THERMAL INFRARED EVIDENCE FOR LIMITED COMPOSITIONAL AND PARTICLE SIZE VARIABILITY ON ASTEROID (101955) BENNU. V.E. Hamilton[1], P.R. Christensen[2], H.H. Kaplan[3], C.W. Haberle[2], A.D. Rogers[4], T.D. Glotch[4], L.B. Breitenfeld[4], C.A.Goodrich[5], D.L. Schrader[2], T.J. McCoy[6], C. Lantz[7], R.D. Hanna[8], A.A. Simon[3], J.R. Brucato[9], B.E. Clark[10], D.S. Lauretta[11], and the OSIRIS-REx Team, [1]Southwest Research Institute (hamilton@boulder.swri.edu), [2]Arizona State University, [3]Goddard Space Flight Center, [4]Stony Brook University, [5]Lunar and Planetary Institute, [6]Smithsonian Institution, [7]Institut d'Astrophysique Spatiale, [8]University of Texas, [9]INAF-Astrophysical Observatory, [10]Ithaca College, [11]Lunar & Planetary Laboratory, University of Arizona.

Introduction: Asteroid (101955) Bennu is the target of NASA's Origins, Spectral Interpretation, Resource Identification, and Security—Regolith Explorer (OSIRIS–REx) mission. The spacecraft's instruments characterized Bennu at multiple scales to select a sampling site and provide context for the returned sample, including thermal infrared spectral characterization by the OSIRIS-REx Thermal Emission Spectrometer (OTES) [1]. To understand the degree of compositional and particle size variation on Bennu, and thereby predict the nature of the returned sample, we studied OTES spectra that are diagnostic of these properties.

Data and Methods: Our analysis used OTES data (~1750 to 100 cm^{-1} at 8 cm^{-1} sampling) from the Detailed Survey Equatorial Stations at 12:30 pm (EQ3) and 8:40 pm (EQ6) local solar time. The nominal nadir spatial resolution of these observations is ~40 m/spot.

To compare and investigate the surface spatial distributions of spectral features observed by visual inspection, we devised spectral indices to identify the presence and strength or orientation of a feature of interest. We also used a non-negative linear least squares (NNLS) model [2] to determine the abundances of data-derived endmember spectra in each spectrum from the EQ3 dataset.

Results: The global average spectrum of Bennu from EQ3 (Fig. 1) is consistent with the hemispheric average spectrum from Preliminary Survey [3]. Visual inspection of individual EQ3 spectra revealed two common variations, one being the slope of the low-wavenumber side of the silicate stretching feature between 987 and 814 cm^{-1} and the other being the depth of the band minimum at 440 cm^{-1} (Fig. 1). We developed two spectral indices to characterize these variations: R987/814 (the ratio of the emissivity at 987 cm^{-1} to that at 814 cm^{-1}) and BD440 (the band depth at 440 cm^{-1}). We averaged the 100 spectra having the lowest and highest values of the R987/814 index to define two endmember spectral types, T1 and T2, respectively.

Both T1 and T2 exhibit overall positive slopes (shallower in T1) between 1500 and 1090 cm^{-1} with a peak near 1420 cm^{-1}. The region of the silicate stretching feature in T1 is asymmetric with a band minimum on the high wavenumber side (~987 cm^{-1}), whereas T2 has a more symmetric shape with a minimum at ~814 cm^{-1} and is shallower overall. The T1 and T2 features between ~520 and 300 cm^{-1} exhibit virtually identical shapes, with the T2 feature being shallower. R987/814 tends to be higher in areas with large, dark boulders and lower in areas with fewer large boulders. The BD440 map resembles the inverse of this trend. However, the R987/814 and BD440 parameters are only weakly inversely correlated ($R^2 = 0.37$), indicating that other factors (e.g., inherent emissivity, roughness, fractures/cavities) are influencing the data.

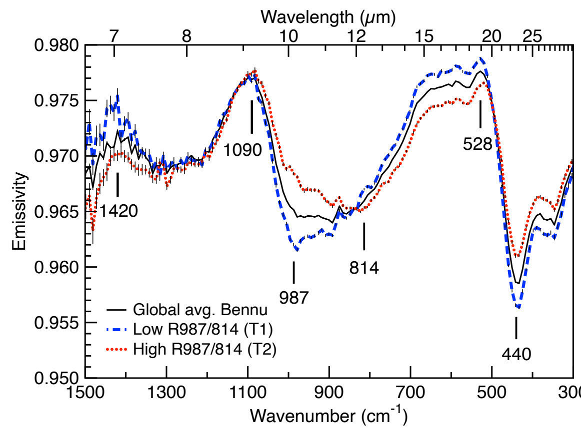

Fig. 1. OTES global average spectrum (black) and spectral types T1 (blue) and T2 (red).

We used the NNLS model to: 1) demonstrate that T1 and T2 spectra are sufficient to model the global OTES dataset, and 2) determine the abundances of each endmember in any given location, which is not possible using the spectral indices. The majority of spectra (2193 of 2395) are modeled as mixtures of T1 and T2. Uncertainties in the modeled values show that there are no spectra that are grossly misfit, which would indicate an unidentified spectral shape not represented by mixtures of T1 and T2. Spectra having higher R987/814 values were observed in association with regions where large, low-albedo boulders occur, dominantly at southern latitudes [4], and these locations typically have >50% T2. T1-like spectra are concentrated near the equator and low northern latitudes.

Origin of T1 and T2 spectral variations: We considered two primary explanations for the observed spectral variations: compositional effects and deposits of fine particulates. We ruled out compositional effects because differences in silicate stretching mode features

(R987/814) should be accompanied by equally pronounced differences in the silicate bending feature (~600–400 cm^{-1}) shape, which we do not observe. The differences between T1 and T2 could be attributable to the presence of more fine particles (<~65–100 µm) in T2 that cause volume scattering and the appearance of transparency features and overall shallowing in silicate fundamental bands.

We eliminated deposits that are volumetrically dominated by fine particulate CC materials as these would exhibit distinctive features across the spectrum including a Christiansen feature shifted to higher wavenumbers and the appearance of strong transparency features [5] modestly enhanced by thermal gradients [6]. We do not see either of these characteristics in Bennu spectra. Instead, the T1-T2 spectral variations are consistent with a weak volume scattering effect produced by relatively thin deposits (up to ~15 µm) of fine particles on coarse particulate (>100 µm) and rocky surfaces [e.g., 7] that do not produce strong transparency features or substantial thermal gradients. However, even T1-dominated spectra appear to include a very small (unquantified) proportion of fines within in the field of view, based on the presence of a spectral slope at >1090 cm^{-1} and possibly the peak at 1420 cm^{-1}. Our interpretation is supported by analysis of nighttime spectra from EQ6 (not shown), when the radiance from any low thermal inertia dust should be reduced, enabling isolation of the high inertia component. In fact, EQ6 data show much less variation in R987/814, indicating that signatures we attribute to volume scattering are not as prevalent.

Constraints on Composition: We compared the Bennu spectra to those of aqueously altered CC meteorites to place constraints on mineralogy (Fig. 2). No single CC meteorite (or class of meteorites) provides a perfect match to Bennu, although Bennu is similar to Almahata Sitta (AhS) 91A_1, Orgueil, and Allan Hills (ALH) 83100, all of which are dominated volumetrically (>~80%) by phyllosilicates [8–10]. A spectral peak/shoulder at 528 cm^{-1} is diagnostic of bulk phyllosilicate abundance; it weakens in CMs with less than 87–89 vol% phyllosilicate and is replaced by a peak at ~580 cm^{-1} in meteorites having <78 vol% phyllosilicate and >10 vol% olivine and pyroxene [10]. We have not yet been able to uniquely attribute the peak at ~1420 cm^{-1} (Fig. 1) to a specific phase, because carbonate, phyllosilicate, and sulfide features appear near this location and other features of these minerals have not been clearly identified, possibly in part because the contrast of Bennu spectra is very low overall (~2%).

Summary: We attribute OTES spectral variations primarily to differences in the areal abundance/distribution of thin deposits of fine particulates, with limited

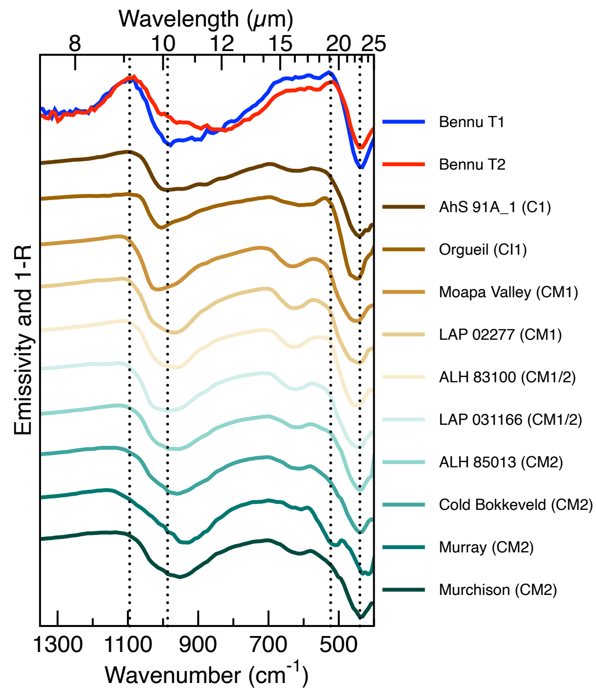

Fig. 2. OTES T1 and T2 spectra of Bennu and thin section spectra of aqueously altered carbonaceous chondrite meteorites. Dotted vertical lines denote features of interest in the Bennu spectra. Meteoritical Bulletin classifications are given for all except AhS 91A_1, which is given by [8]. LAP=La Paz Icefield.

compositional diversity at 40-m/spot scales. Thin dust deposits are consistent with thermal inertia results that limit any dust coatings to <50 µm in thickness, regardless of whether or not the coating is laterally continuous [11]. The association of T2 spectra with areas dominated by rough, dark boulders leads us to hypothesize that these boulders (or characteristics of the terrain [12]) are producing and/or trapping the relatively few, fine particulates that are present on Bennu. Bennu's mineralogy is most consistent with aqueously altered CCs having >90% of the silicate minerals as phyllosilicates, and we expect to confirm these results with the returned sample.

References: [1] Christensen, P.R. et al. (2018) *SSR, 214,* 87. [2] Rogers, A.D. & Aharonson, O. (2008), *JGR, 113*, E06S14. [3] Hamilton, V.E. et al. (2019) *Nat. Astron., 3*, 332. [4] DellaGiustina, D. et al., *Science*, 10.1126/science.abc3660. [5] Salisbury, J.W. et al. (1991) *Icarus, 92*, 280. [6] Donaldson Hanna, K.L. et al. (2019) *Icarus, 319*, 701. [7] Graff, T.G. (2003) M.S. Thesis, ASU. [8] Goodrich, C.A. et al. (2019) *MaPS, 11*, 2769. [9] King, A.J. et al. (2015) *GCA, 165*, 148. [10] Howard, K.T. et al. (2015) *GCA, 149*, 206. [11] Rozitis, B. et al. (2020) *Sci. Adv., 6,* eabc3699. [12] Jawin, E. et al. (2020) *LPSC*, this meeting.