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Diversity of Complex Organic Matter in Carbonaceous Chondrites, IDPs, and UCAMMs

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ABSTRACT

Complex organic matter is present in many extraterrestrial materials such as chondrite meteorites, micrometeorites, and interplanetary dust. The observed complexity of this organic matter is due to the combination of diversity of primitive organic materials that accreted onto asteroids and the subsequent effect of hydrothermal and/or metamorphic alteration that took place after accretion. These processes resulted in a variety of carbonaceous grain morphologies, elemental abundances, and organic functional group compositions. Some carbonaceous dust grains and micrometeorites have cometary origins and provide insights into the unique processing histories on those outer solar system bodies. Isotopic analyses can help distinguish carbonaceous grains that retain their preaccretion heritage, while advanced microscopy techniques reveal the interplay of complex organic matter with surrounding mineral.

KEYWORDS: organic matter, carbonaceous chondrite, micrometeorites, interplanetary dust, aqueous alteration

INTRODUCTION

There are many classes of planetary materials in our solar system that contain carbonaceous matter. The most well-known among these are the carbonaceous chondrite meteorites, identifiable by the dark color of their fine-grained matrix due to incorporation of up to 5 wt.% bulk carbon. Organic matter is also found, to a lesser extent, in ordinary chondrites. Interplanetary dust particles (IDPs) and micrometeorites (MMs), though small (~100 μm or less), can contain significantly more carbon than carbonaceous chondrites - up to 10 to 25 wt.% carbon. Other work has established the extremely carbon-rich composition of ultracarbonaceous Antarctic micrometeorites (UCAMMs). This class of micrometeorites are typically in the IDP size range, are ~50-90% carbon (by volume) and

contains crystalline and amorphous minerals comparable to those detected in comet dust (Duprat et al. 2010). These small particles are significant because they may contribute on the order of five million kg of extraterrestrial material to the Earth annually (Rojas et al. 2021)

The major carbonaceous components in the planetary materials described above include carbonate minerals, soluble organic compounds, such as carboxylic acids and amino acids, collectively termed soluble organic matter (SOM), and more complex macromolecular carbonaceous matter (Alexander et al. 2017). By far, the majority of the carbon budget (> 75%) is found to be in this complex organic matter, and yet this important component can be difficult to study. A common method for extracting this material is through dissolution of the host material with a series of harsh acid washes and rinsing steps, producing a concentrated organic residue called insoluble organic matter (IOM). However, it has been known from the advent of this approach in the 1970s that this process only recovers ~50% of the complex macromolecular material and none of the SOM. In addition, although IOM residues provide a somewhat representative “bulk” sample of organic matter from a given sample, any useful petrologic context is lost. The alternative approach is to investigate the carbon *in situ* using various microscopic and nanoscopic techniques on minimally-processed samples (Kebukawa, Yesiltas, and Glotch, this issue), providing data on a smaller amount of sample, but retaining full petrologic context and all carbonaceous components. Such *in situ* methods are particularly useful for characterizing small samples like IDPs, UCAMMs, and returned samples from spacecraft missions, where producing an IOM residue may not be feasible.

That said, IOM is a good baseline material for comparative studies between chondrite groups and other carbonaceous planetary materials. Composition of IOM (Figure 1A) ranges from $C_{100}H_{75-79}O_{11-17}N_{3-4}S_{1-3}$ in the most primitive chondritic samples (nearly identical to carbonaceous particles from comet Halley) to $C_{100}H_{9-20}O_{9-11}N_{0-2}$ in thermally modified meteorites (Alexander et al. 2017 and references therein). The macromolecular structure of IOM that corresponds to these compositions consists of small-to-medium sized polyaromatic functional units (1-3 carbon rings for primitive samples, and up to 7-8 rings for thermally modified meteorites) that are highly substituted with N and S atoms and cross-linked by short, highly branched, aliphatic hydrocarbon chains (Figure 1B; Derenne and Robert 2010). More in depth information about the structure and composition of IOM can be gained from the review by Alexander et al. (2017).

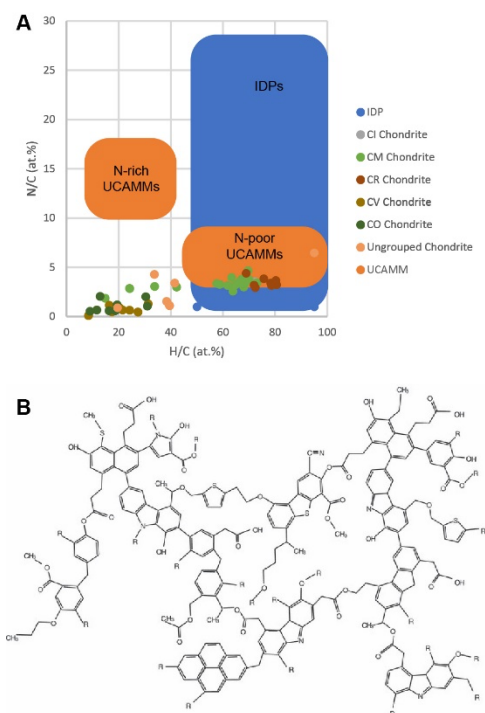


Figure 1. Composition and macromolecular structure of complex organic matter. (A) Carbon, hydrogen, and nitrogen compositions of complex organic matter in carbonaceous chondrite meteorites, IDPs, and UCAMMs. Data from Alexander et al. (2017) and references therein, and Dartois et al. (2018). (B) Molecular structure model of Murchison IOM developed from 11 independent parameters (Derenne and Robert 2010). Reproduced from Derenne and Robert (2010) with permission from John Wiley and Sons.

MORPHOLOGY AND CHEMISTRY OF COMPLEX ORGANIC MATTER

Complex organic matter takes on a variety of forms, often only observable at sub-micrometer length scales. The largest and most well-studied of these are spherical or roundish grains, either solid or hollow, called nanoglobules or globular organic matter (Figure 2; Garvie and Buseck 2006; Nakamura-Messenger et al. 2006). Found in meteorites, IDPs, and UCAMMs, they range in size from <50 nm to ~ 2 μm in diameter, and are either isolated within the fine-grained matrix or form small clusters. Occasionally, larger vein-like clusters have been observed. Nanoglobules are retained within carbonaceous chondrite IOM residues, making them relatively easy to study *en masse*. Comparing nanoglobule populations in IOM across different carbonaceous chondrite groups indicates that they are less prevalent in aqueously altered meteorites (like CI and CM chondrites) and most prevalent in the “primitive” CR chondrites (De Gregorio et al. 2013a). Within a given chondrite group, nanoglobules appear to be most prevalent in samples that experienced moderate levels of aqueous

alteration (e.g., petrologic type 2). Nanoglobules in IOM from the heavily aqueously altered (petrologic type 1) CR chondrite GRO 95577 are extensively modified, with vesicular or desiccated textures, physical deformation features, and outer rind structures (De Gregorio et al. 2013a). Vesicular nanoglobules observed *in situ* within the fine-grained meteorite matrix contain lower nitrogen content than nearby, unmodified nanoglobules, and nanoglobules with outer rinds are bounded by phyllosilicate layers that are presumably removed by the IOM extraction process (Figure 2A; De Gregorio et al. 2013b). Nanoglobules observed in anhydrous IDPs and UCAMMs have similar morphologies to those found in primitive carbonaceous chondrites (e.g., Matrajt et al. 2011; Yabuta et al. 2017).

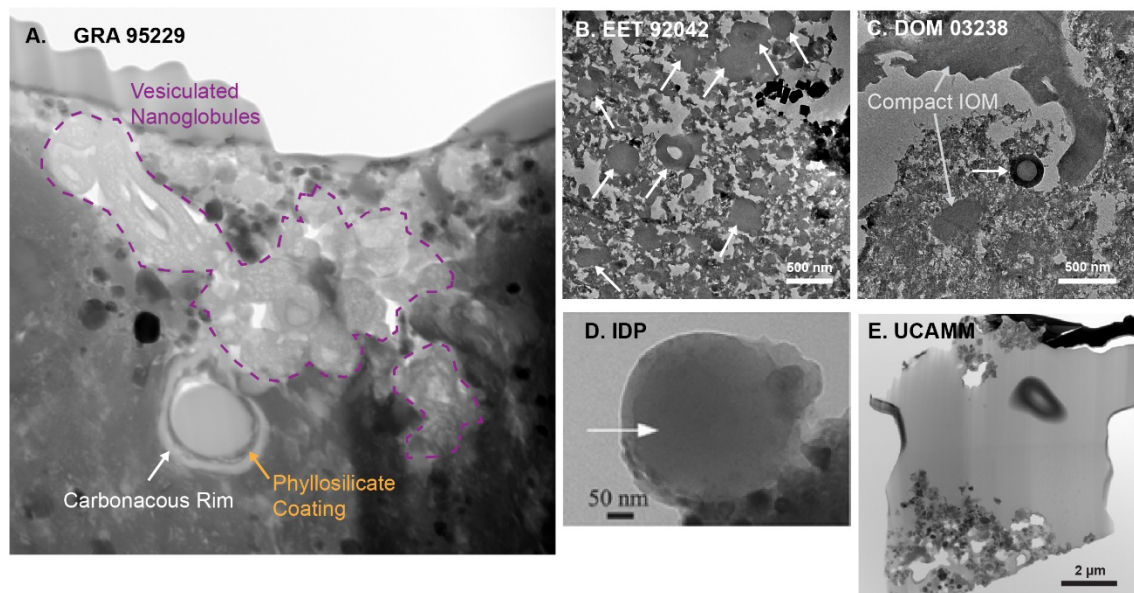


Figure 2. Morphology of complex organic matter from carbonaceous chondrite meteorites, IDPs, and UCAMMs observed by transmission electron microscopy. (A) A cluster of nanoglobules and globule fragments in an *in situ* matrix section of aqueously altered (CR2) chondrite meteorite Graves Nunataks (GRA) 95229. Modified from De Gregorio et al. (2013b). Many of the nanoglobules show evidence of aqueous alteration in the form of internal vesicles. The largest nanoglobule contains a coating of phyllosilicate material and an outer rim of organic matter, likely formed by secondary processes. (B) IOM residue from the aqueously altered (CR2) chondrite Elephant Moraine (EET) 92042. Several solid and hollow nanoglobules (white arrows) are visible against a background of IOM mesoparticles. (C) A hollow nanoglobule (white arrow) in IOM from the heated (CO3) chondrite Dominion Range (DOM) 03238. The IOM has a finer texture than that of EET 92042 and also contains large fragments of compact organic matter, likely organic coatings removed from mineral grains

during acid dissolution of the meteorite. (D) Organic nanoglobule in an IDP. Reproduced from Matrajt et al. (2011) with permission from John Wiley and Sons. (E) Massive, void-filling organic matter in UCAMM DC06-07-18. Image courtesy of H. Leroux.

These morphological variations, along with their functional group chemistry and stable isotope composition, indicate that nanoglobules have a complicated formation and modification history including both pre-accretion and parent body origins (see Yabuta and Nomura, this issue). Chondritic nanoglobules have nearly identical functional group compositions to that of “bulk” IOM from their host meteorite, except for a slightly higher proportion of carbonyl-bearing (C=O) functional groups like ketones and carboxylic acids (De Gregorio et al. 2013a). A smaller fraction of nanoglobules have a different functional group chemistry indicative of larger polyaromatic domains. These are called “aromatic” or “highly aromatic” nanoglobules to distinguish them from those with IOM-like characteristics. Although the available data is small, it appears that the abundance of aromatic nanoglobules has a strong dependence on the petrologic type of the host rock, where they compose about half of all nanoglobules in the mildly heated CO (petrologic type 3) chondrites, and are relatively rare in the heavily aqueously altered type 1 chondrites. The seemingly systematic occurrences of both chemistries would suggest that nanoglobules likely formed on parent bodies, primarily as a product of organic condensation reactions between IOM precursor macromolecules during periods of hydrothermal processing. In fact, nanoglobule morphologies are readily produced in experiments that mimic these aqueous alteration conditions (Cody et al. 2011). However, many nanoglobules are enriched in D and/or ^{15}N isotopes, which are interpreted to indicate an interstellar or protosolar heritage (e.g., Nakamura-Messenger et al. 2006). The abundance of isotopically anomalous nanoglobules, irrespective of functional chemistry, is roughly proportional to the isotopic composition of the host IOM, suggesting that nanoglobules are a significant carrier of isotopically primitive organic matter, although it should be noted that isotopically anomalous nanoglobules only account for ~30% of all the anomalous “hotspot” regions in IOM (De Gregorio et al. 2013a). These isotopic data suggest that many nanoglobules are pre-existing components during asteroid and planetesimal accretion, likely formed through irradiation of organic-ice mixtures in the presolar nebula or cold molecular cloud (Yabuta and Nomura, this issue). Occasionally, the outer ~10 nm of some nanoglobules are observed to be enriched in nitrogen, along with a slight increase in aromaticity (Vollmer et al. 2014). The origins of these nitrogen-rich rims could be due to pre-accretion radiation processing but have also been explained by interaction with asteroidal fluids (Vollmer et al. 2014, 2020). In reality, the population of nanoglobules that we observe in carbonaceous meteorites, micrometeorites, and IDPs were contributed by both pre-accretion

processes and aqueous reactions on asteroids and comets, with modification of their original morphologies and chemistries by further hydrothermal processing.

Apart from nanoglobules, the majority of chondritic IOM consists of a network of connected carbonaceous mesoparticles, in which the larger nanoglobules are embedded (Figure 2B, C). Mesoparticle size and pore size varies from meteorite to meteorite, suggesting a relationship with parent body processing (e.g., Figure 2B vs. 2C). This mesoparticle component of IOM corresponds to “diffuse” or “disseminated” organic matter observed *in situ* within the fine-grained matrix and aggregated through IOM extraction. However, close examination of individual regions of diffuse organics *in situ* reveals a wide variety of functional chemistry that does not match that of IOM, mainly having a low proportion of polyaromatic functionality and rich in oxygen and nitrogen functional groups (Le Guillou et al. 2014). This marked difference between IOM mesoparticles and *in situ* diffuse carbon is due to the likely inclusion of SOM or hydrolysable aliphatic chains in the latter, which are removed during IOM extraction, leaving only the acid-insoluble, polyaromatic-rich mesoparticles. As mentioned above, diffuse organic matter can contain significant D or ¹⁵N isotopic anomalies, requiring high-resolution transmission electron microscopy (TEM) to visualize and characterize individual nanoscale grains *in situ* (Vollmer et al. 2020). The isotopically anomalous diffuse carbon analyzed so far appears to contain the same polyaromatic and carbonyl-rich functional chemistry as their larger anomalous counterparts. Due the larger proportion of organic matter in IDPs and UCAMMs relative to mineral grains, this diffuse organic matter is not found in those sample types.

Complex organic matter also forms thin (<100 nm) coatings around mineral grains in meteorites and IDPs, but have been difficult to analyze due to the small amount of material present. Occasionally, thicker coatings are discovered that enable high-resolution characterization (Figure 3). The host grains are usually Fe-bearing, leading to the interpretation that the organic coatings are the result of Fischer-Tropsch-type catalysis (e.g., Brearley 2021). However, organic coatings are prevalent in anhydrous IDPs, covering most of the inorganic components and performing an adhesive function to keep them together as a coherent unit. Characterization of such coatings in aggregate reveal a functional chemistry similar to the other carbonaceous grains in IDPs and meteorites, rich in highly substituted polyaromatic domains and carbonyl (C=O) functional groups (Flynn, Wirick, and Keller 2013).

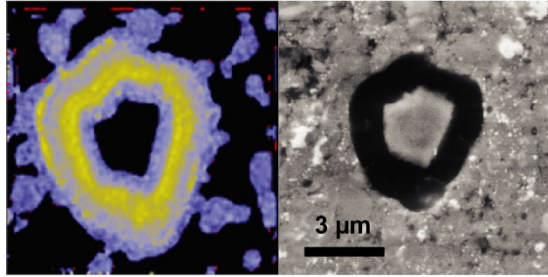


Figure 3. Isotopic enrichment in an organic grain coating in the aqueously altered CR2 chondrite Renazzo. (Left) $^{15}\text{N}^{12}\text{C}/^{14}\text{N}^{12}\text{C}$ -ratio image from nanoscale secondary ion mass spectrometry, where blue denotes a terrestrial value and yellow denotes significant ^{15}N enhancement over the terrestrial value (several hundred per mil). ^{15}N enrichment varies concentrically in the coating, indicating temporal variations in the isotopic composition of the organic precursor material during aqueous alteration. (Right) Corresponding scanning electron microscopy (SEM) image showing the organic matter (black) within the mineral matrix, surrounding a single mineral grain. Figure from Vollmer et al. (2020). Reproduced from Vollmer et al. (2020) with permission from John Wiley and Sons.

In addition to organic grain coatings, IDPs and UCAMMs can also contain large continuous regions of organic matter not seen in meteorites (Figure 2E). In IDPs, this “gap-filling” organic matter has a lower abundance of polyaromatic domains and a higher proportion of aliphatic cross-linking side chains than that found in carbonaceous chondrites (Flynn et al. 2003). This material can have various textures of unknown origin, described as “spongy”, “vesicular”, and “smooth” (Matrajt et al. 2011). In UCAMMs, the complex organic matter is generally enriched in nitrogen and sulfur (Yabuta et al. 2017; Dartois et al. 2018) and the relative proportion of polyaromatic to side-chain functionality varies across the regions (Mathurin et al. 2019). The UCAMM organics are in fact a mixture of two or three distinct organic phases, one of them containing up to 20 at.% nitrogen, whereas the other phase(s) share similarities in composition with IOM in carbonaceous chondrites (Figure 1A; Guérin et al. 2020). The high amount of organic matter in these carbon-rich IDPs and UCAMMs can be interpreted as the result of short term exposure to aqueous fluids on comets and other icy planetesimals (Yabuta et al. 2017) or from extensive radiation processing of ices in the outer regions of the protoplanetary disk (Dartois et al. 2018 and references therein).

AQUEOUS ALTERATION ON ASTEROIDS AND COMETS

Asteroids and comets accreting past the “snow line” of the early solar nebula, which is also outside of the “soot line” where polycyclic aromatic hydrocarbons can condense, will include a significant amount of both water-ice and organic matter. The initial carbonaceous precursor material accreted

to parent bodies ranged from simple organic molecules to fully formed carbonaceous grains due to the wide variety of interstellar and/or nebular reaction mechanisms (Yabuta and Nomura, this issue). A combination of radioactive heating from short-lived isotopes like ^{26}Al , compression melting, and major impact events led to the formation of hydrothermal fluids on asteroids, and transient aqueous melts were also present on comets (Suttle et al. 2020). These fluids percolated among accreted organic molecules, carbonaceous dust, and mineral grains in the fine-grained matrix. Some soluble organic molecules, such as formaldehyde, will react through well-established chemical pathways to form complex sugars, branched and highly substituted cyclic molecules, and ultimately polyaromatic molecules (Cody et al. 2011). Further cross-linking of these complex polyaromatics results in the complex organic matter and IOM we observe today in carbonaceous planetary materials. Minerals containing transition metals like Fe are also well known to catalyze surface-bound organic reactions, such as Fischer-Tropsch-type synthesis. The combination of these chemical processes when aqueous fluids were present resulted in chemical and morphological modification of pre-existing carbonaceous grains as well as generation of brand new carbonaceous grains. Fluid-assisted breakdown of D- or ^{15}N -enriched carbonaceous grains can result in larger regions of isotopically anomalous diffuse organics in the fine-grained matrix (Floss, Le Guillou, and Brearley 2014) or layered organic matter with different isotopic compositions (Figure 3; Vollmer et al. 2020).

Phyllosilicate clay minerals have been shown to have an increasingly important role in the generation or modification of complex organic matter. These sheet silicates are produced by the breakdown of crystalline and amorphous silicate grains that are prevalent in IDPs and the most unaltered chondrites, and are therefore some of the earliest fresh surfaces available for catalyzing organic reactions (Figure 4A). Phyllosilicates can interact with organic macromolecules through direct adsorption or chemisorption on the surfaces of individual sheets, or through intercalation between sheets (Figure 4B). Diffuse organic matter is observed to be intercalated within phyllosilicate layers even in the most unaltered carbonaceous chondrites, indicating these organic-clay interactions occur rapidly (Le Guillou and Brearley 2014), and laboratory analog experiments with smectite produce not only more complex organic molecules than without smectite but also organic-clay mixtures (Vinogradoff et al. 2020). The unique catalytic environment on phyllosilicate surfaces may also enable formation of distinct organic functionality. For example, evidence for carbonate (CO_3) functional groups has been observed occasionally within diffuse organic matter associated with phyllosilicates in *in situ* sections (Le Guillou et al. 2014 and references therein), but never in IOM.

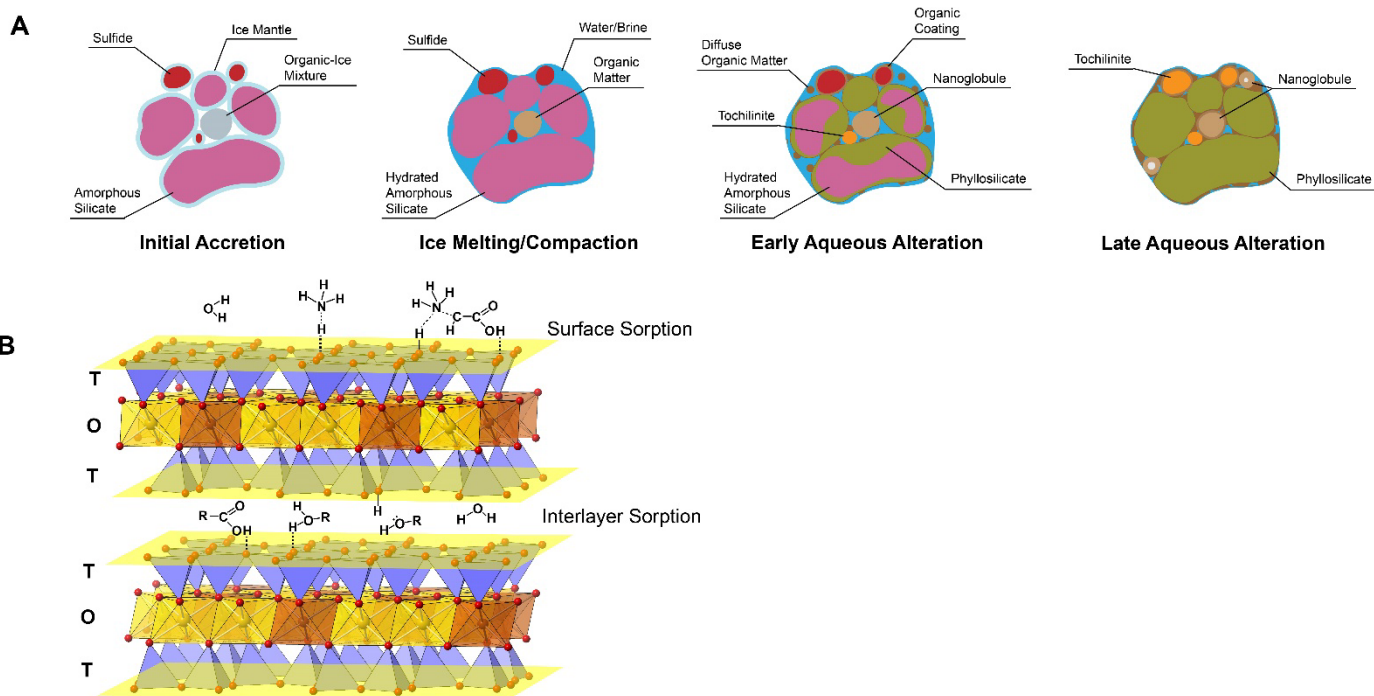


Figure 4. Interaction of accreted water-ice and organic matter with silicate minerals. (A) Interaction of ice-coated accreted grains during the initial and later stages of hydration and aqueous alteration, after the model of Le Guillou and Brearley (2014). The rapid formation of phyllosilicates from amorphous silicates and hydroxysulfides like tochilinite from sulfides is aided by interaction with organic matter. (B) Active interlayer and surface sites on clays and phyllosilicate minerals (highlighted in yellow) that can catalyze organic reactions.

THERMAL METAMORPHISM ON ASTEROIDS

Some asteroidal bodies accreted a lower proportion of water-ice or a greater amount of short-lived ^{26}Al , leading to a different style of alteration of accreted organic precursor material. In these planetesimals, organic matter and matrix minerals predominantly show effects of thermal metamorphism rather than aqueous processing. In IOM residues from heated carbonaceous chondrites (petrologic type 3), atomic stacking of polyaromatic domains may be observed, and their lateral dimensions correlate with estimated metamorphic temperatures (Le Guillou et al. 2012), following the same metamorphic trends observed in terrestrial kerogens. The functional chemistry of the IOM also reflects this heating history, as polyaromatic functionality is more prevalent and the amount of oxygen-bearing functional groups (e.g., ketones and carboxyl groups) are reduced, relative to IOM from aqueously altered carbonaceous chondrites (De Gregorio et al. 2013a).

IOM isolated from CO chondrites, which have all been mildly thermally metamorphosed, frequently contain μm -sized crescent-shaped or onion-shaped carbonaceous grains in addition to nanoglobules. These relatively large morphologies are also often enriched in elements like N, Si, Ca, or S, and have been interpreted to be organic coatings that formed on matrix mineral grains. The internal grain no longer exists, having been removed during acid dissolution for IOM extraction. Heating experiments of organic analogs mixed with olivine produced macromolecular products via reaction of carboxylic acid functional groups to form cross-linking ester bonds rather than normal degradation by hydrocarbon “cracking” (Hirakawa et al. 2021), and it is possible that synthesis of macromolecular organics on mineral surfaces could incorporate cations chelated by ligand bonds. However, detailed *in situ* studies of type 3 CO or CV samples is needed to confirm this hypothesis.

IRRADIATION OF SPACE-EXPOSED ORGANIC MATTER

Irradiation of organic matter on the surfaces of icy dust grains in the interstellar medium or early solar nebula is thought to produce some of the precursor organic matter that accreted onto asteroids and comets (Yabuta and Nomura, this issue). However, recent work (e.g., Thompson et al. 2020) has also investigated the effect of space weathering and other surface processes on organic matter after accretion. In the outer Solar System and Oort Cloud, fluxes of galactic cosmic rays and UV irradiation may be significant enough to continue activating organic reactions on comets. At these cold outer Solar System temperatures, nitrogen gas (N_2) and ammonia frozen with organic molecules and water ice could be transformed into nitrogen-rich organic matter with similar chemical functionality as the nitrogen-rich organic matter observed in IDPs and UCAMMs (Dartois et al. 2018; Augé et al. 2016). Subsequent sublimation of the ices could leave behind an organic crust on the surface of the comet, which could be the source materials for the formation of gap-filling, nitrogen-rich, organic matter in IDPs and UCAMMs (Figure 2E). Further work is needed to understand the transient fluid interactions necessary to accumulate and cross-link this material into a coherent macromolecular solid, or whether irradiation processes alone could produce it.

In the inner Solar System, micrometeorite bombardment and solar wind irradiation play a major role in the space weathering of carbonaceous asteroid surfaces. Phyllosilicate clay and serpentine minerals in the regolith decompose through amorphization and partial melting, leading to reduction of iron and formation of nanophase iron metal grains (Thompson et al. 2020). These major redox reactions are occurring in the presence of diffuse organic matter associated with the phyllosilicates, and the potential effects on the complex organic matter has not been studied, although laboratory experiments to simulate space weathering of carbonaceous asteroids is ongoing. Alteration of

complex organic matter as a result of space weathering in this environment could significantly impact the interpretations of carbonaceous materials discovered in surface regolith samples returned from asteroids 162173 Ryugu and 101955 Bennu by the Hayabusa2 and OSIRIS-REx missions, respectively.

PRESERVATION OF PRE-ACCRETIONARY PHASES

As organic matter in planetesimals was altered through interaction with parent body fluids and local mineralogy, it has been recognized that complex organic matter can also have an effect on the alteration of inorganic phases. Interstellar and nebular organic precursor materials are retained within IOM residues and *in situ* samples as isotopic enrichments of D and/or ^{15}N in isotopic “hotspots” and morphologically distinct grains like nanoglobules. These isotopically anomalous features somehow resisted destruction by aqueous alteration or thermal degradation. The hydrophobic, “water resistant” character of complex organic matter can be explored by studying additional occurrences of interaction or mixing with inorganic phases, such as O-rich presolar silicate grains, which show a clear destruction trend with parent body aqueous alteration. For example, a foreign, carbon-rich clast found within the CR2 carbonaceous meteorite La Paz Icefield (LAP) 02342 contains a presolar O-rich grain abundance of 360 ppm, which includes both presolar silicates and oxides, while the surrounding fine-grained matrix contains ~30 ppm presolar O-rich grains (Figure 5; Nittler et al. 2019). Since this meteorite has been aqueously altered (petrologic type 2), the extremely high C-rich makeup of the clast must be responsible for protecting the internal presolar silicate grains from destruction. On closer inspection, the clast contains many similarities to UCAMMs, such as the extremely high abundance of carbon (~ 70% carbon by area) and inclusion of amorphous silicates and sodium sulfates. Nanoscale x-ray absorption spectroscopic mapping of the iron oxidation state of minerals found that iron oxides within the carbon-rich clast were more reduced and showed a greater variance in oxidation state than those in the fine-grained matrix. This difference suggests that iron oxides in the surrounding matrix were equilibrated with parent body fluids, yet those within the clast retained much of their original valency.

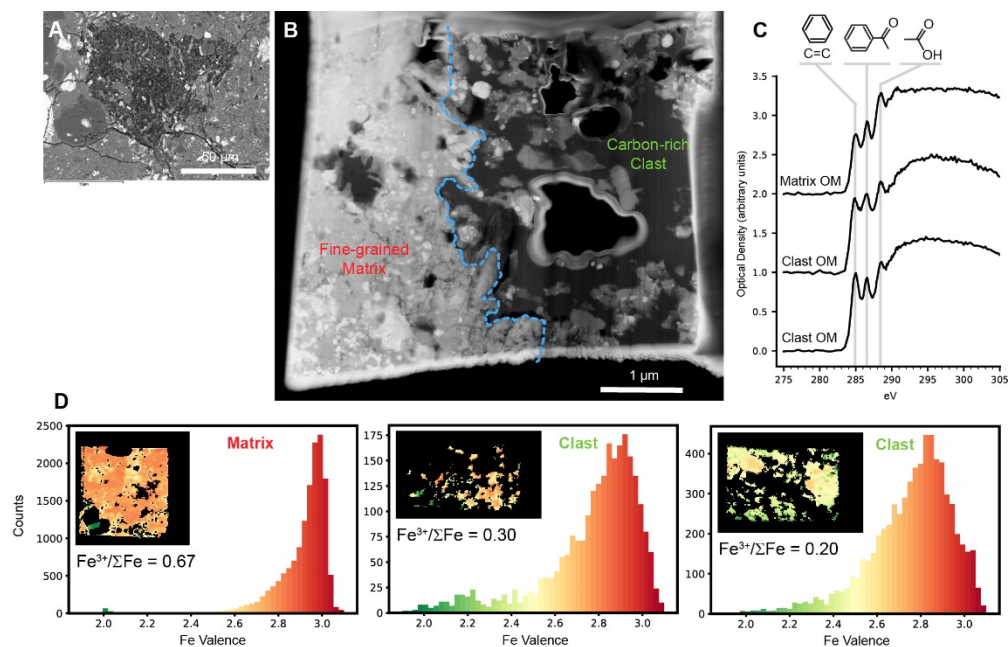


Figure 5. Preservation of primitive inorganic grains in a carbon-rich clast in the aqueously altered CR2 chondrite La Paz Icefield 02342 (data modified from Nittler et al. 2019). (A) Scanning electron microscope image of the clast (darker material) within the fine-grained matrix. (B) High-angle annular dark field scanning transmission electron microscope image of an *in situ* section taken from the edge of the clast. The clast is ~70% carbonaceous matter and includes primitive features such as amorphous silicates and sodium sulfates that would be easily destroyed by aqueous alteration. (C) X-ray absorption near-edge structure spectroscopy (XANES) of complex organic matter from the clast and surrounding matrix. (D) Iron XANES mapping of other *in situ* sections from the carbon-rich clast and surrounding fine-grained matrix, showing the spread of Fe valence state values estimated from quantification of the XANES spectra. Inset images show the spatial distribution of Fe valence in the histogram plots.

Complex organic matter may be a protective host to other mineral phases as well that would normally be destroyed by aqueous alteration. Nanoscale electron energy-loss spectroscopy of IOM revealed copious nanodiamond grains hidden within IOM mesoparticles, but not within the larger grains or nanoglobules (De Gregorio, Alexander, and Stroud 2019). Highly reduced iron carbide grains, which would otherwise be transformed into iron oxides by oxidizing hydrothermal fluids, are retained in aqueously altered meteorites by virtue of their protective organic coatings (Brearley 2021). In IDPs and UCAMMs, primitive amorphous silicates are embedded within continuous regions of complex organic matter (Yabuta et al. 2017; Guérin et al. 2020). The extent to which complex organic matter

acts as a barrier to aqueous fluids on asteroid parent bodies is largely unknown and is only beginning to be studied.

CONCLUSION

The unique thermal and fluid processing histories of asteroids and comets resulted in an increase in the diversity of complex organic matter that was present in the early solar system, creating the range of elemental compositions, morphologies, functional group chemistries, and isotopic compositions we observe today. Advanced microscopy and spectroscopy methods allow characterization of complex organic matter *in situ* within the fine-grained matrix of carbonaceous chondrite meteorites and in IDPs and UCAMMs with an unprecedented level of spatial detail. These *in situ* studies provide additional petrographic context and access a more holistic picture of complex organic matter than previous studies of IOM residues. As a result, we are discovering that complex organic matter had a more active role in parent body processing, affecting changes of inorganic components even as those components are affecting change of organic materials.

Complex organic matter has continually been deposited on the surface of the Earth since its formation (Martins and Pasek, this issue). As described above, it contains a much greater complexity and diversity than purely interstellar and nebular carbonaceous matter, but it is unclear to what extent this extra diversity influenced the emergence and evolution of life on Earth. As our knowledge of the diversity and intricate formation pathways of complex organic matter grows, future research should explore how much of this material could have provided bioavailable nutrients to early microorganisms.

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