Shock fabrics in fine-grained micrometeorites

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Abstract—The orientations of dehydration cracks and fracture networks in fine-grained, unmelted micrometeorites were analyzed using rose diagrams and entropy calculations. As cracks exploit pre-existing anisotropies, analysis of their orientation provides a mechanism with which to study the subtle petrofabrics preserved within fine-grained and amorphous materials. Both uniaxial and biaxial fabrics are discovered, often with a relatively wide spread in orientations (40°–60°). Brittle deformation cataclasis and rotated olivine grains are reported from a single micrometeorite. This paper provides the first evidence for impact-induced shock deformation in fine-grained micrometeorites. The presence of pervasive, low-grade shock features in CM chondrites and CM-like dust, anomalously low-density measurements for C-type asteroids, and impact experiments which suggest CM chondrites are highly prone to disruption all imply that CM parent bodies are unlikely to have remained intact and instead exist as a collection of loosely aggregated rubble-pile asteroids, composed of primitive shocked clasts.

INTRODUCTION

Craters are ubiquitous on the surfaces of solar system small bodies (Melosh 2011) and testify to the prevalence and importance of impact events as a major geological process in our solar system. On small, primitive asteroids, residual heat from planetesimal formation and heat generated from radiogenic decay are lost to space (Kunihiro et al. 2004). Impact events are, therefore, the principal source of energy which drives geological processes (Rubin 1995; Nakato et al. 2008; Davison et al. 2012). On such asteroids, impacts are responsible for compaction, shock metamorphism, fracturing, regolith gardening, and potentially aqueous alteration (Housen et al. 1979; Tomeoka et al. 1999; Rubin 2012; Hanna et al. 2015).

Shock fabrics are widely reported among meteorites (Gattacceca et al. 2005; Watt et al. 2006). Stöffler et al. (1991) established a classification scheme to quantify the shock state of individual meteorites. This system ranges from S1 to S6 and is based on petrographic features observable under thin section. Shock stages relate to ranges in absolute shock pressure and reflect the deformation responses of diagnostic index minerals, notably olivine and plagioclase. Different meteorite groups appear to show different shock stages, for example, the most shocked carbonaceous chondrite groups are the anhydrous CV and CK chondrites, typically exhibiting shock stages of S3–S4, while CM chondrites display the lowest shock stage (S1) with only very rare S2 and S3 members (Scott et al. 1992; Rubin 2012).

Although CM and CI chondrites are classified with low S1 shock stages (<5 GPa, essentially unshocked), abundant petrographic evidence of shock has been reported; this includes crushed chondrules (Scott et al. 1992; Nakamura 2006; Hanna et al. 2015), fracture melt veins (Zolensky et al. 2014a), and heterogeneous brecciated regolith samples, representing amalgamations of several distinct CM lithologies (Metzler et al. 1992; Nakamura 2006; Lee and Nicholson 2009; Zolensky et al. 2014b, 2016). At the microstructural level, brittle deformation cataclasis and grain boundary sliding have also been reported from within chondrules (Hanna et al. 2015). As CM chondrites contain a significant matrix component (up to 85% volume) (McSween 1979), which
is composed of hydrated sheet silicates, pervasive deformation fabrics may be expected after shock. Several studies have identified a subtle foliation among CM chondrites, formed where platy phyllosilicate minerals align parallel to the σ3 stress axis and wrap around flattened chondrules. These petrofabrics have been revealed by analysis of aligned chondrules using 3D μCT (Lindgren et al. 2015) and 2D BSE imaging techniques (Rubin 2012) and from the analysis of aligned matrix phyllosilicates via X-ray goniometry (Fujimura et al. 1982, 1983).

In large impact events, asteroids are broken up, generating an asteroid family, composed of many smaller objects with similar orbital properties (Hirayama 1918). Some of the youngest asteroid families are <300 Ka (Nesvorný and Vokrouhlický 2006), while the oldest recognizable asteroid family is the Themis superclass whose break-up event is dated to 2.0 ± 0.5 Ga (Nesvorný et al. 2003). During the disruption of chondritic asteroids, abundant submillimeter dust is liberated (Flynn et al. 2009); a fraction of this material arrives on Earth and is recovered from sedimentary rocks. This material is termed micrometeorites (MMs) (Genge et al. 2008). Geologically, recent break-up events are expected to supply Earth with the current dust flux. Today MM collections are dominated by hydrated, phyllosilicate-bearing grains (Genge et al. 2001; Taylor et al. 2012) which most closely resemble CM chondrites in their geochemistry (Steele 1992; Kurat et al. 1994), oxygen isotopes (Suavet et al. 2010; Van Ginneken et al. 2015), microscale textures (Genge et al. 1997), and organic matter (Suzuki et al. 2010; Dobrică et al. 2011).

Although shock deformation features (annealed metal sulfide veins and mosaism in olivine) were identified in anhydrous, coarse-grained micrometeorites (Genge 2007), corresponding shock deformation in fine-grained micrometeorites (FgMMs) has not been reported. Tomioka et al. (2007) suggested that the flash heated matrix in unmetelated FgMMs and partially melted scoriaceous micrometeorites (ScMMs) may be products of rapid in-space shock metamorphism during dust liberation. This is because experimentally shocked fragments of the CM chondrite Murchison, at pressures ranging 10–49 GPa, show similarities to heated FgMMs. In low-level shocks (<10 GPa), phyllosilicates become dehydrated or dehydroxylated, while in high-pressure events (~49 GPa), the matrix anneals, forming a recrystallized olivine groundmass. However, the presence of igneous rims on most unmetelated FgMMs demonstrates that the majority of dust grains are hydrated at the point of collision with the Earth’s atmosphere and experience dehydration and recrystallization during atmospheric entry (Toppani et al. 2001; Genge 2006). Mineralogical changes are, therefore, unlikely to accompany shock deformation in MMs. However, as the internal textures in FgMMs most closely resemble CM chondrites, these grains may be expected to preserve weak petrofabrics inherited from their parent asteroid.

Individual phyllosilicate crystals in FgMMs are submicron scale (Nakamura et al. 2001). Therefore, SEM-BSE imaging cannot directly observe the orientation of phyllosilicate crystals (nor are crystal cleavage planes or crystal grain boundaries resolvable). Instead, petrographic proxies for phyllosilicate orientation are required. This study measures sublinear void space in fine-grained and ScMMs. The majority of sublinear voids will be products of atmospheric entry heating. In the early stages of thermal decomposition, phyllosilicates dehydrate. Sheet silicates contract along the [001] plane as interlayer water is lost from in between sheets (Shen et al. 1990; Nozaki et al. 2006). This results in the formation of dehydration cracks within the matrix (Toppani et al. 2001; Genge 2008). The orientation of dehydration cracks will be defined by the basal cleavage planes of the phyllosilicate crystals and will, therefore, reveal the local alignment of micron-scale grains. This means that if the phyllosilicates in a MM were aligned prior to atmospheric entry then the dehydration cracks within a heated MM should also be aligned. With continued atmospheric heating, dehydration cracks grow and coalesce. As cracks widen, they lose their linearity and form rounded vesicles (Toppani et al. 2001). In scoriaceous particles where dehydration cracks have evolved into larger rounded vesicles, residual traces of the relict fabric within the matrix are lost. However, as many unmetelated MMs experience complete recrystallization of their matrix phyllosilicates into a hyperfine olivine groundmass prior to significant partial melting (Nakamura 2005; Lee et al. 2016; Suttle et al. 2017), the preatmospheric phyllosilicate orientation will be preserved in both dehydroxylated and annealed, recrystallized FgMMs. The measurement of dehydration crack orientation may therefore provide a mechanism with which to study preatmospheric parent body petrofabrics. In this article, 20 unmetelated fine-grained and ScMMs are investigated using high-resolution BSE imaging. Image analysis techniques are employed to evaluate the internal textures of grains, thereby revealing whether MMs preserve preatmospheric petrofabrics.

METHODS

The MMs analyzed in this study were recovered by melting and filtering blue ice at Cap Prudhomme in Antarctica (Maurette et al. 1991). The resulting residues
were picked under an optical binocular microscope, and potential MMs were embedded in resin, sectioned, and polished. The exposed particle interiors were imaged by scanning electron microscope (SEM) at the Imaging and Analysis Centre of the Natural History Museum, London. All grains analyzed in the present study had previously been established as extraterrestrial on the basis of diagnostic textures (Genge et al. 1997), and chondritic bulk compositions, following the criteria outlined in Genge et al. (2008). The majority of these particles have previously been published in Genge (2006), Genge et al. (2008), and in Genge (2008).

A high-resolution field emission FEI Quanta 650 SEM was used to collect whole particle BSE images of the entire MM population. The image analysis software, ImageJ (Schindelin et al. 2015), was used to resolve void space (dehydration cracks, fractures, and sublinear vesicles) from matrix. This was achieved by thresholding until a bimodal black-and-white image of the particle was produced. The “particle analysis” function then identified individual voids. Accepting voids whose circularity value was between 0 and 0.7 (approximately 80–98% of the total voids identified) ensured that only linear and sublinear features were considered. All voids <2 μm in length and <1 μm² were ignored to reduce the noise in data sets. Many of these small, nanoscale voids are likely to be artifacts of the processing procedure, especially where a void space is identified by only a few pixels. For each void, the Feret’s diameter or caliper length (long axis) and the Feret’s angle (the angle that long axis makes with respect to an arbitrary reference frame) were calculated. The void space outlines, identified by the software, were cross-referenced against the original BSE images to ensure accurate extraction of data. Voids which were in contact with the particle perimeter could not be resolved by the image analysis software and are not included in the analysis. Figure 1 provides an example of the processed and raw images for a single MM.

Void orientations were binned by 10° increments and used to generate a circular histogram plot, referred to as a rose diagram. These plots were constructed in GeoRose (Yong Technology Inc. 2014) and directional statistics were calculated using GEOrient (Holcombe 2017). In this study, we report standard directional statistics (Tables 1 and 2), including circular standard deviation, circular kurtosis, circular variance, and the kappa coefficient (Mardia and Jupp 2000, p. 19–23; Berens 2009).

Circular kurtosis calculates the peakedness of a distribution. For uniaxial data sets which are accurately described by a von Mises distribution (the circular analog of a normal distribution), kurtosis values are close to 0. Consequently, positive values indicate a sharp peak and negative values indicate a flat peak. The kappa coefficient (κ), also known as the von Mises concentration parameter estimate, is a reciprocal measure of dispersion. When κ is small, the distribution approaches a uniform isotropic model, with no preferred orientation, while high values of κ reflect void orientations concentrated around the mean direction. As κ increases, the distribution approximates the von Mises distribution (Mardia and Jupp 2000, pp. 36–40). Circular variance and circular standard deviation also provide measures of the spread in the data set around the resultant vector. Variance values range between 0 and 1, and low values reflect a narrow spread in void orientations and consequently, imply a preferred orientation. Conversely, high variance values, close to 1, imply a random spread in orientations and a lack of preferred orientation.
However, as circular variance, standard deviation, kurtosis, and kappa all measure the spread of voids away from a resultant vector, these metrics are appropriate only for uniaxial distributions and can produce inaccurate and misleading values for multimodal distributions (Mardia and Jupp 2000, pp. 19–23 and 36–40; Berens 2009). For example, a perfectly biaxial fabric may produce in a high variance value, owing to a significant spread in orientations (e.g., at ~90° intersection angles), despite a strong degree of preferred orientation, with all voids concentrated into relatively few bins. This effect is most pronounced in equal-strength multimodal fabrics and less problematic for pseudo-uniaxial fabrics which contain a dominant orientation and weaker secondary orientation (Table 1).

To counteract the problem of multimodal fabrics being mistakenly interpreted as weak or nonexistent, we also employed an alternative metric to quantify petrofabric strength, entropy. Mohajeri and Gudmundsson (2012) and Mohajeri et al. (2014) developed a simplified version of Shannon’s entropy to evaluate the degree of preferred orientation among street networks in urban settlements and fracture networks in fault blocks. We employed the same approach, altering only the constant (α) to evaluate the void orientations measured from our FgMM population. This entropy calculation provides a quantitative assessment of petrofabric in a perfectly isotropic uncompacted MM, void orientations should plot randomly to produce a circular uniform rose diagram. Conversely, in a compacted MM, voids should be aligned, demonstrate a preferred orientation, and plot within a restricted arc (or in the case of a multimodal fabric, several arcs) on a rose diagram. Consequently, the entropy of a rose diagram with a preferred orientation will be lower than that of a random rose (as demonstrated in Table 1). The following entropy calculation is used in this study:

\[ S = -\alpha \sum_{i=1}^{t} P_i \ln(P_i) \]  

(1)

In this equation, \( \alpha \) is an arbitrary constant (in this case 1) which corrects for negative values, \( t \) is the number of bins on the rose diagram (in this case 18 bins of 10° each), and \( P_i \) is the percentage of voids aligned in a given orientation. Entropy values are dimensionless numbers, and for this system, maximum entropy, calculated assuming a perfectly even distribution of voids per bin (Table 1), gives \( S_{\text{MAX}} = 2.89 \). By contrast, entropy values calculated from our MM population ranged from 2.17 to 2.83.

Because the entropy calculation makes no assumptions about the underlying distribution and instead calculates fabric strength only on the basis of void partitioning, this calculation can evaluate both uniaxial and multimodal fabrics simultaneously. For example, in a low entropy system, and therefore a strong petrofabric, the majority of voids are concentrated into relatively few bins. This could be either as a single narrow arc, or as two separate arcs. As long as the partitioning is the same, the clustering or location of the bins on the rose does not matter; the resulting entropy value will be the same. However, the entropy calculation does not provide an assessment of the fabric type, that is, uniaxial fabrics cannot be distinguished from multimodal fabrics on the basis of the entropy values. Therefore, assessment of petrofabric strength, entropy. Mohajeri and Gudmundsson (2012) and Mohajeri et al. (2014) developed a simplified version of Shannon’s entropy to evaluate the degree of preferred orientation among street networks in urban settlements and fracture networks in fault blocks. We employed the same approach, altering only the constant (α) to evaluate the void orientations measured from our FgMM population. This entropy calculation provides a quantitative assessment of petrofabric. In a perfectly isotropic uncompacted MM, void orientations should plot randomly to produce a circular uniform rose diagram. Conversely, in a compacted MM, voids should be aligned, demonstrate a preferred orientation, and plot within a restricted arc (or in the case of a multimodal fabric, several arcs) on a rose diagram. Consequently, the entropy of a rose diagram with a preferred orientation will be lower than that of a random rose (as demonstrated in Table 1). The following entropy calculation is used in this study:

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Table 2. Circular statistics and entropy data for the MM population. CM chondrites Cold Bokkeveld and Jbilet Winselwan are also included as references. These samples were sourced from the NHM, London collections on a research loan and are identifiable by their section and processing numbers BM19002, P20501, and BM1023,M4 P18927, respectively. Error margins for calculated entropy values vary by <0.12. Entries shown in black have low entropy values ($S < 2.62$ [Cold Bokkeveld]), low variance values ($r^2 < 0.3$), and high kappa concentration factors ($\kappa > 0.5$), and therefore have a well-defined preferred in their void orientations and consequently strong petrofabrics. By contrast, entries shown in gray have higher variance values and lower kappa concentration factors; although their entropy values may still be within error of the threshold value defined by Cold Bokkeveld, the presence of petrofabrics in these grains carries a higher degree of uncertainty.

| No. | Sample     | Type | N (subjective) | Fabric parallel to elongation axis | Entropy ($S$) | $S < S_{\text{cutoff}}$ | Circular variance ($r^2$) | Circular kurtosis | Circular SD (°) | Kappa ($\kappa$) |
|-----|------------|------|----------------|-----------------------------------|--------------|-------------------------|-------------------------|------------------|----------------|-----------------|
| 1   | CP94-050-079 | ScMM | 40             | No—perpendicular                  | 2.17         | Positive               | 0.10                    | -40.74           | 26.84          | 1.71            |
| 2   | CP94-050-136 | FgMM | 31             | Yes                              | 2.31         | Positive               | 0.13                    | -18.4            | 30.52          | 1.38            |
| 3   | CP94-050-167 | FgMM | 175            | Yes                              | 2.38         | Positive               | 0.11                    | -29.4            | 28.14          | 1.58            |
| 4   | CP94-050-140 | FgMM | 32             | No—oblique                       | 2.51         | Positive               | 0.41                    | -7.91            | 39.78          | 0.82            |
| 5   | CP94-050-110 | FgMM | 90             | No—oblique                       | 2.62         | Probable               | 0.23                    | -7.14            | 41.13          | 0.76            |
| 6   | CP94-050-170 | FgMM | 72             | No—oblique                       | 2.64         | Probable               | 0.21                    | -5.67            | 38.53          | 0.87            |
| 7   | CP94-050-096 | ScMM | 151            | Yes                              | 2.66         | Probable               | 0.33                    | 0.08             | 51.18          | 0.41            |
| 8   | CP94-050-127 | FgMM | 88             | No—elongation axis               | 2.71         | Probable               | 0.25                    | -3.78            | 43.07          | 0.68            |
| 9   | CP94-050-123 | FgMM | 121            | No—oblique                       | 2.71         | Probable               | 0.24                    | -5.34            | 42.56          | 0.7             |
| 10  | CP94-050-096 | FgMM | 79             | Yes                              | 2.73         | Probable               | 0.27                    | -1.49            | 54.72          | 0.33            |
| 11  | CP94-050-160 | FgMM | 107            | No—perpendicular                 | 2.73         | Probable               | 0.37                    | -1.11            | 53.82          | 0.35            |
| 12  | CP94-050-139 | FgMM | 90             | Yes                              | 2.74         | Probable               | 0.38                    | -0.99            | 58.54          | 0.25            |
| 13  | CP94-050-163 | FgMM | 187            | Yes                              | 2.74         | Probable               | 0.39                    | -1.17            | 51.95          | 0.39            |
| 14  | CP94-050-142 | FgMM | 74             | No—perpendicular                 | 2.75         | Probable               | 0.37                    | -1.12            | 53.82          | 0.35            |
| 15  | CP94-050-152 | FgMM | 78             | No—oblique                       | 2.75         | Probable               | 0.41                    | -0.99            | 58.54          | 0.25            |
| 16  | CP94-050-074 | FgMM | 66             | No—elongation axis               | 2.75         | Probable               | 0.34                    | -1.17            | 51.95          | 0.39            |
| 17  | CP94-050-270 | FgMM | 134            | No fabric                        | 2.80         | Negative               | 0.34                    | -2.1             | 52.57          | 0.38            |
| 18  | CP94-050-054 | FgMM | 155            | No fabric                        | 2.82         | Negative               | 0.38                    | -0.89            | 56.29          | 0.29            |
| 19  | CP94-050-048 | ScMM | 98             | No fabric                        | 2.82         | Negative               | 0.52                    | -0.48            | 68.99          | 0.11            |
| 20  | CP94-050-168 | FgMM | 214            | No fabric                        | 2.83         | Negative               | 0.53                    | -0.05            | 70.9           | 0.09            |
| 21  | Cold Bokkeveld | CM2.2 | 1054        | –                                | 2.62         | Positive              | 0.23                    | 0.32             | 41.43          | 0.75            |
| 22  | Jbilet Winselwan | TM-CM | 950        | –                                | 2.78         | Threshold value        | 0.44                    | 0.36             | 61.52          | 0.2             |

Shock fabrics in fine-grained micrometeorites
type was performed on the basis of intersection angle between local maxima on rose diagrams.

The calculated entropy values were used to infer the presence and strength of petrofabrics. This was achieved by comparing the entropy values from the micrometeorite population against the entropy values calculated for two CM chondrites with known shock textures. Cold Bokkeveld and Jbilet Winselwan were used as reference standards. These samples were available for analysis on a temporary loan from the NHM, London and are both regolith breccias whose petrographic evidence implies they have spent significant time on the surface of their parent asteroid (Greenwood et al. 1993, 1994; Lee 1993; Zolensky et al. 2016) and contain abundant shock textures. Twinned calcite (Barber 1981); elongated, flattened chondrules (Metzler et al. 1992); flattened CAIs (Greenwood et al. 1993, 1994); and calcium sulfate-filled fracture sets (Lee 1993) are reported as evidence of shock from Cold Bokkeveld. Jbilet Winselwan has experienced flash heating effects from intense shock events and contains metal sulfide melt veins (Zolensky et al. 2016). The entropy values for Cold Bokkeveld and Jbilet Winselwan are \( S = 2.619 \) and \( S = 2.783 \), respectively. These values therefore provide context to the entropy values determined for the MM population and allow interpretation of petrofabric strength. An arbitrary cut-off value is set at \( S < 2.78 \) (the value for Jbilet Winselwan). Any MMs whose entropy values are greater than this threshold cannot reliably be considered to demonstrate a petrofabric.

As the MM samples are embedded in resin and sectioned prior to analysis, the observation of textures is restricted to the exposed surface. “Plane of section” effects will prevent direct measurement of a preferred orientation perpendicular to the long axis. The rose diagram data are, therefore, flattened two-dimensional approximations of the true particle’s texture and calculated fabric strengths will be underestimates of true fabric strength.

**RESULTS**

On the basis of the maximum entropy threshold \( (S < 2.783 \) [Jbilet Winselwan]) defined in the methods section, a preferred orientation in void alignment is identified among 80% (16 particles) of the MMs analyzed (see Table 2; Figs. 2 and 3). However, if the circular variance and kappa concentration factor statistics are also considered, then the number of MMs with a distinct fabric decreases and a clear split in the data set is observed (Table 2; Fig. 4). Nine micrometeorites (45%) (and Cold Bokkeveld) share low entropy values \( (S < 2.78 \) [Jbilet Winselwan]), low variance values \( (\sigma^2 < 0.3) \), and high kappa values \( (\kappa > 0.5) \). Such agreement between the conventional circular statistics and the entropy calculation indicates that these two techniques provide complementary results, at least for uniaxial and pseudo-uniaxial distributions. Furthermore, this agreement also ensures a high degree of confidence for rejecting the null hypothesis (that elongated voids within MMs are randomly orientated). Instead, it can be concluded that a preferred orientation in voids, and by inference the presence of well-developed petrofabrics, are present in at least 45% of the FgMMs analyzed.

For the remaining 11 micrometeorites (55%), their entropy values and circular statistics indicate that preferred alignments are either weak or absent. Three grains (CP94-050-110, CP94-050-127, and CP94-050-160) have low entropy values \( (S < 2.619) \) but moderate variance \( (0.3 < \sigma^2 < 0.45) \) and moderate kappa values \( (0.5 > \kappa > 0.41) \). Analysis of the rose diagrams for these grains (Figs. 3.5, 3.8, and 3.11) show void orientations are concentrated into relatively few bins and therefore produce low entropy values. However, these bins are not clustered in a single arc and hence produce higher variance and lower kappa values. As a result, it can be concluded that these grains contain multimodal fabrics of moderate strength (biaxial in CP94-050-127 and CP94-050-160, and triaxial in CP94-050-110). The circular statistics have, therefore, underestimated the fabric strength in this instance.

Among particles with a uniaxial fabric and a moderate entropy \( (S < 2.7) \), more than 80% of voids plot in a narrow arc \( (40^\circ–60^\circ) \). As entropy increases, void orientations scatter and the dominant direction becomes less pronounced. For particles with \( S > 2.75 \) (Figs. 2.14–2.16, and 3.14–3.16), trends are less evident from the rose diagram; these particles have therefore been considered as possible fabrics in Table 2, while particles with \( S > 2.8 \) (Figs. 2.17–2.20 and 3.17–3.20) have essentially random distributions.

Biaxial fabrics typically show a small intersection angle \( (<40^\circ) \) between void sets, similar to conjugate fracture pairs formed in triaxial compression experiments (Wawersik and Fairhurst 1970). Conversely, in CP94-050-127 (Figs. 2.8 and 3.8), void sets are perpendicular and present as a dominant and subordinate pair. In 30% of grains, the direction of the dominant void orientation follows the elongation axis of the particle; this is most clear in CP94-050-136, CP94-050-167, and CP94-050-109 (Figs. 2.2, 2.3, 2.7, 3.2, 3.3, and 3.7) which have well-defined fabrics and a clear particle elongation direction.

Both CM chondrites have biaxial fabrics (Fig. 5) composed of a dominant and subordinate pair of voids. The angle of intersection between fabrics is \(-90^\circ \) for Cold Bokkeveld and \(80–90^\circ \) for Jbilet Winselwan.
Intersection angles within the meteorites are, therefore, significantly wider than those typically observed among the FgMM population. Cold Bokkeveld ($S = 2.619$, $\sigma^2 = 0.23$, and $\kappa = 0.75$) has a stronger fabric than Jbilet Winselwan ($S = 2.783$, $\sigma^2 = 0.44$, and $\kappa = 0.20$). In Cold Bokkeveld, large (>1 mm) voids are clearly resolvable in the BSE image and their orientation agrees well with the dominant void set identified in the rose

Fig. 2. BSE image panel for the 20 unmelted fine-grained or partially melted scoriaceous MMs analyzed in this study. This figure should be cross-referenced with Fig. 4, which illustrates the rose diagram fabrics for each grain. All scale bars are 50 $\mu$m.
Fig. 3. Image panel depicting rose diagrams of void orientation for the entire MM population. Plots are ordered by increasing entropy, such that frame 1 shows the particle with the strongest petrofabric. The metadata for each rose is shown below and includes: N, the number of cracks considered; S, the entropy value for the subject rose; and F, the fabric type, either uniaxial (U), biaxial (B), triaxial (T), or absent (X).

diagram; pervasive voids are absent from this chip of Jbilet Winselwan. For all samples, void length follows a power law distribution, an example of which is shown in Fig. 6 (particle CP94-050-109), by a linear regression line in log–log plot of void length versus cumulative number of voids greater than a defined length.
A single MM, particle CP94-050-167 (Fig. 7), has a unique set of fractures. This grain has a low entropy ($S = 2.383$, the 3rd strongest fabric observed), low variance ($r^2 = 0.11$), and high kappa value ($\kappa = 1.58$). The internal texture is dominated by elongate, angular, olivine crystals and long, subparallel voids. Olivines are tabular, occupy approximately 50% of the particles’ exposed surface area and range in size from submicron to ~10 $\mu$m in length. These crystals are homogenous (lack zoned profiles or smooth irregular Fe-enriched mantles) and show a narrow compositional range, demonstrated by their similar grayscale values under BSE. The matrix of this particle matrix is similar to other FgMMs analyzed in this study and composed of a fine-grained mix of amorphous dehydroxylates and Fe-oxide phases. Both magnetite rims and igneous rims are absent but dehydration cracks are common. The olivine grains in CP94-050-167 are strongly aligned with the elongation axis of the particle, creating a pervasive fabric. Clustered, granoblastic Fe-oxide aggregations form equigranular obstacles, which the elongate olivine grains wrap around, forming a weakly foliated texture. Abundant subparallel crack structures are also present and aligned with the elongation direction of the particle. In addition, two prominent shear fractures are present and have intersected and split multiple olivine crystals, leading to a distinctive cataclasis texture. The exposed jagged terminal ends of angular olivine crystals interlock. Adjacent to the shear fractures, olivine grains are rotated toward the fracture plane, allowing a dextral shear sense to be identified. Crystal grain size also decreases with proximity to the fracture planes.

**DISCUSSION**

**Petrofabrics in Fine-Grained Micrometeorites**

In this study, between 45 and 80% of FgMMs analyzed contain a petrofabric (dependent on the statistical metric used). Although these fabrics are defined by dehydration cracks, formed during atmospheric entry, their orientation is dependent on the pre-existing orientation of phyllosilicates, which is a parent body signature. Three formation mechanisms are possible: (1) aligned coarse-grained phyllosilicates formed during aqueous alteration; (2) crystals aligned by static compaction on an accreting planetesimal, in a manner analogous to burial of sediments on Earth; or (3) alignment through (successive) compaction from impact events.

Coarse-grained phyllosilicates are reported in CM and CI chondrites and found replacing anhydrous silicates, occupying vugs and veins or infilling chondrules mesostasis (Tomeoka and Buseck 1988; Zolensky et al. 1993). These coarse-grained phyllosilicates develop planar parallel crystals several microns in length. However, these coarse-grained phyllosilicates are localized, relatively rare components of chondrites. Furthermore, several distinct coarse-
grained clusters are unlikely to be aligned in the same orientation. Therefore, it is unlikely that aqueous alteration is responsible for the observed petrofabrics. Terrestrial shales and mudstones, rich in phyllosilicate minerals, develop bedding-parallel fabrics during burial as phyllosilicates align (and recrystallize) under pressure. The overburden necessary before phyllosilicate alignment occurs is empirically constrained by two independent studies at depths >2400 m (Ho et al. 1999; Day-Stirrat et al. 2008). However, the alignment of phyllosilicates during diagenesis may also require the loss of pore fluid, fluid overpressure, and the recrystallization of smectite as illite (Ho et al. 1999; Day-Stirrat et al. 2008). Assuming a simplistic scenario in which pore fluid is negligible, a likely scenario as porosities are observed to decrease below 10% at ~1000 m below the seafloor (Ho et al. 1999), the effective pressure at 2400 m will be a product of the entire vertical stress of the overlying sediment, transmitted by grain-to-grain stress bridges, plus the weight of the overlying water column. Using the average water depth of the ocean (2000 m) and a generic crustal sediment density (2500 kg m\(^{-3}\)), the effective pressure needed to generate aligned phyllosilicates in terrestrial shales is approximately 78.5 MPa (calculations are shown in Data S1 A in supporting information). Based on calculations of core pressure within the four largest C-complex asteroids (shown in Data S1 B), only bodies >300 km in diameter are able to support sufficient core pressure to form aligned phyllosilicates, and therefore, contain discernible petrofabrics. The observed petrofabrics in our MM population are, therefore, unlikely to have formed by static compression.

Alternatively, impact events were common in the early solar system and many meteorite samples present evidence of shock deformation. Several FgMMs in this

![Fig. 5. Petrofabrics in CM chondrites Cold Bokkeveld and Jbilet Winselwan. BSE images of each chip are accompanied by their rose diagram analysis of fracture orientation. Both chondrites contain biaxial fracture networks, with a dominant and subordinate pair of orientations with approximately perpendicular intersection angles. The alignment of fractures from the rose diagrams agrees well with a subjective assessment of fabric in both these grains. Although these were not explicitly analyzed in this study, both chondrites appear to contain flattened chondrules which are aligned with the dominant fracture orientation. Scale bars are 1000 μm.](image)

![Fig. 6. Log–log plot depicting cumulative crack length in CP94-050-109. A linear regression line on a log–log plot indicates a power law relationship; this is the expected size distribution profile for all fracture networks.](image)
study show biaxial fabrics with oblique intersection angles, this may be explained by considering shock wave propagation through CM lithology. Hydrated carbonaceous chondrites contain abundant pore space. During an impact event, shock waves are rapidly attenuated by the closure of pore space (Davison et al. 2012; Rubin 2012; Lindgren et al. 2015). Consequently, shock deformation primarily affects only the outer layers of an asteroid. Here, shocked phyllosilicates align approximately perpendicular to the local surface. Successive impact events, impinging over a range of random angles, result in noncoaxial shear. This causes the generation and subsequent rotation of local foliation toward the shear plane (Fossen 2010, pp. 41–46). Initially, immature multimodal fabrics are produced whose intersection results in the secondary lineation fabrics (Gattacceca et al. 2005; Smith et al. 2006; Hanna et al. 2015). With continued compaction, previous petrofabrics are overprinted (Smith et al. 2006), and ultimately develop into a single dominant uniaxial petrofabric (Smith et al. 2006; Fossen 2010, pp. 41–46; Lindgren et al. 2015). The range of petrofabrics observed within our FgMM population is, therefore, consistent with a multiple event impact-processing origin.

Fig. 7. Cataclasis fabric and shear band deformation in CP94-050-167. A) BSE image of CP94-050-167 with magnified areas C and D shown. A pervasive fabric can be discerned, highlighted by the alignment of olivine crystals and fractures, which trend left–right. B) A schematic sketch of CP94-050-167 illustrating the inferred stress regime, the presence of major fractures (which form a conjugate pair), and position of the cataclastic shear band. C) This image focuses attention toward a zone of local shear; both the matrix and olivine grains appear to have rotated clockwise against a dextral shear stress. D) This image focuses attention to the angular olivine fragments on either side of a prominent fracture. Grain size decreases toward the fracture zone and crystals interlock.
Cataclasis Fabric in CP94-050-167

This MM is unusual, owing to the presence of several long, relatively wide, sublinear voids, here interpreted as fractures, while smaller elongated voids (dehydration cracks) are absent. Particle CP94-050-167 contains two grain-scale shear fractures that form a conjugate fracture set (Fig. 7). These fractures pass through olivine grains resulting in a cataclasis texture of crushed and rotated grains. Similar brittle deformation features were reported from the anhydrous chondrules of the CM chondrite Murchison by Hanna et al. (2015). However, here the presence of brittle deformation in phyllosilicate-rich lithology is highly unexpected and has significant implications for the parent body history of this grain. Where phyllosilicate abundances exceed 15% volume, platy minerals provide slip planes and accommodate deformation by the flow and rotation of resistant grains (Fossen 2010, pp. 120–148). As CM and CI lithologies are porous, hydrated, and contain >60% volume phyllosilicates (Howard et al. 2009), deformation should occur by phyllosilicate smearing and the formation of ductile disaggregation bands or slip bands (Fossen 2010, pp. 120–148). Conversely, in phyllosilicate-poor rocks, in rocks with granoblastic textures, and in rocks with abundant cement, brittle failure and cataclastic flow will prevail. The dominant deformation response in CP94-050-167 is a brittle cataclastic failure and fracturing, despite the abundance of fine-grained phyllosilicate matrix. For intragranular deformation to be the favored strain response in a lithology so prone to ductile deformation, this particle must have experienced high strain rates, with slip velocities in excess of 1 μm s\(^{-1}\) (Niemeijer and Spiers 2005). Tomeoka et al. (1999) were able to produce subparallel fracture sets, similar to those observed in CP94-050-167, within the phyllosilicate-rich matrix of Murchison, by experimentally shocking samples to peak pressures >15 GPa. At lower shock pressures and therefore lower strain rates, matrix-hosted fractures were not generated (Tomeoka et al. 1999). These experiments demonstrate that high strain rates are required to generate a brittle deformation response from a phyllosilicate-bearing matrix and provide an estimate from the minimum impact pressure (15 GPa) sustained by CP94-050-167 (Tomeoka et al. 1999).

The petrographic features of particle CP94-050-167, including the abundance of Fe-oxide phases, most likely from Fe-Ni metal, the narrow compositional range of olivine crystals, and the lack of geochemical variation within the phyllosilicate-rich matrix are indications that this grain has experienced extensive aqueous alteration, resulting in textures similar to those described for the low-petrographic grade CM1 chondrites (Rubin et al. 2007). However, because the conjugate fracture set and elongation-parallel fractures are not infilled with a mineral cement, suggesting that particle CP94-050-167 lacked significant pore fluid at the time of impact and therefore aqueous alteration must have preceded shock at this locality on the parent body.

Limitations of Fabric Determination in MM

Petrofabrics in meteorites have been studied by EBSD (Watt et al. 2006), μCT (Friedrich et al. 2008; Hanna et al. 2015; Lindgren et al. 2015), and X-ray goniometry (Fujimura et al. 1982, 1983). However, these techniques cannot be applied to the majority of FgMMs, which have experienced significant thermal alteration during atmospheric entry. This is because phyllosilicate crystals have decomposed to form amorphous dehydroxylates. Furthermore, the scale of fabrics that can be analyzed are also beyond the resolution of current μCT techniques, with the majority of micron-scale voids being unresolvable. As phyllosilicates could not be directly observed, their orientation was inferred from the presence of dehydration cracks. This method is therefore less reliable than techniques which directly measure phyllosilicate alignment.

As the BSE images of the CM chondrites are at a different scale to that of the FgMMs, it can be argued that the nature of the voids within the two populations is different. For the CM chondrites, their voids are most likely larger fractures arising either from shock processing on the parent asteroid or as a result of the residence, collection, and storage on Earth. By contrast, the voids within the MM are primarily products of atmospheric entry heating (dehydration cracks). Despite this difference in origin, both void types are a result of brittle response within a fine-grained (or amorphous) matrix, in which cracks exploit pre-existing anisotropies. As a result, both void types are governed by the orientation of their host phyllosilicates and therefore reveal inherit petrofabrics within these materials. Consequently, comparison of the CM chondrite voids to the FgMM voids remains justified.

Additionally, in grains with few cracks and therefore low count statistics, the signal-to-noise ratio is relatively low and this may impact the confidence in fabrics identified. The lowest number of fractures considered (\(N = 32\)) is in particle CP94-050-140; conversely, most particles contained between 70 and 200 voids and therefore carried sufficiently high counts to avoid random noise generating an artificial petrofabric. The greatest source of error lies in the image analysis procedure. The reduction of a 255-channel grayscale BSE image to a bimodal matrix-void data set requires thresholding. The threshold chosen was largely...
arbiter; however, tests involving repeat thresholding of the same image at different values produced similar rose diagrams with entropy values varying by $S < 0.12$. This provides an estimation of the error associated with each entropy value and means that the relative position of each MM in Table 2 may change but the general trend and presence of fabrics identified in the majority of particles is not a statistical artifact.

Given the limitations and difficulties outlined above, this analysis should be considered a preliminary study, which points toward the existence of subtle petrofabrics in FgMMs.

**IMPLICATIONS**

**Shock Fabrics During Entry Heating**

In 30% of MMs, the dominant crack orientation lies parallel to the particle's elongation axis. In these MMs, the pre-existing petrofabric was likely important in defining fragmentation dynamics during break-up and liberation from the parent asteroid. However, as some MMs lack a discernible fabric, this suggests that the parent asteroid is capable of disrupting without a petrofabric being imparted onto all dust released. Furthermore, the majority of MMs in this paper have previously been analyzed by Raman and mid-IR spectroscopy; we found no correlation between the Raman data, nor the mid-IR data and a particle’s rose diagram entropy. This suggests that the compaction processes on the parent asteroid do not significantly affect a MM's bulk mineralogy or organic matter and instead later atmospheric entry heating dominates a MM's petrography. During atmospheric entry, the peak temperatures experienced by elongated particles may differ significantly from the predictions of entry heating models, thereby producing anomalously low- or high-peak temperature grains.

**Parent Bodies of FgMMs**

Abundant evidence suggests that FgMMs are related to CM/CI chondrites, representing either a similar but unique chondrite class (Engrand and Maurette 1998), or sourced for the exact same genetic group of objects as CM chondrites (Genge et al. 1997). Owing to the P-R drag delivery mechanism, MMs are likely to sample a larger population of parent bodies than meteorites (Genge et al. 1997; Vokrouhlický et al. 2008; Gounelle et al. 2009) and could, therefore, provide a more coherent picture of the carbonaceous asteroid population.

This paper presents the first evidence of weak but pervasive shock fabrics in FgMMs; these conclusions therefore support findings from previous works which have identified pervasive shock fabrics among CM chondrites (Barber 1981; Fujimura et al. 1983; Lee 1993; Hanna et al. 2015; and others), despite their classification as unshocked materials (S1 shock state). These combined observations appear paradoxical, as high-grade shock features (>S1) are considered necessary before a petrofabric can develop (Lindgren et al. 2015). To reconcile these apparently conflicting observations, Lindgren et al. (2015) suggested that the CM parent body, or bodies, have likely avoided hypervelocity impacts and instead, developed their shock fabrics through successive low-intensity impacts (<5 GPa). In contrast, both Tomeoka et al. (2003) and Rubin (2012) suggested that the porous composition of CM chondrites provides a mechanism for the efficient dissipation of impact energy. On collision, fine-grained matrix experiences compaction, which shields the more resistant index minerals (olivine and plagioclase) from higher shock pressures and prevents the development of high-grade (>S1) shock features.

However, simulations of the early solar system suggest that hypervelocity impacts were common and therefore the survival of large (>100 km) asteroids which evaded any high-energy collisions would be extremely unlikely (Davison et al. 2013). While CM compositions are capable of absorbing and dissipating impact energy efficiently (Bland et al. 2014; Hanna et al. 2015), and low-energy impacts would intensify petrofabrics, it seems likely that high-energy (>5 GPa) hypervelocity impact did occur. Several impact experiments have concluded that the CM lithology is highly prone to fragmentation and the generation of ~100 μm scale dust, even at relatively low-impact speeds (~5 km s⁻¹) (Durda and Flynn 1999; Flynn et al. 2009). The friable texture, the low compressive strength, and the collapse of pore space are all mechanisms to absorb and dissipate impact energy. The dissipation of impact energy by the dehydration of phyllosilicates can be ruled out because the majority of FgMMs (and CM chondrites) enter the Earth’s atmosphere hydrated (Genge 2006; Nakato et al. 2008).

It seems probable, therefore, that instead of avoiding hypervelocity impacts, CM parent bodies have, most likely, experienced large impact events and responded by catastrophic disruption and subsequent re-accretion as loose aggregations, forming rubble-pile asteroids (Benz and Asphaug 1999; Britt and Consolmagno 2000). The ability of the CM lithology to dissipate impact energy by disruption would then explain the lack of high-grade shock features while explaining the presence of shock fabrics, which developed during high-intensity events. Further evidence to support this proposition can be found by considering
the density estimations for several C-type asteroids. Most of the inferred (and measured) densities for prominent C-types range from 1300 to 3000 kg m$^{-3}$; these values are much lower than expected for an asteroid composed of CM material (Britt and Consolmagno 2000). Instead, to explain these abnormally low densities requires the host asteroids to support abundant macroporosity, in the form of large, meter-scale voids (Britt and Consolmagno 2000; Carry 2012). Additionally, as CM and CM-like materials are the most common micrometeorite types (Brownlee et al. 1997; Taylor et al. 2012), as well as the principal contaminant among Lunar regolith (Wasson et al. 1975) and are even identified as fossil micrometeorites embedded in ordinary chondrites (Gounelle et al. 2003) and howardites (Wilkening 1978), this implies that the CM parent body(ies) disrupted early in the solar system’s history and since shed abundant material into interplanetary space.

A low compaction strength, a tendency to disrupt, as well as the observation of anomalously low-density C-type asteroids and the ubiquity of CM chondrite materials (Wilkening 1978) and their contamination among other meteorite classes and upon planetary surfaces all support the proposition that the CM parent body is no longer intact and instead remains as a series of rubble-pile relict asteroids and interplanetary dust particles.

CONCLUSIONS

Dehydration cracks in thermally altered, unmelted fine-grained micrometeorites and partially melted scoriaceous micrometeorites form during atmospheric entry heating. These cracks are a result of contraction between sheet silicates, forming parallel to the [001] plane. Dehydration cracks can, therefore, act as proxies for preatmospheric phyllosilicate orientation, in dehydrated, dehydroxylated, and completely recrystallized fine-grained micrometeorites. This study reveals the presence of pervasive, grain-scale fabrics in the majority of micrometeorites. The presence of biaxial fabrics among several particles as well as brittle deformation features, including cataclasis and conjugate fracture sets, in a single micrometeorite suggest at least some fabrics are impact-generated, at shock pressures $>$78.5 MPa. Although micrometeorites demonstrate phyllosilicate alignment, additional higher grade shock features ($>$S1), such as planar fractures in olivine, are absent. As CM chondrites also display a near-ubiquitous, low-shock state, we suggest the parent bodies of hydrated, primitive chondritic materials likely cannot sustain hypervelocity impacts without disrupting catastrophically. This proposition is supported by laboratory-scale impact experiments on CM chondrites and anomalously low-density C-type asteroids. The parent bodies of FgMMs are likely loosely bound rubble-pile asteroids.

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**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of this article:

**Data S1.** Phyllosilicate alignment by static compaction. Empirical observations of terrestrial shales in deep sea sediment cores are used to provide an estimate of the minimum overburden pressure required to generate phyllosilicate alignment (A). This value is then compared against the core pressure of the four largest C-type asteroids (B).