**PETROFABRICS IN A CHONDRULE RIM – EVIDENCE FOR A NEBULA ORIGIN.**  

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**Introduction:** The description and interpretation of petrofabrics is a fundamental aspect of geology. Although chondritic meteorites are the most primitive rocks available to us, due to the abundance of fine-grained matrix they have largely resisted traditional fabric analysis. Magnetic susceptibility, natural remanent magnetisation, and X-ray pole goniometry studies of bulk meteorites (1-4) have revealed that many chondrites contain petrofabrics. But the fabrics themselves are only observed in situ in the preferred orientation of large (>100s µm) components e.g. non-spherical chondrules (1,5-8), lithic fragments (9), and large isolated grains (10). We have used electron backscatter diffraction (EBSD) in a field emission gun scanning electron microscope to map the orientation of fine-grained materials in Allende, and quantify petrofabrics in this meteorite.

**Results:** We used automated EBSD maps (see (11) for details) with 50-200nm step sizes to reconstruct FGR microstructures around an Allende chondrule; grain orientation data (typically comprising several hundred thousand data points, and 300-1200 grains) were extracted from these maps. Earlier EBSD mapping has shown that matrix material in Allende possesses a planar fabric defined by a preferred orientation of the a-axis of fayalite grains 100nm - µm’s in size (11,12). This short-axis fabric is coherent over cm-scales (11,12). The FGR also exhibits a short a-axis orientation in fayalite grains, but in this case the fabric is spherically symmetric, centred on the chondrule (Figure 1). Sub- µm to µm-scale fayalitic olivine laths effectively ‘tile’ the chondrule.

Within the mapped areas restoration of fabrics to give random orientations requires compaction by a factor of 2. In addition, the strength of the observed fabric varies by <9% over the entire rim, suggesting an absence of strain shadows.

**Interpretation:** Magnetic susceptibility anisotropy in Allende (4) was interpreted as arising from a preferred orientation of a matrix component, acquired during uniaxial compaction of matrix grains (either during accretion of the parent body, or through a subsequent impact). Our earlier observations of a sample-scale short-axis fabric are entirely consistent with uniaxial compression within a parent body (11).

In contrast to the matrix petrofabric, the spherically symmetric chondrule rim fabric is not consistent with uniaxial compression within a meteorite parent body: both the known properties of chondrule rims, and the specific nature of the fabric we observe, indicate that the rim fabric was emplaced in a nebula setting. 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 commonly referred to as ‘accretionary rims’. In Allende, there is a clear relationship between the radius of the chondrule and the thickness of the FGR (13), suggesting an accretionary origin. Oxygen isotopic studies of accretionary rims around CAIs in CV chondrites find substantial heterogeneity in rim materials, indicating that a pre-accretionary signature has survived subsequent parent body processing (14). Similarly, analysis of trace element abundances in FGRs from Mokoia indicate an accretionary origin, and multiple dust reservoirs (15). Finally, preliminary trace element analyses of chondrule and CAI FGRs in CVs by LA-ICP-MS suggests they have distinct compositions, supporting an accretionary origin (16). If the FGR is accretionary, it is reasonable to conclude that the rim fabric may also have arisen during accretion of the rim.

We observe a fabric in fine-grained rim materials that is spherically symmetric around the chondrule. This would imply a spherically symmetric stress field acting on rim particles either before or after they accreted onto the chondrule. It is difficult to envisage how such a field could occur within an asteroid. Spherically symmetric fabrics have not been described in terrestrial rocks, where the most common principal stress field is uniaxial. However, they may well be present in situations where nodules, concretions, or porphyroblasts have grown in a mass of finer grained material – volume change during growth should produce a compaction fabric in the surrounding material. Clearly, this does not apply in the case of chondrules and rims. It has been sug-
gested that rims in CM chondrites were formed by compaction of high-porosity matrix against comparatively incompressible chondrules and CAIs during multiple impact events, followed by regolith gardening (17). While we cannot comment on the CM chondrites, it would appear to be more difficult to apply this model to Allende. Allende possesses a uniform, planar, short-axis alignment fabric that is pervasive on a cm-scale and likely the result of a single major deformational shortening event (12). Our chondrule+FGR (with a spherically symmetric fabric) is therefore embedded within a matrix that shows a fabric consistent with uniaxial compression. In addition, dark inclusions in Allende possess fabrics that are conformable with the broader matrix fabric, and strain shadows are observed in matrix close to parts of the inclusion margins - analogous to augen in terrestrial rocks (12). Strain shadows are absent in our FGR. These observations suggest that the chondrule acquired a FGR, it was compacted prior to accretion, chondrule+FGR were accreted with high-porosity matrix (and DI), and the whole was then subjected to a major uniaxial compressive event.

It is likely that chondrule rims initially accreted with extremely high porosity (18). Yet, accretionary rims in primitive meteorites have rather low porosity (~20%). In addition, they were robust enough to survive accretion onto meteorite parent bodies, as well as any regolith processing that occurred prior to final burial and compaction. Modelling of collisions between fluffy aggregates (19) found that with low collision energies clusters will stick and attach at their first point of contact, just as two monomers would, forming a larger cluster. With larger collision energies, the aggregates restructure, and become more compact. This process proceeds to greater degree and density, until some disruption threshold energy is reached. In addition, triboelectric charging effects (20,21) might play a role, potentially increasing the disruption threshold. In modelling the process of rim formation, Cuzzi (22) found that restructuring of fluffy aggregate rims starts at impact velocities of ~10 cm/sec, with maximum compaction near ~50 cm/sec, and disruption beginning >300 cm/sec. Could our rim fabric have formed by compaction of a high-porosity rim in the nebula as new rim materials were accreted (22)? This mechanism would certainly be consistent with the observed rim fabric. While each individual impact on a porous rim would produce local uniaxial compression, the time-integrated result of multiple impacts would be spherically symmetric compression.

Conclusion: The origin of Allende matrix components remains a matter of debate. Certainly, analyses of Allende matrix chemistry do not provide evidence for a secondary origin (23-25). But whether the fayalitic olivine that dominates matrix was formed in a nebula or asteroidal setting, the most straightforward interpretation of our data is that the fabric now delineated by rim fayalites was imposed in the nebula. This clearly favours a nebula origin for fayalitic olivine, but does not necessarily preclude asteroidal formation. If fayalitic olivine was produced by an asteroidal process, our data do place constraints on the nature of that alteration. It would suggest that alteration must have been topotactic – replacement of the primary mineral without substantially disturbing the original crystal structure, with wide-spread inheritance of structural polymers by the weathering product. This type of alteration is frequently observed in terrestrial samples (26-29). In the context of Allende, such a process could allow a primordial fabric to be preserved by a secondary mineralogy. But whatever the origin of fayalitic olivine, the observation of a spherically symmetric chondrule rim fabric seems to require that primordial rim grains must have been crystalline and tabular - irregular amorphous materials would not be oriented by compaction.