

**LESSONS LEARNED FROM PREPARING OSIRIS-REx SPECTRAL ANALOG SAMPLES FOR BENNU.**

D. L. Schrader<sup>1,2</sup>, T. J. McCoy<sup>2</sup>, G. D. Cody<sup>2</sup>, A. J. King<sup>2</sup>, P. F. Schofield<sup>2</sup>, S. S. Russell<sup>2</sup>, H. C. Connolly Jr.<sup>2</sup>, L. P. Keller<sup>2</sup>, K. Donaldson Hanna<sup>2</sup>, N. Bowles<sup>2</sup>, E. A. Cloutis<sup>2</sup>, J. P. Mann<sup>2</sup>, D. M. Applin<sup>2</sup>, D. S. Lauretta<sup>2</sup>, B. E. Clark<sup>2</sup>, V. E. Hamilton<sup>2</sup>, L. Lim<sup>2</sup>, and the OSIRIS-REx team<sup>2</sup>. <sup>1</sup>Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA (devin.schrader@asu.edu), <sup>2</sup>The OSIRIS-REx Science Team, University of Arizona, Tucson, AZ, USA.

**Introduction:** NASA's OSIRIS-REx sample return mission launched on September 8<sup>th</sup>, 2016 to rendezvous with B-type asteroid (101955) Bennu in 2018. Type C and B asteroids have been linked to carbonaceous chondrites because of their similar visible – to – near infrared (VIS-NIR) spectral properties [e.g., 1,2]. The OSIRIS-REx Visible and Infrared Spectrometer (OVIRS) and the Thermal Emission Spectrometer (OTES) will make spectroscopic observations of Bennu during the encounter. Constraining the presence or absence of hydrous minerals (e.g., Ca-carbonate, phyllosilicates) and organic molecules will be key to characterizing Bennu [3] prior to sample site selection.

The goal of this study was to develop a suite of analog and meteorite samples and obtain their spectral properties over the wavelength ranges of OVIRS (0.4–4.3  $\mu\text{m}$ ) and OTES (5.0–50  $\mu\text{m}$ ). These spectral data were used to validate the mission science-data processing system. We discuss the reasoning behind the study and share lessons learned.

**Samples:** The samples in this study included both terrestrial minerals and well-characterized meteorites from the Smithsonian Mineral and Meteorite Collections, and meteorites from the United States Antarctic Meteorite Collection and Arizona State University Center for Meteorite Studies. The minerals for the analog powders were the closest possible compositional matches to minerals from carbonaceous chondrites. Mineral mixtures replicated abundances in a progression from unaltered (anhydrous) to highly aqueously altered (hydrous) carbonaceous chondrites.

*Analog Minerals, Anhydrous Samples:* Olivine, pyroxene (high- and low-calcium), plagioclase, metal, and troilite are known to be major components in chondritic meteorites that have not been subjected to significant degrees of aqueous alteration (e.g., OCs, CO3s, CV3s; CR2/3s) [4–6]. The anhydrous analog minerals used were: San Carlos olivine; Johnstown orthopyroxene; Kakanui augite; Amelia albite; Mundrabilla troilite; and Fe powder from Alfa Aesar<sup>®</sup>. The first four of these are Smithsonian microprobe standards and, thus, exceptionally well-characterized chemically. These minerals were mixed in abundances consistent with type 3 carbonaceous chondrites.

Since unaltered chondrites are also known to contain organics, we included a synthetic insoluble organic matter (IOM) to simulate meteoritic organics in sub-

sequent samples. The production of this analog IOM involves hydrothermal treatment of simple sugars (e.g., dextrose) at modest temperatures (200–250°C) to produce a black organic polymer whose functional characteristics are similar to meteoritic IOM [7].

*Lessons learned:* (1) Imitating polymineralic systems (i.e., matrix clumps, chondrules, and metal-sulfide assemblages) with mono-mineralic grains is problematic. Spectra of polymineralic mm-cm size particles are not equivalent to those of mono-mineralic mm-cm size particles. Using large grain sizes (>100  $\mu\text{m}$ ) for mono-mineralic grains is typically unrealistic for minerals in most chondrites. Fine particulates (<45  $\mu\text{m}$ ) can coat larger particles and are also known to dominate VNIR reflectance spectra [8,9]. To address this problem, analog samples were prepared at one size fraction (<38  $\mu\text{m}$ ) except for chondrule-analog minerals (i.e., olivine and orthopyroxene), which consisted of 50 wt.% fine (<38  $\mu\text{m}$ ) and 50 wt.% coarse (105–38  $\mu\text{m}$ ) material. While there will certainly be larger grains and pebbles (mm to cm, and larger) in Bennu's regolith [e.g., 9,10], these grains are likely polymineralic. In addition, making representative analogs with grains sizes mm to cm in diameter is restricted by our analytical capabilities and available sample masses. Sample mass requirements for VIS-NIR and thermal infrared (TIR) measurements were ~0.5 g and ~4 g, respectively. Assuming a density of 3.3 g/cm<sup>3</sup> and spherical grains, making a 4-gram sample with 1-mm diameter grains would produce ~2315 grains, 3-mm grains would produce a scant ~86 grains, and 1-cm grains would produce a highly unrepresentative ~2 grains. Therefore, larger grain sizes lead to less representative samples within the mass requirement or much larger masses than are available of well-characterized minerals and precious meteorites.

(2) Even using fine-grained analog powders, the sample requirement of ~4 grams for TIR measurements restricted the number of samples that we could make with available masses of well-characterized minerals. If technological advances allow measurement of TIR on much smaller samples, a broader range of mixtures could be measured and/or measurements could consume lower quantities of well-characterized minerals. Additionally, smaller sample sizes would allow archiving of multiple samples, rather than a serial ap-

proach in which minerals are added to existing powders to mimic alteration.

**Analog Minerals, Hydrous Samples:** Phyllosilicates, Ca-carbonate, and magnetite are known to be major components in chondritic meteorites that have been subjected to significant degrees of aqueous alteration (e.g., CM2s, CM1s and CIs) [6,11,12]. In mineral mixtures analogous to partially- to extensively-hydrated carbonaceous chondrites, we included hydrous minerals to replicate the progression of aqueous alteration (e.g., replacing Fe metal with magnetite, mafic silicates with phyllosilicates). The hydrous minerals we used were: Mono Lake saponite; Morris County lizardite; Minas Gerais magnetite; and New Mexico calcite.

Phyllosilicates are the major alteration phase in the matrix of aqueously altered carbonaceous chondrites (e.g., CM and CI). We used lizardite as a substitute for chrysotile, a Mg-rich serpentine group mineral. We used saponite as an FeO-rich phyllosilicate mineral from the smectite group. Saponite was selected for two reasons: (i) FeO-rich serpentine minerals are rare on Earth but common in meteorites (e.g., Fe-cronstedtite in CM chondrites) [11,13]; and (ii) the phyllosilicate component of the CI chondrites is a mixture of serpentine and saponite [e.g., 12]. Phyllosilicate abundances in analog mixtures were based on their abundances in CM and CI chondrites [e.g., 11–13]. Minor amounts of magnetite and calcite were included as common accessory phases produced during aqueous alteration of carbonaceous chondrites (e.g., CI and CM) [11–13].

**Lessons learned:** Identifying analogs for the more Fe-rich meteoritic minerals (i.e., phyllosilicates) is difficult, as terrestrial minerals are commonly Mg-rich and formed under different  $fO_2$  conditions. This is problematic as the Fe content and  $Fe^{2+}/Fe^{3+}$  ratio (oxidation state) of minerals are responsible for important spectral features [e.g., 14].

**Meteorites.** Although telescopic spectra of Bennu in the VNIR are most consistent with CI and CM chondrites [2], we selected a broader range of chondrites of low petrologic type that have experienced varying degrees of aqueous alteration and have low albedos. The samples include falls and finds, but where practical we used observed falls that are minimally affected by terrestrial alteration. The meteorites range from a progression of relatively anhydrous (Allende (CV3<sub>OxA</sub>), Vigarano (CV3<sub>red</sub>), and Farmington (L5, shock darkened), to increasingly hydrated (Miller Range 090001 (CR2) and Murchison (CM2)), to extensively aqueously altered (Allan Hills 83100 (CM1/2) and Orgueil (CI)).

Because meteorites are naturally polymineralic, we used larger grain sizes than those used for the analog

minerals. The meteorite samples were crushed and sieved into three sieve fractions (150–100  $\mu\text{m}$ , 100–38  $\mu\text{m}$  and <38  $\mu\text{m}$ ) in order to generate a size distribution as close as possible to that obtained by impact comminution of meteoritic samples [e.g., 15,16]. The mass distribution at these grain sizes is ~11 wt.% material at 150–105  $\mu\text{m}$ , 22 wt.% material at 105–38  $\mu\text{m}$ , and 67 wt.% material <38  $\mu\text{m}$ .

**Modal Mineralogy:** Although the mineralogy of these meteorites are known, the modes are not as the matrix is exceptionally fine grained. To determine the modal mineralogy, we used Position-Sensitive X-ray diffraction [e.g., 5,13] and digital point counting of thin-section X-ray element maps [e.g., 17].

**Future Work:** Amorphous silicates are a major component of primitive meteoritic materials including comets and a few of the least altered carbonaceous chondrites (up to ~40 vol.%) [e.g., 6,18–20]. High abundances of amorphous silicates may prove key to identifying a sample site of high science value on Bennu. However, the detection of amorphous silicates is difficult in the VNIR and their accurate identification in TIR spectra will rely on having representative spectra in our spectral library [e.g., 21]. Analyses of carbonaceous chondrites in the mid-infrared shows promise in detecting amorphous silicates [22]. We have started a pilot study to advance the detection of amorphous silicates.

The results of the spectral analyses from this study are ongoing. Preliminary analyses of TIR laboratory measurements are presented at this conference by [23].

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