1. Comment: The use of OptiPit largely centers on the approach to place a second ICP laser pit either within the Helium pit (Geometry A) or engulfing the Helium pit (Geometry B). Alternatively, Maier et al. (2026) recently proposed an approach where whole-grain parent zonation maps were obtained after multiple helium ablation pit transects were analyzed across a single grain. Instead of obtaining the Helium budget from a single ablation pit, the Helium budget was determined from the apparent mapped zonation. A benefit of the Maier et al. (2026) approach is that parent zonation within and around the helium pit can be evaluated. The use of OptiPit anchors on the simpler double-ablation approach; perhaps these contrasting approaches warrant some discussion in the manuscript? Are there times when the double-ablation pit may be preferred with OptiPit optimization (perhaps with detrital analyses?), or are there times where the Maier et al. (2026) approach may be preferred? In the latter case, is there a way for OptiPit to be incorporated to properly determine the helium budget from the parent zonation maps?

Answer: We thank the reviewer for pointing out the connection between our work and the recent paper by Maier et al. (2026). While there are many similarities in the processes addressed by both contributions, there are also evident differences in the approach and aim of both methods, which we discuss in the revised manuscript and in more detail in the following paragraphs.

The method demonstrated by Maier et al. 2026 develops on a similar approach introduced by Danisik et al. (2017) and relies on He pits with a depth of 8 μm and diameter of 10 to 30 μm ablated along transects of polished apatite grains. Subsequently, 8 to 10 μm of material are removed by repolishing, and new ICP pits with a depth and diameter of 24 μm are drilled within a grid along the repolished surface to map the radionuclides that emitted radiogenic helium into the He pits. Thereafter, the acquired helium ages can theoretically be corrected for heterogeneous radionuclide distributions using C_{aw}, and furthermore be inverted into thermal histories that consider alpha particle ejection and subsequent diffusion in two dimensions.

Table 1: Maximally attainable proportion of helium generating parents of the laser pit geometries used by Danišík et al. (2017), Maier et al. (2026), and our optimisation.

	Optimised double ablation pit	*Danišík et al. (2017)*	*Maier et al. (2026)*
He pit			
Depth [µm]	10	1.8	8
Diameter [µm]	25	~10	10-30
ICP pit	One overprinting He pit	Several beneath He pit	Several beneath He pit
Depth [µm]	20	(na; ~20?)	24
Diameter [µm]	65	15	24
Maximum proportion of helium generating parents [%]	**~50**	**<50**	**<11 – 14**

C_{aw} calculates the contribution of all radionuclides within one stopping distance of the He pit to the helium budget within it. Thereby, an expected amount of helium can be calculated for the He pit and the measured He age can be corrected for a known radionuclide zonation. While C_{aw} can correct over- and underestimations of in-situ (U-Th)/He ages if the distribution of parent nuclides in the vicinity of the He pit is known, as can OptiPit, it does not provide an estimate of the uncertainty of an in-situ He date associated with the pit and radionuclide zonation geometries used. Therefore, it cannot be used to determine the most efficient analytical set-up to minimize apparent age offsets caused by He redistribution during alpha decay, which is the aim of OptiPit.

Furthermore, calculations performed using OptiPit demonstrate that the ablation geometries used by Maier et al. (2026) produce highly imbalanced He and radionuclide quantifications (Table 1). The proportion of helium-generating parents is a measure for the comparability of the helium from the He pit with the radioactive nuclides within the ICP pit. Table 1 demonstrates that this proportion is highest for our optimised double ablation pit and comparable to the geometry used by Danišík et al. (2017). In contrast, the method of Maier et al. (2026) reaches only a fraction of this proportion, as most of the parent nuclides are removed during repolishing. This means that the measured radionuclide maps and modelled helium maps do not represent the distribution of parent nuclides that actually emitted helium into the He pits. This is likely the reason why their approach is unable to reproduce dates in heterogeneous grains, as acknowledged by Maier et al. (2026).

In summary, while no technique can provide an absolute correction of in-situ (U-Th)/He ages modified by heterogeneous radionuclide zonation we believe that OptiPit is a tool more adequate to optimizing routine in-situ (U-Th)/He analyses in natural samples, whereas the approach of Danisik (2017) and Maier et al (2026) yield more information about thermal histories from gem-quality homogenous crystals.

2. Comment: One thing that may differ significantly in practice between the end-member Geometries A and B is the laser ablation down-hole fractionation of U and Th during parent ICP analyses. Geometry A results in a notably easier downhole-fractionation to correct for compared to Geometry B. May there be a case that an increased uncertainty/complexity in the Geometry B laser ablation fractionation correction actually further amplifies in-situ date disparities? I question whether this increased complexity in downhole fractionation may actually result in a preference for Geometry A, regardless if the OptiPit results favor Geometry B?

Answer: This is an interesting observation. OptiPit demonstrates that unfavourable laser ablation geometries can result in strongly imbalanced quantifications of He and radionuclides. This can lead to significant apparent age offsets in zoned crystals, surpassing the uncertainties introduced by mass fractionation. Ultimately, this is an issue that has received little attention in the development of the in-situ (U-Th)/He technique, and that necessarily needs to be balanced against other analytical considerations by the eventual users. In contrast, there is a robust experience on mass fractionation and how to handle the problem in the LA-ICP-MS community.

Following this comment and others from the reviewers, the revised manuscript includes a new section discussing practical implications of the conclusions drawn from using OptiPit. This includes comparisons with alternative analytical approaches for in-situ (U-Th)/He (see previous comment), how diffusion affects our results (comment 5), as well as the impact of our observations in analytical considerations, such as downhole fractionation (this comment), pit characterization (comment 4 of reviewer 2), and matrix matching (comment 5 of Reviewer 2).

3. Comment: Whereas I appreciate the powerful demonstration of potential zonation impacts in section 3.4, I do not entirely understand the utility/application of this function beyond purely demonstrative purposes. Of course, with the double ablation approach, the lateral parent zonation gets averaged out, so it can only be assumed that x% of the shells are enriched/depleted by a factor of y. Although the authors suggest the use of other zonation proxies, this may still be largely indirect. For apatite as an example, it has been suggested that U and Th zonation do not always correspond with BSE/CL zonation patterns (Ault and Flowers, 2012), nor have many assessed Raman mapping on apatite (at least to my knowledge), and so it's perhaps impossible to properly assess the impact of zonation in practice without true measurements (perhaps prior Ce mapping in apatite could help as a parent zonation reference). Without the direct measurement of zonation, is the utility of OptiPit zonation calculations aimed at simply providing a range of permissible dates based on assumed end-member zonation patterns within the ICP pit?

Answer: OptiPit's goal goes beyond providing a range of permissible dates based on assumed end-member zonation patterns within the laser ablation pits. On one hand, OptiPit demonstrates that the geometry of the laser ablation pits used for in-situ (U-Th)/He dating strongly influences the impact of heterogeneous radionuclide distributions on the He age. If the laser ablation spots are measured blindfolded, i.e., without exact knowledge of the present radionuclide zonation, OptiPit demonstrates that it is advisable to use a certain combination of He pit and ICP pit geometries, which can be easily optimized using the software. This guarantees that the He age stays within a range of permissible dates even in the case of unfavourable zonation. This may be especially important in apatite, since the mineral's radionuclide zonation, as you mention, may not always correspond to proxies like BSE/CL or Raman imaging. On the other hand, assuming three-dimensional data is available about a heterogeneous radionuclide distribution, and taking into account the caveats mentioned in the comment, OptiPit can provide an estimate of the under- or overestimation of the in-situ (U-Th)/He age for every single pit. The demonstration of the influence of zonation is an important stage at the sensitivity experiments. Such are crucial to limit the potential over- and underestimation. Both of these points are now clarified in the revised manuscript.

4. Comment: The authors state a couple times in the manuscript that radionuclide zonation and variable double-pit geometries controls age bias and dispersion inherit to the in-situ method. While in part true, these statements partly undermine the impact that thermal history mediated diffusion has on observed in-situ date dispersion. How do we truly distinguish between analytically induced in-situ (U-Th)/He date dispersion versus expected date dispersion in natural samples considering all the natural complexities involved in the (U-Th)/He system? Do measured data exist testing observed analytical disparities from contrasting pit geometries on large standard xenocrysts like Durango apatite, where we may expect spatially uniform in-situ (U-Th)/He dates? Do measured data exist testing observed analytical disparities from contrasting pit geometries on large standard xenocrysts like Durango apatite, where we may expect spatially uniform in-situ (U-Th)/He dates?

Answer: This is an important point, since natural complexities that modify the (U-Th)/He system within minerals through time go beyond even the processes mentioned in the comment. They also include inclusions (of other minerals or fluid), heterogeneous parent isotope distribution, fast diffusion pathways (for example microcracks or strain induced discontinuities in the crystal lattice), irregularly shaped diffusion domains or diffusion domains of unknown shape, and diffusion sinks (Guo et al. 2024). As demonstrated by Sousa et al. (2024), even detailed 3D characterizations of apatite crystals using access to exceptionally complex equipment cannot resolve all possible sources of date dispersion in natural samples. If these sources of uncertainty cannot be resolved, the analytically induced dispersion and date dispersion in natural samples can hardly be distinguished. In this context, our manuscript highlights that, whereas He redistribution during alpha decay is rarely considered during in-situ (U-Th)/He analysis, its impact in the results can potentially dominate the method's uncertainty.

For a future contribution, a potential approach aimed at distinguishing analytical from diffusion-controlled sources of dispersion could include analysing a dataset of numerous grains that experienced the same, simple thermal history of rapid cooling. In our manuscript we accessed the impact on the age offset produced by the combination of pit geometries and zonations quantitatively in theory. Then we compared our results qualitatively with in-situ (U-Th)/He ages produced by Léger et al. (2023) on the quickly cooled Fish Canyon Tuff age standard. However, we do not go beyond a qualitative assessment as the analytical uncertainty can be quite big even in this quickly cooled age standard. Only with data having much lower uncertainty dates falling out of this relationship could be investigated further for sources beyond the analytically induced (U-Th)/He date dispersion.

5. Comment: On the topic of in-situ date variability: How much should inter and intragranular age dispersion should actually be embraced with in-situ dating, given that date variability has potential to provide even more detailed thermal-history information considering the complex kinetics that we partly understand (Glotzbach and Ehlers, 2024). Only in rare cases where a grain was rapidly quenched and unaltered after may we actually expect an in-situ, single spot (U-Th)/He date from the center of a grain to be interpreted as an age and match the grain's bulk (U-Th)/He date. To my understanding, in its current state, OptiPit only assumes this comparatively simple scenario with no diffusion. In nearly all other thermal history scenarios, spatial variability in in-situ dates should be expected, as well as discrepancies between observed in-situ dates and the bulk grains (U-Th)/He dates. The authors are clearly aware of the effects of diffusion—they note that OptiPit does not currently implement diffusional loss and adequately discuss such complications in Section 4. Although I acknowledge it may be beyond the scope of this manuscript, it would be helpful to evaluate at first order the sensitivity of the pit geometries to an ablation pit with identical helium concentrations but varying spatial distribution within the helium pit controlled by (1) a rapidly cooled quenched thermal history, and (2) a steady-state, purely diffusive end member. Would we actually expect the parent-daughter imbalance mismatch to increase or decrease if we factor in the mobility of helium after its initial ejection emplacement?

Answer: This is another interesting point. We consciously did not explore this question in the original submission because we wanted to highlight the, in our opinion, underexplored topic of He redistribution during alpha decay in the in-situ technique. Following this and other comments, however, we have included a new section in the discussion of the manuscript with practical implications of our findings, as mentioned in other replies. This new section which will also cover this topic, following the arguments presented in the next paragraphs. In summary, the modification of the parent-daughter imbalance by diffusion is a function of the exact cooling history a grain has experienced, the position of the in-situ laser ablation pits within the grain, the geometry of the laser ablation pits, and the exact radionuclide distribution within the grain. This relationship can be, as a simplification, investigated with a simple diffusion exercise in HeFTy considering three apatite grains: a) one with a homogeneous radionuclide distribution; b) one with an elevated concentration in its centre; and c) one with an elevated concentration in the rim of the grain.

A thermal history that is defined by rapid cooling through the helium partial retention zone (PRZ) preserves a helium distribution that essentially reflects the alpha ejection redistribution. Thus, in all three grains, the age offset illustrates the mismatch calculated by OptiPit and depends on the positioning of the laser ablation pits relative to the zonation as well as the geometry of the pits.

However, the result changes if a thermal history with a prolonged stay within the PRZ followed by rapid or slow cooing is assumed. Grain a, without radionuclide zonation, will develop a diffusion profile with significant diffusive loss of helium along the whole transect from the grain rim to the grain centre. However, the helium present at any location does not show a greater or smaller mismatch compared to the radionuclide budgets measured by any laser ablation pit position and geometry. Instead, it reflects a diffusion profile controlled by its thermal-history, as demonstrated by Maier et al. (2026).

A similar story is true for a heterogeneous radionuclide concentration close to the centre of the grain (grain b). Here, the helium loss by diffusion is small, as the diffusive gradient closer to the grain's centre is limited by alpha emission from radionuclides closer to the grain rim, which decreases the diffusion gradient and thereby diffusive loss from the centre. This is demonstrated by the fact that the helium profiles produced by this grain through both possible thermal histories preserve the same overall shape. Thus, the mismatch calculated by OptiPit does not increase strongly at any location, although an increase in mismatch is to be expected by the movement of helium along the gradient, both within the centre of the grain and along its transect.

However, the mismatch is exacerbated by diffusion if in-situ spots are taken close to the grain boundaries of a grain with an elevated radionuclide concentration close to its rim (grain c). In this case, a peak of the helium profile close to the grain rim compared to the grain centre produced by an increased radionuclide zonation is lost due to diffusion. The elevated radionuclide concentration produces a much higher concentration gradient, which accelerates diffusive loss of helium along the grain boundary. Thereby, the concentration gradient is flattened relatively quickly. Consequently, the mismatch between measured parent and daughter isotopes is strongly increased by diffusion, while preserving the mismatch in the grain centre.

In summary, the mismatch calculated by OptiPit is not strongly affected if a pit is positioned close to the centre of a zoned grain, even for prolonged stays in the PRZ, but it is highly affected if a pit is located close to the rim of a grain.

6. **Comment:** Consider providing a simple 'layman' definition/explanation for the term 'mismatch' introduced in LINE 341 that may help improve the reader's understanding of the figures.

Answer: We realised that our equations were out of order in the submitted manuscript due to a formatting problem. We now moved the equations into correct order and added a clear definition of mismatch in line 226.

7. **Comment:** OptiPit incorporates simple perfect cylindrical geometries for assessment. I'm curious if the authors have attempted to evaluate the impact of the Parent-Daughter imbalance with true, imperfect laser ablation pits measured from optical profilers?

Answer: No, we have not attempted to investigate imperfect laser ablation pit geometries. We have performed ICPMS measurements in five different laboratories and the topographic profiles across the laser pits are typically regular, having flat bottoms and relatively steep walls. The correction of these deviations from the perfect cylinder would have only minor influence on the results. The added complexity to a problem that already has too many sources of uncertainty does not scale with the minor benefit we expect from such a change.

8. Comment: The link provided to download OptiPit was dead, but I was able to easily search the database for the software. The software was relatively easy to open and test with the README file, though the experience could be improved with a user guide with screenshots and walk-through example.

Answer: Thank you very much for the information! The static link is provided by our university and should not change. However, they updated the repository to a new version, seemingly killing old URLs, which should NOT happen in a *static* repository. I updated the URL in our manuscript.

In retrospect, it is clear that providing a user guide would have made the software much more approachable for external users. I wrote a pictured user guide to improve the overall user-friendliness and added it to the repository.

Line by line comments:

LINE 19: Consider rephrasing to “IN PART controls the overdispersion”

Modification done.

LINES 67–68: Unclear what is meant by “production of meaningful He ages impossible in some samples” First, are the authors referring to ‘conventional’ dates, or in situ dates here? Second, I believe ‘impossible’ is bit strong here—datasets with complex, damage induced date-disparity can still provide meaningful information.

We refer to the conventional entire grain method here, which is now clarified in the manuscript. We agree that many datasets with complex, damage induced date-disparity can provide meaningful information. If a wide range of eU is covered by the sampled zircons even more information could be retrieved from such a dataset than from one that does not contain highly damaged crystals. However, not every sample provides such a range in eU. In this section we explicitly refer to samples with a small eU-range and/or strong zonation (e.g. zircon from Proterozoic granites) which, even as a population, are too damaged and complex to produce meaningful ages.

LINES 69–77: To me, a huge benefit of in-situ dating missing from this list is the ability to directly measure thermal history-dependent helium diffusive profiles in a grain at varying resolutions.

Indeed, that was missing. We added it into the section.

LINE 277: Replace “chapter” with “section?”

Modification done.

LINE 353: I don’t believe ‘inevitable’ is the proper word here? We should not ever expect a zero mismatch, correct? If so, consider rephrasing to state that a zero mismatch is inherently not possible with the double-pit in situ approach.

Yes, that word does not really make sense there. We replaced it by “impossible to achieve”.

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