

FAIR fission track analysis with geochron@home

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Abstract. Fission track geochronology is based on the visual analysis of optical images. This visual process is prone to observer bias. Fission track datasets are currently reported as small data tables. The interpretation of these tables requires a high degree of trust between the fission track analyst and the user of the data. geochron@home is software that removes this requirement of trust. It combines a browser-based ‘virtual microscope’ with an online database to provide FAIR (Findable, Accessible,

5 Interoperable and Reproducible) access to fission track data.

geochron@home serves four different purposes. It can be used (1) to count fission tracks in ‘private mode’, i.e. hidden from other users on the internet; (2) to archive fission track images and counts for inspection by other users; (3) to create tutorials for new students of the fission track method; and (4) to generate crowd-sourced fission track data, by serving randomly selected selections of images to citizen scientists. We illustrate these four applications with examples that demonstrate (1)

10 geochron@home’s ability to compare and combine fission track counts for multiple users within a lab group; (2) the value of the geochron@home archive in the peer review system; (3) the use of simple tutorials in teaching novice users how to count fission tracks; and (4) the ‘wisdom of crowds’ in fission track identification.

geochron@home was written in Python and Javascript. Its code is freely available for inspection and modification, allowing users to set up their own geochron@home server. Alternatively, users who would like to upload data to the archive, but do not 15 have the facilities to set up their own server, may use the server at University College London free of charge. The archive accepts image stacks acquired on any type of digital microscope, and accommodates fission track data (counts and length measurements) from external fission track analysis suites such as Fission Track Studio and TrackFlow.

We anticipate that the introduction of FAIR workflows will make fission track data more accurate and more future proof. Storing fission track data online will benefit future developments in fission track thermochronology. For example, archival 20 datasets of peer reviewed fission track counts can be used to train and improve machine learning algorithms for automated fission track analysis. We hope that other geochronological methods will follow the fission track community’s lead in FAIR data processing. This would benefit all the other Earth Science disciplines that depend on geochronological data.

1 Introduction

Science is on an irreversible trajectory towards greater openness. Geochronology is no exception to this trend, as this journal
25 illustrates with its open access and review policies. Funding agencies increasingly demand that research results and data are shared with the public. Currently, geochronological data are generally provided as flat tables of dates or isotopic ratio estimates. However, in other fields of science such as physics, it is common practice to share the raw unprocessed measurements along with processing instructions (e.g., Abbott et al., 2016). This paper moves geochronology in the same direction. It presents a mechanism to generate and store fully FAIR (Findable, Accessible, Interoperable and Reproducible; Wilkinson et al., 2016)
30 data in the context of fission track analysis.

Unlike most other geochronometers, which require mass spectrometers to estimate parent-daughter ratios, fission tracks are observed under an optical microscope and counted by a human observer. In recent years, digital microscopy has moved fission track data acquisition from the objective lens of a microscope to the computer screen (Gleadow et al., 2009; Van Ranst et al., 2019; Gleadow, 2019). Ongoing developments in artificial intelligence generate further opportunities to improve the throughput
35 and accuracy of fission track data (Nachtergaele and De Grave, 2020). But despite the richness of the digital datasets produced by these novel tools, fission track data are still reported as small summary tables. These tables require an unnecessary degree of trust between the ‘producer’ and ‘consumer’ of the data.

geochron@home is a free and open software platform that allows geochronologists to share their raw fission track data over the internet for perusal by peer reviewers, colleagues and the general public. geochron@home is a virtual petrographic
40 microscope connected to a database with digital image stacks of etched fission track samples. The platform can be used to acquire, archive and inspect fission track data in full adherence to the FAIR data principles. In Section 2, we will describe geochron@home’s software architecture in five steps. We will show that this architecture accommodates imagery from any type of digital microscope. It enables flexible workflows that can be adapted to four different applications.

Using image stacks of Mount Dromedary apatite, we will show how geochron@home can be used to count fission tracks
45 in ‘private mode’ (Section 3); to archive published fission track datasets in ‘public mode’ (Section 4); to build tutorials for training purposes (Section 5); and to crowd-source fission track data on the internet (Section 6). Because geochron@home is free and open, it can be extended and improved by any interested party. We make some suggestions for future improvements in Section 7. We hope that the geochron@home’s example will be followed in other geochronological disciplines, as this will benefit not only geochronology itself, but all the other disciplines that depend on it (Section 8).

50 2 Workflow

The geochron@home workflow separates the acquisition of microscope images from their analysis, providing the flexibility to accommodate data from different microscope manufacturers. The workflow can be broken down into five steps.

1. Acquisition of z-stacks of microscope images in reflected and transmitted light for each of the grains in a sample and, optionally, for the accompanying external detector (Figure 1). At University College London, this first step is currently

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accomplished by a Python macro within Zeiss' Zen Blue software. However, geochron@home can also accommodate imagery from other platforms, such as Fission Track Studio (Zeiss; Gleadow et al., 2009) and TrackFlow (Nikon; Van Ranst et al., 2019).

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2. Prepare the z-stacks for uploading to the geochron@home database. This database requires that the images are organised as a nested sequence of directories, in which a 'project' consists of 'samples' that comprise a number of 'grains'. Each grain corresponds to a numbered sequence of .jpeg images, one for each layer of the z-stack. Note that the raw microscope images are generally not stored as .jpeg files but in uncompressed .czi (for Zen Blue), .tif (for Fission Track Studio) or .nd2 (for Nikon/TrackFlow) formats. Conversion from these raw images to sequences of .jpeg files is done with a shell script using ImageMagick (Still, 2006).

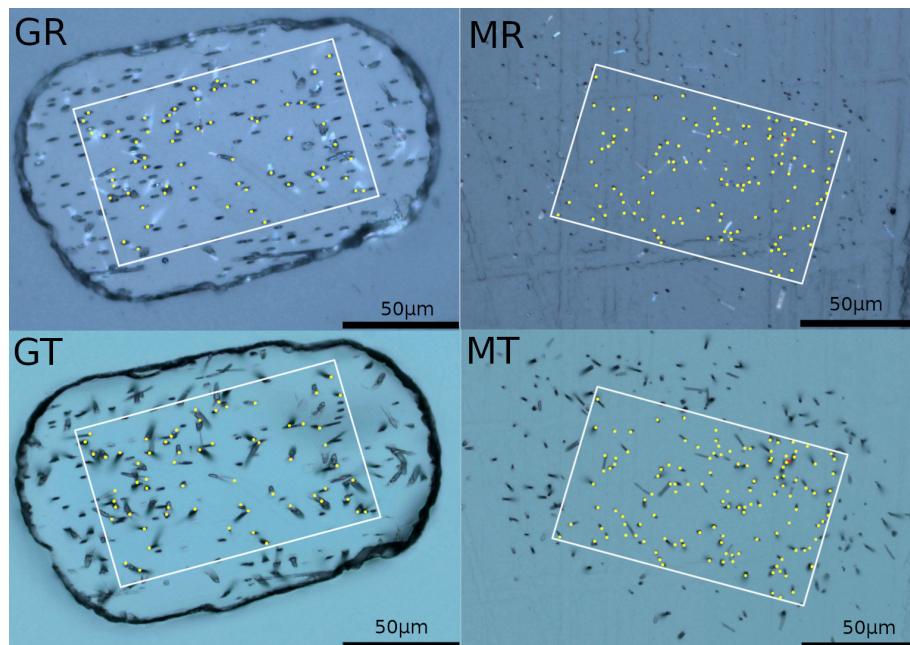
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In addition to the sequence of .jpeg images, a low level 'grain' folder can also include an optional file called `roi.json` containing the vertices of a default region of interest for spontaneous (and/or induced) track counting. The database structure can also accommodate existing fission track counting results. For example, if a user has already counted their fission tracks in Fission Track Studio, then they can store those results in a .json file at the 'sample' level directory. Because Fission Track Studio stores its results in an .xml format, a second conversion script is needed to translate those results into an equivalent .json format.

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3. Upload the data to the geochron@home platform. geochron@home is a Django web-app with a PostgreSQL database. The database can be accessed via a Python API and a (more limited) web-based GUI. Accessing the API requires administrator privileges. Administrators can create projects, samples and grains; download data; and set the access rights of 'ordinary' users. Projects can be private or public. The source code and installation instructions for geochron@home are freely available over GitHub (see the Data Availability statement at the end of this paper). This allows fission track users to set up their own server. Alternatively, fission track labs can upload their data to the UCL server by contacting the corresponding author.
4. Analyse the images with a browser-based 'virtual fission track microscope' powered by the Leaflet library (JavaScript). This virtual instrument acts as a front-end to geochron@home. It has a simple user interface with controls to zoom, pan and focus in or out of the digital image stack. Depending on the permissions granted to the user by the administrator, the virtual microscope offers a number of different options. Entry level 'ordinary' users are only allowed to count tracks by clicking within a pre-defined 'region of interest'. In contrast, 'superusers' are allowed to define their own regions of interest. Once the user is satisfied that they have counted all the fission tracks in a particular grain, they can submit the results to the server. They are then presented with a new set of images until all grains are counted.
5. Post-processing. The fission track data can either be downloaded as a flat data table of counts and area, or as a .json file containing the locations of all the counted tracks. geochron@home does not provide any tools to post-process these files. They are meant to be passed on to other tools such as spreadsheet applications or IsoplotR (Vermeesch, 2018).

The five-step workflow can be used for several applications, including (1) conventional fission track analysis; (2) archiving published fission track results; (3) building tutorials; and (4) crowd-sourcing fission track data. The next sections of this paper will illustrate these four different applications with real world examples.



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Figure 1. Screenshots of raw fission track data for the external detector method in geochron@home. GR: an apatite grain in reflected light; GT: the same grain in transmitted light; MR: the corresponding mica detector in reflected light; MT: the mica detector in transmitted light. White rectangles mark the region of interest (ROI), within which an analyst has counted fission tracks by marking their etch pits (shown in yellow). The raw data for this figure can be viewed on the geochron@home archive (<https://github.com/pvermees/GaHa>).

3 Counting fission tracks in ‘private mode’

Administrators can define regions of interest (ROI) and count or edit the fission track coordinates of any grain in a geochron@home database. They can also assign other users to groups, and give these groups access to a subset of the projects in the database. Administrators have fine control over the permissions of the groups. For example, they can allow the members of one group to 95 define their own ROIs, whilst requiring members of another group to count fission tracks in predefined ROIs. Groups provide a mechanism to compare and combine the results of multiple analysts of the same sample. Figure 2 illustrates this with two sets of fission track density estimates (in tracks per μm^2) for the same sample of Mount Dromedary apatite (Green, 1985), analysed by two users (PV and AC).

Let N_1 and N_2 be the numbers of spontaneous tracks counted by PV and AC over areas A_1 and A_2 , respectively. Then their 100 estimated track densities are given by $\hat{\rho}_1 = N_1/A_1$ and $\hat{\rho}_2 = N_2/A_2$. In this situation when the two areas overlap, N_1 and N_2 cannot be treated as independent Poisson counts because the two analysts will count some of the same tracks. It can be shown

that, under simple (ideal) assumptions, the uncertainty of the ratio of the estimated track densities is given approximately by

$$\frac{\text{se}(\hat{\rho}_1/\hat{\rho}_2)}{\hat{\rho}_1/\hat{\rho}_2} \approx \sqrt{\frac{1}{N_1} + \frac{1}{N_2} - \frac{2N_0}{N_1 N_2}} \quad (1)$$

where N_0 is the number of tracks counted by both observers in the area of overlap (A_0 , say) between their respective ROIs.

105 The radial plot of Figure 2b contains two sets of counts, with $\sum N_1 = 686$ and $\sum N_2 = 679$, and a weighted mean track density ratio $\hat{\rho}_1/\hat{\rho}_1 = 0.94$ with relative standard error 0.013. PV counted 600 tracks in those common areas A_0 , of which 549 were also counted by AC. Conversely, AC counted 622 tracks of which 549 were also counted by PV. The ratio of the two analysts' track density estimates based just on the common area is therefore $600/622 = 0.965$ with relative standard error 0.016, calculated from Equation 1. This is close to the weighted mean ratio of 0.94 (Figure 2b), and is slightly nearer to 1. It
110 indicates that PV under-counts the Mount Dromedary apatite by 3.5% relative to AC. The existence of 'observer bias' is well documented (Tamer et al., 2025). It is one of the reasons why fission track analysis is often done relative to age standards: observer bias does not have to be a problem provided that it is consistent between grains, and between samples.

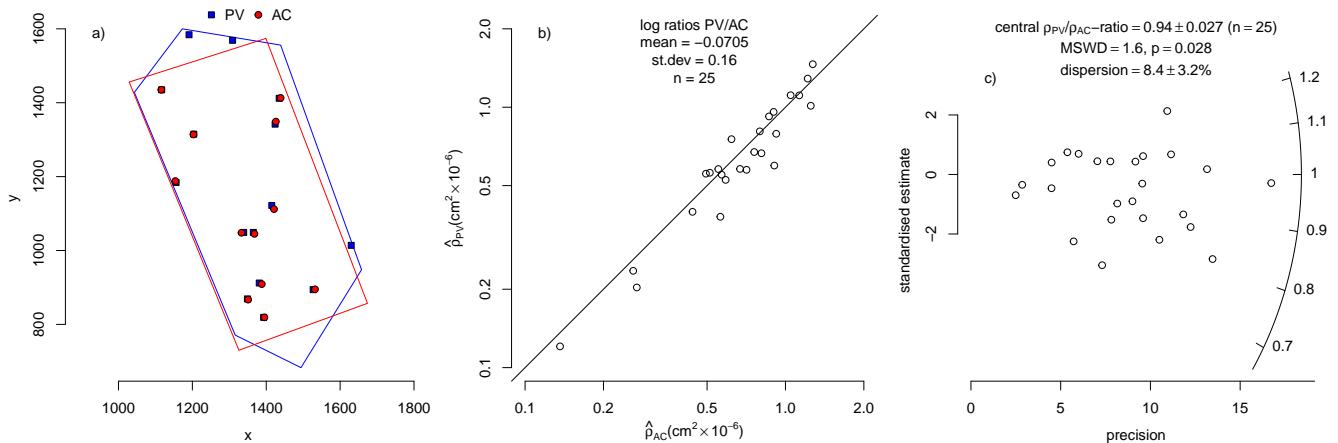


Figure 2. Comparison of fission track data for Mount Dromedary apatite by two analysts (PV = Pieter Vermeesch and AC = Andrew Carter). a) the track counts and ROIs of both users for grain 4648, shown in blue (PV) and red (AC); b) comparison of the track densities for PV and AC for all 25 grains analysed by the two analysts with a reference line for $\hat{\rho}_{\text{PV}} = \hat{\rho}_{\text{AC}}$; c) radial plot of the same data, using Equation 1.

4 The geochron@home archive (GaHa)

115 Once a set of fission track images has been analysed and the analyst is confident that the results are accurate, the status of the results can be changed from private to public. This makes the results visible over the internet as a list of URLs, where each grain number and user ID corresponds to a unique address. The geochron@home archive (GaHa) brings fission track geochronology into the era of FAIR science. It allows peer reviewers to inspect the raw data from which thermochronological inferences are made. The archive is open to submissions from any fission track laboratory, free of charge. However, as mentioned in Section 2,
120 it is also possible to establish a new archive elsewhere. At the time of writing, GaHa contains data for three studies:

1. Guo et al. (2025): this is an LA-ICP-MS based fission track study of detrital apatite from the northeastern Tibetan Plateau. It contains image stacks of semitracks in 1146 apatite grains from 16 different samples.

2. Tamer et al. (2025): this is a round-robin study in which digital image stacks of 44 apatite crystals were circulated among 14 different analysts. These analysts used the FastTrack image analysis software (which is part of the Fission Track Studio suite; Gleadow et al., 2009) to define their own ROIs and count the semitracks and horizontally confined fission tracks in them. GaHa presents the results of the round-robin experiment as a 44×14 grid of URLs.

3. This study: All the raw fission track data used in this article are available on GaHa, along with the post-processing software that was used to produce the figures. Together, these resources provide the reader with all the information needed to fully reproduce our results, ‘from cradle to grave’. To our knowledge, this is the first geochronological study to do so.

5 geochron@home tutorials

Given the right permissions (assigned by an administrator), users can build tutorial pages by annotating features in fission track images. These features can be tracks or other objects such as scratches, inclusions, dislocations or holes. A selection of tutorial pages is presented to new users when they first log into geochron@home. They must complete the tutorial before being allowed to count fission tracks. The tutorial pages can be revisited at any time by visiting the corresponding link on the geochron@home landing page.

The annotations in the current tutorial pages were made by an experienced fission track analyst (Andrew Carter). This basic tutorial provides a quick and easy mechanism to train novice users in the art of fission track analysis. The tutorial pages are in their infancy, and offer only a limited degree of interactivity. Users can click on features to read the annotations. The tutorial will grow with input from experienced analysts and future plans include the addition of fully interactive ‘quizzes’ (Section 8). The limitations of the current tutorials are apparent in the results of the crowd-sourcing experiment described in the next section of this paper.

6 Crowd-sourcing fission track data

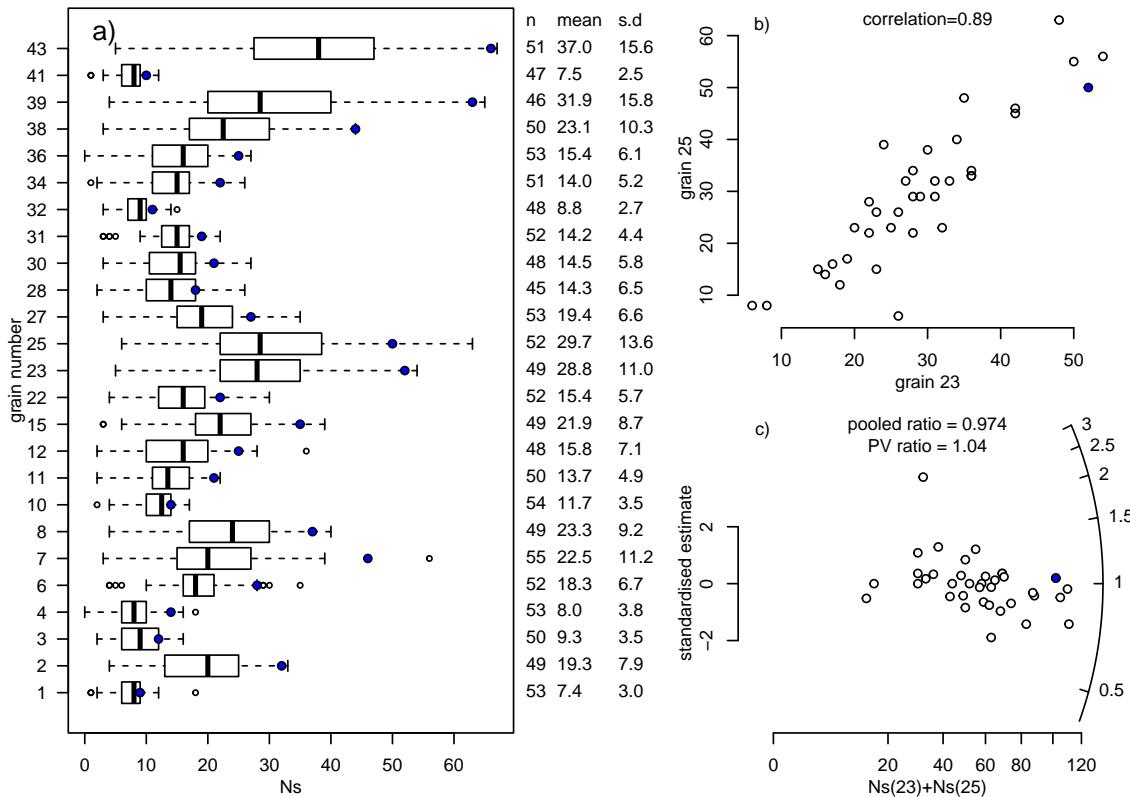


Figure 3. a) Box plots and summary statistics of numbers of spontaneous fission tracks counted in each of 25 grains by 68 novice counters (geology students) all using the same ROIs. Each student counted tracks in a subset of the grains. b) The track counts for Grain 23 plotted against those for Grain 25 for 37 students who counted both of those grains. c) Radial plot of the ratios of the counts in panel b) using the precisions given by Equation 2. In each panel, the counts made by PV are added as blue dots.

145 In 1906, Sir Francis Galton visited a county fair in which a contest was held to guess the weight of an ox. 787 people participated in the event. Galton discovered that the median of all their estimates was within 0.8% of the true weight of the ox and more accurate than 90% of the individual estimates. Such is the ‘wisdom of crowds’ (Galton, 1907). Similar effects are seen in fission track geochronology.

150 A 1984 interlaboratory comparison study (Miller et al., 1985) showed that the average of several fission track age estimates is closer to the known age of mineral standards than the age obtained by any individual observer. Unfortunately, routine measurement of fission track samples by multiple analysts is prohibitively expensive in a normal laboratory environment. geochron@home changes this, by bringing fission track analysis to a proverbial ‘county fair’ of citizen scientists.

Figure 3a shows box plots and summary statistics for the raw counts made by 68 students (two of the students were unable to complete the assignment) for the same selection of 25 grains that were analysed by AC and PV in Section 3. Everyone

155 counted tracks in the same ROIs, and counts made by PV for those ROIs have been added as blue dots. Variation between
the mean values is to be expected because of the differing numbers of tracks due to varying areas and uranium contents of the
grains. But the variation between counts within grains (shown by the standard deviations) is due entirely to differences between
the students' recognising and counting exactly the same tracks. These standard deviations increase with the mean number of
tracks and are considerable in size, being on average about 40% of the mean. Also, the vast majority of students counted fewer
160 tracks than PV did, often many fewer. In 21 of the 25 grains, PV's count is above the upper quartile of the students', and on 2
occasions someone counted no tracks at all. With expert trained counters one would expect much smaller differences between
counts. Nevertheless there are many repeated counts also.

165 Figure 3b shows a scatter plot of pairs of counts for two grains made by 33 students who counted both of them. They
average around 23 and 30 tracks per grain compared with PV's pair of 44 and 63, which is highlighted in blue. There is a
positive correlation between the pairs, consistent with systematic observer effects (i.e., people who count a low value in one
170 grain tend to count similarly low in the other, and vice versa). Comparing other pairs of grains shows similar results, with
correlations varying between 0.3 and 0.9. In all cases we have looked at, the residual variation, after allowing for systematic
differences between students, is consistent with Poisson variation. Figure 3c shows a radial plot of the ratios of the counts in
Panel b, using the precisions given by

$$170 \frac{\text{se}(N_1/N_2)}{N_1/N_2} \approx \sqrt{\frac{1}{N_1} + \frac{1}{N_2}} \quad (2)$$

The context here is rather different from that in Figure 2b, where we were comparing the ratios of counts made by 2 analysts
on each of 25 grains. Here we are comparing the ratios of counts for the same 2 grains made by each of 33 analysts. There is no
theoretical justification for Equation 2 here, but it still provides a useful benchmark for assessing variation between the ratios.
175 In Figure 3c, that variation is consistent with Poisson variation (as it is for most other pairs of grains) but with expert counters
one would expect less variation than that. However, in spite of the under-counting by the students, the pooled the students'
ratio of 0.76 is quite close to PV's ratio of 0.70. This happens quite often in this data set, but not always, and there are some
pairs of grains where the students' pooled ratio differs somewhat from PV's.

180 As mentioned in Section 2, geochron@home stores the actual track positions marked by the users. This raw data can be
downloaded as a .json file and inspected in detail. Figure 4 is a two-dimensional histogram for the x-y positions of all the
track positions generated by the students in the two apatite crystals. Visual comparison of the histogram with the optical image
confirms that the students unanimously identified the most obvious semitracks, which contain a clearly visible etch pit and tail.
Shorter and fainter tracks received fewer clicks. Datasets like this can be used to replace integer counts of fission tracks with
probabilities, reflecting the ambiguity of some fission track datasets.

185 Figure 4 also shows that some students counted the tails of the fission tracks rather than their etch pits, despite being told the
opposite in the tutorial. Fixing this issue will require some improvements to the tutorial pages (Section 7).

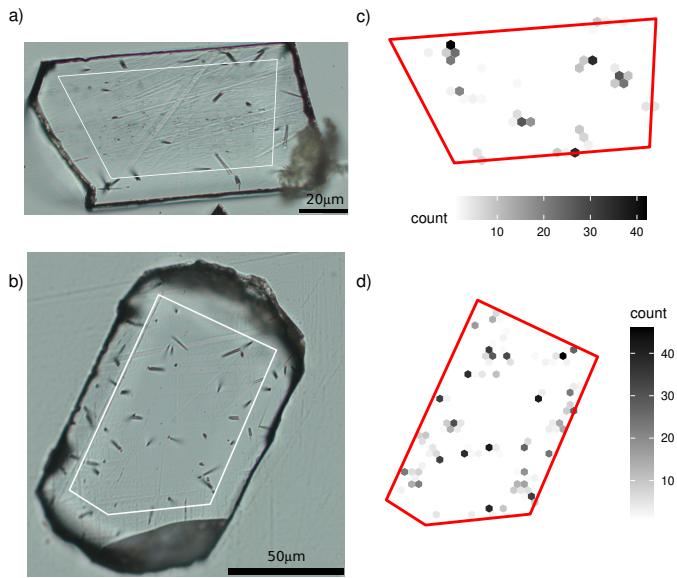


Figure 4. a,b) Optical images in transmitted light of Mount Dromedary apatites 4649 and 4673 in the crowd-sourcing experiment. c,d) Two-dimensional histogram of the track locations for the two grains, as identified by the citizen scientists.

7 Outlook

geochron@home has been in development for 10 years and remains a work in progress. Planned improvements include:

1. Interactive tutorial pages. To ensure that novice users do not count the tails but the etch pits of fission tracks, we will add a ‘quiz’ to the tutorial pages. Only users who click on the ‘correct’ features in an unlabelled set of images will be allowed to count new samples. The pilot data of the crowd-sourcing experiment show that, despite the large scatter of the raw track counts obtained by the citizen scientists, their pairwise ratio estimates scatter evenly around the expert opinion. This suggests that the collective wisdom of the entire group of students is greater than that of the individual analysts. When applied to a group that has achieved a good level of training and experience, crowd sourcing should improve the precision and accuracy of fission track data.
2. Length measurements. The geochron@home archive already contains horizontally confined fission track measurements (Tamer et al., 2025). However, these results must be generated externally (e.g., using Fission Track Studio) and uploaded via a .json file. The virtual microscope currently lacks the functionality to generate length data within geochron@home. This functionality will be added in a future update.
3. Dpar and Dper. Etch pits are currently stored as simple sets of x- and y-coordinates. In reality, etch pits have a finite length (‘Dpar’) and width (‘Dper’), which serve as useful indicators for the horizontal etch rates along the c-axis and parallel to it (Donelick, 1993). Functions will be added measure and visualise these type of data in geochron@home.

4. Machine learning. Data science is experiencing an artificial intelligence revolution that has already started to transform
the fission track method (Nachtergael and De Grave, 2020). Convolutional neural networks must be trained with exam-
205 ple data. geochron@home is ideally suited for this task. Section 6 showed how the collective wisdom of multiple fission
track analysts can label fission track images with probabilities rather than counts. This data format is close to the form
in which data are treated within an AI algorithm.

Once trained on historical data, AI algorithms can be used to count fission tracks automatically. Following the model of
Fission Track Studio (Gleadow et al., 2009; Gleadow, 2019), machine learning can be used to reverse the fission track
210 counting process. Instead of asking users to count the fission tracks in a sample, the software can ask them to check the
results proposed by an AI algorithm, and to remove any features that are *not* fission tracks.

Regardless of whether fission tracks were counted manually or with a machine, the value of the geochron@home archive
remains the same. It is important to document data so that samples can be reanalysed in the future, for example when a
new and improved generation of machine learning algorithms becomes available.

215 These four improvements will be made by ourselves pending additional funding. However, because geochron@home is free
and open software, we invite any interested parties to join the effort and extend or improve our code.

8 Conclusions

This paper introduced geochron@home, a software platform for FAIR fission track analysis. We demonstrated four different
applications of this platform using real data. Putting the FAIR data paradigm into practice, all the imagery, counts and source
220 code for this paper are publicly available. Using these resources, the reader can reproduce all the results that were presented
in this publication. We hope that other geochronologists will follow this example. FAIR data promises to address the repro-
ducibility crisis in science (Miyakawa, 2020).

geochron@home's rich archive of raw data can be reanalysed in the future. We anticipate that the adoption of FAIR data
processing workflows will open up new research opportunities. For example, archived pairs of peer-reviewed fission track
225 images and counts could be used to train the next generation of automated machine learning algorithms. Conversely, it is also
possible that future improvements in fission track images analysis will be used to update the count data for published datasets,
improved their accuracy.

Another advantage of the geochron@home workflow is the separation of image acquisition and image analysis. This separ-
ation reduces the hardware requirements for fission track geochronology. It opens up the possibility to share resources.
230 State-of-the-art digital microscopes are expensive. Using geochron@home, a single microscope can serve multiple users and
make fission track analysis more affordable.

The fission track method has always been a test bed for new geochronological developments. Because fission track data
are imprecise, the fission track community has solicited the help of statisticians and mathematicians to develop its analytical

protocols. Other geochronological communities are still catching up with concepts and tools such as overdispersion, mixture modelling and radial plots, which have been commonplace in fission track analysis for decades (Vermeesch, 2019). In a similar vein, the subjective nature of fission track identification has prompted the fission track community to organise inter-laboratory comparisons and round-robin studies long before other geochronological communities (Miller et al., 1985; Tamer et al., 2025).

With the development of geochron@home, fission track geochronology is once again ahead of the pack in terms of FAIR data analysis. geochron@home currently only stores images and counts. This is enough to reproduce the results of fission track studies using the external detector method, but not for LA-ICP-MS based data. FAIR data processing of LA-ICP-MS data requires a new generation of mass spectrometer data reduction software. We are currently working on this (Vermeesch, 2025). The development of FAIR ICP-MS data pipelines will not only benefit fission track analysis but other chronometers as well, such as in-situ U–Pb, Rb–Sr and Lu–Hf.

With the establishment of FAIR data, geochronology will be well placed to avoid the reproducibility problems that have plagued other fields of science.

Code and data availability. geochron@home is free software released under the GPL-3 license. The package and its source code are available from <https://github.com/pvermees/geochron-at-home> (last access: April 2, 2025). The raw data (imagery) are available at the geochron@home archive (<https://github.com/pvermees/GaHa>, last access: April 3, 2025). R-scripts to reproduce the figures are provided in the supplementary information (<https://github.com/pvermees/supplements>, last access: April 3, 2025).

250 *Author contributions.* Pieter Vermeesch designed the study, acquired the funding, counted fission tracks and wrote the paper. Jiangping He created geochron@home. Tim Band expanded geochron@home and wrote the accompanying microscope image acquisition software. Andrew Carter provided the samples, prepared the training data and counted fission tracks. Rex Galbraith derived Equation 1.

Competing interests. PV is an Associate Editor of *Geochronology*.

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