

**EXTRATERRESTRIAL AMINES AND AMINO ACIDS IN SAMPLES FROM ASTEROID BENNU.** E. T. Parker<sup>1,\*</sup>, H. L. McLain<sup>1,2,3</sup>, D. P. Glavin<sup>1</sup>, J. P. Dworkin<sup>1</sup>, A. Mojarro<sup>1,4</sup>, J. C. Aponte<sup>1</sup>, J. E. Elsilá<sup>1</sup>, D. N. Simkus<sup>1,2,3</sup>, H. C. Connolly Jr.<sup>5,6,7</sup>, and D. S. Lauretta<sup>6</sup>. <sup>1</sup>NASA Goddard Space Flight Center (GSFC), Greenbelt, MD, <sup>2</sup>Department of Chemistry, Catholic University of America, Washington, DC, <sup>3</sup>Center for Research and Exploration in Space Science and Technology, NASA GSFC, Greenbelt, MD, <sup>4</sup>NASA Postdoctoral Program, Oak Ridge Associated Universities, Oak Ridge, TN, <sup>5</sup>Rowan University, Glassboro, NJ, <sup>6</sup>Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, <sup>7</sup>American Museum of Natural History, New York, NY. \*Email: [eric.t.parker@nasa.gov](mailto:eric.t.parker@nasa.gov).

**Introduction:** NASA's OSIRIS-REx mission collected regolith from the surface of Bennu, a B-type carbonaceous asteroid, and delivered it to Earth on September 24, 2023 [1]. These samples contain compounds from pristine solar system matter, which may provide insights into the origin of life.

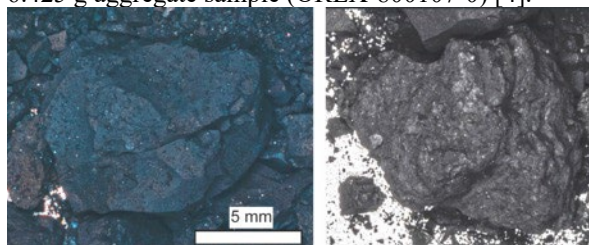
The current exploration addresses the following hypotheses of the OSIRIS-REx Sample Analysis Plan [2]: Hypothesis 2.1—Bennu contains organic compounds important for life, including protein amino acids, and their precursors and side products; Hypothesis 2.2—enantiomeric excesses are present for some chiral amino acids and are of the same handedness as those found in life; and Hypothesis 2.3—Bennu contains soluble organic matter with abundances, distributions, isotopic, and enantiomeric compositions similar to those of aqueously altered CI and CM chondrites. Amines are organics analogous to amino acids as the two compound classes possess similar structural backbones. Therefore, simultaneously studying amines and amino acids can yield insights on the syntheses of both types of organics.

Previous analyses of a 52 mg sample of aggregate (loose, unsorted) Bennu material, OREX-803001-0, detected 16 amines and 33 amino acids, including 14 protein amino acids. [3]. This Bennu sample contained a free amine abundance of  $1,060 \pm 89$  nmol/g (lower by a factor of  $\sim 1.7x$  compared to CM2 Murchison) and a total amino acid abundance of  $70 \pm 2$  nmol/g (lower by a factor of  $\sim 3.5x$  compared to CM2 Murchison) [3]. Additionally, all chiral unbound amino acids were racemic, which contrasts with observations of enantiomeric excesses in some meteorites [3].

It is currently unknown if these reported observations are consistent across other Bennu samples or if organic heterogeneity exists that may reveal enantiomeric excesses, for example. In this work, we analyzed three additional Bennu samples to better understand the origin and distribution of extraterrestrial amines and amino acids.

**Samples:** This study analyzed three Bennu samples: a 35 mg fragment of a hummocky stone (OREX-800088-106), which featured a cauliflower-like appearance; a 49 mg fragment of an angular stone (OREX-800055-110) that possessed sharp edges and faces (Fig. 1); and a 2.6 g subsample of homogenized

powder (OREX-800107-127) obtained after crushing a 6.425 g aggregate sample (OREX-800107-0) [4].



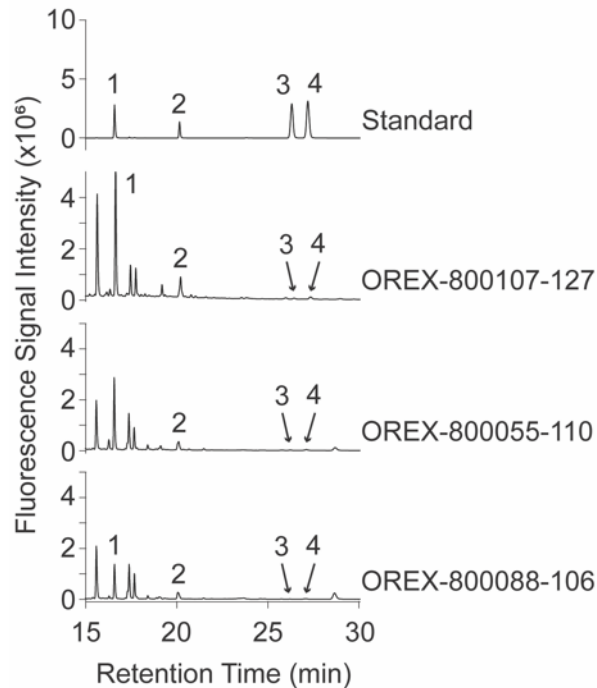
**Figure 1.** Angular (left, OREX-800055-0) and hummocky (right, OREX-800088-0) parent stones from which the fragments analyzed here were obtained. Image credit: NASA Johnson Space Center Curation.

Simultaneously with each of the three Bennu samples, we analyzed as controls similar masses of CM2 Murchison powder and amorphous silica chips that were heated at 500°C in air overnight prior to crushing the same way as OREX-800107-0. All procedural blanks, samples, and controls were analyzed in a coordinated fashion for this work.

**Extraction and Analytical Methods:** Blanks, samples, and controls first underwent hot water extraction using 1 mL of Milli-Q ultrapure water at 100 °C for 24 hours. A portion of this extract was dedicated for amine analyses, and another portion was allocated for amino acid analyses. Subsequent preparation and purification protocols for isolating amines and amino acids, as well as analytical procedures targeting these compounds via liquid chromatography and mass spectrometry, were based on a literature reporting [3].

**Results:** The C<sub>1</sub> to C<sub>3</sub> amines—methylamine, ethylamine, isopropylamine, and propylamine—were each detected in the samples analyzed here (Fig. 2), with the exception being that methylamine was not detected above blank levels in OREX-800055-110. The free amine abundances were  $\sim 69$  nmol/g (OREX-800055-110, angular fragment),  $\sim 251$  nmol/g (OREX-800107-127, powdered aggregate), and  $\sim 1,116$  nmol/g (OREX-800088-106, hummocky fragment). Preliminary data from the amino acid analyses of the aggregate sample (OREX-800107-127) indicate that 18 amino acids, including seven protein amino acids, were detected. These species amounted to a total amino acid abundance of  $\sim 14$  nmol/g. At the time of submission of this

abstract, the full amino acid data set from all three samples is in the process of being tabulated and will be presented in full at the meeting.



**Figure 2.** Fluorescence chromatograms demonstrating the analyses of (1) methylamine, (2) ethylamine, (3) isopropylamine, and (4) propylamine in the aggregate sample (OREX-800107-127), angular fragment (OREX-800055-110), and hummocky fragment (OREX-800088-106).

**Discussion:** The finding of methylamine present at abundances below blank levels in the angular stone (OREX-800055-110) differs from the other samples studied here and the 52 mg aggregate Benu sample (OREX-803001-0) previously analyzed [3]. Across the Benu samples studied in this work, free amine abundances varied by more than one order of magnitude, which suggests that amine abundances are not homogenous on Benu. Compared to other extraterrestrial samples, free amine abundances are as follows: Ryugu (35.8 nmol/g) [5] < OREX-800055-110 (~69 nmol/g) << OREX-800107-127 (~251 nmol/g) < CI1 Orgueil (377 nmol/g) [6] << OREX-803001-0 (1,060 nmol/g) [3] < OREX-800088-106 (~1,116 nmol/g) < CM2 Murchison (1,786 nmol/g) [3]. While some Benu samples possess amine abundances similar to highly aqueously altered bodies like asteroid Ryugu or CI1 Orgueil, others have amine abundances more closely mimicking those of mildly aqueously altered bodies like CM2 Murchison. These observations indicate amine distributions and abundances are subject to sample heterogeneity. Additional amine analyses of

Benu samples, particularly angular stones, would be valuable to verify these findings.

Like the 52 mg Benu aggregate sample reported previously [3], the Benu aggregate sample analyzed here was also dominated by glycine and the  $\alpha$ - and  $\beta$ -isomers of alanine. Furthermore, enantiomeric excesses were not observed for chiral amino acids, except for a  $29 \pm 3$  % total L-valine excess. However, this excess should be interpreted with caution because the total valine abundance was small, at  $\sim 0.2$  nmol/g, and because a relatively high abundance of L-valine was present in the procedural blanks. The otherwise racemic chiral amino acids conflict with observations from some meteorites. For example, L-enantiomeric excesses have been observed for some chiral amino acids, notably upwards of  $\sim 20\%$  for isovaline, in aqueously altered carbonaceous chondrites and Murchison. However, preliminary data from this investigation suggests isovaline enantiomeric excesses are not present in Benu, which is consistent with racemic isovaline found in Ryugu [7]. This represents a notable departure in chiral amino acid chemistry compared to aqueously altered carbonaceous chondrites.

**Conclusions:** Amines and amino acids were analyzed in three different samples of asteroid Benu returned by the OSIRIS-REx mission. A sample of CM2 Murchison was prepared and analyzed alongside each Benu sample. Target analytes were analyzed by liquid chromatography and mass spectrometry.

Hypothesis 2.1 of [2] was confirmed in this work by the detection and quantitation of amines and amino acids. Hypothesis 2.2 was addressed by quantifying the enantiomeric compositions of chiral amino acids; however, chiral amino acids exhibited racemic mixtures, aside from an anomalous bound L-valine excess. The amine data collected here demonstrates that Benu contains soluble organic species with chemical signatures similar to those of aqueously altered CI and CM chondrites, thereby verifying Hypothesis 2.3.

**Acknowledgments:** This work was supported by NASA Award NNH09ZDA0070 and Contract NNM10AA11C issued through the New Frontiers Program. We are grateful to the entire OSIRIS-REx Team for making the return of samples from asteroid Benu possible.

**References:** [1] Lauretta, D.S. & Connolly, H. C. Jr et al. (2024) *M&PS* 59, 2453-2486. [2] Lauretta, D.S. et al. (2023) arXiv [astro-ph.EP] 2308.11794. [3] Glavin, D.P. et al. (2025) *Nat. Astron.*, accepted. [4] Glavin, D.P. et al. (2025) *LPSC*, this meeting. [5] Parker, E.T. et al. (2023) *GCA* 347, 42-57. [6] Aponte, J.C. et al. (2015) *M&PS* 50, 1733-1749. [7] Naraoka et al. (2023) *Science*, 379, eabn9033.