

**THERMAL DECOMPOSITION OF THE MURCHISON CM2 CARBONACEOUS CHONDRITE: IMPLICATIONS OF SPACE WEATHERING PROCESSES FOR SAMPLE RETURN MISSIONS.** S. Lee<sup>1,2</sup>, L. P. Keller<sup>2</sup>, R. V. Morris<sup>2</sup>, J. Han<sup>1,2</sup>, and Z. Rahman<sup>3</sup>. <sup>1</sup>Lunar and Planetary Institute, USRA, Houston, TX 77058, (seungyeol.lee@nasa.gov), <sup>2</sup>ARES, NASA Johnson Space Center, Houston, TX 77058, <sup>3</sup>Jacobs, NASA Johnson Space Center, Houston, TX 77058.

**Introduction:** Primitive carbonaceous asteroids are the target bodies for the JAXA Hayabusa2 mission to Ryugu and the NASA OSIRIS-REx mission to Bennu. Both asteroids share spectral characteristics of CI/CM type carbonaceous chondrites [1-3]. Ryugu, in particular, appears to have undergone thermal processing that has modified its spectral properties [1]. The nature and extent of space weathering processes on the surfaces of Bennu and Ryugu are under active investigation using remote sensing data from the missions [4] and through laboratory studies on analog materials [5-7]. The analog studies are needed in order to understand the mineralogical and chemical changes that occur in space weathered samples that give rise to the observed optical effects measured by remote-sensing and to prepare for the analysis of returned samples.

The space weathering effects of micrometeorite impact and solar wind irradiation on primitive carbonaceous chondrites have been simulated by analog studies on the Murchison CM2 chondrite [5-7]. We performed a coordinated mineralogical, chemical and spectroscopic study to examine in detail the effects of thermal metamorphism on Murchison samples as an analog to processes that may have occurred on Ryugu. The bulk measurements including X-ray diffraction (XRD), Mössbauer spectroscopy, UV-VIS-NIR spectroscopy, thermogravimetric analysis, and evolved gas analysis are reported in a companion paper [8]. Here

we report on our preliminary nanoscale mineralogical and chemical analyses of pre- and post-heated Murchison samples using multiple electron beam techniques to understand how the mineralogical, chemical, and physical characteristics of carbonaceous chondrites change with increasing thermal effects.

**Sample and Methods:** The Murchison carbonaceous chondrite was heated from room temperature to 1300 °C in 100 °C steps (35 °C/min rate) [8]. We examined samples that were heated to 300, 600, 800 and 1100°C. Polished sections of the Murchison meteorite (unheated and heated) were analyzed by JEOL 7600F field emission scanning electron microscope (SEM), and Cameca SX-100 electron probe micro-Analyzer (EMPA) to study their mineralogy, chemistry, and microstructures. For the nanoscale investigation, we extracted thin sections from the polished samples using a FEI Quanta 3D 600 dual beam SEM/focused ion beam (FIB) with a protective carbon strap to minimize surface damage artifacts from the FIB milling. The FIB sections were analyzed using a JEOL 2500SE scanning and transmission electron microscope (STEM) with a JEOL silicon drift detector (SDD).

**Results and Discussions:** TEM analyses of the unheated Murchison samples show the overall textures and mineralogy consistent with previous TEM studies [5,6] including fine-grained serpentine, rounded Mg-rich serpentine (chrysotile), platy Fe-rich serpentine

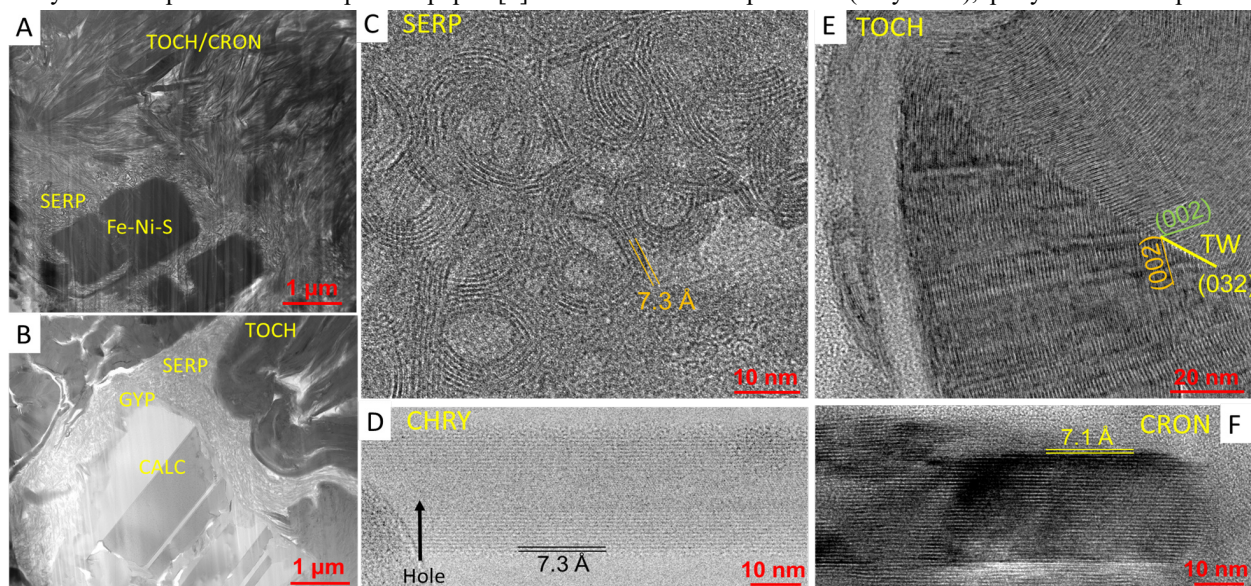


Figure 1. (A,B) Dark-field STEM and (C-F) High resolution TEM images of Murchison meteorite. TOCH = tochilinite, CRON = cronstedite, SERP = serpentine, CHRY = chrysotile, GYP = gypsum, CALC = calcite, and TW = twinning.

(cronstedite), tochilinite, olivine, Ca-poor pyroxene, Ca-rich pyroxene, Fe-Ni sulfides, troilite, magnetite, potassium iron-nickel sulfide, calcite, gypsum, apatite, Cr-bearing spinel, and chromite.

High-resolution TEM imaging shows the rolled morphology of fine-grained serpentine with (001) lattice fringes of 7.3 Å d-spacing (Figure 1C). Chrysotile grains are present as nanotubes of cylindrical morphology (Figure 1D). The tochilinite (ideal chemical formula,  $6\text{Fe}_{0.9}\text{S}\cdot 5(\text{Mg},\text{Fe})(\text{OH})_2$ ) shows the contorted morphology, mainly showing (002) lattice fringes of 5.3 Å spacing and the identification of a new twinning relation on the (032) plane (Figure 1E). The Fe-rich serpentine cronstedite shows strong (001) lattice fringes at 7.1 Å d-spacing and they commonly intergrown with the tochilinite phase (i.e. interstratified layers). The abundant Fe-Ni sulfide nanoparticle (2-5 nm in size) inclusions are widespread in the serpentine matrix.

The XRD results [8] show that the diffraction lines for tochilinite disappear above 300°C and serpentine lines are present at 500°C but are lost by 600°C. The thermal treatment results in the dehydration of serpentine group minerals and tochilinite to form secondary phases such as nanosized angular olivine, magnetite, sulfides (e.g., troilite, pyrrhotite, and pentlandite), and Fe-Ni metals (both taenite and kamacite). TEM analyses of the 800 °C sample show that it mainly consists of chemically homogeneous of micrometer-sized olivine with lesser enstatite and diopside, micrometer-sized sulfides, and fine-grained (sub-micrometer) matrix phases (Figure 2A & 2D) that replace the primary phyllosilicates and tochilinite intergrowths. Figure 2 shows that the fine-grained matrix phases are a mixture

of troilite, magnetite, Fe-Ni metal grains, and secondary olivine. The abundant Fe-Ni sulfide nanoparticles occur throughout the olivine matrix. In the 1100 °C sample, we observed that fibrous tochilinite clusters have been converted into dense anhedral grains consisting of a mixture of micrometer-sized Fe-Ni metal blebs inclusions in troilite (Figure 2D-F). The fine-grained matrix phases show a porous and vesiculated texture (Figure 2A & 2D), indicating the outgassing of volatiles derived from hydrous silicate phases (i.e. serpentine and tochilinite).

**Conclusions:** Thermal processing of Murchison carbonaceous chondrite samples produces distinctive microstructures that correspond to the breakdown of key minerals. Serpentine group minerals are converted into mixtures of sub- $\mu\text{m}$  olivine and pyroxene grains with similar Mg/Mg+Fe ratios as the precursor. Tochilinite breakdown forms troilite, magnetite, and minor metal aggregates at moderate (800°C) and coarser-grained assemblages of troilite and Fe-Ni metal at high temperatures. These mineralogical changes are being correlated with changes in the UV-VIS-NIR spectra of the samples.

**Acknowledgments:** This work was supported in part by NASA ISFM funding to LPK and RVM.

**References:** [1] Kitazato, K. *et al.* (2019) *Science* 364, 272-275. [2] Hamilton, V. E. *et al.* (2019) *Nature Astron.* 3, 332-340. [3] Clark B. E. *et al.* (2011) *Icarus*, 216, 462-475. [4] Trang, D. *et al.* (2019) *LPSC 50th*, #2172. [5] Thompson M. S. *et al.* (2017) *Meteorite Planet Sci*, 52, 413-427. [6] Thompson M. S. *et al.* (2019) *Icarus*, 319, 499-511. [7] Laczniaik, D. L. *et al.* (2020) this volume. [8] Morris, R. V. *et al.* (2020) this volume.

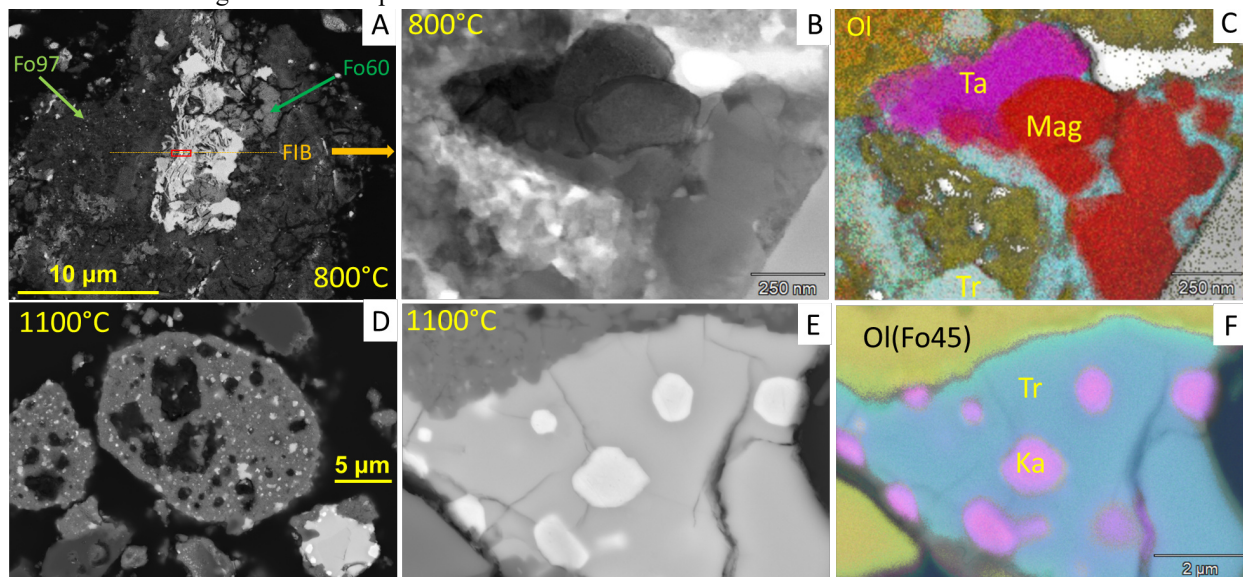


Figure 2. SEM/BSE and dark-field STEM images with corresponding EDS maps in Fe (red), Mg (yellow), Ni (pink), S (sky-blue) of heated Murchison meteorite. Ta = taenite, Mag = magnetite, Tr = troilite, Ka = kamacite, and Ol = olivine.