

Bennu and Ryugu constituents from samples IR analyses and potential source of terrestrial planets' ingredients

Corresponding Author: Dr Cedric Pilorget

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Overview comments

This manuscript presents an important data set collected on returned asteroid samples without those samples leaving a curation nitrogen-atmosphere environment. This is a crucial baseline for understanding these samples without terrestrial alteration, especially considering that fragile mineral phases within these samples have been documented to be susceptible to extensive damage when exposed to the terrestrial environmental for relatively short periods of time (e.g., Na,Ca carbonate that dramatically changed over five months in an air desiccator as reported by McCoy et al. Nature 2025).

The instrumentation and glovebox interface to support collection of this dataset is completely unique – it is the only set-up of this kind in the world. The development and application of this analytical instrument combined with a curation glovebox was a difficult endeavor and its success was an important advancement for studies of returned astromaterials samples – some similar attempts have been unsuccessful (e.g., Fulford et al. 2024: <https://arxiv.org/abs/2402.18674>). This work adds tremendous value to the scientific community in the comparison between Ryugu and Bennu samples under these pristine conditions.

The impact of this manuscript could be expanded by more thoroughly combine the previously published data on Hydrated Ammonium-Magnesium-Phosphorus (HAMP)-rich compounds in Ryugu samples and the published data on ammonium-rich compounds (Glavin et al. Nature Astronomy 2025) and phosphate minerals (McCoy et al. Nature 2025) found in Bennu samples.

The manuscript frequently equates the higher abundance and larger size of olivine fragments in Bennu samples with “less extended aqueous alteration” or “less extensive hydrothermal alteration” or “a lower level of aqueous alteration.” These olivine grains are, reasonably, argued to be primary components that were preserved in Bennu samples despite its apparent secondary aqueous alteration (e.g., phyllosilicates). Based on how similar the samples are, the difference in the aqueous processes that altered Bennu and Ryugu samples is likely more nuanced than a simple “more” or “less” dichotomy. Aqueous alteration includes a diverse range of processes and chemical reactions that have the different capacities to alter separate minerals. It would be more accurate to state more primary components are preserved in Bennu samples than Ryugu samples rather than use a primary component to argue about the extent of secondary processes in samples from separate asteroids.

Detailed Comments to Authors

Introduction – The introduction does not adequately emphasize the special value of measurements, like those presented here, on samples inside of a curation pristine environment (nitrogen isolating glovebox). The advantage of these measurements is not only better than meteorite measurements but also provides important information on these samples before they are exposed to the terrestrial environmental for further measurements. This work is a critical part of rigorously establishing that surprising ammonium and phosphate discoveries are original phases of these asteroids.

Lines 54-57: This would be an ideal place to add a sentence about the sensitivity of Ryugu samples (e.g., Genge et al. 2024) and Bennu samples (McCoy et al. 2025) to terrestrial alteration outside of the curation environment, which would help readers understand the importance and value of the work in this manuscript.

Line 71: Clarify: delete the word “now” so this sentence reads “are stored in pure N₂” because the Bennu samples were stored in nitrogen by NASA before transfer to JAXA

Line 91-93: This sentence needs to be re-phrased. All of the Bennu aggregate samples transferred from NASA to JAXA came from inside of the TAGSAM head (except the contact pad which is not being discussed in this sentence or in this

manuscript). This sample [OREX-800058-0 in the NASA catalog (https://curator.jsc.nasa.gov/osirisrex/sample_details.cfm?sample=sample-1127) and renamed by JAXA using their nomenclature] came from OREX-800012-0 (https://curator.jsc.nasa.gov/osirisrex/sample_details.cfm?sample=sample-1077), which was scooped out of the TAGSAM head from underneath the mylar flap. The other samples delivered to JAXA were removed from the TAGSAM head using a different method and set of tools (a sample pour) but all of the sample delivered to JAXA from NASA came from inside of the TAGSAM. It is of interest to the astromaterials curation community that the samples removed with different tools and a different method are indistinguishable, but probably not particularly compelling to most of the audience of Nature Communications. Figure 1 and this coverage could be more compelling by comparing the spectra of all the JAXA bulk aggregates with those from Ryugu – consider re-working or merging this figure with Supplementary figure 1 and offsetting the spectra from each other to improve the ability for readers to compare spectra.

Lines 127-129: Either here or in the discussion it would strengthen this manuscript to mention that carbonates, including dolomite and breunnerite, have also been identified by complementary methods in non-pristine Bennu samples (Lauretta et al. 2024; McCoy et al., 2025; Connolly et al. 2025)

Lines 160-161: It would strengthen the manuscript to also include that magnesium hydrogen phosphate trihydrate were spectrally observed in non-pristine Bennu samples (Lauretta et al. 2024) and Na, Mg phosphates were recognized in non-pristine Bennu samples by complementary methods (McCoy et al. 2025).

Lines 200-204: Olivine textural association with phyllosilicates reported in Lauretta et al. (2024) using complementary methods could be leveraged to strengthen these interpretations.

Lines 242-245: This sentence is difficult to understand without looking at suppl figure 1. Recommend either cutting this from the manuscript or including a version of that figure in the main manuscript.

Lines 253-254: Mineral abundances for Bennu samples are also included in Lauretta et al. (2024), which support this discussion.

Line 261 – Suggest rephrasing “having experienced a less extended aqueous alteration” to “having preserved a slightly greater abundance of nebular components”

Lines 267-269: Include the narrower range of temperature constraints (20-55 degrees C) for the Bennu evaporite minerals published by McCoy et al. (2025)

Line 279: Suggest rephrasing “less extensive hydrothermal alteration” because the temperatures cited above for Ryugu samples and those from McCoy et al (2025) are too low to be considered hydrothermal. In addition, it would be more precise to focus on the direct evidence for preservation of more nebular (unaltered olivine) in Bennu samples than to extrapolate that they fall into a single progressive aqueous alteration sequence. These differences might be due to subtle chemical differences in fluid composition experienced by the Bennu and Ryugu returned samples.

Line 285: Considering re-phrasing – Similar comment to above regarding “lower level of aqueous alteration”

Lines 286-291: McCoy et al. Nature (2025) should also be included in this discussion of phosphorous species and salt-type compounds in Bennu samples since that work covered Na,Mg phosphate, a variety of carbonates, and salt minerals analyzed in Bennu samples

Lines 312-323: These interpretations do not engage with the new data presented in this manuscript (laboratory measurements). If this publication is close to the length limit, this text could be removed without diminishing the impact of the new work in this manuscript.

Reviewer #2

(Remarks to the Author)

This manuscript presents an analysis of the compositional variations in Bennu samples using the MicrOmega IR hyperspectral microscope, with comparisons drawn to samples from Ryugu. While the study includes intrinsically valuable data and draws conclusions that are generally supported by the results, the manuscript requires substantial revisions prior to publication. We will provide detailed comments below:

Major comments

- Overall focus and comparative analysis: The central objective of this paper is to compare the composition of samples from Bennu and Ryugu using MicrOmega. However, the current presentation of results and discussion lacks sufficient depth and clarity. To strengthen the comparative aspect, the authors should incorporate Ryugu data into all relevant MicrOmega spectral figures. For example:
 - Figure 3 should include the Type 1-Carbonate spectrum from Ryugu
 - Figure 5 should incorporate the Type 3-NH- rich inclusion from Ryugu
- Detailed comparison and interpretation: The manuscript would benefit from a more thorough and structure discussion on the similarities and differences between Bennu and Ryugu samples. First, the legends in Figure 3 to 6 should be improved to clearly indicate the four spectral types. For clarity and ease of reference, each type could be labeled more explicitly, e.g., “Type 1-Carbonate”, “Type 2-OH- + HAMP”, etc., to help the reader follow the results and the corresponding discussion throughout the manuscript. Additionally, the following aspects should be revised or expanded, specifically:
 - Type 1: Carbonate - A direct comparison with Ryugu data is missing and should be included,
 - Type 2: OH- + HAMP - Fig. 4 shows slight differences between the HAMP spectrum from Ryugu and spectrum A from Bennu. Notably, there are two peaks near 3 μm in spectrum A, and the peak positions differ slightly between the two samples (at 3 μm , 6 μm and 8 μm), please elaborate on these distinctions and discuss their potential implications.
 - Type 3: NH-/MgO-H rich inclusions - Please add the spectrum of a NH-rich grain from Ryugu (as reported in Pilorget et al., 2022) and provide a more detailed description of the observed differences.
 - Type 4: Rare olivine
- It is surprising that CH-rich compounds, which typically exhibit a spectral feature around 3.4 μm are not detected or discussed in Bennu samples. Could the authors clarify this absence? If such compounds were observed, please include the corresponding data and compare them with the CH-rich feature identified in Ryugu samples.

- Line 49: The manuscript states that Hydrated Ammonium Magnesium Phosphorous (HAMP)-rich compounds and NH-rich minerals were detected using the MicrOmega instrument. Could the authors clarify why these features were only reported through MicrOmega? Were these detections cross-validated using other techniques? A brief summary on this point would strengthen the interpretation of the data.
- Line 124-125: The spectral signatures at 2.5 μm and 1.2 μm appear to be strong in the mapped images, yet these features are not clearly visible in the corresponding spectra on the right-hand side. For instance, the A2 spectrum is highlighted in green on the map, but the 2.5 μm feature is not prominent in the plotted spectrum. Could the authors please explain this discrepancy?
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- Line 156-159: The authors should include a HAMP-rich spectrum of Ryugu for direct comparison with Bennu data. In addition to MicrOmega observations, do the authors have any complementary analytical techniques to independently confirm the presence of HAMP in Bennu samples?
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- Figure 4: RGB composite image for spectra A and B appear very similar, yet the corresponding spectra show notable differences. Specifically, the absorption at 2.72 μm is negligible in spectrum B, and new features between 3.3 and 3.5 μm appear that are not present in spectra A or C. Could the authors clarify whether these spectral differences are real and, if so, discuss their possible origin?
- Line 180: NH and MgO-H-bearing species: the authors associate the bands at 2.7 and 3.05 μm with NH bearing species linked to MgO-H rich material. How was this identification confirmed? Are there alternative interpretations of these bands (such as NH₄ or NH-organics-bearing phyllosilicates)? Or did you check also the reference samples with the same MicrOmega instrument n Pilorget et al. (2022), the authors note that the 2.7 μm feature could also originate from Mg-OH-bearing minerals. Have the authors applied any complementary analytical methods to support or verify the presence of Mg-OH-bearing phases in these samples?
- NH-bearing composition in Ryugu: The presence of NH-bearing species in Ryugu was first reported in earlier studies. Was the NH-rich grain in Ryugu also analyzed using other techniques (e.g., NanoSIMS, micro-FTIR, or AFM-IR) to confirm and compare with the MicrOmega spectral features? If so, this should be clarified and referenced here.
- Comparison of NH-bearing spectra in Ryugu and Bennu: The NH-bearing spectrum from Ryugu should be included for comparison. The authors should strengthen the discussion by clearly comparing the spectral features of both samples. In particular, how does the 2.32 μm absorption band in Ryugu compare with that in Bennu, is it weaker, stronger, or similar? Please elaborate on the observed differences or similarities and provide a possible interpretation.
- Lines 200–202: Clarification of MgO-H features: The authors attribute a small absorption near 2.7 μm to MgO-H components, while earlier in Line 184, a 2.32 μm feature is also assigned to MgO-H. Could the authors clarify whether both features (2.32 μm and 2.7 μm) can be attributed to MgO-H phyllosilicates, or whether they reflect different phases or species? Furthermore, Line 181 states: “The latter is plausibly a similar phyllosilicate as in the matrix, as indicated by the shape and position of the ~2.7 μm band.” This section of the text should be revised for clarity to ensure consistency and avoid ambiguity regarding the attribution of spectral features.
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 - Why does the B spectrum appear to be collected over a longer spectral range than A?
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 - Were these $\mu\text{FT-IR}$ spectra acquired at the same positions as A and B, as indicated in the visible and RGB images?
 Please clarify and revise the figure legend accordingly.
- The visible and RGB images do not share the same scale. Please add a scale bar to the RGB images and clearly indicate the precise locations (e.g., using arrows or labels) where spectra A and B were collected, both in the visible and RGB images.
- Line 236: There appears to be a contradiction between Line 236, which acknowledges potential H₂O contamination during capsule reentry or after, and Line 71, which describes the samples as “pristine” and “never exposed to the terrestrial environment.” Please clarify the conditions under which Bennu samples were handled and reconcile this inconsistency.
- Discussion structure and logical flow: The discussion section should be reorganized for clarity and coherence. One possible approach is to follow the four spectral types identified by MicrOmega in Bennu, from Type 1 to Type 4. For instance:
 - Start with Type 1 – Carbonate, then proceed to Type 2 – HAMP-bearing compounds, Type 3 – NH/MgO-H inclusions, and finally Type 4 – Anhydrous silicates (e.g., olivine).
 - Ensure that discussion of NH-bearing compounds is not mixed with that of carbonates.
- Lines 257–261: Considering that Bennu’s surface also included exogenic bright boulder with spectral properties similar to those of ordinary chondrite (OC) meteorites (Le Corre et al., 2021), can the authors exclude the possibility that the olivine grains originated from exogenous S-type asteroids?
- Lines 262–269: Are NH-bearing compounds and NH₄⁺ in HAMP phases formed by the same process? Could alternative formation scenarios exist? This should be discussed more thoroughly.
- Lines 270–271: Do the authors interpret NH-bearing compounds as NH₄⁺? If so, why do they appear in two different spectral types (Type 2 and Type 3)? What spectral criteria distinguish them?
- Line 271: C-rich Compounds: The manuscript claims that Bennu samples contain carbon-rich material visible at the sub-millimeter scale, yet no corresponding organic-rich spectra are shown. Please clarify this discrepancy and add relevant spectra if available.
- Lines 284–285: This sentence duplicates the discussion already provided in Lines 259–261. Consider removing or

consolidating to avoid redundancy.

- Lines 286–291 – HAMP in Other Samples:

- Have HAMP-rich compounds been identified in any CI chondrites?

- Were HAMP phases on Ryugu and Bennu confirmed using techniques other than MicrOmega? If not, please explain why or clarify the limitations.

- Discussion Order: Mg-rich Phyllosilicates and Olivine: The discussion of Mg-rich phyllosilicates and olivine appears early in the section but might be better placed toward the end. These phases represent a key difference between Bennu and Ryugu and could serve as a concluding highlight.

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Minor comments:

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- Lines 62–65: You mention that there are “small but significant differences” in the H and N isotopic data between Bennu, CI chondrites, and Ryugu. For clarity and completeness, please briefly summarize these differences in this section. What are the magnitudes or trends in these isotopic shifts?

- Lines 67–70: Regarding the sample's exposure history: if Bennu materials may have been exposed to Earth's atmosphere during the capsule reentry (as emphasized lines 234-236), this should be clearly stated. The text currently implies they are pristine, which may conflict with later acknowledgments of potential H₂O contamination. Please clarify and revise this to avoid contradiction.

- Line 84: “...bulk samples...”. If I understand correctly, what you call here bulk samples are in fact two particles (ORX-19000 and ORX-29000). So, it should be “two bulks samples”.

- Figure 1: The spectrum labeled ORX10007 appears in Figure 1, but it is not mentioned or explained in the main text. What is ORX10007, and how does it relate to ORX29000 and ORX19000?

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Reviewer #3

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Reviewer #4

(Remarks to the Author)

The authors have undertaken a spectral comparison of samples returned from asteroids Bennu and Ryugu, and find that, in general, the samples are quite similar. There are, however, some minor variations that are interpreted as representing differences in the histories of these two asteroids. Specifically, Bennu appears to have preserved a greater fraction of precursor minerals, suggesting that at least some of its parent body underwent less severe aqueous alteration than is observed in all Ryugu materials. Both asteroids (or their parent bodies) appear to be derived from the outer solar system where ammonia ice was prevalent.

With respect to the quality of the data, the data are technically sound, collected appropriately and analyzed and interpreted carefully. Sufficiently strong evidence is provided for the authors’ claims and appropriate controls or caveats have been included. With respect to the potential significance of the results, they are important to the field and advance our understanding in a way that moves the field forward.

Specific comments:

1) There should be an explanation of how the normalization shown in Fig. 1 (right) was calculated — are the data normalized to a common spectral contrast over the entire region, or at a specific wavelength? Recommend updating the Y-axis label to indicate that the spectra are normalized — the figure might be shown without the caption elsewhere.

2) The readability of the methods section would be improved by a reorganization and it would also benefit from the inclusion of additional information. I suggest starting the section with the description of the samples being measured, followed by the instrumentation and related information. The sample section should explain what is a “bulk” sample — is it a sieved or otherwise prepared sample?

Bringing “like” information together would improve the sub-section on the MicrOmega instrument if it included the second paragraph of what is currently shown under “samples” and the “protocol” text. The description of the MicrOmega instrument should include the total wavelength range covered by the instrument, how it is calibrated, and any other relevant parameters or measures of quality. Although the text states that spot sizes as small as 20 μm can be measured, the text does not say explicitly what spot sizes were used in this work or if it is always the same.

The description of the complementary FTIR characterizations should provide equivalent detail to that provided for the MicrOmega: e.g., more information about the spot size that is measured, the spectral resolution, the duration of the measurement, the calibration procedure, etc.

3) In the apparent absence of peer-reviewed, spectroscopy-focused publications by the OSIRIS-REx team (at the time of this review), there are several conference proceedings abstracts/presentations in which that team described many of these same spectral characteristics in the VNIR and TIR, as far back as March of 2024. I suggest, as a matter of professional courtesy, that additional relevant abstracts/presentations be cited here to recognize the full breadth of the earlier, publicly-presented work of the OSIRIS-REx team. Given the authors’ citation of at least one such abstract, it appears they are aware of these presentations, and their interpretations likely benefitted from them. Specific references include overview presentations of the VNIR and TIR spectra of Bennu samples, identification of phosphate, general mineralogy, and initial comparisons to Ryugu by Hamilton et al. [2024, 2025] (LPSC) and Russell et al. [2024] (MetSoc), More detailed discussion of the VNIR data was presented by Milliken et al. [2024], Cloutis et al. [2024], Schultz et al. [2024] (all LPSC), and connections to space weathering by Hiroi et al. [2024, 2025] (LPSC).

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

I appreciate that the authors nicely addressed my questions and comments. I have some additional comments, although mostly minor.

- Line 75-77: It may be helpful for the authors to also include the isotopic values of both Ryugu and Bennu in the text, as this would strengthen and better contextualize the discussion.

- Line 107-108: The manuscript does not include a discussion of CH-rich spectra. As indicated in Fig. 1 and referenced in your response, one would expect to see a representative spectrum here that clearly demonstrates the presence of CH. Could the authors clarify whether the carbon content in Bennu is predominantly in the form of carbonates?

- Figures 1b and 1c appear very similar. I suggest replacing one of them with a zoomed-in view of the 3 μm band to better illustrate the points described in the manuscript.

- Line 285: Could you please clarify how the C–H signature at 3.4 μm can be considered consistent, given that no corresponding spectrum is shown in your paper? We note that no distinct 3.4 μm absorption feature is apparent in our spectra in Fig. 1, suggesting that, if aliphatic C–H absorptions are present, their intensity is below our detection.

- Line 185: “Additionally, a board feature can also be observed”. Do you mean spectrum C in Fig. 4? In the zoomed view, the shape of spectrum A appears quite different, for example, it resembles spectrum C, whereas over the full range it looks relatively flat between 9–10 μm . Did you normalize or rescale the spectra for the zoomed panel? Please clarify.

- The manuscript should be carefully proofread for grammar check and clarity throughout. For example:

o Line 44: “...recently on September” should be corrected to “...recently in September”.

o Line 170: Suggested revision: “Grain sizes range from a few ten...”

o Line 171-173: Suggested revision: “Many detached grains exhibit a whitish, uniform appearance in optical images, punctuated by smaller, dark micrometre-sized grains either embedded within the whitish material or stuck on the surface.”

o Line 186: Suggested revision: “..., attributed to P–O stretching vibrations... Similar spectral signatures have been detected in Ryugu samples..., indicating the presence...”.

o Line 224: Suggested revision: “The spectral properties of these inclusions closely resemble those observed in Ryugu samples.”

o Line 308: It seems you mean “the large number of particles”? The sentence could be revised as “...the large number of particles analysed in this study, combined with the extensive set of similarities identified between two distinct objects, reduced the likelihood...”

o Line 313: I suggest rephrasing as: “the Bennu bulk samples show variations of similar magnitude, whether measured in areas dominated by larger (mm-size) grains or by finer fractions.”

o Line 316: Please specify “The lower band depth...” in what?

- o Line 319: The phrase “No clear band shift...” might be better expressed as “No systematic band shift”. And the sentence could be simplified to “...that would indicate a stronger contribution from space-weathered material...relative to Ryugu samples”
- o Line 324: Should read: “...large olivine grains (tens of microns in size) ...”
- o Line 325: Suggested revision: “Such grains/inclusions have not, so far, been identified...”
- o Line 335: Suggested revision: “The close proximity in most spectral properties at both cm and sub-mm scales between Bennu and Ryugu samples thus suggests that they experienced broadly similar formation and evolutionary processes.”

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We would like to thank all 4 reviewers for their constructive comments and suggestions that significantly contributed to improving the manuscript.

Reviewer #1 (Remarks to the Author):

Overview comments

(A1) This manuscript presents an important data set collected on returned asteroid samples without those samples leaving a curation nitrogen-atmosphere environment. This is a crucial baseline for understanding these samples without terrestrial alteration, especially considering that fragile mineral phases within these samples have been documented to be susceptible to extensive damage when exposed to the terrestrial environment for relatively short periods of time (e.g., Na,Ca carbonate that dramatically changed over five months in an air desiccator as reported by McCoy et al. Nature 2025). The instrumentation and glovebox interface to support collection of this dataset is completely unique – it is the only set-up of this kind in the world. The development and application of this analytical instrument combined with a curation glovebox was a difficult endeavor and its success was an important advancement for studies of returned astromaterials samples – some similar attempts have been unsuccessful (e.g., Fulford et al. 2024: <https://arxiv.org/abs/2402.18674>). This work adds tremendous value to the scientific community in the comparison between Ryugu and Bennu samples under these pristine conditions.

We thank the reviewer for this comment. We are also fully convinced that such approach is key and we hope that it will become generic in the curation and characterization of extraterrestrial samples in the future.

(A2) The impact of this manuscript could be expanded by more thoroughly combine the previously published data on Hydrated Ammonium-Magnesium-Phosphorus (HAMP)-rich compounds in Ryugu samples and the published data on ammonium-rich compounds (Glavin et al. Nature Astronomy 2025) and phosphate minerals (McCoy et al. Nature 2025) found in Bennu samples.

Such comment is connected to the comments about Lines 160-161 (A9) and Lines 286-291 (A17) (see below). We thus provide here a response to all three comments together:

We thank the reviewer for these comments and agree that more context should be put in the manuscript. To our knowledge, first detections of Mg-phosphates in Ryugu samples were reported in Nakamura, E. et al. 2022, and then by Nakamura, T., et al. 2023. In parallel, the extraction and further characterization of hydrated bright grains detected in pristine Ryugu samples by MicrOmega at JAXA Curation Center (Pilorget et al. 2022), led to the identification of Hydrated Ammonium-Magnesium-Phosphorus-rich (HAMP) compounds (Pilorget et al. 2024) with elemental compositions (Mg, O, P, Na, absence of Ca and of Si) similar to that reported by Nakamura, T. et al. 2023. In particular, in these HAMPs, the amount of Na is quite small (< a few % in atomic percentages) and Mg^{2+} and NH_4^+ (detected by Pilorget et al. 2024 thanks to the use of IR spectroscopy) are most likely the main counterions of phosphate ions. Pilorget et al. 2024 proposed a formation scenario for the HAMP, mainly based on thermodynamics, that can be roughly summarized as follows: the early formation of Ca-rich carbonates depletes the environment in Ca, which then favors the formation of HAMPs with regards to Ca-rich

phosphates (apatite) which is much more stable and would thus have formed preferentially if Ca was available. This scenario is supported by the detections by Nakamura, T. et al. 2023 of calcium carbonates, phosphides and Mg-phosphates in the least altered fragments of Ryugu, while no apatite was observed in those samples.

Recently, Lauretta et al. 2024 and then McCoy et al. 2025 reported the detection of Mg-phosphates in Bennu samples. Here, we report that these phases are actually HAMP, very similar in their IR signature to the HAMP that were observed in Ryugu samples. Importantly they incorporate NH_4^+ ions in their structure. In particular, this supports that the parent body of Bennu formed or accreted a part of its material in the outer Solar System, in agreement with Glavin et al. 2025.

Carbonate detections also show that the dolomite and breunnerite dominate the carbonate population at MicrOmega scale, similarly to what was observed on Ryugu (e.g., Loizeau et al. 2023). Together, this suggests a similar process to form HAMP in Ryugu and Bennu, where the availability of NH_4^+ and the formation of carbonates and phosphates are interconnected. Independent observations by McCoy et al. 2025 also show the colocalisation of Mg-phosphates with Ca-rich carbonates, supporting the formation scenario mentioned above.

The preservation of HAMP, with ammonium in their structure, also indicates that Bennu's material has remained at low temperature ($< \sim 70^\circ\text{C}$ if the struvite is considered as analog, Feng et al. 2021), in agreement with McCoy et al. 2025 that derived a temperature range of $20\text{-}55^\circ\text{C}$ based on the salt formation sequence.

We, therefore, modified the text as follows:

L299: “. In particular, the detection of NH_4^+ as part of HAMP-rich compounds indicates that the parent body of Bennu formed or accreted a part of its material in the outer Solar System, in agreement with Glavin et al. 2025. The preservation of HAMPs both in Bennu and Ryugu samples also indicates that their further evolution has remained at low temperature ($< \sim 70^\circ\text{C}$ if the struvite is considered as analog, [48]), in agreement with McCoy et al. 2025 that derived a temperature range of $20\text{-}55^\circ\text{C}$ based on the salt formation sequence, and similar to what has been proposed for Ryugu (e.g., Nakamura et al. 2023). “

And L341: “One of the most critical findings in the samples returned from Ryugu was the presence of Hydrated Ammonium-Magnesium-Phosphorus-rich (HAMP) grains (Pilorget et al. 2024). Such compounds were identified through the analysis of pristine Ryugu samples by the MicrOmega instrument, followed by the extraction and further ex-situ characterization of a few of these grains by complementary methods (SEM/EDS, DRX, mid-IR spectroscopy, Pilorget et al. 2024). These compounds most likely overlap with the Mg-phosphates observed by Nakamura, E. et al. 2022 and Nakamura, T., et al. 2023. Similarly, Lauretta et al. 2024 and then McCoy et al. 2025 reported the detection of Mg-phosphates in Bennu samples. Here we show that at least a fraction of them are actually HAMP-rich compounds, very similar in their IR signature to that observed in Ryugu samples. This last point is critical: as IR spectroscopy is sensitive to vibration modes, it implies a similar molecular structure between HAMP-rich compounds from Ryugu and Bennu.

Pilorget et al. 2024 proposed a formation scenario for the HAMPs found in Ryugu that is mainly based on thermodynamics and where the availability of NH_4^+ and the formation of carbonates and phosphates are interconnected. It can be roughly summarized as follows: the early formation of Ca-rich carbonates depletes the environment in Ca, which then favors the formation of HAMPs with regards to Ca-rich phosphates (apatites). Indeed, the latter is much more stable and would, thus, have formed preferentially if Ca was available. The observation of similar main families of carbonates in

Ryugu and Bennu samples, then suggests a common process to form HAMP-rich compounds. The colocalization of Mg-phosphates with Ca-rich carbonates observed by McCoy et al. 2025 and the formation sequence that they proposed tend to confirm the formation scenario developed by Pilorget et al. 2024.

HAMPs, therefore, appears as a generic product of the process that drove the early evolution of a given class of primitive parent bodies. Such an outcome then supports the high relevance of these salt-type compounds for delivering phosphorous and nitrogenous species, coupled to organics to the primitive Earth that could efficiently contribute to the organic chemistry towards life, as proposed by Pilorget et al. 2024.”

(A3) The manuscript frequently equates the higher abundance and larger size of olivine fragments in Bennu samples with “less extended aqueous alteration” or “less extensive hydrothermal alteration” or “a lower level of aqueous alteration.” These olivine grains are, reasonably, argued to be primary components that were preserved in Bennu samples despite its apparent secondary aqueous alteration (e.g., phyllosilicates). Based on how similar the samples are, the difference in the aqueous processes that altered Bennu and Ryugu samples is likely more nuanced than a simple “more” or “less” dichotomy. Aqueous alteration includes a diverse range of processes and chemical reactions that have the different capacities to alter separate minerals. It would be more accurate to state more primary components are preserved in Bennu samples than Ryugu samples rather than use a primary component to argue about the extent of secondary processes in samples from separate asteroids.

We agree with the reviewer’s comment and caution should be taken about the high level message behind the higher abundance and larger size of olivine fragments in Bennu samples. The discussion section has been restructured and the related part is now as follows:

L307: “Some significant differences could nonetheless be observed between Bennu and Ryugu samples. The large amounts of samples analyzed in this study and the large set of similarities in samples for two distinct objects would tend to minimize the likelihood that these differences translate possible biases from the collection process. The band depth of the $\sim 2.7\ \mu\text{m}$ feature that dominates down to the millimetre scale is weaker in Bennu samples compared to Ryugu samples (10-12 % vs. 12-18 % in Ryugu bulk samples, Pilorget et al. 2022). The grain size does not seem to be the cause of such a discrepancy as the band depth observed at the centimetre scale on the Bennu bulk samples varies over the same magnitude when compared on areas dominated by the larger (mm-size) grains or by the finer fraction (Sup. Figure 2). Both the Ryugu and Bennu samples exhibit a similar band shape (Figure 1), which would argue for a similar mineralogical composition. A lower band depth could then be either due to 1) a less extended aqueous alteration of the initial anhydrous precursor (i.e. less crystallized Mg-rich phyllosilicates) (e.g., Aléon-Toppani et al. 2024), 2) a more space weathered material (Le Pivert-Jolivet et al. 2023), or 3) the presence of more opaque material that could lower (or even hide) the signature. No clear band shift, that would be indicative of the presence of more space weathered material (e.g., Lantz et al. 2017), is observed on average with respect to Ryugu samples. The reflectance level, acquired in identical observational conditions, is also similar between Ryugu and Bennu samples (Figure 1). The first hypothesis is, thus, favored over the two others. Additionally, a greater amount of anhydrous silicates has been observed in Bennu samples ($\sim 2\ \text{vol}\%$, Lauretta et al. 2024) compared to Ryugu samples ($< 0.5\ \text{vol}\%$, Yamaguchi et al. 2023). Here we also show that large olivines (larger than a few tens of microns), either intact or slightly altered, are present in Bennu samples. Such grains/inclusions were not identified - so far - in the Ryugu bulk samples in similar observations by MicrOmega (Pilotget et al. 2022). We cannot rule out that this constitutes one of the potential minor

biases induced by the collection process of Haybusa2. The differences could also translate a possible exogenous origin of these compounds, as exogenic bright boulders with spectral properties similar to ordinary chondrites meteorites have been observed at the surface of Bennu (Le Corre et al. 2021). The preservation of a greater abundance of precursor material could be consistent with the less extended aqueous alteration discussed above. In addition, the detection, here, of volatile-rich species in Bennu samples indicates that the temperature remained low throughout their history and therefore that these olivine grains/inclusions do not originate from thermal metamorphism, but are remnants from the initial material present on the parent body.

The close proximity of both types of samples for most spectral properties both at centimetre and sub-mm scale would then suggest that Bennu and Ryugu samples did experience very similar formation and evolution processes. Differences would thus originate from a greater diversity of local environments - possibly at very fine/sub-mm spatial scale - on their primary parent body. Another possibility would be that Bennu sampled a greater variety of areas and thus of configurations during the disruption and reaccrretion of its parent body.”

Detailed Comments to Authors

(A4) Introduction – The introduction does not adequately emphasize the special value of measurements, like those presented here, on samples inside of a curation pristine environment (nitrogen isolating glovebox). The advantage of these measurements is not only better than meteorite measurements but also provides important information on these samples before they are exposed to the terrestrial environmental for further measurements. This work is a critical part of rigorously establishing that surprising ammonium and phosphate discoveries are original phases of these asteroids.

Lines 54-57: This would be an ideal place to add a sentence about the sensitivity of Ryugu samples (e.g., Genge et al. 2024) and Bennu samples (McCoy et al. 2025) to terrestrial alteration outside of the curation environment, which would help readers understand the importance and value of the work in this manuscript.

We fully agree with the reviewer’s comment and modified the text as follows:

L61: “While some of the differences could be related to deviations on the initial conditions (composition, environment) or subsequent evolution of the parent bodies, the exposure of asteroid material to the terrestrial atmosphere has been shown to significantly alter their mineralogical properties (Imae et al. 2024, McCoy et al. 2025) and their water budget (Yokoyama et al. 2023, Le Pivert-Jolivet et al. 2023,2025). Such results strongly advocate for maintaining carbonaceous asteroids returned samples in their pristine conditions for at least their first characterizations (in this paper, “pristine” qualifies the avoidance of terrestrial alteration, thus the preservation of the properties of the samples since their collection).”

(A5) Line 71: Clarify: delete the word “now” so this sentence reads “are stored in pure N₂” because the Bennu samples were stored in nitrogen by NASA before transfer to JAXA

We agree with that and modified the text accordingly.

(A6) Line 91-93: This sentence needs to be re-phrased. All of the Bennu aggregate samples transferred from NASA to JAXA came from inside of the TAGSAM head (except the contact pad which is not being

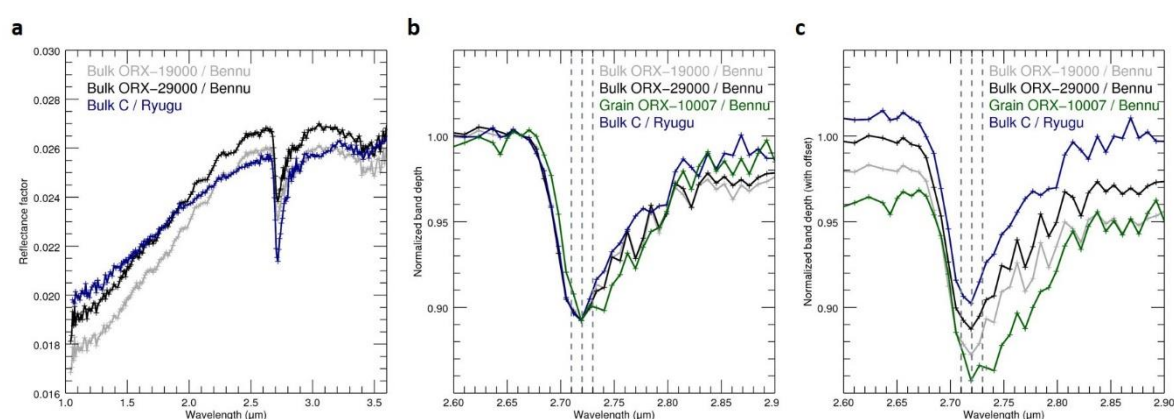
discussed in this sentence or in this manuscript). This sample [OREX-800058-0 in the NASA catalog (https://curator.jsc.nasa.gov/osirisrex/sample_details.cfm?sample=sample-1127) and renamed by JAXA using their nomenclature] came from OREX-800012-0 (https://curator.jsc.nasa.gov/osirisrex/sample_details.cfm?sample=sample-1077), which was scooped out of the TAGSAM head from underneath the mylar flap. The other samples delivered to JAXA were removed from the TAGSAM head using a different method and set of tools (a sample pour) but all of the sample delivered to JAXA from NASA came from inside of the TAGSAM. It is of interest to the astromaterials curation community that the samples removed with different tools and a different method are indistinguishable, but probably not particularly compelling to most of the audience of Nature Communications.

We thank the reviewer for this clarification and removed that sentence for clarity.

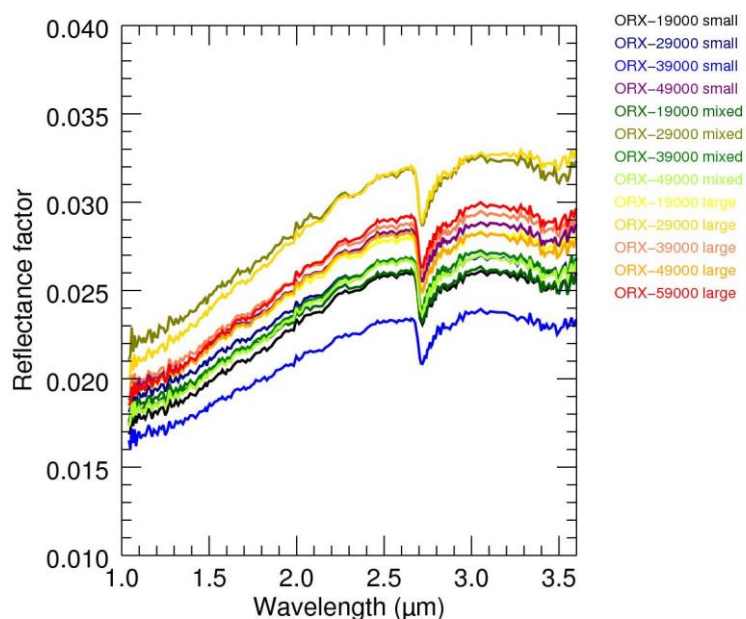
(A7) Figure 1 and this coverage could be more compelling by comparing the spectra of all the JAXA bulk aggregates with those from Ryugu – consider re-working or merging this figure with Supplementary figure 1 and offsetting the spectra from each other to improve the ability for readers to compare spectra.

We thank the reviewer for this comment. In addition to major absorptions features such as the 2.7 μm band for example, the global reflectance level is also a key parameter to compare the different samples, hence the left panel of Figure 1. To increase the capability for reader to compare the spectra, we added a third panel to Figure 1 that shows the normalized 2.7 μm bands with an offset between the different spectra. We also added as Supplementary Figure all bulk spectra measured on different areas of the bulk samples over the entire spectral range to see the small variability between them (hence the representativity of the spectra shown in Figure 1). Note that for consistency, the Benu bulk spectra shown in Figure 1 are extracts from that in Sup. Fig. 1.

Figure 1 is now as follows:



And Supplementary Figure 1:



(A8) Lines 127-129: Either here or in the discussion it would strengthen this manuscript to mention that carbonates, including dolomite and breunnerite, have also been identified by complementary methods in non-pristine Bennu samples (Lauretta et al. 2024; McCoy et al., 2025; Connolly et al. 2025)

We added L149: “Such carbonates have also been identified by complementary methods by Lauretta et al. 2024; McCoy et al., 2025; Connolly et al. 2025.”

(A9) Lines 160-161: It would strengthen the manuscript to also include that magnesium hydrogen phosphate trihydrate were spectrally observed in non-pristine Bennu samples (Lauretta et al. 2024) and Na, Mg phosphates were recognized in non-pristine Bennu samples by complementary methods (McCoy et al. 2025).

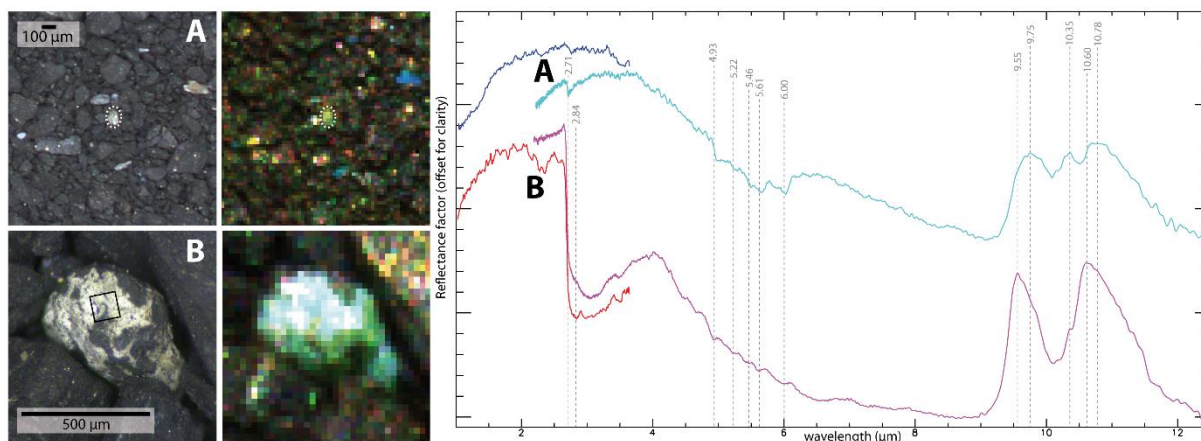
See response to comment A2.

(A10) Lines 200-204: Olivine textural association with phyllosilicates reported in Lauretta et al. (2024) using complementary methods could be leveraged to strengthen these interpretations.

We fully agree with the reviewer. To better assess if the 2.7 μm feature was due to intermingled phyllosilicates or a contribution from the surrounding pixels (as proposed in the initial manuscript), we re-analyzed the data and increased the spectral quality of the olivine spectrum shown in Figure 6 by making a more strict selection of the pixels on the olivine grain in the MicrOmega dataset. We noticed that the (small) 2.7 μm feature tends to disappear. This feature, thus, originates from the surrounding matrix-rich pixels. We have a similar situation for the mid-IR spectrum (for which the observation spot size is close to the olivine grain size). We thus modified the text as follows:

L243: “In addition, a small feature at $\sim 2.7\ \mu\text{m}$ due to OH moieties strongly bonded to Mg atoms can be noticed in the mid-IR spectrum. As the grain size is close to the observation spot size, such a signature most likely originates from the neighboring grains.”

And Figure 6 is now as follows:



(A11) Lines 242-245: This sentence is difficult to understand without looking at suppl figure 1. Recommend either cutting this from the manuscript or including a version of that figure in the main manuscript.

We understand the reviewer’s concern. To increase the readability, we included in the sentence a quantification of the variability when on areas with different grain sizes:

L310: “The band depth of the $\sim 2.7\ \mu\text{m}$ feature that dominates down to the millimetre scale is weaker in Bennu samples compared to Ryugu samples (10-12 % vs. 12-18 % in Ryugu bulk samples, Pilorget et al. 2022). The grain size does not seem to be the cause of such a discrepancy as the band depth observed at the centimetre scale on the Bennu bulk samples varies over the same magnitude when compared on areas dominated by the larger (mm-size) grains or by the finer fraction (Sup. Figure 2).”

(A12) Lines 253-254: Mineral abundances for Bennu samples are also included in Lauretta et al. (2024), which support this discussion.

We fully agree with the reviewer. This is why the mineral abundances from Lauretta et al. 2024 are already referenced Line 253 (now Line 322):

“Additionally, a greater amount of anhydrous silicates has been observed in Bennu samples ($\sim 2\ \text{vol}\%$ Lauretta et al. 2024) compared to Ryugu samples ($< 0.5\ \text{vol}\%$, Yamaguchi et al. 2023).”

(A13) Line 261 – Suggest rephrasing “having experienced a less extended aqueous alteration” to “having preserved a slightly greater abundance of nebular components”

See earlier response to comment A3.

(A14) Lines 267-269: Include the narrower range of temperature constraints (20-55 degrees C) for the Bennu evaporite minerals published by McCoy et al. (2025)

We agree and modified the text as follows to include the results from McCoy et al. 2025:

L301: “The preservation of HAMPs both in Bennu and Ryugu samples also indicates that their further evolution has remained at low temperature ($< \sim 70^{\circ}\text{C}$ if the struvite is considered as analog, Feng et al. 2021), in agreement with McCoy et al. 2025 that derived a temperature range of $20\text{-}55^{\circ}\text{C}$ based on the salt formation sequence, and similar to what has been proposed for Ryugu (e.g., Nakamura et al. 2023).”

(A15) Line 279: Suggest rephrasing “less extensive hydrothermal alteration” because the temperatures cited above for Ryugu samples and those from McCoy et al (2025) are too low to be considered hydrothermal. In addition, it would be more precise to focus on the direct evidence for preservation of more nebular (unaltered olivine) in Bennu samples than to extrapolate that they fall into a single progressive aqueous alteration sequence. These differences might be due to subtle chemical differences in fluid composition experienced by the Bennu and Ryugu returned samples.

We actually used “hydrothermal” as it is commonly used in the literature about such kind of processes. In any case, that sentence was removed in the new version of the manuscript.

(A16) Line 285: Considering re-phrasing – Similar comment to above regarding “lower level of aqueous alteration”

That sentence has been removed in the new version of this part of the discussion. See earlier response to comment A3.

(A17) Lines 286-291: McCoy et al. Nature (2025) should also be included in this discussion of phosphorous species and salt-type compounds in Bennu samples since that work covered Na,Mg phosphate, a variety of carbonates, and salt minerals analyzed in Bennu samples

See response to comment A2.

(A18) Lines 312-323: These interpretations do not engage with the new data presented in this manuscript (laboratory measurements). If this publication is close to the length limit, this text could be removed without diminishing the impact of the new work in this manuscript.

We thank the reviewer for this comment. The discussion here directly comes from the apparent discrepancy between lab results and remote sensing observations on the spectral slope. We suggest here some possible explanations. The conclusion of this section is also important for the astronomers’ community: “Such a result would advocate for a re-evaluation of the significance of the NIR spectral slope when assessing the compositional properties of the different asteroid populations.” We thus suggest to keep this part as is.

Reviewer #2 (Remarks to the Author):

This manuscript presents an analysis of the compositional variations in Bennu samples using the MicrOmega IR hyperspectral microscope, with comparisons drawn to samples from Ryugu. While the study includes intrinsically valuable data and draws conclusions that are generally supported by the results, the manuscript requires substantial revisions prior to publication. We will provide detailed comments below:

Major comments

- (B1) Overall focus and comparative analysis: The central objective of this paper is to compare the composition of samples from Bennu and Ryugu using MicrOmega. However, the current presentation of results and discussion lacks sufficient depth and clarity. To strengthen the comparative aspect, the authors should incorporate Ryugu data into all relevant MicrOmega spectral figures. For example:
 - Figure 3 should include the Type 1-Carbonate spectrum from Ryugu
 - Figure 5 should incorporate the Type 3-NH- rich inclusion from Ryugu

We understand the reviewer's concern. We included examples of carbonate spectra from Ryugu from Loizeau et al. 2023 in Figure 3. For Figure 5, we included an example of Type2 spectrum observed on Ryugu samples (from the NH-rich area shown in Pilorget et al. 2022). Regarding the discussion, please see answers below.

- (B2) Detailed comparison and interpretation: The manuscript would benefit from a more thorough and structure discussion on the similarities and differences between Bennu and Ryugu samples. First, the legends in Figure 3 to 6 should be improved to clearly indicate the four spectral types. For clarity and ease of reference, each type could be labeled more explicitly, e.g., "Type 1-Carbonate", "Type 2-OH- + HAMP", etc., to help the reader follow the results and the corresponding discussion throughout the manuscript.

We thank the reviewer for this comment. We modified the Figures captions accordingly to increase their readability. Regarding the discussion, please see answers below.

(B3) Additionally, the following aspects should be revised or expanded, specifically:

- Type 1: Carbonate - A direct comparison with Ryugu data is missing and should be included,
- Type 2: OH- + HAMP - Fig. 4 shows slight differences between the HAMP spectrum from Ryugu and spectrum A from Bennu. Notably, there are two peaks near 3 μm in spectrum A, and the peak positions differ slightly between the two samples (at 3 μm , 6 μm and 8 μm), please elaborate on these distinctions and discuss their potential implications.
- Type 3: NH-/MgO-H rich inclusions - Please add the spectrum of a NH-rich grain from Ryugu (as reported in Pilorget et al., 2022) and provide a more detailed description of the observed differences.
- Type 4: Rare olivine

As suggested by the reviewer, we added to the corresponding figures Type 1 and Type 3 spectra from Ryugu samples (from Pilorget et al. 2022, Loizeau et al. 2023). For Type 2 spectra, there were already spectra from Ryugu samples, but we added a couple of additional spectra from Pilorget et al. 2024 to show the slight diversity among them. We also added some details in the text about the spectral differences/similarities. See more detailed answers below.

- (B4) It is surprising that CH-rich compounds, which typically exhibit a spectral feature around 3.4 μm are not detected or discussed in Bennu samples. Could the authors clarify this absence? If such compounds were observed, please include the corresponding data and compare them with the CH-rich feature identified in Ryugu samples.

We understand the reviewer's concern. Centimeter and millimeter-scale spectra of Bennu samples show a small feature around 3.4 μm , as shown in Fig.1. Such feature can be attributed to either aliphatic CH compounds and/or carbonates (both compounds have features around 3.4 μm that can be difficult to distinguish when the feature is weak). The relative band depth of the ~ 3.4 μm feature varies typically in the 3-4% range in Bennu samples (vs $\sim 2\%$ in Ryugu samples, Figure 1a, Sup. Figure 1). Importantly its shape, more pronounced at ~ 3.42 μm (aliphatic C-H) compared to a doublet between ~ 3.3 and 3.5 μm that would point toward carbonates, indicates a significant contribution of organics.

We modified the text as follows to include these elements and discuss them wrt to previous results on Ryugu/Bennu samples :

L107: "The relative band depth of the ~ 3.4 μm feature varies typically in the 3-4% range (Figure 1a, Sup. Figure 1). Its shape, more pronounced at ~ 3.42 μm (aliphatic C-H) compared to a doublet between ~ 3.3 and 3.5 μm that would point toward carbonates, indicates a significant contribution of organics. Local enrichments of organics at smaller scales can also be traced, as within the Ryugu samples (Pilorget et al. 2022)."

And L285: "Bennu and Ryugu samples also display similarly a weak feature at ~ 3.4 μm , indicative of the presence of aliphatic CH in organics and of carbonates. This feature is slightly more pronounced in Bennu samples than in Ryugu samples (~ 3 -4% for Bennu samples vs. $\sim 2\%$ for Ryugu sample, Figure 1). Its translation in terms of enhanced abundance of a given constituent (organics or carbonates) must be consistent with both elemental abundances of carbon slightly higher in Bennu than in Ryugu samples (4.7 % in Bennu vs 3.8 % in Ryugu, Naraoka et al. 2023, Lauretta et al. 2024) and a higher H/C atomic ratio in Ryugu samples (Naraoka et al. 2023, Glavin et al. 2025)."

- (B5) Line 49: The manuscript states that Hydrated Ammonium Magnesium Phosphorous (HAMP)-rich compounds and NH-rich minerals were detected using the MicrOmega instrument. Could the authors clarify why these features were only reported through MicrOmega? Were these detections cross-validated using other techniques? A brief summary on this point would strengthen the interpretation of the data.

Regarding HAMP, their spectra are dominated by the deep and broad signature of H_2O around 3 μm in MicrOmega data, that so far appears unique in Ryugu samples. The extraction and further characterization of some of these grains by complementary techniques (including in

particular SEM-EDS, mid-IR spectroscopy, NIR spectroscopy and XRD) led to the identification of Hydrated Ammonium-Magnesium-Phosphorus-rich (HAMP) compounds, as reported in Pilorget et al. 2024. This paper is already referenced in the text. Following the reviewer's suggestion to reorganize the discussion (see comment B17), we also developed the part concerning the HAMP grains as follows:

L341: "One of the most critical findings in the samples returned from Ryugu was the presence of Hydrated Ammonium-Magnesium-Phosphorus-rich (HAMP) grains (Pilorget et al. 2024). Such compounds were identified through the analysis of pristine Ryugu samples by the MicrOmega instrument, followed by the extraction and further ex-situ characterization of a few of these grains by complementary methods (SEM/EDS, DRX, mid-IR spectroscopy, Pilorget et al. 2024)."

Another class of NH-rich grains with sizes up a few hundreds of microns in size was reported in Pilorget et al. 2022 and Jiang et al. 2025 using NIR microscopy (MicrOmega), through the observation of absorption bands around 3.1 μm . Such detection was only possible in pristine Ryugu samples as the $\sim 3.1 \mu\text{m}$ feature tend to be hidden by the signature of H_2O molecules contamination when exposed to the terrestrial atmosphere.

We added the following text in the introduction to emphasize the importance of maintaining the samples non-exposed to the terrestrial environment:

L61: "While some of the differences could be related to deviations on the initial conditions (composition, environment) or subsequent evolution of the parent bodies, the exposure of asteroid material to the terrestrial atmosphere has been shown to significantly alter their mineralogical properties (Imae et al. 2024, McCoy et al. 2025) and their water budget (Yokoyama et al. 2023, Le Pivert-Jolivet et al. 2023,2025). Such results strongly advocate for maintaining carbonaceous asteroids returned samples in their pristine conditions for at least their first characterizations (in this paper, "pristine" qualifies the avoidance of terrestrial alteration, thus the preservation of the properties of the samples since their collection).

- (B6) Line 124-125: The spectral signatures at 2.5 μm and 1.2 μm appear to be strong in the mapped images, yet these features are not clearly visible in the corresponding spectra on the right-hand side. For instance, the A2 spectrum is highlighted in green on the map, but the 2.5 μm feature is not prominent in the plotted spectrum. Could the authors please explain this discrepancy?

The color composite images in the second column of the figure is not a map of spectral features, it is a composite RGB image made from the three images at the three indicated wavelengths, as explained in the caption. The higher reflectance of the carbonate inclusions explains their higher brightness in the images, and the green color can be explained by the strong absorption in the chosen red channel (3.34 μm) and light absorption in the chosen blue channel (1.2 μm). Hence, the smaller absorption at 2.5 μm (chosen green channel) for some carbonate inclusions makes them still look green at it is the stronger reflectance compared to the red and blue channels. We thus consider that the figure is clear enough.

- (B7) Figure 3: A representative carbonate spectrum from Ryugu should be included for comparison, to better assess similarities or differences with Bennu samples. One of the spectra displays a particularly strong peak around 3 μm that differs from the others, could the authors comment on the possible chemical species responsible for this feature?

We modified Figure 3 to include examples of carbonate spectra from Ryugu from Loizeau et al. 2023, as suggested by the reviewer.

Spectrum A2 indeed shows some sort of peak around 3 μm . Carbonates actually generally display absorption features in this spectral region, as shown by the lab spectra shown in Figure 4 top panel.

- (B8) Line 156-159: The authors should include a HAMP-rich spectrum of Ryugu for direct comparison with Bennu data. In addition to MicrOmega observations, do the authors have any complementary analytical techniques to independently confirm the presence of HAMP in Bennu samples?

Spectrum 'HAMP' in Figure 4 (top right) is actually a HAMP spectrum from Ryugu, as mentioned in the figure caption. It was obtained in similar conditions on pristine Ryugu samples within their preservation chamber at ISAS Curation Center by the same instrument (MicrOmega). Spectru 'HAMP (exposed)' in Figure 5 (bottom right) is also a HAMP spectrum from Ryugu, this time in the mid-IR. That sample was characterized outside of its preservation chamber through a multi-analytical sequence, including NIR spectroscopy, mid-IR spectroscopy and SEM-EDS that enabled – in combination with the NIR data obtained on pristine samples by MicrOmega - the identification of the HAMP composition. Note that the in the spectrum of the exposed HAMP, the shape of the 3 μm band (attributed to O-H stretching vibrations of H_2O molecules) is a bit different compared that of non-exposed HAMP samples as the sample has absorbed-adsorbed some terrestrial water.

In the case of Bennu samples, HAMP-type compounds could be characterized both through NIR spectroscopy (MicrOmega) and mid-IR spectroscopy with the sample remaining in their preservation chamber, thus without any exposure to the terrestrial atmosphere. Bennu HAMPs have a very similar shape in the NIR (Figure 4, top right) with - in particular - a very similar 3 μm band shape (characteristic of this type of compounds). In the mid-IR, we can observe in Bennu HAMPs the ~ 6.9 μm feature (attributed to NH_4^+ out of plane bending vibration) and the ~ 9.5 μm feature (peaks) attributed to P-O stretching vibrations. Both in the NIR and mid-IR, the spectra of Ryugu and Bennu HAMPs look very similar. The IR spectroscopy is sensitive to vibrations modes. Thus, similar spectra (shape, band position) imply a similar molecular structure with similar electronic environment (here for H_2O , P-O and NH_4^+), and thus with the presence of magnesium in a similar structure as in Ryugu HAMPs.

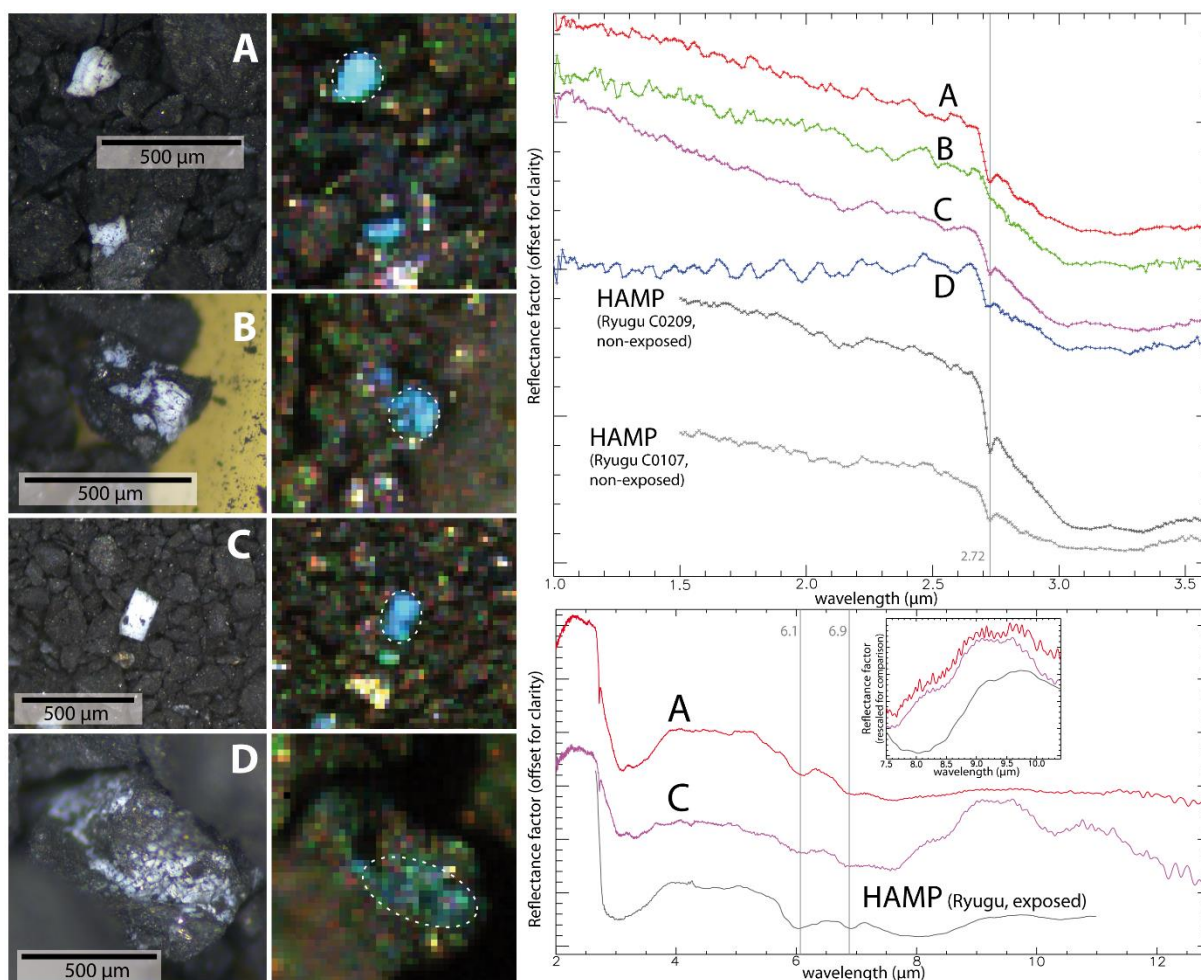
We also remind here that the HAMPs in Ryugu were characterized as amorphous compounds (Pilorget et al. 2024). Such kind of properties imply a slight diversity in the composition/structure, that can be observed through the (slight) diversity of spectral signature with Ryugu HAMPs as shown in Figure 1 and Extended data Figure 1 of Pilorget et al. 2024. Mg-phosphates in Bennu were also characterized as amorphous compounds by Lauretta et al. 2024. Possible small variations between Ryugu and Bennu HAMPs are of the same order as the variability of HAMP spectra from the Ryugu collection.

We clarified the origin of the HAMP spectra in Figure 4. We also added to Figure 4 additional HAMP spectra from Ryugu (Pilorget et al. 2024) to highlight the (slight) spectral diversity among Ryugu HAMPs. We also added the following clarifications:

L347: “Here we show that at least a fraction of them are actually HAMP-rich compounds, very similar in their IR signature to that observed in Ryugu samples. This last point is critical: as IR spectroscopy is sensitive to vibration modes, it implies a similar molecular structure between HAMP-rich compounds from Ryugu and Bennu.”

- (B9 Line 159-160: The text mentions features between 9 and 10 μm attributed to P-O stretching in spectrum A of Fig. 4. However, these features are not clearly visible in the plotted spectrum. Could the authors provide additional evidence or reference other spectra where this weak feature is more discernible?

We agree with the reviewer that the $\sim 9\text{--}10\ \mu\text{m}$ feature in spectrum A of Figure 4 was very weak. We thus added an insert to Figure 4 with a more contrasted version of spectrum A around 9–10 μm to make the feature more visible. We also added an additional mid-IR spectrum where this feature is much more visible (spectrum C in the new version), with visible and RGB images for context (panel C on the left). The new version of Figure 4 is as follows:



- (B10) Figure 4: RGB composite image for spectra A and B appear very similar, yet the corresponding spectra show notable differences. Specifically, the absorption at 2.72 μm is negligible in spectrum B, and new features between 3.3 and 3.5 μm appear that are not present in spectra A or C. Could the authors clarify whether these spectral differences are real and, if so, discuss their possible origin?

As in the carbonate figure, the RGB composite image is not a map of spectral features, it is a composite image made from the three images at the three indicated wavelengths, as explained in the caption. The higher reflectance of the phosphate inclusions explains their higher brightness in the images, and the blue color can be explained by the strong absorption in the chosen red channel (3.34 μm) and the negative spectral slope (for spectra A and B) which makes the reflectance higher at 1.2 μm than 2.5 μm . We do not expect to see differences due to the small absorption at 2.72 μm in these RGB images. We thus consider that the figure is clear enough. Concerning the 2.72 μm absorption, this band might be due to the presence of some Mg-phyllsilicates similar to the dark matrix at the surface or intimately mixed with the phosphate grains, so its variability may just reflect that. Regarding small peaks around 3.3-3.6 μm in Spectrum B, they are artifacts. This was clarified in the caption of Figure 4.

- (B11) Line 180: NH and MgO-H-bearing species: the authors associate the bands at 2.7 and 3.05 μm with NH bearing species linked to MgO-H rich material. How was this identification confirmed? Are there alternative interpretations of these bands (such as NH_4 or NH-organics-bearing phyllosilicates)? Or did you check also the reference samples with the same MicrOmega instrument n Pilorget et al. (2022), the authors note that the 2.7 μm feature could also originate from Mg-OH-bearing minerals. Have the authors applied any complementary analytical methods to support or verify the presence of Mg-OH-bearing phases in these samples?

The 3.05 μm feature is due to the N-H stretching vibration (e.g., Berg et al. 2016). NH can be in NH_4^+ or in organics for instance. Independently, the ~ 2.7 μm feature is due to the stretching vibration of O-H strongly bonded to Mg atoms that we typically find in Mg-rich phyllosilicates (e.g., Takir et al. 2013) that constitutes about 80% of these samples (Lauretta et al. 2024). This was clarified as follows:

L212: “A third family of spectra (‘Type 3’) – quite rare (about a dozen of occurrences in the bulk samples) - exhibits both ~ 2.7 μm and ~ 3.05 μm features (Figure 5). The ~ 3.05 μm band is attributed to the N-H stretching vibration (e.g., Berg et al. 2016), in NH_4^+ or in NH-rich organics for instance. The 2.72 μm feature is attributed to the stretching vibration of O-H strongly bonded to Mg atoms that we typically find in Mg-rich phyllosilicates (e.g., Takir et al. 2013). Together, these point towards an NH-bearing species associated with a MgOH-rich material, plausibly a phyllosilicate similar to that of the matrix, as indicated by the shape and position of the band.”

- (B12) NH-bearing composition in Ryugu: The presence of NH-bearing species in Ryugu was first reported in earlier studies. Was the NH-rich grain in Ryugu also analyzed using other

techniques (e.g., NanoSIMS, micro-FTIR, or AFM-IR) to confirm and compare with the MicrOmega spectral features? If so, this should be clarified and referenced here.

Hydrated Ammonium Magnesium Phosphorus-rich grains were identified using combined analyses (NIR and MIR spectroscopy, SEM-EDS, XRD) as described in Pilorget et al. 2024. We mentioned that paper in the text. The other kind of NH-bearing grains (up to a few hundreds of microns in size) and that most likely contain Mg-phyllsilicates, as reported in Pilorget et al. 2022, is much less common and has to our knowledge – not been characterized using other techniques. IR spectroscopy is, however, a technique that is sensitive to bonds and that has proven to be quite efficient to characterize NH-rich organic matter, NH_4^+ salts and NH_4^+ phyllsilicates for example (e.g., Berg et al. 2016, Ehlmann et al. 2018, Ferrari et al. 2019). Such identification through IR spectroscopy is, thus, quite robust. The link with organics (in particular N-rich organics detected in the matrix of Ryugu and Bennu samples (Yabuta et al. 2023, Naraoka et al. 2023, Glavin et al. 2025), is not clear and will require more investigations. We added some references to N-rich organics found in Ryugu samples:

L52: “Various CHNOS-based organic materials and rare anhydrous silicates (olivine and pyroxene) have also been reported (e.g., Yabuta et al. 2023, Naraoka et al. 2023, Nakamura et al. 2023, Brunetto et al. 2023)

- (B13) Comparison of NH-bearing spectra in Ryugu and Bennu: The NH-bearing spectrum from Ryugu should be included for comparison. The authors should strengthen the discussion by clearly comparing the spectral features of both samples. In particular, how does the 2.32 μm absorption band in Ryugu compare with that in Bennu, is it weaker, stronger, or similar? Please elaborate on the observed differences or similarities and provide a possible interpretation.

As mentioned in a previous reply, we added to Figure 5 an example of NH-rich spectrum observed on Ryugu samples. Both spectra of Bennu and Ryugu NH-bearing phases display two main features at $\sim 2.7 \mu\text{m}$ and $\sim 3.05 \mu\text{m}$. Additionally, a weaker $\sim 2.32 \mu\text{m}$ feature can also be observed. We added some details about this point as follows:

“L218: A weak $\sim 2.32 \mu\text{m}$ feature, that we attribute to combination vibrations involving the O-H stretch and the bend of O-H strongly bonded to Mg atoms (e.g., Clark et al. 1990), can also sometimes be observed. Its presence is fully consistent with that of the 2.72 μm feature, in particular in the context of ‘high’ albedo grains which increases the visibility of spectral features compared to dark material. This spectral family is generally associated with bright whitish to yellowish inclusions (reflectance factor of $\sim 5\text{-}20\%$ typically), with sizes from a few tens to a few hundreds of micrometers (Figure 5 left). Spectral properties of such kind of compounds appear very similar to that detected in Ryugu samples. “

A future study will focus on the statistical analysis of such type of grains.

- (B14) Lines 200–202: Clarification of MgO-H features: The authors attribute a small absorption near 2.7 μm to MgO-H components, while earlier in Line 184, a 2.32 μm feature is also assigned to MgO-H. Could the authors clarify whether both features (2.32 μm and 2.7 μm) can be attributed to MgO-H phyllsilicates, or whether they reflect different phases or species? Furthermore, Line 181 states: “The latter is plausibly a similar phyllsilicate as in the matrix, as

indicated by the shape and position of the $\sim 2.7 \mu\text{m}$ band.” This section of the text should be revised for clarity to ensure consistency and avoid ambiguity regarding the attribution of spectral features.

The $\sim 2.7 \mu\text{m}$ feature is due to the stretching vibration of O-H when the hydroxyl is linked to metal (Al, Mg, Fe). Its position here at $\sim 2.71 \mu\text{m}$ indicates that such metal is Mg (e.g., Takir et al. 2013), in agreement with the detection in Bennu samples of $\sim 80\%$ of Mg-phylosilicates (Lauretta et al. 2024). The $2.32 \mu\text{m}$ feature is due to combination vibrations involving the OH stretch and metal-OH bend (e.g., Clark et al. 1990). It is commonly used to characterize phyllosilicates main cation in NIR datasets (e.g., Bishop et al. 2002, Poulet et al. 2006, Loizeau et al. 2007, Carter et al. 2013). Its presence is fully consistent with the presence of the $2.71 \mu\text{m}$ feature. In carbonaceous chondrites which exhibit a very low albedo, the $\sim 2.3 \mu\text{m}$ feature is very weak and might not be observed, contrary to the $\sim 2.7 \mu\text{m}$ feature (e.g., Takir et al. 2013). Here, in the case of NH-bearing compounds (Type 3 spectra), the albedo is generally much higher, which likely enables to distinguish this feature.

This clarification has been incorporated in the text (see reply to comment B13).

- (B15) The presentation of figures can be improved. The presentation of Figure 6 is currently confusing. The legend does not clearly distinguish which spectra correspond to which observations.
 - Are the blue and red spectra from MicrOmega (A and B)?
 - Why does the B spectrum appear to be collected over a longer spectral range than A?
 - Are the cyan and purple spectra obtained using $\mu\text{FT-IR}$ in the mid-infrared range?
 - Were these $\mu\text{FT-IR}$ spectra acquired at the same positions as A and B, as indicated in the visible and RGB images? Please clarify and revise the figure legend accordingly.
 - The visible and RGB images do not share the same scale. Please add a scale bar to the RGB images and clearly indicate the precise locations (e.g., using arrows or labels) where spectra A and B were collected, both in the visible and RGB images.

The blue and red spectra (A and B) are indeed MicrOmega spectra. We clarified that in the caption.

We modified Spectrum B to cover the entire spectral range of MicrOmega, similar to Spectrum A. Note that Spectrum B has been slightly refined to increase spectral quality by selecting more strictly the spectra with an olivine signature and avoid contamination by the surrounding pixels with a phyllosilicate signature.

The cyan and purple spectral were obtained with the μFTIR . We clarified that in the caption.

We modified the figure to show the footprint of the mid-IR observation of Region B

The RGB image ‘B’ was indeed not as the same scale. We rescaled it to match the scale of the visible image.

- (B16) Line 236: There appears to be a contradiction between Line 236, which acknowledges potential H₂O contamination during capsule reentry or after, and Line 71, which describes the samples as “pristine” and “never exposed to the terrestrial environment.” Please clarify the conditions under which Bennu samples were handled and reconcile this inconsistency.

We understand the reviewer’s concern and modified the text as follows:

L278: “The absence of a significant $\sim 3\ \mu\text{m}$ contribution to the matrix spectra, similar to the one observed in the spectra of CI chondrites and air exposed Ryugu samples (e.g., Takir et al. 2013; Le Pivert-Jolivet et al. 2023,2025), confirms that the samples have never been exposed to the terrestrial environment since their collection on the asteroid (“pristine”).”

- (B17) Discussion structure and logical flow: The discussion section should be reorganized for clarity and coherence. One possible approach is to follow the four spectral types identified by MicrOmega in Benu, from Type 1 to Type 4. For instance:
 - Start with Type 1 – Carbonate, then proceed to Type 2 – HAMP-bearing compounds, Type 3 – NH/MgO-H inclusions, and finally Type 4 – Anhydrous silicates (e.g., olivine).
 - Ensure that discussion of NH-bearing compounds is not mixed with that of carbonates.

We understand the reviewer’s concern and modified the structure of the discussion. The first part of the discussion now discusses similarities then differences observed between Ryugu and Benu samples. The second part focuses on the detection of HAMPs and its implications regarding the genericity of the formation of such compound. The last part focuses on the differences observed at more macroscopic level between our data and that obtained by remote sensing and telescopes (NIR slope) and its implication regarding the interpretation of NIR spectra of asteroids.

- (B18) Lines 257–261: Considering that Benu’s surface also included exogenic bright boulder with spectral properties similar to those of ordinary chondrite (OC) meteorites (Le Corre et al., 2021), can the authors exclude the possibility that the olivine grains originated from exogenous S-type asteroids?

We thank the reviewer for this comment. We cannot exclude this possibility. However, the preservation of a greater abundance of precursor material would be consistent with the less extended aqueous alteration highlighted by the weaker $\sim 2.7\ \mu\text{m}$ band. We modified the text as follows:

L324: “Here we also show that large olivines (larger than a few tens of microns), either intact or slightly altered, are present in Benu samples. Such grains/inclusions were not identified - so far - in the Ryugu bulk samples in similar observations by MicrOmega [4]. We cannot rule out that this constitutes one of the potential minor biases induced by the collection process of Haybusa2. The differences could also translate a possible exogenous origin of these compounds, as exogenic bright boulders with spectral properties similar to ordinary chondrites meteorites have been observed at the surface of Benu (Le Corre et al. 2021). The preservation of a greater abundance of precursor material could be consistent with the less extended aqueous alteration discussed above. In addition, the detection, here, of volatile-rich species in Benu samples indicates that the temperature remained low throughout their history and therefore that these olivine grains/inclusions do not originate from thermal metamorphism, but are remnants from the initial material present on the parent body.”

- (B19) Lines 262–269: Are NH-bearing compounds and NH_4^+ in HAMP phases formed by the same process? Could alternative formation scenarios exist? This should be discussed more thoroughly.

Regarding HAMPs, a formation process was proposed in Pilorget et al. 2024. Thus, the extensive discussion is in that paper. For clarity, we, however, added some details about the rationales in the discussion as follows:

L351: “Pilorget et al. 2024 proposed a formation scenario for the HAMPs found in Ryugu that is mainly based on thermodynamics and where the availability of NH_4^+ and the formation of carbonates and phosphates are interconnected. It can be roughly summarized as follows: the early formation of Ca-rich carbonates depletes the environment in Ca, which then favors the formation of HAMPs with regards to Ca-rich phosphates (apatites). Indeed, the latter is much more stable and would, thus, have formed preferentially if Ca was available.”

For the other NH-bearing phases, the state of NH (NH_4^+ ? NH in organics?) is these phases is not determined yet and is under study. Here, we only report the existence of these phases in Benu samples and their strong similarities in those found in Ryugu samples.

- (B20) Lines 270–271: Do the authors interpret NH-bearing compounds as NH_4^+ ? If so, why do they appear in two different spectral types (Type 2 and Type 3)? What spectral criteria distinguish them?

We do not consider that all NH are in the form NH_4^+ . The $\sim 3.1\ \mu\text{m}$ feature, observed in Type 3 spectra, corresponds to the N-H stretching vibration. It is not sufficient to conclude if this is in the form of NH_4^+ . We clarified that by mentioning the different possibilities:

L213: “The $\sim 3.05\ \mu\text{m}$ band is attributed to the N-H stretching vibration (e.g., Berg et al. 2016), in NH_4^+ or in NH-rich organics for instance”.

In the case of HAMP grains (Type 2 spectra), however, complementary spectral information in the MIR could be obtained (Pilorget al. 2024): they show a $\sim 7\ \mu\text{m}$ feature that corresponds to the NH_4^+ out of plane bending mode.

- (B21) Line 271: C-rich Compounds: The manuscript claims that Benu samples contain carbon-rich material visible at the sub-millimeter scale, yet no corresponding organic-rich spectra are shown. Please clarify this discrepancy and add relevant spectra if available.

See response to comment B4.

- (B22) Lines 284–285: This sentence duplicates the discussion already provided in Lines 259–261. Consider removing or consolidating to avoid redundancy.

We removed that sentence, as suggested by the reviewer.

- (B23) Lines 286–291 – HAMP in Other Samples:
 - Have HAMP-rich compounds been identified in any CI chondrites?
 - Were HAMP phases on Ryugu and Benu confirmed using techniques other than MicrOmega? If not, please explain why or clarify the limitations.

As far as we know, for aqueous altered chondrites, there is no report of HAMP-like phases detection, yet (as indicated L53). However, that does not imply the absence of that type of material in those chondrites. In fact, the detection of HAMP material requires a specific suite

of technics which, for as far as we know, have not yet been carried out. For instance, by contrast to IR spectroscopy, well suited to identify ammonium or NH-rich compounds, the technics used to characterize mineralogy (e.g. XRD) can barely characterize very poorly crystalline phases (as is the case for HAMP), and require a windowless detector to detect atoms emitting low energy X-rays, such as N, and most of the previous analyses may have just missed it. It should be noted that this may be the case for many ammonium salts that, after the Rosetta era (Poch et al. 2020), have now regained some interest. One should also not underestimate the possible effects of terrestrial weathering that affects chondrites and alter their content to some extent. (a key finding resulting from Ryugu analyses). As terrestrial weathering involves interaction with terrestrial water (in all three phases) and also induces the formation of sulfates, its occurrence may modify HAMP-like material and prevent any detection of it, especially in the more exposed chondrites. However, the absence of detection of HAMP in meteorites, although critical to the relevant community, does not impact the detections we made here, nor its consequences. The identification of HAMPs in Ryugu samples through a multi-analytical sequence (including NIR and mid-IR spectroscopy, SEM-EDS and XRD) (Pilorget et al. 2024) and now in Bennu samples (see responses above) strongly supports that their formation process is not something specific to Ryugu but to a whole class of objects.

- (B24) Discussion Order: Mg-rich Phyllosilicates and Olivine: The discussion of Mg-rich phyllosilicates and olivine appears early in the section but might be better placed toward the end. These phases represent a key difference between Bennu and Ryugu and could serve as a concluding highlight.

See earlier response about the changes in the structure of the discussion.

- (B25) Line 330: Carbon-rich Compounds: Once again, there is a reference to carbon-rich components in Bennu (organic matter?), yet no data or spectra are shown to support this. Please clarify or revise this statement to reflect the available evidence.

We replaced “C-rich compounds” by “organic compounds” and added references to Yabuta et al. 2023, Naraoka et al. 2023 and Glavin et al. 2025.

See also response to comment B4.

Minor comments:

- (B26) Line 48: “Analyses of the Ryugu samples...”. Could the authors clarify what types of analyses are you considering?

We summarize here some key observations on Ryugu samples. “Analyses of the Ryugu samples...” thus refers to these observations, made through multiple techniques, and not one in particular. As an example, HAMP were identified through a multi-analytical sequence that involved NIR and mid-IR spectroscopy, SEM-EDS and XRD.

- (B27) Line 50: The authors mention that NH-bearing components have also been identified in meteorites. Could you please provide specific examples or references to the meteorite types or studies in which these NH-bearing species have been reported? This would strengthen the scientific context of the statement.

We agree that this sentence was misleading. Our intent was to mention that the large size (a few hundred of microns large) NH-bearing phases coupled to Mg-phyllsilicates detected by MicrOmega in Ryugu samples have not (so far) been observed in meteorites. Since these phases are still poorly characterized, we suggest to remove this mention. The text is now as follows:

L55: “Analyses of the Ryugu samples have also highlighted the presence of Hydrated Ammonium-Magnesium-Phosphorus (‘HAMP’)-rich compounds (Pilorget et al. 2024), that were so far not observed in meteorites.”

- (B28) Lines 62–65: You mention that there are “small but significant differences” in the H and N isotopic data between Bennu, CI chondrites, and Ryugu. For clarity and completeness, please briefly summarize these differences in this section. What are the magnitudes or trends in these isotopic shifts?

We quote here the Lauretta et al. 2024 paper: “The bulk isotopic compositions of H and N in Bennu samples show slight distinctions from carbonaceous chondrites and Ryugu samples. Although falling within the range of carbonaceous astromaterials, Bennu’s $\delta^{15}\text{N}$ and δD compositions align more closely with those of the ungrouped carbonaceous meteorites Tarda and Tagish Lake than with other meteorites.

Although the Lauretta et al. 2024 is already referenced here, we modified the sentence for clarity and completeness:

L73: “H and N isotopic analyses on Bennu samples have also shown some small but significant differences with CI chondrites and Ryugu material. While Ryugu’s $\delta^{15}\text{N}$ and δD compositions are consistent with those of CI chondrites (Naraoka et al. 2023), Bennu’s $\delta^{15}\text{N}$ and δD compositions are closer to those of the Tarda and Tagish Lake meteorites (C2, ungrouped) (Lauretta et al. 2024), raising the question of the potential connection that exists between their parent bodies and the processes that drove their evolution.”

- (B29) Lines 67–70: Regarding the sample's exposure history: if Bennu materials may have been exposed to Earth's atmosphere during the capsule reentry (as emphasized lines 234-236), this should be clearly stated. The text currently implies they are pristine, which may conflict with later acknowledgments of potential H_2O contamination. Please clarify and revise this to avoid contradiction.

See response to a comment B16.

- (B30) Line 84: “...bulk samples...”. If I understand correctly, what you call here bulk samples are in fact two particles (ORX-19000 and ORX-29000). So, it should be “two bulks samples”.

We actually report here the results of the analyses performed on the 5 bulk samples that were delivered to JAXA (as mentioned Line 77). We clarified that in the text as follows:

L95: “At the scale of a few mm, the analyses performed with MicrOmega on the five Bennu “bulk samples” delivered to JAXA show that they mainly consist of a dark matrix (~2-3 %

reflectance at 2.5 μm) that exhibits a red slope at shorter wavelengths, a $\sim 2.72 \mu\text{m}$ feature consistent with OH moieties (O-H stretching) strongly bonded to Mg atoms – and most likely due to Mg-rich phyllosilicates – and a weaker $\sim 3.4 \mu\text{m}$ feature that can be attributed to the presence of organic compounds and/or carbonates (Figure 1 a, Sup. Figure 1), in agreement with Fukai et al. (in review)."

- (B31) Figure 1: The spectrum labeled ORX10007 appears in Figure 1, but it is not mentioned or explained in the main text. What is ORX10007, and how does it relate to ORX29000 and ORX19000?

We clarified that in the caption:

"Average spectrum obtained on mm-size grain ORX-10007 (extracted from bulk ORX-19000, Benu) has been added for comparison."

- (B32) Figure 2 caption: The authors present a set of wavelengths, but it is unclear which specific chemical compositions these correspond to. Could the authors clarify and explicitly indicate the chemical species or functional groups associated with each wavelength shown?

The RGB composite image is not a map of spectral features, it is a composite image made from the three images at the three indicated wavelengths, as explained in the caption. Such wavelengths tend to highlight specific compounds like carbonates and HAMP grains, identified through the entire spectral dataset. We consider that the caption is clear enough.

- (B33) Line 143: "Weak absorptions between ~ 3.0 and $3.3 \mu\text{m}$ are also sometimes present". Could the authors clarify which specific components or chemical species in the Benu samples are associated with these weak absorption features? A brief interpretation or reference would help the reader understand their significance.

As mentioned in an earlier reply, the spectra of HAMPs are dominated in MicrOmega data by the deep and broad signature of H_2O molecules around $3 \mu\text{m}$. Some weaker sub-features between ~ 3.0 and $3.3 \mu\text{m}$ are also sometimes present. The broad and deep $3 \mu\text{m}$ band is, however, generally close to saturation, which makes possible sub-features difficult to recognize. Their presence and position are, nonetheless, consistent with the presence of ammonium in HAMPs that produce multiple bands in the $3.0\text{-}3.3 \mu\text{m}$ spectral range (e.g., Berg et al. 2016).

We modified the text as follows for clarity:

L180: "Complementary mid-IR spectra obtained with a $\mu\text{-FT-IR}$ spectrometer (see Methods) on a couple of inclusions/grains displaying such kind of signature exhibit a $\sim 6.1 \mu\text{m}$ as well as a $\sim 6.9 \mu\text{m}$ absorption band that we attribute respectively to the presence of H_2O (bending ν_2 mode (Bishop et al. 1994, Libnau et al. 1994), and NH_4^+ (out of plane bending mode ν_4 , e.g., Banks et al. 1975, Berg et al. 2016). In particular, the presence of NH_4^+ could explain the spectral bands observed between 3.0 and $3.3 \mu\text{m}$ in MicrOmega data (e.g., Berg et al. 2016)."

- (B34) Figure 4, when you put HAMP (exposed) and HAMP in Fig. 4, are they different? And these spectra are come from the Ryugu samples if I understand well, so you should indicate some legends in Fig to be easier to follow.

Spectrum 'HAMP' in Figure 4 (top right) is actually a HAMP spectrum from Ryugu, as mentioned in the figure caption. It was obtained on pristine Ryugu samples within their preservation chamber at ISAS Curation Center by the same instrument (MircOmega). Spectrum 'HAMP (exposed)' in Figure 4 (bottom right) is also a HAMP spectrum from Ryugu, this time in the mid-IR. That sample was characterized outside of its preservation chamber through a multi-analytical sequence, including NIR spectroscopy, mid-IR spectroscopy and SEM-EDS that enabled – in combination with the NIR data obtained on pristine samples by MircOmega - the identification of the HAMP composition. In the spectrum of the exposed HAMP, the shape of the 3 μm band (attributed to O-H stretching vibrations of H_2O molecules) is a bit different compared that of non-exposed HAMP samples as the sample has absorbed-adsorbed some terrestrial water.

Following the reviewer's suggestions, we clarified that in the Figure and related caption.

- (B35) Line 179: “– quite rare –” Could you provide an estimate of the abundance of these Type 3 spectra compared to the other types? Same for “very rare” at line 193.

We modified the text as follows:

L212: “A third family of spectra ('Type 3') – quite rare (about a dozen of occurrences in the bulk samples) - exhibits both $\sim 2.7 \mu\text{m}$ and $\sim 3.05 \mu\text{m}$ features, indicating NH-bearing species associated with a MgO-H-rich material (Figure 5 right).”

L235: “A fourth kind of spectral family ('Type 4a') – very rare (only a few occurrences) - exhibits a strong $< 1.6 \mu\text{m}$ slope and a flat continuum at longer wavelengths, that is consistent with olivine (Figure 6 - spectrum A).”

Complementary articles will focus specifically on these compounds and their characteristics.

- (B36) Line 278: “...not observed so far in Ryugu samples...” by MircOmega? Please clarify.

We clarified that in the text as follows:

L324: “Here we also show that large olivines (larger than a few tens of microns), either intact or slightly altered, are present in Bennu samples. Such grains/inclusions were not identified - so far - in the Ryugu bulk samples in similar observations by MircOmega (Pilorget et al. 2022).”

Supporting information

- (B37) Only one figure is provided showing the bulk spectra. To aid interpretation and support spectral variability, it would be beneficial if the authors could also include visible images of the

grains, ideally covering a range of sizes from “large” to “small”. This would provide valuable context for understanding the relationship between grain morphology, size, and the observed spectral features.

In Sup. Fig1 (now Sup. Fig2), “large grains” actually correspond to areas dominated by grains that are $> \sim 25\text{-}30$ pixels large (typically mm-size grains), whereas “small grains” correspond to the areas dominated by the fine fraction. We also replaced the “medium” label by “mixed” as these spectra actually correspond to cases where both the fine grains and mm-size grains are within the FOV.

Figure 2 is actually quite helpful to understand what we are talking about: the upper part of the sample holder is filled with mm-size grains (“large”) whereas the lower part is filled with a much finer fraction (“small”). We clarified that in the caption of Sup. Fig. 2.

Reviewer #3 (Remarks to the Author):

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

We thank the reviewer for the “co-review” and for the constructive comments.

Reviewer #4 (Remarks to the Author):

The authors have undertaken a spectral comparison of samples returned from asteroids Bennu and Ryugu, and find that, in general, the samples are quite similar. There are, however, some minor variations that are interpreted as representing differences in the histories of these two asteroids. Specifically, Bennu appears to have preserved a greater fraction of precursor minerals, suggesting that at least some of its parent body underwent less severe aqueous alteration than is observed in all Ryugu materials. Both asteroids (or their parent bodies) appear to be derived from the outer solar system where ammonia ice was prevalent.

With respect to the quality of the data, the data are technically sound, collected appropriately and analyzed and interpreted carefully. Sufficiently strong evidence is provided for the authors' claims and appropriate controls or caveats have been included. With respect to the potential significance of the results, they are important to the field and advance our understanding in a way that moves the field forward.

Specific comments:

(C1) There should be an explanation of how the normalization shown in Fig. 1 (right) was calculated — are the data normalized to a common spectral contrast over the entire region, or at a specific wavelength? Recommend updating the Y-axis label to indicate that the spectra are normalized — the figure might be shown without the caption elsewhere.

We understand the reviewer's concern. We modified the Y-axis label as suggested and added the following sentence in the caption: "Both the band depth and the continuum were normalized to that of ORX-29000 spectrum to enable a comparison of the band shapes and positions."

Note that the normalization of the continuum was changed from 2.60 μm to 2.66 μm , similarly to what is done on Sup. Fig. 2 as a matter of consistency.

(C2) The readability of the methods section would be improved by a reorganization and it would also benefit from the inclusion of additional information. I suggest starting the section with the description of the samples being measured, followed by the instrumentation and related information. The sample section should explain what is a "bulk" sample — is it a sieved or otherwise prepared sample?

We thank the reviewer for this suggestion and restructured the Methods section accordingly.

We also added some explanations about the selection and extraction of the "bulks samples":

L560: "In August 2024, JAXA/ESCuC received 0.5 wt.% of "unprocessed" and "unbiased" samples returned by OSIRIS-REx [18]. The samples consist of five different aggregate samples, including numerous particles larger than 1 mm: OREX-800058-0, OREX-800111-0, OREX-800116-0, OREX-800120-0 and OREX-800125-0 on the OSIRIS-REx Samples Database from NASA, renamed ORX-19000, ORX-29000, ORX-39000, ORX-49000 and ORX-59000 by JAXA. All samples were extracted from trays than contained materials directly collected from inside of the TAGSAM head cover: ORX-19000 from material collected underneath the mylar flap and ORX-29000, ORX-39000, ORX-49000 and ORX-59000 from material collected after the TAGSAM container was fully disassembled. The selection process is fully described in [18]. The weights for the individual bulk samples are as follows: 0.183 g for ORX-

19000, 0.135 g for ORX-29000, 0.152 g for ORX-39000, 0.047 g for ORX-49000 and 0.148 g for ORX-59000 (Fukai et al. in review)."

(C3) Bringing "like" information together would improve the sub-section on the MicrOmega instrument if it included the second paragraph of what is currently shown under "samples" and the "protocol" text. The description of the MicrOmega instrument should include the total wavelength range covered by the instrument, how it is calibrated, and any other relevant parameters or measures of quality. Although the text states that spot sizes as small as 20 μm can be measured, the text does not say explicitly what spot sizes were used in this work or if it is always the same.

MicrOmega is a NIR hyperspectral microscope. It thus builds hyperspectral datacubes (x, y, λ) . For each wavelength, a 250x256 pixels image is generated (pixel size of $\sim 20 \mu\text{m}$).

Following, the reviewer's comments and suggestions, the MicrOmega section was restructured and modified as follows:

"MicrOmega analyses"

The MicrOmega instrument is an NIR hyperspectral microscope originally developed for the ExoMars 2028 rover mission (Bibring et al. 2017) and that is capable to characterize in a non-destructive and non-invasive manner the mineralogical and molecular composition of samples down to the scale of $\sim 20 \mu\text{m}$. The model installed at the ESCuC of JAXA (Sagamihara, Japan) is a copy of the ExoMars model. The instrument works as follows: MicrOmega sequentially illuminates the sample at different wavelengths with an incidence angle of $\sim 35^\circ$; for each illuminated wavelength, a 256x250 pixels image is acquired in a 'nadir' configuration (pixel size of $22.5 \mu\text{m}$). A hyperspectral (x, y, λ) cube is built by scanning the different monochromatic channels in the 0.99–3.65 μm wavelength range. Thanks to the use of an acousto-optic tunable filter (AOTF) as dispersive system, with a full width at half maximum of $\sim 20 \text{ cm}^{-1}$, the wavelengths can be selected and repeated in any order with minimum sampling steps of $\sim 2 \text{ cm}^{-1}$. For the baselined operations, the typical number of spectral channels per cube varies between ~ 200 and ~ 300 .

MicrOmega is mounted on a copper plate maintained at 10°C in an ultraclean- N_2 purged chamber. For the analysis, the samples are introduced within a 'sample chamber' part of the main curation facility suite, separated from the MicrOmega chamber by an NIR-transparent sapphire (Al_2O_3) window, and continually flowed with N_2 . This setup is similar to the one used in the Hayabusa2 curation facility for the analysis of the Ryugu samples.

Each of the five "bulk samples" was deposited on a dedicated sapphire sample holder (15 mm diameter at the base of the sample cavity, 23 mm diameter at the top) set on a polished gold-coated mirror, similarly to what was done for Ryugu samples (Pilorget et al. 2022). The sample holder was set on a $(x, y, z, \theta, \Delta)$ moving stage (3 axes translation, 360° rotation in the horizontal plane, $\pm 10^\circ$ tilt), remotely controlled, enabling to position the entire surface of the sample within the MicrOmega Field of View (useful area of $\sim 5 \times 5 \text{ mm}^2$) and to illuminate the grains with different geometries.

Each bulk sample was fully covered by a mosaic of 10-15 MicrOmega acquisitions, some with a different focus to account for irregularities of the top surface of the grains. Such analyses were repeated for a couple of different orientations (e.g., $\theta = 0^\circ, 90^\circ, 180^\circ, 270^\circ$) to minimize the effects of shadowing. Additional acquisitions were also performed on specific regions of interest.

The wavelength calibration of the illumination beam has been performed at the Institut d'Astrophysique Spatiale using two reference targets: a Wavelength Calibration Standard from Labsphere and a calcite pellet. Radiometric calibration was performed first at the Institut d'Astrophysique Spatiale and then periodically within the Curation Facility, using two reference

targets: Spectralon 99% and Infragold from Labsphere. The potential contribution of the sapphire window to the signal has been removed using acquisitions performed without any sample in the field of view. The radiometric calibration is evaluated to be better than 20% in absolute value and ~1% in relative value (from one spectral channel to the next). The spectral accuracy is evaluated to be better than 5 nm. Details about the calibration procedure and performances can be found in Riu et al. 2022 and Le Pivert-Jolivet et al. 2023.”

(C4) The description of the complementary FTIR characterizations should provide equivalent detail to that provided for the MicrOmega: e.g., more information about the spot size that is measured, the spectral resolution, the duration of the measurement, the calibration procedure, etc.

We agree with the reviewer that some information was missing. The FTIR section has been modified as follows:

L617: “For each “bulk sample”, complementary optical images were obtained with a LEICA visible microscope, set next to the MicrOmega instrument. Importantly, the MicrOmega data were also used to identify and locate regions of interest, that were then targeted by a μ -FT-IR spectrometer JASCO IRT-5200/VIR-200 with a 2.0-13 μm spectral range (footprint of ~ 50 -100 μm), providing access to complementary spectral signatures, while still within the Curation facility. The spectral resolution is 4 cm^{-1} and the spectral sampling is 1 cm^{-1} . The microscope’s incidence, emission, and phase angles are 0°, 0°, and 0°, respectively. Calibration was performed using a gold mirror, as well as an Infragold reference target from Labsphere (Fukai et al. in review).”

(C5) In the apparent absence of peer-reviewed, spectroscopy-focused publications by the OSIRIS-REx team (at the time of this review), there are several conference proceedings abstracts/presentations in which that team described many of these same spectral characteristics in the VNIR and TIR, as far back as March of 2024. I suggest, as a matter of professional courtesy, that additional relevant abstracts/presentations be cited here to recognize the full breadth of the earlier, publicly-presented work of the OSIRIS-REx team. Given the authors’ citation of at least one such abstract, it appears they are aware of these presentations, and their interpretations likely benefitted from them. Specific references include overview presentations of the VNIR and TIR spectra of Bennu samples, identification of phosphate, general mineralogy, and initial comparisons to Ryugu by Hamilton et al. [2024, 2025] (LPSC) and Russell et al. [2024] (MetSoc), More detailed discussion of the VNIR data was presented by Milliken et al. [2024], Cloutis et al. [2024], Schultz et al. [2024] (all LPSC), and connections to space weathering by Hiroi et al. [2024; 2025] (LPSC).

We would like to emphasize here that the present work is fully aligned with previous work on the Ryugu samples, performed with the same instrument and procedures (Pilorget et al. 2022, Loizeau et al. 2023, Le Pivert-Jolivet et al. 2023, Pilorget et al. 2024, Furukawa et al. 2025, Le Pivert-Jolivet et al. 2025, if we only cite the refereed publications). Specific references to published information about Bennu’s samples mineralogy and overall properties, IR data and interpretation is already done by citing Lauretta et al. 2024, McCoy et al. 2025 and Glavin et al. 2025, which are to our knowledge the only published references with a connection to the present work and that have a DOI (which is mandatory and which was the subject of a comment from the Editor).

Since LPSC abstracts cannot be cited here (no DOI), we chose to remove the part of the discussion about the possible effects of HAMP on the macroscopic spectral properties of Bennu that cited the Milliken et al. 2025 LPSC abstract.

Additional changes

The rank of one of the coauthors has been slightly modified to account for her most recent contribution to MicrOmega activities and the preparation of the current paper.

We also slightly developed the abstract as we understood that the limit was 200 words (and not 150 words as initially considered).

Reviewer #2 (Remarks to the Author):

I appreciate that the authors nicely addressed my questions and comments. I have some additional comments, although mostly minor.

We thank the reviewer for his constructive comments and suggestions. Please find below the detailed answers.

1) Line 75-77: It may be helpful for the authors to also include the isotopic values of both Ryugu and Bennu in the text, as this would strengthen and better contextualize the discussion.

We understand the reviewer's concern. The isotopic values have been added. The text is now as follows:

L74: "While Ryugu's $\delta^{15}\text{N}$ and δD compositions ($\delta^{15}\text{N}=43.0\pm9.0\text{‰}$, $\delta\text{D}=252\pm13\text{‰}$, [14]) are consistent with those of CI chondrites, Bennu's $\delta^{15}\text{N}$ and δD compositions ($\delta^{15}\text{N}=82\pm15\text{‰}$, $\delta\text{D}=344\pm13\text{‰}$, [3]) are closer to those of the Tarda and Tagish Lake meteorites (C2, ungrouped), raising the question of the potential connection that exists between their parent bodies and the processes that drove their evolution."

2) Line 107-108: The manuscript does not include a discussion of CH-rich spectra. As indicated in Fig. 1 and referenced in your response, one would expect to see a representative spectrum here that clearly demonstrates the presence of CH. Could the authors clarify whether the carbon content in Bennu is predominantly in the form of carbonates?

We agree with the reviewer that organics are important compounds of such type of samples. The spectra shown in Figure 1 and Sup. Fig.1 of Bennu bulks (integrating areas that are a few mm in size) clearly display an absorption band between ~ 3.3 and ~ 3.5 μm that has a maximum of absorption around 3.4 μm . This feature is typically a few percent deep, as indicated in the text. Both types of compounds (carbonates and aliphatic CH present in the organics) have signatures over the same wavelength range (~ 3.3 -3.5 μm), but with different shapes and peak positions. As indicated in the text, the shape of the absorption band, more pronounced at ~ 3.42 μm (aliphatic C-H) compared to a doublet between ~ 3.3 and 3.5 μm that would point toward carbonates, demonstrate that organics (aliphatic CH) are present in significant abundances and dominate the spectral signature at ~ 3.4 μm . Since the spectra are calculated over large areas here (a few mm in size typically), organics and carbonates are presumably both present, intimately mixed within the matrix, most likely in relatively minor amounts, which would explain the broad and shallow band depth. Notably, the feature observed on Bennu bulk sample is similar to typical absorption features due to organics (aliphatic CH) and carbonates observed on carbonaceous chondrites (e.g., Kaplan et al. 2019) and on Ryugu samples (e.g., Pilorget et al. 2022, Yada et al. 2022, Yabuta et al. 2023) at similar spatial scale. Quantifying the relative abundances between carbonates and organics, however, would require further analyses with different techniques, and is therefore out of the scope of this paper.

We modified the text as follows:

L106: "The relative band depth of the ~ 3.4 μm feature typically varies in the 3-4% range (Figure 1a, Sup. Figure 1). Its shape, more pronounced at ~ 3.42 μm , indicates that the signature of organics (aliphatic CH, e.g., Yabuta et al. 2023) dominates over that of carbonates (which would show a doublet at ~ 3.3 -3.5 μm) when integrating over areas a few mm wide. These organic compounds are presumably

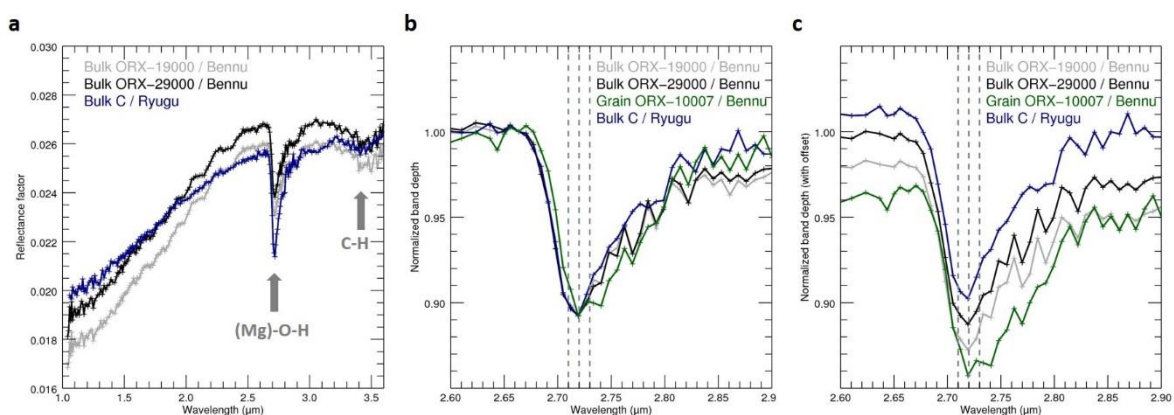
mixed with other matrix constituents at sub-micron scale, but local enrichments at larger scale could also be present, as within the Ryugu samples [4].”

3) Figures 1b and 1c appear very similar. I suggest replacing one of them with a zoomed-in view of the 3 μm band to better illustrate the points described in the manuscript.

Figures 1c has been added after a suggestion from one of the reviewers, to ease the comparison between the spectra between 2.6 and 2.9 μm , where the $\sim 2.7 \mu\text{m}$ feature due to the presence of phyllosilicates dominates at such large spatial scale. Indeed, the characteristics of the $\sim 2.7 \mu\text{m}$ feature (shape and absorption maximum) are critical to assess the type/composition/structure of the phyllosilicates and the possible exposure of the samples to space weathering (e.g., Lantz et al. 2017, Le Pivert-Jolivet et al. 2023). It is not fully clear to us what the reviewer means by “3 μm band”. There is actually no feature around “3 μm ” (which would point towards the presence of H_2O molecules) as indicated in the text. We suggest to keep Figure 1 as is.

4) Line 285: Could you please clarify how the C–H signature at 3.4 μm can be considered consistent, given that no corresponding spectrum is shown in your paper? We note that no distinct 3.4 μm absorption feature is apparent in our spectra in Fig. 1, suggesting that, if aliphatic C–H absorptions are present, their intensity is below our detection.

We share the reviewer’s view that organics are essential compounds of such type of samples. We, however, disagree with the reviewer’s comment: the spectra shown in Figure 1 and Sup. Fig.1 of Benu bulks clearly display an absorption band between ~ 3.3 and $\sim 3.5 \mu\text{m}$ that has a maximum of absorption around 3.4 μm . Such feature is typically a few percent deep, as indicated in the text. The shape of the absorption band, more pronounced at $\sim 3.42 \mu\text{m}$, demonstrates the presence of aliphatic C–H. Additionally, and as discussed above, the feature observed on Benu bulk sample is similar to typical organics-related (aliphatic CH) absorption features observed in carbonaceous chondrites (e.g., Kaplan et al. 2019) and in Ryugu samples (e.g., Pilorget et al. 2022, Yada et al. 2022, Yabuta et al. 2023). As mentioned in the response to comment 2), we added a reference to Yabuta et al. 2023 regarding the interpretation of this feature. We also added arrows on Figure 1a to indicate more clearly the different signatures and therefore ease their identifications:



5) Line 185: “Additionally, a board feature can also be observed”. Do you mean spectrum C in Fig. 4? In the zoomed view, the shape of spectrum A appears quite different, for example, it resembles

spectrum C, whereas over the full range it looks relatively flat between 9–10 μm . Did you normalize or rescale the spectra for the zoomed panel? Please clarify.

The feature that we mention in the text corresponds to the feature that can be observed in the bottom right panel of Figure 4 on all 3 spectra (spectra A, C and Ryugu's HAMP). The feature is indeed more pronounced in spectrum C than in spectrum A and HAMP spectrum from Ryugu. It is important to note that contrary to other features that are bands (i.e. towards the bottom), the $\sim 9.5 \mu\text{m}$ feature is a peak (i.e. towards the top). This is due to different scattering regime between the first part of the spectrum $< \sim 7\text{--}8 \mu\text{m}$ and the second part $> \sim 7\text{--}8 \mu\text{m}$: when the absorptivity is very high, as is the case around 9–10 μm , the reflectivity tends to increase with the absorptivity (see Hapke et al. 1993 for example). Additionally, the intensity of such kind of feature is very sensitive to various parameters, such as the local geometry, and might drastically change when slightly moving the observation spot. When rescaled (as indicated by the y-label of the insert), all 3 spectra show a similar type of feature in the 9–10 μm range indicative of P-O stretching vibrations.

We clarify that in the caption of Figure 4:

“An insert with rescaled reflectance factor provides a better view at the $\sim 9.5 \mu\text{m}$ feature attributed to the P-O stretching vibration. Indeed, the intensity of this feature is quite sensitive to local geometric conditions and might significantly vary between the samples”.

6) The manuscript should be carefully proofread for grammar check and clarity throughout. For example:

- o Line 44: “...recently on September” should be corrected to “...recently in September”.
- o Line 170: Suggested revision: “Grain sizes range from a few ten...”
- o Line 171–173: Suggested revision: “Many detached grains exhibit a whitish, uniform appearance in optical images, punctuated by smaller, dark micrometre-sized grains either embedded within the whitish material or stuck on the surface.”
- o Line 186: Suggested revision: “..., attributed to P-O stretching vibrations...Similar spectral signatures have been detected in Ryugu samples..., indicating the presence...”.
- o Line 224: Suggested revision: “The spectral properties of these inclusions closely resemble those observed in Ryugu samples.”
- o Line 308: It seems you mean “the large number of particles”? The sentence could be revised as “...the large number of particles analysed in this study, combined with the extensive set of similarities identified between two distinct objects, reduced the likelihood...”
- o Line 313: I suggest rephrasing as: “the Bennu bulk samples show variations of similar magnitude, whether measured in areas dominated by larger (mm-size) grains or by finer fractions.”
- o Line 316: Please specify “The lower band depth...” in what?
- o Line 319: The phrase “No clear band shift...” might be better expressed as “No systematic band shift”. And the sentence could be simplified to “...that would indicate a stronger contribution from space-weathered material...relative to Ryugu samples”
- o Line 324: Should read: “...large olivine grains (tens of microns in size) ...”
- o Line 325: Suggested revision: “Such grains/inclusions have not, so far, been identified...”
- o Line 335: Suggested revision: “The close proximity in most spectral properties at both cm and sub-mm scales between Bennu and Ryugu samples thus suggests that they experienced broadly similar formation and evolutionary processes.”

We thank the reviewer for these helpful suggestions above. They have been included in the new version of the manuscript. We also did a careful grammar/syntax check of the manuscript as suggested by the reviewer. The corrections can be tracked in the new version of the manuscript.

REVIEWERS' COMMENTS

Manuscript NCOMMS-25-37650 entitled “Compositional diversity in pristine Bennu samples revealed by the IR hyperspectral microscope MicrOmega at JAXA Curation Center and comparison with Ryugu Samples”.

Author(s): Pilorget, C. et al.,

This manuscript presents an analysis of the compositional variations in Bennu samples using the MicrOmega IR hyperspectral microscope, with comparisons drawn to samples from Ryugu. While the study includes intrinsically valuable data and draws conclusions that are generally supported by the results, the manuscript requires substantial revisions prior to publication. We will provide detailed comments below:

Major comments

- Overall focus and comparative analysis: The central objective of this paper is to compare the composition of samples from Bennu and Ryugu using MicrOmega. However, the current presentation of results and discussion lacks sufficient depth and clarity. To strengthen the comparative aspect, the authors should incorporate Ryugu data into all relevant MicrOmega spectral figures. For example:
 - Figure 3 should include the Type 1-Carbonate spectrum from Ryugu
 - Figure 5 should incorporate the Type 3-NH- rich inclusion from Ryugu
- Detailed comparison and interpretation: The manuscript would benefit from a more thorough and structure discussion on the similarities and differences between Bennu and Ryugu samples. First, the legends in Figure 3 to 6 should be improved to clearly indicate the four spectral types. For clarity and ease of reference, each type could be labeled more explicitly, e.g., “Type 1-Carbonate”, “Type 2-OH- + HAMP”, etc., to help the reader follow the results and the corresponding discussion throughout the manuscript. Additionally, the following aspects should be revised or expanded, specifically:
 - **Type 1: Carbonate** - A direct comparison with Ryugu data is missing and should be included,
 - **Type 2: OH- + HAMP** - Fig. 4 shows slight differences between the HAMP spectrum from Ryugu and spectrum A from Bennu. Notably, there are two peaks near 3 μm in spectrum A, and the peak positions differ slightly between the two samples (at 3 μm , 6 μm and 8 μm), please elaborate on these distinctions and discuss their potential implications.
 - **Type 3: NH-/MgO-H rich inclusions** - Please add the spectrum of a NH-rich grain from Ryugu (as reported in Pilorget et al., 2022) and provide a more detailed description of the observed differences.

- **Type 4: Rare olivine**

- It is surprising that CH-rich compounds, which typically exhibit a spectral feature around 3.4 μm are not detected or discussed in Bennu samples. Could the authors clarify this absence? If such compounds were observed, please include the corresponding data and compare them with the CH-rich feature identified in Ryugu samples.
- Line 49: The manuscripts states that Hydrated Ammonium Magnesium Phosphorous (HAMP)-rich compounds and NH-rich minerals were detected using the MicrOmega instrument. Could the authors clarify why these features were only reported through MicrOmega? Were these detections cross-validated using other techniques? A brief summary on this point would strengthen the interpretation of the data.
- Line 124-125: The spectral signatures at 2.5 μm and 1.2 μm appear to be strong in the mapped images, yet these features are not clearly visible in the corresponding spectra on the right-hand side. For instance, the A2 spectrum is highlighted in green on the map, but the 2.5 μm feature is not prominent in the plotted spectrum. Could the authors please explain this discrepancy?
- Figure 3: A representative carbonate spectrum from Ryugu should be included for comparison, to better assess similarities or differences with Bennu samples. One of the spectra displays a particularly strong peak around 3 μm that differs from the others, could the authors comment on the possible chemical species responsible for this feature?
- Line 156-159: The authors should include a HAMP-rich spectrum of Ryugu for direct comparison with Bennu data. In addition to MicrOmega observations, do the authors have any complementary analytical techniques to independently confirm the presence of HAMP in Bennu samples?
- Line 159-160: The text mentions features between 9 and 10 μm attributed to P-O stretching in spectrum A of Fig. 4. However, these features are not clearly visible in the plotted spectrum. Could the authors provide additional evidence or reference other spectra where this weak feature is more discernible?
- Figure 4: RGB composite image for spectra A and B appear very similar, yet the corresponding spectra show notable differences. Specifically, the absorption at 2.72 μm is negligible in spectrum B, and new features between 3.3 and 3.5 μm appear that are not present in spectra A or C. Could the authors clarify whether these spectral differences are real and, if so, discuss their possible origin?
- Line 180: NH and MgO-H-bearing species: the authors associate the bands at 2.7 and 3.05 μm with NH bearing species linked to MgO-H rich material. How was this identification confirmed? Are there alternative interpretations of these bands (such as NH_4 or NH-organics-bearing phyllosilicates)? Or did you check also the reference samples with the same MicrOmega instrument n Pilorget et al. (2022), the authors note that the 2.7 μm feature could also originate from Mg-OH-bearing minerals. Have the authors applied any complementary

analytical methods to support or verify the presence of Mg–OH-bearing phases in these samples?

- NH-bearing composition in Ryugu: The presence of NH-bearing species in Ryugu was first reported in earlier studies. Was the NH-rich grain in Ryugu also analyzed using other techniques (e.g., NanoSIMS, micro-FTIR, or AFM-IR) to confirm and compare with the MicrOmega spectral features? If so, this should be clarified and referenced here.
- Comparison of NH-bearing spectra in Ryugu and Bennu: The NH-bearing spectrum from Ryugu should be included for comparison. The authors should strengthen the discussion by clearly comparing the spectral features of both samples. In particular, how does the 2.32 μm absorption band in Ryugu compare with that in Bennu, is it weaker, stronger, or similar? Please elaborate on the observed differences or similarities and provide a possible interpretation.
- Lines 200–202: Clarification of MgO–H features: The authors attribute a small absorption near 2.7 μm to MgO–H components, while earlier in Line 184, a 2.32 μm feature is also assigned to MgO–H. Could the authors clarify whether both features (2.32 μm and 2.7 μm) can be attributed to MgO–H phyllosilicates, or whether they reflect different phases or species? Furthermore, Line 181 states: “The latter is plausibly a similar phyllosilicate as in the matrix, as indicated by the shape and position of the ~ 2.7 μm band.” This section of the text should be revised for clarity to ensure consistency and avoid ambiguity regarding the attribution of spectral features.
- The presentation of figures can be improved. The presentation of Figure 6 is currently confusing. The legend does not clearly distinguish which spectra correspond to which observations.
 - Are the blue and red spectra from MicrOmega (A and B)?
 - Why does the B spectrum appear to be collected over a longer spectral range than A?
 - Are the cyan and purple spectra obtained using $\mu\text{FT-IR}$ in the mid-infrared range?
 - Were these $\mu\text{FT-IR}$ spectra acquired at the same positions as A and B, as indicated in the visible and RGB images? Please clarify and revise the figure legend accordingly.
 - The visible and RGB images do not share the same scale. Please add a scale bar to the RGB images and clearly indicate the precise locations (e.g., using arrows or labels) where spectra A and B were collected, both in the visible and RGB images.
- Line 236: There appears to be a contradiction between Line 236, which acknowledges potential H_2O contamination during capsule reentry or after, and Line 71, which describes the samples as “pristine” and “never exposed to the terrestrial environment.” Please clarify the conditions under which Bennu samples were handled and reconcile this inconsistency.
- Discussion structure and logical flow: The discussion section should be reorganized for clarity and coherence. One possible approach is to follow the four spectral types identified by MicrOmega in Bennu, from Type 1 to Type 4. For instance:

- Start with Type 1 – Carbonate, then proceed to Type 2 – HAMP-bearing compounds, Type 3 – NH/MgO-H inclusions, and finally Type 4 – Anhydrous silicates (e.g., olivine).
- Ensure that discussion of NH-bearing compounds is not mixed with that of carbonates.
- Lines 257–261: Considering that Bennu’s surface also included exogenic bright boulder with spectral properties similar to those of ordinary chondrite (OC) meteorites (Le Corre et al., 2021), can the authors exclude the possibility that the olivine grains originated from exogenous S-type asteroids?
- Lines 262–269: Are NH-bearing compounds and NH_4^+ in HAMP phases formed by the same process? Could alternative formation scenarios exist? This should be discussed more thoroughly.
- Lines 270–271: Do the authors interpret NH-bearing compounds as NH_4^+ ? If so, why do they appear in two different spectral types (Type 2 and Type 3)? What spectral criteria distinguish them?
- Line 271: C-rich Compounds: The manuscript claims that Bennu samples contain carbon-rich material visible at the sub-millimeter scale, yet no corresponding organic-rich spectra are shown. Please clarify this discrepancy and add relevant spectra if available.
- Lines 284–285: This sentence duplicates the discussion already provided in Lines 259–261. Consider removing or consolidating to avoid redundancy.
- Lines 286–291 – HAMP in Other Samples:
 - Have HAMP-rich compounds been identified in any CI chondrites?
 - Were HAMP phases on Ryugu and Bennu confirmed using techniques other than MicroOmega? If not, please explain why or clarify the limitations.
- Discussion Order: Mg-rich Phyllosilicates and Olivine: The discussion of Mg-rich phyllosilicates and olivine appears early in the section but might be better placed toward the end. These phases represent a key difference between Bennu and Ryugu and could serve as a concluding highlight.
- Line 330: Carbon-rich Compounds: Once again, there is a reference to carbon-rich components in Bennu (organic matter?), yet no data or spectra are shown to support this. Please clarify or revise this statement to reflect the available evidence.

Minor comments:

- Line 48: “Analyses of the Ryugu samples...”. Could the authors clarify what types of analyses are you considering?
- Line 50: The authors mention that NH-bearing components have also been identified in meteorites. Could you please provide specific examples or references to the meteorite types or studies in which these NH-bearing species have been reported? This would strengthen the scientific context of the statement.

- Lines 62–65: You mention that there are “small but significant differences” in the H and N isotopic data between Bennu, CI chondrites, and Ryugu. For clarity and completeness, please briefly summarize these differences in this section. What are the magnitudes or trends in these isotopic shifts?
- Lines 67–70: Regarding the sample's exposure history: if Bennu materials may have been exposed to Earth's atmosphere during the capsule reentry (as emphasized lines 234-236), this should be clearly stated. The text currently implies they are pristine, which may conflict with later acknowledgments of potential H₂O contamination. Please clarify and revise this to avoid contradiction.
- Line 84: “...bulk samples...”. If I understand correctly, what you call here bulk samples are in fact two particles (ORX-19000 and ORX-29000). So, it should be “two bulks samples”.
- Figure 1: The spectrum labeled ORX10007 appears in Figure 1, but it is not mentioned or explained in the main text. What is ORX10007, and how does it relate to ORX29000 and ORX19000?
- Figure 2 caption: The authors present a set of wavelengths, but it is unclear which specific chemical compositions these correspond to. Could the authors clarify and explicitly indicate the chemical species or functional groups associated with each wavelength shown?
- Line 143: “Weak absorptions between ~ 3.0 and 3.3 μm are also sometimes present”. Could the authors clarify which specific components or chemical species in the Bennu samples are associated with these weak absorption features? A brief interpretation or reference would help the reader understand their significance.
- Figure 4, when you put HAMP (exposed) and HAMP in Fig. 4, are they different? And these spectra are come from the Ryugu samples if I understand well, so you should indicate some legends in Fig to be easier to follow.
- Line 179: “– quite rare –” Could you provide an estimate of the abundance of these Type 3 spectra compared to the other types? Same for “very rare” at line 193.
- Line 278: “...not observed so far in Ryugu samples...” by MicrOmega? Please clarify.

Supporting information

Only one figure is provided showing the bulk spectra. To aid interpretation and support spectral variability, it would be beneficial if the authors could also include visible images of the grains, ideally covering a range of sizes from “large” to “small”. This would provide valuable context for understanding the relationship between grain morphology, size, and the observed spectral features.

REVIEWERS' COMMENTS (2nd) (Reviewer #2 + #3)

Manuscript NCOMMS-25-37650 entitled “Compositional diversity in pristine Bennu samples revealed by the IR hyperspectral microscope MicrOmega at JAXA Curation Center and comparison with Ryugu Samples”.

Author(s): Pilorget, C. et al.,

I appreciate that the authors nicely addressed my questions and comments. I have some additional comments, although mostly minor.

- Line 75-77: It may be helpful for the authors to also include the isotopic values of both Ryugu and Bennu in the text, as this would strengthen and better contextualize the discussion.
- Line 107-108: The manuscript does not include a discussion of CH-rich spectra. As indicated in Fig. 1 and referenced in your response, one would expect to see a representative spectrum here that clearly demonstrates the presence of CH. Could the authors clarify whether the carbon content in Bennu is predominantly in the form of carbonates?
- Figures 1b and 1c appear very similar. I suggest replacing one of them with a zoomed-in view of the 3 μ m band to better illustrate the points described in the manuscript.
- Line 285: Could you please clarify how the C–H signature at 3.4 μ m can be considered consistent, given that no corresponding spectrum is shown in your paper? We note that no distinct 3.4 μ m absorption feature is apparent in our spectra in Fig. 1, suggesting that, if aliphatic C–H absorptions are present, their intensity is below our detection.
- Line 185: “*Additionally, a board feature can also be observed*”. Do you mean spectrum C in Fig. 4? In the zoomed view, the shape of spectrum A appears quite different, for example, it resembles spectrum C, whereas over the full range it looks relatively flat between 9–10 μ m. Did you normalize or rescale the spectra for the zoomed panel? Please clarify.
- The manuscript should be carefully proofread for grammar check and clarity throughout. For example:
 - Line 44: “*...recently on September*” should be corrected to “*...recently in September*”.
 - Line 170: Suggested revision: “*Grain sizes range from a few ten...*”
 - Line 171-173: Suggested revision: “*Many detached grains exhibit a whitish, uniform appearance in optical images, punctuated by smaller, dark micrometre-sized grains either embedded within the whitish material or stuck on the surface.*”
 - Line 186: Suggested revision: “*..., attributed to P-O stretching vibrations...Similar spectral signatures have been detected in Ryugu samples..., indicating the presence...*”.

- Line 224: Suggested revision: “The spectral properties of these inclusions closely resemble those observed in Ryugu samples.”
- Line 308: It seems you mean “*the large number of particles*”? The sentence could be revised as “*...the large number of particles analysed in this study, combined with the extensive set of similarities identified between two distinct objects, reduced the likelihood...*”
- Line 313: I suggest rephrasing as: “*the Bennu bulk samples show variations of similar magnitude, whether measured in areas dominated by larger (mm-size) grains or by finer fractions.*”
- Line 316: Please specify “*The lower band depth...*” in what?
- Line 319: The phrase “*No clear band shift...*” might be better expressed as “*No systematic band shift*”. And the sentence could be simplified to “*...that would indicate a stronger contribution from space-weathered material...relative to Ryugu samples*”
- Line 324: Should read: “*...large olivine grains (tens of microns in size) ...*”
- Line 325: Suggested revision: “*Such grains/inclusions have not, so far, been identified...*”
- Line 335: Suggested revision: “*The close proximity in most spectral properties at both cm and sub-mm scales between Bennu and Ryugu samples thus suggests that they experienced broadly similar formation and evolutionary processes.*”

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