Response letter – Anonymous Referee #1

Comments of reviewers in black, author responses in blue

This paper presents a large number (n > 150) of MC-ICP-MS U-series dating of stalagmites from a cave in the northeastern Yucatán Peninsula, Mexico. These stalagmites are particularly important because they cover the entire period of Maya cultural evolution and can be used to reconstruct a continuous, high-resolution climate record over the past 2700 years. These samples are characterized by high U and low Th concentrations, which is generally favorable for precise U-series dating. However, dating results reveal significant age inversions. These inversions are attributed to elevated initial 230Th/232Th ratio, ranging from 4 to 68, as estimated through multiple approaches, including U-series dating of modern carbonate and drip water, isochron analyses, stratigraphic constraints, and lamina counting. This paper demonstrates the potential of large variations of initial 230Th/232Th ratio in speleothem, which may pose a substantial challenge for accurate U-series dating. I think this is well-organized study supported by convincing evidence.

We thank referee #1 for taking the time to review our manuscript and their overall positive feedback.

My major comments are given below:

- The study focuses on stalagmites from Áaktun Kóopo Cave, located in the northeastern Yucatán Peninsula, and cites several other stalagmites records from elsewhere on the Peninsula. Is the elevated initial 230Th/232Th ratio specific for Áaktun Kóopo Cave, or does it reflect a regional characteristic?

We thank Referee #1 for this important question. Elevated and highly variable R02i, like those observed in Áaktun Kóopo' Cave, are not unique to this site. Previous studies from the Yucatán Peninsula have already reported similarly high initial ratios based on isochrons or stratigraphic constraints, drip water and zero-age carbonate (e.g., Ridley et al. (2015); Moseley et al. (2015); Kennett et al. (2022); Stinnesbeck et al. (2020)). However, systematic, cave-by-cave surveys are still sparse, so it is not yet possible to map this behavior at the scale of the entire peninsula. Nevertheless, the existing evidence strongly suggests that elevated and temporally variable R02i, is a regional characteristic of many (sub-) tropical karst systems, rather than a peculiarity of Áaktun Kóopo' alone. We now highlight this point more clearly in the revised conclusions by adding the sentence:

"Considering the vast number of other studies suggesting high and variable R02i ratios in (sub-) tropical caves, we expect that this could be a characteristic of other, comparable cave systems." (L572)

In addition, we will change the statement in L73 of the introduction to:

"*These observations highlight the need for more systematic assessments of initial Th variability when correcting ^{230}Th/U ages from such environments*."

- Samples with (^{230}Th/^{232}Th) activity ratio <200 were excluded from age modeling, and their corrected ages are not presented in Table S3. However, their initial (^{230}Th/^{232}Th) activity ratios are still presented. I suggest either presenting both the corrected ages and the initial

values, or removing both sets of values. In the main text, the initial ($^{230}Th/^{232}Th$) activity ratios are reported between 4 and 68, but the corrected ages corresponding the higher initial values (>50) were discarded. Does this imply that the derived high initial values (>50) are unreliable?

We thank Referee #1 for this careful observation. Samples with ($^{230}Th/^{232}Th$) < 200 were excluded from age-depth modelling because the age uncertainty for these highly Th-contaminated samples is dominated by the poorly constrained initial Th correction, so their corrected ages would not add meaningful information to the chronologies. For this reason, we do not report their corrected ages in Table S3.

We nevertheless report the corresponding initial ($^{230}Th/^{232}Th$) activity ratios for all dated samples, including those excluded from modelling, because these ratios themselves help to characterize the range and variability of initial Th in the system. In other words, for low ($^{230}Th/^{232}Th$) samples the corrected ages are not considered robust, but the inferred R02i values still provide qualitative evidence that very high initial ratios can occur.

Regarding the highest initial ratios (>50), these mostly arise in strongly Th-contaminated samples with large, propagated age uncertainties, so the exact numerical values are not tightly constrained and should be interpreted with caution. However, the fact that independent approaches (isochrons, stratigraphic constraints, and layer-counted chronologies) all require elevated initial ($^{230}Th/^{232}Th$) to restore stratigraphic order indicates that high initial values are plausible and likely necessary. To avoid misunderstanding, we will clarify in the Methods/Supplement that (i) samples with ($^{230}Th/^{232}Th$) < 200 are excluded because their ages do not add value to the age models, and (ii) the reported initial ratios for these samples are used only to illustrate the range of initial Th contamination, not as precise constraints on individual ages. In detail, we will change the last paragraph in section 4.1 to

"Given the difficulty in accurately constraining R02i, all samples with ($^{230}Th/^{232}Th$) ratios <200 (n=68) were excluded from the age–depth modelling and from further chronological interpretation (Figure 2b), because for such highly Th-contaminated samples the propagated age uncertainty is dominated by the initial Th correction and does not add meaningful information to the chronologies. This criterion also applies to all samples within 7.5 mm of the stalagmite tops, which are generally highly contaminated and have limited ^{230}Th ingrowth."

In addition, we will add the following statement to the end of 4.1.1:

"Taken together, these independent approaches indicate that strongly elevated initial Th activity ratios are plausible and necessary at least in parts of the record to obtain stratigraphically consistent age models, even though the exact numerical values of R02i for individual, highly contaminated samples remain poorly constrained."

In addition, we will add a clarifying statement in the caption of Table S3:

"For samples with ($^{230}Th/^{232}Th$) < 200, corrected ages are not reported, because age uncertainties are dominated by initial Th correction and do not constrain the chronologies. The corresponding initial ($^{230}Th/^{232}Th$) ratios are shown only to illustrate the range of initial Th contamination and should not be treated to calculate ages for individual samples."

- The sample EO-C-81.5 has the lowest Th concentration (~0.00013 ppb) and the highest (230Th/232Th) activity ratios (213749), yet its corrected age is still not consistent with the stratigraphic order.

Thank you for spotting this. Indeed, the measurement E0-C-81.5 constitutes an outlier within the E0-C dataset: despite its very low ^{232}Th concentration and extremely high (^{230}Th/^{232}Th) activity ratio, the corrected age is not consistent with the surrounding stratigraphy. In line with our general strategy, this analysis was therefore excluded from the age–depth modelling and from any chronological interpretation. We retain the measurement only in the full analytical table for completeness, but do not use it to constrain the chronology or to infer initial Th systematics.

- In Table S3, there are two rows of data for sample E6-31.5 and three rows of data for E6-220. Are these replicated analyses? Given the challenging of the Áaktun Kóopo Cave samples, it would be beneficial to present replicate analyses to show the reproducibility.

Thank you for spotting this. The entries for stalagmite E6 in the original Table S3 mixed older and more recent measurements that had not yet been evaluated consistently with the rest of the dataset. We have now corrected Table S3 so that only the final, consistently processed results for E6-31.5 and E6-220 are reported, and we apologize for this oversight.

Regarding replicates: In fact, we tried repeat analyses in several key intervals, in particular within stalagmite E0-C. For example, we measured three samples at 75–77 mm depth, and in this case the resulting data agree within their analytical uncertainties. However, it was not always possible to obtain sufficient material at exactly the same depth (e.g., where growth rates are slow or variable), so replicated ages are only available for selected horizons rather than systematically throughout all stalagmites.

References

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