VNIR AND TIR SPECTRAL CHARACTERISTICS OF (101955) BENNU FROM OSIRIS-REX DETAILED SURVEY AND RECONNAISSANCE A OBSERVATIONS. V. E. Hamilton[1], A. A. Simon[2], H. H. Kaplan[1], P. R. Christensen[3], D. C. Reuter[2], D. N. DellaGiustina[4], C. W. Haberle[3], R. D. Hanna[5], J. R. Brucato[6], A. Praet[7], T. D. Glotch[8], A. D. Rogers[8], H. C. Connolly, Jr.[4,9], T. J. McCoy[10], J. P. Emery[11], E. S. Howell[4], M. A. Barucci[7], B. E. Clark[12], and D. S. Lauretta[4], [1]Southwest Research Institute, Boulder, CO (hamilton@boulder.swri.edu), [2]NASA Goddard Space Flight Center, Greenbelt, MD, [3]Arizona State Univ., Tempe, AZ, [4]Lunar and Planetary Laboratory, Univ. of Arizona, Tucson, AZ, [5]Univ. of Texas, Austin, TX, [6]INAF, Firenze, Italy, [7]LESIA-Paris Obs, PSL, CNRS, Sorbonne Univ., Université de Paris, France, [8]Stony Brook Univ., Stony Brook, NY, [9]Rowan Univ., Glassboro, NJ, [10]Smithsonian Institution, Washington, D.C., [11]Northern Arizona Univ., Flagstaff, AZ, [12]Ithaca College, Ithaca, NY.

Introduction: Early spectral observations of the asteroid Bennu by the spectrometers onboard the Origins, Spectral Interpretation, Resource Identification, Security–Regolith Explorer (OSIRIS-REx) spacecraft revealed evidence of widespread hydrated phases on the surface of asteroid (101955) Bennu [1]. Here we describe results from higher-spatial resolution observations collected during subsequent phases of the mission, which have revealed new spectral variability from the visible through the thermal infrared.

Background and Data: The primary objective of the OSIRIS-REx mission is to collect and return to Earth a pristine sample of carbonaceous material from the near-Earth (and potentially hazardous) asteroid Bennu [2]. For characterization of Bennu's composition, OSIRIS-REx carries two hyperspectral, point spectrometers, the OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS) [3, 4] and the OSIRIS-REx Thermal Emission Spectrometer (OTES) [5]. An automated data processing pipeline produces quicklook spectral science (Level 3) products immediately after the data are downlinked (described by [6]).

Mission Phases: OSIRIS-REx mission phases utilize different observing strategies to best characterize Bennu and the eventual sampling site. Spectral results from the Approach and Preliminary Survey phases were described by [1]. Here we describe results from the Detailed Survey and Reconnaissance A phases.

Spectral observations in the Detailed Survey phase. The first part of the Detailed Survey (DS) phase, known as Baseball Diamond, took place in March and April 2019. This was primarily an imaging campaign in which spectral observations from OVIRS and OTES were collected on a best-effort, or ride-along, basis during the fly-bys. The local time of the observations varied between 10:00 am and 12:30 pm while the spacecraft was passing northern latitudes, the equator, or southern latitudes and roughly along or perpendicular to Bennu's rotation axis. The spatial resolution of OVIRS and OTES spots during this phase ranges from 12–20 m and 25–40 m, respectively, depending on the specific fly-by, although spots (in all mission phases) are elongated at increased emission angles and due to spacecraft motion along the trajectory/scan direction.

The second part of Detailed Survey (April–June 2019) focused on Equatorial Stations for global spectral and temperature mapping. The spacecraft was located approximately over the equator, scanning roughly north-south at seven local times of day. In chronological order, these were: 3:00 pm, 3:20 am, 12:30 pm, 10:00 am, 6:00 am, 6:00 pm, and 8:40 pm. These local times allowed spectral data collection to be optimized for reflectance and emission spectroscopy observations as well as thermal inertia studies. The spatial resolutions of OVIRS and OTES spots during this phase are nominally ~20 m and ~40 m, respectively. Both spectrometers acquired data at all stations, although the only OVIRS data suitable for compositional science were collected at 10:00 am, 12:30 pm, and 3:00 pm.

Spectral observations during Reconnaissance A. "Recon A" observations (October 2019) were fly-bys aimed primarily at obtaining increased resolution imaging of the final four candidate sampling sites identified from the Detailed Survey data. The spectrometers collected data on a best-effort basis for all four sites and other observations of opportunity. For data with mean emission angles ≤50-55°, local times varied from ~8:30 am to 4:00 pm and the spatial resolutions of OVIRS and OTES were typically ~3-5 and ~7-10 m.

OVIRS Results: The visible blue slope observed in OVIRS disk-integrated Approach data is present in all DS and Recon A data; although the blueness of the slope varies above the level of the noise, there are no visible spectral features above the level of the noise. Specifically, a 0.55-µm feature observed in OCAMS data [7] during Approach remains undetected in OVIRS data. Several weak bands have been observed between 1.00-2.55 µm but are not yet uniquely identified [8]. At longer wavelengths, the 2.74-µm hydration band first observed in Approach data is present in all DS spectra and varies in depth across the surface of Bennu. The band position does not change substantially and we continue to attribute it to phyllosilicates like those in low petrologic type CI and CM carbonaceous chondrite (CC) meteorites. Modeling of the average band strength yields an estimate of wt.% H in H_2O/OH^- that is consistent with measurements from CC meteorites [9]. A major new discovery in DS and Recon A data is a complex set of bands around ~3.4 µm that vary in their relative depths with location. We attribute these features to carbon-bearing compounds and minerals, primarily organics and carbonates [10], consistent with compositions known to occur in CC meteorites. Due to their complexity, we have focused on mapping the integrated area of these bands, and observe it to vary across the surface of Bennu; the details of the relationship with geology are still under analysis. Finally, six unusually bright boulders (relative to the average global albedo of 4.4%) have been identified in OCAMS images; these are associated with very weak (~1%) bands of pyroxene in OVIRS spectra. Based on the pyroxene compositions and other properties, these boulders are interpreted to have originated on Vesta [11]. None of the boulders are within the primary or secondary sampling sites.

OTES Results: OTES spectra collected during Preliminary Survey exhibited a spectral shape that is broadly consistent with CC meteorites in the CI and CM groups. With the improved spatial resolution of DS data, we now are able to distinguish spectral differences across Bennu, primarily in the shape of the ~1100 - 650 cm^{-1} (~9.1 - 15.4 µm) region and in the band depths at <650 cm^{-1} (>15.4 µm). There appear to be two end member spectra, Type 1 and Type 2, and virtually all OTES spectra can be modeled well by linear mixtures of these two types. We interpret the Type 1 spectra as being dominated by coarse particulate (>~100 µm) to solid materials, whereas Type 2 spectra exhibit properties consistent with weak scattering in fine particulates (<~100 µm). A peak at ~1420 cm^{-1} in averaged OTES spectra is apparent due to the presence of fine particulates; it may be attributable to one or more components, including organics, carbonate, serpentine, spinel, and/or pyrrhotite, and is under continuing study. The strong similarity of the Type 1 and 2 spectra at <650 cm^{-1} suggests that we are not observing mineralogical variability beyond a relatively small range of phyllosilicate-dominant CI and CM compositions. Specifically, the strong spectral feature at 440 cm^{-1} (~22.7 µm) in both spectral types indicates phyllosilicates are volumetrically dominant, and small features at 555 and 340 cm^{-1} (~18.0 and 29.4 µm) are consistent with magnetite [1]. A peak in the OTES spectra at 523 cm^{-1} (19.1 µm) is also observed in some CI/C1/CM meteorites and is not present in spectra of meteorites having more than ~5 - 10 vol.% olivine plus pyroxene [12, 13]. At the spatial scales of DS and Recon A observations, we cannot rule out a fractional contribution from Type 2 materials in the Type 1 spectrum, although such a contribution is not required to match available meteorite spectra. For example, the Type 1 spectrum can be reasonably well approximated by mixtures of solid sample and fine particulate Tagish Lake (C2-ung) spectra but it is similarly well approximated by a solid sample of a C1 fragment from Almahata Sitta (Ureilite-anom) [14]. The Type 1/Type 2 ratio spectrum strongly resembles CI and low petrologic subtype CM meteorites; this could be interpreted as indicating the presence of fines in the Type 1 spectrum, or it may indicate a difference in the dominant composition. The distribution of Type 1 and Type 2 spectra exhibits some correlation (R^2 = 0.687) with thermal inertia [15]. Interestingly, the Type 2 materials correspond to some of the largest boulders and boulder clusters, which is opposite to the trend expected for typical planetary surfaces. The details of this relationship are under ongoing study and likely will inform our understanding of the distribution of fine particulates and the physical properties of rocky materials on Bennu.

Implications for the Returned Sample: All major spectral features described above are present in spectra acquired in the Recon A data over the primary and backup sampling sites. As such, we expect the returned sample to include materials having a range of particle sizes down to 10s-100s of µm and containing abundant phyllosilicates, along with lesser quantities of secondary minerals (carbonate, oxides) and organics.

Future Observations: In 2020, additional medium- and low-altitude fly-bys over the primary and backup sampling sites will take place. OVIRS and OTES will collect data during these fly-bys, and the low altitude passes will provide even higher spatial resolution. These data will enable us to continue refining the mineralogy and chemistry of Bennu.

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