

Refractory inclusions in Benu samples indicative of outer Solar System accretion

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

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The manuscript "Refractory inclusions in Benu samples indicative of outer Solar System accretion" by Kawasaki et al. is well written and would make a strong contribution to Nature Communications. In particular, the extensive and rigorous petrographic and isotopic analyses of refractory inclusions from returned asteroid samples represents a unique contribution to the fields of planetary science and cosmochemistry that will also be of interest to a wider audience. I recommend acceptance of the manuscript for publication, with just a few minor comments listed below.

Line 115-119, Line 165-166, and Fig. 4: A more thorough discussion comparing these Benu inclusion results with the O isotope compositions of previously measured AOAs/CAIs would be beneficial. For example, it is mentioned that these Benu inclusion compositions are consistent with other carbonaceous chondrites including CIs, but further discussion on this point would be useful. I understand that there are space constraints in a paper written in this format, but I would be interested to see if some minor compositional differences might be discerned (particularly if graphically represented in a figure showing the newly acquired data plotted with literature data). Also, some important references on the topic of AOAs (including O isotope compositions) are not included (e.g., Krot et al. (2004) GCA and Krot et al. (2004) Chem de Erde). Some additional comparison with previously published data for inclusions from meteorites may strengthen the discussion. I am also curious whether the results of this work might provide the authors with the opportunity to discuss the formational relationship between chondrules, AOAs, and CAIs.

Line 156: The word "of" in this sentence is unnecessary and should be deleted.

Line 190-192: The wording of this sentence is slightly confusing, and I recommend rewording it for clarity. Specifically, the statement, "These inclusions are also mineralogically, isotopically, and chronologically similar to those in ordinary and carbonaceous chondrites other than CIs..." could be misinterpreted to mean that they are not similar to those in CI chondrites, even though that is stated earlier in the paragraph. I think simply making a minor adjustment to this sentence would help make things clearer for readers. For example, "These inclusions are also mineralogically, isotopically, and chronologically similar to those in ordinary and other carbonaceous chondrites..."

Figures: In all figures, but most noticeably Fig. 4 and Fig. 5, the resolution of the figures appears blurry when enlarged. I am not sure if this is because the images are compressed for the reviewer copy of the manuscript, but please make sure the figures are in high resolution in the proofing stage prior to publication.

Reviewer #2

(Remarks to the Author)

This study investigates the chemical and oxygen isotopic compositions of CAIs and AOAs in the Benu samples brought back by the OSIRIS-REx space mission. Chronological data are also reported thanks to ^{26}Al - ^{26}Mg measurements. From a general manner, the paper is pleasant to read and the data are robust. I have however the feeling that some key assertions should be better detailed and alternative possibilities should be also considered. In any case, the paper should be published after major revisions.

1- A key observation is that CI chondrites represent an endmember of the CC field in multi-isotopic space. This is observed

for Cr–Te (Hellmann et al., 2020, EPSL), Rb–Te and Rb–Zn (Nie et al., 2021, Science Advances), and Fe–Te (Marrocchi et al., 2023, ApJ Letters). This has been interpreted as reflecting (i) the ubiquitous presence of CI-like dust throughout the carbonaceous reservoir and (ii) CI-like dust representing the matrix component of carbonaceous chondrites. In this scenario, CI-like dust would have been distributed throughout the outer disk. This interpretation appears to contradict that proposed by the authors. This discrepancy should be discussed, and this alternative scenario should be considered.

2- The authors suggest that CI chondrites accreted through streaming instability in an environment distinct from that of other CCs. Alternatively, it has been proposed that CIs accreted via a different process triggered by photoevaporation during the final stages of the disk's lifetime (Spitzer et al., 2024, Science Advances). This mechanism would favor the accretion of small dust particles (and thus CAIs and AOAs), whereas streaming instability, in contrast, tends to promote the incorporation of larger inclusions. Such a process could also account for the pronounced isotopic heterogeneity of volatile elements (H and N) observed in CIs (Marrocchi et al., 2026, Geochemical Perspectives Letters). In what way do the data presented here specifically support an accretion scenario driven by streaming instability?

3- The process responsible for transporting CAIs and AOAs to the outer regions of the disk remains unclear. It may involve viscous spreading or alternatively disk winds and outflows. None of the references cited by the authors (e.g., refs. 1–8, lines 45–47) directly address this issue, although it has been extensively discussed in a recent study (Morbidelli et al., 2024, Astronomy & Astrophysics).

4- I struggle to understand how large-scale alteration by brines would not erase the micro-environments associated with CAI and AOA alteration. In addition, recent studies have revisited the condensation of phyllosilicates in the protoplanetary disk (e.g., Viennet et al., 2025, EPSL).

5- Claiming that most CCs contain large (> submillimeter-sized) CAIs and AOAs is an overstatement, as this is mainly the case for CV chondrites. In addition, the mean size of chondrules in CV, CO, and CM chondrites is larger than that of CAIs (May et al., 1999, LPSC abstract). Therefore, the assertion that only CIs accreted small CAIs and AOAs appears questionable. How do the authors reconcile this observation with their model?

6- The authors should provide a figure showing $\Delta^{17}\text{O}$ versus trace element concentrations in the olivine they analyzed, and compare these data with those reported for CI chondrites, Ryugu samples, AOAs, and metal–olivine inclusions (for the latter, see e.g., Ebel et al., 2025, MAPS; Ochem and Marrocchi, 2026, Icarus).

7- Lines 176–178. Why the authors did not consider the possibility of alteration-induced isotopic exchange? (see recent review by Krot et al., 2025, space science review).

8- I am surprised that the authors did not consider the work of Hellmann et al. (2023, ApJ Letters), who show that the abundances of refractory inclusions and chondrules are coupled and systematically decrease with increasing matrix abundance. They propose that these correlated variations reflect the trapping of chondrule precursors, including refractory inclusions, in a pressure maximum in the disk. This model has important implications for the scenario proposed here and should therefore be discussed.

9- I struggle to fully understand the model presented here. If I understand correctly, CAIs and AOAs condensed in the inner disk and were subsequently transported to the outer disk. Small CAIs and AOAs would have escaped inward drift and remained in the outer CI-accreting region. If so, it should be acknowledged and discussed that small CAIs and AOAs are also observed in CM, CO, and CV chondrites. Conversely, larger CAIs and AOAs would have drifted inward and been trapped at a pressure bump. In that case, what is the origin of the CAIs and AOAs observed in ordinary chondrites, which the authors claim are similar to those found in CIs?

Reviewer #3

(Remarks to the Author)

Overall, this is an interesting study reporting on the properties of refractory inclusions in Bennu samples and comparison of those properties to other CC meteorites. It is found that the properties of the inclusions are most similar to those found in CI chondrites or Ryugu samples, which the authors then use to argue that this meant that the parent bodies of these objects (Bennu, Ryugu, and CIs) formed in a distinct location in the solar nebula than the other carbonaceous chondrites; the latter of which is hypothesized to form in the pressure bump immediately outside of Jupiter's orbit.

The paper provides interesting measurements and results that will be of interest to a diverse audience. I do think the picture presented by the authors is a bit overly simplified and suggest some considerations below. These do not change the fundamentally interesting part of the paper (the observations and data) and only partly require a reconsideration of the speculations included at the end of the paper in regards to what this means. Should the authors address these points, then I think the paper would be worthy of publication in Nature.

The major point that I would make here in regards to the interpretation of the data is that the authors immediately interpret the lack of inclusions larger than ~100 micron as being a sign that Bennu (and others) formed in a different spatial location than the other carbonaceous chondrites which contain larger CAIs. I think this point needs to be discussed further. Firstly, are the sizes of the inclusions statistically different from those found in CM chondrites? CM meteorites generally have small CAIs of order tens of microns in size, with the occasional large one representing an extreme outlier on the tail end of the distribution. Given the amount of material that has been searched through with Bennu, Ryugu, and CIs, can we confidently say that the

size distribution of the refractory inclusions is demonstrably different? CM meteorites generally have provided much greater amounts of samples to sort through (Murchison was nearly 100 kg!) than what we have in these rarer samples, so it's easier to sample the tale end of the distribution in these meteorites, possibly finding larger objects. I suggest looking at recent work by Dunham et al. 2023 (not referenced here) who compiled and reported sizes of CAIs in different meteorite types.

Secondly, let's assume that the authors are correct in that the size distribution is different than CMs and all other CCs (this very well may be the case, my point above is just to strengthen the argument if it's true or to provide context). Another way of explaining this observation would be that Bennu and friends formed at a different time than all other CCs, but possibly not a different location. The authors make the point that drift of larger CAIs would deplete the very outer disk in those objects over time, leaving smaller objects behind to be incorporated into the CI/Bennu/Ryugu parent bodies. However, the same reasoning would suggest that the drift would be most effective for the larger objects, concentrating them somewhere and allowing them to be incorporated into planetesimals early on. In fact, this was an explicit prediction of Cuzzi et al. (2003; not cited) who looked at the redistribution of CAIs in the early solar nebula. As the big things get removed early, they leave small things behind to serve as the solids that get incorporated into later-formed planetesimals. This particularly makes sense if planetesimals form via processes like the streaming instability or other mechanisms which rely on solids having similar aerodynamic properties as one another to clump into planetesimals; as the gas dissipates from the solar nebula smaller objects behave more like larger objects at an earlier time.

Question re: Figure 5: why is there no Saturn in the schematic? Saturn grew similarly to Jupiter, would have opened a gap, and would also have created a pressure bump outside of it. Are the authors saying that all CC parent bodies formed prior to the formation of Saturn or its core? If so, this should be discussed and evidence provided to support the argument.

Lines 219-220: "Formation beyond the dust-trapping region of the pressure bump, and the paucity of large refractory inclusions, are consistent with the chemically primitive nature of Bennu." I don't understand this sentence. Why is the paucity of large refractory inclusions a sign of chemical primitiveness? My understanding of meteorite classification based on alteration is that it thermal and aqueous alteration is characterized by various properties but the sizes of the constituents are not among them. Are CV chondrites less chemically primitive than CM chondrites because they have bigger chondrules and CAIs? Further, why does "formation beyond the dust-trapping region of the pressure bump" mean anything related to the chemically primitive nature of the samples? This reads a bit like an unnecessary sales-job rather than a scientific argument of conclusion following evidence.

A further note: differences in CAIs among different meteorite types have been noted not just based on size, but compositions as well. Can the authors provide any discussion of those qualities to provide context of how the Bennu et al. CAIs compare to others in the meteorite record?

Finally, it's worth pointing out that planets are not the only way to produce pressure bumps in a protoplanetary disk that may halt drift of solids.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

From a general standpoint, the authors have taken into account the reviewers' comments. I still have a few minor comments that should be addressed before acceptance.

1. I think the possibility that CI chondrites accreted late in the outer disk (regardless of the exact heliocentric distance; e.g., Spitzer et al., 2024) should be acknowledged in the abstract.
2. It has recently been proposed that CI phyllosilicates could be related to disk processes (Viennot et al., 2025, EPSL). This should at least be mentioned.
3. Why do OC CAIs support mechanisms similar to those proposed for Bennu/Ryugu? OC CAIs show 50Ti–54Cr excesses (Ebert et al., 2018) and likely originate from outer reservoirs. This implies that they crossed the barrier and thus experienced inward drift.
4. I agree that CAIs are unlikely to constitute major components of CI chondrites, but AOAs with solar-like chemical compositions (Jansen et al., 2024, EPSL; Toranno et al., 2024, EPSL) could.

Reviewer #3

(Remarks to the Author)

I am grateful for the work the authors have done to address the comments that I and the other referees raised on the first draft of this manuscript. I believe they have put significant work into addressing them and the paper is improved as a result.

Two issues that occur to me in looking at the revised paper and the response to the referees that I believe need to be addressed for completeness and to provide proper context. The first relates to my comment that the authors may consider time in addition to location as setting the environment in which Bennu and CI chondrites formed and how they are different from other carbonaceous chondrites. The authors say in response to my original comment, that the CIs could not have formed at a later time in the pressure trap outside of Jupiter because that's where the CAIs and AOAs would have been

preferentially concentrated in the disk. While this is true, the authors seem to assume that there is an infinite supply of these objects to the pressure bump, when in reality, there is a finite population of these objects in the disk. If the CAIs and AOs concentrate in the pressure bump, particularly early on, then the early formed planetesimals will have these objects in abundance, and as these planetesimals form, the amount remaining in the disk will decrease, meaning later formed planetesimals would have lower abundances or none of these objects. So one need not have them form elsewhere to avoid incorporating large inclusions; they just need the inclusions to have been contained in earlier formed planetesimals, so that later ones would not have them.

Also, I must take issue with the authors saying that one can make the argument Ryugu accreted earlier than other CC parent bodies based on published work saying they formed ~2 Myr after CAI formation. The Nakamura et al. paper that the authors cite to support their argument has large uncertainties, saying that they estimate the formation to have occurred 1.8-2.9 Myr after CAI formation; a range that exceeds 50% of the total age the authors cite (the authors, for some reason, only consider the lowest values of this range). The authors cannot say with any certainty based on available measurements and model uncertainties that one class of bodies clearly accreted earlier as far as I can see, so they should not make such a claim.

The other issue that occurs to me is that the authors seem to favor the formation of the other CC parent bodies in the pressure bump of Jupiter due to the collection of the large inclusions in that region. I point the authors to the 2022 paper by Carrera and Simon in *Astrophysical Journal Letters* entitled, "The Streaming Instability Cannot Form Planetesimals from Millimeter-size Grains in Pressure Bumps." If the authors are going to claim that the CC parent bodies formed in that location of the disk, then they need to explain how the streaming instability (the cited favored mechanism for forming planetesimals in the paper) would work in this situation given the result of that paper. If the other CC's did not form in the pressure bump, that's fine, but then there's no explanation for the concentration of the larger inclusions as the authors discuss in the paper. This is contradictory and must be addressed.

If the authors can appropriately address these matters, I'm happy to see the paper published.

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Dear Editor,

Thank you very much for your editorial handling of our manuscript. We have revised our manuscript NCOMMS-26-006878-T, entitled “Refractory inclusions in Bennu samples indicative of outer Solar System accretion”, in accordance with the comments and suggestions provided by the three reviewers. All points raised have been addressed in the revised manuscript, and we provide detailed responses to each comment below.

Response to the reviewer #1’s comments

The manuscript “Refractory inclusions in Bennu samples indicative of outer Solar System accretion” by Kawasaki et al. is well written and would make a strong contribution to Nature Communications. In particular, the extensive and rigorous petrographic and isotopic analyses of refractory inclusions from returned asteroid samples represents a unique contribution to the fields of planetary science and cosmochemistry that will also be of interest to a wider audience. I recommend acceptance of the manuscript for publication, with just a few minor comments listed below.

We thank Reviewer #1 for the positive and helpful comments on our manuscript. We have revised the manuscript accordingly and provide our point-by-point responses below.

Line 115-119, Line 165-166, and Fig. 4: A more thorough discussion comparing these Bennu inclusion results with the O isotope compositions of previously measured AOAs/CAIs would be beneficial. For example, it is mentioned that these Bennu inclusion compositions are consistent with other carbonaceous chondrites including CIs, but further discussion on this point would be useful. I understand that there are space constraints in a paper written in this format, but I would be interested to see if some minor compositional differences might be discerned (particularly if graphically represented in a figure showing the newly acquired data plotted with literature data). Also, some important references on the topic of AOAs (including O isotope compositions) are not included (e.g., Krot et al. (2004) GCA and Krot et al. (2004) Chem de Erde). Some additional comparison with previously published data for inclusions from meteorites may strengthen the discussion. I am also curious whether the results of this work might provide the authors with the opportunity to discuss the formational relationship between chondrules, AOAs, and CAIs.

We thank the reviewer for this helpful comment. In response, we have added a new comparison

of the chemical compositions of olivine in CAIs and AOAs and isolated olivine grains from Benu, Ryugu, and the CI chondrite Ivuna, together with olivine in AOAs and chondrules from the most primitive carbonaceous chondrites, Acfer 094 and Yamato 81020 (Extended Data Fig. 5). This comparison supports the genetic relationships among olivine in AOAs and CAIs, as well as ^{16}O -rich isolated olivine grains, in Benu, Ryugu, and Ivuna, and also with olivine in AOAs from carbonaceous chondrites.

Regarding the O-isotope compositions, olivine grains in AOAs from Benu, like those in previously studied samples, are consistently ^{16}O -rich, as already noted in the text. We therefore consider the current level of discussion to be sufficient for the purposes of this study. We have added the important reference suggested by the reviewer (Krot et al., 2004, *Chemie der Erde*) and added the following sentence: “...*olivine grains in the Benu AOAs are consistent with those of AOAs in carbonaceous chondrites, including CI (refs. 6,12,33,34: [Krot et al. 2004](#)). These olivine grains are also likely genetically related to ^{16}O -rich, isolated olivine grains in Benu, Ryugu, and CI chondrites (Kawasaki et al., 2022, 2025; Morin et al., 2022; Barnes et al., 2025; Russell et al., 2026).*”

In the present study, we confirmed the mineralogical, O-isotopic, and chronological similarities among CAIs and AOAs in Benu, Ryugu, and CI chondrites, as well as with those in ordinary and other carbonaceous chondrites. This supports the widespread occurrence of refractory inclusions in the accretion regions of chondritic planetesimals. However, we do not consider the present dataset to provide a sufficient basis for new discussion of the formation relationship between chondrules, AOAs, and CAIs.

Line 156: The word “of” in this sentence is unnecessary and should be deleted.

Line 190-192: The wording of this sentence is slightly confusing, and I recommend rewording it for clarity. Specifically, the statement, “These inclusions are also mineralogically, isotopically, and chronologically similar to those in ordinary and carbonaceous chondrites other than CIs...” could be misinterpreted to mean that they are not similar to those in CI chondrites, even though that is stated earlier in the paragraph. I think simply making a minor adjustment to this sentence would help make things clearer for readers. For example, “These inclusions are also mineralogically, isotopically, and chronologically similar to those in ordinary and other carbonaceous chondrites...”

We revised the text accordingly.

Figures: In all figures, but most noticeably Fig. 4 and Fig. 5, the resolution of the figures appears blurry when enlarged. I am not sure if this is because the images are compressed for the reviewer copy of the manuscript, but please make sure the figures are in high resolution in the proofing stage prior to publication.

We thank the reviewer for this comment. The apparent blurriness is likely due to compression of the reviewer PDF generated by the submission system. The original figure files are of sufficiently high resolution.

Response to the reviewer #2's comments

This study investigates the chemical and oxygen isotopic compositions of CAIs and AOAs in the Bennu samples brought back by the OSIRIS-REx space mission. Chronological data are also reported thanks to ^{26}Al - ^{26}Mg measurements. From a general manner, the paper is pleasant to read and the data are robust. I have however the feeling that some key assertions should be better detailed and alternative possibilities should be also considered. In any case, the paper should be published after major revisions.

We thank Reviewer #2 for the careful reading of our manuscript and for the constructive comments. We have revised the manuscript accordingly and provide our point-by-point responses below.

1- A key observation is that CI chondrites represent an endmember of the CC field in multi-isotopic space. This is observed for Cr–Te (Hellmann et al., 2020, EPSL), Rb–Te and Rb–Zn (Nie et al., 2021, Science Advances), and Fe–Te (Marrocchi et al., 2023, ApJ Letters). This has been interpreted as reflecting (i) the ubiquitous presence of CI-like dust throughout the carbonaceous reservoir and (ii) CI-like dust representing the matrix component of carbonaceous chondrites. In this scenario, CI-like dust would have been distributed throughout the outer disk. This interpretation appears to contradict that proposed by the authors. This discrepancy should be discussed, and this alternative scenario should be considered.

We thank the reviewer for this important comment. We first note that bulk isotopic data for Bennu

samples have not yet been published for the elemental systems mentioned here, with the exception of Zn (Barnes et al., 2025 *Nat. Astron.*), and therefore a direct evaluation of whether Benu occupies the same endmember position as CI chondrites in multi-isotopic space is not yet possible. Nevertheless, we understand the reviewer's broader point that previous bulk isotopic studies (Hellmann et al., 2020; Nie et al., 2021; Marrocchi et al., 2023) indeed suggest that CI-like dust was widespread throughout the carbonaceous reservoir and likely represented the matrix component accreted by carbonaceous chondrites. Our interpretation does not contradict this framework. In our interpretation, CI-like dust may have been widespread throughout the outer carbonaceous reservoir, while the relative proportions and size distributions of refractory inclusions varied among carbonaceous chondrite groups. In this sense, Benu, Ryugu, and CI chondrites do not represent an isolated reservoir distinct from other carbonaceous chondrites; rather, their parent planetesimals accreted dust populations with different size distributions through size-dependent migration and filtering in the disk.

To clarify this point, we have revised the related sentences and added the relevant references. The revised text now reads: *"These inclusions are also mineralogically, isotopically, and chronologically similar to those in ordinary and other carbonaceous chondrites, demonstrating the ubiquitous presence of refractory inclusions across chondritic astromaterials more broadly. Bulk isotopic systematics further indicate that CI-like dust was widespread throughout the region of the solar protoplanetary disk from which carbonaceous chondrites accreted (Hellmann et al., 2020; Nie et al., 2021; Marrocchi et al., 2023). Thus, parent planetesimals of carbonaceous chondrites shared at least some building blocks in common, though in different relative proportions, probably reflecting dust migration and filtering in the disk."*

2- The authors suggest that CI chondrites accreted through streaming instability in an environment distinct from that of other CCs. Alternatively, it has been proposed that CIs accreted via a different process triggered by photoevaporation during the final stages of the disk's lifetime (Spitzer et al., 2024, *Science Advances*). This mechanism would favor the accretion of small dust particles (and thus CAIs and AOAs), whereas streaming instability, in contrast, tends to promote the incorporation of larger inclusions. Such a process could also account for the pronounced isotopic heterogeneity of volatile elements (H and N) observed in CIs (Marrocchi et al., 2026, *Geochemical Perspectives Letters*). In what way do the data presented here specifically support an accretion scenario driven by streaming instability?

We thank the reviewer for this comment. In the scenario proposed in this study, the key process is the migration and filtering of dust in the disk, whereas the specific planetesimal-formation mechanism itself is of secondary importance. In this sense, our statement that “within this outer-disk environment, streaming instability may have played a role...” was intended broadly and encompasses cases in which streaming instability is triggered under different disk conditions, including photoevaporation-driven enhancement of the dust-to-gas ratio as discussed by Carrera et al. (2017 *ApJ*), which is the theoretical framework cited by Spitzer et al. (2024). In the scenario of Spitzer et al. (2024), photoevaporation is not itself the direct accretion mechanism; rather, following Carrera et al. (2017), it acts to remove gas and thereby trigger planetesimal formation by streaming instability. In our model as well, the critical point is that large refractory inclusions had already been preferentially removed from, or filtered out of, the CI-accreting region before planetesimal formation. Therefore, even if streaming instability preferentially concentrates larger particles, this is not problematic, because such particles were already scarce in the local reservoir available for accretion.

We have revised the Discussion and added the relevant references (Carrera et al., 2017 *ApJ*; Spitzer et al., 2024, *Sci. Adv.*) to read: “*Within this outer-disk environment, streaming instability may have played a role in assembling 100-km-scale parent bodies⁴², sweeping up fine dust particles that dominated the local solid reservoir, whereas larger inclusions had already been removed by rapid inward drift before the onset of streaming instability. This possibility is also compatible with scenarios in which streaming instability is triggered by photoevaporation-driven enhancement of the dust-to-gas ratio (Carrera et al., 2017; Spitzer et al., 2024).*”

3- The process responsible for transporting CAIs and AOAs to the outer regions of the disk remains unclear. It may involve viscous spreading or alternatively disk winds and outflows. None of the references cited by the authors (e.g., refs. 1–8, lines 45–47) directly address this issue, although it has been extensively discussed in a recent study (Morbidelli et al., 2024, *Astronomy & Astrophysics*).

We thank the reviewer for this comment. We have added the relevant reference (Morbidelli et al., 2024) to sentences of the Introduction “*Refractory inclusions, namely calcium-aluminium-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs), formed in high-temperature regions of the solar protoplanetary disk during its earliest stage and were subsequently transported to the accretion regions of chondritic planetesimals (refs.1-8; Morbidelli et al., 2024).*” and the

Discussion “*Refractory inclusions (CAIs and AOAs) formed in the high-temperature regions of the solar protoplanetary disk during its earliest stage and were subsequently transported across the disk to the accretion regions of various parent planetesimals (Morbidelli et al., 2024).*”

4- I struggle to understand how large-scale alteration by brines would not erase the micro-environments associated with CAI and AOA alteration. In addition, recent studies have revisited the condensation of phyllosilicates in the protoplanetary disk (e.g., Viennet et al., 2025, EPSL).

We do not consider large-scale brine formation at the planetesimal scale to be inconsistent with local heterogeneity in aqueous alteration. Spatial and temporal variations in water-to-rock ratio are entirely plausible, and such heterogeneity could preserve local micro-environments associated with CAI and AOA alteration. In particular, micro-pores generated during parent-body accretion would likely have produced local heterogeneity in water permeability, even if fluid circulation occurred on the scale of the entire body. Such heterogeneity may have been especially pronounced if the parent planetesimal accreted from pebbles. Evidence for such heterogeneity in water-to-rock ratio is also supported by lithology-dependent differences in mineral assemblages (this study; Connolly et al., 2025, *MaPS*; McCoy et al., 2025, *Nature*).

5- Claiming that most CCs contain large (> submillimeter-sized) CAIs and AOAs is an overstatement, as this is mainly the case for CV chondrites. In addition, the mean size of chondrules in CV, CO, and CM chondrites is larger than that of CAIs (May et al., 1999, LPSC abstract). Therefore, the assertion that only CIs accreted small CAIs and AOAs appears questionable. How do the authors reconcile this observation with their model?

We thank the reviewer for this important comment. We agree that the largest (centimeter-sized) CAIs and AOAs are most characteristic of CV chondrites. However, CAIs and AOAs larger than ~100 μm , which are absent from Bennu and Ryugu samples and from CI chondrites, have also been frequently reported from other carbonaceous chondrite groups (MacPherson, 2014 *Treatise on geochemistry*). In particular, AOAs in CO, CM, and CR chondrites commonly include clearly submillimeter-sized or larger objects (e.g., Krot et al., 2004 *Chemie der Erde*; Ushikubo et al., 2017 *GCA*; Larsen et al., 2020 *EPSL*; Fukuda et al., 2021 *GCA*), and in this respect they are distinct from Bennu, Ryugu, and CI chondrites. The key point in our argument is this contrast in the size distributions of CAIs and AOAs.

At the same time, we do not argue that small ($<100\ \mu\text{m}$) CAIs and AOAs are unique to Bennu, Ryugu, and CI chondrites. On the contrary, small CAIs and AOAs, including fragments, are also abundant in CV, CO, CM, and CR chondrites (e.g., Dunham et al., 2023 *MaPS*), and this is entirely consistent with our model. In our interpretation, small CAIs and AOAs that could survive inward drift toward the Sun over several million years should be present in all carbonaceous chondrite groups. The distinctive feature of non-CI carbonaceous chondrites is not the absence of such small inclusions, but the additional presence of larger ($>\text{submillimeter}$) CAIs and AOAs, which were likely trapped at a pressure bump. This point (common presence of small CAIs and AOAs in non-CI carbonaceous chondrites) was already implicit in our interpretation, but we agree that the manuscript did not state it explicitly enough and could therefore be difficult to follow in this respect.

To clarify this point, we have revised the Discussion and added the relevant references. The revised text now reads: “*Refractory inclusions (CAIs and AOAs) formed in the high-temperature regions of the solar protoplanetary disk during its earliest stage and were subsequently transported across the disk to the accretion regions of various parent planetesimals (Morbidelli et al., 2024). In Bennu samples analyzed thus far, as in those from Ryugu and CI chondrites^{13,14,19}, large ($>\text{submillimeter}$) refractory inclusions are absent. In contrast, inclusions larger than $\sim 100\ \mu\text{m}$, including submillimeter- to centimeter-sized objects, as well as numerous smaller inclusions, are common in non-CI carbonaceous chondrite groups (Krot et al., 2004; MacPherson, 2014; Ushikubo et al., 2017; Larsen et al., 2020; Fukuda et al., 2021; Dunham et al., 2023). CAIs in CM chondrites are mostly small ($<\sim 100\ \mu\text{m}$) (Dunham et al., 2023), whereas large ($>\sim 100\ \mu\text{m}$) AOAs are commonly observed (Krot et al., 2004; Kimura et al., 2020). This difference in size distribution could be explained by size-dependent dust migration in the disk (Fig. 5).*”

We have also revised the caption of Fig. 5 to read: “...*Parent planetesimals of most carbonaceous chondrites (CCs) other than CI are inferred to have formed within this dust-trapping region, incorporating both large and small refractory inclusions...*”

6- The authors should provide a figure showing $\Delta^{17}\text{O}$ versus trace element concentrations in the olivine they analyzed, and compare these data with those reported for CI chondrites, Ryugu samples, AOAs, and metal–olivine inclusions (for the latter, see e.g., Ebel et al., 2025, *MAPS*; Ochem and Marrocchi, 2026, *Icarus*).

We thank the reviewer for this suggestion. Instead of plotting $\Delta^{17}\text{O}$ against trace-element concentrations, we have added a new figure comparing the FeO and CaO contents of olivine in CAIs and AOAs and isolated olivine grains from Benu, Ryugu, and the CI chondrite Ivuna, together with olivine in AOAs and chondrules from the most primitive carbonaceous chondrites, Acfer 094 and Yamato 81020 (Extended Data Fig. 5). We consider this comparison to be more informative for the present discussion of Benu AOAs. By contrast, plotting $\Delta^{17}\text{O}$ against trace-element concentrations would not add substantial information in this case, because the reported $\Delta^{17}\text{O}$ values of AOA olivines are consistently restricted to a narrow range of approximately -23 to -24‰ (e.g., this study; Ushikubo et al., 2017 *GCA*; Fukuda et al., 2021 *GCA*; Kawasaki et al., 2022 *Sci. Adv.*; Kawasaki et al., 2025 *Commun Earth Env.*). We therefore do not consider such a plot necessary in the present study.

We have added the sentence to the Discussion: “These olivine grains are also likely genetically related to ^{16}O -rich, isolated olivine grains in Benu, Ryugu, and CI chondrites (Kawasaki et al., 2022, 2025; Morin et al., 2022; Barnes et al., 2025; Russell et al., 2026).”

We agree that AOAs and metal–olivine inclusions may have important genetic relationships. However, the focus of the present manuscript is on Benu AOAs and CAIs. We therefore consider a detailed comparison with metal–olivine inclusions to be beyond the scope of the present study, and leave this as a subject for future work.

7- Lines 176-178. Why the authors did not consider the possibility of alteration-induced isotopic exchange? (see recent review by Krot et al., 2025, space science review).

We did not consider alteration-induced O-isotope exchange to be a likely explanation for the Benu CAI, because the aqueous-alteration temperatures experienced by Benu’s parent body were very low ($<100^\circ\text{C}$; Zega et al., 2025 *Nat. Geosci.*). Under such conditions, diffusion-controlled O-isotope exchange of the kind proposed for CAI minerals in thermally metamorphosed chondrites (Krot et al., 2025) is highly unlikely. Rather, the similar chemical compositions and ^{16}O -poor isotope compositions of Al-Ti diopsides in CV CAIs and in the Benu CAI suggest that ^{16}O -poor compositions of Al-Ti diopsides are more likely to preserve primary signatures acquired prior to accretion.

8- I am surprised that the authors did not consider the work of Hellmann et al. (2023, *ApJ Letters*),

who show that the abundances of refractory inclusions and chondrules are coupled and systematically decrease with increasing matrix abundance. They propose that these correlated variations reflect the trapping of chondrule precursors, including refractory inclusions, in a pressure maximum in the disk. This model has important implications for the scenario proposed here and should therefore be discussed.

We had not cited Hellmann et al. (2023) because one of the assumptions underlying their model, namely a correlation between matrix abundance and accretion age, may need to be reconsidered in light of recent studies suggesting that the parent bodies of Ryugu and CI chondrites formed within ~ 2.0 Ma after CAI formation (Nakamura et al., 2023 *Science*; Arakawa et al., in press, *EPSL*). Indeed, Hellmann et al. (2023) themselves noted that Ryugu and C1-ungrouped parent bodies may have accreted earlier than expected, and cautioned that this issue requires further consideration.

That said, we agree that their model has important implications for our interpretation. In particular, Hellmann et al. (2023) also invoke trapping of larger dust, including refractory-inclusion- and chondrule-related material, at a proto-Jupiter-associated pressure bump to explain the differing proportions of refractory inclusions, chondrules, and matrix among chondrite groups. In this respect, their framework is broadly consistent with our model.

We thank the reviewer for pointing out this important connection. We have now cited Hellmann et al. (2023) in the revised manuscript (Fig. 5 caption).

9- I struggle to fully understand the model presented here. If I understand correctly, CAIs and AOAs condensed in the inner disk and were subsequently transported to the outer disk. Small CAIs and AOAs would have escaped inward drift and remained in the outer CI-accreting region. If so, it should be acknowledged and discussed that small CAIs and AOAs are also observed in CM, CO, and CV chondrites. Conversely, larger CAIs and AOAs would have drifted inward and been trapped at a pressure bump. In that case, what is the origin of the CAIs and AOAs observed in ordinary chondrites, which the authors claim are similar to those found in CIs?

We thank the reviewer for this important comment. We agree that small CAIs and AOAs are also present in CM, CO, and CV chondrites. This point was already implicit in our interpretation, but it was not stated explicitly enough in the original manuscript and may therefore have been difficult to follow. We have revised the manuscript to make this point clearer, as noted in our response to

comment #5. This is fully consistent with our model. In our interpretation, small CAIs and AOAs that could survive inward drift over several million years should be present across a wide range of chondrite groups. The distinctive feature of Benu, Ryugu, and CI chondrites is therefore not the mere presence of small CAIs and AOAs, but the absence of larger (>submillimeter) inclusions that are additionally present in non-CI carbonaceous chondrites.

With regard to ordinary chondrites, we do not argue that their CAIs and AOAs require a separate origin. Rather, their mineralogical, isotopic, and chronological similarities to Benu inclusions indicate that at least some high-temperature refractory components were widely transported across the disk and incorporated into multiple chondrite-forming regions. In this sense, the occurrence of small refractory inclusions in ordinary chondrites is compatible with the same broad framework of early outward transport and subsequent size-dependent migration and filtering.

Response to the reviewer #3's comments

Overall, this is an interesting study reporting on the properties of refractory inclusions in Benu samples and comparison of those properties to other CC meteorites. It is found that the properties of the inclusions are most similar to those found in CI chondrites or Ryugu samples, which the authors then use to argue that this meant that the parent bodies of these objects (Benu, Ryugu, and CIs) formed in a distinct location in the solar nebula than the other carbonaceous chondrites; the latter of which is hypothesized to form in the pressure bump immediately outside of Jupiter's orbit.

The paper provides interesting measurements and results that will be of interest to a diverse audience. I do think the picture presented by the authors is a bit overly simplified and suggest some considerations below. These do not change the fundamentally interesting part of the paper (the observations and data) and only partly require a reconsideration of the speculations included at the end of the paper in regards to what this means. Should the authors address these points, then I think the paper would be worthy of publication in Nature.

We thank Reviewer #3 for the constructive and encouraging comments on our manuscript. We have revised the manuscript accordingly and provide our point-by-point responses below.

The major point that I would make here in regards to the interpretation of the data is that the authors immediately interpret the lack of inclusions larger than ~100 micron as being a sign that

Bennu (and others) formed in a different spatial location than the other carbonaceous chondrites which contain larger CAIs. I think this point needs to be discussed further. Firstly, are the sizes of the inclusions statistically different from those found in CM chondrites? CM meteorites generally have small CAIs of order tens of microns in size, with the occasional large one representing an extreme outlier on the tail end of the distribution. Given the amount of material that has been searched through with Bennu, Ryugu, and CI's, can we confidently say that the size distribution of the refractory inclusions is demonstrably different? CM meteorites generally have provided much greater amounts of samples to sort through (Murchison was nearly 100 kg!) than what we have in these rarer samples, so it's easier to sample the tale end of the distribution in these meteorites, possibly finding larger objects. I suggest looking at recent work by Dunham et al. 2023 (not referenced here) who compiled and reported sizes of CAIs in different meteorite types.

We thank the reviewer for this important comment. As the reviewer points out, CM chondrites do contain some CAIs larger than $\sim 100\ \mu\text{m}$, although most CAIs in CM chondrites are smaller. We therefore agree that, if CAIs alone are considered, the currently available data may not be sufficient to demonstrate a statistically robust difference between Bennu/Ryugu/CI and CM chondrites.

However, our discussion is based not only on CAIs but also on AOAs. Both CAIs and AOAs (refractory inclusions) are high-temperature, ^{16}O -rich condensates that formed under broadly similar nebular conditions and were subsequently transported to the lower-temperature accretion regions of Bennu, Ryugu, and CI chondrites. In the context of the dust migration and filtering discussed here, it is therefore appropriate to consider them together. In this respect, CM chondrites differ clearly from Bennu/Ryugu/CI because they commonly contain large AOAs, including submillimeter-sized and larger objects (Krot et al., 2004, *Chemie der Erde*).

To make this point clearer, we have revised the Discussion and added the relevant references. The revised text now reads: “*Refractory inclusions (CAIs and AOAs) formed in the high-temperature regions of the solar protoplanetary disk during its earliest stage and were subsequently transported across the disk to the accretion regions of various parent planetesimals (Morbidelli et al., 2024). In Bennu samples analyzed thus far, as in those from Ryugu and CI chondrites^{13,14,19}, large (>submillimeter) refractory inclusions are absent. In contrast, inclusions larger than $\sim 100\ \mu\text{m}$, including submillimeter- to centimeter-sized objects, as well as numerous smaller inclusions, are common in non-CI carbonaceous chondrite groups (Krot et al., 2004; MacPherson, 2014; Ushikubo et al., 2017; Larsen et al., 2020; Fukuda et al., 2021). CAIs in CM chondrites are mostly*

small ($<\sim 100\ \mu\text{m}$) (Dunham et al., 2023), whereas large ($>\sim 100\ \mu\text{m}$) AOAs are commonly observed (Krot et al., 2004; Kimura et al., 2020). This difference in size distribution could be explained by size-dependent dust migration in the disk (Fig. 5)."

Secondly, let's assume that the authors are correct in that the size distribution is different than CMs and all other CCs (this very well may be the case, my point above is just to strengthen the argument if it's true or to provide context). Another way of explaining this observation would be that Bennu and friends formed at a different time than all other CCs, but possibly not a different location. The authors make the point that drift of larger CAIs would deplete the very outer disk in those objects over time, leaving smaller objects behind to be incorporated into the CI/Bennu/Ryugu parent bodies. However, the same reasoning would suggest that the drift would be most effective for the larger objects, concentrating them somewhere and allowing them to be incorporated into planetesimals early on. In fact, this was an explicit prediction of Cuzzi et al. (2003; not cited) who looked at the redistribution of CAIs in the early solar nebula. As the big things get removed early, they leave small things behind to serve as the solids that get incorporated into later-formed planetesimals. This particularly makes sense if planetesimals form via processes like the streaming instability or other mechanisms which rely on solids having similar aerodynamic properties as one another to clump into planetesimals; as the gas dissipates from the solar nebula smaller objects behave more like larger objects at an earlier time.

We thank the reviewer for this important comment. We agree that differences in accretion timing may also have influenced the size distributions of refractory inclusions among chondrite groups. However, this does not alter our main conclusion that the parent bodies of Bennu, Ryugu, and CI-like materials accreted outside the influence of the proto-Jupiter dust trap. Proto-Jupiter is thought to have formed very early, within ~ 1 Ma after CAI formation (Kruijer et al., 2017 *PNAS*), and in that case the associated pressure bump (dust trap) would also have been present at an early stage. Therefore, because larger CAIs and AOAs would have been preferentially concentrated within the dust trap, our interpretation still requires that the parent body of CI-like materials accreted outside it in order to avoid incorporating such large inclusions. We also note that recent studies suggest that the parent bodies of Ryugu and CI chondrites formed within ~ 2.0 Ma after CAI formation (Nakamura et al., 2023, *Science*; Arakawa et al., in press, *EPSL*), and thus likely formed earlier than the parent bodies of other carbonaceous chondrite groups.

Question re: Figure 5: why is there no Saturn in the schematic? Saturn grew similarly to Jupiter, would have opened a gap, and would also have created a pressure bump outside of it. Are the authors saying that all CC parent bodies formed prior to the formation of Saturn or its core? If so, this should be discussed and evidence provided to support the argument.

From the observations presented in this study, we can conclude that the CI-like parent body accreted at least beyond the proto-Jupiter-induced dust trap. However, unlike the case of Jupiter (Kruijer et al., 2017, *PNAS*), there are currently no equally robust chronological constraints on the timing of Saturn's formation, and the size and location of dust traps produced by Jupiter and Saturn are model-dependent. Quantitative discussion of the effects of Saturn's formation timing and orbital location is therefore not currently possible and is beyond the scope of the present study. We agree that this is an important issue for future work.

Lines 219-220: "Formation beyond the dust-trapping region of the pressure bump, and the paucity of large refractory inclusions, are consistent with the chemically primitive nature of Bennu." I don't understand this sentence. Why is the paucity of large refractory inclusions a sign of chemical primitiveness? My understanding of meteorite classification based on alteration is that it thermal and aqueous alteration is characterized by various properties but the sizes of the constituents are not among them. Are CV chondrites less chemically primitive than CM chondrites because they have bigger chondrules and CAIs? Further, why does "formation beyond the dust-trapping region of the pressure bump" mean anything related to the chemically primitive nature of the samples? This reads a bit like an unnecessary sales-job rather than a scientific argument of conclusion following evidence.

We thank the reviewer for this important comment. By "chemically primitive," we refer to bulk chemical compositions that remain close to solar abundances (e.g., Yokoyama et al., 2023 *Science*), rather than to the degree of aqueous alteration or thermal metamorphism. In this sense, the paucity of large refractory inclusions is relevant because Bennu samples do not show the refractory-element enrichment characteristic of many other carbonaceous chondrite groups (Lauretta et al., 2024 *MaPS*; Barnes et al., 2025 *Nat. Astron.*). Indeed, it has been estimated that the addition of only ~0.5 mol% CAIs would be sufficient to shift CI compositions away from solar values (Frank et al., 2023, *MaPS*). Therefore, if Bennu's parent planetesimal had formed within a dust trap that efficiently concentrated large refractory inclusions, its chemically primitive,

near-solar bulk composition would be difficult to preserve.

We agree that this point was not explained clearly enough in the original manuscript. We have therefore revised the related sentence and added the relevant reference. The revised sentence now reads: *“The formation of Bennu’s parent planetesimal beyond the dust-trapping region of the pressure bump, together with the paucity of large refractory inclusions, is consistent with Bennu’s chemically primitive nature (i.e., a near-solar bulk composition)^{15,16}, because even minor addition of CAI-like refractory material would shift Bennu’s bulk composition away from solar values (Frank et al., 2023).”*

A further note: differences in CAIs among different meteorite types have been noted not just based on size, but compositions as well. Can the authors provide any discussion of those qualities to provide context of how the Bennu et al. CAIs compare to others in the meteorite record?

In this study, we compare the mineral chemistry, oxygen-isotope compositions, and Al–Mg chronologies of Bennu CAIs and AOAs with those of CAIs and AOAs from carbonaceous and ordinary chondrites, as well as CI chondrites and Ryugu samples. Based on these comparisons, we conclude that Bennu refractory inclusions are mineralogically, isotopically, and chronologically similar to those in other chondritic materials, and we therefore believe that the manuscript already includes sufficient discussion of these compositional relationships.

The relevant paragraph now reads: *These mineralogical, isotopic, and chronological similarities among refractory inclusions in Bennu samples, Ryugu samples, and CI chondrites provide evidence that their parent planetesimal(s) accreted a common suite, and likely similar relative abundances, of high-temperature refractory inclusions and their fragments. This suggests a close affinity in the primary building blocks of their parent planetesimal(s). These inclusions are also mineralogically, isotopically, and chronologically similar to those in ordinary and other carbonaceous chondrites, demonstrating the ubiquitous presence of refractory inclusions across chondritic astromaterials more broadly. Bulk isotopic systematics further indicate that CI-like dust was widespread throughout the region of the solar protoplanetary disk from which carbonaceous chondrites accreted. Thus, parent planetesimals of carbonaceous chondrites shared at least some building blocks in common, though in different relative proportions, probably reflecting dust migration and filtering in the disk.*

Finally, it's worth pointing out that planets are not the only way to produce pressure bumps in a protoplanetary disk that may halt drift of solids.

We thank the reviewer for this comment. We agree that planets are not the only possible source of pressure bumps in protoplanetary disks. Our intention was not to imply that proto-Jupiter was the unique cause of dust trapping, but rather to use it as one plausible example in the early Solar System. We have therefore revised the text to clarify this point. The revised sentence now reads: *“One plausible mechanism is the formation of gas pressure bumps, where large dust particles are locally trapped and prevented from drifting inward⁴¹. Although planets are not the only possible source of such pressure bumps, proto-Jupiter provides one plausible example in the early Solar System and could have concentrated submillimeter- to centimeter-sized refractory inclusions, accounting for their occurrence in carbonaceous chondrites other than CIs¹⁰.”*

Response to the reviewer #2's comments

From a general standpoint, the authors have taken into account the reviewers' comments. I still have a few minor comments that should be addressed before acceptance.

1. I think the possibility that CI chondrites accreted late in the outer disk (regardless of the exact heliocentric distance; e.g., Spitzer et al., 2024) should be acknowledged in the abstract.

We thank the reviewer for this comment. We consider late accretion of the parent bodies of CI chondrites to be implausible on chronological grounds. The ^{53}Mn – ^{53}Cr formation ages of dolomites in Ryugu and CI chondrites, measured using appropriate, matrix-matched standards (synthetic dolomite crystals; Sugawara et al., 2024; *GCA*), range from 2.0 (+0.6/–0.6) to 4.1 (+0.9/–0.8) Ma after CAI formation (i.e., the formation of the first solids in the Solar System) (Sugawara et al., 2024 *GCA*; Kawasaki et al., *Science*, in press). According to thermal evolution models, the parent bodies of Ryugu and CI chondrites are inferred to have accreted earlier than 2.0 Ma regardless of the choice of age anchors (Arakawa et al., *EPSL*, in press; Kawasaki et al., *Science*, in press). These inferred accretion ages are older than those of other carbonaceous chondrite groups such as CM, CR, and CV, in which carbonates and secondary silicates formed at ~3–5 Ma and whose accretion ages are inferred to be ~2.5–4 Ma (Doyle et al., 2015, *Nat. Commun.*; Lee et al., 2025, *Space Sci. Rev.*). Therefore, late accretion of the parent bodies of CI chondrites is not supported by the available chronological evidence, and we do not consider it necessary to introduce this possibility into the Abstract. However, we note that we have already mentioned in the Discussion the scenario proposed by Carrera et al. (2017) and Spitzer et al. (2024), in which streaming instability is triggered by photoevaporation-driven enhancement of the dust-to-gas ratio, as one possible mechanism of accretion in the outer disk.

2. It has recently been proposed that CI phyllosilicates could be related to disk processes (Viennet et al., 2025, *EPSL*). This should at least be mentioned.

Viennet et al. (2025) investigated the CI chondrite Orgueil, and whether that interpretation can be applied to Bennu remains uncertain and will require future study.

3. Why do OC CAIs support mechanisms similar to those proposed for Bennu/Ryugu? OC CAIs show ^{50}Ti – ^{54}Cr excesses (Ebert et al., 2018) and likely originate from outer reservoirs. This implies that they crossed the barrier and thus experienced inward drift.

Ebert et al. (2018) showed that CAIs from ordinary (OC), CO, and CV chondrites have similar ^{50}Ti excesses, and thus share a common isotopic reservoir. They also discussed the possibility that a limited number of small CAIs crossed the gap created by proto-Jupiter and were incorporated into OCs. This interpretation is consistent with our view that small refractory inclusions could be distributed widely across the disk, whereas the presence or absence of larger inclusions reflects size-dependent migration and filtering.

4. I agree that CAIs are unlikely to constitute major components of CI chondrites, but AOAs with solar-like chemical compositions (Jansen et al., 2024, EPSL; Toranno et al., 2024, EPSL) could.

We thank the reviewer for this important comment. We agree that, from the perspective of chemical composition alone, AOAs with near-solar compositions could in principle constitute a significant component of CI-like materials. However, AOAs are characterized by ^{16}O -rich O-isotope compositions, as also shown for the Bennu AOAs in the present study. If AOAs had constituted a major component of Bennu, Ryugu, or CI chondrites, it would be difficult to reconcile this with their bulk O-isotope compositions. We therefore agree that AOAs are chemically distinct from CAIs in this respect, but do not consider them likely to have been a major component of the bulk material.

Response to the reviewer #3's comments

I am grateful for the work the authors have done to address the comments that I and the other referees raised on the first draft of this manuscript. I believe they have put significant work into addressing them and the paper is improved as a result.

Two issues that occur to me in looking at the revised paper and the response to the referees that I believe need to be addressed for completeness and to provide proper context. The first relates to my comment that the authors may consider time in addition to location as setting the environment in which Bennu and CI chondrites formed and how they are different from other carbonaceous chondrites. The authors say in response to my original comment, that the CIs could not have formed at a later time in the pressure trap outside of Jupiter because that's where the CAIs and AOAs would have been preferentially concentrated in the disk. While this is true, the authors seem to assume that there is an infinite supply of these objects to the pressure bump, when in reality, there is a finite population of these objects in the disk. If the CAIs and AOAs concentrate

in the pressure bump, particularly early on, then the early formed planetesimals will have these objects in abundance, and as these planetesimals form, the amount remaining in the disk will decrease, meaning later formed planetesimals would have lower abundances or none of these objects. So one need not have them form elsewhere to avoid incorporating large inclusions; they just need the inclusions to have been contained in earlier formed planetesimals, so that later ones would not have them.

Also, I must take issue with the authors saying that one can make the argument Ryugu accreted earlier than other CC parent bodies based on published work saying they formed ~ 2 Myr after CAI formation. The Nakamura et al. paper that the authors cite to support their argument has large uncertainties, saying that they estimate the formation to have occurred 1.8-2.9 Myr after CAI formation; a range that exceeds 50% of the total age the authors cite (the authors, for some reason, only consider the lowest values of this range). The authors cannot say with any certainty based on available measurements and model uncertainties that one class of bodies clearly accreted earlier as far as I can see, so they should not make such a claim.

We thank the reviewer for this important comment. We agree that late accretion of the parent bodies of Ryugu and CI chondrites could in principle account for the absence of large refractory inclusions, if such inclusions had already drifted toward the proto-Sun and/or been trapped at pressure bumps and incorporated into earlier-formed planetesimals. However, later accretion of the parent bodies of Ryugu and CI chondrites is not supported by the current chronological evidence. We recognize that our previous explanation was not sufficiently clear, and therefore we explain here the current chronological constraints on Ryugu and CI chondrites in more detail.

Nakamura et al. (2023, *Science*) proposed, on the basis of thermal modeling, that the parent body of Ryugu accreted 1.8 Ma (for a planetesimal with $W/R = 0.9$) to 2.9 Ma ($W/R = 0.2$) after CAI formation, using the inferred precipitation age of 5.2 Ma for Ryugu dolomite (Ca–Mg carbonate) measured by Yokoyama et al. (2023, *Science*). However, Yokoyama et al. determined the ^{53}Mn – ^{53}Cr formation age of Ryugu dolomite using a calcite (Ca carbonate) standard, which is now recognized to yield an analytically younger apparent age because of the different correction factor for Mn/Cr ratios in secondary ion mass spectrometry analyses (Sugawara et al. 2024, *GCA*). Sugawara et al. prepared appropriate matrix-matched standards (synthetic dolomite crystals) and reevaluated the Ryugu dolomite age, obtaining 4.1 Ma, i.e., 1.1 Ma older than the age reported by Yokoyama et al.; they also obtained an age of 2.9 Ma for dolomite in the CI chondrite Ivuna. In addition, an older dolomite age of 2.0 (+0.6/–0.6) Ma has been identified in another Ryugu

particle (Kawasaki et al., *Science*, in press). According to thermal evolution models based on these refined dolomite ages, the parent bodies of Ryugu and CI chondrites are inferred to have accreted **earlier than 2.0 Ma** (Arakawa et al., *EPSL*, in press; Kawasaki et al., *Science*, in press).

These inferred accretion ages appear older than those of other carbonaceous chondrite groups such as CM and CR, in which carbonates formed at ~3–5 Ma and whose accretion ages are inferred to be ~3–4 Ma (Fujiya et al., 2012, *Nat. Commun.*; Lee et al., 2025, *Space Sci. Rev.*). Likewise, CV chondrites, which contain abundant large refractory inclusions, have been inferred to have accreted at ~2.5 Ma after CAI formation based on the formation age of fayalite (Doyle et al., 2015, *Nat. Commun.*). Therefore, later accretion of the parent bodies of Ryugu and CI chondrites than those of other carbonaceous chondrite groups containing large refractory inclusions is not supported by the currently available chronological evidence.

We agree that this discussion should be incorporated into the manuscript. We have added the following sentences: *“If the parent planetesimal(s) of Ryugu and CI chondrites accreted later than those of other carbonaceous chondrite groups containing large refractory inclusions, the refractory inclusions remaining in the disk would have been predominantly small, and such later accretion could in principle account for the absence of large refractory inclusions in Ryugu and CI chondrites. However, their parent planetesimal(s) are inferred to have accreted earlier than 2.0 Ma after the formation of the canonical CAIs (Arakawa et al., 2026; Kawasaki et al., 2026), earlier than the inferred accretion ages of other carbonaceous chondrite parent bodies (Fujiya et al., 2012; Doyle et al., 2015; Lee et al., 2025). These chronological relationships support formation beyond the dust-trapping region associated with proto-Jupiter.”*

The other issue that occurs to me is that the authors seem to favor the formation of the other CC parent bodies in the pressure bump of Jupiter due to the collection of the large inclusions in that region. I point the authors to the 2022 paper by Carrera and Simon in *Astrophysical Journal Letters* entitled, "The Streaming Instability Cannot Form Planetesimals from Millimeter-size Grains in Pressure Bumps." If the authors are going to claim that the CC parent bodies formed in that location of the disk, then they need to explain how the streaming instability (the cited favored mechanism for forming planetesimals in the paper) would work in this situation given the result of that paper. If the other CC's did not form in the pressure bump, that's fine, but then there's no explanation for the concentration of the larger inclusions as the authors discuss in the paper. This is contradictory and must be addressed.

We thank the reviewer for this important comment. We believe there may be some misunderstanding on this point. In the manuscript, we do not argue that streaming instability operated within the proto-Jupiter pressure bump to form the parent bodies of other carbonaceous chondrites. Rather, our interpretation is that the pressure bump acted as a dust trap for larger refractory inclusions, whereas streaming instability may have played a role in forming the parent bodies of Bennu, Ryugu, and CI chondrites in the outer-disk environment beyond the influence of the proto-Jupiter-associated dust trap.

To clarify this point, we have revised the relevant sentence to read: “*Within this outer-disk environment beyond the dust-trapping region associated with proto-Jupiter, streaming instability may have played a role in assembling 100-km-scale parent bodies⁵⁶, sweeping up fine dust particles that dominated the local solid reservoir, whereas larger inclusions had already been removed by rapid inward drift before the onset of streaming instability and/or had been concentrated near the proto-Jupiter pressure bump.*”

If the authors can appropriately address these matters, I'm happy to see the paper published.

We hope that the revised manuscript is now suitable for publication.