the eigenvalues are equal to each other (hence = 1/3). For a set of parallel lines (i.e. a perfect cluster), G_{max}=1, and G_{int}=G_{min}=0. These eigenvalues are related to, but do not equal, the strain values X, Y and Z. Any "isotropic" component of strain, which increases or decreases all three of X, Y and Z in proportion, does not rotate passive markers and hence does not alter the dispersion tensor $\boldsymbol{G}$. Thus the eigenvalues of $\boldsymbol{G}$ are functions of the strain ratios X/Y and Y/Z, and are used to deduce those strain ratios. The method of Harvey & Laxton[17] applies to passive *linear* markers. Instead we deal with normals to passive *planar* markers, but these behave according to similar equations in which the strain values are replaced by their inverses[27].

The dependence of dispersion tensor eigenvalues on strain ratios is expressed via indefinite elliptic integrals: equations 5-9 of Harvey & Laxton[17]. In Supplementary Material we give a Matlab implementation of that dependence for passive linear markers. Note that indefinite elliptic integrals can be defined in terms of various combinations of input parameters (angles or signs of angles), so care must be taken. For example the function F used by Harvey & Laxton[17] is related to the Maple indefinite elliptic function as follows;

$$F(\phi, \alpha) = \mathrm{EllipticF}(\sin \phi, \sin \alpha)$$

There are no analytic expressions to convert dispersion tensor eigenvalues to strain ratios, so we used an iterative numerical procedure involving the code included in Supplementary Material. Once we had a satisfactory solution for X/Y and Y/Z, we inverted those strain values because we are dealing with normals to passive planes[27]. In standard notation, Z is used for the shortest strain axis, so axes become renamed at this stage.

$X_{new}=1/Z$

$Y_{new}=1/Y$

$Z_{new}=1/X$

so that

$X_{new}/Y_{new}=Y/Z$

$Y_{new}/Z_{new}=X/Y$

In other words, the two strain ratios are simply swapped, and are shown as such in Table 1.

As mentioned above, we cannot determine the three strains X, Y and Z by this method: we need one extra constraint. When a non-porous material is deformed, and volume remains fixed, then $XYZ=1$. During the compaction we propose here, in contrast, we expect X and Y to retain their initial values of 1 (ie. no deformation parallel to the nearby chondrule surface), and $Z < 1$ (that is, lines perpendicular to the surface get shorter as compaction proceeds). Thus, we expect $X/Y=1$. In practice, the finite sample size of olivine measurements in each subarea mean that X/Y sometimes departs from this expected value. To calculate Z we cannot force both $X=1$ and $Y=1$ so assume that $X/Y=1$ ie. no area change perpendicular to the compaction direction. Consequently $Y = 1/\sqrt{(X/Y)}$ can be calculated and then Z deduced knowing Y/Z.

In summary, our method calculates dispersion tensor from measured olivine orientations; strain ratios assuming passive rotation of olivines during compaction; and strains assuming no area change perpendicular to the compaction direction.

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Author contributions

P.A.B. designed the project; P.A.B., L.E.H., D.J.P. and R.M.H. collected and analysed the data; J.W. performed strain calculations; P.A.B. wrote the manuscript; K.A.D. contributed to supplementary material; L.E.H., D.J.P., J.W. and R.M.H. edited the manuscript.

Figure captions

Figure 1. Electron backscatter diffraction (EBSD) maps of an Allende barred olivine chondrule, fine grained rim (FGR) areas that surround it, and matrix. a, Allende chondrule surrounded by [100] contoured, lower-hemisphere pole figures (PF) from high resolution EBSD maps (located by boxes) from within the FGR. The number alongside each rim PF is the number of individual olivine grains measured. In EBSD the statistical description of the intensity of a fabric is known as the multiple of uniform density (MUD) and is quantified using the maximum intensity of the contoured pole figures. A MUD of 1 indicates randomly oriented grains; a MUD significantly >1 is indicative of a fabric. The PFs at the bottom show the orientation of the chondrule; there is one point for every pixel in the map in each PF. **b,** EBSD map of matrix away from the FGR and PFs showing background matrix orientation. If matrix compaction was responsible for the FGR fabric we would see strain shadows to the right and left of the chondrule: we do not. **c,** Expanded view of the orientation contrast map from the right of the chondrule. Most FGR areas were mapped with a step size of 50 or 75nm: precise crystallographic data were obtained from grains down to ~0.3μm diameter.

Table caption

Table 1. The dispersion tensor eigenvalues, calculated strain ratios, and final value of Z for the 8 rim datasets. In quantifying an error in our estimates of strain and compaction we follow earlier work[17] suggesting that several hundred measurements are needed for reliable strain estimates: our smallest sample sets have ~300 values. We expect the X/Y values to be near 1. The table shows that for the largest sample sets this is true to within 3-5%. We therefore suggest that the Z values estimated from those large datasets are within 3-5% of the “true” values.

Figure 1.

See attached.

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Table 1.

	Eigenvalues of dispersion tensor			**Inferred strain parameters**		
	Smallest		**Biggest**	Y/Z	X/Y	**Z**
Bottom left	0.21	0.261	**0.529**	1.85806	1.18125	**0.495187**
Bottom	0.194	0.285	**0.521**	1.70593	1.34605	**0.505252**
Bottom right	0.206	0.238	**0.556**	2.10392	1.11665	**0.449793**
Right	0.226	0.236	**0.538**	2.04517	1.03386	**0.480883**
Left	0.202	0.231	**0.567**	2.19905	1.1075	**0.432109**
Top left	0.239	0.275	**0.486**	1.63769	1.11625	**0.577946**
Top	0.228	0.245	**0.527**	1.94464	1.0571	**0.500153**
Top right	0.195	0.297	**0.507**	1.605747	1.38619	**0.528946**