THE GLOBAL MINERALOGY OF (101955) BENNU FROM VNIR AND TIR OBSERVATIONS DURING THE DETAILED SURVEY PHASE OF THE OSIRIS-REx MISSION. V. E. Hamilton1, A. A. Simon2, H. H. Kaplan1, D. C. Reuter2, P. R. Christensen3, R. D. Hanna4, D. N. DellaGiustina5, E. S. Howell5, T. J. McCoy6, H. C. Connolly, Jr.4,5, J. P. Emery6, B. E. Clark6, and D. S. Lauretta5, 1Southwest Research Institute, 1050 Walnut St. #300, Boulder, CO 80302 USA (hamilton@boulder.swri.edu), 2Goddard Space Flight Center, Greenbelt, MD, 3Arizona State University, Tempe, AZ, 4University of Texas, Austin, TX, 5Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 6National Museum of Natural History, Smithsonian Institution, Washington, D.C., 7Rowan University, Glassboro, NJ, 8University of Tennessee, Knoxville, TN, 9Ithaca College, Ithaca, NY.

Introduction: Spectral data of Bennu acquired just after OSIRIS-REx arrived at the asteroid in December 2018 showed globally homogeneous signatures dominated by features attributable to hydrated minerals most similar to low petrologic type CM chondrites [1]. Since then, global mapping data acquired at spatial resolutions of ~20-40 m/pixel and under optimized observing conditions have revealed that Bennu’s surface is not as compositionally homogeneous as it initially appeared. Here we describe the full range of spectral variability that has been identified so far during the Detailed Survey phase of the mission and implications for the future returned sample.

Spectral Instruments: OSIRIS-REx carries two point spectrometers: OVIRS, the visible and near-infrared (VNIR) spectrometer, and OTES, the thermal emission spectrometer. OVIRS and OTES measure mineralogy, chemistry, and temperature on the surface of Bennu. OVIRS has a 4-mrad field of view (FOV) and measures reflected solar energy from 0.4 to 4.3 μm with a spectral sampling of 2 nm (0.002 μm) from 0.392 to 2.4 μm, and 5 nm (0.005 μm) from 2.4 to 4.3 μm [2, 3]. OVIRS spectral band positions are reported in units of microns. OTES has an 8-mrad FOV and measures emitted energy from ~1650-100 cm⁻¹ (~5.5 to 100 μm) at a spectral sampling of 8.66 cm⁻¹ [4]. OTES spectral feature positions are reported in wavenumbers. The OVIRS FOV is within that of OTES but the boresights are not precisely co-aligned.

OVIRS Results: Visible wavelength spectra from the early mission phases are consistent with ground-based spectra having a blue slope and no discernible features; we have not yet made any determination as to the effects of space weathering, which can cause both bluing and reddening of the spectral slope [1, 5]. The most prominent spectral feature observed at longer wavelengths is a ~2.7-μm hydration band whose position (2.74 μm ±0.01) is most consistent with CI and low petrologic subtype CM carbonaceous chondrites (CC) [1, 6]. During the Detailed Survey phase of the mission, this feature remains the most prominent and is observed in every spectrum; the band depth is strongly correlated with temperature, and separation of this effect is an ongoing effort. OVIRS spectra of very rare, bright (albedo = ~0.14 at 0.55 μm) boulders identified in color imagery have ~1 and ~2-μm bands attributed to pyroxene [7]. The band positions, as determined by modified gaussian modeling (MGM) [8], represent pyroxene solid solution compositions that are most consistent with the howardite-eucrite-diogenite (HED) group meteorites that are believed to originate from the asteroid (4) Vesta [e.g., 9, 10]. Based on their rarity and composition, these boulders are inferred to have an exogenous origin [7]. Absorption features also are evident in the 3.2 - 3.6 μm region and are attributed to C-bearing compounds that could be hosted in organics and/or carbonate minerals. These features are quite complex and variable in shape and are not readily attributed to specific compounds in most spectra. As a result, we are presently mapping these features by their total band area rather than by specific band positions. The mapped band area does not correspond with the distribution of other spectral or geologic features.

OTES Results: As with the OVIRS data, OTES spectra acquired early in the mission appeared globally homogeneous and are characterized by spectral properties best matched by aqueously altered carbonaceous chondrites of the CI and CM groups [1]. Data acquired in the Detailed Survey phase have now revealed that there appear to be two globally prevalent spectral end members. These end members differ in shape in the region dominated by silicate bending mode features (~1100-650 cm⁻¹), where one of the end members has a strongly asymmetric band shape with a minimum near 987 cm⁻¹, and the other has slightly less asymmetric band with a similar depth and a minimum near 814 cm⁻¹. At the wavenumbers dominated by silicate bending vibrations (~525-300 cm⁻¹) the two end member spectra have a similar shape but differing depths relative to each other and the Si-O stretching bands. By comparison with CC meteorite spectra [e.g., 11, 12], the low wavenumber spectral shape, regardless of depth, is consistent with meteorites of petrologic type <2.5. The ratio of the two spectral types strongly resembles a phyllosilicate or amorphous/poorly crystalline/disordered phase. The spectra are not well mod-
eled by a library containing spectra representing coarse/solid (non-scattering) and volume scattering particulate (<90 \(\mu m\)) minerals and meteorites (where the fine particulates were measured under simulated asteroid conditions [13]). The origin of the observed spectral variations remains enigmatic, potentially arising from differences in one or more of the following: composition, phyllisilicate crystallinity/ordering, particle size effects not replicated by available laboratory spectra, space weathering, surface textural effects, porosity, and others. The distribution of the two spectral types corresponds with visible albedo and thermal inertia [14], which in turn correspond with areas that are relatively rich or poor in large boulders. Surprisingly, the spectral shape that might be expected to represent a contribution from fine, scattering particulates corresponds to the most boulder-rich areas.

**Characterization of Candidate Sampling Sites:** OVIRS and OTES spectra over all candidate sampling sites were examined for their diagnostic features relative to the global average spectrum for that instrument. Here we summarize the results for the final four sites in wavelength order (OVIRS followed by OTES).

**Sandpiper.** This southern hemisphere site is generally similar to the global average in OVIRS data other than having a deeper hydration band (which is correlated with temperature). This site has greater spectral contrast than the global average OTES spectrum and resembles the spectral end member having an Si-O stretching band minimum near 987 cm\(^{-1}\).

**Nightingale.** At OVIRS wavelengths, this site is redder than the global average with a comparable hydration band depth. Nightingale differs from the global average OTES spectrum by its strong resemblance to the spectral end member having a silicate stretching band minimum near 814 cm\(^{-1}\).

**Osprey.** Like Nightingale, Osprey is also characterized as being redder than the global average and having a similar hydration band depth in OVIRS data. The average thermal spectrum of this site is most similar to the global average OTES spectrum, but nonetheless exhibits characteristics of the end member having the Si-O stretching band minimum near 987 cm\(^{-1}\).

**Kingfisher.** This site’s average spectrum is very similar to the global average OVIRS spectrum, exhibiting only slight reddening. OTES spectra of this site have greater spectral contrast than the global average and also resemble the end member with the silicate stretching minimum near 987 cm\(^{-1}\).

**Implications for the Returned Sample:** Based on the combined spectral results to date, we can be quite certain that the OSIRIS-REx returned sample will contain abundant hydrated minerals that will inform our understanding of aqueous alteration on Bennu’s parent body. There appear to be at least two globally-distributed spectral types that may represent compositional or physical variations on Bennu’s surface. As a consequence of the mission requirements for selecting a sample site, the candidate sampling sites are in relatively boulder-free regions that preferentially correspond to one of the two OTES spectral end members, but they exhibit differences at OVIRS wavelengths. There are tantalizing hints that carbon-bearing compounds (organic and/or inorganic) are widespread and will be sampled. Only a few of the exogenous, bright, pyroxene-enriched boulders are large enough (~1 meter) to be readily detected at the scale of existing OVIRS observations and they have not been detected yet in OTES data; depending on the global distribution and abundance of these materials, they may be present within the sampling site and might also be collected.

**Summary and Conclusions:** The surface of Bennu not only exhibits evidence of hydrated silicates but appears to be dominated volumetrically by such minerals and remains consistent with a bulk composition similar to the most aqueously altered CM carbonaceous chondrites with a potentially included component of CI-like material. Detailed Survey data display heterogeneity that was not previously identified although the origin of this heterogeneity is not entirely understood at this time. The Reconnaissance phase of the mission, starting in September 2019, is expected to result in the acquisition of spectral data at resolutions of ~5-10 m/pixel for the further characterization of the top four candidate sampling sites. These higher spatial resolution data may reveal additional details of the compositional diversity of Bennu.

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**References:**