

IN SITU ANALYSIS OF CHEMICAL VARIATIONS IN METEORITIC ORGANIC MATTER FOR CONSTRAINING ALTERATION HISTORIES

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Introduction: Insoluble organic matter (IOM) in meteorites and other chondritic samples can provide useful information on the aqueous and thermal processing histories of their source parent bodies [1], and will be a key factor for understanding the aqueous alteration on the carbonaceous asteroids 162173 Ryugu and 101955 Bennu once regolith samples from these two bodies collected by the Hayabusa2 and OSIRIS-REx missions, respectively, are available for laboratory analysis. State-of-the-art micro- and nano-scale analytical methods are necessary for maximizing the scientific results from these small samples (relative to typical meteorite falls). Here, we use nanoscale scanning-transmission X-ray microscopy (STXM) and scanning transmission electron microscopy (STEM) to investigate the processing history of IOM in analog material for Ryugu regolith.

Samples and Methods: Due to evidence for variable, low-level shock processing similar to that inferred for Ryugu [2], the CM2 chondrite Jbilet Winselwan [3] was selected as an analog. Ultramicrotome sections were created from a 15x15 μm region of a ~ 350 μm matrix particle using a hybrid focused ion beam + S-embedding + ultramicrotomy approach [4] and placed on lacey C transmission electron microscopy (TEM) grids. Several grains of insoluble organic matter (IOM) were located by C-mapping with polymer STXM beamline 5.3.2.2 at the Advanced Light Source (Berkeley, CA). Their composition and functional chemistry was measured by simultaneous energy dispersive X-ray spectroscopy (EDS) and electron energy-loss spectroscopy (EELS) at 60 keV with the aberration-corrected Nion UltraSTEM 200X at NRL. Using these 30 nm/pixel hyperspectral datasets, nanoscale variations in elemental abundance observed in EDS spectra can be correlated with subtle variations in functional chemistry in EELS spectra that would not otherwise be noticed.

Results: Two IOM grains with unique morphologies were studied—an isolated nanoglobule and a nanoglobule cluster intimately mixed with nanophase silicate. The organic functional group chemistry for each of these grains indicated by both STXM and EELS is similar, consistent with slightly-heated CM IOM. The nanoglobules associated with silicate material are enriched in S (~ 0.5 at.%), but the solitary nanoglobule and the lacey C substrate do not contain measureable S. This indicates that the nanoglobule cluster formed in the presence of a S-rich fluid. In addition, the nanoglobule cluster contains a few at.% variations in O and N abundance, while the isolated nanoglobule has a homogenous composition within EDS detection limits. Comparing the most O-rich pixels with the most O-poor pixels reveals variations in the abundance of ketone ($\text{C}=\text{O}$) functional groups. A similar analysis of N-rich and N-poor pixels can be explained by variations in the abundance of pyrrole and pyridine ($\text{C}=\text{N}$) functional groups [5], likely representing stable aromatic N.

The observed nanoscale variations in functional group abundance represent a combination of pre-accretionary and parent-body processes. Identification of spatial associations of specific functional group abundances with surrounding matrix minerals and isotope anomalies in N and D will help further deconvolve the different processing histories. Ketones and aromatic imines are likely not the only functional group carriers of compositional variations within Jbilet-Winselwan. Our parallel ex situ study of CR and CO IOM used a similar approach to detect correlated N and nitrile ($\text{C}\equiv\text{N}$) heterogeneity [6]. This coordinated STXM-STEM experimental approach will be used on samples returned from Ryugu and Bennu in future work to assess the extent of aqueous processing on those asteroids from small amounts of returned regolith particles.

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