MS No.: egusphere-2026-1925 - A different take on fission-track annealing in apatite – CC1

Comments	Response
The study by Jonckheere et al. examines the model for the annealing of fission tracks in apatite. They propose a new model based on existing data obtained from laboratory experiments on the fission track annealing. The three aspects that have been debated for over 40 years are the role of apatite chemistry, low-temperature annealing over geological timescales, and extrapolation to geological annealing processes.	We thank the commentator for his challenging remarks. However, we prefer to think of our work as presenting a new conceptual approach rather than another model. We described it as a brittle-failure model to contrast it with the mainstream plastic resilience models. Wauschkuhn et al. (2015) list 24 models, all except that of Carlson, (1990) based on the same concept. We are aware of the debate around extrapolation, composition, and low-T annealing. We are not aware of a solution, except for empirical equations, e.g., relating the annealing rate to composition. These have no physical foundation to our knowledge.
The new model is based on a strong assumption: only the mean length is used to simulate annealing, taking into account the difference between the length after the experiment and the initial length. This deliberately simplified approach is intended to be more realistic, particularly by taking into account the variations that may exist between analysts in the measurement of average lengths. This assumption, however, disregards the strong influence of crystallographic orientation on the annealing kinetics of fission tracks, which has been well known since the pioneering work of Green and Durrani (1977). This assumption results in the shape of the histogram of average track lengths not being utilised; this shape is partly controlled by crystallographic orientation, the user's choice, and also the thermal history, which is central to the application of this method. I find this somewhat regrettable.	Yes and no. Modelling programs offer the option to use ***c***-axis projection or, not. In the latter case, each modelled track length is the mean length of an otherwise unsampled population, which is traced from its formation to the present. At the end a Gauss distribution is constructed around it, with a standard deviation dependent on the mean. The distributions are summed and corrected for length bias. The theoretical distribution is thus constructed without considering the track orientations. However, the empirical standard deviation covers both the effects of random variation and of length anisotropy (Figure 1). Thus, each mean length reflects the angular variation in a condensed form. This applies to geological and calibration data and assumes that the angular frequencies are not so variable as to contribute significantly to the variation of the mean length. Modelling with ***c***-axis projection is the same. However, on the sample (data) side, the actual track orientations are used to convert each length into its ***c***-axis equivalent. The same procedure was applied to the calibration data in order to fit annealing equations to the ***c***-axis data. The modelling is much the same in that it traces the ***c***-axis length of each sub-population from its origin to the present. A Gauss distribution is then constructed around it before it is de-biased and added together with the distributions for the other timesteps. As intended, the standard deviation of the ***c***-axis projected length for a given time-step is not due to anisotropy, but to random variation **and** to the ***c***-axis projection! The distributions being summed are also not normal distributions but leptokurtic. It is not clear to us how this is accounted for in constructing the overall model distribution. In short, on the sample (data) side, the measured track orientations are taken into account but on the model (theoretical) side they are not. It is instead assumed that the angular frequencies are fixed, like for non-***c***-axis models. I.e., the model distributions, with which the measured distribution is compared do not take into account the actual angles of the measured tracks. ***c***-axis projection is therefore not a precise tool. Moreover, ***c***-axis projection also causes loss of resolution (temperature sensitivity) because ***c***-axis parallel tracks anneal at a lower rate over a shorter length interval between no and full annealing. It is therefore not right to present ***c***-axis projection as the solution to everything, and common mean lengths as an outdated relic, insensitive to the angular length variation. Figure 1 illustrates the trade-off between length and standard deviation in ***c***-axis projection.

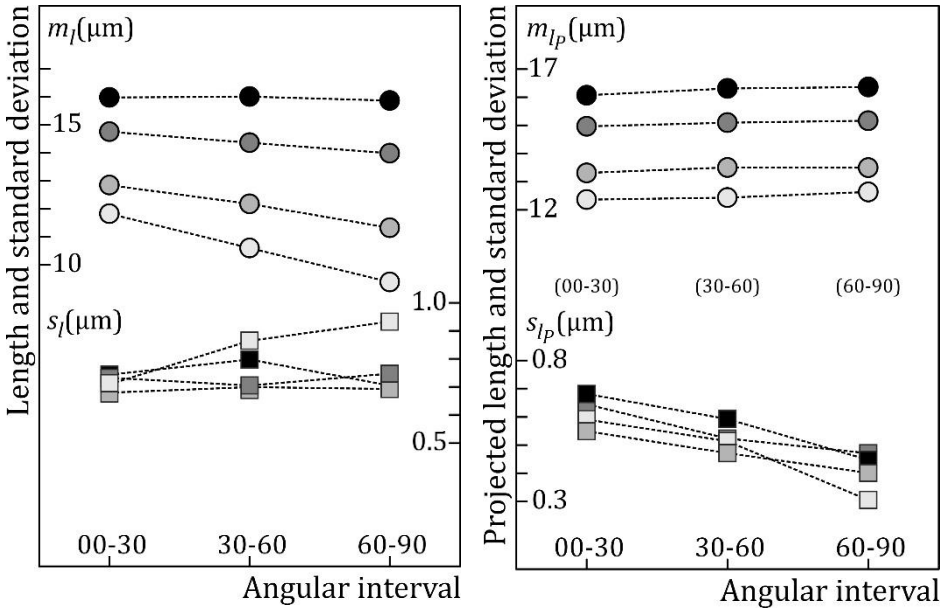
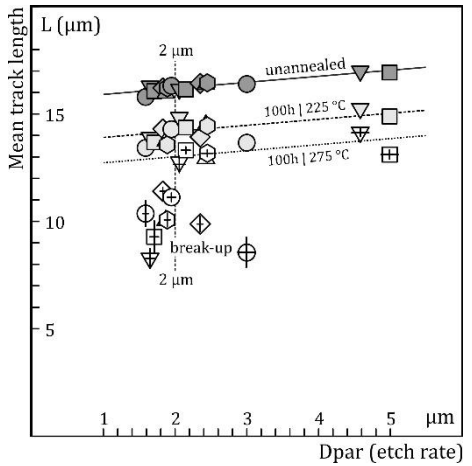


Figure 1. Mean lengths and standard deviations of four samples in different stages of annealing, subdivided in three angular intervals (0-30°, 30-60°, and 60-90°), before (left) and after (right) ***c***-axis projection. Before projection, the mean lengths (m_l) decrease and standard deviations (s_l) increase with increasing ***c***-axis angle due to anisotropy. After projection, the mean lengths are the same in all angular intervals but the standard deviations show a steep drop with increasing ***c***-axis angle, due to the ***c***-axis projection itself (!).

There is an intriguing aspect to modelling with ***c***-axis projection. In condensed form: if we accept ***c***-axis projection, we do not need to model at all; we can just calculate the Tt-path. To calculate the ***c***-axis equivalent of a measured length, we must assume that it is a mean length, i.e., that it is free from random variation. In that case we can arrange the c-axis projected lengths in ascending order. Because mean lengths only decrease, never increase, the order of short to long is also the order from old to young. Using the length-density relationship, we can assign a fractional age (time interval) to each length. With these we can reconstruct the Tt-path without having to generate candidate paths. There is a minor complication caused by the need to apply equivalent time to undo the effect of later annealing steps (Rebetez et al., 1994; Jensen, 2026). So why do we accept this assumption for converting lengths to ***c***-axis equivalents but not for calculating Tt-paths?

The abstract and introduction lack an explanation of the rationale for developing this new model: what are the shortcomings of the previous models? Are these shortcomings

We argued above that ***c***-axis projection is not the ideal solution. There can be value in modelling without angular data. We have also argued that the common mean lengths

addressed by this new model? Why develop this new model based on the same data as the previous models?	and standard deviations reflect anisotropic annealing. There is therefore no obscure motivation needed for our work; it is set out in our introduction. We used the existing data, like numerous others before us, because they are ample and good. Our motivation is that we believe that the data call for a different interpretation from before. Our approach and our equations are based on close inspection of the data themselves, as explained with reference to Figures 1, 2, 6, 7, supplement Figure S1, and confirmed by the results. Figure 1 plots the mean lengths against *Dpar* for three annealing runs (data from Carlson et al., 1999). What would we expect from a perspective of most models regarding the compositional effect on shortening? Smooth trends with an increasing tilt or downward curvature towards small *Dpar*, not a set of parallel lines and an unstructured bunch of clear outliers. In our opinion, the data are indicative of an initial gradual length reduction that collapses at a different stage in different samples. This differs only in detail from what has been known to occur since Green et al. (1986). The illustrated case is 1 of 112 to which our interpretation applies (supplement Figure S1). Also consider that the error bars are 2σ. 
Page 2, first paragraph: add the references to Ketcham et al. 1999 and Ketcham et al. 2007, which present the annealing models	Done.
L78: use a term other than 'break in slope' as this refers to something else in fission track terminology (shape of the length versus age distribution)	We hadn't foreseen the confusion; we now write "break point", the original term used by Green (1988).
L147–161: Is the distribution of the residuals the same if we consider only the data corresponding to the first plateau, for which the analysts' choices are not, a priori, very different?	We regret that we cannot answer this comment; the "first plateau" is not a term that we use or can relate to any in the cited section. We request the commentator to give more details.
Paragraph on ambient temperature: the conclusions are fairly similar to what was already known, and the question remains as to the very precise definition of the thermal history of samples described as volcanic but which may have been slightly heated by the overlying layer.	Indeed, ambient temperature annealing (ageing, seasoning, radiation assisted annealing) have all been considered as possible explanations for the excess shortening of fossil tracks in samples with flat low-T histories, such as volcanics, in particular also those with no known overburden. The doubt lingers in our opinion because the problem is mostly ignored. A conventional approach attempts to accommodate ambient-temperature annealing within the lab-based equations, i.e., the perceived misfit is removed by adjusting the model describing a single process. Our approach is to assume a separate process. From the perspective of geological modelling it does not matter, as long as the predictions are on target. It does matter however when one aims to reflect the physical phenomena.
L321: The suggestion that the experimental data are not robust enough is an interesting point and could easily be resolved, given that the samples must exist. The text	The ongoing experiments are part of an initiative of creating a virtual KTB, consisting of a database of detailed measurements and images of all grains and confined tracks for the entire borehole. These will be made available on a suitable server, so that, through

mentions that measurements are currently being carried out. It would be worth including these.	discussion and comparison, we might in time reach a consensus on the data, and perhaps also on their significance. This is a comprehensive undertaking that cannot be done as an addendum to the present theoretical work, which is not aimed at producing data.
L355: We can read that “the annealing model is incorrect”. Why, then, should the readers use this new model ?	The sentence on L355-56 reads: "*This, at first sight, implies that the annealing model is incorrect*". The text continues: "*On the other hand …*", and goes on to give possible reasons for the mismatch between the predicted and measured mean track lengths that need to be addressed, just as they have been for other annealing models. Which model people use is not our concern. Still, we insist that it is necessary to know the alternatives.

Sincerely,

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F. Trilsch

B. Härtel

T. Nagel