Widely distributed exogenic materials of varying compositions on asteroid (101955) Bennu. Marcel Popescu[1*], Eri Tatsumi[2,3*], Humberto Campins[4], Julia de León[2], Juan Luis Rizos García[2], Javier Licandro[2], Amy A. Simon[5], Hannah H. Kaplan[6], Daniella N. DellaGiustina[7], Dathon R. Golish[7], Dante S. Lauretta[7], [1]Astronomical Institute of the Romanian Academy, Bucharest, Romania; [2]Instituto de Astrofísica de Canarias (IAC), La Laguna, Spain; [3]Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan; [4]Physics Department, University of Central Florida, Orlando, FL, USA; [5]Solar System Exploration Division, NASA Goddard Space Flight Center, Greenbelt, MD, USA; [6]Southwest Research Institute, Boulder, CO, USA; [7]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA. [*]M. Popescu (popescu.marcel1983@gmail.com), E. Tatsumi (etatsumi@iac.es),

Introduction: Rubble-pile asteroids formed as a result of the catastrophic disruption of a parent body and re-accumulation of the resulting fragments. This process could incorporate materials from both the parent body and its catastrophic impactor. Evidence of this was shown for rubble-pile asteroid 2008 TC3 and the corresponding Almahata Sitta meteorite [1]. DellaGiustina et al. [2] reported six unusually bright, basaltic, meter-scale boulders identified on the dark surface of another rubble-pile asteroid, (101955) Bennu, in images acquired by the OSIRIS-REx mission. The closest spectral matches to these boulders are with the Howardite-Eucrite-Diogenite (HED) meteorites and with V-type asteroids. Using data provided by the Hayabusa 2 mission, Tatsumi et al. [3] reported bright, anhydrous-silicate–rich materials on the surface of rubble-pile asteroid (162173) Ryugu. These exogenic objects are more consistent with ordinary chondrite meteorites, based on their albedo and weak or even absent absorption band at 2 µm.

In this work, we report additional possibly exogenic boulders on Bennu's surface within the latitude range –70˚ to 70˚. First, we searched the multi-band images obtained by the OSIRIS-REx mission in order to find surface materials with possible 1-µm absorptions representative for mafic minerals. Then, we classified them by visible spectrophotometry and morphology. Finally, we discuss the origin of the proposed exogenic materials on Bennu.

Methods: The images used for our work were obtained by MapCam on 26 September 2019, with a resolution of ~0.25 m/pixel [4]. This instrument is a medium-angle imager onboard the OSIRIS-REx spacecraft equipped with four chromatic filters (b': 473 nm, v: 550 nm, w: 698 nm, and x: 847 nm). The wavelength interval covered allowed us to conduct a search for the 1-µm absorption feature. This is indicative of olivines and pyroxenes, which are the main constituents of ordinary chondrites and HED meteorites, and may not be present endogenically on Bennu. For the identified boulders, we retrieved the spectrophotometric curves and classified their morphological characteristics using PolyCam images [4].

Additionally, we used the data obtained by the OVIRS (OSIRIS-REx Visible and InfraRed Spectrometer [5]) instrument during the mission campaign known as Recon A. These data are available for nine of the identified exogenic boulders. Four of them show the absorption bands around 1 and 2 µm in the OVIRS data, confirming the olivine-pyroxene composition.

Last, we compared the spectral and spectrophotometric curves of these possible exogenic boulders with the spectra of meteorites reported in the RELAB database, and with those of the exogenic material found on asteroid Ryugu by the Hayabusa 2 mission [3].

Results: We report 77 boulders containing possible exogenic material widely distributed across Bennu's surface. The MapCam spectrophotometric data was retrieved for the 46 of them that are larger than 0.4 m. The morphological categorization determined from PolyCam images includes: homogeneous rocks, breccia-like rocks, inclusion-like features, and partially bright rocks . The most common are the inclusion-like features, which are observed in boulders all over the surface. They usually occur in dark and cauliflower-like host rocks. There is correspondence between spectrophotometric curve shape and the morphology. The brightest candidates are preferentially pristine or breccia-like rocks.

Principal component analysis (PCA) of MapCam spectrophotometry reveals two major trends (Trend I and Trend II), suggesting a mixing of Bennu's average composition with two endmembers. Trend I has a deep 1-µm band absorption, possibly indicating pyroxene-rich material, and Trend II has a shallow 1-µm absorption). The ones with deeper 1-µm band absorptions, which make up Trend I, only match with HED meteorite spectra. Those with shallow 1-µm band absorptions, which make up Trend II, match HED meteorite, ordinary chondrite, and carbonaceous chondrite spectra. The OVIRS near-infrared reflectance spectra are also consistent with the compositional diversity inferred from the colors, showing different absorption depths in the 1- and 2-µm bands. The majority of exogenic materials are darker than HEDs or ordinary chondrites.

The exogenic boulders with a spectral peak in the v-filter are matched well spectrophotometrically by the Macibini Cl.3 melt sample. This is consistent with impact melt resulting from Vesta-family material colliding with Bennu's parent body.

Laboratory spectra of some carbonaceous chondrites match some of our exogenic candidates in visible wavelengths, and in particular those with reflectance factor REFF(30˚,0˚,30˚) < 5%. Thus, we cannot exclude an endogenic origin for the relatively dark candidates.

The comparison of proposed exogenic materials on Bennu with those on Ryugu suggests different compositions and abundances between the two asteroids, indicating different impact histories for these two bodies. Both asteroids show diversity in exogenic compositions on their surfaces, indicating they have undergone impacts with objects of different compositions.

Acknowledgments: This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program. We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible. OCAMS and OVIRS data are available via the Planetary Data System (Rizk et al. 2019; Reuter et al. 2019). Shape models of Bennu are available in the Small Body Mapping Tool at http://sbmt.jhuapl.edu/. M.P. acknowledges the support of the Romanian National Authority for Scientific Research and Innovation, CNCS - UEFISCDI, project number PN-III-P1-1.1-TE-2019-1504.

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