Author reply on RC3

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We thank reviewer #3 David Whipp for comments on preprint gchron-2024-3. We appreciate the opportunity to clarify some points. Below we respond to each of the comments in detail.

RC3 denotes reviewer #3 comments and **AC** and bold text marks the authors' replies.

RC3: General comments
McDannell and Keller presents a new method for robustly determining the timing of cooling from thermal histories produced by inverse thermal history models. While it may seem obvious that periods of cooling are visible in reconstructed thermal histories, the goal of this work is to move beyond visual identification of periods of cooling and place quantitative constraints on the time ranges during which cooling occurs to better link cooling to geological events. The utility of the new model is demonstrated using both synthetic and natural datasets, and the software needed to utilize the new approach is provided via links to relevant websites. The general concept behind the model appears sound and quantifying the timing of cooling is clearly important for thermochronology. However, as noted below, it does seem that some discussion about the timing of peak cooling and its association with geological processes would be beneficial in the text, as the peak cooling does not necessarily represent the peak in activity of a geological process due to various time lags. Beyond this, it would also be beneficial to provide some visual depiction of how the new model works to help readers see the concept of the model more clearly. I think these changes are possible in moderate revision of the text, and otherwise feel this is a suitable contribution for Geochronology. More detailed comments can be found below.

AC: We appreciate RC3 (Whipp) taking the time to review our manuscript. We will be adding figures to better illustrate the method. The points raised about relating 'peak cooling' with geologic process are important. Our method cannot address variables such as time lag etc. that are a concern in rapidly exhuming settings, therefore, as we mention below, the most suitable applications for the FDHM method are in deep time—applied to more slowly cooled regions where such factors are not a major concern. We reiterate here—the time of half-maximum cooling can be considered an approximation of the time when the first derivative of the cooling curve is maximized if the cooling curve is smooth, symmetrical, and unimodal (under those caveats it's also the inflection point, or the time when the second derivative changes sign). In such a case, it represents the time at which half the total exhumation has occurred—if the thermal history is being interpreted in that manner.

Specific comments (L = line number)

RC3: L1: I think that "typically" here is an overstatement. It may be that many researchers use inverse thermal history models, but there are numerous approaches to reconstruct past events and associated processes from thermochronology data.

AC: We will remove "typically"

RC3: L4: Statistical comparison of what? Between models or between studies?

AC: We meant 'statistical' in the sense of quantitative—both comparisons between t–T models and between studies. We will edit the text here to be clear.

RC3: L7: The "half-maximum cooling isotherm" might be confusing to readers at this stage in the paper. It should either be defined somehow or referenced in a way that is easier for readers to understand.

AC: Agreed. We will remove that sentence. The previous sentence is adequate.

RC3: L19: This might be nitpicking, but I prefer "identifying" or "calculating" here in place of "predicting". The models produce suites of cooling histories that are analyzed to determine the ranges of histories that best explain the data. Only an opinion.

AC: Thank you for pointing that out. We will change the wording.

RC3: L32: I think "increasingly" is not needed here. Critical is critical.

AC: True.

RC3: L35: What about situations where slow cooling accelerates? I would imagine there are many of those that are addressed in thermochronology studies, and the "heating to cooling" transition could occur simply due to cessation of sedimentation, for example. I realize you aim not to describe every situation here, but I feel like studying the transition from heating to cooling is a smaller subset of thermochronology studies.

AC: The situations we are addressing are the "most common" from our perspective and this method is not necessarily tied to "process." In a similar manner, the 'onset of cooling' is often linked to a geologic process, but that is because there is an assumption that the cooling onset is accurately recovered in a model, which may not be valid, or that cooling onset in a t-T model is recording the onset of a geologic process. Thermochronometer sensitivity directly governs those outcomes, yet many published studies nonetheless discuss interpretations of high temperature portions of a thermal history, when only low-temperature data are modeled. That is not to say that those interpretations are "wrong" but only that there is a very big assumption being made, especially if the high temperature parts of a history are based only on time-temperature 'exploration' boxes that may also be interpretations/assumptions. All that to say that the FDHM is merely a way to quantify the midpoint of any cooling path segment, rather than rely on "eyeball" estimates that may vary between eyeballs. Interpretation of a cooling path or whether or not the heating that preceded cooling is related to the end of sedimentation is up to the geologist to interpret. To be clear, the t–T cooling signal being

assessed and the interpreted meaning of that signal are separate, and our method does not address the latter. We are not saying that the transition from heating to cooling is something addressed in many studies. We also aren't necessarily interested in the [cause of a] transition from heating to cooling, other than to point out that such t–T path behavior is frequently the basis for interpreting when cooling "begins" in a model with reheating. In the simplest sense, heating-cooling histories, or so-called "V-shaped" thermal histories, are commonly shown in sensitivity tests (e.g., Gallagher 2012, doi: 10.1029/2011JB008825; their Figs. 1–2) or other published examples, such as the one referenced by Reviewer #1 in Figure 8 of Murray et al. (2022). In general most studies are focused on a particular part of a t–T model that involves cooling, or specifically the "onset of cooling" – with the onset being a murky time to pin down due to methodological limitations; this is something we discuss in the manuscript and show in the Figure 1 in our author reply to RC1.

RC3: L46-54: I don't think this text is needed. It could be useful to introduce relevant methods for the data that is analyzed, but otherwise this is not necessary to include.

AC: We will remove this section of text. It was only included as context for potential readers unfamiliar with thermochron mineral systems

RC3: L71-72: Is the target to identify a single period of "peak cooling time" or the periods when cooling is most rapid? As stated here it seems a single peak cooling time is sought, but the slowly cooled regions may have longer and more complicated cooling histories. Could this be rephrased?

AC: That depends on what you are interested in quantifying. We are generally focused on a single peak cooling time. As cooling becomes progressively slower, the FDHM loses meaning. For example, what does the midpoint of a path mean for 200°C of total monotonic cooling over 500 Myr at rates of 0.4°C/Myr? That is hard to assess by any means and is most often just interpreted as "slow erosion." We will rephrase this as necessary.

RC3: L74: This applies elsewhere, but it may be helpful to somewhere state what is meant by a t-T model. Do you mean the thermal history itself, the software, or something else?

AC: We will change this where appropriate. We use "t–T path(s)/history" to refer to the thermal history, and more generally, software output.

RC3: L84-98: This is an important point, but I don't think this belongs in this article as it distracts from the main point as presented. If you would like to include a point about the importance of the model constraints, I think it could be presented more succinctly, focussing on how the constraints influence the thermal history rather than the implications of the constraints in terms of the geological history associated with the resulting models (a point beyond the scope of this paper, in my opinion).

AC: Other reviewers have mentioned this as well. We will remove section 2.3

RC3: L111: An additional figure in this section would be very helpful to illustrate how the FDHM model works. The text here is somewhat challenging to read without a visual reference, and might be able to be simplified with a nice diagram of how the model works.

AC: We are going to add a figure to clarify this.

RC3: L119: Preferred over what?

AC: We will edit this text. Poor word choice.

RC3: L120-124: I'm a bit slow to pick up new acronyms and model names, but I find the text here a bit confusing. Again, a labeled diagram might help, but I have difficulty to visualize the "half-maximum temperature".

AC: Refer to reply about adding figure above.

RC3: L126: The version of the software presented in this article should be linked in a repository that preserves the version history, such as Zenodo.

AC: The software is located on Github: `https://github.com/OpenThermochronology/CoolingFDHM`**. Version history is preserved.**

RC3: L184-185: "which is a common misconception" is not needed here, in my opinion.

AC: We appreciate RC3's sentiments, however, comments we have received on QTQt model output in some of our other publications support the statement that it is a misconception (held by some) that areas of the general prior "without paths" have not been searched. We can rephrase this.

RC3: L205-215: This text feels out of place here, and perhaps could be moved to another location earlier in the manuscript, possibly in or around Section 2.

AC: We will move this text.

RC3: L247-250: It would be nice to list what the aims of the subsections here are in this introductory text. Why compare the applications for rapidly cooled and slowly cooled regions? This might help readers see how they could apply the software.

AC: This was meant to do just that—demonstrate to readers how the tool could be applied. The comments we have received thus far on the manuscript suggest to us that application of this method to "young" settings may not be well received, or considered unnecessary. However, it is only meant as a quantification tool using a simple metric that is easy to assess and implement, nothing more than that as far as geologic interpretation or considerations involving 3D heat/mass transfer etc.

RC3: L263: It might be helpful to have a different topic sentence here that indicates the aim of this paragraph is to describe the dataset you have modeled for this article.

AC: We will change this and/or potentially remove this section altogether.

RC3: L266: Although a "high quality QTQt" inversion might not exist, the way it is phrased here would suggest a low quality QTQt inversion might. Maybe you could state that although they presented results from an inversion with other software, you've performed your own inversion to be consistent with the results from the other case studies. Just a suggestion.

AC: We appreciate RC3 catching this oversight. We will edit this accordingly.

RC3: L275: What is the reference for the maximum cooling rate (and why refer to it as dT/dt instead of cooling rate?)?

AC: The reference is Ketcham et al. 2018 in the next sentence. We will change this text.

RC3: L282: Perhaps "our results suggest" or a similar phrase would be better here than "we maintain".

AC: We will change this text to state "our results suggest".

RC3: L298: It might be interesting to have a closer comparison with the results from HeFTy to emphasize the potential of the FDHM model, though I understand that this could possibly distract from the focus of the work. That said, the comparison could also drive home the point that it can be difficult to identify the timing of cooling from the inversion results alone.

AC: While we mention HeFTy output may be a future option, it would not be a simple task. HeFTy model output is in a very different format than QTQt. We also do not want to inadvertently make this contribution about comparisons between modeling software. In addition, usage of HeFTy varies in terms of the user setting the number of allowed path segments (a priori), which will have an effect on the FDHM calculation. This alludes somewhat to one of the main points editor/reviewer Vermeesch made in their comments. If a path has 5 segments with a stepped cooling pattern—what do you do? In such a case we argue that the total amount of cooling or the broader cooling pattern observed for an ensemble of thermal histories is the preferred focus. If many segments are allowed in HeFTy, they are primarily to introduce additional "complexity" or to allow more t–T nodes to be distributed in parts of a history that may need them—but whether than is necessary or warranted is an open question and dependent upon the situation. Obviously if candidate paths contain many nodes and a thermal history is poorly resolved in a certain portion of t–T space, then the envelope of acceptable histories will often be wide, this in turn made the FDHM uncertainty large (see Section 3.4 and Figs. 4 and 5 in the text). The take-home message being that if a pool of thermal histories exhibit cooling, but the timing is highly uncertain or occurs over a long interval, then the FDHM will not necessarily be very informative—it works for some cases and not others, like all tools.

RC3: L323: It seems that more discussion of the results from the different case studies could be helpful toward the end of the article (perhaps around here). For example, it would be helpful to have a sense of which are the most challenging cases for interpreting timing of cooling from inverse models and when it might be most important to use a tool such as the FDHM. Discussion points like this would be helpful to guide readers to know when to use your software.

AC: We will address this during edits. Challenging cases would be very slow cooling over protracted intervals or small temperature changes over short durations.

RC3: L323, continued: One of the main concerns I have with the text is the lack of a discussion about what the timing of peak cooling means in terms of a geological event. If the goal in interpreting thermochronometer ages is to link cooling to some kind of geological process it does also seem important to consider various time lags that could offset both cooling and ages from the onset of activity of a geological process. Changes in crustal thermal structure take time, so cooling rates may vary simply due to the continued activity of a process. Thus, changes in geothermal gradient could result from continued activity of a process at a constant rate (fault motion or erosional exhumation, for example). In that case one might erroneously conclude that faster cooling equals a higher rate of activity of a process. This may not be a major concern for slowly cooled regions, which perhaps are the places where the model might be most useful, but regardless it would be beneficial to discuss how one could link the time of peak cooling to geological processes in a meaningful way. Presumably, the goal is still to link the timing of cooling to something like the onset of exhumation or some other process.

AC: We appreciate RC3 mentioning a very important point about linking cooling to geologic process. If that is indeed the goal and we need to "consider various time lags that could offset both cooling and ages from the *onset of activity* [our emphasis] **of a geological process..." — then it seems that interpreting the 'onset of cooling' (as is most often referenced in studies) is perhaps the incorrect metric to use, as stated in our manuscript. While RC3's comments are all valid, we would ask which published studies that include basic thermal history inversions (i.e., HeFTy/QTQt) consider thermal lag, changes in crustal thermal structure, fault motions, and other such factors? Often those processes are neglected or speculated upon, whereas more sophisticated 3D modeling methods (e.g., Pecube) are probably required to move beyond speculation in a quantitative manner.**

Slowly cooled regions or deep-time thermochronology is the most suitable application for this method where such factors are not a major concern.

RC3: Figure 1: The labeled peak cooling should probably read "peak cooling rate".

AC: We will edit this text.

RC3: Figure 6: Could the HeFTy results be shown as well for comparison? It might be interesting to see how the FDHM peak cooling timing compares.

AC: See previous comment on HeFTy

Technical corrections (L = line number)

RC3: L68: "rapid exhumation" rather than "rapid uplift"

AC: Thank you. We will edit this text.

RC3: L74: What does "here" refer to? Is it this part of the article or the article as a whole?

AC: We will remove this text.

RC3: L114, 116: "That is" is used in consecutive sentences, so perhaps one instance could be replaced with an equivalent phrase.

AC: We will edit this text.