Some aspects of the application of image analysis to the study of fission tracks

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Abstract

Analysis and processing of electronic images generated using confocal scanning laser microscopy (CSLM) provide a new means of counting and determining the angular distribution of fission tracks in crystalline solids. Using image analysis techniques, large numbers of fission tracks in external mica detectors can be counted rapidly, while measurement of aspect ratio and area of a track entry hole at its intersection with a surface can provide a means of assessing the angle of inclination of individual tracks within minerals and plastics. CSLM imaging, combined with image processing, offers a new and powerful way of probing the surfaces and interiors of crystalline materials. The techniques might also prove useful in the study of fluid inclusions and chemical zoning patterns in minerals.

KEYWORDS: confocal microscopy, fission tracks, image analysis, external detectors.

Introduction

FISSION tracks are micrometre sized linear damage trails that form in uranium bearing minerals through the spontaneous decay of atoms of ^{238}U. Since their discovery in the late 1950s (Silk and Barnes, 1959), they have been used extensively in dating geological and archaeological materials, and more recently as a means of estimating burial and uplift rates in mountain belts and sedimentary basins (Wagner and Van den haute, 1992). From a practical point of view two of the main tasks encountered in fission track dating are the recognition of tracks and their counting. Skill in recognition comes from experience, but counting takes time, which in extreme circumstances can take up to 40 man hours per sample (Fleischer *et al.*, 1975). In recent years a number of allempts have been made at developing automatic track counting methods using conventional microscopy (Birkholtz *et al.*, 1989; Rebetez *et al.*, 1991) but none has proved entirely successful. The development of image analysis has added fresh impetus to this field of endeavour (Petford and Miller, 1992, 1993). Much of the difficulty has arisen from the quality of images produced from the conventional light microscope which is an instrument suited ideally to the examination of two-dimensional objects. In the instance of 3D targets, the depth of focus characteristics mean that while part of the object is in focus other parts are not and although such images can be recognised by eye they can present problems when subjected to image analysis. With suitable programming, it might be possible to process images of this sort, but it is an advantage to supply the system with clear and apparently two-dimensional images. In this contribution we outline how the technique of confocal scanning laser microscopy (CSLM), combined with image processing can be used to count and measure large numbers of fission tracks quickly and provide information about their shape and angular distribution. We also show how the unique information provided by CSLM-image analysis has allowed us to use equations to correct fission track counts for tracks lost during the etching of external mica detectors.

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Confocal Scanning Laser Microscopy (CSLM)

A large amount of technical literature exists on the theory and practice of confocal microscopy and

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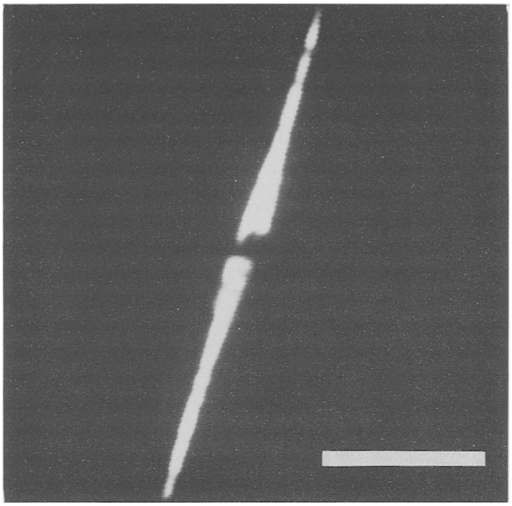

FIG. 1. Confocal scanning laser microscopy (CSLM) grey-scale image of a confined, horizontal fission track in apatite. Scale, 4 μm.

readers interested in the finer details of the technique are referred to Wilson (1990) for an excellent summary of CSLM. In essence, the confocal lens arrangement involves focusing light from the objective and source at the same point within the specimen to produce an image with a very shallow (± 100 nm) depth of field.

Using scanning laser light (wavelengths 488–633 nm) we have been able to produce images of fission tracks in both minerals (Fig. 1) and mica detectors (Fig. 2) successfully (see also Petford and Miller, 1990, 1992; Petford *et al.*, 1993). While it is possible to build up a stack of electronically recorded images to produce stereographic views of tracks and to determine their length and angle of inclination (Petford and Miller, 1992), the process is slow and does little towards the objective of general track recognition and counting (Fig. 3). However, our results have shown that etched tracks in micas are rod-like features and usually not the etch pits often depicted in the literature (Petford and Miller, 1992). In CSLM, the instrument can be focused just below the surface of the specimen but within the restricted depth of focus to provide a clear picture of track exit/entry holes depending upon whether it is a mineral or an external detector being viewed (see Figs 1 and 2). In order to describe progress made so far, much of this account is restricted to our work on the measurement of tracks in external detectors.

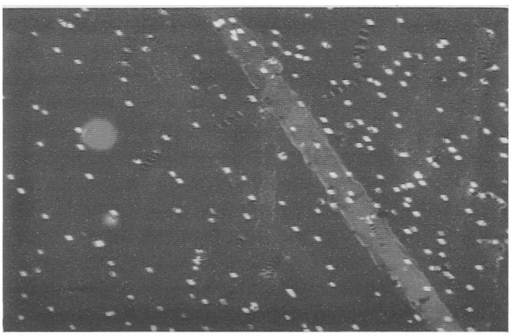

FIG. 2. Greyscale-enhanced CSLM image of the surface of an etched mica external detector. Diamond-shaped track entry holes are highlighted in white. Images formatted in this way allow individual track etch pits to be counted rapidly. Surface area and aspect ratio can also be measured. Scale bar, 10 μm.

Image analysis

A practical means of counting fission tracks in external mica detectors using image analysis has been given recently by Petford *et al.* (1993). Five steps are involved in the analysis: (1) CSLM image generation, (2) image procurement, (3) segmentation, (4) measurements, and (5) data manipulation and analysis. Images from the confocal microscope are either procured as hard copy or are more conveniently held in electronic format. Electronically stored images have the advantage in that they can be read directly into the image analysis system and stored as XYZ pixel elements. Most electronically recorded CSLM images are stored as tagged image format files (TIFF). A typical CSLM image containing fission track data is approximately 350 kbytes in size with a picture element width of 768 pixels and a height of 512 pixels (Petford and Miller, 1992). If large numbers of (2D) optical slices are being made for reconstruction into a three-dimensional Z-series, correspondingly large amounts of storage space are required. In our experience, we have found optical disks the most effective storage medium, although read-write CD ROMs might in the future provide better storage facilities.

The ability of CSLM to make non-destructive optical sections within the interiors of crystalline materials is demonstrated in Plate 2*a–f* (see colour-plate section) which shows a stacked Z-series comprising six optical slices taken at 0.5 μm depth intervals through the horizontal, confined fission track shown in Fig. 1. The sequence also provides an example of how image analysis techniques can be used to good effect in enhancing simple grey-scale images. Thus, each optical slice has been processed in false colour in order to highlight the fine detail present within each image. The range in colour

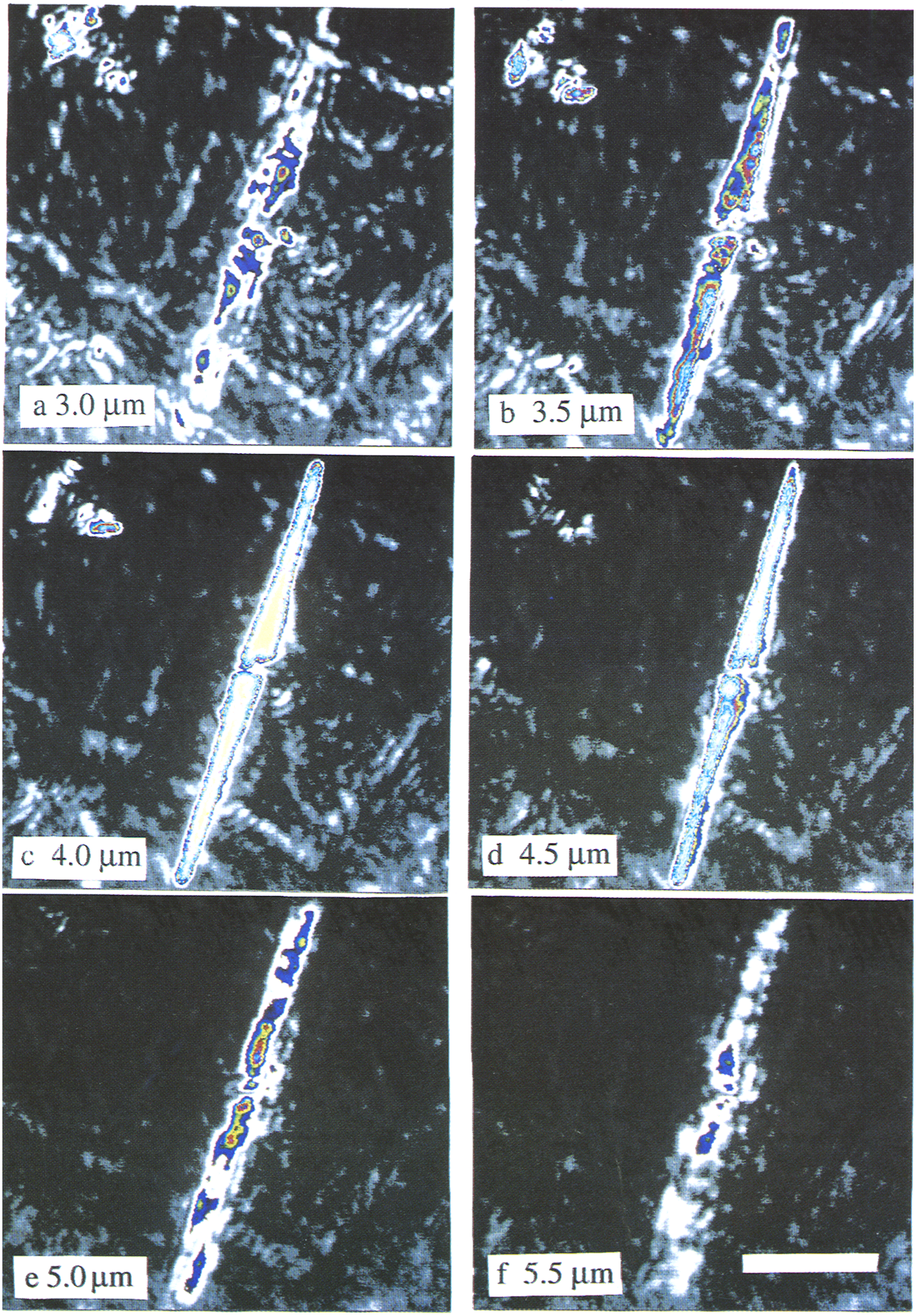

PLATE 2. False colour Z-series through an etched horizontal (confined) fission track in apatite. The sequence starts 3.0 µm inside the grain (a), and continues at steps of 0.5 µm to a depth of 5.5 µm (f). Maximum pixel intensity (yellow) occurs at approximately 1.0 µm inside the track (image c), which has a measured thickness of 2.5 µm. Scale bar, 2.0 µm (*a–d* reproduced from Petford and Miller (1992), Fig. 5, with permission).

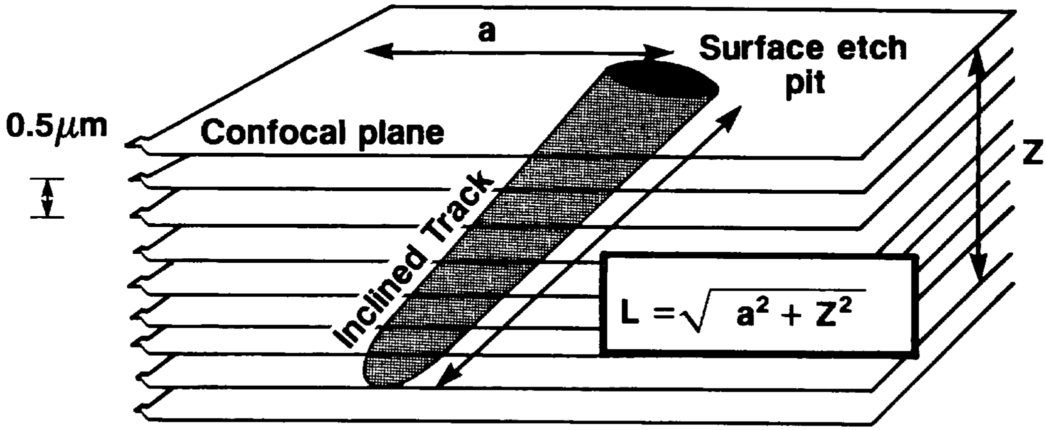

FIG. 3. Cartoon showing how the true length (L) and angle of inclination of an etched, inclined fission track (shaded) can be determined from a stacked sequence of CSLM images. The inclined track is traced along its length at increments of 0.5 μm to a depth in Z of 4.0 μm. Determination of Z allows the true track length to be found using Pythagoras theorem.

relates to pixel intensity. Image 2*a* was taken at 3.0 μm below the surface of the sample (an apatite grain from the Fish Canyon Tuff). Maximum pixel intensity occurs at a depth of 4.0 μm (image 2*c*, *c*. 1.0 μm inside the fission track), with pixel intensity and track definition becoming progressively less distinct thereafter. At depths > 5.5 μm (image 2*f*), the track is no longer visible. Measurement in XY and XZ show the track to be approximately 12.3 μm long and ~ 2.5 μm thick.

Outline of the problem

To produce fission track ages it is necessary to count the number of tracks per unit area of mineral and to provide a measure of the mineral's uranium content. Tracks in minerals are exposed by chemical etching. The uranium content is usually measured by irradiating the mineral in contact with a low uranium mica external detector, then exposing the induced tracks by chemical etching (for details of procedures see Fleischer *et al.*, 1975 and Wagner and Ven den haute, 1992). Problems arise as the result of the different ways in which minerals and detectors respond to the etching process (Vincent *et al.*, 1984, Fig. 11).

Tracks are exposed because the damaged material comprising the tracks will etch away faster (V_T) than the surface of the minerals containing the track (V_S). It is well known that tracks having angles of inclination $\sin\theta < V_S/V_T$ will be lost (Fleischer *et al.*, 1975). In minerals, a steady state is reached during etching such that only those tracks are destroyed. In external detectors the problem is more serious because all tracks originate externally and the number that remain after etching will depend upon the duration and nature of the etching conditions. Etch for long enough and all will be destroyed.

To circumvent these problems it is necessary to correct counts from both minerals and detectors for tracks lost, otherwise the age obtained will be influenced by the particular technique adopted. To do this the minimum retained angles of tracks in both mineral and detector must be measured, which has so far not been possible without image analysis. The problem is compounded by the fact that minerals and mica detectors have crystalline structures and do not produce circular or elliptical holes as would plastics and glasses when etched. For these simple cases, the angle of inclination of the track is:

$$\sin\theta = 1/R \qquad (1)$$

where R is the aspect ratio of the cross section of track subtended at the surface of the sample (Petford *et al.*, 1993).

The analysis of fission tracks in external detectors

In etched external mica detectors, the track entry holes have a diamond shape resulting from the symmetry of the mica lattice [001] plane (Fig. 2). It has proved possible to count thousands of track entry holes in seconds and selection criteria can be applied to recognize overlapping holes. Aspect ratios, areas and XY coordinates of individual tracks can be measured and the first two of these variables plotted against their frequency of occurrence (Petford *et al.*, 1993).

It can be shown by geometry that the sine of the angle of inclination of a track is equal to the cross sectional area of the track divided by the area subtended at the surface; the shallower the angle, the greater the area subtended. While it is relatively straightforward to use image analysis to identify the largest area subtended and verify that it does not comprise overlapping tracks the determination of true cross section is not so simple. It could be argued that vertical tracks would subtend the smallest area but this is unlikely to be the case as the smallest could be a pit representing the tip of a track that originated at distance. A good approximation of cross sectional area can be obtained from the mode value of area, θm (Miller *et al.*, 1993*a*). In an unetched detector, the tracks of most common area (A) would have an angle of inclination of 45°. The cross sectional area of such tracks would therefore be equal to 0.707A (0.707 = sin 45°).

Using this value and the largest area of track subtended, a close but approximate value of the minimum retained angle (ϕ) can be calculated from:

$$\phi = \sin^{-1}\left[\frac{\cos^2\theta_m - \sin^2\theta_m}{\sin\theta_m}\right] \tag{2}$$

where θ_m is the mode angle (Miller *et al.*, 1993*a*). A revised value for θ_m can be derived which allows a refined value of A to be calculated to provide a better estimate of minimum retained angle ϕ. The mode angle will increase as the minimum retained angle increases (Fig. 4).

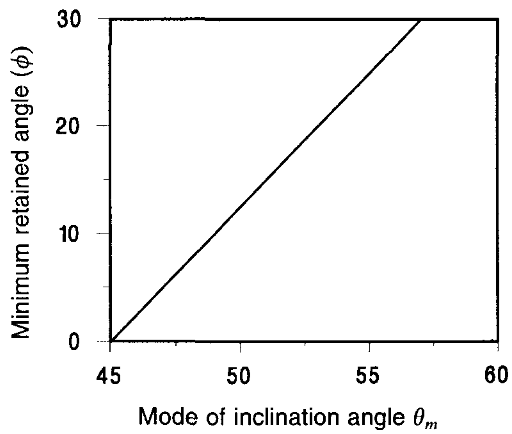

FIG. 4. Plot showing the relationship between minimum retained angle (ϕ) and the mode of inclination angle. The mode of the inclination angle (θ_m) increases with increased etching (see text and eqn. (2)).

Perhaps a better means of determining A in that it involves more data is to consider the frequency distribution of the cross sectional area of vertical tracks. If it is assumed that tracks have constant cross sectional area for most of their lengths but have tapered extremities (Petford and Miller, 1992, 1993) there is a greater chance of the body of the vertical track intersecting the surface of the detector than the tip. It has been shown that experimental results and computer simulation of this assumption appear in good agreement (Miller *et al.*, 1993*b*). Direct measurement of cross sectional area and most frequent area allow a direct measurement of θ_m to be made. The value of ϕ can be determined directly using equation 2. Such calculations allow the number of tracks counted per unit area to be corrected for those lost during etching from:

$$N = \frac{C}{2[\frac{1}{4}(1+\cos 2\phi) - \sin\phi + \sin^2\phi]} \tag{3}$$

(Miller *et al.*, 1993*b*), where N = original number of tracks per unit area prior to etching, and C = tracks counted per unit area. Results obtained so far on two samples of external mica detector have suggested values of ϕ = 9.8 and 10.0°, giving track losses of 31.1% and 31.7% (Miller *et al.*, 1993*b*). These findings have major implications for fission track dating and perhaps also for the use of CR-39 type plastics in environmental monitoring.

Conclusions

We conclude that with the use of CSLM and image analysis, progress can be made in quantifying some of the procedural problems encountered in fission track dating and environmental monitoring using CR-39 plastics. The reported combination of CSLM and image analysis techniques developed for studying fission tracks might also prove useful in the study and quantification of other crystalline defects such as fluid inclusions and zoning patterns (Petford **et al.**, 1995), where 3D analysis might provide important information about their internal distribution.

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