OBJECTIVE TAXONOMY OF SOLID ORGANIC MATERIAL IN CHONDRITES.

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Introduction: Organic material (OM) occurs as a component of chondrites in minor to trace concentrations [1]. Insoluble organic matter (IOM) is the acid insoluble fraction of OM remaining from extreme acid digestion of the host meteorite and makes up the major fraction of total organic carbon. Having a macromolecular organic composition, it has affinities to terrestrial kerogen but is of non-biological origin. Its origins remain enigmatic. Different types of astrophysical environments have been used to describe the origins of IOM [2]. Early studies of IOM were performed using electron microscopy [e.g. 3]. With the advent of more precise mass spectroscopy techniques, the stable isotopic composition of IOM (^{15}N, D and ^{13}C) has been measured [e.g. 4]. Heavy enrichments in ^{15}N and D certainly determined an extraterrestrial origin of this material but also invoked presolar origins [4]. With the use of highly spatially resolved imaging techniques such as S/TEM, it is clear that the IOM residues display complex morphologies with nanometer variation [e.g. 5]. The largest features in IOM are typically spherical compounded or hollow particles that have more recently been classified as nanoglobules [6,7]. This has stimulated investigation into the properties of nanoglobules and their origins [5,8]. More recently, [9] and [8] identified nanoglobules in the IOM residues from a range of carbonaceous chondrites (CCs). [5] attempted to classify the IOM into distinctive morphologies. However, the classification of organic nanoglobules as circular/spherical, compounded or hollow objects was found to be ambiguous in IOM residues from the CM and CR chondrites. This is due to the self-similar or fractal property of the residues [5]. Here, issues in identifying nanoglobules in IOM residues are addressed with implications for the interpretations made by previous studies [e.g. 8,9]. Furthermore, in an attempt to provide an unambiguous, objective and therefore empirical means for the study of OM formation and evolutionary history, a classification system is proposed to morphologically differentiate between OM phases in chondrites *in situ*.

Imaging IOM using BF and DF TEM Techniques: Bright Field (BF) TEM and DF STEM imaging has been used to study the morphology of IOM [e.g. 5,8]. The type of S/TEM imaging technique used has been governed by the need to minimize electron dosage when imaging IOM prior to the coordination of other chemical and isotopic characterization techniques [8]. Figure 1 shows a DF STEM and BF TEM image of IOM from Grosvenor Mountains (GRO) 95577 (CR1) from [5] and [8], respectively. The boundaries of finer scaled IOM around the largest feature sizes typically identified as nanoglobules seems clearer under DF STEM rather than TEM BF imaging (Fig. 1). The surrounding mass of IOM around the largest feature sizes in Figure 1a (labelled 1 and 2) shows the presence of rounded shapes to the finest scales of the image. This morphology is found in similar fashion in the BF TEM images from [8]. Thus, previous studies such as [8] may have identified the largest features in the images (arrowed in Fig. 1b) as distinctive objects whilst neglecting the smaller-scale surrounding material arguably of the same morphology.

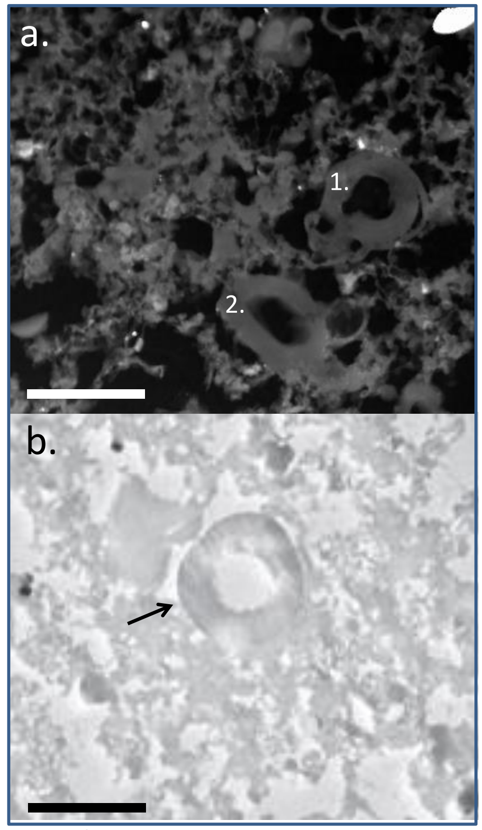

Figure 1: *IOM from GRO 95577 (CR1).* (a) DF STEM image from [5]. Two large nanoglobules based on previous nomenclature are noticeable and labelled. However, the rest of the image seems to display the same shapes that describe nanoglobules. BF TEM image from [8]. A single nanoglobule has been identified (arrowed) by the authors. (b) Scale bar is 500 nm.

The Self Similarity of Tagish Lake IOM: Similar issues to those discussed in the previous section also seem evident in studies by [9]. Herd et al. (2011) made nanoglobule abundance measurements in various aqueous-altered stones of the Tagish Lake meteorite. Observation of the images used in the supplementary material of [9] at higher magnifications exhibit similar ambiguities when identifying nanoglobules. The identification of the largest round or pseudo-circular features as nanoglobules in Figure 2 by [9] (arrowed) has neglected the surrounding mass of IOM that upon smaller-scale inspection arguably has the same morphology throughout the image. However, this is not as clear at the presented image magnification by [9]. These same textural arguments can be applied to the rest of the images used by [9].

The process of identifying nanoglobules in order to measure their properties as objects morphologically distinct to the rest of the IOM should be approached with extreme caution if the same morphology arguably exists consistently across most of the IOM. For example, the interpretations made by [8] should also consider the consequences of classifying only the largest features of IOM as the same objects that arguably exhibit the same morphology at all scales of the images. For example, [8]'s identification of 'non globular regions' would, based on the observations of this study, be false under their current interpretation and corrections would have to be made. The same would apply to [5] and [9]'s measurements of nanoglobule area fraction measurements.

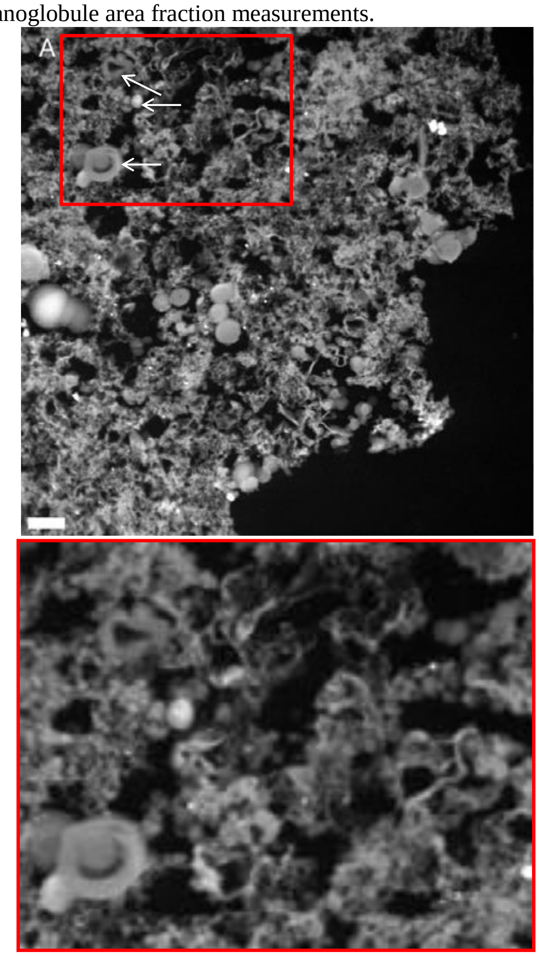

Figure 2: *IOM from Tagish Lake measured by Herd et al*. (*2011) [9]*. The area in red has been magnified in the red rectangle. The objects arrowed were marked by [9] as nanoglobules. However, note the nanoglobular shapes that seem ubiquitously distributed in the enlarged image. Scale bar is 500 nm.

The need for the characterization of IOM *in situ*: Additional chondrite groups and classes that perhaps display more diverse IOM morphologies are important to document. Unequilibrated ordinary chondrites and other CC groups such as the CO chondrites display elevated thermal histories when compared to the more primitive CI, CM and CR chondrites [10]. More recently, [11] reported IOM from the CO chondrite Dominion Range (DOM) 08006 which has noticeably different morphology to IOM from the more aqueous altered and organic rich CCs. The self-similarity of rounded features as shown in [5] and this study are erased by a 'smoother' or 'coarser' IOM. The entire coverage of IOM within microtome samples of the residues represents a mixture of insoluble organic phases from different locations in the host meteorite. As an example, the entire coverage of IOM in the DOM 08006 image represents a mixture of IOM from different locations in the host meteorite. [11] showed a single discrete nanoglobule within this mass of 'smooth' IOM. Such coverage of OM in the CO chondrite would most likely not occur *in situ* where the context of the single nanoglobule identified by [11] is completely lost in the IOM residues. Furthermore, heterogeneity in OM morphology and chemistry is evident *in situ* [12]. This emphasizes the need to understand morphological and chemical variation of OM *in situ* whilst also objectively classifying the types of OM in order to constrain origins and processing histories.

Objective Taxonomy of Organic Phases: Various terms have been used to describe the presence of OM in chondrites leading to confusion in the literature. Terms such as 'nanoglobules', 'blobs,' 'grains' and 'inclusions' have all been used. Whilst such terms provide a description on their existence in the samples, ambiguity can arise in determining how many of these phases actually empirically exist. For instance, the arrowed feature in Fig. 1 shows an image of an object typically interpreted as a nanoglobule by researchers. However, a smaller rounded feature is connected to the large round feature (labelled 1). Thus, two or perhaps three rounded features are identifiable but there is only one external boundary of the entire object that, as a whole, is not a circular or rounded object. Therefore there are linguistic ambiguities in determining whether this phase is in fact one or multiple objects. It is therefore suggested that a generic term be used to classify an organic object based on its context with inorganic material. This will enable morpological distinctions to be made between those objects if they exist. The term 'OM inclusion' seems pertinent to this rationale considering the usage of the term 'inclusion' for other chondrite components such as calcium aluminium inclusions (CAIs) and dark inclsuions (DIs). Based on this, a formal definition can be made for an OM Inclusion and morphological types that exist:

OM INCLUSION = An isolated organic phase surrounded by inorganic material.
NANOGLOBULE = a single rounded OM inclusion, whether compounded or hollow.
IRREGULAR OM INCLUSION = A non-rounded OM inclusion.

As an example, the feature in Fig.1b (labelled 1), hypothetically surrounded by inorganic material *in situ*, can be described objectively as an irregularly shaped OM inclusion due to its external boundary not tracing a circular or rounded object. However, it can be described subjectively as having nanoglobular shapes within it.

References:
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