Authors’ response to Review 2

- Reviewer: Julien Amalberti
- Citation: https://doi.org/10.5194/egusphere-2025-3879-RC2

Note: The reviewer comments are presented in black print in their original, unabridged wording. The author’s response is displayed in blue.

Review of Maier et al. (submitted to Geochronology)

This manuscript describes a recent effort to develop in situ (U-Th-Sm)/He analytical methods and a modeling strategy applied to single apatite grains. The paper builds upon previous work by Danišík et al. (2017) and Glotzbach & Ehlers (2024), exploring specific analytical parameters such as ablation laser spot density, size, and location. The authors use natural apatite samples with both homogeneous and heterogeneous U-Th-Sm concentrations to evaluate their proposed in situ (U-Th-Sm)/He strategy. The manuscript also details the methodology used for both 4He measurement and parent nuclide analysis.

Results indicate that 4-6 laser spots, ranging from 20-30 µm in diameter, are sufficient to derive a 4He profile from 16 Ma apatite grains of approximately 145 µm. The authors recommend these parameters as the minimum analytical requirement for in situ (U-Th-Sm)/He analyses. They also combine 4He profiles along the c-axis (3-4 profiles per grain) with 3D reconstructions of radiogenic parent nuclide distributions to improve the accuracy of modelled thermal histories.

Overall, the paper is well written and easy to follow, but some sections lack sufficient methodological detail (see comments below). The methodology section would benefit from clearer descriptions to remove potential biases in the extracted He dataset. Moreover, the modeling approach would have been strengthened by including a case study using a well-characterized apatite standard (e.g., Fish Canyon Tuff or Durango) to test the validity of the authors’ strategy.

In addition, the study decouples the He pit locations from the parent isotope analyses by re-polishing the surface (of unknown thickness) between the 4He and U-Th-Sm analyses. To my knowledge, previous studies tend to perform parent isotope ablations within the same pits as 4He measurements (e.g., Pickering et al., 2020) to avoid losing spatial information during re-polishing. It would have been useful if the authors provided more justification for this approach (see comments below).

Nevertheless, this study represents a meaningful advancement in in situ (U-Th-Sm)/He methodology, particularly with the introduction of the new Caw parameter for parent nuclide correction at 4He ablation sites, which accounts for surrounding α-ejection effects. In my opinion, this is the most novel and valuable aspect of the study, as it tries to addresses 4He implementation influenced by α-ejection from zones of differing eU within the grain (see

Pickering et al., 2020, Fig. 8). Therefore, I consider this manuscript a valuable contribution to the advancement of in situ (U-Th-Sm)/He thermochronology.

Below I provide my main comments, followed by detailed comments. In summary, the paper is well constructed and represents a significant contribution, but requires clarification of several methodological aspects (particularly data acquisition and error handling) and would benefit from comparison to a well-known system for validation. I therefore recommend this manuscript for publication after revision.

We thank the reviewer for their time and careful review of our manuscript. The reviewer's main concern is a lack of sufficient methodological detail. Furthermore, they express the need for a better justification of methodological choices, particularly with respect to the re-polishing step between ^{4}He and parent nuclide measurements. Lastly, they point out the lack of analysis of a well-characterised standard material. We address these concerns in our answers to the main and detailed comments below. We are optimistic that our answers and suggested revisions to the manuscript will alleviate the reviewer's concerns.

We have numbered the reviewer comments (RC) and author responses (AR).

Main Comments

- **RC 1:** **Lack of comparison with a well-known system:** Although not critical, the study would be considerably strengthened by comparison with a well-characterized apatite system such as Fish Canyon Tuff (FCT) or Durango. FCT apatite, in particular, would be an excellent candidate given recent 4He/3He data from the distal (FCT-D) and classic (FCT-C) localities (Colleps et al., 2024). These samples provide a well-constrained framework (Renne et al., 1998; Reiners et al., 2002; Phillips & Matchan, 2013; Gleadow et al., 2015) encompassing both non-diffusive alpha-ejection-only (FCT-D) and more diffusive post-eruptive burial reheating (FCT-C) apatite behavior. Using such a reference material could effectively validate the authors' analytical and modeling strategy.
- **AR 1:** We agree with the reviewer that analysing a well-characterised standard material such as Fish Canyon Tuff (FCT) or Durango would have greatly improved the direct comparability of our approach to whole-grain (U-Th-Sm)/He and ^{4}He/^{3}He analyses.
  We did not analyse FCT or Durango, because the FCT grains available at our laboratory were too small for our analytical approach, while our Durango apatite material was too large to be analysed within a reasonable time and cost investment. Furthermore, FCT has been shown to exhibit significant parent nuclide zonation (e.g. Pickering et al. (2020) which disqualified it from being good validation material for our purposes.
  Against this background, we chose to use the Apatite-URG sample as validation material for our in situ approach, because it contained reasonably large, euhedral, clear and homogeneous crystals. Additionally, Apatite-URG (being sourced from

Miocene foiditic tuff and with an independently determined apatite U-Pb age (Binder et al., 2023) has a sufficiently simple and well-constrained expected cooling history. We suggest modifying Section 2.1 “Samples and Sample preparation” to explicitly explain and justify our choice in sample material and address the absence of well-characterised standards with the reasoning provided above.

- **RC 2: Decoupling of 4He and parent nuclide locations:** The authors performed parent nuclides measurements after re-polishing the apatite surface, but the thickness removed is not specified. I am concerned that their 3D reconstructions, built from an unknown removed material layer below the 4He spots, may miss critical information. A simple addition of analyzing parent nuclides directly within or immediately below the 4He pits could have provided a valuable internal check. These data would allow the authors to test whether their calculated Caw values are consistent with measured parent concentrations. Clarification and justification of this methodological choice are needed.
- **AR 2:** We thank the reviewer for this comment. We will expand Section 2.3 “Parent nuclide mapping” to include necessary details and justification for the repolishing step. Additionally, we will add annotations and a better depiction of this analytical step in Fig. 1.
    - We repolished the grain surface after the ^{4}He measurement to map the distribution of parent nuclides across the entire exposed internal grain surface, rather than only obtaining concentrations at the ^{4}He ablation sites. While it is theoretically possible to avoid repolishing the grain surface and instead measure the concentration of the parent nuclide in and around the ^{4}He ablation pits, doing so in practice presents challenges. Parent nuclide signals would originate from different depths within the grain (because the measurements do not start in a flat plane). This would require us to correct for ablation depth when constructing parent nuclide maps, because parent nuclide measurements from around the ^{4}He ablation pits would not reach the same depth in the grain as measurements conducted inside the ^{4}He pits, introducing another source of uncertainty.
    - To polish away the visible ^{4}He pit traces, we needed to remove a maximum of 10 µm, based on the maximum depth of the deepest pits. We were very careful during re-polishing and checked the state of the removal regularly to avoid removing too much material. Our re-polishing protocol was as follows: “Prior to parent nuclide measurements, the grains were polished for 3.5 h on a polishing machine at intervals of 4 to 20 min with a decreasing force from 20 to 10 N to remove the helium extraction pits and create an even surface for U, Th and Sm distribution mapping. The state of removal was checked multiple times during the process, and polishing was stopped as soon as all visible pit traces had been removed.” We will add this information to the methods section.

- **RC 3: Methodological transparency:** Several detailed comments below relate to blanks, uncertainties, and analytical procedures. Although the authors provide substantial data, key aspects of measurement uncertainty remain unclear, particularly where modeling results appear counterintuitive. Providing additional information on blank correction and error propagation would significantly improve the reproducibility and credibility of the dataset.
- **AR 3:** We will add the requested information.

Detailed Comments

- **RC 4: Line 101:** The authors mention acquisition of a 4He profile parallel to the c-axis, yet no such data are presented. Did this profile yield similar results to the perpendicular one? If so, it should be shown or discussed.
- **AR 4:** Thank you for bringing this to our attention. The data for the c-axis parallel profile are available in the supplementary material. We will refer to this in the text. We will also add sentences to the methods section explaining the reason for measuring the c-axis parallel profiles.
  - We measured a c-axis parallel profile to verify whether the ^{4}He concentrations were consistent in the grain along this direction. In retrospect, we realised the same information can easily be obtained by comparing the perpendicular profiles, making the c-axis parallel measurements superfluous. Hence, we don't display this data in the manuscript.
  - Geometric considerations for ^{4}He diffusion are different for c-axis parallel profiles. Thus, we did not attempt thermal modelling.

- **RC 5: Line 109:** 4He blanks are given in ncc, whereas Table 3 and Appendix B use atoms/g for 4He measurements. I strongly recommend using consistent units to avoid conversion errors. Reporting blanks in atoms or normalizing to ccSTP would be most appropriate.
- **AR 5:** We can convert the blanks to atoms. As atoms/g is the unit used for our inverse and forward modelling, we will continue using this unit for the tables and figures in the manuscript. The ^{4}He measurements are already reported both in ncc and in atoms/g in the supplementary data. We will refer to the supplementary material in the text.

- **RC 6: Line 111:** The blank correction error for successful 4He measurements is specified as 6–15%, corresponding to apatite URG and BaF in Table 2. The blanks reported by the authors range from 0.0003 to 0.0005 cc (or 8.07×106 to 1.35×107 atoms), yielding an average blank of 1.08×107 atoms ± 2.7×106 atoms (or 0.0004 ± 0.0001 cc). Assuming no additional error from the 4He content itself (not provided in the dataset), the propagated error based solely on the blank value would be approximately 14% for Ap-URG and 7–10% for Ap-BaF. Including the pit volume errors reported in Table 2 (~5% for URG and ~9% for BaF) increases the total 4He concentration uncertainty to roughly 15% for URG and 11–14% for BaF. These estimates, based on the average blank and its uncertainty using a weighted blank contribution factor (i.e., signal/blank ratio), are close to the authors' stated range of 6–15%, and even exceed the maximum 4He error reported for apatite BaF (<6%). This is without considering any analytical uncertainty associated with the laser ablation measurements. I therefore question how the authors derived their total error estimates. Furthermore, published RESOchron systems typically report 4He blank values between 3.2×107 atoms (0.0012 ncc; Evans et al., 2015) and 6.7×107 atoms (0.0025 ncc; Danišík et al., 2017), whereas the authors report significantly lower blanks (8×106 to 1×107 atoms, or 0.0003–0.0005 ncc). While I acknowledge that each analytical setup is unique and background levels can vary, it would be helpful if the authors provided additional details about their analytical protocol that could explain these notably lower 4He blank values. Finally, the authors report 1σ uncertainties on the measured in situ AHe ages ranging from 10% to 21% for both URG and BaF, yet my own propagation of the reported errors on 4He, 238U, 232Th, and 147Sm value (Table 3) yields roughly twice those values. It would therefore be useful if the authors detailed their analytical setup and blank correction procedure to explain these unusually low blank values and how final age uncertainties (10–21%) were propagated.

- **AR 6:** We have rechecked our blank levels and reviewed our calculations. We continue to obtain the same measurement uncertainties as reported in our manuscript. Below, we provide details on our analytical setup and the error propagation. We will include this information as a supplementary file to our manuscript.

- **In-situ (U-Th)/He Analytical Procedure**
  1. Mass Spectrometer Calibration

     Quantification of radiogenic ^{4}He extracted from individual laser pits relies on calibration against an internally monitored ^{4}He reference reservoir ("Q-tank"). The ^{4}He volume of the Q-tank is known but not constant: it undergoes predictable exponential depletion as Q-shots are consumed during routine analytical work. To maintain accuracy, the Q-tank is recalibrated at regular intervals, typically annually or after several thousand Q-shots, using a secondary reference reservoir ("D-tank"). The D-tank contains an independently certified amount of ^{4}He, externally calibrated by Des Patterson, and serves as the long-term stability anchor for all Q-tank recalibrations. Calibration factors derived from these intercomparisons are used to convert measured ion currents into absolute ^{4}He amounts in sample analyses.

2. Sample Loading and Preparation

Each sample mount is individually placed in an ultra-high-vacuum (UHV) laser cell and evacuated for a minimum of 24 hours to ensure that vacuum levels reach the low-pressure regime required for high-precision He analysis. In fact, our cold cathode was unable to measure the pressure since it reached values below the detection limit 1E-8 torr. Before analysing samples, several initial blank analyses are run until blank ^{4}He/^{3}He ratios reached values <0.0001. These blanks use the identical valve and volume configuration as the subsequent sample measurement, but without firing the laser.

3. Measurement Sequence Design

Because Q-shots yield extremely stable ^{4}He/^{3}He ratios (<1% variability) and analytical sequences are comparatively short (typically 20–40 analyses), each sequence begins and ends with two Q-shots. No Q-shots are included between samples to avoid flushing the line with high amounts of ^{4}He and potential memory effects. The ^{4}He content of Q-shots is 3–4 orders of magnitude higher than the He liberated during in-situ laser extraction. For this reason, the initial Q-shots are followed by 3–4 blank measurements to allow the system to return to pre-Q-shot blank levels. Sample measurements only begin once these blank values stabilize back to the initial baseline.

Blanks are measured frequently throughout the sequence. For the first three samples, a blank is run immediately before each measurement. As the system stabilizes, the number of sample analyses between blanks is gradually increased (from one, to two, three, four, and finally up to five), while maintaining sufficient blank coverage for accurate correction.

4. Blank Characterization and Correction

For each blank and sample measurement, ^{4}He/^{3}He ratios are calculated. During the Apatite-URG and Apatite-BaF analytical sessions, mean blank ratios and standard deviations were:

- 0.0000677±0.0000034 (Apatite-URG)
- 0.0000700±0.0000016 (Apatite-BaF)

With a Q-standard ^{4}He content of 10.69 ncc for these sessions, these ratios correspond to mean blank ^{4}He amounts of approximately:

- 0.000700±0.000046 ncc (Apatite-URG)
- 0.000757±0.000048 ncc (Apatite-BaF)

Blank correction for each sample is performed by subtracting the pre-sample blank ^{4}He/^{3}He ratio from the sample's measured ratio. This ensures that sample-derived radiogenic ^{4}He is isolated from procedural background contributions, and that time-dependent drift in blank characteristics does not introduce bias into the final (U-Th)/He age calculations.

5. Helium error propagation

All measured masses are measured during 10 individual cycles (i) that last in total roughly 50 sec, and the ratio (R43) between masses 4 (M4) and 3 (M3) of each run is calculated with:

$$R43_i = \frac{M4_i}{M3_i} \qquad \text{Eq. 1}$$

The mean and absolute standard deviation (SD) of the R43 measurement is calculated with:

$$\overline{R43} = \frac{1}{N}\sum_{i=1}^{N} R43_i \qquad \text{Eq. 2}$$

$$SD_{R43} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(R43_i - \overline{R43})^2} \qquad \text{Eq. 3}$$

The ^{4}He content of Q-shot j (number of Q-shot) is derived from the depletion factor (DF = 0.999899832 with SD = 4.26343E-6) and the ^{4}He content (11.098 ncc with SD = 0.011 ncc) determined for Q-shot 1000 with the following equation:

$$^4He_{Q_j} = {}^4He_{Q_{442}} DF^{(j-442)} \qquad \text{Eq. 4}$$

Accordingly, the absolute standard deviation is:

$$SD_{^4He_{Q_j}} = {}^4He_{Q_i}\sqrt{\left(\frac{SD_{^4He_{Q442}}}{^4He_{Q442}}\right)^2 + \left((j-1000)\frac{SD_{DF}}{DF}\right)^2} \qquad \text{Eq. 5}$$

To calculate the ^{4}He content of a sample, we have to know the ^{3}He content added to the sample. This is estimated based on the ^{4}He of nearby Q-shots ($^4He_{Qj}$). Accounting for a drift during measuring time we fit a spline-function to $^4He_{Qj}$. We used a Monte-Carlo approach to take into account the uncertainty of the $^4He_{Qj}$, and randomly sampled N-times $^4He_{Qj}$ data from a normal distribution (using the mean $^4He_{Qj}$ and corresponding standard deviations). Afterwards, we evaluate the N-times fitted functions at the measuring time of our samples and the resulting $^4He_{Qt}$ and SD at measuring time are:

$$^4He_{Qt} = \frac{1}{N}\sum_{i=1}^{N} f_i(t) \qquad \text{Eq. 6}$$

$$SD_{^4He_{Qt}} = {}^4He_{Qt}\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(f_i(t) - {}^4He_{Qt})^2} \qquad \text{Eq. 7}$$

Blank ratios R_{bl} are calculated with Eq. 1 and used to calculate blank-correct R43 sample measurements (R_{Sbc}) with:

$$R_{Sbc} = \frac{1}{N}\sum_{i=1}^{N}(R_i - R_{bl_i}) \qquad \text{Eq. 8}$$

Accordingly, the absolute standard deviation is:

$$SD_{R_{Sbc}} = R_{Sbc}\sqrt{\left(\frac{SD_{RS}}{R_S}\right)^2 + \left(\frac{SD_{Rbl}}{R_{bl}}\right)^2} \qquad \text{Eq. 9}$$

Where the sample and blank ratios and standard deviations have been calculated with Eq. 2 and 3. Finally, the ^{4}He content of a sample at time t is calculated with:

$$^{4}He_{Sbc_t} = R_{Sbc}\,\frac{^{4}He_{Q_t}}{R_{Q_t}} \qquad \text{Eq. 10}$$

Accordingly, the absolute standard deviation is:

$$SD_{\,^{4}He_{Sbc_t}} = \,^{4}He_{Sbc_t}\sqrt{\left(\frac{SD_{R_{Sbc}}}{R_{Sbc}}\right)^2 + \left(\frac{SD_{\,^{4}He_{Q_t}}}{^{4}He_{Q_t}}\right)^2 + \left(\frac{SD_{R_{Q_t}}}{R_{Q_t}}\right)^2} \qquad \text{Eq. 11}$$

4He concentration and uncertainty:

We divide the ^{4}He content ($^{4}He_{Sbc_t}$) by the ablation pit volume (V_{Pit}) to obtain the ^{4}He concentration (C_{He}). Finally, the pit volume uncertainty (SD_{VPit}) is propagated into the total measurement uncertainty for the ^{4}He concentration (SD_{CHe}) as follows:

$$SD_{CHe} = C_{He}\sqrt{\left(\frac{SD_{\,^{4}He_{Sbc_t}}}{^{4}He_{Sbc_t}}\right)^2 + \left(\frac{SD_{VPit}}{V_{Pit}}\right)^2} \qquad \text{Eq. 12}$$

- **AHe age calculation and uncertainties:**
  To calculate the AHe age and uncertainty we use the equations for the non-iterative solution to the age equation by Meesters & Dunai (2005).

- **RC 7: Line 122:** The re-polished thickness should be specified. By how much was the surface re-polished before parent isotope analysis?
- **AC 7:** We will add the requested details to the text. Please refer to **RC 2/AR 2,** where we have already elaborated in the repolishing procedure for detailed information.

- **RC 8: Line 178:** The authors note they cannot measure ablation spots within 40 µm of the rim due to potential 4He loss. This limitation could strongly affect the ability to model cooling histories, since rim regions often contain critical diffusional information (as in 4He/3He methods). Have the authors evaluated the potential impact of this constraint on slow-cooled samples?
- **AR 8:** We agree with the reviewer that the inability to calculate C_{aw} <40 µm from the grain rim is a major drawback of our approach.
  - We would like to note that the sentence in line 178, “*we chose not to calculate C_{aw} for ^{4}He ablation spots with centres <40 µm to the grain rim*,” refers only to C_{aw} calculation and consequently the ability to use the measurements for inverse modelling. We did not mean to state that we cannot or did not measure ^{4}He concentrations <40 µm from the grain rim. We recognise that this is worded confusingly in several places in the manuscript, and we will revise the relevant sections.

  - Although we cannot utilise the spots that are <40 µm from the grain rim in the inversion for thermal histories, we can still use them for misfit calculation and comparison between measured and forward-modelled ^{4}He profiles to ensure the inversion results are reasonable. We thus still use information from the rim region. We will emphasise this in the discussion and suggest adding annotations to both Figs. 2 and 6 to distinguish which spots were used for the inversion and which were used for forward modelling/misfit calculation.
  - For further discussion on thermal history modelling, please refer to RC 10/AR 10.

- **RC 9:** **Lines 209-214:** I am curious where the large 4He errors (>40%) originate. Based on the reported concentrations, apatite McClure appears to have 4He concentration ranging between the other two apatite grains, suggesting that each ablation pit should provide sufficient 4He for reliable analysis. However, the laser spot size for McClure (10 µm) is the smallest among the samples (BaF: 20 µm; URG: 30 µm), which could potentially explain the high uncertainties if the ablated volume, and thus the total 4He signal, was too low despite appropriate concentrations. Nevertheless, according to Appendix B (Table B1), the 4He concentrations measured in individual pits fall within the same range as those for URG and BaF. While the latter two samples display relatively low uncertainties (see also my previous comments regarding error propagation), apatite McClure exhibits unusually large errors. These discrepancies cannot be explained solely by 4He concentration or laser spot size, as the pit-by-pit 4He concentrations for McClure are intermediate between URG and BaF. In addition, the pit measurement error is reported at approximately 10% for 10µm laser spot size, which cannot account for the >40% uncertainties reported for McClure 4He concentrations. Could the authors clarify how these large errors were derived and identify the main contributing factors?
- **AR 9:** The large uncertainties for ^{4}He measurements in Apatite-McClure stem from the too small ablated volume, which in turn resulted in a too low ^{4}He signal. As the reviewer correctly noted, the ^{4}He concentration in Apatite-McClure is comparable to Apatite-URG. However, the ablation pit volume for Apatite-McClure was only ~7% of the ablation pit volume for Apatite-URG (see Table 2 in our manuscript). Keeping in mind that the ^{4}He concentration is the amount of ^{4}He in a specific volume (of apatite that was ablated), it follows that if the ablated volume is small, the ^{4}He content will also be small (assuming a constant ^{4}He concentration).
  Consequently, the ^{4}He signal that we measured for Apatite-McClure was much lower than that for Apatite-URG, even though the concentrations are comparable. In fact, for Apatite-McClure, the ^{4}He signal was so low that it was not significantly different from the blank level. Hence, the associated measurement uncertainty is very large. Kindly refer to AR 6 for details on error propagation. We will add a few sentences to clarify the reason for the high measurement uncertainty for Apatite-McClure in the manuscript.

- **RC 10: Figure 2:** For BaF-P2 and P4, some data points lie within 40 µm of the rim, contradicting the minimum distance limitation from the rim. How does this affect model results for these profiles (see comment line 178)? Does that be responsible for the lack of acceptable paths?
- **AR 10:** We have indeed measured ^{4}He at a distance of less than 40 µm from the grain rim (see AR 8).
  As the reviewer points out in RC 8, excluding spots less than 40 µm from the rims may result in the loss of crucial information. However, in terms of inverse modelling (which aims to minimise the misfit between predicted and observed data), having fewer constraints or data points to fit should make it easier for the model to find acceptable paths rather than harder. We thus do not think having to exclude spots (e.g. for being too close to the rim for C_{aw} calculation) is the reason for the lack of acceptable paths in Ap-BaF-P2 to Ap-BaF-P4.
  We observe that the un-invertible profiles Ap-BaF-P2 and Ap-BaF-P4 are significantly skewed and lack c-axis symmetry, while our inverse model is designed to operate under the assumption of c-axis symmetry. (The model is optimised for homogeneous grains.) The fact that the c-axis symmetric ^{4}He profile Ap-BaF-P1 could be successfully inverted suggests to us that the model design and the assumption of symmetry are critical factors. We will include a few additional sentences in Section 4.7 to clarify this point.

- **RC 11: Line 332:** The McClure 4He profile is not shown. Should this be included in supplementary materials?
- **AR 11:** We will remove sentences concerning Apatite-McClure from this section as they are not a main result.

- **RC 12: Line 334:** Spot size uncertainties (10-15%) appear inconsistent with volume errors reported in Table 3 (4-9%). Since pit volume depends on spot size, the propagated uncertainties should scale accordingly. Please clarify.
- **AR 12:** Thank you for bringing this to our attention. “Spot measurement uncertainties” refer to the ^{4}He measurement uncertainties, not to He ablation pit dimensions or ablation spot size. The wording in the sentence is misleading and will be rephrased.

- **RC 13: Line 335:** The text seems to conflate 4He measurement error and spot measurement error; numbers also differ from Table 2. Please clarify what each percentage refers to.
- **AR 13:** We will re-phrase these sentences as per our response to RC 12.

- **RC 14: Line 376:** The blank rejection criterion requires signals >3x blank according to the text. However, URG ablation pit data appear to fall below this threshold. For instance, for the Ap-URG-1 spot, the calculated 4He signal is 2.73×107 atoms (using an apatite density of 3.2×10-12 g/µm³), whereas the average blank reported by the authors is 1.08×107 atoms (or 0.0004 cc). Comparing the net 4He signal (after blank subtraction) with the blank value indicates that the measured signal is less than three times the blank. This relationship holds for all URG spots listed in Table 3, where signals are only slightly above twice the blank level. I suggest that the authors verify these calculations and discuss how this may affect the reported 4He uncertainties for the URG apatite.

- **AR 14:** We acknowledge that this is poorly worded in the text. We will revise it. For our measurement setup, we consider a signal significantly above 3x blank level and an SD <5% as ideal. However, we do not treat this as a strict rejection criterion. The reviewer is correct in their assessment that ^{4}He concentrations for Apatite-URG are less than 3x the blank level. We consider this still acceptable, but not ideal. Generally, the lower the ^{4}He signal and the closer to the blank level, the larger the associated measurement uncertainties. We report the ^{4}He measurement quality (whether the ^{4}He signal is >3x blank level or lower) in the supplementary information. For detailed equations, please refer to AR 6.

- **RC 15:** **Line 387:** What does "B1" refer to in Table 2?
- **AR 15:** This should read Table 2 and Table B1. We will fix this.

- **RC 16:** **Lines 422 - section 4.4:** The authors report an interesting and somewhat unexpected result in their modelled ages: the crystal cores yield younger ages, while the rims show older ages. This pattern is indeed counterintuitive. The authors suggest that this discrepancy might stem from the material removed during re-polishing between the 4He and parent nuclide analyses. However, it is unclear why they did not acquire additional data from the same layer as the 4He measurements, either directly within the initial laser spots (as done by Pickering et al., 2020) or from nearby locations. Such data could have provided a valuable cross-check to support the modelled Caw values. Because the thickness of the polished layer is not specified, it is possible that too much material was removed, potentially invalidating the 3D extrapolation at the actual 4He spot depth. A quick verification at or near the 4He ablation sites would have allowed the authors to confirm or adjust their model accordingly. As it stands, the observed age pattern is difficult to interpret and may indicate underlying issues with either the dataset or the modeling approach.
- **AR 16:** We kindly refer to RC 2/ AR 2 for the reasoning behind the re-polishing and the amount of material removed. We are unsure how measuring "directly within the initial laser spots (as done by Pickering et al., 2020)" as the reviewer suggests, would yield better information compared to our approach. Measuring "in" the ablation spot also means accessing information from below the ^{4}He ablation layer. This is nicely illustrated in Fig. 4 of Pickering et al. (2020). In our opinion, we do essentially retrieve information from the same layer as we would when ablating inside the ^{4}He pits.

  Further, in section 4.4, we initially aimed to highlight that the grinding and polishing required to expose the internal grain surface after Teflon mounting result in the loss of approximately half of the grain and thus lead to a significant loss of information for heterogeneous grains. We will clarify in section 4.4 which specific polishing step we are referring to.

- **RC 17:** **Line 482-483:** The comparison presented for the BaF model (Fig. 7b) would have been more informative if the modelled curves had included a zoned parent nuclide distribution rather than only a homogeneous system. As the authors correctly point out, a homogeneous model does not adequately represent this grain's characteristics. Incorporating a modelled zoned profile based on the observed 2D parent nuclide distribution would have provided a more meaningful test of whether the Caw correction significantly improves the model outcomes, since its benefit is not particularly evident in the homogeneous case.
- **AR 17:** Thank you for this good suggestion. We will add such a profile to Fig. 7b.

- **RC 18:** **Figure 7:** Why is the 5x5 µm grid model for URG not shown? Additionally, since increasing grid resolution seems to improve model outputs, it would be helpful to test finer resolutions (e.g., 1 µm) and discuss limiting factors.
  AR 18: We do not show a 5x5 µm grid model for Apatite-URG in Fig. 7, because we did not calculate one. We agree with the reviewer that a higher grid resolution appears to improve the model outputs. However, as Fig. 7a shows, the 10x10 µm grid model is already indistinguishable from the homogenous model within measurement uncertainty, and the misfits between modelled and measured 4He profiles are nearly the same. Hence, we do not see justification for generating even finer resolution maps for Apatite-URG. We will add this reasoning for the missing 5x5 µm grid model for Apatite-URG to the manuscript.
  Regarding the general testing of finer interpolation resolutions and their limiting factors, in our opinion, this should be addressed in a separate study. It is important to not only systematically test the interpolation resolution for parent nuclide maps, but also the combination of ablation spot size and interpolation grid resolution. This is beyond the scope of the manuscript.

- **RC 19:** **Line 510-512:** The authors claim that six laser spots are sufficient to reconstruct a simple, rapid cooling history with minimal or no parent nuclide zonation. However, for more complex and strongly zoned samples, it appears that only five laser spots (e.g., Ap-BaF-P1) were enough to produce acceptable time–temperature paths. I find this conclusion somewhat surprising and possibly overinterpreted. Could the authors clarify how five laser spots were sufficient in the more complex case, and whether this is supported by model sensitivity tests?
- **AR 19:** We will modify the text to clarify that the minimum number of spots needed for a ^{4}He profile is not strictly implied by our results. We will also add a paraphrased version of our explanation below to the manuscript.
  Generally, we recommend using as many points as possible to measure a ^{4}He profile.

As the reviewer points out, we cannot derive the minimum number of spots in a ^{4}He profile purely based on our measurements. The number that we give is our best estimate based on the data that we have available and a mathematical thought experiment: The minimum number of ^{4}He spots required to define a ^{4}He profile can be compared to determining how many points are needed to define a curve. It is trivial that two points define a straight line, and given any two distinct points, there is only one unique line that can be drawn through them. The minimum number of points required to define a curve is a more nuanced problem, as it depends on the complexity of the curve. The simplest assumption is that if the definition of a straight line requires two points, a simple curve should require at least three points. Indeed, it can be shown that a simple quadratic function of the form $f(x) = ax^2 + bx + c$ is uniquely determined by three distinct points.

If we assume, in the simplest mathematical case, that the ^{4}He profile within a homogeneous grain has a parabolic shape, we would thus only need three points from the core to the rim to measure the ^{4}He profile. (We cannot make the same assumption for rim-to-rim profiles, because three points would mean defining one shared central point and one outer point for each half of the grain. This would result in describing a line in each grain half, rather than capturing a curved profile.)

For rim-rim profiles, we would double the number required for a core-rim profile, resulting in six spots. In the case that the ^{4}He profile is parabolic in shape and symmetric about the c-axis (meaning the vertex of the parabola is located at the grain centre), five spots can be sufficient. Then, the middle spot should be located exactly at the grain centre. By chance, Ap-BaF-P1 is sufficiently close to that condition, and five spots are enough for measuring the ^{4}He profile.

We do not know beforehand how complex the ^{4}He profile's shape in the grain will be, and thus how many measurements are needed. It can very well be more than six. However, we can conclude with some confidence that one should not start with less than six (rim-rim).

- **RC 20:** **Line 519-521:** Do the blue, red, and black curves shown in Fig. 7 represent two separate models extending from the core to the rim on each side (i.e., toward positive and negative distances from the center)? If so, this could explain the slight discrepancies observed between the curves at the grain center, where the two models meet. This point is not enough clearly stated in the text to my opinion, and it would be important to clearly specify that these are half-grain models (core-to-rim) rather than full-grain simulations (rim to rim). Is the same modeling approach also applied to the URG apatite? Similar minor mismatches are visible near the center of those plots as well.
- **AR 20:** We indeed merge two core-rim profiles for forward-modelling. We will add explanations to the text and modify the figure captions to highlight this.

- **RC 21:** **Appendix B:** This table provides information for the McClure sample but does not include the calculated in situ AHe date. Although this sample was not used in the modeling section, the authors successfully measured 4He signals and corresponding Caw U-Th-Sm values for numerous ablation pits. Do these individual ages combine to yield a whole-grain equivalent age given at ~523 Ma (see table 1)? it would be useful to include calculated in situ AHe dates, as it provides additional context and comparability with URG, especially given similar parent nuclide homogeneity (Fig. 3).

- **AR 21:** We did not calculate AHe dates because we were doubtful of their significance, given the large uncertainties on the ^{4}He concentrations. It is an interesting question how the in situ AHe dates compare to the crystallisation age reported for the McClure Mountain Syenite. Previous studies (e.g., Anderson et al., 2017) report AHe dates that are significantly younger than the crystallisation age of ~523 Ma, ranging from ~100 to 140 Ma. We will add AHe dates for Apatite-McClure to the Appendix.

References

Danišík, M., McInnes, B. I. A., Kirkland, C. L., McDonald, B. J., Evans, N. J., and Becker, T. 2017: Seeing is believing: Visualization of He distribution in zircon and implications for thermal history reconstruction on single crystals, Science Advances, 3(2), 1–10, https://doi.org/10.1126/sciadv.1601121

N. Evans , J. Byrne , J. Keegan and L. Dotter LE , Determination of Uranium and Thorium in zircon, apatite, and fluorite: application to laser (U–Th)/He thermochronology, J. Anal. Chem., 2005, 10.1007/s10809-005-0260-1, 60, 1159 -1165.

Glotzbach, C. and Ehlers, T. A.: Interpreting cooling dates and histories from laser ablation in situ (U– Th–Sm)/He thermochronometry: a modeling perspective, Geochronology, 6, 697–717, https://doi.org/10.5194/gchron-6-6972024 , 2024.

Pickering, J., Matthews, W., Enkelmann, E., Guest, B., Sykes, C., and Koblinger, B. M., 2020, Laser ablation (U-Th-Sm)/He dating of detrital apatite: Chemical Geology, v. 548, p. 119683. https://doi.org/10.1016/j.chemgeo.2020.119683

Phillips, D., and Matchan, E., 2013, Ultra-high precision 40Ar/39Ar ages for Fish Canyon Tuff and Alder Creek Rhyolite sanidine: new dating standards required?: Geochimica et Cosmochimica Acta, v. 121, p. 229-239. https://doi.org/10.1016/j.gca.2013.07.003

Reiners, P. W., Farley, K. A., and Hickes, H. J., 2002, He diffusion and (U-Th)/He thermochronometry of zircon: initial results from Fish Canyon Tuff and Gold Butte: Tectonophysics, v. 349, no. 1-4, p. 297- 308. https://doi.org/10.1016/S0040-1951(02)00058-6

Renne, P. R., Swisher, C. C., Deino, A. L., Karner, D. B., Owens, T. L., and DePaolo, D. J., 1998, Intercalibration of standards, absolute ages and uncertainties in 40Ar/39Ar dating: Chemical Geology, v. 145, no. 1-2, p. 117-152. https://doi.org/10.1016/S0009-2541(97)00159-9

Additional references cited by the authors in their response:

Anderson, A. J., Hodges, K. V., & van Soest, M. C. (2017). Empirical constraints on the effects of radiation damage on helium diffusion in zircon. *Geochimica et Cosmochimica Acta*, *218*, 308–322. https://doi.org/10.1016/j.gca.2017.09.006

Binder, T., Marks, M. A. W., Gerdes, A., Walter, B. F., Grimmer, J., Beranoaguirre, A., Wenzel, T., & Markl, G. (2023). Two distinct age groups of melilitites, foidites, and basanites from the southern Central European Volcanic Province reflect lithospheric heterogeneity. *International Journal of Earth Sciences*, *112*(3), 881–905. https://doi.org/10.1007/s00531-022-02278-y

Meesters, A. G. C. A., and T. J. Dunai (2005), A noniterative solution of the (U-Th)/He age equation, *Geochem. Geophys. Geosyst.*, 6, Q04002, doi:10.1029/2004GC000834.