Introduction: Preliminary examination of the mineralogy and composition of surface regolith grains from near-Earth Cb-type asteroid (162173) Ryugu indicate a strong connection to CI chondrite group [1]. However, reflectance spectroscopy of the Ryugu asteroid show a greater similarity to laboratory spectra of heated and partially dehydrated carbonaceous meteorites [2]. The Ryugu return samples are extensively hydrated, containing abundant fine-grained and course-grained [1], similar to CI chondrites, yet laboratory visible and near infrared (NIR) reflectance spectra are relatively featureless like previous orbital observations [3].

Heating a sample of Orgueil to 300 °C under reducing conditions matches the Ryugu spectra reasonably well [4]. Vis-NIR, IR, and mid-IR reflectance changes due to this low-level heating indicate dehydration of the sample, while x-ray diffraction (XRD) showed no significant change in phyllosilicate mineralogy with heating. This heating also induces the disappearance of hydrated sulfate and reduction of Fe associated with phyllosilicates. Heating to higher temperatures causes more significant mineralogical changes [4]. Serpentine decomposition is complete by 500 °C, and secondary anhydrous silicates such as olivine begin to form by 600°C. All hydrated minerals are absent from the sample at 700 °C, and by 900°C, taenite and kamacite have replaced magnetite.

Changes in organic matter and the formation of nanophase Fe particles have been implicated for the flattening of reflectance spectra of “dark” asteroid surfaces like Ryugu [5]. In this study, we characterized the heated Orgueil samples of Amano et al. [4] using x-ray absorption near-edge structure spectroscopy (XANES) to observe nanoscale changes in C and Fe to correlate with previous IR and XRD measurements.

Methods: Powder samples of the Orgueil CI chondrite were heated to temperatures of 400 °C, 500 °C, 600 °C, 700 °C, and 900 °C at reducing conditions for 50 hours as described in Amano et al. [4]. Individual particles were mounted on carbon tape, carbon-coated, and 100 nm thin lamellae were extracted using a Thermo Fisher Helios G3 focused ion beam (FIB) SEM. Electron beam imaging was avoided after attaching the lamellae to Cu transmission electron microscopy (TEM) grids to limit potential radiolysis damage of organic matter.

Sample lamellae were characterized with polymer scanning-transmission x-ray microscope (STXM) at beam line 5.3.2.2 at the Advanced Light Source, Berkeley, CA. X-ray absorption images and 3D “stacks” were acquired at energies around the C K-edge (~290 eV), O K-edge (~540 eV) and Fe L-edge (~710 eV). XANES stacks were acquired with a 50 nm pixel size and energy steps as small as 0.1 eV to resolve the near-edge spectral features.

Results and Discussion: In the 400 °C, 500 °C, and 600 °C samples, the overall mineralogy is dominated by silicate matrix, with clear patches of Fe-poor and Fe-rich silicates (e.g., Figure 1). Correlated TEM analysis of the samples [6] indicates that the Fe-poor regions are dominated by coarse-grained phyllosilicate such as saponite, while the Fe-rich regions consist of fine-grained phyllosilicates. XANES spectra from both Fe-
rich and Fe-poor regions in the 400 °C sample indicate that nearly all of the Fe is Fe\(^{3+}\). Magnetite is also indicated, visible as bright spots in the Fe maps (e.g., Figure 1), and ferrihydrite may also be present.

With heating, both Fe-poor and Fe-rich regions show reduction of Fe, eventually ending with all regions dominated by an olivine-like spectrum (Figure 2). Reduction of Fe happens more quickly in the Fe-poor regions, corresponding to saponite and other coarse-grained phyllosilicates. The Fe-rich silicates and oxides reduce more gradually from 400 °C to 500 °C, and evidence for olivine formation is seen at 600 °C. The entirety of the 700 °C sample appears to be olivine, and no Fe-XANES data was acquired for the 900 °C sample. These observations confirm the general mineralogical changes observed by Amano et al. [4].

Several different carbonaceous phases were observed. In the 400 °C sample, the diversity of carbonaceous phases is similar to that in unheated Orgueil, including IOM-like grains, aromatic globules, and carbonate minerals. In regions dominated by coarse-grained phyllosilicates, we found the same molecular carbonate signature as seen in Ryugu phyllosilicates (2nd panel in Figure 1), with a characteristic CO\(_3\) absorption peak at 290.4 eV but without the extended spectral structure typically seen in mineral carbonates [7]. These same phases are present in the 500 °C and 600 °C samples, but their spectra look more like IOM from CO chondrites (petrologic type 3), and aromatic nanoglobules are more prevalent. Little carbonaceous matter was observed in the 700 °C sample, but the few measurable grains showed a highly aromatic functional chemistry, and no molecular carbonate was detected. In the 900 °C sample, all carbonaceous matter was highly aromatic or graphitic.

The 400 °C, 500 °C, and 600 °C data are consistent with observations of increasing order and aromatization of organic matter in petrologic type 3 carbonaceous chondrites [8]. The 700 °C sample is roughly equivalent to petrologic type 4, and the 900 °C sample is roughly equivalent to petrologic type 6. The CK chondrites would be an appropriate analog for these latter samples, but no comparable XANES data exists for those meteorites.

**Acknowledgments:** This work was supported by NASA through LARS award 80HQTR20T0050 and SSERVI RISE2 award 80HQTR20T0014.

**References:**


---

**Figure 2.** Fe-XANES comparison of Fe-poor and Fe-rich silicate regions in heated Orgueil samples, corresponding to coarse-grained and fine-grained phyllosilicates, respectively. At 700 °C, all regions show a characteristic olivine spectrum.

**Figure 3.** C-XANES of representative carbonaceous grains in heated Orgueil samples.